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EFFECT OF SOIL SUCTION AND MOISTURE ON RESILIENT MODULUS OF SUBGRADE SOILS IN OKLAHOMA

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ABSTRACT

The present study focuses on evaluating the effect of post-compaction moisture content on the resilient modulus of selected soils in Oklahoma. The soils are selected to represent a wide variation of soil types in Oklahoma. The resilient modulus tests were performed on specimens compacted and subjected to a wetting and drying process. After the completion of resilient modulus testing, the filter paper tests are performed in accordance with the filter paper technique. The same technique is used to establish the soil-water characteristic curves.

Results for the tested soils, namely, Burleson, Binger, Kirkland, Port, Minco, Sandy soil, Kingfisher, Renfrow, showed that the resilient modulus (M_r) exhibited a hysteric loop with moisture variations. The M_r values due to wetting are lower compared to the corresponding values after drying. It was also found that the initial compaction moisture content followed by drying or wetting affect the hysterics loop of both SWCC and the Mr-moisture variation curve (MrMC). It was also observed that the resilient modulus increased as the soil suction increased; however, such increase varies from one soil to another.

This study generated useful information that would enrich the database pertaining to resilient modulus and suction of selected soils in Oklahoma. An enriched database would benefit highway agencies, specifically pavement engineers, when dealing with construction of new pavements or rehabilitation of existing pavements. It will also facilitate the implementation of the new AASHTO 2002 pavement design guide.

1.1 Background

In recent years, interests in determining the influence of moisture changes on resilient modulus (M_r) of subgrade soils beneath a pavement have increased. This is due to the fact that the 1993 AASHTO Guide for Design of Pavement Structures recommended the use of a single M_r value to account for the seasonal variation in subgrade moisture content, known as the effective roadbed resilient modulus. Several studies have been undertaken previously to address the influence of moisture changes on M_r. For example, Li and Selig (1994) developed a new method to estimate the resilient modulus under different physical states, represented by moisture content and dry density. This model is generally applicable to compacted fine-grained subgrade soils. In a related study, Drumm et al. (1997) evaluated the effect of post-compaction moisture content on the resilient modulus of subgrade soils in Tennessee. All soils, ranging from A-4 to A-7-6 in accordance with AASHTO classification, exhibited a decrease in resilient modulus with an increase in the degree of saturation. The degree of reduction in M_r values varied with soil types. Consequently, they presented a method for correcting the resilient modulus value due to an increase in degree of saturation. More recently, Yuan and Nazarian (2003) investigated the effect of compaction and post-compaction moisture content on the modulus of base and subgrade soils.

Other previous studies have also recognized the importance of suction in pavement application. Kassif et al. (1969) reported that the post-construction changes in moisture content depend on the condition of soil (wet or dry, i.e., low suction or high suction) at the time of laying the pavement. Construction specifications usually require that subgrade soils be compacted in the field at or near optimum moisture content (OMC) and maximum dry density (MDD). As such, they should be treated as unsaturated soils. Tinjum et al. (1996) conducted a laboratory study to determine the soil-water characteristic curve (SWCC) for compacted clays. Other related studies (Mckeen, 1981; Nevels, 1995) have highlighted the importance of soil suction in evaluating the damage to pavements from expansive clay-type soil beneath a pavement structure.

Based on these and other related studies, it is evident that there is a need to examine the influence of moisture variations on resilient modulus and soil suction of compacted subgrade soils. The knowledge gained from such a study would be helpful in predicting the short-term and long-term performance of pavements. The experimental study reported herein addresses the variations in resilient modulus with post-compaction moisture content of selected sandy and clayey soils in Oklahoma due to wetting and drying processes. New laboratory procedures for wetting and drying of compacted specimens are suggested in order to establish correlations among M_r, moisture variation, and soil suction. The proposed procedures are significantly time-efficient than the existing procedures.

1.2 Objectives

The primary objective of the present study is to evaluate the effect of moisture changes and soil suctions on the resilient modulus of typical subgrade soils in Oklahoma. This will be achieved through the following:

- Determine AASHTO soil classification parameters, moisture-density relationship, and other relevant properties for each selected soil type.
- Determine the soil-water characteristic curve (i.e., moisture content vs matric suction) for selected soil series.
- Determine M_r values from cyclic triaxial tests on remolded (unsaturated) specimens with different moisture contents.

- Measure soil suction in specimens already tested for resilient modulus by using the filter paper technique.
- Develop regression correlations between resilient modulus and stress levels.
- Observe the variation of M_r and Suction with compaction and post-compaction moisture contents.

2.1 Selected Soils

A total of eight soils were selected and tested for this study. They were identified in close collaboration with the geotechnical engineer at the Oklahoma Department of Transportation. The selected soils belong to the following series: (1) Burleson; (2) Binger; (3) Kirkland; (4) Minco; (5) Port; (6) Kingfisher; (7) Renfrow; and (8) a natural sand collected from an existing project, in Stephens County, Oklahoma.

2.2 Materials and Classification Tests

Classification tests, namely liquid limit, plastic limit and gradation were performed according to the AASHTO tests methods. Results show that Burleson is an A-7 soil with a Liquid Limit (LL) of 55% and Plasticity Index (PI) of 30%. Binger is a non-plastic soil. Kirkland has a LL and PI of 50 and 30, respectively. It is classified as an A-7 soil. Minco, which is a silty soil, has a LL of 25% and a PI of 8%. Port series was named by the state legislature as the Oklahoma State Soil. It occurs in 33 counties and covers about 1 million acres in Oklahoma. The Port series has an average liquid limit of approximately 35% and a plasticity index of approximately 14%. The Kingfisher soil was collected from Norman, Oklahoma. It is classified as a lean clay with a LL of 39% and a PI of 11%. The Renfrow series, a lean clay with sand soil, has a LL of 35% and a PI of 20%. The last soil was collected from an existing project, located in Stephens County, Oklahoma. For convenience, this soil is called Stephens soil in this report.

2.3 Proctor Test

Proctor tests were performed in accordance with the AASHTO T 90 test method to establish the moisture-density relationships. The moisture-density curves are presented in

Figures 2-1 through 2-8. A summary of the optimum moisture content and maximum dry density is presented in Table 2-1. From Table 2-1, it is evident that Burleson has the highest OMC and the lowest MDD, 23.5% and 95.6 pcf, respectively, while Binger has the highest MDD of 113.5 pcf and lowest OMC of 12.5%.

Table 2- 1 A summary of OMCs and MDDs

Soil's name	OMC (%)	MDD (pcf)
Burleson	23.5	95.6
Binger	12.5	113.5
Kirkland	19.0	104.3
Minco	12.75	112.5
Port	14.5	110.7
Kingfisher	16.5	110.5
Renfrow	16.5	105.5
Stephens	12.8	105.6

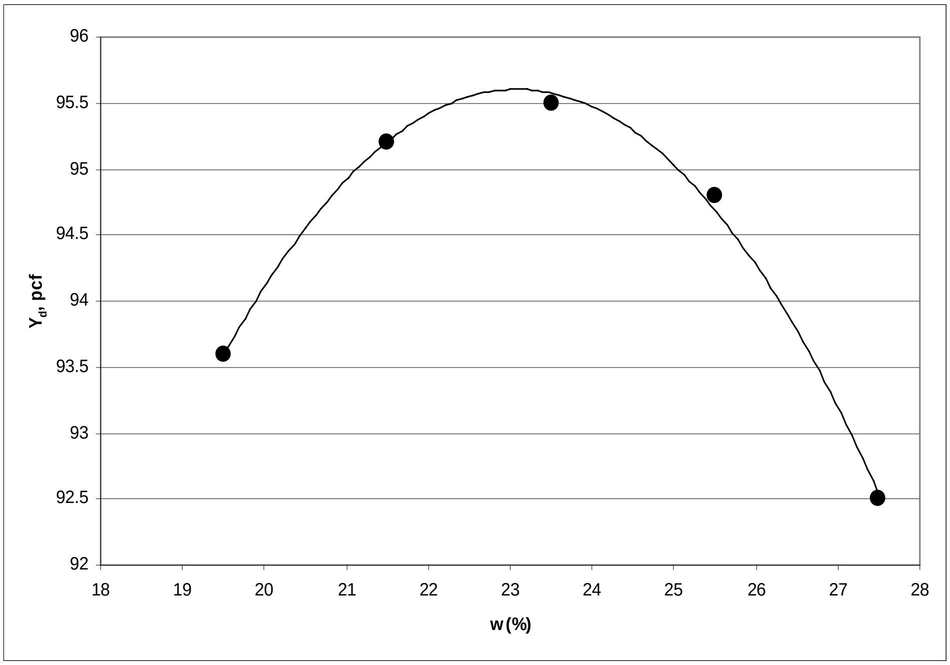

Figure 2-1 Moisture-Density Relationship for Burleson Series

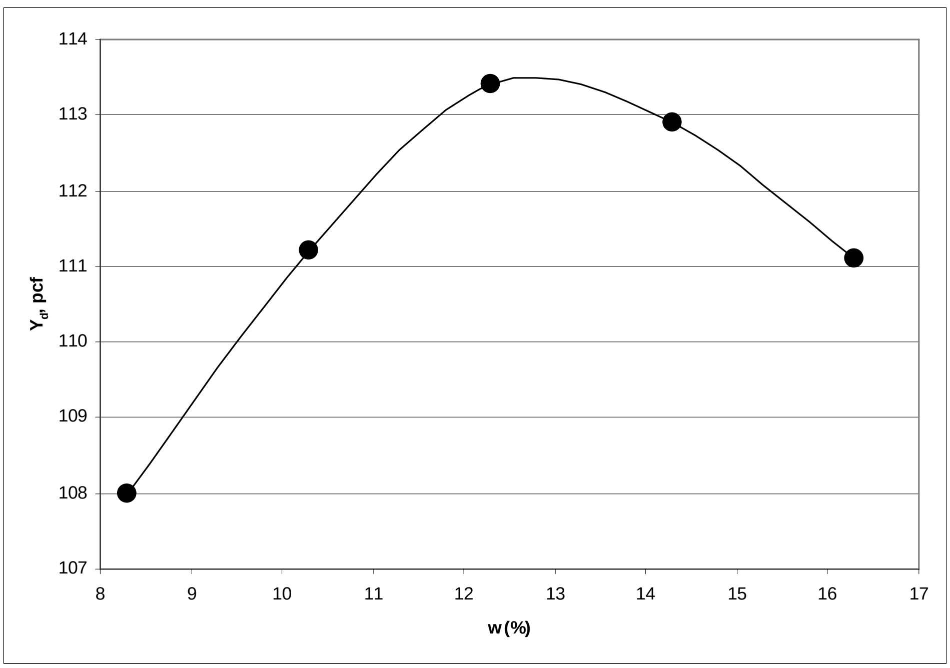

Figure 2-2 Moisture-Density Relationship for Binger Series

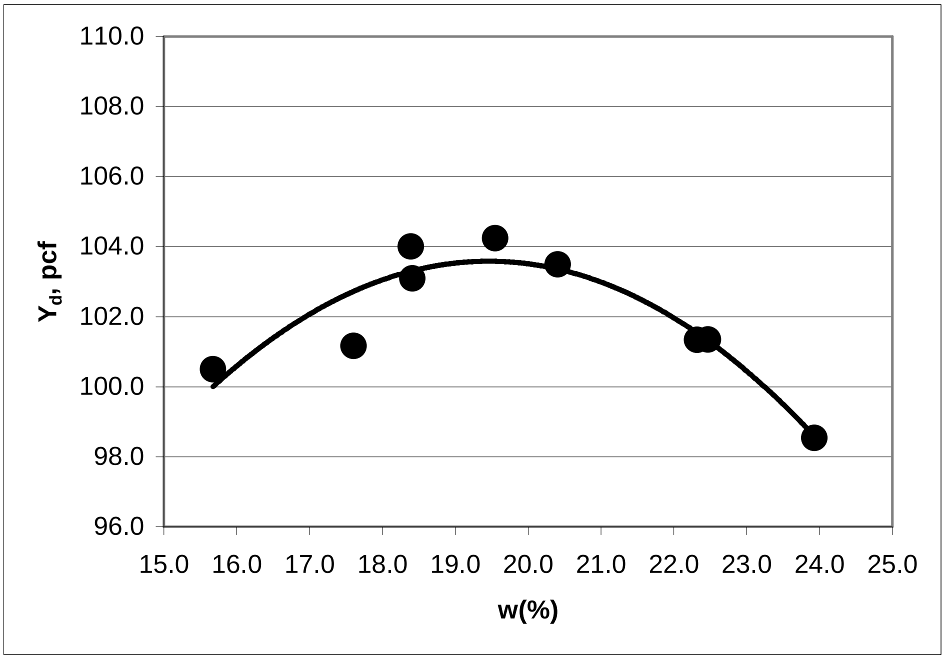

Figure 2-3 Moisture-Density Relationship for Kirkland Series

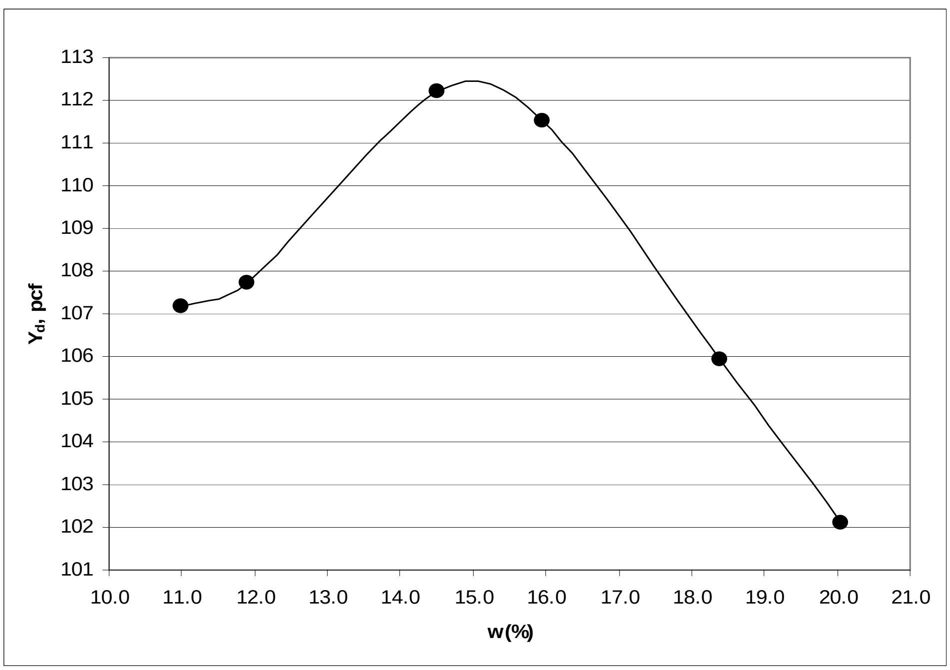

Figure 2-4 Moisture-Density Relationship for Port Series

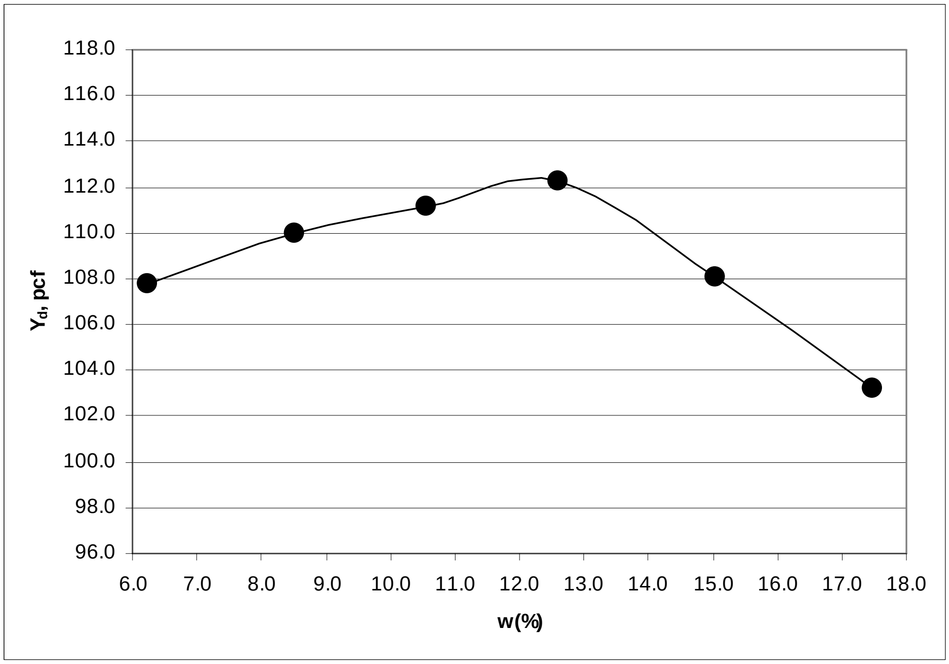

Figure 2-5 Moisture Density Relationship for Minco Series

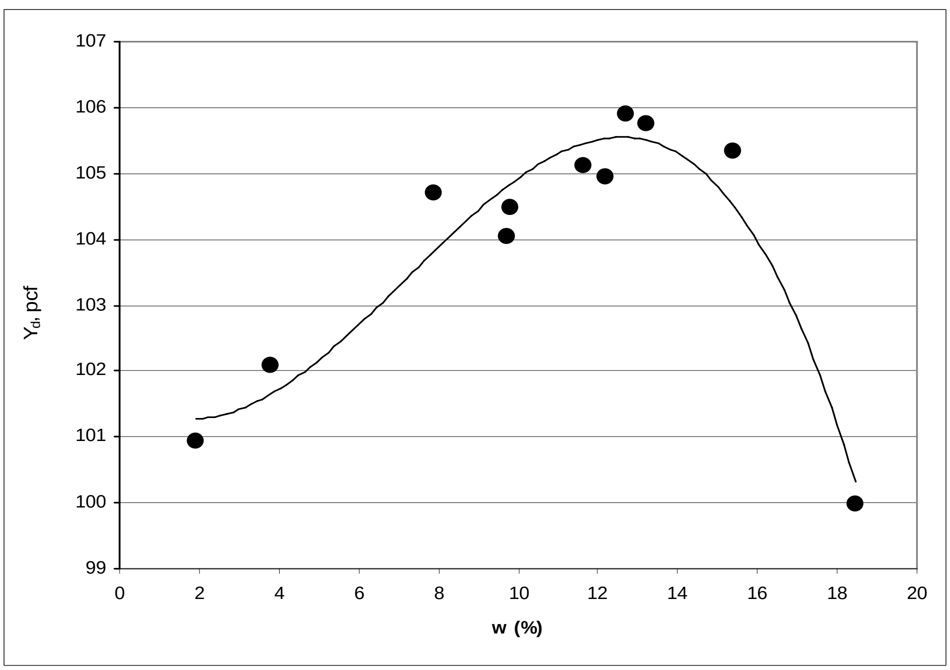

Figure 2-6 Moisture-Density Relationship for Stephens Soil

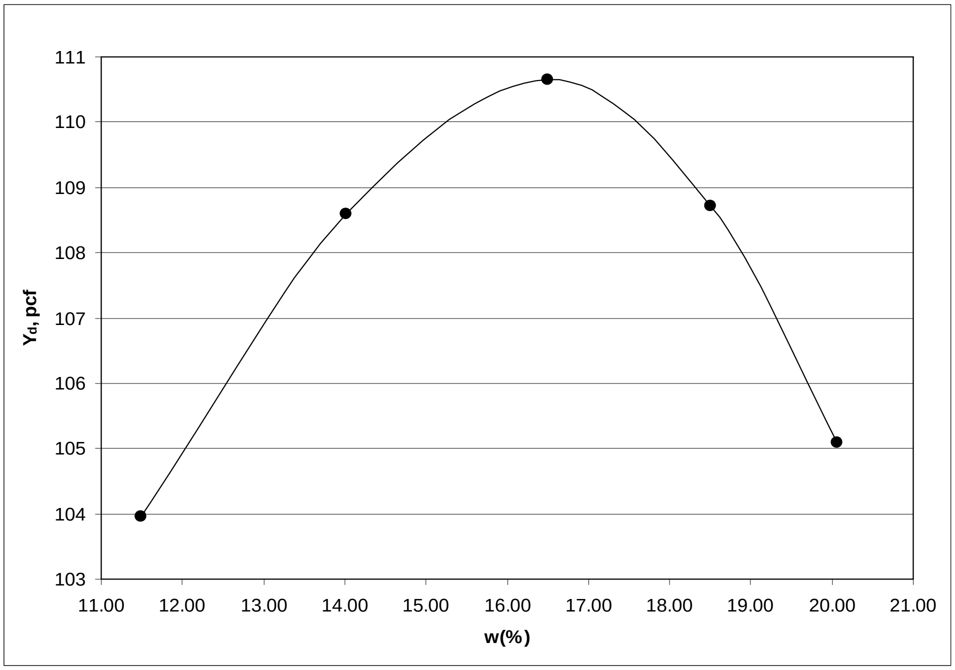

Figure 2-7 Moisture-Density Relationship for Kingfisher Series

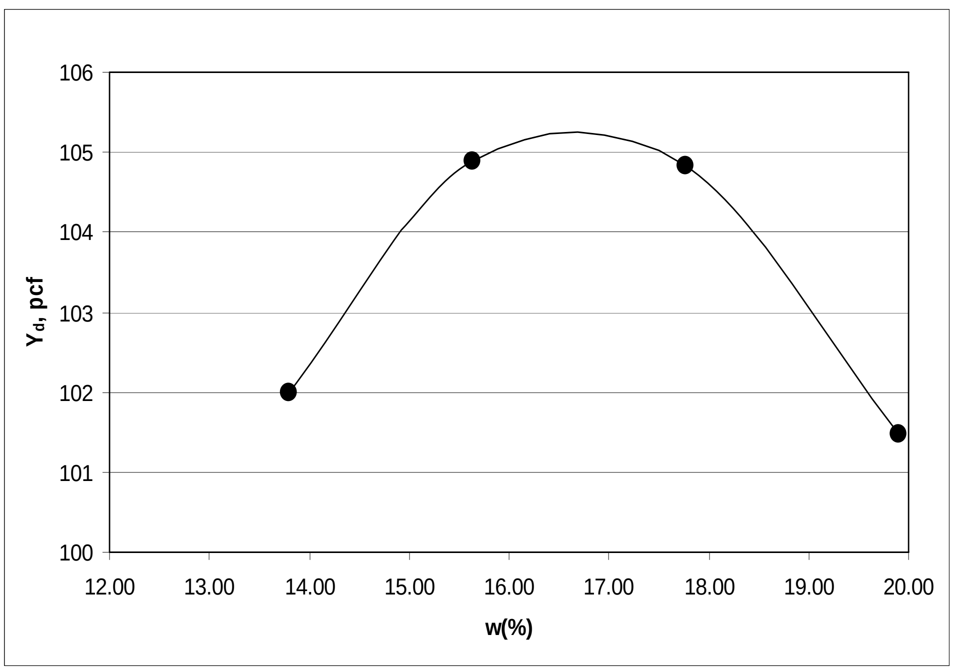

Figure 2-8 Moisture-Density Relationship for Renfrow Series

3.1 Specimen Preparation

Specimens were prepared in accordance with the kneading compaction procedure for Type 2 soil given in AASHTO T 307-99. These specimens were divided into five groups: (1) the first group consisted of a series of specimens compacted at 4% drier than the optimum moisture content (OMC-4%), at OMC, and OMC+4%, and then tested for M_r; (2) the second group consisted of specimens compacted at OMC-4%, then wetted to OMC and OMC+4%; (3) the third group consisted of specimens that were compacted at OMC+4%; some of these specimens were dried to OMC and the others to OMC-4%; (4) the fourth group consisted of specimens compacted at OMC, dried to OMC-4%, and then tested for M_r; and (5) the firth group is a series of specimens compacted at OMC, wetted to OMC+4% prior to testing for M_r. Specimens in group two to five were tested for resilient modulus, after the completion of wetting and drying process. It is also important to note that the effect of wetting and drying on specimens compacted at OMCs were only performed on selective soil series, namely, Burleson and Kirkland.

3.2 Wetting Procedure

There are several laboratory procedures reported in the literature for wetting of compacted subgrade soils. For example, Drumm et al. (1997) used a triaxial cell to saturate compacted specimens by applying water pressure from the bottom of a specimen, while the top was exposed to atmospheric pressure. In this procedure, the back pressure applied to specimens varied from 2 to 4 psi (13.8 to 27.6 kPa) and the effective confining pressure was not permitted to exceed 6 psi (41.4 kPa). Alternatively, Yuan and Nazarian (2003) placed each specimen in a mold having small holes at the bottom so it can absorb water prior to testing. This procedure may not be applicable for wetting compacted clays because moisture gradient would develop across the height of the specimen. In the present study a laboratory procedure developed and used by Khoury and Zaman (2004) is employed. This procedure consists of injecting the same amount of water into a set of specimens (usually six), having the same initial water content. These specimens are divided into three groups, each group containing a pair of specimens. Each of these pairs is then wetted using a different wetting method. One of the goals of this experimental program is to examine whether or not these methods will develop a moisture gradient within a specimen. This will also help observe the influence of moisture gradients, if any, on the resilient modulus. Further discussions of the proposed wetting methods are presented in details in Khoury and Zaman (2004).

3.3 Drying Procedure

Literature review reveals a number of laboratory procedures that have been used in the past for drying of compacted specimens. For example, Yuan and Nazarian (2003) placed compacted specimens in an oven at 105^{o}F (41^{o}C). However, their procedure may not be applicable to compacted clay soils because of potential occurrence of fissures inside a specimen. Other techniques such as axis translation can be used in drying compacted specimens by driving the water out. Tinjum et al. (1996) used pressure plate extractors to evaluate the soil-water characteristic curve (SWCC) corresponding to desorption (drying). Unfortunately, this is a very time consuming method, requiring three to four months to complete one test. In some cases, even the O-ring seals in the extractor failed. A laboratory drying procedure developed by Khoury and Zaman (2004) is employed in the present study. The proposed drying procedure requires less effort and is much more time-efficient. It consists of the following steps: (a) placing a rubber membrane around the specimen after compaction; (b) placing a circular plastic sheet on each end of the specimen; (c) placing two platens on the top of the plastic sheet; (d) sealing off the membrane from the platens with a masking tape; (e) placing the specimen in an oven at 105^{o}F (41^{o}C); (f) weighing the specimen at a desired time interval. The resilient modulus and soil suction tests were performed after the desired moisture content was achieved.

3.4 Resilient Modulus Test Procedure

The AASHTO T 307-99 test method was used to determine the resilient modulus of all the specimens. The resilient modulus test consisted of applying a cyclic haversine-shaped load with a duration of 0.1 seconds and rest period of 0.9 seconds. For each sequence, the applied load and the vertical displacement for the last five cycles were measured and used to determine the resilient modulus. The load was measured by using an externally mounted load cell, having a capacity of 500 lbf (2.23 KN). The resilient displacements were measured using two linear variable differential transformers (LVDTs) fixed to opposite sides of and equidistant from the piston rod outside the test chamber. The LVDTs had a maximum stroke length of 0.75 inches (25.4 mm). An MTS frame was used in running the tests. A program using G language (Labview) was used to control the applied cyclic deviatoric stress as well as to acquire the load and displacement data.

3.5 Soil Suction Test

At the conclusion of each resilient modulus test, specimens were sliced into five layers. Each layer was divided into five parts. Four of these parts were used to determine the moisture content, and one part for suction. Soil suction tests were performed using the filter paper technique according to the ASTM D 5298-94 test method. The filter paper moisture contents were converted to matric suction using the calibration curves in ASTM 5298-94. The soil-water characteristic curve was established and the variations in resilient modulus with both matric suction and total suction were developed, revealing the effect of soil suction.

One way to observe the effect of moisture variations on the resilient modulus is to evaluate the changes in M_r values at a specific deviatoric stress and confining pressure (SHRP, 1989). A simple and commonly used model was selected in this study for this purpose.

$$M_r = k_1 \times S_d^{\,k_2} \times S_3^{\,k_3}$$

In this model, the resilient modulus (M_r) is expressed as a function of deviatoric stress (S_d) and confining pressure (S_3). The model parameters (k_1, k_2, and k_3) were determined for each condition and used to calculate M_r values at a deviatoric stress of 4 psi (28 kPa) and a confining pressure of 6 psi (41 kPa), as suggested by SHRP protocol P-46 (1989). Tables 4-1 through 4-11 show the model parameters along with the resilient moduli, for all soils, at the aforementioned stresses and different moisture contents. The following sections discuss the effect of moisture content and post-compaction moisture content, due to wetting and drying, on M_r values.

4.1 Mr-Moisture Relationship for Burleson Soil (Wetting)

The variation in M_r values for specimens compacted at OMC-4% and wetted to approximately OMC+4% are represented by curve MrMC-1 in Figure 4-1, while curve MrMC-2 represents the MrMC relationship for specimens compacted at OMC and then wetted to OMC+4%. Comparatively, for a given moisture content, the M_r values from MrMC-1 are lower than the corresponding values from MrMC-2 indicating that both the initial moisture content and the extent of wetting are important factors. For example, the average M_r value from MrMC-1 at OMC is 7, 000 psi (48.2 MPa) compared to 10, 000 psi (68.9 MPa) from MrMC-2. It appears that both of these curves (MrMC-1 and MrMC-2) would intersect at a higher moisture content, approximately OMC+4%, for this soil.

4.2 M_r-Moisture Relationship for the Burleson (Drying)

The MrMC relationships for specimens compacted at OMC+4% and OMC and dried to a lower moisture content were established and are presented by curves MrMC-3 and MrMC-4, respectively, in Figure 4-1. It is evident that the MrMC-3 is higher than the MrMC-4 at a moisture content ranging between OMC and OMC-2%. These curves intersect at a moisture content between OMC-2% and OMC. Results show that the percentage increase in the resilient modulus for specimens compacted at OMC+4% and dried to approximately OMC-4% is approximately 200%, while specimens compacted at OMC and dried to OMC-4% exhibited only 80% increase in M_r values. From these results it can be concluded that the changes in M_r values due to drying is influenced by the initial moisture content of a specimen. From Figure 4-1, it is further evident that the MrMC relationship of compacted clay, due to wetting and drying, is hysteretic. For a given water content, the M_r values are higher for a drying cycle than for a wetting cycle. This behavior is qualitatively similar to the hysteresis behavior of the Kirkland soil series.

4.3 M_r-Moisture Relationship for Binger Soil (Wetting and Drying)

From Figure 4-2, it is evident that the MrMC relationship for this type of soil is hysteretic. The resilient modulus values (approximately 10, 000 psi; 68.9 MPa) at approximately OMC, from the wetting process, is lower than the corresponding value (approximately 19,000; 131 MPa), from the drying process. In addition, the resilient modulus of specimens compacted at OMC-4% and wetted to OMC+4% decreased about 60%. Specimens compacted OMC+4%

and then dried to approximately OMC-4% exhibited an increase in M_r values of approximately 400%.

4.4 Mr-Moisture Relationship for Kirkland (Wetting and Drying)

The M_r-moisture content (MrMC) relationship for specimens compacted at OMC-4% and OMC, and then wetted to higher moisture contents is presented in Figure 4-3. The variation in M_r values (at the aforementioned states of stress) for specimens compacted at OMC-4% and wetted to approximately OMC+4% are represented by curve MrMC-1 in Figure 4-3, while curve MrMC-2 represents the MrMC relationship for specimens compacted at OMC and then wetted to OMC+4%. Comparatively, for a given moisture content, the M_r values from MrMC-1 are lower than the corresponding values from MrMC-2 indicating that both the initial moisture content and the extent of wetting are important factors. For example, the average M_r value from the MrMC-1 curve at OMC is 7,000 psi (48 MPa) compared to 13,350 psi (93 MPa) from the MrMC-2 curve. It appears that both of these curves (MrMC-1 and MrMC-2) would intersect at a higher moisture content, approximately OMC+4% for this soil.

The MrMC relationships for specimens compacted at OMC+4% and OMC and dried to a lower moisture content were established and are presented by curves MrMC-3 and MrMC-4, respectively, in Figure 4-3. It is evident that the MrMC-3 is higher than the MrMC-4 at a moisture content ranging between OMC and OMC-2%. These curves intersect at a moisture content around OMC-4%. The results also show that the percentage increase in the resilient modulus for specimens compacted at OMC+4% and dried to approximately OMC-4% is approximately 200%, while specimens compacted at OMC and dried to OMC-4% exhibited only 75% increase in M_r values. From these results, it can be concluded that the changes in M_r values due to drying is influenced by the initial moisture content of a specimen. From

Figure 4-1, it is further evident that the MrMC relationship of compacted clay, due to wetting and drying, is hysteretic. For a given water content, the M_r values are higher for a drying cycle than for a wetting cycle. This behavior is similar to the hysteresis of the soil-water characteristic curve reported by Khoury and Zaman (2004), Tinjum et al. (1996) and others (Fredlund and Rahardjo, 1993).

4.5 M_r-Moisture Relationship for the P-Soil (Wetting and Drying)

The M_r-Moisture (MrMC) relationship for specimens compacted at OMC+4% and dried to lower moisture contents were established and are presented by curves MrMC-1, while the effect of compaction moisture content on M_r values is presented by MrMC-2, as shown Figure 4-4. It is evident that the MrMC-1 is higher than the MrMC-2 at a moisture content ranging between OMC and OMC-4%. The percentage increase in the resilient modulus for specimens compacted at OMC+4% and dried to approximately OMC-4% is approximately 225%. From Figure 4-4, it is further evident that the M_r values of specimens dried to lower moisture contents were higher than the corresponding values for specimens compacted at the same moisture content. For example, the M_r values of specimens compacted at OMC+4% and dried to approximately OMC-4% were approximately 20,000 psi (137.8 MPa) compared to approximately 11,500 psi (79.2 MPa) for specimens compacted at OMC-4% and then tested for M_r.

The effect of wetting on M_r values is shown in curve MrMC-3, in Figure 4-4. the M_r values decreased as the post-compaction moisture content increased from approximately 10.5% to 17.5%. The percentage decrease is approximately 45. It is also interesting to note that specimens compacted at OMC have higher M_r values than specimens compacted at OMC-4% and then wetted to OMC, similar to the behavior exhibited by the other soils.

4.6 Mr-Moisture Relationship for the M-Soil (Wetting and Drying)

The resilient moduli for M-Soil specimens are summarized in Table 4-8 and graphically illustrated in Figure 4-5. The resilient modulus decreases with the compaction moisture content, as depicted by the MrMC-2 curve in Figure 4-5. The MrMC-2 curve is lower than the MrMC-1 curve and higher than the MrMC-3 curve; the MrMC-1 curve shows the variation of resilient modulus values with the post-compaction moisture content due to drying and the MrMC-3 curve represents the variation of M_r with the increase in the post-compaction moisture content. The M_r values increase as the moisture content decrease due to drying. The percentage increase in M_r values of specimens compacted at OMC+4% and dried to OMC and OMC-4% are approximately 70% and 115%, respectively. Also, the M_r values of specimens dried to OMC-4% are 130.9 MPa (19,000 psi) compared to 100 MPa (14,500 psi) for specimens compacted at OMC-4% and tested for M_r without any drying.

4.7 Mr-Moisture Relationship for the Stephens Soil (Wetting and Drying)

Results correlating moisture content and resilient modulus for the S-Soil are graphically illustrated in Figure 4-6 and summarized in Table 4-9. The resulting graph clearly shows the hysteretic behavior predicted due to wetting and drying, as illustrated by the vertical difference in the curves. The drying specimens had an M_r which is approximately 12 MPa (1,750 psi) higher at OMC than the corresponding M_r values of wetted specimens. Similarly, higher M_r values (approximately roughly 10 MPa (1,450 psi) seen for those dried to OMC-4%. The percentage increases for specimens compacted at OMC+4% and dried to OMC and OMC-4% were approximately 15% and 20%, respectively. The resilient modulus of specimens compacted at OMC-4% and wetted to OMC and OMC+4% exhibited a decrease of approximately 5% and 10%, respectively.

4.8 Mr-Moisture Relationship for the Kingfisher Soil (Wetting and Drying)

The variation of M_r values with moisture content is summarized in Table 4-10 and illustrated in Figure 4-7. A similar qualitative trend has been observed for the Kingfisher series soil. The M_r values decreased as the compaction and post-compaction moisture content increased from approximately OMC-4% to OMC+4%. The behavior is represented by MrMC-2 and MrMC-3, respectively. The percent decrease in M_r values is approximately 52%, due to increase in post-compaction moisture from OMC-4% to OMC. In addition, the effect of drying on M_r values is illustrated in Figure 4-7 by curve MrMC-1. As one can observe, the M_r values, as expected, increased as the post-compaction moisture content decreases from approximately OMC+4% to OMC-4%.

4.9 M_r-Moisture Relationship for the Renfrow Soil

The Renfrow soil series exhibited a similar qualitative behavior with post-compaction and compaction moisture contents. The behavior is illustrated by curves MrMC-1, MrMC-2 and MrMC-3, in Figure 4-8. Also, Table 4-11 summarizes the variations of M_r with moisture content. From Figure 4-8, MrMC-1 (due to drying) is higher than MrMC-2 (compaction moisture content) and MrMC-3 (due to wetting). Results show that the percentage of M_r due to drying increases approximately 500%. On the other hand, the M_r values decreased approximately 95% due to the increase in post-compaction moisture content.

4.10 Soil-Water Characteristic Curves (SWCC)

Tinjum et al. (1996) used pressure plate extractors to establish the SWCC corresponding to drying, while anomalous results were reported for sorption (wetting) test because diffused air through the ceramic disk flew back into the specimen. Likos and Lu (2003) used the so-called “filter paper technique” to determine the SWCC. Since this is an inexpensive method, measures a full range of suction, and requires less time, it was used here in developing the soil-water characteristic curves for Burleson, Kirkland, Kingfisher, and Renfrow soils. Tests were performed on dried and wetted specimens already tested for M_r. The results are presented in Figures 4-9 through 4-12, respectively.

Figure 4-9 shows the SWCC for the Burleson soil series. It is evident that a higher soil suction value is observed for drying cycle than for wetting cycle. For example, the suction values at OMC for a drying cycle is approximately 435 psi (3,000 kPa) compared to 145 psi (1,000 kPa) for the wetting cycle. From Figure 4-9, it is also clear that OMC-4% wet curve (SMC-1) would intersect with the OMC wet curve (SMC-2). On the other hand, the SMC-3, presenting specimens dried from OMC+4% to OMC-4%, would intersect the SMC-4 curve. SMC-4 is the suction-moisture curve for specimens compacted at OMC and dried to OMC-4%.

From Figure 4-10, for a given water content, a higher soil suction value is observed for drying cycle than for wetting cycle. For example, the suction values for Kirkland soil at OMC for a drying cycle is approximately 4,000 kPa (580 psi) compared to approximately 1, 000 kPa (145 psi) for the wetting cycle. Figure 4-10 represents four different curves: (1) SMC-1 is the SWCC for specimen compacted at OMC-4% and then wetted to OMC+4%; (2) SMC-2 is the SWCC for specimen compacted at OMC and then wetted to OMC+4%; (3) SMC-3 is the SWCC for specimens compacted at OMC+4% and then dried to OMC-4%; and (4) SMC-4 is for specimens compacted at OMC and dried to OMC-4%. The SMC-1 and SMC-2 curves intersected at a moisture content near OMC+4%, while the SMC-3 and SMC-4 curves intersected near OMC-4%.

The SWCCs of Kingfisher and Renfrow soil series are shown in Figures 4-11 and 4-12, respectively. The suction increased due to drying and decreased due wetting, as expected. The behavior is illustrated in SMC-1 and SMC-2, respectively. The Kingfisher specimens had suction values of 4,500 kPa, at OMC due to drying, compared to 750 kPa at OMC due to wetting. The effect of compaction moisture content is also observed and illustrated in curve SMC-1, in both Figure 4-11 and Figure 4-12.

From the aforementioned results, the changes in M_r and suction due to drying and wetting processes are influenced by the initial moisture content of a specimen. For example, changes in M_r and suction values for specimens compacted at OMC and wetted to OMC+4% is different than the corresponding changes for specimens compacted at OMC-4% and wetted to OMC+4%. It was also found that the resilient modulus and soil suction qualitatively exhibited a similar trend due to moisture variations

Table 4- 1 k_1, k_2, k_3 and R-squared values for compacted Burleson specimens

Sample #	Compaction w(%)	Model: $Mr = k_1 \times S_d^{k2} \times S_3^{k3}$				Mr @ S_d = 4psi; & S_3 = 6 psi
		k1	K2	k3	R^2	
1	18.05	11549	-0.075	0.123	0.88	12980
2	19.03	12300	-0.054	0.087	0.73	13326
3	19.51	13397	-0.061	0.051	0.69	13492
4	19.60	10685	-0.006	0.118	0.66	13101
5	22.72	11044	-0.153	0.065	0.83	10035
6	23.50	10267	-0.109	0.091	0.82	10397
7	23.48	11704	-0.195	0.037	0.82	9537
8	23.50	10019	-0.138	0.087	0.81	9664
9	26.6	8371	-0.415	0.123	0.80	5865
10	27.60	8376	-0.425	0.130	0.82	5873
11	27.50	10850	-0.476	-0.036	0.87	5259

1 psi = 6.89 kPa

Table 4-2 k_1, k_2, k_3 and R-squared values for wetted Burleson specimens

Sample #	w (%) After Wetting	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				Mr @ S_d = 4psi; & S_3 = 6 psi
		k_1	k_2	k_3	R^2	
Specimen compacted at OMC-4% then wetted						
12	22.56	9401	-0.234	0.103	0.93	8169
13	23.13	9467	-0.275	0.078	0.90	7431
14	23.35	8483	-0.329	0.075	0.96	6145
15	23.64	8580	-0.316	0.069	0.96	6257
16	23.83	7938	-0.243	0.113	0.95	6941
17	23.89	6842	-0.259	0.133	0.91	6064
18	24.03	7405	-0.228	0.124	0.93	6740
19	25.12	6281	-0.207	0.139	0.92	6047
20	25.51	7288	-0.349	0.083	0.92	5210
21	26.23	7304	-0.385	0.072	0.93	4878
22	26.63	6676	-0.431	0.072	0.96	4182
Specimen compacted at OMC then wetted						
22	25.18	7528	-0.140	0.153	0.93	8154
23	26.15	7325	-0.188	0.090	0.87	6632
24	26.63	7096	-0.424	0.150	0.92	5162
25	26.88	7344	-0.260	0.098	0.89	6103
26	27.02	5916	-0.401	0.219	0.92	5026

1 psi = 6.89 kPa

Table 4-3 k_1, k_2, k_3 and R-squared values for dried Burleson specimens

Specimen #	w(%) After Drying	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				Mr @ S_d = 4psi; & S_3 = 6 psi
		k_1	k_2	k_3	R^2	
Compacted specimens at OMC then dried						
27	19.29	13648	0.061	0.118	0.86	18376
28	19.2	14513	0.040	0.122	0.84	19072
29	20.95	12734	-0.001	0.119	0.77	15726
Compacted specimens at OMC+4% then dried						
30	20.95	14918	-0.026	0.069	0.79	16304
31	18.41	14906	0.013	0.088	0.82	17759
32	22.34	11187	-0.077	0.084	0.80	11688
33	23.42	11075	-0.020	0.097	0.85	12824
1 psi = 6.89 kPa						

Table 4- 4 k_1, k_2, k_3 and R-squared values for compacted Binger specimens

Specimen#	Compaction w(%)	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				Mr @ S_d = 4psi; & S_3 = 6 psi
		k_1	K_2	k_3	R^2	
1	8.00	13354	0.057	0.207	0.94	20937
2	8.86	10168	0.029	0.242	0.95	16327
3	9.20	10897	-0.031	0.238	0.97	15984
4	9.30	12602	-0.044	0.219	0.96	17564
5	16.31	1679	0.392	0.232	0.79	4379
6	16.87	2321	0.146	0.450	0.79	6371

1 psi = 6.89 kPa

Table 4- 5 k_1, k_2, k_3 and R-squared values for wetted and dried for Binger specimens

Specimen #	w(%) After Wetting/Drying	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				Mr @ S_d = 4psi; & S_3 = 6 psi
		k_1	k_2	k_3	R^2	
Specimen compacted at OMC-4% then wetted						
7	12.26	5668	-0.085	0.412	0.99	10539
8	12.418	5542	-0.075	0.390	0.99	10041
9	12.806	5551	-0.069	0.394	0.99	10226
10	12.842	5592	-0.132	0.378	0.99	9161
11	14.414	6040	-0.094	0.392	0.99	10708
12	15.036	5053	-0.091	0.445	0.99	9889
Compacted specimens at OMC+4% then dried						
13	9	15016	0.131	0.181	0.95	24903
14	12.5	11521	0.066	0.253	0.95	19850
15	8.75	16883	0.073	0.176	0.96	25590
1 psi = 6.89 kPa						

Table 4- 6 k_1, k_2, k_3 and R-squared values for wetted and dried for Kirkland specimens

Conditions	Model: $Mr = k_1 \times S_d^{k2} \times S_3^{k3}$			R^2
	k_1	k_2	k_3	
Compacted at OMC and then tested for Mr and Suction	17401	-0.356	0.127	0.97
	21660	-0.313	-0.032	0.98
Compacted at OMC, dried, and then tested for Mr and Suction	15591	0.059	-0.047	0.37
	17486	0.015	0.078	0.26
	25466	-0.053	0.129	0.53
Compacted at OMC, wetted, and then tested for Mr and Suction	13046	-0.273	0.051	0.97
	7042	-0.343	0.173	0.93
	6670	-0.374	0.07	0.96
Compacted at OMC+4%, and then tested for Mr	9222	-0.219	0.075	0.92
	8456	0.053	-0.05	0.49
Compacted at OMC+4%, dried, and then tested for Mr and suction	14119	-0.023	0.027	0.11
	17793	0.256	-0.068	0.93
	16378	0.024	0.054	0.48
	15058	0.154	0.044	0.86

1 psi = 6.89 kPa; Mr, S_d, and S_3 are in psi

Conditions	Model: $Mr = k_1 \times S_d^{k2} \times S_3^{k3}$			R^2
	k_1	k_2	k_3	
Compacted at OMC-4%, and then tested for Mr and suction	17652	0.022	0.028	0.34
	17705	0.016	-0.094	0.86
Compacted at OMC-4%, wetted, and then tested for Mr and suction	10263	-0.113	0.098	0.74
	8283	-0.191	0.095	0.96
	7149	-0.178	0.049	0.94
	8181	-0.129	0.068	0.62
	9245	-0.168	0.035	0.97
	8765	-0.221	0.105	0.94
	6465	-0.243	0.114	0.86
	8169	-0.189	0.057	0.94
	4920	-0.389	0.13	0.97
	6718	-0.352	0.132	0.97
	7356	-0.288	0.003	0.97

1 psi = 6.89 kPa; Mr, S_d, and S_3 are in psi

Table 4- 7 k_1, k_2, k_3 and R-squared values for wetted and dried for Port specimens

Specimen #	w(%)	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				Mr @ S_d = 4psi; & S_3 = 6 psi
		K_1	k_2	k_3	R^2	
Compacted specimens at OMC+4% then dried to OMC and OMC-4%						
1	14.53	11288	-0.121	0.144	0.97	12348
2	13.63	9102	-0.059	0.156	0.92	11091
3	10.00	16500	0.004	0.095	0.65	19671
4	10.34	17232	0.006	0.107	0.65	21070
Compacted specimens at OMC-4%, OMC, and OMC+4% then tested for M_r						
5	10.21*	9424	-0.089	0.188	0.97	11683
6	10.51*	10202	-0.130	0.162	0.88	11378
7	13.69*	9192	-0.064	0.155	0.94	11108
8	13.72*	7299	-0.077	0.279	0.98	10715
9	17.32*	3415	0.006	0.353	0.84	6489
Compacted specimens at OMC-4%, wetted to OMC+4%; then tested for M_r						
10	14.00	10281	-0.185	0.063	0.88	8900
11	14.20	9340	-0.262	0.150	0.97	8500
12	16.00	7731	-0.123	0.070	0.93	7250
13	17.00	7596	-0.137	0.060	0.89	7000
14	17.32	8722	-0.263	0.004	0.96	6100

* Compaction moisture content; specimens not subjected to drying action

1 psi = 6.89 kPa

Table 4- 8 k_1, k_2, k_3 and R-squared values for wetted and dried for Minco specimens

Specimen #	w(%)	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				M_r @ S_d = 4psi; & S_3 = 6 psi
		K_1	k_2	k_3	R^2	
Specimen compacted at OMC+4% then dried OMC and OMC-4%						
1	11.94	8951	0.012	0.260	0.96	14516
2	13.90	8291	0.016	0.285	0.95	14124
3	8.22	13436	0.014	0.191	0.86	19287
4	8.08	12877	0.060	0.179	0.88	19301
Compacted specimens at OMC-4%, OMC, and OMC+4% then tested for Mr						
5	8.34*	9000	-0.001	0.277	0.96	14769
6	8.17*	8192	-0.061	0.349	0.91	14056
7	12.05*	8793	0.044	0.213	0.95	13690
8	12.26*	7810	-0.002	0.295	0.89	13189
9	15.80*	4833	0.103	0.242	0.84	8750
Compacted specimens at OMC-4%, OMC, and OMC+4% then tested for Mr						
10	12.08	5366	0.021	0.310	0.83	9623
11	13.18	5286	0.014	0.330	0.84	9735
12	15.09	5016	0.012	0.351	0.91	9558
13	12.18	5673	0.003	0.309	0.89	9907
14	14.76	5123	0.019	0.278	0.96	8662
15	15.47	5498	0.025	0.277	0.89	9352
16	13.12	5952	0.012	0.253	0.92	9530
17	13.90	5453	0.040	0.294	0.99	9762
18	15.34	5670	-0.036	0.337	0.97	9866
19	15.75	5236	-0.010	0.332	0.99	9227

* Compaction moisture content; specimens not subjected to drying action

1 psi = 6.89 kPa

Table 4- 9 k_1, k_2, k_3 and R-squared values for Stephens soil specimens

Sample #	**w(%)**	**Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$**				**M_r @ S_d = 4 psi; S_3 = 6psi**
		k_1	**k_2**	**k_3**	**R^2**	
1	13.48	6900	0.093	0.219	0.98	11612
2	12.99	6954	0.081	0.253	0.97	12253
3	13.38	7148	0.049	0.255	0.95	12088
4	9.78	5239	0.091	0.369	0.98	11512
5	9.35	6576	0.078	0.334	0.97	13388
6	9.04	7225	0.044	0.261	0.95	12257
7	17.06	9185	0.077	-0.038	0.85	9347
8	16.38	6869	0.074	0.257	0.97	12059
9	16.43	6328	0.055	0.349	0.97	12758
		Wetted Specimens				
10	10.75	7072	0.035	0.268	0.94	12004
11	12.78	5761	0.066	0.356	0.89	11937
12	15.57	5680	0.141	0.265	0.97	11465
13	16.06	5560	0.180	0.265	0.98	11111
		Dried Specimens				
14	13.24	7789	0.046	0.296	0.94	14089
15	10.26	7403	0.062	0.305	0.96	13928
16	13.99	5676	0.108	0.349	0.97	12319
17	12.98	6816	0.030	0.387	0.96	14228

Table 4- 10 k_1, k_2, k_3 and R-squared values for wetted and dried for Kingfisher specimens

Specimen #	w(%)	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				M_r @ S_d = 4psi; & S_3 = 6 psi
		K_1	k_2	k_3	R^2	
Compacted specimens at OMC+4% then dried to OMC and OMC-4%						
1	17.5	12998	-0.225	0.109	0.96	11579
2	15.93	16771	-0.084	0.079	0.90	17423
3	13.2	20133	-0.081	0.087	0.92	21045
Compacted specimens at OMC-4%, OMC, and OMC+4% then tested for M_r						
4	12.4	13522	-0.155	0.121	0.97	13542
5	12.6	13493	-0.162	0.155	0.96	14234
6	15.96	10900	-0.309	0.129	0.96	8941
7	16.2	11165	-0.301	0.126	0.95	9210
8	18.9	7284	-0.450	0.170	0.98	5291
Compacted specimens at OMC-4%, wetted to OMC+4%; then tested for M_r						
9	15.2	7300	-0.377	0.204	0.99	6594
10	15.9	5862	-0.337	0.204	0.99	5295
11	18.1	4775	-0.329	0.197	0.86	4312
12	19.1	4014	-0.418	0.285	0.97	3744

* Compaction moisture content; specimens not subjected to drying action

1 psi = 6.89 kPa

Table 4- 11 k_1, k_2, k_3 and R-squared values for wetted and dried for Renfrow specimens

Specimen #	w(%)	Model: $Mr = k_1 \times S_d^{k_2} \times S_3^{k_3}$				M_r @ S_d = 4psi; & S_3 = 6 psi
		K_1	k_2	k_3	R^2	
Compacted specimens at OMC+4% then dried to OMC and OMC-4%						
1		11313	-0.182	0.150	0.94	11499
2		15855	-0.084	0.08	0.89	16289
3		17742	-0.089	0.086	0.90	18294
Compacted specimens at OMC-4%, OMC, and OMC+4% then tested for M_r						
4	11.6	12745	-0.135	0.112	0.95	12934
5	12.0	12993	-0.136	0.114	0.94	13201
6	11.87	7515	-0.213	0.226	0.99	8385
7	16.2	8025	-0.225	0.238	0.97	9001
8	20.4	3258	-0.295	0.336	0.93	3953
Compacted specimens at OMC-4%, wetted to OMC+4%; then tested for M_r						
9	15.2	5421	-0.207	0.292	0.99	6863
10	15.9	4312	-0.222	0.322	0.99	5648
11	17.2	3643	-0.229	0.357	0.99	5034
12	19.1	2633	-0.226	0.372	0.99	3744

* Compaction moisture content; specimens not subjected to drying action

1 psi = 6.89 kPa

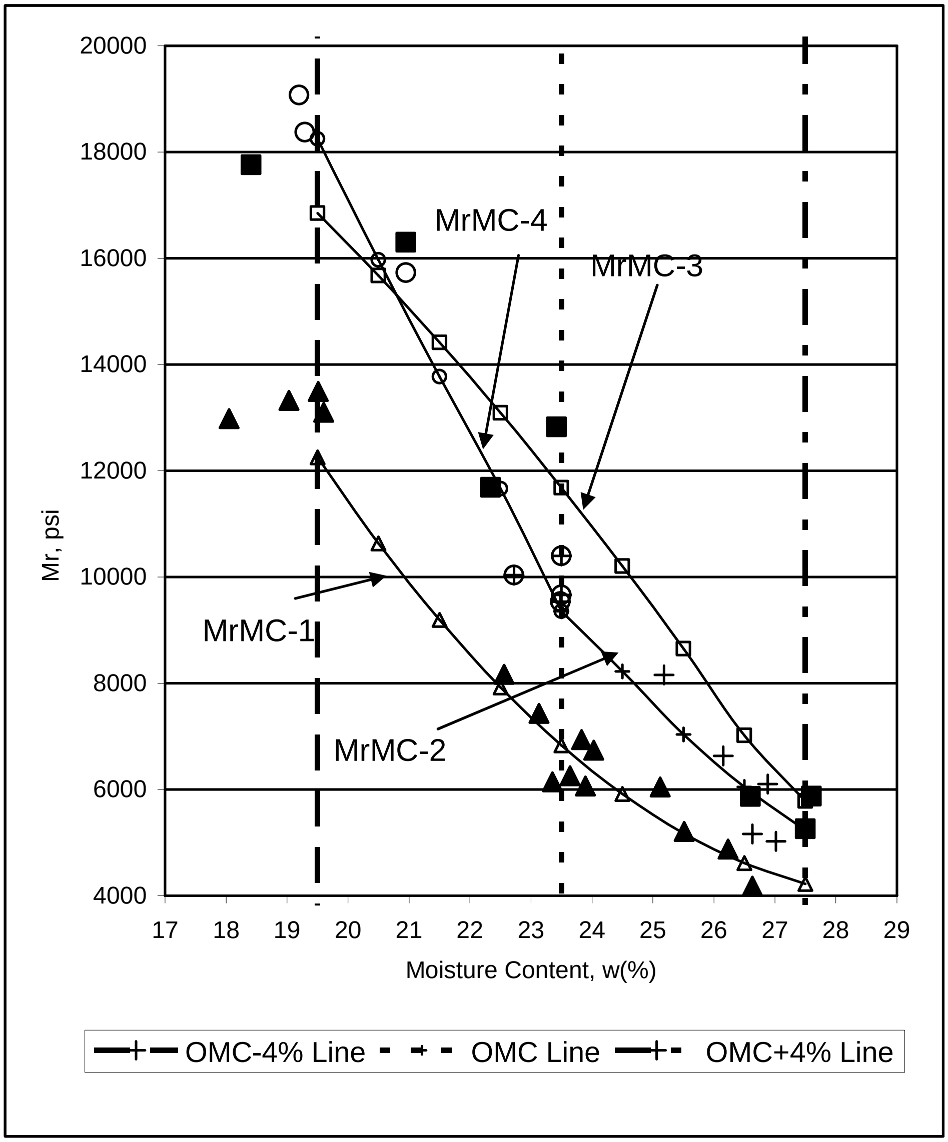

Figure 4-1 Variation of resilient modulus with moisture content for Burleson soil

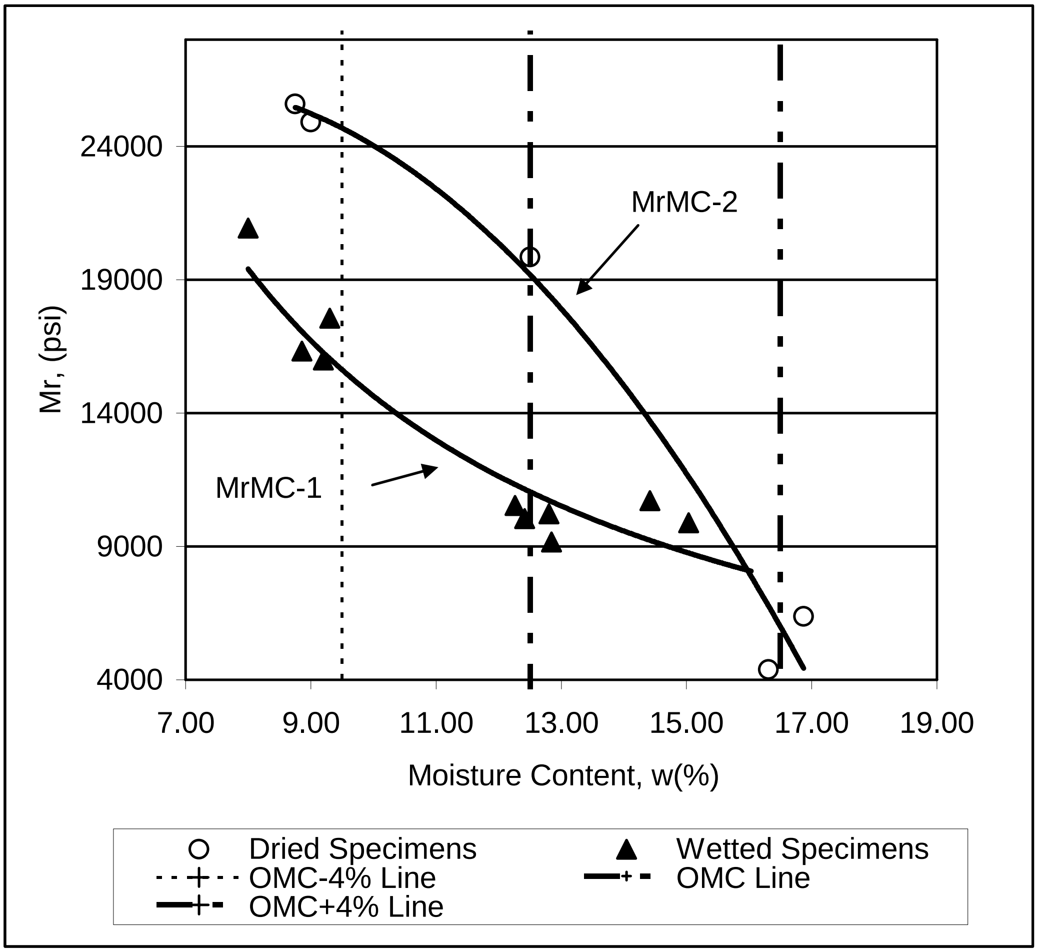

Figure 4-2 Variation of resilient modulus of with moisture content for Binger soil

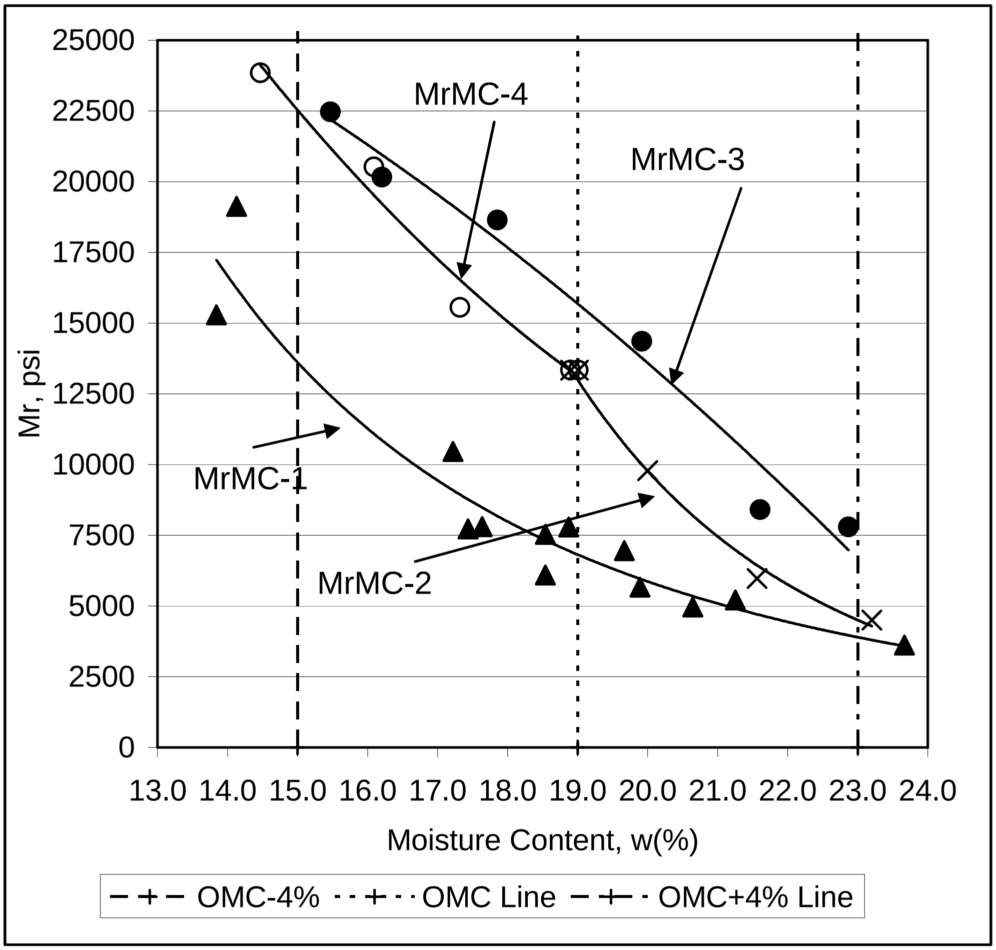

Figure 4-3 Variation of resilient modulus with moisture content for Kirkland soil

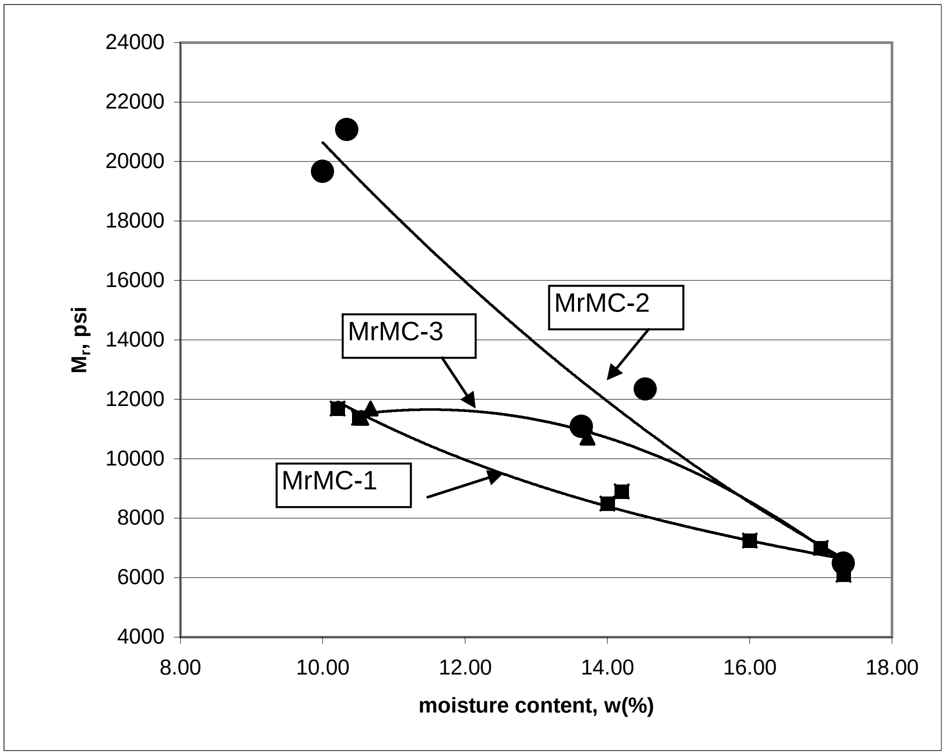

Figure 4-4 Variation of resilient modulus with compaction and post-compaction moisture content of Port Series specimens

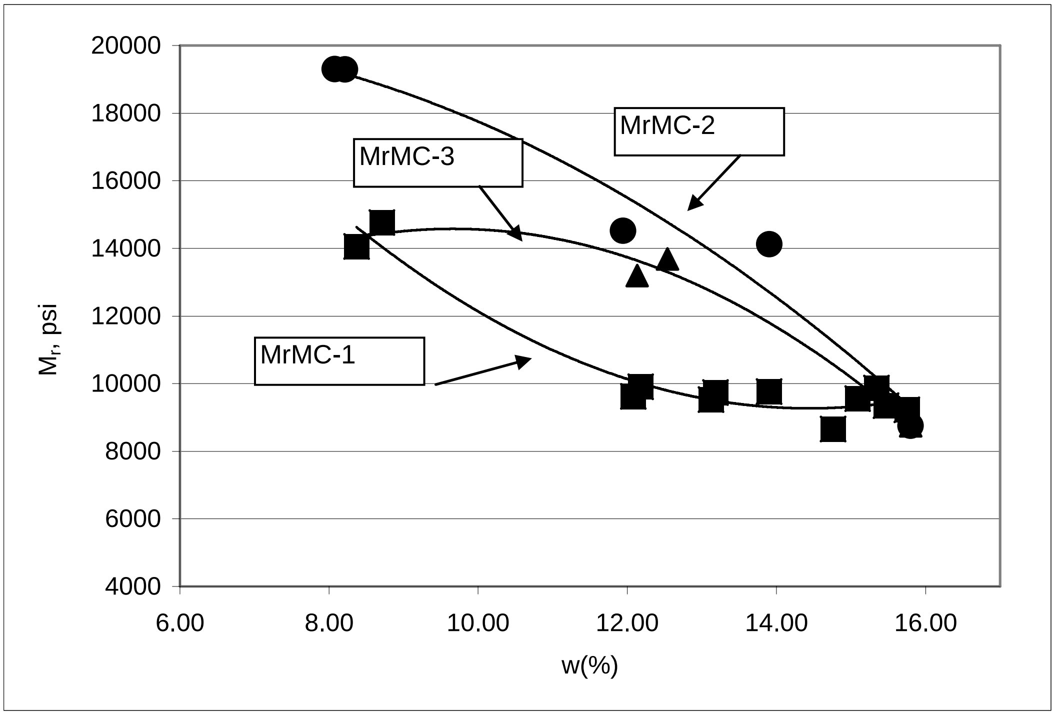

Figure 4-5 Variation of resilient modulus with compaction and post-compaction moisture content of Minco Series specimens

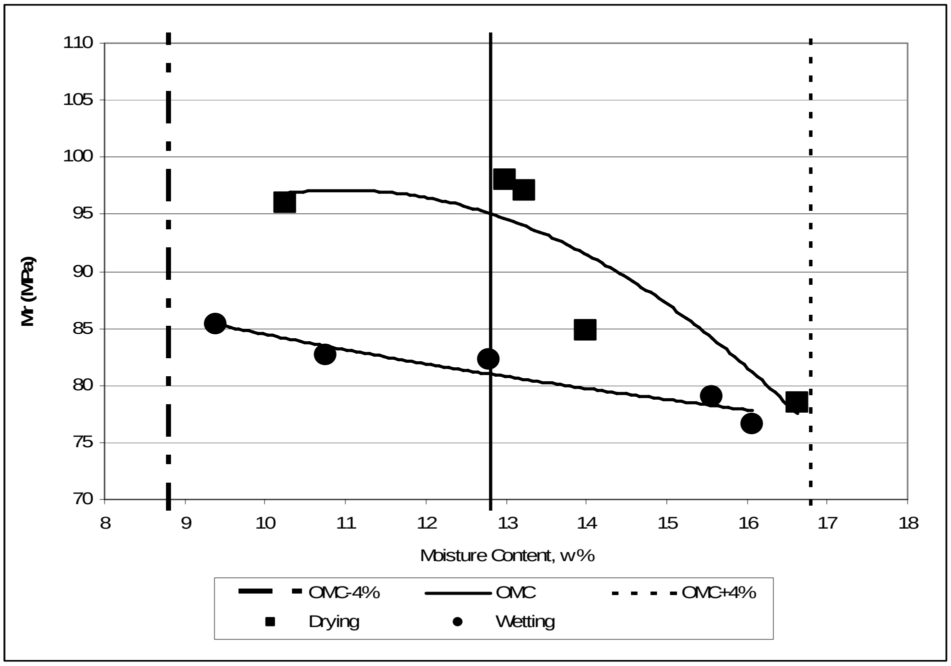

Figure 4-6 Variation of resilient modulus with moisture content of Stephens soil specimens

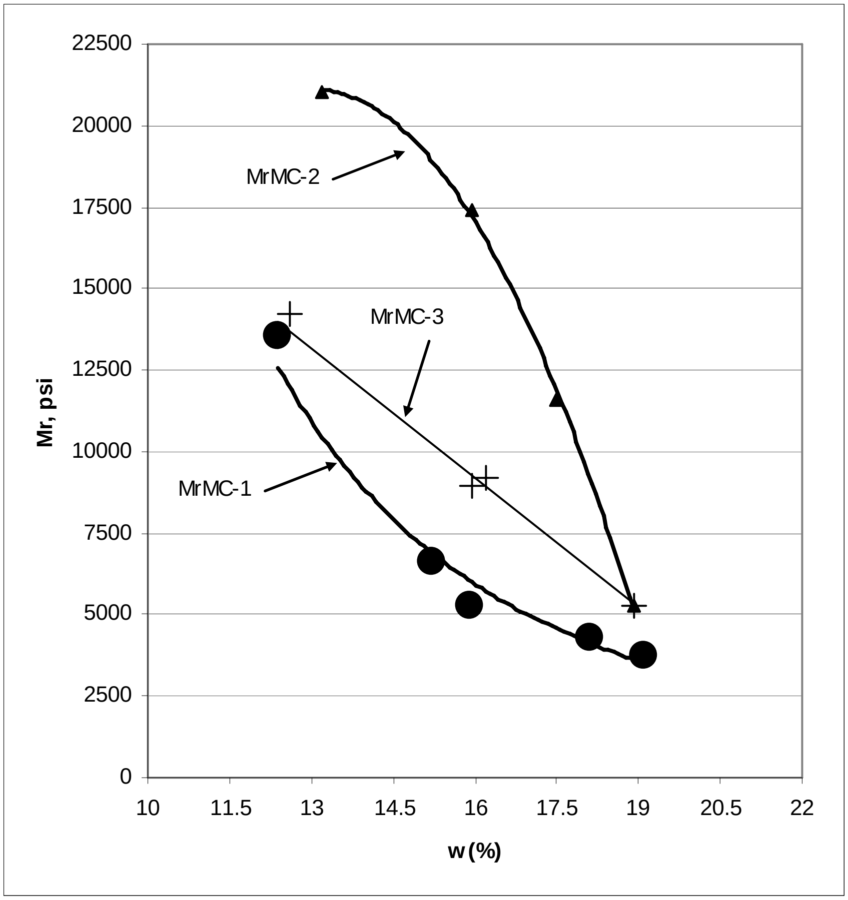

Figure 4-7 Variation of resilient modulus with moisture content of Kingfisher specimens

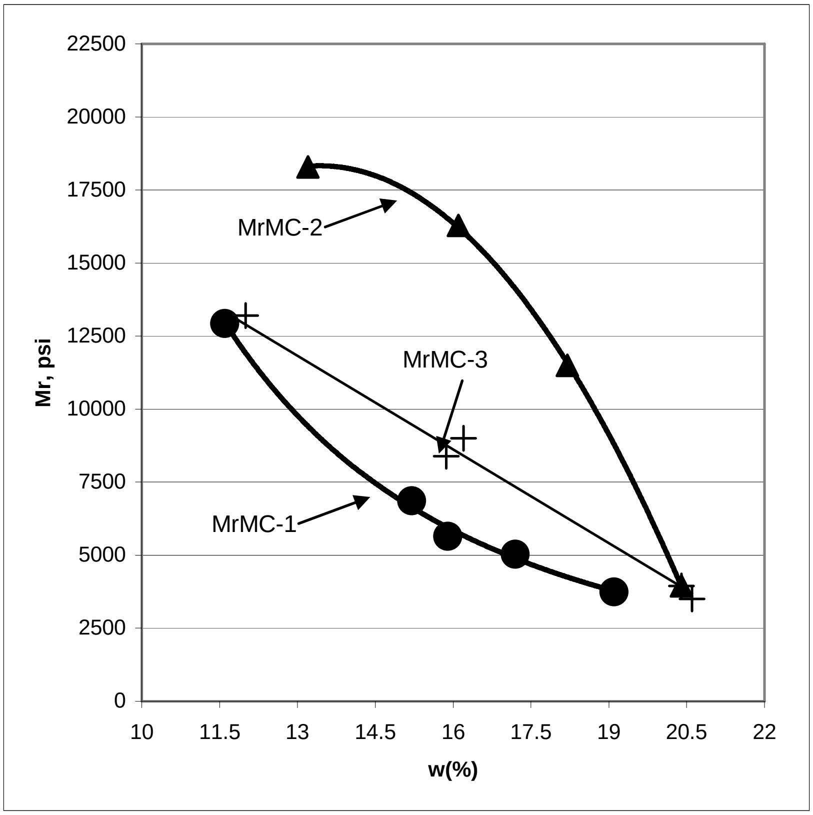

Figure 4-8 Variation of resilient modulus with moisture content of Renfrow specimens

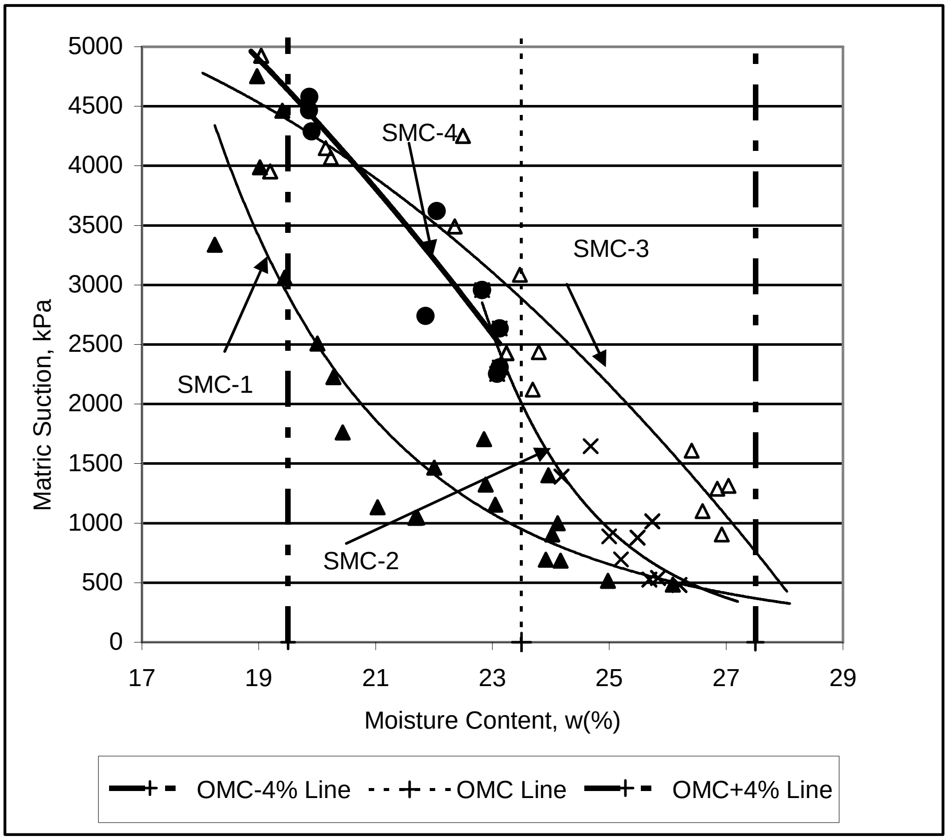

Figure 4-9 Soil water characteristic curve for compacted Burleson-soil specimens

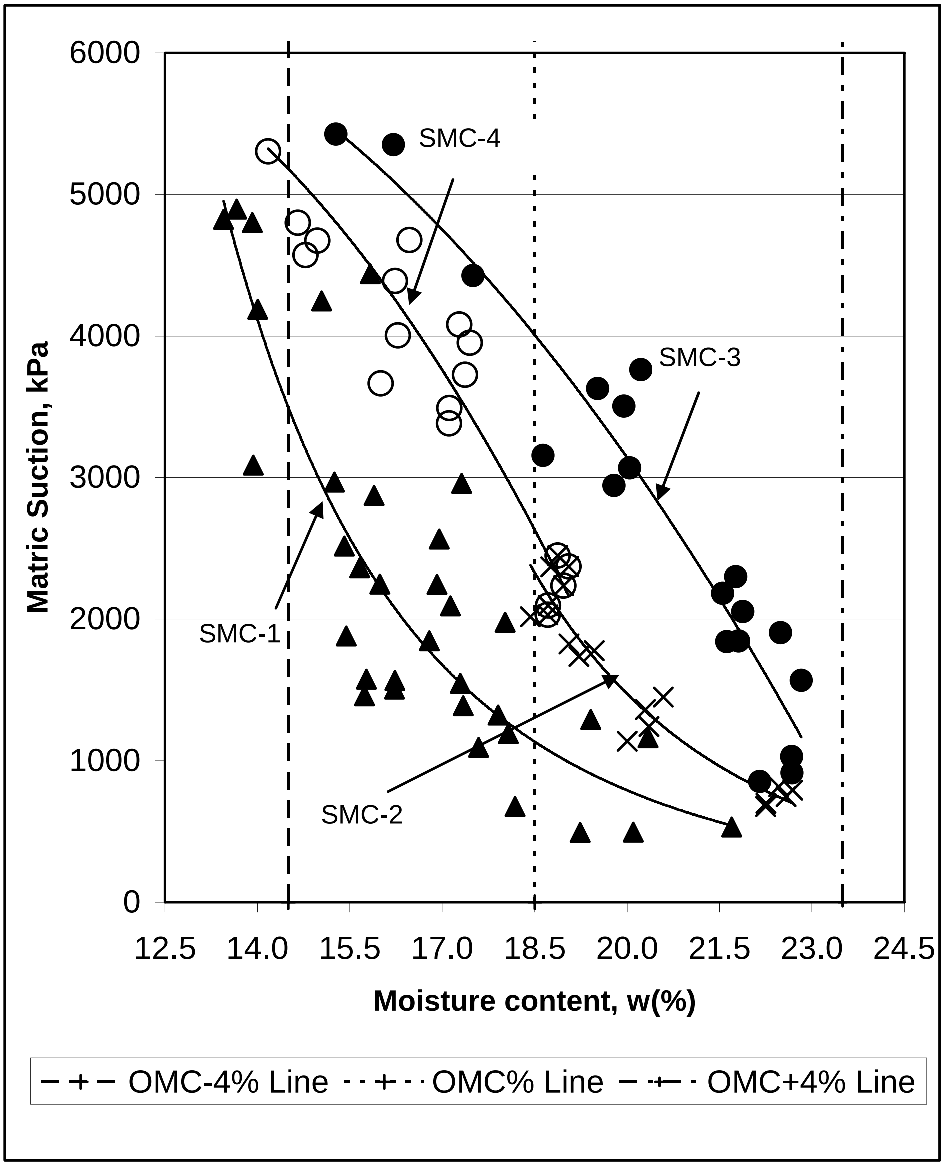

Figure 4-10 Soil water characteristic curve for compacted Kirkland-soil specimens

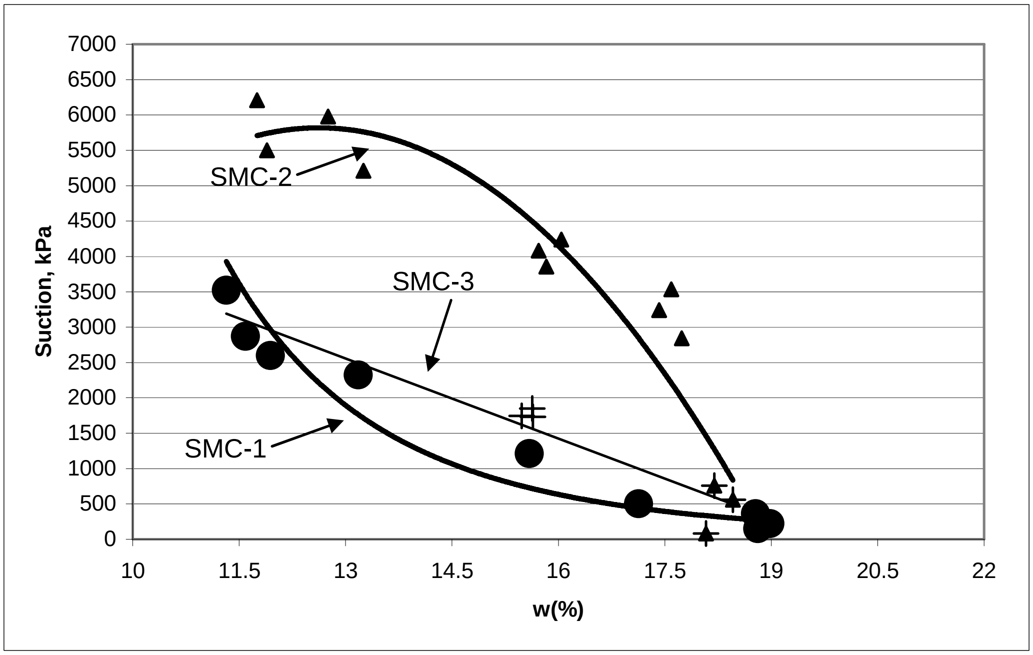

Figure 4-11 Soil water characteristic curve for compacted Kingfisher specimens

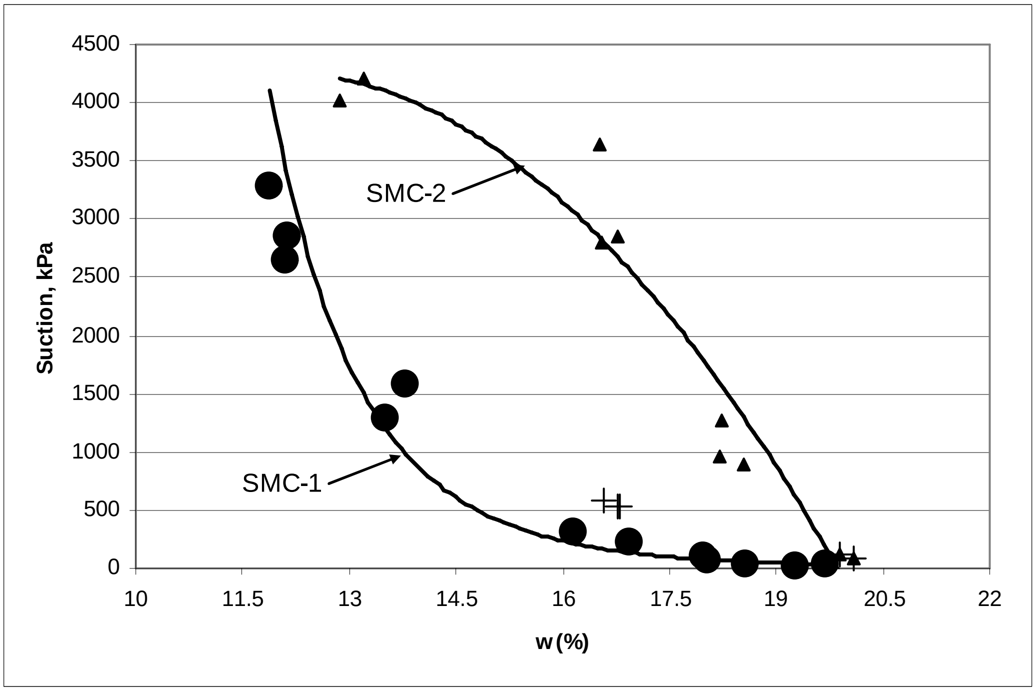

Figure 4-12 Soil water characteristic curve for compacted Renfrow specimens

5.1 Conclusions

The study was undertaken to evaluate the effect of wetting and drying on resilient modulus of eight selected soils in Oklahoma. Also, the study focuses on assessing the soil water characteristics curves (SWCC) of the soils selected. The resilient modulus-moisture content (MrMC) relationships of all the selected soils exhibit a hysteretic behavior due to the wetting and drying process. For a given water content, the M_r values are higher for a drying cycle than for the wetting cycle. The influence of the wetting-drying process is more dominant for the clayey soils. For the example, the decrease in resilient modulus of Burleson, a clayey soil, was found to be 66% as the compaction moisture content increased from approximately OMC-4% to OMC+4%. On the other hand, the M_r values for Binger, a sandy soil, exhibited a decrease of approximately 50% for the corresponding moisture contents. The soil water characteristic curves (SWCCs) found for the selected soils exhibited the same qualitative trends. The values varied from one soil to another and are similar to those reported by others for similar soils. The changes in soil suction and resilient modulus are influenced by the initial (compaction) moisture content. The resilient modulus values for specimens compacted at OMC-4% have higher resilient modulus than specimens compacted at OMC, followed by specimens compacted at OMC+4%.

5.2 Recommendation for Future Studies

Based on the findings, it is recommended that additional studies be conducted to evaluate resilient modulus and SWCCs of specimens subjected to wetting and cycles. Such a study would provide useful on the behavior of soil's repeated seasonal conditions. Also, a field study assessing the performance of resilient modulus, by performing falling weight deflectometer, and resilient modulus on push tubes is expected to be beneficial.

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