Correlations Between Index Properties and Unconfined Compressive Strength of Weathered Ocala Limestone

Raoaa Farah
University of North Florida

CORRELATIONS BETWEEN INDEX PROPERTIES AND UNCONFINED COMPRESSIVE STRENGTH OF WEATHERED OCALA LIMESTONE

by

Raoaa Farah

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Committee Member:	Date:
Signature Deleted Nick Hudyma, PhD PE Thesis Advisor and Committee Chairperson	April 12-2011
Signature Deleted N. Mike Jackson, PhD PE	April 12, 2011
Signature Deleted Alexandra Schönning, PhD	April 12, 2011

Accepted for the School of Engineering:

Signature Deleted Murat Tiryakioglu, PhD CQE Director of the School of Engineering	April 14, 2011

Accepted for the College of Computing, Engineering, and Construction:

Signature Deleted Peter Braza, PhD Interim Dean of the College of Computing, Engineering, and Construction	4/14/11

Accepted for the University:

Signature Deleted Len Roberson, PhD Dean of the Graduate School	5/2/11

To my Family who gave me all the support needed to be where I am now.

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ABSTRACT

Weathering has a negative effect on both physical and engineering properties of rock specimens and rock masses. When rock masses are weathered it is often difficult to obtain core segments that are the correct size for unconfined compressive strength testing. Thus engineers must use index testing to estimate the strength of specimens for design purposes. This thesis relates the unconfined compressive strength to index strength tests of Ocala limestone. The relationships developed include weathering states of the specimens and proximity of unconfined compressive strength specimens to index specimens.

One hundred and ninety five specimens were classified using International Society for Rock Mechanics (ISRM) weathering designations, had their unit weight determined, and were tested under unconfined compression, point load, or indirect tensile conditions. Qualitative results show the average unit weight decreases with an increase in weathering state and the range of index strength values decreases with an increase in weathering state. The data also shows low index strength test results across a wide range of unit weights.

Quantitative relationships were also developed with the strength data. All of the developed relationships were linear. Point load strengths have better correlations with unit weight than indirect tensile strengths. Unconfined compressive strength was correlated to index strength and weathering using three different approaches. For all approaches, indirect tensile strength has a better correlation with unconfined compressive strength than point load strength. Specimen pairs from the same weathering state also have a better correlation than specimen pairs from different weathering states. Unconfined compressive strength was also correlated to index strength results by incorporating specimen proximity. Once again, indirect tensile strength is a better predictor of unconfined compressive strength than point

load strength. Specimen pairs, consisting of unconfined compressive strength and index strength test specimens, had better correlations when the two specimens are located close together.

CHAPTER 1

INTRODUCTION

In Florida large and important infrastructure is often supported by limestone bedrock. In northeast Florida the near surface bedrock is Ocala Limestone, which is variably weathered due to its genesis during transgression and regression events and the on-going chemical and physical weathering. Since much of the large infrastructure is supported by the weathered limestone, it is imperative to understand how weathering affects the physical and engineering properties.

To design the large infrastructure the limestone must be characterized; typically through drilling activities to recover core and unconfined compression tests to determine strength and stiffness parameters. Typically core recovery from drilling is very good but the rock quality designation (RQD) is very poor. This means there are very few core pieces that can be used for unconfined compressive strength testing and engineers must rely on index property to estimate strength and stiffness properties.

The purpose of this thesis is to relate the unconfined compressive strength to index tests as a function of weathering and proximity to specimen location. The index tests that will be used are indirect (Brazilian) tensile strength and point load strength. Weathering states of the specimens will be classified using International Society for Rock Mechanics (ISRM) weathering states. The specimen proximity designation will account for the distance between the unconfined compressive strength and the index test specimens.

The thesis is divided into five chapters. Chapter 2 presents a literature review which includes a discussion on the weathering process of limestone, the classification of the weathered limestone, and previous studies describing how weathering affects the physical and engineering properties of rock.

Chapter 3 is a discussion of the specimens, classification, and testing performed as part of this thesis. The discussion includes the specimens preparation, tests performed, testing methods, and summarized test results. The main focus of this chapter is the process of classifying the specimens two different techniques; weathering state using ISRM descriptions and proximity of the index specimens to the unconfined compressive strength specimens.

Chapter 4 presents the relationships developed from the testing. Simple relationships are developed between weathering state and unit weight, indirect tensile strength, and point load strength. Advanced relationships are also developed for unconfined compressive strength as a function of both indirect tensile strength and point load strength. These relationships incorporate either weathering states or the proximity of index test specimens to UCS test specimens.

Chapter 5 presents the conclusions and recommendations for future work for other researchers who may wish to investigate the effects of weathering on the physical and engineering properties on the weathered limestone in Florida.

CHAPTER 2

LITERATURE REVIEW

The degree of weathering of rock masses and the resulting effects on physical and engineering properties has long been a concern for engineers. Numerous studies have been conducted on many different rock types to investigate the effects of weathering on physical and engineering properties of rock specimens. This chapter contains a basic discussion on weathering of limestone, introduces the weathering classification scheme used in this study, and presents a review of relevant studies that investigated the effects of weathering on strength and index properties of rock.

2.1 Weathering of Limestone

Weathering is a group of processes that transforms rock into mechanically weak and easily eroded material (Parriaux, 2009) which changes both the texture and engineering properties of the rock. Weathering processes are divided into physical and chemical weathering. Physical weathering, such as erosion and freeze-thaw cycles, is the mechanical breakdown of a rock mass into smaller pieces without a change in the chemical composition of the rock mass. The basic premise of physical weathering is that the rock mass is divided into smaller and smaller pieces.

Chemical weathering, such as carbonation, oxidation and dissolution, causes changes to the rock mass on an atomic level. The various chemical reactions occur and change the properties of the rock mass.

The shallow bedrock in Florida is comprised of a series of carbonate-evaporite sequences, which include limestone (Randazzo, 1997). These limestone formations contain horizontal and vertical discontinuities which include unconformities and bedding planes, fractures, joints and fissures. Slightly acidic rain water percolates through the surficial soils or directly into limestone outcrops. Once in the subsurface, the water preferentially flows along discontinuities. Water can make its way through these discontinuities which cause the weathering in the rock mass. The equilibrium reaction of slightly acidic rainwater is:

$$CO_{2\,gas} + H_2 0 \leftrightarrow H_2CO_{3\,carbonic\ acid}$$

As the slightly acidic rainwater travels preferentially along discontinuities and through pore space within the limestone, it acts as a solvent which contributes to the dissolution process. The acidity is derived from dissociation of carbonic acid by:

$$H_2CO_3 \leftrightarrow H^+ + HCO_3$$

The dissolution process results in significant changes to rock fabric and development of various types of pore spaces within the limestone (Randazzo, 1997). The dissolution equation can be written as:

$$CaCO_{3\,calcite} + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^-$$

This equation illustrates the reaction of acidic soil water with calcite to form karst features (Randazzo, 1997). When limestone ($CaCO_3$) encounters acidic soil water (H_2CO_3), the carbonate constituent (CO_3) of limestone is separated and dissolved calcium (Ca^{2+}) and bicarbonate ($2HCO3^-$) are produced.

2.2 ISRM Weathering Classification

The use of weathering classification system and subsequent weathering state designation is very subjective and is highly dependent upon professional judgment and experience (Pinho et al., 2006). The weathering for the rock masses is measured in different scales; however, one of the most common classification systems for the rock masses is the international Society for Rock Mechanics (ISRM, 1981), where the weathering states vary between W1 to W5 (fresh unweathered to completely weathered). Table 1 contains the ISRM weathering classification system.

Table 1. Description of weathering states of rock (after ISRM, 1981)

Weathering State	Descriptor	Qualitative Description
W1	Fresh	No visible sign of rock material weathering. Slight discoloration may be present on major discontinuity surfaces
W2	Slightly Weathered	Weathering indicated by discoloration of rock material and discontinuity surfaces. Rock may be weaker than W_1
W3	Moderately Weathered	Less than half of the rock material is weathered into a soil. Fresh or discolored rock is present as a discontinuous framework or as corestones.
W4	Highly Weathered	More than half of the rock material is weathered into a soil. Fresh to discolored rock is present as a discontinuous framework or as corestones.
W5	Completely Weathered	All rock material is weathered into soil. The original mass structure is still largely intact.

Table 1 shows that the ISRM weathering state classification is a general visual way to classify weathering zones within rock masses and cores. When classifying rock specimens, there is never a distinguishing line between different weathering states; the transition between the different weathering states is gradual.

Judgment and experience on weathering classification is very important, also consistency is very important. It is easier to distinguish highly weathered and fresh limestone over the slightly and moderately weathered limestone. However; studies showed that weathering classification is more consistent for slightly weathered rock than highly weathered rock (Pinho et al., 2006). Therefore, the use of objective and consistent criterion to designate weathering states throughout a project is very important and recommended, since having one consistent error in weathering classification is easier to deal with than having many errors that can get complicated at a further state of a project.

Classification of the limestone samples is based on experience and engineering judgment, and can vary from one person to another. A wide verity of samples could be classified as Weathering States 1, 2, 3, 4, or 5 as the range is more general and not specific for each sample. In a study conducted by Pinho et al. (2006) about the dependence of judgment and experience on weathering classification, 21 engineers were asked to classify 25 rock samples based on weathering using the ISRM system. The study showed many divergent opinions among the assessors. Significant evaluation errors happened to 72% of the specimens. However, more consistent weathering states classifications were found for slightly weathered rock than highly weathered rock. Therefore, classifying the rock samples is more subjective and it depends on the person classifying the samples. Consistency is the most important thing while classifying the samples. If a weathering state was misinterpreted, then consistent changes should be done to repair the misinterpretation.

2.3 The Effect of Weathering on Geotechnical Properties

Weathering negatively influences the geotechnical properties of rock. A review of relevant work in laboratory rock characterization that investigated the effects of weathering on various geotechnical properties are described below.

Sarno et al. (2009) conducted a study on weathered Ocala limestone. One hundred and seventy five limestone specimens were tested to relate index and physical properties to ISRM weathering state. The index tests performed were point load strength, indirect tensile strength, Schmidt hammer test, and hardness assessment. The unit weight was also measured. The results indicated that each weathering state was associated with either 2 or 3 hardness values, and as the weathering state increased the hardness values decreased. No clear relationship could be established between weathering and unit weight however, the standard deviation of unit weight values increased as the weathering state increased. There was increase in Schmidt hammer rebound number with increase of unit weight. The nondestructive Schmidt hammer test was actually a destructive test for higher weathering states. Indirect tensile strength and point load strength (Is_{50} values) increased as the unit weight increased but for the highly weathered specimens no relationship could be developed.

Gupta and Rao (1998) conducted a study to investigate the interrelationships of index properties of weathered rocks. Their work focused on both sedimentary and igneous rock but did not include limestone. Physical properties such as specific gravity, dry and saturated densities, moisture content, void ratio, absolute and effective porosity, quick absorption index, and dry and saturated sonic wave velocities were evaluated. Schmidt hammer, point load strength, indirect tensile strength, and unconfined

compressive strength tests were also performed. The study presented relationships between unconfined compressive strength (UCS) and other measurement such as the point load strength, the indirect tensile strength, and the Schmidt hammer rebound number. The test results indicated a linear positive relationship between UCS and point load strength as well as the indirect tensile strength test and Schmidt hammer test, and exponential positive relationship between Schmidt hammer and point load strength. A relationship between point load strength and indirect tensile strength test was not presented.

Kiliç and Teymen (2008) investigated the mechanical properties of nineteen different rock types; ten igneous rocks, seven sedimentary rocks (including limestone) and two metamorphic rocks. All specimens were from southern Anatolia, Turkey. The researchers conducted uniaxial compressive strength, point load strength, P-wave velocity, shore hardness index, porosity, Schmidt hammer test, and indirect tensile strength testing. The test results indicated a good correlation between the measured uniaxial compressive strength and shore hardness index, direct P-wave velocity, point load strength, porosity, and Schmidt hammer rebound number, but none of the relationships was linear. A positive exponential relationship was developed between uniaxial compressive strength (UCS) and P-wave velocity, shore hardness index, and Schmidt rebound number, and inversed positive exponential relationship between UCS and point load strength, and negative exponential relationship between UCS and porosity. Also a positive exponential relationship was developed between indirect tensile strength and shore hardness index, P-wave velocity, and Schmidt rebound number. An inverse positive exponential relationship was developed between indirect tensile strength and

point load strength. A negative exponential relationship was developed between indirect tensile strength and porosity.

Tungal and Zarif (2000) conducted research on the engineering aspects of weathered limestone found in Istanbul, Turkey. The specimens were obtained from the Kartal Quarry in Istanbul with specimens coming from depths as great as 80 meters. They presented the results of field and laboratory investigations, which included weathering characteristics along with physical and engineering properties. The testing program comprised the determination of specific gravity, dry and saturated unit weight, water absorption, effective and total porosity, P-wave velocity, point load strength, indirect tensile strength, uniaxial compressive strength and modulus of elasticity of the limestone. A positive linear relationship was found between UCS and point load strength, P-wave velocity, unit weight, elasticity modulus and indirect tensile strength, and a negative linear relationship was developed between porosity and UCS, P-wave velocity, and dry unit weight.

Dincer et al. (2004) conducted a study correlating Schmidt hardness, uniaxial compressive strength and Young's modulus for andesities, basalts and tuffs. Block rock samples were taken from 24 different locations in the volcanic formulations of the Bodrum Peninsula in Turkey. Schmidt hammer tests were performed on the block samples and core samples were taken for uniaxial compressive tests to determine unconfined compressive strength and Young's modulus. Unit weight was measured for the rock samples. Linear relationships were developed between Schmidt hammer rebound number and UCS along with Schmidt hammer rebound number and Young's modulus for basalt, tuff, and andesite. The authors indicated that more accurate results

can be developed when the rock samples are from the same weathering state and similar mineralogical structure.

Another study was performed on volcanic rocks by Arikan et al. (2007) regarding the characterization of weathered acidic volcanic rocks and a weathering classification based on rating system. Index and strength properties of rock specimens with weathering states ranging from 1 to 6 were performed. Unit weight, unconfined compressive strength (UCS), indirect tensile strength, and P-wave velocity measurements were made. Point load strength and grain size distribution of extremely and completely weathered rocks were also determined. The results of the test indicated a close relationship between the degree of weathering and the engineering properties. The decrease in UCS and indirect tensile strength from weathering grade 1 to 3 indicates that the strength of the rock types is significantly influenced by the change in the character of material due to weathering. Grain distribution tests indicated grade 5 mainly consists of gravel and some sand soils while grade 6 samples consisted of sand and fine grained material. The main conclusion drawn from this study are that the rock quality designation (RQD) decreases with the increase of the weathering grades, and Schmidt rebound values seems good field indicator of weathering grades 1 to 4. All the index and mechanical properties show close correlations between uniaxial compressive strength and indirect tensile strength for weathering grades 1 to 3. For rock masses a weathering assessment can be based on field descriptions and Schmidt rebound value.

A study investigating the effect of weathering on the geotechnical properties of andesite was conducted by Orhan et al. (2006). Weathered andesite specimens were obtained from three different sites and nine different boreholes from depths of up to 25

meters. The andesite deposits at all three sites had residual soil, completely weathered and highly weathered rocks within the first 25 meters. The study found that the strength and shear wave velocity was reduced with an increase in weathering. They determined the sites contained different weathering zones varying from fresh to residual soil, and the geotechnical properties are adversely affected by weathering.

Tugrul and Gurpinar (1997) investigated the weathering classification and engineering properties of basalts from the Niksar Region of eastern Turkey. The weathering classification of the basalts followed the following criteria: the color of the rock mass, rock-soil ratio, existence of core stones and their color and shapes, the color of discontinuity surface and hardness of rocks. Four basic weathering groups were defined and each weathering group was divided into 3 sub-groups; fresh rock, rock-soil mixture, and soil. Dry density, porosity, coefficient of permeability, uniaxial compressive strength, indirect tensile strength and Young's modulus were determined in accordance with ISRM standards. They found the dry density of the basalts decreases with the increasing of the degree of weathering. The uniaxial compressive strength, Young's modulus, and indirect tensile strength decrease sharply with the change from fresh to completely weathered basalt. Correlations between the physical and mechanical properties of the weathered basalt were also determined. The permeability of the rock material increases as the porosity increases with the increasing of the weathering grade. The uniaxial compressive strength decreased to almost zero as the dry density of the rock material decreased to 2 g/cm^3 with the increase with weathering grade. The uniaxial compressive strength decreased with an increase of porosity. An exponential relationship between the indirect tensile strength and dry density was developed which shows a

decrease in both properties with an increase in weathering. In general, good correlations between the physical and mechanical properties of the basalt were established which is useful for estimates to be made of one other single property from one another single property.

Irfan (1999) conducted a study on the weathered volcanic rocks in Hong Kong. The rock masses were deeply weathered to depths ranging from 20 to 60 meters. Six weathering grades were used to classify the weathered state of the rock material: residual soil, completely decomposed, highly decomposed, moderately decomposed, slightly decomposed, and fresh. Moisture content, Atterberg limits, particle size determination, specific gravity and compaction tests were conducted. The study determined that direct comparison if an index value at a particular weathering grade is not generally possible even for the same volcanic rock occurring in different formations. The standard laboratory preparation and testing methods used to determine the engineering classification and index properties of temperate soils need to be modified in order to obtain more repeatable and meaningful results of these soils.

2.4 Chapter Summary

Weathering in a rockmass is the culmination of various processes that change rock at or near the earth's surface. In general there are two categories of weathering, physical weathering and chemical weathering. Physical weathering, such as erosion and freeze-thaw cycles, is the mechanical breakdown of a rock mass into smaller pieces without a change in the chemical composition of the rock mass. Chemical weathering, such as carbonation, oxidation and dissolution, causes changes to the rock mass on an atomic level. Weathering changes the texture and properties of the limestone rock mass.

The weathering for the rock masses is measured in different scales; field scales, core scale, and microscopic scale. One of the most common classification system for the rock masses is from the International Society for Rock Mechanics (ISRM, 1981), where the weathering states vary between W1 to W5 (fresh, slightly weathered, moderately weathered, highly weathered and completely weathered).

A number of recent studies investigating the effect of weathering on physical and engineering properties of rock show a close relationship between the degree of weathering and engineering properties. All studies have clearly demonstrated that geotechnical properties are adversely affected by weathering. Specifically for limesont, indirect tensile strength and point load strength (Is_{50} values) increased as the unit weight increased but for the highly weathered specimens no relationship could be developed (Sarno, 2009). In addition, Gupta and Rao (1998) showed a linear positive relationship between unconfined compressive strength and point load strength, indirect tensile strength, and Schmidt hammer rebound number. Kiliç and Teymen (2008) showed an inverse positive exponential relationship between unconfined compressive strength and point load strength.

CHAPTER 3

SPECIMENS, CLASSIFICATION, AND TESTING

This chapter discusses the limestone specimens which were used in this study, where the specimens were obtained, the geologic origin of the specimens, how they were prepared, and the number of specimens obtained. Also the specimens classification methods used; the specimens were classified based on weathering state using the International Society for Rock Mechanics (ISRM) weathering classification scheme, and were also classified according to their proximity to unconfined compression strength test specimens. This chapter also discusses the tests performed, unit weight, indirect tensile test, point load strength and unconfined compression strength test, and it discuss the test results.

3.1 Specimens

This section contains a discussion about the limestone specimens which were used in this study. Included in the discussion are where the specimens were obtained, the geologic origin of the specimens, how they were prepared, and the number of specimens obtained.

3.1.1 Test Site and Geologic Setting

The specimens were obtained from coring operations at a UNF-UF-FDOT geotechnical test site on the southeastern corner of the intersection of State Road 26 and County Road 235 near Newberry Florida in Alachua County. The site is approximately

90 miles from Jacksonville. The geotechnical test site is a dry retention pond, approximately 4 acres in size. Eight borings were conducted within a 72,800 square foot area for site characterization purposes. The cores were obtained using double barrel wireline drilling and are PQ size (3.4 inch diameter). A total length of 229 feet of rock core was drilled in five foot long core runs. A total of 171.5 feet of limestone core was obtained.

In the geotechnical test site area, the overburden is undifferentiated siliciclastic sediments that overlie the Hawthorn group which overlie the Ocala limestone. The dominant lithology within the sediments is quartz sands that contain variable mixtures of clay. This unit virtually blankets Alachua county ranging in depth from a few feet to greater than 20 feet thick. The Hawthorn group consists of intermixed carbonate and siliciclastic containing varying percentage of phosphate grains. The Hawthorn group has variable thickness within the region and lies unconformably on the Ocala limestone. The core samples are from the Ocala limestone unit, which is between 34 and 56 million years old. The Ocala limestone is predominately calcium carbonate and is generally soft and porous; however portions of the unit are hard and dense, Scott (2001).

3.1.2 Specimen Preparation

The five foot long core runs were taken into the laboratory and the top and bottom of each core run was noted. There are two common measures that indicate the quality of a rock core run, the recovery and the rock quality designation. The recovery, expressed in percentage, is the length of core recovered divided by the length of core drilled. The rock quality designation (RQD) is the sum of the core lengths greater than 4 inches divided by the run length, expressed as a percentage (Waltham, 2002). In general, the

recovery was very high (typically between 90 and 100 percent but as low as 20 percent) but the RQD varied between 0 and 100 percent with a number of very low RDQ zones.

The goal of the specimen preparation was to obtain the maximum number of specimens from each of the core runs. The specimens from the core must be greater than 6.8 inches in length for unconfined compressive strength testing and greater than 1.6 inches in length for indirect tensile strength and point load strength. The specimens for unconfined compressive strength testing must have length-to-diameter ratios of 2:1 or greater. The specimens for indirect tensile strength and point load strength are commonly referred to as puck specimens. A typical core run is shown schematically in Figure 01.

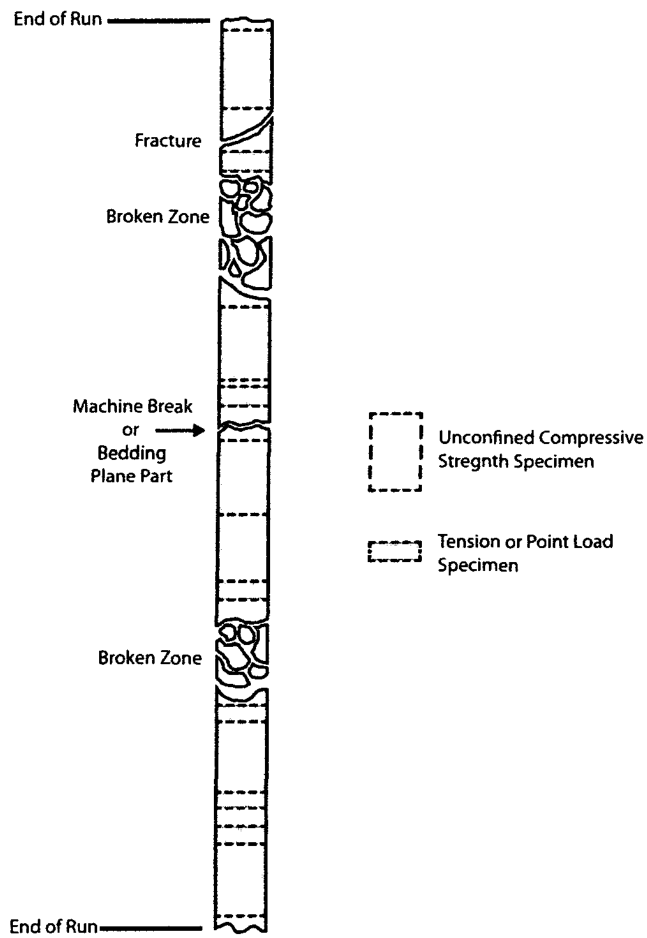


Figure 1. Schematic depiction of a core run showing specimen selection and locations

There are numerous features within the core, such as fractures, machine breaks, bedding plane parts, or broken zones which prohibit obtaining specimens. The broken zones, which are typically highly weathered zones, were highly fractured from drilling. Machine breaks are fresh breaks caused by drilling and are typically horizontal. Bedding plane parts are breaks along different depositional events; these breaks are natural discontinuities and may be open or closed within the subsurface. Fractures are natural discontinuities which are typically inclined.

The first type of specimen to be obtained was the unconfined compression test specimens because of the strict length requirements. The depth of the specimens was noted. After all potential unconfined compression test specimens within a single core run were identified, the depth was recorded and the specimens were cut using a wet diamond saw.

A similar approach was used for the index test specimens. All potential specimens were noted, depths were recorded and specimens were cut from the core using a wet diamond saw.

Since the goal of this work is to compare point load strength and indirect tensile strength test (index tests) results with unconfined compression strength (UCS) test results, all attempts were made to obtain index test specimens right above and/or right below the UCS specimens for direct comparison. Unfortunately the variation in degree of weathering variation within the same core run and the low RQD values made it impossible to always have a core segment enough to obtain a UCS specimen and an index test specimen. In those cases, one specimen, either indirect tensile strength or point load strength, was selected either below or above the UCS sample.

In some cases, index test specimens were not available directly above or below the UCS specimen. However all possible index specimens were cut from the core and associated with the closest UCS specimen. Depth for all of the index specimens and unconfined compressive strength specimens was always recorded.

A total of 195 specimens were collected from the 171.5 feet of core. There were 50 unconfined compression strength test specimens, 46 point load strength specimens, and 99 indirect tensile strength test specimens.

3.1.3 Summary

Eight boring were conducted as part of site characterization activities at the UNF-UF-FDOT geotechnical test site near Newberry Florida. From the borings, 171.5 feet of Ocala limestone core was obtained. Ocala limestone is between 34 and 56 million years old. It is predominately calcium carbonate and is generally soft and porous; however portions of the unit are hard and dense. The recovered core was sampled to produce 195 specimens; 50 specimens for unconfined compression testing and 145 specimens for index testing. The index testing specimens consisted of 46 specimens for point load strength and 99 specimens for indirect tensile strength testing. The goal of the core sampling was to obtain index test specimens as close as possible to the unconfined compression test specimens for direct comparison.

3.2 Specimen Classification

The specimens were classified using two different approaches. The specimens were classified based on weathering state using the ISRM weathering classification scheme. The specimens were also classified according to their proximity to unconfined compression strength test specimens. This section describes both classification methods.

3.2.1 ISRM Weathering Classification

Classifying any rock specimens based on weathering is a qualitative effort based on experience and engineering judgment. As previously indicated, work by Pinho et al (2006) demonstrated the assigning of weathering states to samples varies between professionals, especially for highly weathered specimens. It is very important to be consistent when assigning weathering states or values. If weathering states are assigned consistently, any modifications or changes to assigned weathering states can easily be corrected.

The index test specimens were classified in accordance with ISRM weathering classification system. The specimens were first grouped based on color and surface texture, without regard to location or depth of the specimen, and the weathering state was assigned.

Weathering states 1 through 4 were assigned to all of the index specimens; W1 (fresh), W2 (slightly weathered), W3 (moderately weathered), and W4 (highly weathered) based on the ISRM descriptions. In most cases, color was a good indicator of weathering state; the darker the color the more weathered the specimen. This is thought to be associated with staining from the ground water moving through highly weathered zones. Texture was also a good indicator of weathering; in general as weathering increased the texture of the specimens became coarse and rough as voids get developed. Table 2 contains typical pictures and descriptions of the assigned weathering states.

Forty eight specimens were classified as W1. In general W1 specimens show no visible signs of weathering and have a concrete-like appearance. The color of the specimens was light to medium gray and there was a smooth texture from the wet

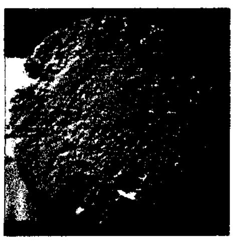
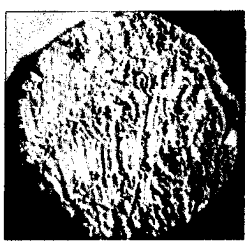
diamond saw cutting. The specimens had some surface features such as small voids and minor cracks. These specimens are very competent and show no signs of disintegration. One of the most important indicators of the W1 designation was that all of the specimens were the full diameter of the core.

Fifty six specimens classified as W2. When compared to the W1 specimens, the W2 specimens have a more creamy color. The texture of these specimens is coarser and they begin to exhibit and earthy-type fracture appearance. There is minor pitting of the surface.

Fifty-three specimens were classified as W3. When compared to the W2 specimens, the W3 specimens have a darker color. It is important to note that it is within the W3 and W4 specimens that the color classification begins to breakdown; some of the specimens are darker than the W2 specimens however whitish colored specimens begin to appear in this weathering state. The texture of the specimens is much coarser and surface pitting is very evident. These specimens have an earthy-type fracture appearance. The specimens start to appear fragile.

Thirty six specimens are classified as W4. The color of these specimens ranges from very dark creamy to yellow but also include white specimens. These specimens appear to be very fragile. The specimen surfaces are very pitted and the wet diamond saw appears to have smeared some of the surface material during cutting. These specimens appear very fragile.

Table 2. Photographs and descriptions of weathering states

Typical Photograph	Weathering State and Description	General Color Trend	Texture
	**Weathering State W1** • Appear very competent • Full core diameter • Concrete-like appearance	• Light to medium gray	• Fine texture • Very minor pitting
	**Weathering State W2** • Appear competent • Not always full core diameter • Beginning of earthy-type fracture appearance	• Creamy color	• Coarser texture • Minor pitting
	**Weathering State W3** • Appear somewhat competent/somewhat fragile • Never full core diameter • Earthy-type fracture appearance	• Dark creamy color • Whitish color also seen	• Even coarser texture • Pitting is very evident
	**Weathering State W4** • Appear very fragile • Never full core diameter • Earthy-type fracture	• Very dark creamy color to yellowish color • Whitish color also seen	• Very coarse texture • Major pitting • Smearing of the saw blade on specimens is often noted
	**Weathering State W5** • Very fragile • Core segment completely broken	• Very dark creamy color to yellowish color • Whitish color also seen	• Unable to obtain specimen for testing

3.2.2 Classification Based on Proximity to UCS Samples

To determine the relationships between index properties and unconfined compressive strength (UCS) the index specimens were classified according to their proximity to unconfined compression strength test specimens, ie how far the index specimen is from its associated UCS specimen. All attempts were made to obtain an index test specimen above and below UCS specimens however this was not possible in most of the times because of the features within the core, such as fractures, machine breaks, bedding plane parts, or broken zones which prohibited obtaining specimens. Therefore three index specimen categories were defined based on the distance between the unconfined compressive strength specimens and the indirect tensile strength and point load strength samples. Figure 2 shows the three different categories of specimens.

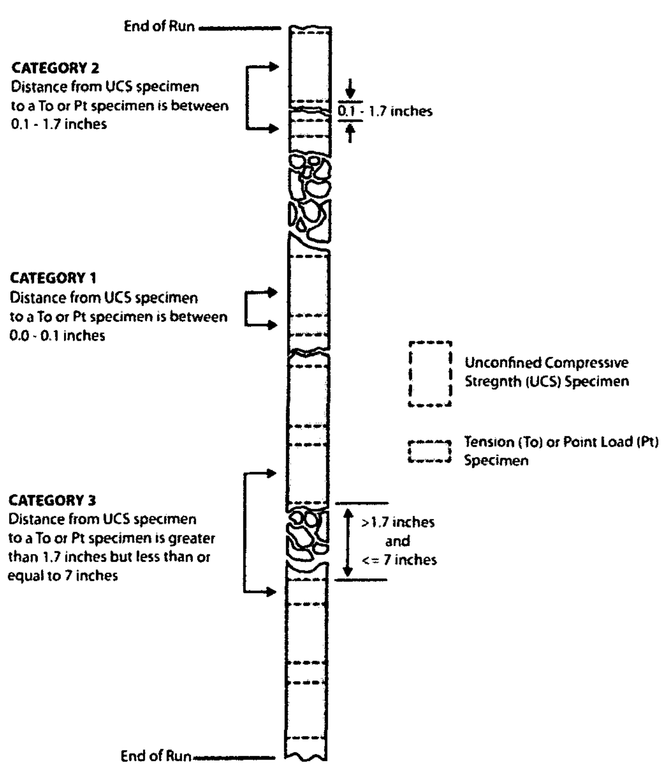


Figure 2. Classification based on proximity to UCS specimens

The first category consists of specimens that were taken right above and/or right below the unconfined compressive strength (UCS) specimens for direct comparison. The distance between the UCS samples the index test samples was 0 to 0.1 inch. The index specimens in Category 1 were not separated from the UCS specimens by discontinuities; there was a continuous piece of core that contained the UCS specimen and the index specimen(s). Thirty-five index specimens were identified as Category 1; 16 indirect tensile strength-UCS specimen pairs and 19 point load strength-UCS specimen pairs.

Category 2 specimens are comprised of index test specimens located a distance of 0.1 to 1.7 inches away from UCS specimens. This distance was chosen since it is the same as the length of an index test specimen. For this category, the UCS specimen and the index test specimen did not come from the same piece of core; there was a discontinuity (fracture, machine break, bedding plane part, or broken zone) which separated the two specimens. Thirty-five index specimens were identified as Category 2 specimens; 17 indirect tensile strength-UCS specimen pairs and 18 point load strength-UCS specimen pairs.

Category 3 specimens are comprised of index test specimens located a distance greater than 1.7 inches but less or equal to 7 inches from the UCS specimens. All of the Category 3 index specimens did not come from the same piece of core as the UCS specimens. Seven specimens were identified as Category 3 specimens; 5 indirect tensile strength-UCS pairs and 2 point load strength-UCS specimen pairs.

3.2.3 Specimen Classification Summary

The weathering states were determined for each sample in accordance with ISRM weathering classification system. Weathering states 1 through 5 were assigned to the

samples. W1 (fresh), W2 (slightly weathered), W3 (moderately weathered), W4 (highly weathered), and W5 (completely weathered). 48 samples and specimens were classified as W1, 56 samples and specimens were classified as W2, 53 samples were classified as W3, and 36 samples and specimens were classified as W4. The index strength specimens were also classified according to their proximity to unconfined compression strength test specimens. Three different categories were defined, Category 1: index specimens directly above/below the UCS specimens, Category 2: index specimens and UCS specimens separated by 1.7 inches, and Category 3: index specimens and UCS specimens separated by a distance greater than 1.7 inches but less than or equal to 7 inches.

3.3 Testing

This section describes the tests performed on the index test specimens and provides the range of results for each test. The unit weight for all index test specimens was determined and then the specimens were subjected to either indirect tensile (Brazilian) strength testing or point load strength testing.

3.3.1 Unit Weight

Prior to the destructive index testing, the unit weight of the index test specimens was determined. The specimens were weighed in an air-dried condition. The volume of the specimen was computed by measuring the diameter of the puck specimen at two locations and the thickness of the puck specimen at four locations. The average thickness and diameter of the specimen was computed and the volume of the specimen determined. The unit weight of the specimen is simply the weight divided by the volume:

$$\gamma = \frac{weight\,(lb)}{volume\,(ft^3)}$$

Unit weight was calculated for 165 specimens designated for index testing, of these 45 specimens were classified as W1, 31 specimens were classified as W2, 53 specimens were classified as W3, and 36 specimens were classified as W4. The unit weight values ranged between 60.8 to 147.8 pounds per cubic foot (pcf).

3.3.2 Indirect Tensile Strength Testing

Indirect tensile strength testing, commonly referred to as the Brazilian strength test, was conducted on ninety nine specimens. Thirty-three of the specimens were classified as W1, 43 specimens were classified as W2, 21 specimens were classified as W3, and 2 specimens were classified as W4. The indirect tensile strength test was performed following the procedure outlined in ISRM (1978) with the exception that flat platens rather than curved platens were used. The use of flat platens rather than curved platens is common in assessing the indirect tensile strength of rock is common (Coviello et al., 2005).

The test set-up for the indirect tensile strength test is shown in Figure 3. The indirect tensile strength testing was conducted using an apparatus consisting of a hydraulic pump and small load frame. The index test specimen was placed on edge between two flat platens. The load was applied using a hand pump at a continuous rate. The bottom platen moved upwards under the action of the hydraulic pump. This test method is intended to indirectly measure directly the indirect tensile strength of a rock specimen of regular geometry. The indirect tensile strength was calculated by dividing the maximum load applied to the specimen by the cross sectional area. The indirect tensile strength of the specimens ranged between 6.2 and 423.2 pounds per square inch (psi).

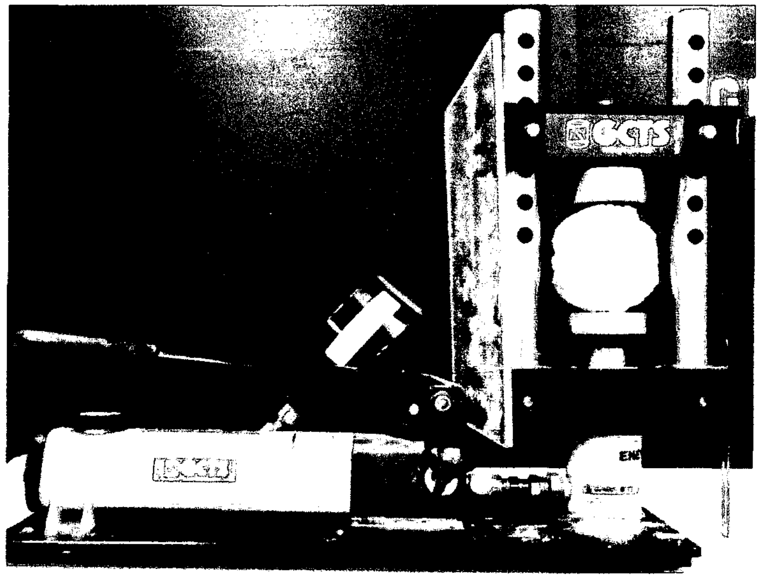


Figure 3. Configuration used for the indirect tensile strength test

3.3.3 Point Load Strength Testing

The point load strength test is an index test for strength classification of rock and is often used as an indicator of the unconfined compressive strength (Hudson and Harrison, 2007). Forty-six specimens were tested under point load conditions, of these specimens 15 specimens were classified as W1, 13 specimens were classified as W2, 15 specimens were classified as W3, and 3 specimens were classified as W4. The same testing apparatus was used for the point load strength testing with the exception of the flat platens were replaced by the appropriate point load inserts. The point load strength testing followed the procedures outlined in ISRM (1985).

The specimens were tested in axial configuration as shown in Figure 4. Specimen dimensions had to adhere specific criterion; the height of the specimen (D) had to be between $0.3W<D<W$, where W is the diameter of the specimen. The specimen dimension criterion is shown in Figure 5. During the test the load, as applied by the hand pump, is steadily increased such that failure of the specimen occurs with 10 to 60

seconds. Furthermore, tests where the fracture surface passed through only one loading point are considered invalid and rejected.

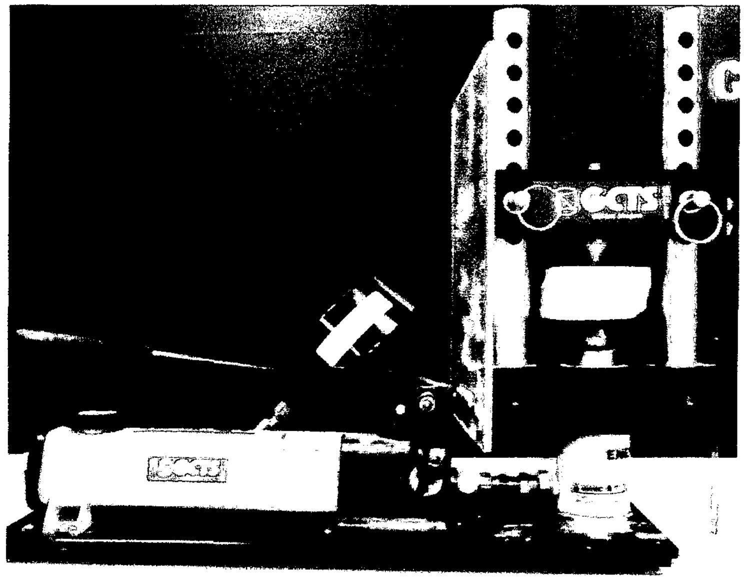


Figure 4. Point load strength test apparatus and specimen in the axial loading condition

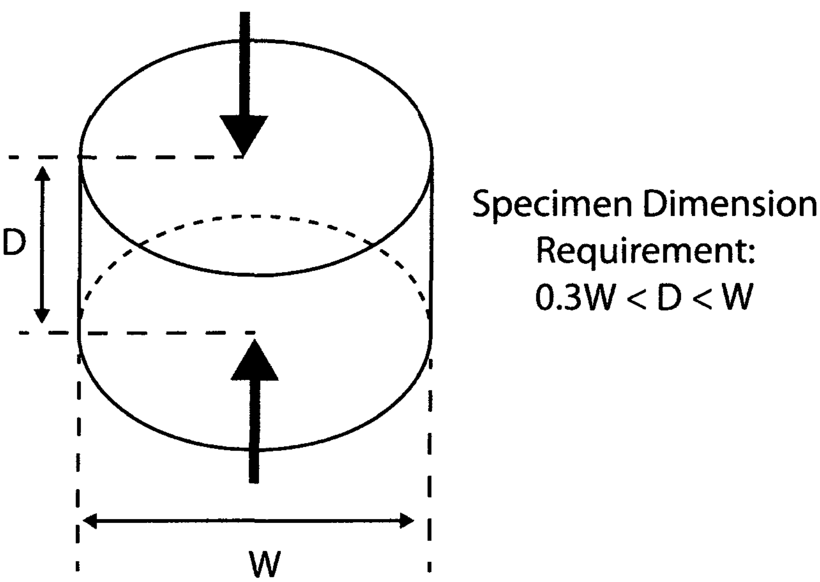


Figure 5. Specimen dimension requirements for the point load axial loading condition (after ISRM, 1985)

The point load strength test yields a load (P) in force units. The uncorrected point load strength is calculated as:

$$I_s = \frac{P}{D_e^2}$$

Where $D_e^2 = 4A/\pi$ and A=WD where D is the width (thickness) of the specimen and W is the diameter of the specimen. The term D_e^2 represents the cross sectional area of plane through platen contact points.

The results of the point load strength testing (I_s) were corrected to achieve I_{s50}, which is the point load strength corrected to a specimen of diameter of 50 mm.

$$I_{S(50)} = I_s \times F$$

Where $F = \sqrt{(D_e/50)}$

3.3.4 Index Test Results

The unit weight was measured for 165 specimens and the unit weight 60.8 to 147.8 pcf. Ninety-nine indirect tensile strength tests were performed on puck specimens with indirect tensile strengths ranging between 6.2 and 423.2 psi. Forty-six specimens were tested under point load conditions and the point load strength ranged between 1.6 and 327.6 psi.

3.4 Chapter Summary

Eight boring were conducted as part of site characterization activities at the UNF-UF-FDOT geotechnical test site near Newberry Florida. From the borings, 171.5 feet of Ocala limestone core was obtained. Ocala limestone is between 34 and 56 million years old and is predominately calcium carbonate and is generally soft and porous; however portions of the unit are hard and dense. The recovered core was sampled to produce 195

specimens; 50 specimens for unconfined compression testing and 145 specimens for index testing. The index testing specimens consisted of 99 specimens for indirect tensile strength testing and 46 specimens for point load strength testing. The goal of the core sampling was to obtain index test specimens as close as possible to the unconfined compression test specimens for direct comparison.

The weathering states were determined for each sample in accordance with ISRM weathering classification system. Weathering states 1 through 5 were assigned to the samples. W1 (fresh), W2 (slightly weathered), W3 (moderately weathered), W4 (highly weathered), and W5 (completely weathered). Forty-five specimens were classified as W1, 31 samples and specimens were classified as W2, 53 samples were classified as W3, and 36 samples and specimens were classified as W4. The specimens were also classified according to their proximity to unconfined compression strength test specimens. Three different categories were defined, Category 1: index samples directly above/ below the UCS samples, Category 2: index specimens and UCS specimens were separated by a distance of 1.7 inches, and Category 3: indes specimens and UCS specimens separated by a distance greater than 1.7 inches.

Unit weights were determined for 165 specimens. Ninety-nine index test specimens were tested to determine indirect tensile strength test using ISRM suggested methods and 46 specimens were tested to determine point load strength test using ISRM suggested methods. Table 3 is a summary of the number of specimens tested and weathering classifications.

Table 3. Testing, number of specimens, weathering classifications, and results

Test Method	Number of Specimens Tested	Specimen Breakdown	ISRM Weathering State			
			W1	W2	W3	W4
Unit Weight (pcf)	165	Number of Specimens	45	31	53	36
		Range of Values	81.6 – 138.4	68.6 – 133.7	62.6 – 147.8	60.8 – 113.4
Indirect Tensile Strength (psi)	99	Number of Specimens	33	43	21	2
		Range of Values	6.2 – 423.2	9.5 – 236.6	20.3 – 222.7	17.4 – 84.1
Point Load Strength (psi)	46	Number of Specimens	15	13	15	3
		Range of Values	3.5 – 327.6	8.24 – 209.5	7.6 – 128.8	1.6 – 10.8

CHAPTER 4

DEVELOPED RELATIONSHIPS AND DISCUSSION

The purpose of this thesis is to develop relationship between the physical properties of Ocala limestone specimens, unconfined compressive strength (UCS), indirect tensile strength, point load strength, weathering states, and distance between index and UCS specimens. The chapter begins with a brief discussion on regression analysis. The effects of weathering on unit weight, indirect tensile strength, and point load strength results are then qualitatively analyzed. Relationships are then developed for indirect tensile strength and point load strength as a function of unit weight. Finally relationships between unconfined compressive strength and index tests are presented as a function of weathering and index test specimen proximity to unconfined compressive strength test specimens. The unconfined compression test results used in this study are from the work of Sarno (2010).

4.1 Regression Analysis

In order to develop relationships between unit weights, unconfined compression strength (UCS), indirect tensile strength, and point load strength regression analyses were used. Regression analysis is normally used to create a mathematical model that can be used to predict the values of a dependent variable based upon the values of an independent variable. To perform the regression analyses, test data was plotted in 2 dimensions as a scatter plot. This format allows visualization/inspection of the data prior to running a regression analysis. Different curve fitting relationships, such as linear,

exponential, logarithmic, polynomial, and power, can be used to analyze the relationship between a dependent and independent variable. The curve fitting relationships produce a coefficient of determination (R^2). The coefficient of determination is the measure of the proportion of variability on one variable that can be accounted for by variability on the other variable (Sheskin, 2000). Once all possible regression curve fits and associated R^2 values have been determined, a researcher will then decide which curve fit is most appropriate. Typically the most appropriate is the curve fit is the one with the highest R^2 value.

Based on the literature review, linear or exponential relationships are expected between unit weight and point load strength, and indirect tensile strength. Also a linear or exponential relationship is expected between the unconfined compressive strength (UCS) and point load strength, and indirect tensile strength.

4.2 Weathering Relationships

The relationship between weathering and unit weight, point load strength results, indirect tensile strength were determined. Weathering states for the specimens ranged from W1 through W4; no W5 specimens were obtained because they are weathered to the state of soil and specimens could not be cut without destroying the specimen. As such, none of the relationships include a W5 weathering state; however based on the results of the testing if W5 specimen could be included, the specimens would have been weaker in point load strength results and indirect tensile strength and have lower unit weights.

4.2.1 Unit Weight and Weathering

The first qualitative relationship developed was between unit weight and weathering state. Figure 6 shows the relationship between weathering and unit weight.

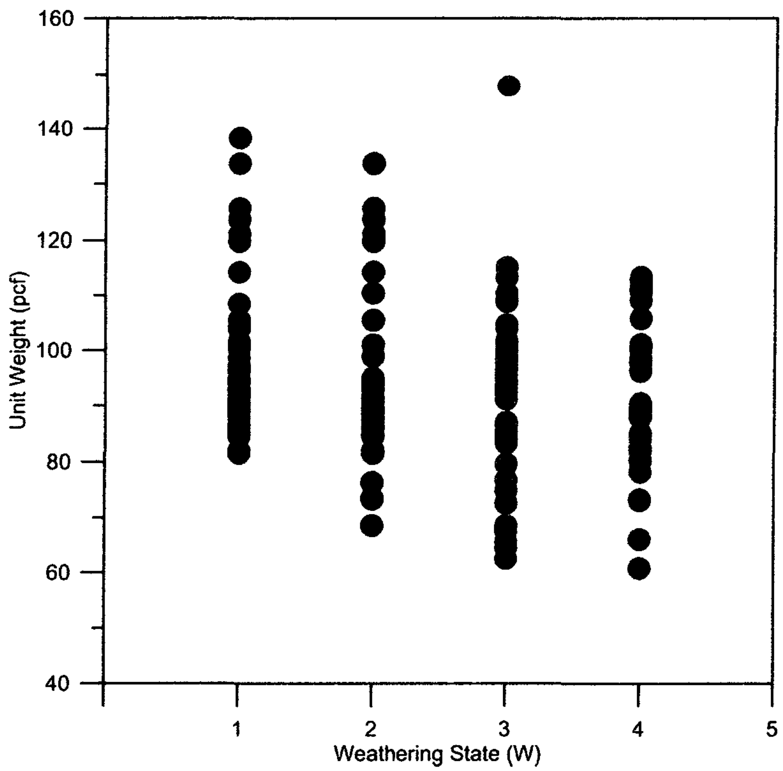


Figure 6. Range of unit weight values as a function of weathering

In general, there is a wide range of unit weight values within all weathering states. Interestingly, weathering states W1 and W2 have very similar ranges of unit weight and weathering states W3 and W4 have similar ranges of unit weight. The range of unit weights decreases with increasing weathering state; weathering states W1 and W2 have larger ranges of unit weights whereas weathering states W3 and W4 have smaller ranges of unit weights. Considerate overlap of the unit weight was noted in all the weathering states. There is one anomalous unit weight; a W3 specimen has a high unit weight relative to those classified as W3. The ranges and averages for the unit weights as a function of weathering are also presented in Table 4. As expected, the average unit weight for specimens decreases with increasing weathering state. In general, the standard

deviation of the unit weights in each of the weathering states decreases with increasing weathering.

Table 4. Descriptive statistics for specimen unit weight as a function of weathering state

Weathering State	Number of Specimens	Unit Weight Values
W1	48	Minimum = 68.6 pcf
		Average = 98.2 pcf
		Maximum = 138.4 pcf
		Standard Deviation = 15.5 pcf
W2	31	Minimum = 68.6 pcf
		Average = 97.6 pcf
		Maximum = 133.7 pcf
		Standard Deviation = 17.1 pcf
W3	53	Minimum = 62.6 pcf
		Average = 92.6 pcf
		Maximum = 147.8 pcf
		Standard Deviation = 14.9 pcf
W4	36	Minimum = 60.8 pcf
		Average = 91.6 pcf
		Maximum = 113.4 pcf
		Standard Deviation = 12.9 pcf

4.2.2 Indirect Tensile Strength and Weathering

The next qualitative relationship determined was between indirect tensile strength and weathering state. In general, indirect tensile strength decreases as weathering increases. Figure 7 shows the results of the indirect tensile strength test with respect to specimen weathering state.

As seen Figure 7, there is a wide range of indirect tensile strength for each weathering state. Weathering state W1 specimens (33 specimens) had indirect tensile

strengths ranging between approximately 425 to 3 psi. Weathering state W2 specimens (43 specimens) had indirect tensile strengths ranging between approximately 8 and 250 psi. Weathering state W3 specimens (21 specimens) had indirect tensile strength ranging between approximately 13 and 225 psi. Only two weathering state W4 specimens were obtained for indirect tensile strength testing and their strength values were 17 and 84 psi.

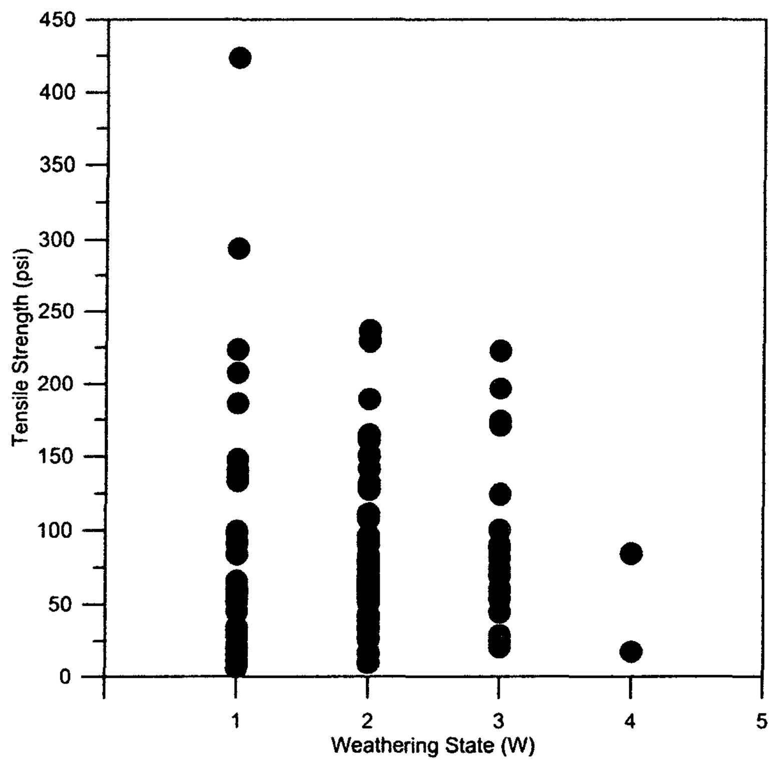


Figure 7. Indirect tensile strength as a function of weathering state

The data in Figure 7 is presented also presented in Table 5. As seen in the figure, considerate overlap of the indirect tensile strength was also noted in all the weathering states. All weathering states have specimens with very low indirect tensile strengths. The highest indirect tensile strength within each weathering state decreases with

increasing weathering. Thus the range of indirect tensile strengths decreases with an increase in weathering state; simply put, indirect tensile strengths are more variable at lower weathering states. This is apparent from the general decrease in standard deviation of the data within each weathering state as weathering increases.

Table 5. Descriptive statistics for specimen indirect tensile strength as a function of weathering states

Weathering State	Number of Specimens	Indirect Tensile Strength Values
W1	33	Minimum = 6.2 psi
		Average = 95.3 psi
		Maximum = 423.2 psi
		Standard Deviation = 90.6 psi
W2	43	Minimum = 9.5 psi
		Average = 83.4 psi
		Maximum = 236.6 psi
		Standard Deviation = 54.1 psi
W3	21	Minimum = 20.3 psi
		Average = 91.9 psi
		Maximum = 222.7 psi
		Standard Deviation = 61.5 psi
W4	2	Minimum = 17.4 psi
		Average = 50.8 psi
		Maximum = 84.1 psi
		Standard Deviation = N/A

4.2.3 Point Load Strength and Weathering

The final qualitative relationship developed was between point load strength test results and weathering state. In general, point load strength test result values decrease as

the weathering increases. Figure 8 shows the results of the point load strength test with respect to the weathering state of each specimen.

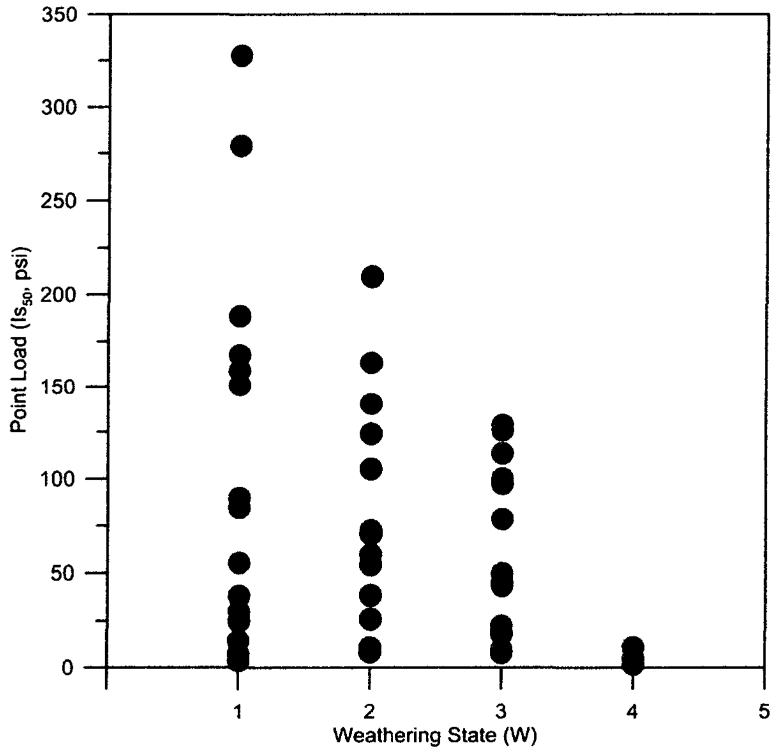


Figure 8. Point load strength results as a function of weathering state

As seen in Figure 8, there is a wide range of point load strength test results for weathering states W1, W2, and W3. Weathering state W1 (15 specimens) point load strength test results ranged between 4 to 327 psi. Weathering state W2 (13 specimens) point load strength test results values ranged between 8 and 209 psi. Weathering state W3 (15 specimens) point load strength results ranged between 8 and 129 psi. Lastly weathering state W4 (3 specimens) point load strength test results ranged between 2 and 11 psi. The data is also presented in table form in Table 6.

As seen in the Figure 8, considerate overlap of the point load strength was also noted in all the weathering states. All weathering states had specimens with very low

point load strengths. The highest point load strength within each weathering state decreases with increasing weathering. Thus the range of point load strengths decreases with an increase in weathering state; simply put, point load strengths are more variable at lower weathering states. As also discussed in Brady and Brown (1985) caution must be exercised in carrying out point tests and interpreting the results. Very soft rocks and highly anisotropic rocks or rocks containing marked planes of weakness such as bedding planes, are likely to give spurious results.

Table 6. Descriptive statistics for specimen point load strength as a function of weathering states

Weathering State	**Number of Specimens**	**Point Load Strength Values**
W1	15	Minimum = 3.5 psi
		Average = 108.0 psi
		Maximum = 327.6 psi
		Standard Deviation = 101.2 psi
W2	13	Minimum = 8.2 psi
		Average = 83.2 psi
		Maximum = 209.5 psi
		Standard Deviation = 61.7 psi
W3	15	Minimum = 7.6 psi
		Average = 57.8 psi
		Maximum = 128.8 psi
		Standard Deviation = 45.1 psi
W4	3	Minimum = 1.6 psi
		Average = 5.8 psi
		Maximum = 10.7 psi
		Standard Deviation = N/A

4.2.4 Weathering Relationships Summary

As discussed above, unit weight, indirect tensile strength, and point load strength were plotted as a function of weathering state. From each of the plots a qualitative relationship was developed. In regards to unit weight, weathering states W1 and W2 had the same range in unit weight and weathering state W3 and W4 had the same range in unit weight. The average unit weight for decreased with an increase in weathering state. In regards to indirect tensile strength and point load strength, every weathering state had specimens with very low strength values. As weathering increased the highest index strength values decreased. The variability in index strength values decreases with an increase in weathering state. A considerate overlap of the properties was noted in all the weathering states.

4.3 Unit Weight Relationships

Quantitative relationships are between unit weight and index test results; indirect tensile strength and point load strength are expressed as functions of unit weight. Based on the literature review, it is expected that increases in unit weight should correspond to increases in indirect tensile strength and point load strength.

4.3.1 Indirect Tensile Strength as a Function of Unit Weight

Figure 9 presents the relationship between indirect tensile strength and unit weight. The specimens used to develop the relationship are differentiated by weathering state.

In general, there is an increase in indirect tensile strength with increasing unit weight. Focusing on the weathering states, no clear relationships are noted. There is much overlap between unit weights and indirect tensile strengths for all weathering

states. The best fit regression line is plotted for the indirect tensile strength vs. unit weight; the R^2 value (0.35) is not high. As seen in Figure 7, the points are scattered around the best fit line; therefore, the R^2 value is not very reliable.

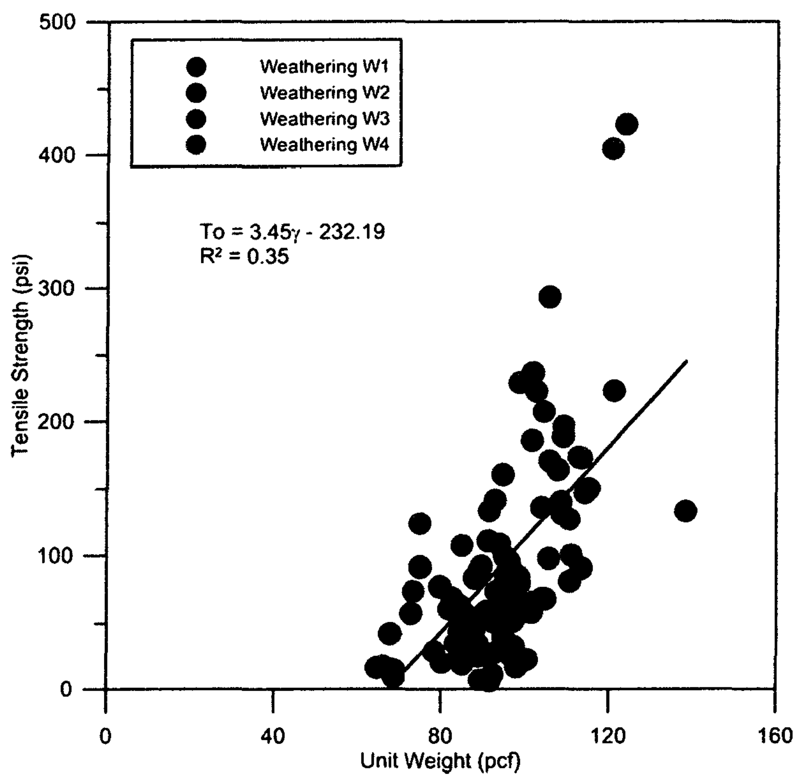


Figure 9. Relationship between indirect tensile strength and unit weight

4.3.2 Point Load Strength as a Function of Unit Weight

The relationship between point load strength and unit weight is linear, as shown in Figure 10. The specimens were differentiated with different symbols based on the weathering state.

As shown in Figure 10, the point load strength increases with increasing unit weight in a linear fashion. W1 specimens had higher point load strength than all other weathering states. As noted previously, the lowest point load strength values for all

weathering states are approximately the same. There is much scatter in the data a low point load strength values. As point load strength increases, there is less scatter in both unit weight and point load strength values. The majority of the data shows a large number of very small point load strength values across a wide range of unit weights. Since there were only three W4 point load strength tests, it was difficult to determine a general trend for that particular data set. One possible assessment is that point load strength test may not be appropriate for W3 and greater weathering states. Research has shown that point load strength results are ambiguous when rock strength is less than 3600 psi (Hoek, 1999). The best fit regression line is plotted for the Point Load Strength vs. Unit Weight; the R^2 value (0.41) is not high. As seen in the figure 10, the points are scattered around the best fit line; therefore, the R^2 value for the point load strength relationship is also not very reliable.

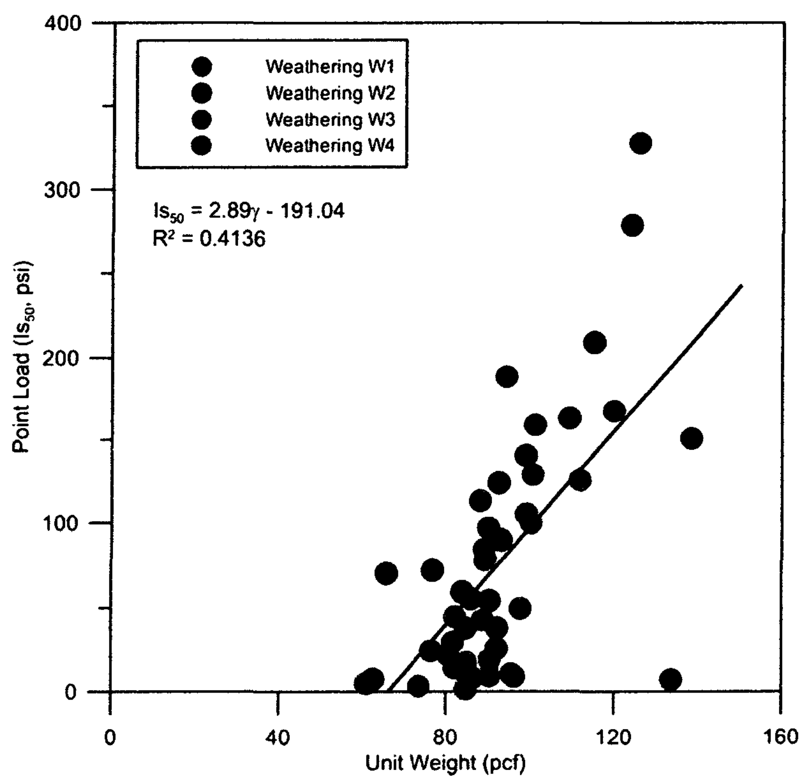


Figure 10. Relationship between point load strength results and unit weight

4.3.3 Unit Weight Relationships Summary

As discussed above, indirect tensile strength, and point load strength were plotted as a function of unit weight. From each of the plots a relationship was developed. The indirect tensile strength plot shows a linear relationship, as the indirect tensile strength increase the unit weight increase. Also, the point load strength plot shows a linear relationship, as the point load strength increase the unit weight increase. The majority of the data shows a large number of very small index strength values across a wide range of unit weights. The point load strength values have a better correlation with unit weight than the indirect tensile strength values.

4.4 Unconfined compressive strength Relationships

The main purpose of this thesis is to obtain relationships between index properties and unconfined compression strength (UCS) tests. The design of geotechnical structures that will be supported on limestone require site characterization and obtaining representative core specimens. Once the core is recovered, unconfined compression tests are performed to determine strength and stiffness parameters. Typically core recovery during drilling is very good but the rock quality designation (RQD) is very poor. This means there are very few core pieces that can be used for unconfined compressive strength testing. Therefore engineers must rely on index properties to estimate strength and stiffness properties.

Index tests, point load strength and indirect tensile strength, were performed to develop relationships to unconfined compressive strength. The data was assessed using two approaches, one based on weathering state and one based on the proximity of index test specimens to UCS specimens.

4.4.1 UCS as a Function of Indirect Tensile Strength with Weathering

Relationships for UCS as a function of indirect tensile strength were developed for three different scenarios incorporating weathering. The first relationship is shown in Figure 11 with UCS presented as a function of indirect tensile strength with weathering state of the indirect tensile strength specimens indicated. Total of 37 data pairs were used, of these 17 specimens were classified as W1, 13 specimens were classified as W2, 5 specimens were classified as W3, and 2 specimens were classified as W4. The data pairs in the figure (indirect tensile strength, UCS) are made up of a UCS data point and the closest, terms of depth, indirect tensile strength data point. The weathering state of the UCS specimens is not included in the figure.

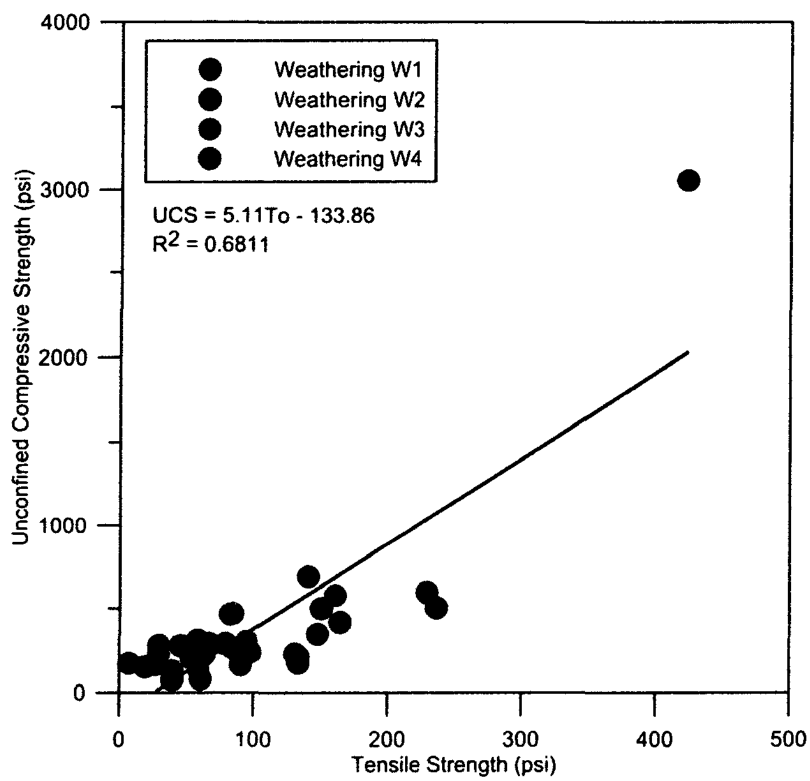


Figure 11. Relationship between unconfined compressive strength and indirect tensile strength

Overall there is a very good overall relationship between unconfined compressive strength and indirect tensile strength. The best fit linear line with R^2 value of 0.6811 captures the trend of all of the data. However focusing on the weathering states of the indirect tensile strength specimens, there is no relationship. W4 specimens, which should be the weakest specimens, plot as high as W1 specimens, which should be the strongest.

The overall general trend of UCS as a function of indirect tensile strength as shown previously was very good. However incorporating weathering states of the indirect tensile strength specimens did not add any value to the relationship. The next attempt was to plot the same data but to highlight UCS specimens and indirect tensile strength specimens with the same weathering state, as shown in Figure 12. This plot does reveal additional information regarding the effects of weathering. As expected, the data pairs with the highest combination of UCS and indirect tensile strength is the combination of W1 UCS and W1 indirect tensile strength specimens. Unfortunately this reasoning does not hold true with all combinations. As shown in Figure 12, there are W3 UCS and W3 indirect tensile strength specimens that have greater strength combinations that W1 UCS and W1 indirect tensile strength specimen pairs. Additionally there are only six specimen pairs used in the figure, three W1 specimen pairs and three W3 specimen pairs. It should be noted, one of the 6 points plotted has strength value higher than all the other points, but since there is limited numbers of data points, this point was needed in the analyses. The remaining specimen pairs have different weathering state combinations. The regression line shown is for the six specimen pairs with the same weathering states. Care must be taken when using a relationship developed using a limited number of data points.

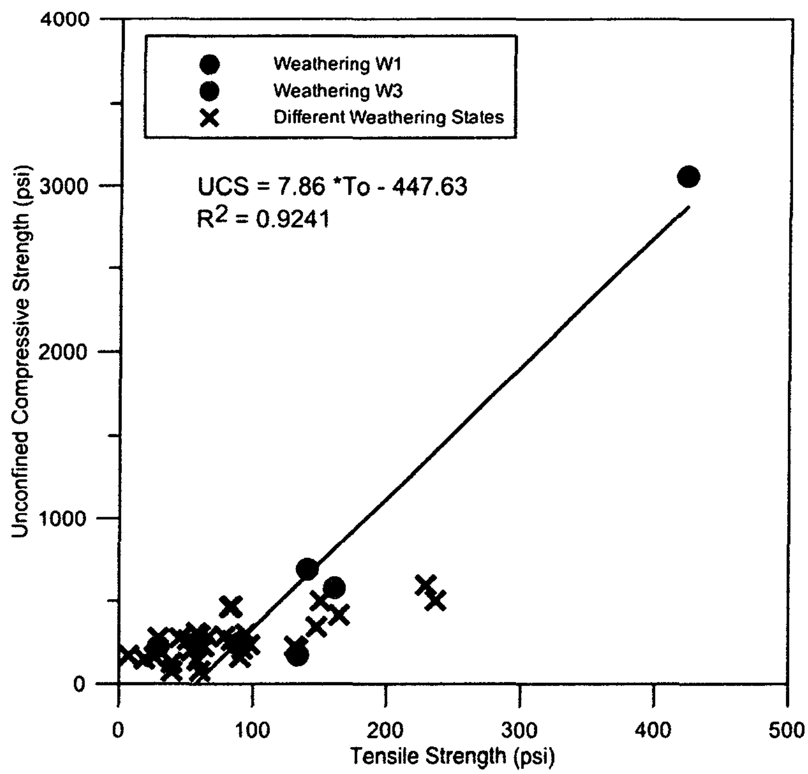


Figure 12. Relationship between unconfined compressive strength and indirect tensile strength with similar weathering states

The final attempt to reconcile UCS as a function of indirect tensile strength with the incorporation of weathering states is shown in Figure 13. Again, the figure shows the same data points as the previous two figures but differentiates the data points by indicating the number of weathering states separating the UCS and indirect tensile strength specimen pairs. The specimen pairs with two or three weathering state differences are clustered near the bottom left hand corner of the graph. Specimen pairs with more similar weathering state differences, same weathering state or one weathering state difference, plot as expected with an increase in UCS with an increase in indirect tensile strength. The regression line shown in Figure 13 is for the specimens with the

same weathering state and one weathering state difference between specimens. However there are only 10 data points that were used to produce the regression line. Also, it should be noted, one of the 10 points plotted has strength value higher than all the other points, but since there is limited numbers of data points, this point was needed in the analyses.

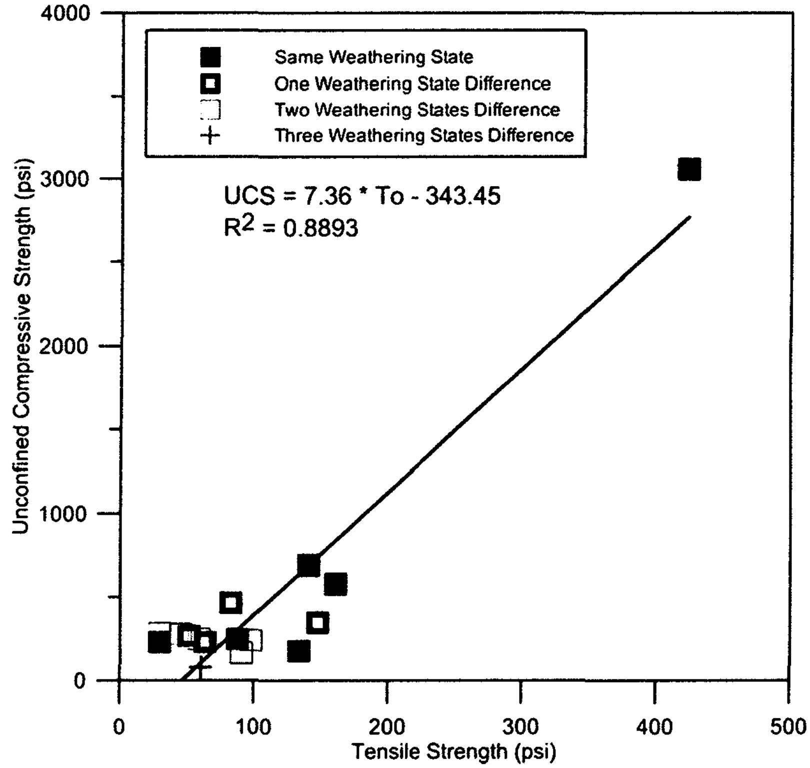


Figure 13. Weathering states variation between unconfined compressive strength and indirect tensile strength

4.4.2 UCS as a function of Indirect Tensile Strength with Proximity between Specimens

To better define the relationship between indirect tensile strength and unconfined compressive strength, three specimen categories based on proximity of indirect tensile strength specimens to unconfined compressive strength specimens were developed.

Figure 14 depicts the relationship between UCS and indirect tensile strength for the three different categories

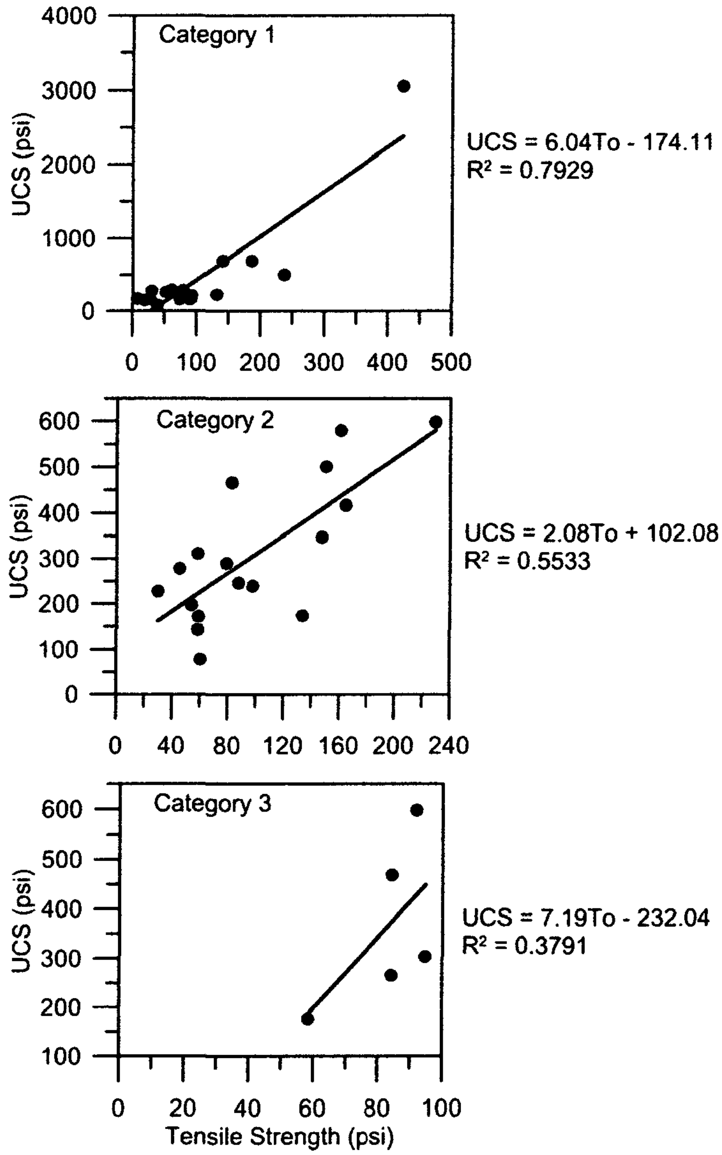


Figure 14. Relationship between unconfined compressive strength and indirect tensile strength for specimen Categories 1, 2, and 3

Specimen pairs in Category 1 consist of UCS and indirect tensile strength specimens that were directly under or above the UCS samples, as depicted in Figure 2. Specimen pairs

in Category 2 consist of indirect tensile strength specimens that were 0.1 to 1.7 inches from the UCS specimens. Category 3 specimen pairs consist of indirect tensile strength specimens that were greater than 1.7 inches from UCS specimens. Sixteen specimen pairs were in Category 1, seventeen specimen pairs were in Category 2, and five specimen pairs were in Category 3.

As seen in the Figure 14, the best fit regression line for all three specimen categories is a linear regression line. As expected, the best regression was found for Category 1 specimens (R^2 of 0.7929). The coefficient of determination for Category 2 data and the Category 3 data decreases with the increase in separation between unconfined compressive strength specimen and indirect tensile strength specimens (category classification). It is interesting to note that the Category 1 specimen pairs have the largest range of both UCS and indirect tensile strength even though Category 1 has the highest coefficient of determination.

4.4.3 UCS as a Function of Indirect Tensile Strength Summary

A number of relationships between UCS and indirect tensile strength were developed. The results were compared based on weathering and proximity of UCS and indirect tensile strength specimens. All developed relationships were linear.

The first approached used specimen pairs (indirect tensile strength, unconfined compressive strength) which were closest to each other, in terms of depth. The weathering state of the indirect tensile strength specimens was indicated on the figure. The coefficient of determination was high (R^2=0.6811) but weathering state was not properly represented.

A second approach, which incorporated the same data, highlighted specimen pairs with the same weathering state. Unfortunately there were only six specimen pairs with the same weathering state, three W1 weathering state pairs and three W3 weathering state pairs. The coefficient of determination for the six specimen pairs was determined (R^2=0.9214) but the limited data set used to develop the relationship was deemed unacceptable.

A third approach, which also incorporated the same data, highlighted the variation in weathering state between indirect tensile strength specimens and unconfined compressive strength specimens. A regression line and coefficient of determination was computed using specimen pairs with the same weathering state (6 specimen pairs) and a one weathering state difference between the two specimens (4 specimen pairs). The derived linear relationship produced a coefficient of determination (R^2) of 0.8893.

Instead of incorporating weathering, a relationship was developed for specimen pairs based on the proximity of indirect tension specimens to unconfined compressive strength specimens. The specimen pairs were grouped into three different categories. Specimen pairs in Category 1 consist of UCS and indirect tensile strength specimens that were directly under or above the UCS samples, as depicted in Figure 2. Specimen pairs in Category 2 consist of indirect tensile strength specimens that were 0.1 to 1.7 inches from the UCS specimens. Category 3 specimen pairs consist of indirect tensile strength specimens that were greater than 1.7 inches from UCS specimens. Sixteen specimen pairs were in Category 1, seventeen specimen pairs were in Category 2, and five specimen pairs were in Category 3. The best regression was found for Category 1 specimens (R^2 of

0.7929). The coefficient of determination for Category 2 data and the Category 3 data decreases with the increase in category classification.

4.4.4 UCS as a Function of Point Load strength with Weathering

Relationships for UCS as a function of point load strength were developed for three different scenarios incorporating weathering. The first relationship is shown in Figure 15 with UCS shown as a function of point load strength with weathering state of the point load strength specimens indicated. The data pairs in the figure (point load strength, UCS) are made up of a UCS data point and the closest, terms of depth, point load strength specimen. The weathering state indicated is that of the point load specimen. Thirteen of the specimen pairs were classified as W1, eight specimen pairs were classified as W2, ten specimen pairs were classified as W3, and one specimen pair was classified as W4. The weathering state of the UCS specimens is not included in the figure.

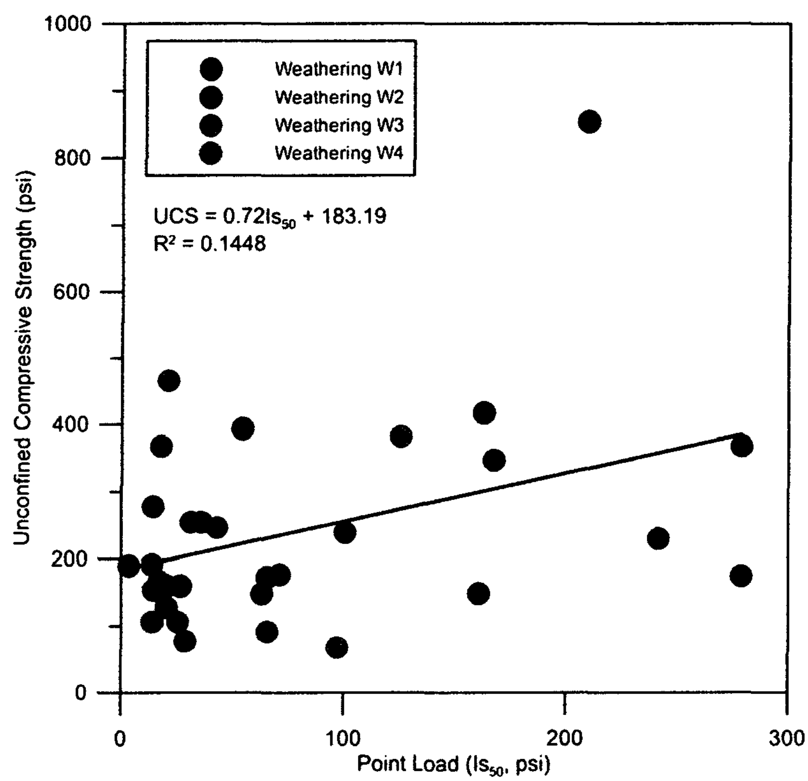


Figure 15. Relationship between unconfined compressive strength and point load strength with weathering

Overall there is not a good overall relationship between UCS and point load strength. The best fit linear regression line with R^2 value of 0.1148 captures the trend of all of the data. There appears to be no relationship when focusing on the weathering states of the point load strength specimens. However, W1 specimens show the highest results and appear to be closest to the best fit line.

Incorporating weathering states of the point load strength specimens did not appear to add value to the UCS-point load strength relationship. Therefore, the next attempt was to plot the same data but to highlight UCS specimens and point load strength specimens with the same weathering state, as shown in Figure 16.

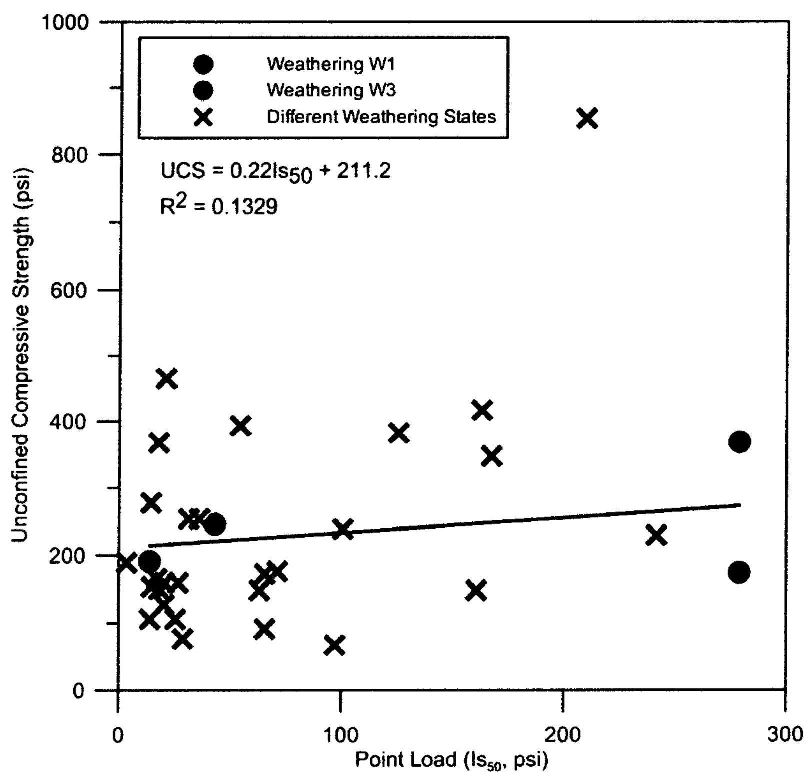


Figure 16. Relationship between unconfined compressive strength and point load strength with similar weathering states

This plot does reveal additional information regarding the effects of weathering. As expected, the data point with the greatest combination of UCS and point load strength is the combination of a W1 UCS and W1 point load strength specimen. Unfortunately this reasoning does not hold true with all combinations. As shown in Figure 16, there is a W3 UCS and W3 point load strength specimen that have a greater strength combination than W1 UCS and W1 point load strength specimen pair. Additionally, there are only four specimen pairs, two W1 and two W3, within the data set. The remaining specimen pairs have different weathering state combinations. The regression line shown is for the four specimen pairs with the same weathering states and the coefficient of determination is 0.1329.

The final attempt to reconcile UCS as a function of point load strength with the incorporation of weathering states is shown in Figure 17. Again, the figure shows the same data points as the previous two figures but differentiates the data points by indicating the number of weathering states separating the UCS and point load strength specimen pairs. The specimen pairs with two weathering state differences are clustered on the left side of the graph. Specimen pairs with more similar weathering state differences, same weathering state or one weathering state difference, plot as expected with an increase in UCS with an increase in point load strength. A best fit linear regression line best represented the data with the same weathering state and one weathering state difference. The coefficient of determination for the regression is 0.0174.

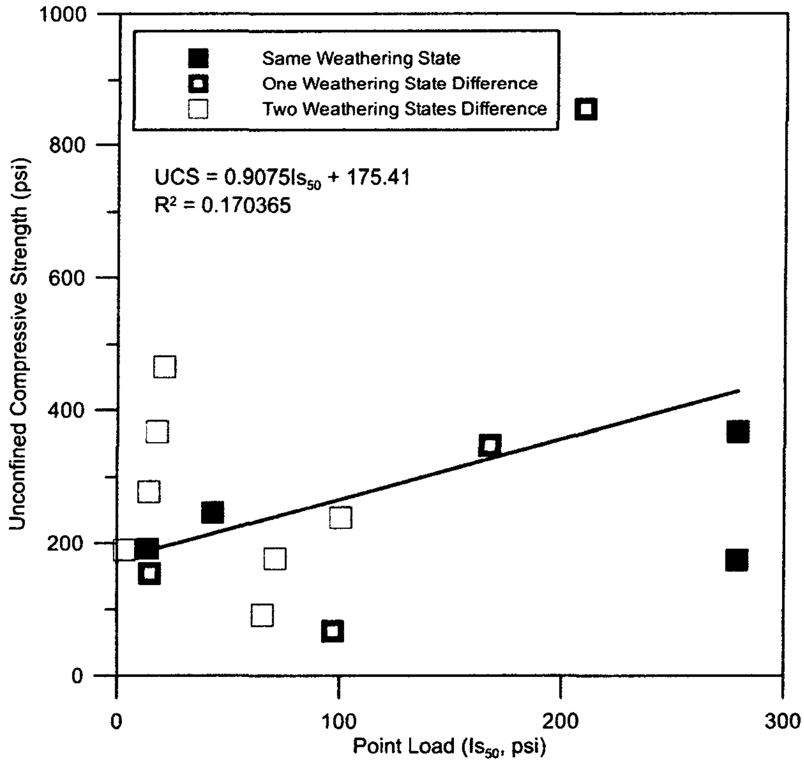


Figure 17. Weathering state variation between unconfined compressive strength and point load strength

4.4.5 UCS as a Function of Point Load strength with Proximity between Specimens

To better define the relationship between point load strength and unconfined compressive strength, three categories of specimens based on proximity of point load strength specimens to unconfined compressive strength specimens was developed. Specimen pairs in Category 1 consist of UCS and point load strength specimens that were directly under or above the UCS samples, as depicted in Figure 2. Specimen pairs in Category 2 consist of point load strength specimens that were 0.1 to 1.7 inches from the UCS specimens. Category 3 specimen pairs consist of point load strength specimens that were greater than 1.7 inches from UCS specimens. Nineteen specimen pairs were identified as Category 1, eighteen specimen pairs were identified as Category 2, and two

specimen pairs were identified as Category 3. Figure 18 depicts the relationship between UCS and point load strength for the three different categories.

As seen in the Figure 18, the best fit regression line for Category 1 and Category 2 is a linear regression line. No relationship was developed for Category 3 since only two specimen pairs identified in this category. As expected, the regression for Category 1 specimen pairs (R^2 of 0.0566) was better than the regression line for Category 2 (R^2 of 0.0491). It is also interesting to note that the Category 1 specimen pairs have the largest range of UCS and point load strength, and the range decrease between Category 1, 2, and 3.

4.4.6 UCS as a Function of Point Load strength Summary

A number of relationships between UCS and point load strength were attempted. The results were compared based on weathering and proximity of UCS and point load strength specimens. All developed relationships were linear.

The first approached used specimen pairs (point load strength, unconfined compressive strength) which were closest to each other, in terms of depth. The weathering state of the point load strength specimens was indicated on the figure. The coefficient of determination was high (R^2=0.1148) but weathering state was not properly represented.

A second approach, which incorporated the same data, highlighted specimen pairs with the same weathering state. Unfortunately there were only five specimen pairs with the same weathering state, three W1 weathering state pairs and two W3 weathering state pairs. Since there was only a limited data set and visual inspection of the data indicated a

very limited correlation, a linear regression line and coefficient of determination of 0.1329 were computed.

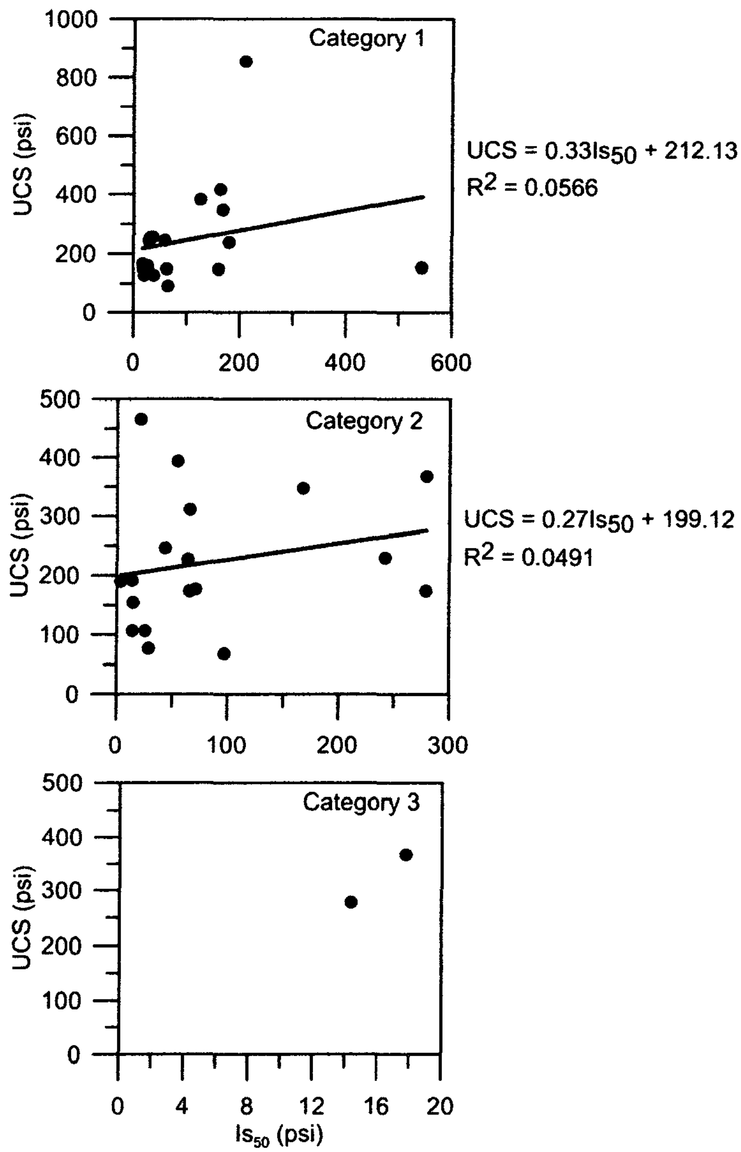


Figure 18. Relationship between unconfined compressive strength and point load strength for specimen Categories 1, 2, and3

A third approach, which also incorporated the same data, highlighted the variation in weathering state between point load strength specimens and unconfined compressive

strength specimens. The data set consisted of only eight specimen pairs with the same weathering state or one weathering state difference between specimens. A linear regression line best represented the data with a coefficient of determination of 0.1704.

Instead of incorporating weathering, a relationship was developed for specimen pairs based on the proximity of point load specimens to unconfined compressive strength specimens. The specimen pairs were grouped into three different categories. Specimen pairs in Category 1 consist of UCS and point load strength specimens that were directly under or above the UCS samples, as depicted in Figure 2. Specimen pairs in Category 2 consist of point load strength specimens that were 0.1 to 1.7 inches from the UCS specimens. Category 3 specimen pairs consist of point load strength specimens that were greater than 1.7 inches from UCS specimens. Nineteen specimen pairs were in Category 1, eighteen specimen pairs were in Category 2, and two specimen pairs were in Category 3. Regression lines and coefficients of determination were computed for both Category 1 and Category 2 specimens. The R^2 values were very low, 0.0566 and 0.0491, respectively.

4.5 Chapter Summary

The purpose of this chapter was to develop relationships between the physical properties of Ocala limestone specimens, unconfined compressive strength (UCS), indirect tensile strength, point load strength, weathering states, and distance between index and UCS specimens.

Unit weight, indirect tensile strength, and point load strength were plotted as a function of ISRM weathering state. In regards to unit weight, weathering states W1 and W2 had the approximately same range in unit weight and weathering state W3 and W4

had approximately the same range in unit weight. The average unit weight for decreased with an increase in weathering state.

In regards to indirect tensile strength and point load strength, every weathering state had specimens with very low strength values. As weathering increased the highest index strength values within each weathering state decreased. The variability in index strength values decreases with an increase in weathering state.

Indirect tensile strength, and point load strength were plotted as a function of unit weight. There is a positive correlation between indirect tensile strength and unit weight; the indirect tensile strength increases as the unit weight increases. The point load strength plot shows a very similar relationship. The point load strength has a better correlation with unit weight than tensile strength.

A number of relationships were developed between unconfined compressive strength and index strength tests (indirect tensile strength and point load strength). These relationships incorporated weathering of the specimens and proximity of the index strength specimens to the unconfined compressive strength specimens. A summary of the regression analyses are shown in Table 7.

Table 7. Summary of regression analyses for UCS as a function of index strength test

Analysis Type		Coefficient of Determination (R^2)			
		Indirect Tensile Strength	**Number of Specimens**	**Point Load Strength**	**Number of Specimens**
Weathering	**Approach 1**	0.6811	37	0.1448	32
	Approach 2	0.9241	6	0.1329	5
	Approach 3	0.8893	10	0.1704	8
Proximity	**Category 1**	0.7929	16	0.0566	19
	Category 2	0.5533	17	0.0491	18
	Category 3	0.3791	5	N/A	2

Regression analyses were conducted incorporating weathering and proximity of index strength specimens to unconfined compressive strength specimens. The analyses incorporating weathering were divided into three approaches. The first approach presented the unconfined compressive strength as a function of either indirect tensile strength or point load strength. The data pairs consisted of UCS specimens and the nearest index strength specimen. The plots indicated the weathering state of the index strength specimen. Using approach 1, indirect tensile strength was a much better predictor of unconfined compressive strength than point load strength.

The second approach used the same data with the exception of the regression lines were computed using data pairs of the same weathering state. This approach significantly reduced the number of data pairs that were used for the regression analysis; only specimen pairs with the same weathering state were used. Once again indirect tensile strength was a better predictor of unconfined compressive strength.

The third approach used the same data as approach 1 and approach 2 with the exception that specimen pairs were distinguished using the difference in weathering states between index strength specimens and unconfined compressive strength specimens. Regression analyses were performed on specimen pairs with the same weathering state and one weathering state difference between specimens. This approach increased the number of specimen pairs used in the regression analyses. Once again indirect tensile strength was a better predictor of unconfined compressive strength than point load strength.

Instead of incorporating weathering, a relationship was developed for specimen pairs based on the proximity of index strength specimens to unconfined compressive

strength specimens. The specimen pairs were grouped into three different categories. Specimen pairs in Category 1 consist of UCS and index strength specimens that were directly under or above the UCS samples, as depicted in Figure 2. Specimen pairs in Category 2 consist of index strength specimens that were 0.1 to 1.7 inches from the UCS specimens. Category 3 specimen pairs consist of index strength specimens that were greater than 1.7 inches from UCS specimens. For all three categories, indirect tensile strength was a better predictor of unconfined compressive strength than point load strength. As expected, the coefficient of determination decreased as the spacing between specimens increased.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The purpose of this thesis was to relate the unconfined compressive strength to index tests as a function of weathering and proximity to specimen location. The index tests that were used are indirect (Brazilian) tensile strength and point load strength. Weathering states of the specimens were classified using International Society for Rock Mechanics (ISRM) weathering states. The specimen proximity designation will account for the distance between the unconfined compressive strength and the index test specimens

Site characterization activities at a geotechnical test site in central Florida yielded 195 specimens; 50 specimens for unconfined compression testing and 145 specimens for index strength testing. The index testing specimens consisted of 46 specimens for point load strength testing and 99 specimens for indirect tensile testing. The goal of the core sampling was to obtain index test specimens as close as possible to the unconfined compression test specimens for direct comparison.

A number of qualitative and quantitative relationships were developed from the testing. Weathering reduced the unit weight of the index specimens; in general, the greater the degree of weathering the lower the unit weight. However there is considerable overlap between unit weights and weathering states. Another general trend that was noted was weathering lowered the index strength (indirect tensile strength and

point load strength) of the specimens. Every weathering state had specimens with very low index strengths. The highest index strength within each weathering state decreased with an increase in weathering.

Quantitative relationships were developed between unit weight and index strength as well as unconfined compressive strength and index strength. Unit weight was a better predictor of point load strength than indirect tensile strength. A number of approaches were used to include weathering state in developing relationships between unconfined compressive strength and index strength. The first approach was to present data pairs (index strength, unconfined compressive strength) for index strength specimens that were closest to unconfined compressive strength specimens. Weathering state of the index test strength specimens was indicated in the plots. Using this approach, indirect tensile strength was a better predictor of unconfined compressive strength than point load strength.

The second approach used the same data pairs but distinguished data pairs of the same weathering state. Regression analyses were performed on the specimen pairs with the same weathering state. Once again, indirect tensile strength was a better predictor of unconfined compressive strength than point load strength.

The third approach, which also used the same data pairs, distinguished data pairs by the number of weathering states separating the index strength specimens and the unconfined compressive strength specimens. Regression analyses were conducted on specimens with the same weathering state and one weathering state difference. Once again, indirect tensile strength was a better predictor of unconfined compressive strength than point load strength.

Instead of incorporating weathering, a relationship was developed for specimen pairs based on the proximity of index strength specimens to unconfined compressive strength specimens. The specimen pairs were grouped into three different categories. Specimen pairs in Category 1 consist of UCS and index strength specimens that were directly under or above the UCS samples. Specimen pairs in Category 2 consist of index strength specimens that were 0.1 to 1.7 inches from the UCS specimens. Category 3 specimen pairs consist of index strength specimens that were greater than 1.7 inches from UCS specimens. For all three categories, indirect tensile strength was a better predictor of unconfined compressive strength than point load strength. As expected, the coefficient of determination decreased as the spacing between specimens increased.

In general, the results of all the testing were as expected. The main conclusions that could be drawn are as follows:

- Weathering reduces the unit weight, indirect tensile strength, and point load strength.
- Indirect tensile strength is a better test for prediction of unconfined compressive strength than point load strength.
- Proximity is an important factor for predicting relationships between unconfined compressive strength and index testing.

5.2 Future Work

Historically there has been insufficient investigation of the physical and engineering properties of the various limestone units in Florida. To design infrastructure that will be supported by the limestone bedrock in Florida, significantly more research will be needed to help designers with the difficult decision of assessing the strength and

stiffness of variably weathered limestone. One avenue of research that should be conducted is to extend this study to limestone units from different areas in Florida.

This study has shown there is significant overlap in physical and engineering properties in assigned weathering states. It would be advantageous to develop a comprehensive weathering classification system for weathered Florida limestone.

The engineering properties needed to design foundations supported on the limestone includes unconfined compressive strength, elastic modulus, angle of internal friction, and cohesion values of limestone specimens. For future work it is recommended to extend the index test results to estimate elastic modulus values. With respect to cohesion and angle of internal friction, it may be possible to use the indirect tensile strength results and the unconfined compressive strength results to determine the angle of internal friction and cohesion value for the limestone specimens. This could be done using the Mohr-Coulomb or Hoek-Brown relationships.

APPENDIX – SPECIMEN PROPERTIES

Unit Weight

Core Number	Depth (ft)	Weathering	Unit Weight (pcf)
A-120	10.9-11.0	1	90.601
A-120	11.0-11.2	1	85.300
A-120	11.2-11.3	4	98.257
A-120	11.65-11.75	4	96.300
A-120	12.0-12.1	1	89.398
A-120	12.3-12.4	1	89.473
A-120	14.7-14.8	1	98.904
A-120	14.8-14.9	1	100.683
A-120	15.0-15.2	1	101.834
A-120	15.5-15.6	1	97.265
A-120	17.4-17.5	3	104.275
A-120	18.8-18.9	3	94.906
A-120	18.9-19.0	3	97.427
A-120	23.2-23.3	3	113.563
A-120	29.4-29.5	1	105.814
A-120	30.3-30.4	2	110.730
A-120	30.4-30.5	1	133.995
A-120	30.5-30.6	2	133.995
A-120	31.8-31.9	4	101.396
A-215	1.9-2.0	4	89.343
A-215	11.7-11.8	3	110.712
A-215	11.8-11.9	3	101.700
A-215	14.8-14.9	3	95.631
A-215	14.9-15.1	3	95.185
A-215	16.7-16.8	3	87.258
A-215	16.8-16.9	3	85.908
A-215	16.9-17.0	3	83.593
A-215	18.6-18.7	3	86.667
A-215	18.7-18.8	3	97.349
A-215	19.3-19.4	3	96.381
A-215	19.4-19.5	3	96.689
A-215	2.4-3.0 (B)	4	84.429
A-215	27.0-27.5 (A)	3	95.008
A-215	3.3-3.4	4	111.274
A-215	7.5-7.6	2	87.468
A-215	7.6-7.7	2	90.055
A-215	7.7-7.8	2	81.350
A-65	32.7-32.8	3	109.130
A-65	32.8-32.9	3	104.959
A-65	34.6-34.7	1	91.832
A-65	34.7-34.8	1	92.530
A-65	35.3-35.4	1	96.682
A-65	35.9-36.0	3	93.339
A-65	36.15-36.25	3	100.268
A-65	37.0-37.1	3	98.218
A-65	37.1-37.2	3	92.556
A-65	37.8-37.9	3	96.689
A-65	37.9-38.0	3	148.147
A-65	38.6-38.7	4	110.889
A-65	39.0-39.1	1	108.742
A-65	39.6-39.7	1	101.829
A-65	40.6-40.7	1	104.197
A-65	40.7-40.8	1	97.494
F-10	23.6-23.8	4	90.624
F-10	24.5-24.8	4	100.288
F-10	24.8-24.9	4	109.346

Core Number	Depth (ft)	Weathering	Unit Weight (pcf)
F-10	24.9-25	4	113.637
F-10	25.2-25.3	4	106.047
F-10	25.3-25,5	4	97.963
F-10	30.7-30.8	4	100.763
F-10	31.3-31.4	4	89.457
F-10	31.4-31.6	4	88.908
F-10	32.7-32.8	4	88.932
F-10	33.3-33.4	4	89.693
F-10	33.4-33.5	4	80.692
F-10	44.4-44.6	4	82.725
F-10	44.6-44.7	4	82.314
F-10	44.8-45	4	80.414
F-10	45.6-45.7	4	88.186
F-10	45.8-45.9	4	73.422
F-45	11.5-11.7	4	66.244
F-45	11.7-11.8	4	60.932
F-45	11.8-12	4	85.215
F-45	12.6-12.8	3	92.358
F-45	12.8-12.9	3	67.835
F-45	12.9-13.1	3	62.689
F-45	13.2-13.3	3	72.885
F-45	13.3-13.5	3	68.820
F-45	14.1-14.2	3	64.814
F-45	14.2-14.3	3	115.375
F-45	19.1-19.2	3	109.507
F-45	20.5-20.6	3	91.382
F-45	21.8-21.9	3	94.074
F-45	23.2-23.3	4	84.911
F-45	24.8-25.1	4	78.454
F-45	26.8-26.9	3	84.461
F-45	26.9-27.1	3	92.630
F-45	31.7-32	4	98.681
F-45	39.3-39.5	1	82.013
F-45	39.5-39.7	2	82.013
F-45	42.2-42.3	3	95.798
F-45	42.6-42.8	3	99.236
F-45	42.8-42.9	3	102.011
F-45	45.7-45.8	3	115.412
F-45	50.7-50.8	3	92.654
U-80	29.4-29.5	4	113.018
U-80	31.2-31.4	2	68.755
U-80	31.4-31.5	1	86.169
U-80	31.5-31.6	1	86.816
U-80	31.6-31.7	1	101.286
U-80	31.7-31.8	1	105.747
U-80	31.8-32	1	94.446
U-80	31-31.2	1	88.792
U-80	33.6-33.8	3	98.813
U-80	33.8-33.85	3	79.868
U-80	33.8-33.9	3	86.489
U-80	35.5-35.7	3	76.969
U-80	35.7-35.8	3	75.118
U-80	39.7-39.9	3	98.798
U-80	39.9-39.95	3	93.096
U-80	41.4-41.6	3	85.143
U-80	41.6-41.8	3	84.078
U-80	42.4-42.6	3	75.136
U-80	42.6-42.8	3	65.798
Z-115	25.1-25.3	4	85.002
Z-115	25-25.1	4	85.132
Z-115	32.2-32.3	2	124.059

Core Number	Depth (ft)	Weathering	Unit Weight (pcf)
Z-115	33.3-33.4	1	91.668
Z-115	33.8-34	1	89.742
Z-115	34.7-34.8	1	81.792
Z-115	34-34.2	1	88.094
Z-115	35.2-35.3	2	76.560
Z-115	35-35.2	1	89.133
Z-115	36.2-36.3	1	95.233
Z-115	36.4-36.6	2	93.188
Z-115	37.4-37.5	3	96.357
Z-72	29.5-29.9	4	90.156
Z-72	30-30.2	4	88.441
Z-72	33.6-33.8	1	84.791
Z-72	33.6-33.8	2	84.791
Z-72	33.8-34	2	73.676
Z-72	35.3-35.5	1	90.886
Z-72	35.5-35.7	1	82.193
Z-72	44.4-44.5	1	87.982
Z-72	44.5-44.6	2	84.841
Z-72	51.2-51.3	4	111.962
Z-72	54.2-54.3	2	123.948
Z-72	54.3-54.5	1	126.000
Z-72	54.7-54.8	1	121.404
Z-72	54.8-55	1	120.119
Z-72	55.8-56	1	114.535

Indirect Tensile Strength

Core Number	Depth (ft)	Weathering	Unit Weight (pcf)	Brazilian load (P) (lb)	Indirect Tensile Strength (psi)
A-215	3.3-3.4	3	111.27	793.54	100.08
A-215	7.5-7.6	1	87.47	182.09	19.95
A-215	7.6-7.7	1	90.05	227.05	26.38
A-215	11.7-11.8	2	110.71	1056.56	127.69
A-215	11.8-11.9	2	101.70	600.22	58.18
A-215	14.8-14.9	2	95.63	847.50	82.66
A-215	14.9-15.1	2	95.19	544.02	60.70
A-215	16.7-16.8	2	87.26	254.02	26.58
A-215	16.8-16.9	2	85.91	548.51	56.48
A-215	16.9-17.0	2	83.59	274.26	34.64
A-215	18.6-18.7	2	86.67	292.24	33.42
A-215	18.7-18.8	2	97.35	586.73	66.64
A-215	19.3-19.4	2	96.38	712.62	60.66
A-215	19.4-19.5	2	96.69	701.38	78.99
A-65	30.5-30.6	1	142.00	3677.738	437.35
A-65	30.6-30.7	1	104.66	1688.25	207.91
A-65	32.7-32.8	2	109.13	1063.30	131.26
A-65	32.8-32.9	2	104.96	557.50	68.17
A-65	34.6-34.7	1	91.83	53.95	6.23
A-65	34.7-34.8	1	92.53	98.91	11.15
A-65	35.3-35.4	1	96.68	800.29	90.58
A-65	35.9-36.0	2	93.34	660.91	73.68
A-65	36.15-36.25	2	100.27	424.87	64.01
A-65	37.0-37.1	2	98.22	146.12	16.69
A-65	37.1-37.2	2	92.56	220.30	27.15
A-65	37.8-37.9	2	96.69	233.79	26.66
A-65	37.9-38.0	2	148.15	74.18	15.22
A-65	38.6-38.7	3	110.89	717.11	80.69
A-65	39.0-39.1	1	108.74	1261.13	140.52
A-65	39.6-39.7	1	101.83	1240.90	186.01
A-65	40.6-40.7	1	104.20	1216.17	136.11
A-65	40.7-40.8	1	97.49	276.50	32.60
A-120	10.9-11.0	1	90.60	555.26	58.71
A-120	11.0-11.2	1	85.30	166.35	19.29
A-120	11.2-11.3	3	98.26	510.30	58.84
A-120	12.0-12.1	1	89.40	496.81	53.73
A-120	12.3-12.4	1	89.47	64742.4	7.23
A-120	14.7-14.8	1	98.90	487.82	58.17
A-120	14.8-14.9	1	100.68	170.85	22.39
A-120	15.0-15.2	1	101.83	546.26	65.80
A-120	15.5-15.6	1	97.27	555.26	51.68
A-120	17.4-17.5	2	104.28	613.70	68.56
A-120	18.8-18.9	2	94.91	379.91	53.52
A-120	18.9-19.0	2	97.43	478.82	53.32
A-120	19.9-20.0	1	#VALUE!	254.02	31.04
A-120	23.2-23.3	2	113.56	809.28	90.44
A-120	29.4-29.5	1	105.81	843	97.74
A-120	31.8-31.9	3	101.40	54.85	60.57
F-10	24.8-24.9	3	109.35	1380.27	196.55
F-10	24.9-25	3	113.64	1375.77	173.31

Core Number	Depth (ft)	Weathering	Unit Weight (pcf)	Brazilian load (P) (lb)	Indirect Tensile Strength (psi)
F-10	25.2-25.3	3	106.05	1497.16	170.72
F-10	31.4-31.6	3	88.91	802.53	87.67
F-10	33.3-33.4	3	89.69	744.08	89.89
F-10	44.4-44.6	3	82.72	618.2	69.34
F-10	44.8-45	3	80.41	170.84	20.33
F-10	45.8-45.9	3	73.42	705.87	74.14
F-45	11.5-11.7	4	66.24	182.08	18.04
F-45	12.8-12.9	2	67.84	409.13	42.30
F-45	13.2-13.3	2	72.89	548.51	57.74
F-45	13.3-13.5	2	68.82	96.66	9.46
F-45	14.1-14.2	2	64.81	173.09	16.47
F-45	20.5-20.6	2	91.38	919.43	110.93
F-45	21.8-21.9	2	94.07	847.49	108.48
F-45	24.8-25.1	3	78.45	231.54	29.61
F-45	26.8-26.9	2	84.46	528.28	63.50
F-45	26.9-27.1	2	92.63	368.67	51.41
F-45	31.7-32	4	98.68	694.63	84.28
F-45	39.3-39.5	1	82.01	503.55	60.53
F-45	42.8-42.9	2	102.01	1614.06	236.63
Z-72	30-30.2	3	88.44	523.78	53.86
Z-72	33.6-33.8	1	84.79	292.24	29.54
Z-72	35.3-35.5	1	90.89	591.22	59.05
Z-72	44.4-44.5	1	87.98	370.92	45.31
Z-72	54.2-54.3	1	123.95	3279.83	423.17
Z-72	54.7-54.8	1	121.40	1519.64	223.39
Z-72	55.8-56	1	114.54	1306.08	147.47
Z-115	25-25.1	3	85.13	188.83	20.77
Z-115	33.3-33.4	1	91.67	984.62	133.60
Z-115	33.8-34	1	89.74	741.84	92.16
Z-115	34-34.2	1	88.09	784.55	83.82
Z-115	36.2-36.3	1	95.23	818.27	99.05
Z-115	37.4-37.5	2	96.36	809.28	95.31
U-80	29.4-29.5	3	113.02	1535.38	174.06
U-80	31-31.2	1	88.79	249.52	34.57
U-80	31.2-31.4	1	68.76	148.36	14.83
U-80	31.5-31.6	1	86.82	168.6	28.01
U-80	31.7-31.8	1	105.75	2391.87	293.48
U-80	33.6-33.8	2	98.81	681.14	79.96
U-80	33.8-33.85	2	79.87	730.6	77.33
U-80	35.7-35.8	2	75.12	791.29	91.82
U-80	39.7-39.9	2	98.80	2023.2	229.27
U-80	39.9-39.95	2	93.10	1402.75	141.54
U-80	41.4-41.6	2	85.14	912.68	107.70
U-80	42.4-42.6	2	75.14	1146.48	124.20

Point Load Strength

Core Number	Depth (ft)	Weathering	Unit Weight (pcf)	I_s (psi)	F (Size Correction)	$I_{s(50)}$ (psi)
F-10	23.6-23.8	3	90.62	16.52	1.16	19.11
F-10	24.5-24.8	3	100.29	94.07	1.06	100.12
F-10	25.3-25,5	3	97.96	44.97	1.11	49.74
F-10	30.7-30.8	3	100.76	120.48	1.07	128.77
F-10	31.3-31.4	3	89.46	69.80	1.12	78.45
F-10	32.7-32.8	3	88.93	37.21	1.16	43.15
F-10	33.4-33.5	3	80.69	19.78	1.13	22.29
F-10	44.6-44.7	3	82.31	40.12	1.12	44.95
F-10	45.6-45.7	3	88.19	106.27	1.07	113.34
F-45	11.7-11.8	4	60.93	4.24	1.15	4.90
F-45	11.8-12	4	85.22	9.78	1.10	10.79
F-45	12.6-12.8	2	92.36	33.76	1.13	38.26
F-45	12.9-13.1	2	62.69	6.70	1.13	7.59
F-45	13.5-13.7	2	92.27	22.50	1.15	25.89
F-45	14.2-14.3	2	115.38	201.12	1.04	209.48
F-45	18.8-18.9	2	90.52	50.78	1.07	54.36
F-45	19.1-19.2	2	109.51	155.08	1.05	163.10
F-45	20.7-20.8	4	99.13	133.16	1.05	140.44
F-45	23.2-23.3	4	84.91	1.31	1.22	1.60
F-45	42.2-42.3	2	95.80	9.34	1.13	10.53
F-45	42.6-42.8	2	99.24	94.64	1.11	105.30
F-45	50.7-50.8	2	92.65	117.56	1.05	123.90
Z-72	29.5-29.9	3	90.16	81.75	1.19	97.15
Z-72	33.8-34	1	73.68	2.80	1.26	3.51
Z-72	35.5-35.7	1	82.19	12.15	1.18	14.38
Z-72	44.5-44.6	1	84.84	32.10	1.18	38.03
Z-72	51.2-51.3	3	111.96	100.64	1.25	125.54
Z-72	54.3-54.5	1	126.00	283.40	1.16	327.58
Z-72	54.8-55	1	120.12	152.52	1.10	167.46
Z-115	25.1-25.3	3	85.00	15.85	1.12	17.75
Z-115	32.2-32.3	1	124.06	250.07	1.12	278.91
Z-115	34.7-34.8	1	81.79	26.83	1.11	29.76
Z-115	35-35.2	1	89.13	74.44	1.14	84.49
Z-115	35.2-35.3	1	76.56	22.25	1.11	24.67
Z-115	36.4-36.6	1	93.19	80.57	1.12	89.98
U-80	31.4-31.5	1	86.17	51.96	1.07	55.43
U-80	31.6-31.7	1	101.29	156.65	1.01	158.92
U-80	31.8-32	1	94.45	159.48	1.18	188.54
U-80	33.8-33.9	2	86.49	7.23	1.14	8.24
U-80	35.5-35.7	2	76.97	61.18	1.18	72.42
U-80	41.6-41.8	2	84.08	56.36	1.06	59.54
U-80	42.6-42.8	2	65.80	60.00	1.18	70.58

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VITA

Raoaa Farah was born in Homs, Syria. She moved to the United States with her family in September, 2000. She attended Englewood high school in Jacksonville, Florida. Ms. Farah graduated magna cum laude with a BS in Civil Engineering in May, 2008. As an undergraduate student she was on the Dean's Honor List and received academic scholarships from the American Society of Highway Engineers (ASHE). Ms. Farah also obtained her FE license during her undergraduate studies. After graduation, she joined Ellis and Associates as a geotechnical engineer where she specializes in all aspects of geotechnical engineering. Ms. Farah was the Young Engineer of The Year for ASHE in 2008 and was nominated for the NE Florida Young Engineer of the Year award in 2009. Ms. Farah successfully defended her MS thesis in April 2011 and will graduate at the Spring 2011 graduation. The topic of her thesis is Correlations between Index Properties and Unconfined Compressive Strength of Weathered Ocala Limestone.