EVALUATION AND PETROLOGIC CHARACTERISTICS OF FLORIDA RIP RAP SOURCES

FINAL REPORT

Department of Geological Sciences
University of Florida

UNITS AND CONVERSION FACTORS

LENGTH

meter (m)	1 m = 3.28083 feet = 39.370 inches = 100 cm = 10^{10} A
centimeter (cm)	1 cm = 10^{-2} m
millimeter (mm)	1 mm = 10^{-3} m = 0.0394 inches
micrometer (µm)	1 µm = 10^{-6} m = 10^{-3} mm = 10^{4} A
nanometer (nm)	1 nm = 10^{-9} m = 10^{-7} cm = 10 A
angstrom (A)	1 A = 10^{-8} cm = 10^{-4} µm = 10^{-1} nm, or 0.1 nm
(inch)	1 inch = 2.54 cm
(foot)	1 foot = 30.48 cm

MASS

gram (g)	1 g = 10-3 kg = 2.205 × 10 -3 lb
kilogram (kg)	1 kg = 1000 g = 2.2046 lb
pound (lb)	1 lb = 0.4536 kg = 453.6 g

VOLUME

liter (l)	1 liter = 1000 cm^3 = 1.0567 quarts (U.S.)
cubic centimeters (cm^3)	
cubic foot (ft^3)	1 ft^3 = 0.02832 m^3 = 28.32 liters = 7.477 gallons
(gallon)	1 gallon = 3.788 liters

TEMPERATURE

degrees Celsius (°C)	5/9 (°F - 32); F = Fahrenheit
kelvins (K)	K = °C + 273.15; C = Celsius; absolute zero = -273.15°C

PRESSURE

(bar)	1 bar = 0.9869 atm = 10^{5} Pa
pascal (Pa)	1 pascal = 10^{-5} bars
atmosphere (atm)	1 atm = 760 mm Hg
1 lb/in^2 (psi)	1 lb/in^2 = 6891 Pa
1 lb/ft^2	1 lb/ft^2 = 47.85 Pa

ENERGY

foot pound (ft·lb)	1 ft·lb = 1.356 J
joule (J)	1 J = 10^{7} ergs = 0.239 cal

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Sponsored by the Florida Department of Transportation
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RPWO #33

DEPARTMENT OF GEOLOGICAL SCIENCES
COLLEGE OF LIBERAL ARTS AND SCIENCES
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The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation or the U.S. Department of Transportation

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Executive Summary

The problem undertaken was an evaluation of the quality control methods currently in use by Florida's Department of Transportation (FDOT) and how they relate to protocols proposed in recent literature on such armor stones. In addition, alternative test methods were developed and evaluated to accelerate the test period and provide results for predicting field performance as well as, or better than, current methods.

Four limestones and one chert sample were collected from quarries around that State and represent a range of geologic ages, petrologic characteristics, and mechanical properties. At present, the FDOT uses water absorption, sulfate soundness, and Los Angeles abrasion test results as criteria for acceptance of rip rap.

A modification of the absorption method using vacuum extraction showed significant increases in the quantity of solution absorbed. Distilled water, synthetic seawater, and a 50:50 mixture of methanol and distilled water were the saturating solutions used for these tests. Results indicate this method may be an excellent, and simple, alternative to the current methods being used.

A recently published protocol has proposed specific gravity standards for stones used as rip rap. Based on these criteria, the greater the specific gravity, the better the potential field performance. When these criteria are applied to the five stones tested in this study, all would be classified as poor quality. A broader study of Florida materials is needed before acceptance or rejection of this protocol's specific gravity criteria.

Previous work sponsored by the FDOT has shown a method called petrographic number (PN) can be used as a potential acceptance criterion for concrete aggregates. The application of PN methodology to the five stones in this study showed that three would be expected to have good

field performance (Avon Park Limestone, Suwannee Limestone, and chert), while two (Ocala Limestone and Key Largo Limestone) are too porous to have good field performance as rip rap.

Rhodamine epifluorescent microscopy (REFM) was tested on these five stones. This method has been used in other fields to study microcracks and porosity. Sample preparation problems did not allow a fair evaluation of this method on these stones. The results of all the tests tried were negative, but additional work with this technique may be useful if new sample preparation techniques are found or developed.

Mercury intrusion porosimetry can be used to measure a wide range of voids in a variety of materials. The number and size of voids is thought to be an important parameter related to moisture absorption, an important quality control criterion. Results of porosimetry testing showed almost no porosity in the chert, low total porosity in the Suwannee and Avon Park Limestones, and high total porosity in the Ocala and Key Largo Limestones. The very small sample sizes used in this method of testing places a premium on the collection and preparation of representative materials.

The Gyratory Testing Machine (GTM) was evaluated as an alternative to the Los Angeles abrasion test. The GTM has several design and operational advantages over the LA abrasion test method. Results showed that the least degradation occurred with the chert and that the Suwannee was the least degraded of the four limestones tested.

An accelerated weathering test device was fabricated that allowed exposure of eight test specimens to 24 wet-dry cycles/ 24 hour period. This small scale Ferris-wheel device immersed the samples in a test solution and then dried them on the apparatus using heat lamps. The two solutions tested were conventional saturated sodium sulfate and synthetic seawater with exposure periods ranging from 3 to 28 days. The specimens were tested as 1" diameter cores. The results showed that sodium sulfate solution was more effective in causing changes in the specimens than was the synthetic seawater. This may be the result of differences in their crystallization and hydration properties in the pores of the exposed stones. The apparatus offers several advantages in allowing specimens of various shapes and sizes to be tested under a variety of conditions and with a range of test solutions.

A rip rap rating system based on the work of Lienhart (1998) and focused on stone durability was developed using a matrix classification scheme. This scheme was tested using data from the various testing components of this project. The quality ratings would classify the five stones tested as good to marginal for use as rip rap. This preliminary rating system is encouraging, but will require a better understanding of geological properties and processes and quarry evaluations be incorporated with the in-service processes to provide a true three-tiered interaction matrix.

A supplemental series of tests were run using this apparatus with saturated sodium sulfate, synthetic seawater solutions, and prismatic specimens (1" X 1" X 2") sawn from the original four limestones and chert plus an additional five materials provided by the FDOT State Materials Office staff. The results showed that after 14-days exposure to sodium sulfate solution, a sand-cement mixture, the Tamiami Limestone, the Fort Thompson Limestone, and a Georgia granite were all showing significant degradation. The Key Largo, the Suwannee Limestone, the Avon Park Limestone, the Ocala Limestone, and the chert all held up well for the 14-day test period.

CHAPTER 1
INTRODUCTION

Rip rap (equivalent terms are riprap and armoring) refers to an assemblage of large, broken stones used for shoreline protection and the preservation of waterside structures (Figure 1-1 and Figure 1-2). The loose rock is used to form breakwaters, jetties, sea walls, and groins that generally do not fail catastrophically and can be repaired with regular maintenance (Froehlich and Benson, 1996). Aggregates used as rip rap must be resistant to chemical and physical breakdown and disintegration under various conditions of use.

Rip rap stability depends largely on the shape, size, strength, density, mechanical durability, and physico-chemical durability of the rock material selected for use as coastal armor. Additional variables affecting the stability of rip rap include the gradation of the rock mixture, material thickness, and the method of rock placement (Froehlich and Benson, 1996). The designers of coastal protection structures specify the properties of the rip rap used at an installation. The majority of coastal rip rap structures will be subjected to more severe environmental conditions than aggregate used for other construction purposes (Poole, 1991). Increasing severity of marine conditions also will require additional levels of strength and durability. As stated above, there are numerous factors affecting rip rap durability, these multiple attributes also make its specification and testing very complex (Latham, 1998). The processes involved in assessing and selecting a potential rip rap source includes the inspection of the quarry and its production methods, testing of the rip rap, evaluation of its quality and consideration of transportation and placement methods (Latham, 1998). In addition, these processes

Figure 1- 1 : Rip rap jetty located in Venice, Florida.

Figure 1-2: Granite rip rap on jetty in Venice, Florida.

must be integrated into satisfying the objectives of a particular location within local economic constraints (Poole, 1991).

Soundness testing, used in the evaluation of aggregates, including rip rap, encompasses physical and chemical durability characteristics, resistance to wetting and drying, heating and cooling, freezing and thawing and reaction to chemical solutions. The major problem with soundness testing, other than the time and expense required for testing, is that no one test has been devised that can adequately determine the physical and chemical properties of an aggregate. Physical tests tend to measure the mechanical degradation potential of an aggregate, but fail to simulate chemical degradation that may be common in aggregates. Conversely, chemical tests may be better indicators of physical durability than physical testing since mechanical weathering reactions encountered in nature may be difficult to duplicate in the laboratory at suitable rates of study.

The objective of this research was to evaluate laboratory and quality control methods currently used by the Florida Department of Transportation (FDOT) to predict field performance of rip rap materials and to develop and evaluate alternative test methods that might be employed to better define rip rap soundness. The absence of generally accepted selection criteria has led to a minimum of testing standards for rip rap testing and quality control. The FDOT currently requires only specific gravity (i.e., density), sulfate soundness, and abrasion testing for rip rap quality control. These laboratory-scale accelerated weathering tests attempt to predict the useful life of the rip rap material; however, in a large, non-Florida-based dataset, there is a poor correlation between laboratory test results and in-service performance (Poole, 1991). A review of the literature on aggregate soundness was done in order to evaluate the problems associated with testing rip rap. In addition the identification of index rock properties that might indicate a possible correlation with aggregate durability was undertaken. These index properties then were used to develop and evaluate alternative test methods that could be used to either supplement or replace currently accepted methods.

The goal was to develop methods that can quantify aggregate performance and permit the prediction of field performance. Data on field performance on rip rap aggregates are not well documented. Therefore, it will ultimately be necessary to establish a link between alternative testing procedures and actual field performance.

CHAPTER 2
STATEMENT OF THE PROBLEM

The problem undertaken was an evaluation of the current program in Florida rip rap quality control and consideration of alternative test methods that might be used to better predict field performance. Sample identifications, source locations and mined geologic units of stones examined in this study are listed in Figure 2-1 and Table 2-1. The Florida Department of Transportation (FDOT) currently uses imported materials (domestic and non-domestic) for marine rip rap construction. The five Florida materials tested in this study have not been widely used for marine rip rap applications within the State.

At present, the FDOT is using specific gravity (i.e., density), moisture absorption, sulfate soundness, and Los Angeles abrasion testing for rip rap quality control. According to Section 530 of the FDOT Construction Specifications Manual, rip rap must meet the following physical requirements:

Test	Acceptable Limit
Bulk Specific Gravity	Bank & Shore: 2.3 (Minimum) Ditch Lining: 1.9 (Minimum)
Absorption (FM 1-T 085)	5% (Maximum)
Sodium Sulfate Soundness (FM 1-T 104)	12% (Maximum)
Los Angeles Abrasion (FM 1-T 096)	45% (Maximum)

These accelerated weathering tests attempt to predict the useful life of rip rap material. There is, however, a poor correlation between laboratory test measurements and field performance.

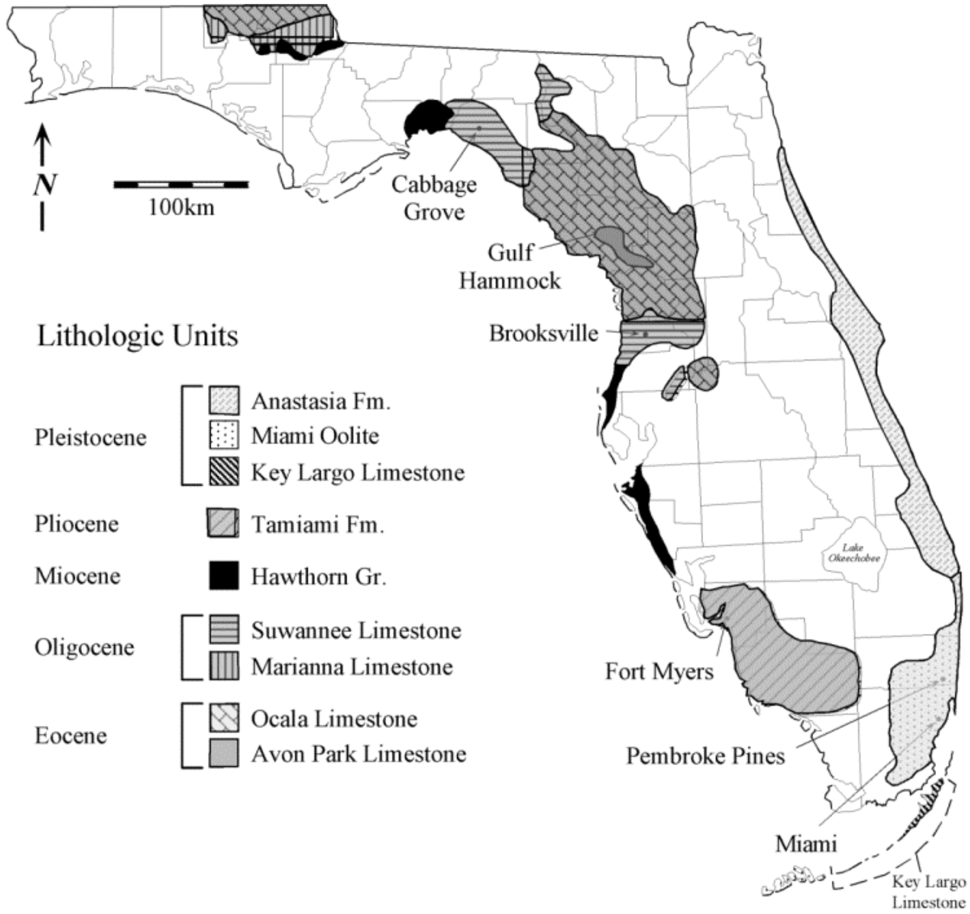


Figure 2-1: Map of Florida showing sample collection locations.

Table 2- 1. Aggregate locations.

FDOT ID	Location	Geologic Unit	Geologic Age
08-005	Brooksville, FL	Suwannee Limestone	Oligocene
08-005	Brooksville, FL	Hawthorne -Suwannee Unconformity	Miocene-Oligocene
26-098	Newberry, FL	Ocala Limestone	Eocene
34-106	Gulf Hammock, FL	Avon Park Limestone	Eocene
87-090	Miami, FL	Key Largo Limestone	Pleistocene

Accelerated weathering tests have several drawbacks. In addition to the poor laboratory-field correlation, these tests are expensive and very time-consuming (Lienhart et al., 1995). Moreover, there are numerous inherent problems with the accelerated weathering tests currently being used. Therefore, there may be a need for modification of the current methods as well as the development of faster, less expensive alternative testing procedures that will more reliably predict rip rap performance. Some problems associated with the current methods are discussed below.

Absorption

Water absorption values are calculated from the change in weight of material when the pore spaces are filled compared to the weight of the dry material. The current test method for absorption determination requires the sample to be dried in an oven for 24 hours at 110°C, then completely immersed in deionized water for 15 hours, and finally the "free-drained, saturated" sample weighed to determine the weight gain. This procedure, however, may cause the entrapment of air within the pore spaces and result in an incorrect absorption value (Lienhart et al., 1995). This is particularly problematic with Florida's carbonate stones because of their high porosity values. A modification of this method to accommodate Florida aggregates may be needed to overcome or minimize this problem. Additional testing should be performed on porous stone aggregates (i.e., Florida and others) to augment existing test data because absorption values greater than 5% that have been determined on stones with free-draining pore structures and then have been shown to perform well in-service (CIRIA Special Publication 83).

Because of the high porosity values typical of Florida stones, particular attention needs to be focused on pore size and distribution. This study attempted to combine the results of several methods for an improved assessment of porosity relative to stone durability. Petrographic analysis was used to examine pore size distribution as well as determine mineralogical composition and grain size. Rhodamine epifluorescent microscopy and scanning electron microscopy (SEM) also were utilized to determine quantitative and qualitative measurements of microporosity. In addition, mercury intrusion porosimeter testing was used to determine the volume and volume distribution of pores in the sample with respect to the apparent entrance diameters.

Los Angeles Abrasion

The Los Angeles Abrasion Test is a dry abrasion and impact test that involves placing a sample of stone and a charge of steel balls into a hollow steel cylinder with a rigid steel shelf (lifting flight) extending into the chamber. The Los Angeles Abrasion test measures abrasion and impact resistance. Research involving Canadian aggregates has shown that the Los Angeles Abrasion Test is a good predictor of susceptibility of aggregates to mechanical breakdown, but little else (Rogers, 1990). The Los Angeles Abrasion Test also has numerous problems that make it a poor test for rip rap performance. In addition to being a costly and time-consuming test, the results of Los Angeles Abrasion testing are poorly correlated with field performance. The Los Angeles Abrasion Test measures autogenous grinding and impact resistance effects (steel balls dropped by the lifting flight) on oven-dry stone. In the field, while coastal rip rap is subjected to salt spray, tidal wet-dry cycling, and wave impacts, the stone is seldom dry. Also, some stone types tend to slake or have reduced strength when wet (Rogers, 1990). Therefore, mechanical degradation tests using wet aggregate should more closely simulate actual service conditions. The Los Angeles Abrasion Test is very difficult to perform on wet materials due to the difficulty of cleaning the test drum.

The Los Angeles Abrasion Test procedure also results in the creation of fines that can cushion the impact of autogenous pieces as well as falling steel balls on the tested materials. The presence of cushioning fines can lead to anomalous test results. Therefore, the need exists for an alternative testing method that allows for wet aggregate testing and eliminates errors associated with fine cushioning. This study used the Gyratory Testing Machine (GTM) as an alternative to the Los Angeles Abrasion Test. The GTM procedure is relatively inexpensive and simple, does not require excessive time, can provides information at various moisture contents, and does not have a problem with fines cushioning the test specimen because the fines are continuously removed (Ruth and Tia, 1996).

In addition, this research sought to add tests, described in the following section, that would provide a more accurate assessment of the mechanical durability of rip rap sources. For example, slake durability testing was used to measure the resistance of a rock sample to weakening and disintegration resulting from a standard cycle of climatic wetting and drying (Franklin and Chandra, 1972). While typically used to evaluate shales and other clay-bearing rocks, the slake durability test is useful for Florida aggregates because the test simulates field conditions and measures weakening, swelling and disintegration that can occur under those conditions.

Uniaxial or unconfined, compressive strength testing was used to determine the strength of aggregate cores by applying pressure in one direction and recording the pressure at failure. While the strengths of rock cores measured in the laboratory usually do not accurately reflect large-scale *in-situ* properties, they may be useful in predicting the mechanical durability of aggregate, especially when examined along with the results of other mechanical durability tests.

Sodium Sulfate Soundness

The sodium sulfate soundness test measures a stone's ability to withstand the crystallization and hydration of a salt within its pore spaces throughout five cycles of immersion in saturated salt solution and drying. The test is considered a simulation of the action of unconfined freeze-thaw cycles, but actually measures both physical and chemical durability of aggregates. The primary mode of failure stress involves the internal tensile stress during cooling and drying (Minty and Smith, 1980). The internal expansive force is derived from the rehydration of the sodium sulfate upon re-immersion in a saturated solution following initial precipitation in permeable pore spaces (Minty and Smith, 1980). In addition to being an expensive and time-consuming test, sodium sulfate soundness testing has numerous factors that impact its precision. Some of these factors are:

1. Temperature variation of the solution during testing
2. Temperature of samples at time of immersion after drying
3. Chemical grade of sulfate used
4. Purity of water used to make the solution

5. Design of containers used for immersing samples.

All of these factors have been identified as affecting the precision of the sodium sulfate soundness test (Sheftick, 1986). These subtle and not so subtle problems detract from the simplicity and usefulness of the sodium sulfate soundness test. A need may exist for modifications to the method or the identification of an alternative test to improve the correlation between sodium sulfate soundness values and in-service performance.

This study also attempted to use insoluble residue analysis to augment sodium sulfate soundness data. Insoluble residue testing is a technique that was employed to estimate the resistance of carbonate rocks to weathering. Insoluble residues of limestones and dolomites are the non-carbonate materials that are left behind after dissolving the rock in hydrochloric acid. The most common residues are silica, clay and pyrite. Insoluble residue testing has been shown to be a good indicator of in-service durability when analyzed in conjunction with sodium sulfate soundness testing. Research involving eastern Ohio limestones revealed that rocks containing greater than 20% insoluble residue and high sulfate soundness loss values exhibited poor durability under surface weathering conditions (Fisher, 1993). This limited research indicates that there may be good correlation between insoluble residue testing and field performance.

CHAPTER 3
EVALUATION OF ABSORPTION AND SPECIFIC GRAVITY TEST METHODS

Modified Absorption

Portions of samples from each of the five stone sources were cored with a one- inch diameter diamond-bit drill to collect samples of each limestone. The chert sample was too tenacious to be cored using this equipment although several attempts were made. The twenty cores collected were used to conduct alternative stone testing. Photographs of the limestone core samples appear in Figures 3-1 to 3-4.

The FDOT defines absorption as the increase in the weight of aggregate due to water in the pores of the material, but not including water adhering to the outside surface of the particles, expressed as a percentage of the dry weight. The standard test method at atmospheric pressures is principally used to indicate durability. Because rip rap materials used in coastal structures are frequently submerged, it is imperative to generate maximum absorption values for these materials.

Prior to initiating modified absorption testing, base line absorption values were generated for each of the twenty rock core samples using the Florida Method of Test for Absorption of Coarse Aggregate (1-T 085). This test procedure involved drying the core samples to constant weight at a temperature of 110 ± 5 °C (230 ± 9°F). The cores then were cooled for one to three hours, and then immersed in distilled water at room temperature for a period of 15 to 19 hours. Following immersion, each sample was removed from the water and gently rolled in an absorbent cloth to remove all visible

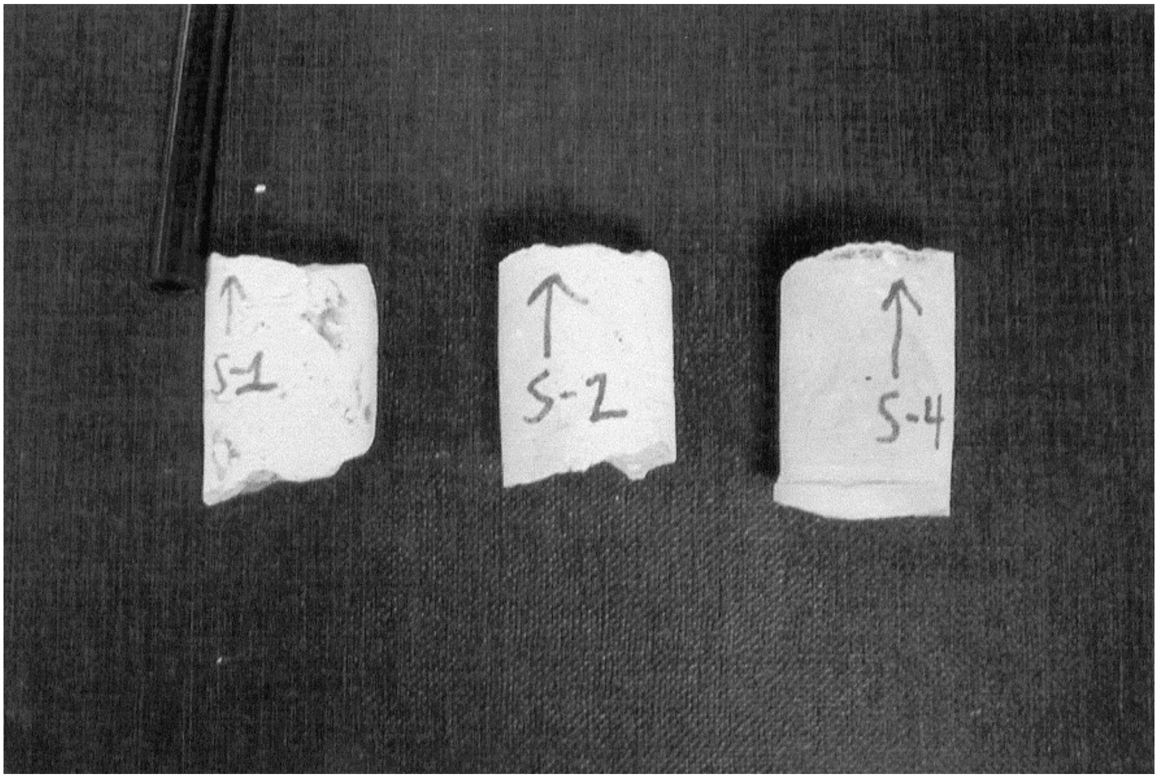


Figure 3-1: Close up view of Suwannee Limestone cores.

Figure 3-2: Close up view of Avon Park Limestone cores.

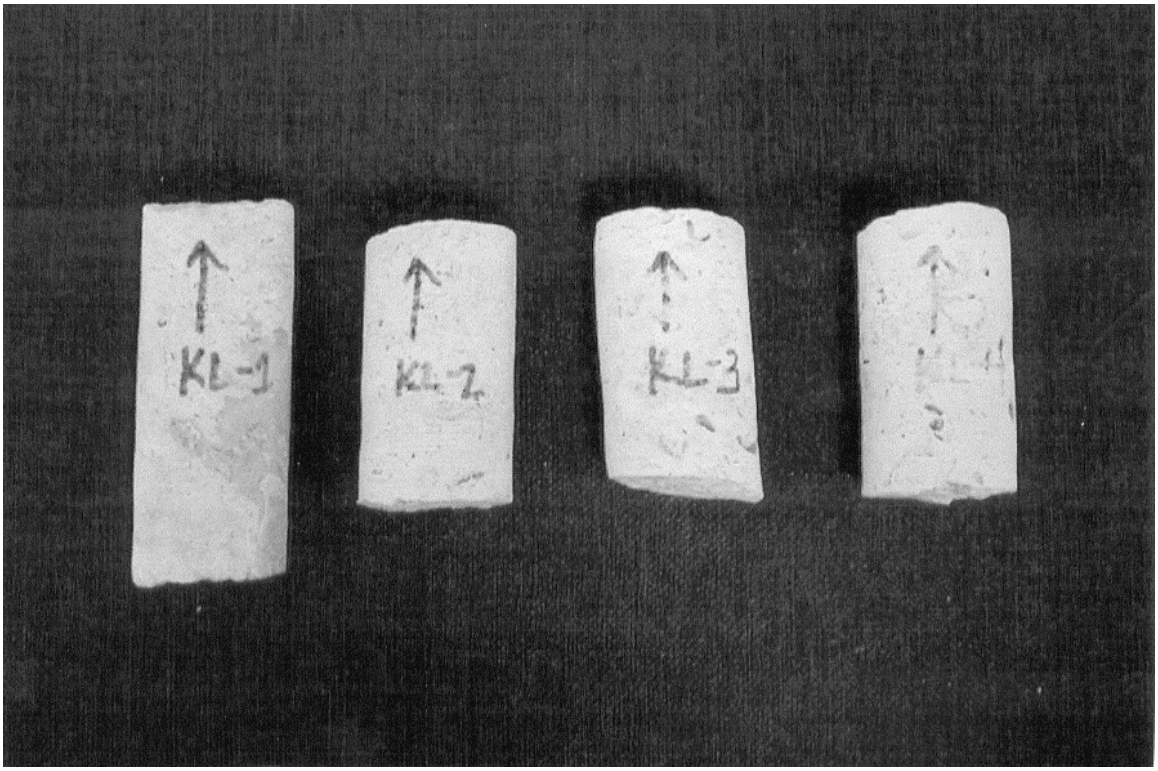


Figure 3-3: Close up view of Key Largo Limestone cores.

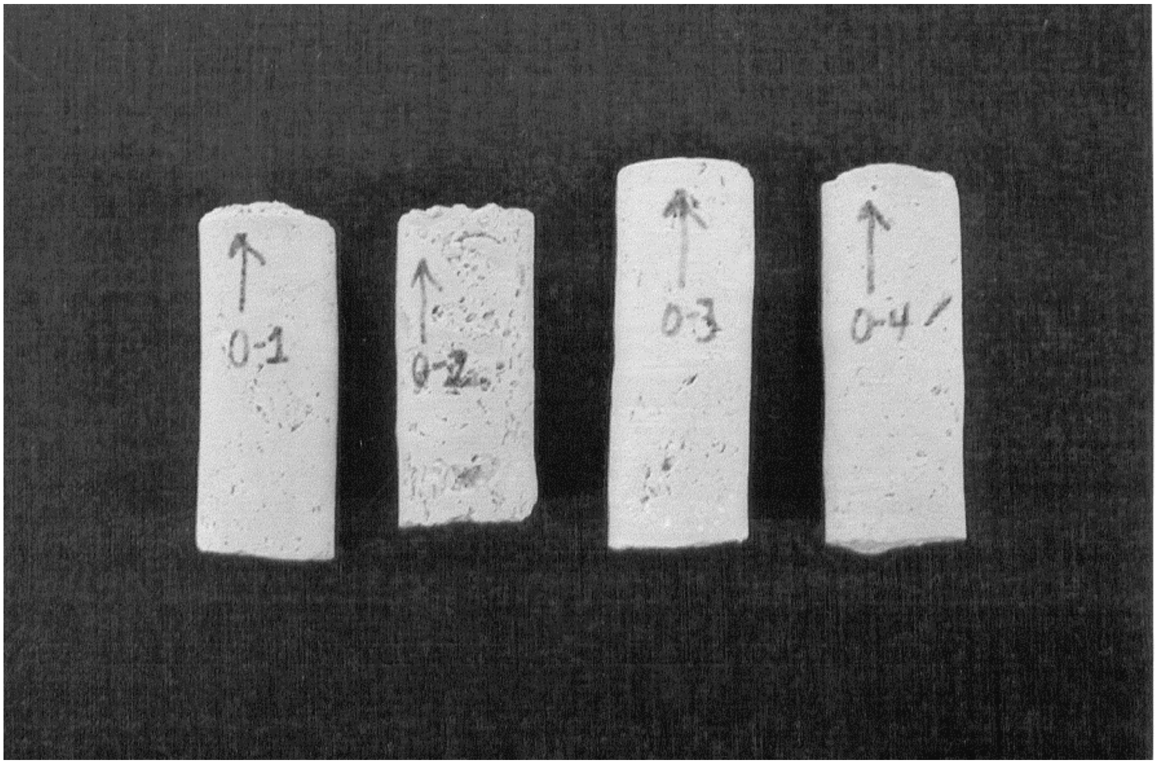


Figure 3-4: Close up view of Ocala Limestone cores.

films of water from the exteriors of the cores. Particular care was taken to avoid evaporation of water from aggregate pores during the surface drying process. The saturated, surface-dry samples were weighed, and the results were used to calculate absorption values using the following equation:

$$\textbf{Absorption (\%)} = \frac{\textbf{(saturated surface-dry weight) – (oven dry weight)}}{\textbf{(oven dry weight)}} \times \textbf{100}$$

Quadruplicate measurements were made performed for each stone. The results for these trials and their average absorption values are presented in Table 3-1.

This procedure, however, may permit entrapment of air within pores in the stone resulting in incorrect values for absorption (Lienhart et al., 1995). Because maximum absorption values are of particular importance for materials used in rip rap, an alternative testing method might be necessary. Lienhart et al. (1995) suggests that future studies utilize progressive immersion of samples to produce total saturation and correct values for absorption. This method recommends immersion of 25% of the sample for the first 24 hours, followed by 50% immersion for a second 24 hour period, followed by 75% immersion for a period of 48 hours, and, finally, 100% immersion for a period of 48 hours (Lienhart et al., 1995). While this method would likely produce correct maximum values for absorption, it also significantly increases the time and expense involved in testing. As a result, this study focused on the identification and evaluation of an alternative absorption test method that would produce correct maximum absorption values while retaining the relatively rapid turnaround time and ease of performance that is characteristic of the currently accepted test method.

Table 3-1. Absorption testing results: distilled water

Sample ID	Absorption Trial #1	Absorption Trial #2	Absorption Trial #3	Absorption Average
KL-1	5.24	5.20	5.24	5.23
KL-2	2.16	2.07	2.03	2.09
KL-3	2.73	2.69	2.73	2.71
KL-4	1.94	1.95	1.97	1.95
S-1	3.82	3.76	3.82	3.80
S-2	4.41	4.38	4.53	4.44
S-3	2.72	2.76	2.69	2.72
S-4	4.04	4.04	4.05	4.04
O-1	1.68	1.62	1.61	1.63
O-2	2.28	2.25	2.28	2.27
O-3	1.17	1.17	1.13	1.16
O-4	1.26	1.26	1.21	1.24
AP-1	4.80	4.78	4.77	4.78
AP-2	1.99	2.00	2.03	2.00
AP-3	2.14	2.15	2.16	2.15
AP-4	2.60	2.56	2.62	2.60
C-1	2.06	2.11	2.02	2.06
C-2	2.76	2.73	2.79	2.76
C-3	0.64	0.70	0.65	0.66
C-4	2.06	2.18	2.13	2.12

KL = Key Largo limestone
S = Suwannee limestone
O = Ocala limestone
AP = Avon Park
C = Chert

The alternative test method developed for absorption involved a simple modification to the currently accepted test method. This modification involved placing the oven dried samples in a dessicator and covering them with distilled water. The dessicator was closed and placed under a vacuum (15-19 hours) in order to remove air from the pores of the rock samples. As with FM 1-T 085, the samples were soaked for a period of 15 to 19 hours before being removed, surface dried and weighed. Triplicate modified absorption measurements were made on the twenty rock core samples. The average modified absorption values for the triplicate measurements are presented in Table 3-2. Results of the two methods are compared in Table 3-3.

In addition to identifying an alternative test method for absorption testing of rip rap, this investigation also studied the effects on absorption values with modifications to the test solution. The first solution modification involved replacing the distilled water solution with synthetic seawater (Instant Ocean™). Synthetic seawater was chosen in order to more closely approximate in-service conditions of rip rap used in coastal applications. Six replicate analyses were performed on the twenty rock core samples using synthetic seawater in place of distilled water. Three of the trials were conducted using the conventional soak-test method, while the remaining three trials were conducted using the alternative vacuum extraction test method. The average absorption values for the synthetic seawater testing are presented in Tables 3-4 and 3-5.

A second alternative test involved replacing the distilled water soak with a 50/50 mixture of distilled water and methanol (methyl alcohol). It was hypothesized that the addition of a simple alcohol-water mixture with a surface tension (50:50 MeOH-H_2O mixture has a surface tension of 35.31 dynes cm^{-1} @ 20^o C) significantly lower than that

Table 3-2. Absorption testing results: distilled water with vacuum extraction.

Sample ID	Absorption Trial #1	Absorption Trial #2	Absorption Trial #3	Absorption Average
KL-1	6.25	6.76	6.56	6.53
KL-2	2.26	2.24	2.24	2.25
KL-3	3.11	3.11	3.19	3.14
KL-4	2.10	2.10	2.14	2.11
S-1	4.46	4.40	4.40	4.42
S-2	4.86	4.86	4.92	4.88
S-3	3.07	3.08	3.15	3.10
S-4	4.41	4.52	4.52	4.48
O-1	2.69	2.68	2.73	2.70
O-2	3.17	2.81	2.70	2.90
O-3	1.80	1.85	1.90	1.85
O-4	2.02	2.02	2.07	2.04
AP-1	6.38	6.46	6.50	6.45
AP-2	2.12	2.09	2.20	2.14
AP-3	2.26	2.19	2.37	2.28
AP-4	2.76	2.74	2.94	2.81
C-1	2.11	2.06	2.16	2.11
C-2	2.82	2.84	2.82	2.83
C-3	0.65	0.65	0.76	0.68
C-4	2.26	2.12	2.29	2.23

Table 3-3. Comparison between standard and modified absorption testing.

Sample ID	Absorption Average Distilled Water Soak	Absorption Average Distilled Water with Vacuum Extraction
KL-1	5.23	6.53
KL-2	2.09	2.25
KL-3	2.71	3.14
KL-4	1.95	2.11
S-1	3.80	4.42
S-2	4.44	4.88
S-3	2.72	3.10
S-4	4.04	4.48
O-1	1.63	2.70
O-2	2.27	2.90
O-3	1.16	1.85
O-4	1.24	2.04
AP-1	4.78	6.45
AP-2	2.00	2.14
AP-3	2.15	2.28
AP-4	2.60	2.81
C-1	2.06	2.11
C-2	2.76	2.83
C-3	0.66	0.68
C-4	2.12	2.23

Table 3-4. Absorption testing results: synthetic seawater.

Sample ID	Absorption Trial #1	Absorption Trial #2	Absorption Trial #3	Absorption Average
KL-1	5.13	5.09	5.03	5.09
KL-2	1.90	1.94	1.99	1.94
KL-3	2.61	2.68	2.60	2.63
KL-4	1.86	1.83	1.86	1.85
S-1	3.64	3.63	3.60	3.62
S-2	4.19	4.19	4.25	4.21
S-3	2.64	2.66	2.64	2.65
S-4	3.88	3.83	3.80	3.84
O-1	1.51	1.59	1.61	1.57
O-2	2.03	1.90	2.20	2.04
O-3	1.10	1.11	1.08	1.09
O-4	1.22	1.22	1.20	1.21
AP-1	4.64	4.68	4.67	4.67
AP-2	1.98	2.00	1.99	1.99
AP-3	2.10	2.13	2.10	2.11
AP-4	2.56	2.52	2.53	2.54
C-1	1.68	1.86	1.60	1.72
C-2	2.56	2.65	2.52	2.58
C-3	0.60	0.63	0.44	0.56
C-4	1.69	1.88	1.64	1.74

Table 3-5. Absorption testing results: synthetic seawater with vacuum extraction.

Sample ID	Absorption Trial #1	Absorption Trial #2	Absorption Trial #3	Absorption Average
KL-1	6.34	6.47	6.32	6.38
KL-2	2.29	2.29	2.44	2.34
KL-3	3.07	3.20	3.24	3.17
KL-4	2.05	2.09	2.01	2.05
S-1	4.32	4.45	4.32	4.36
S-2	4.74	4.68	4.65	4.69
S-3	3.05	3.04	3.01	3.03
S-4	4.27	4.21	4.21	4.23
O-1	2.61	2.77	2.71	2.70
O-2	2.85	3.00	3.58	3.14
O-3	1.80	1.82	1.82	1.81
O-4	2.01	1.97	2.02	2.00
AP-1	6.16	6.50	6.41	6.36
AP-2	2.00	2.01	1.98	2.00
AP-3	2.09	2.09	2.08	2.09
AP-4	2.58	2.61	2.55	2.58
C-1	1.71	1.91	1.53	1.71
C-2	2.59	2.78	2.49	2.62
C-3	0.54	0.63	0.54	0.57
C-4	1.72	2.03	1.64	1.80

Table 3-6. Comparison between standard and modified absorption testing.

Sample ID	Absorption Average	Absorption Average
	Synthetic Seawater Soak	Synthetic Seawater with Vacuum Extraction
KL-1	5.09	6.38
KL-2	1.94	2.34
KL-3	2.63	3.17
KL-4	1.85	2.05
S-1	3.62	4.36
S-2	4.21	4.69
S-3	2.65	3.03
S-4	3.84	4.23
O-1	1.57	2.70
O-2	2.04	3.14
O-3	1.09	1.81
O-4	1.21	2.00
AP-1	4.67	6.36
AP-2	1.99	2.00
AP-3	2.11	2.09
AP-4	2.54	2.58
C-1	1.72	1.71
C-2	2.58	2.62
C-3	0.56	0.57
C-4	1.74	1.80

of water (72.75 dynes cm^{-1} @ 20ºC) would produce increased values for maximum absorption. Six replications were performed on the twenty rock core samples using the distilled water/methanol mixture in place of distilled water. Three of the trials were conducted using the conventional soak test method, while the remaining three trials were conducted using the alternative vacuum extraction method. The average absorption values for the distilled water/methanol testing are depicted in Tables 3-7 and 3-8. Results of the two methods are compared in Table 3-9.

Specific Gravity

This project also collected data necessary for the calculation of specific gravity values for each of the rock cores. Bulk specific gravity is defined as the ratio of the weight in air of a unit volume of stone, including the permeable and impermeable voids in the particles, but not including the voids between particles, to the weight of that same volume of water at a given temperature. Specific gravity measurements were collected with reference to Florida Method of Test for Specific Gravity and Absorption of Coarse Aggregate (FM 1-T 085). Testing was conducted at the FDOT Materials Laboratory in Gainesville, Florida. Each core was soaked in distilled water for a period of 24 hours. Each core was subsequently removed from the soaking solution and rolled in an absorbent cloth to remove the exterior film of water. After weighing the surface-dry saturated sample, the core was placed in a submerged basket attached to an electronic balance for measuring the sample’s weight in water. The bulk specific gravity was then calculated using the following equation:

$$\textbf{Bulk Specific Gravity} = \mathbf{A/\,(B - C)}$$

where: A = weight of oven-dry aggregate (g)

B = weight of saturated-surface-dry sample in air (g)

C = weight of saturated-surface dry sample in water (g)

Specific gravity results, which are presented in Table 3-10, ranged from 2.21 (Key Largo Limestone) to 2.58 (chert and Avon Park Limestone).

Table 3-7. Absorption testing results: 50% methanol and 50% distilled water.

Sample ID	Absorption Trial #1	Absorption Trial #2	Absorption Trial #3	Absorption Average
KL-1	4.71	4.91	4.83	4.82
KL-2	1.80	1.97	1.91	1.89
KL-3	2.47	2.62	2.55	2.55
KL-4	1.71	1.77	1.68	1.72
S-1	3.40	3.63	3.43	3.49
S-2	3.97	4.04	4.07	4.03
S-3	2.40	2.46	2.51	2.46
S-4	3.65	3.77	3.68	3.70
O-1	1.48	1.57	1.54	1.53
O-2	1.97	2.00	2.26	2.08
O-3	1.00	1.01	1.01	1.01
O-4	1.12	1.13	1.20	1.15
AP-1	4.55	4.72	4.63	4.63
AP-2	1.69	1.73	1.72	1.72
AP-3	1.77	1.82	1.77	1.79
AP-4	2.27	2.27	2.29	2.28
C-1	1.56	1.53	1.58	1.56
C-2	2.54	2.59	2.56	2.57
C-3	0.57	0.44	0.44	0.48
C-4	1.63	1.48	1.62	1.58

Table 3-8. Absorption testing results: 50% methanol and 50% distilled water soak with vacuum extraction.

Sample ID	Absorption Trial #1	Absorption Trial #2	Absorption Trial #3	Absorption Average
KL-1	5.78	6.19	6.67	6.21
KL-2	2.34	2.38	2.36	2.36
KL-3	3.07	3.03	3.33	3.15
KL-4	2.13	2.01	2.11	2.08
S-1	4.43	4.36	4.53	4.44
S-2	4.76	4.73	4.86	4.78
S-3	3.00	2.98	3.14	3.04
S-4	4.36	4.39	4.51	4.42
O-1	2.77	2.74	2.88	2.80
O-2	3.31	3.34	3.34	3.33
O-3	1.90	1.79	1.87	1.85
O-4	2.13	2.05	2.13	2.10
AP-1	6.54	6.51	6.63	6.56
AP-2	1.97	1.88	2.09	1.98
AP-3	2.07	1.95	2.20	2.07
AP-4	2.57	2.53	2.66	2.59
C-1	1.63	1.48	1.51	1.54
C-2	2.66	2.63	2.59	2.63
C-3	0.57	0.44	0.32	0.44
C-4	1.72	1.57	1.42	1.57

Table 3-9. Comparison between standard and modified absorption testing.

Sample ID	Absorption Average 50% Methanol/50% Distilled Water Soak	Absorption Average 50% Methanol/50% Distilled With Vacuum Extraction
KL-1	4.82	6.21
KL-2	1.89	2.36
KL-3	2.55	3.15
KL-4	1.72	2.08
S-1	3.49	4.44
S-2	4.03	4.78
S-3	2.46	3.04
S-4	3.70	4.42
O-1	1.53	2.80
O-2	2.08	3.33
O-3	1.01	1.85
O-4	1.15	2.10
AP-1	4.63	6.56
AP-2	1.72	1.98
AP-3	1.79	2.07
AP-4	2.28	2.59
C-1	1.56	1.54
C-2	2.57	2.63
C-3	0.48	0.44
C-4	1.58	1.57

Table 3-10. Specific gravity test results.

Sample ID	Material	Saturated Weight, g.	Weight in Water, g.	Oven Dry Weight, g.	Bulk Specific Gravity
0-1	Ocala Limestone	69.3	41.5	68.2	2.45
0-2	Ocala Limestone	60.9	36.3	59.6	2.42
0-3	Ocala Limestone	78.7	47.9	77.8	2.53
0-4	Ocala Limestone	76	46.1	75.1	2.51
0-7	Ocala Limestone	39.7	24.1	39.1	2.51
AP-1	Avon Park Limestone	71.5	42.2	68.3	2.33
AP-2	Avon Park Limestone	77.9	48.3	76.4	2.58
AP-3	Avon Park Limestone	86.6	53.6	85	2.58
AP-4	Avon Park Limestone	69.3	42.6	67.7	2.54
KL-1	Key Largo Limestone	64.2	36.5	61.1	2.21
KL-2	Key Largo Limestone	50.3	30.1	49.4	2.45
KL-3	Key Largo Limestone	47.9	28.2	46.7	2.37
KL-4	Key Largo Limestone	52.2	31.8	51.3	2.51
S-1	Suwannee Limestone	31.7	18.8	30.6	2.37
S-2	Suwannee Limestone	32.4	19	31	2.31
S-4	Suwannee Limestone	37.1	21.7	35.7	2.32
C-1	Chert	64.2	38.8	63.1	2.48
C-2	Chert	64.8	39.1	63.2	2.46
C-3	Chert	32.1	19.7	32	2.58
C-4	Chert	12.2	7.3	11.9	2.43

CHAPTER 4
PETROGRAPHIC AND EPIFLUORESCENT MICROSCOPY

Petrographic Number Evaluation

A problem associated with rip rap stone testing is that no single test can adequately determine both physical and chemical properties. Physical tests tend to measure the mechanical degradation potential, but do not simulate the concurrent chemical degradation that is common in laboratory testing or field performance. Conversely, chemical tests may more closely approximate physical durability because chemical weathering reactions, which occur in nature, often are difficult to reproduce in the laboratory study.

Petrographic examination of stones has traditionally been used to complement various physical and chemical durability tests. Petrographic number (PN) analysis can provide information useful in relating both physical and chemical soundness attributes of aggregate materials. For example, Rogers (1990) examined a variety of lithologies and described them using a PN technique refined from Bayne and Brownridge (1955). This work showed the PN technique to be a good predictor of field performance for concrete aggregates. In order to extend the application of the PN technique to Florida aggregates, Oyen et al. (1998) modified previous PN techniques from macroscopic identification of aggregate lithologies and applied them to petrographic thin sections in a new method of PN determination. While this system was developed to predict concrete aggregate field performance, it also appears to be useful, with some minor modifications, in predicting potential rip rap performance.

In the application of PNs to Florida aggregates, Oyen et al. (1998) developed a numeric system following the general principles of earlier systems used by Bayne and Brownridge

(1955). This recently developed system focused on using descriptors that allow variations in Florida carbonates to be distinguished. The descriptive components include:

- the type of allochem or grain matrix (fossil vs. non-fossil grains)
- the type of porosity present
- the type of cement or matrix (micrite, sparite or microsparite)
- additional noncarbonate minerals

These common carbonate components were subsequently used to establish numeric rankings, or factor weights (FW). FWs are ultimately multiplied by the percentage value of each carbonate component to determine the PN. The value of the FW is relative to its strength or resistance to physical and chemical weathering (Oyen et al., 1998). FWs of 1.0 represent an ideally durable grain, while progressively larger FWs are indicative of poorer quality material with regard to potential durability.

The PN system proposed by Oyen et al. (1998) assigned non-fossil grains, such as peloids, ooids, intraclasts and aggregate grains, a FW of 1.0 due to their dense (i.e., non-porous) nature and potentially greater strength. In addition, non-fossil grains in Florida aggregates are typically composed of calcite rather than the less stable mineral phase, aragonite. This PN system assigns a FW of 1.3 to fossil grains because the majority of fossils that occur in Florida limestones were originally aragonitic and, thus, are more susceptible to chemical weathering than those composed of calcite. This is particularly important when distinguishing geologically younger (Pliocene-Pleistocene) carbonates that have higher proportions of aragonitic fossils from older formations (Oligocene-Eocene) that have relatively higher proportions of calcitic fossils. Moreover, fossils are typically thin-walled in Florida carbonates and, as a result, may have lower strengths and resistance to physical weathering (Oyen, et al., 1998). Typical fossil grains seen in Florida carbonates are depicted in Figures 4-1 and 4-2.

The Oyen PN system assigns FWs for the cement-matrix component of the carbonates by separating differences in potential chemical reactivity according to grain size. For example, micrite (< 4 μm) is assigned a FW of 1.5 because micrite commonly occurs as an accumulation of biogenic carbonate detritus with free grain boundaries that are subject to chemical reactions. Conversely, sparite, with larger calcite crystals than micrite, has a lower potential chemical reactivity due to decreased surface area. Sparite also typically precipitates directly from solution and has tightly bonded crystal boundaries. As a result, sparite and microsparite were assigned a FW of 1.0 (Oyen et al., 1998).

Oyen et al. (1998) also recognized that porosity is the most important factor when attempting to distinguish durable and non-durable aggregates. They selected the five most common types of porosity that occur in Florida carbonates from the 15 basic porosity types recognized by Choquette and Pray (1970). FW values were assigned to each porosity type based upon typical pore sizes. The larger the average pore size, the larger the assigned FW because of the potentially lower physical durability of such grains. For example, vuggy pores that generally form by solution enlargement processes have the largest typical pore sizes, >1.5 mm (Figure 4-3). As a result, they were assigned a FW of 3.0.

Moldic pores are formed by the dissolution and removal of fossil grains (Figures 4-4 through 4-6). This is common with aragonitic fossils in Florida aggregates and results in larger pore sizes. Based upon this, moldic pores also were assigned a FW of 3.0.

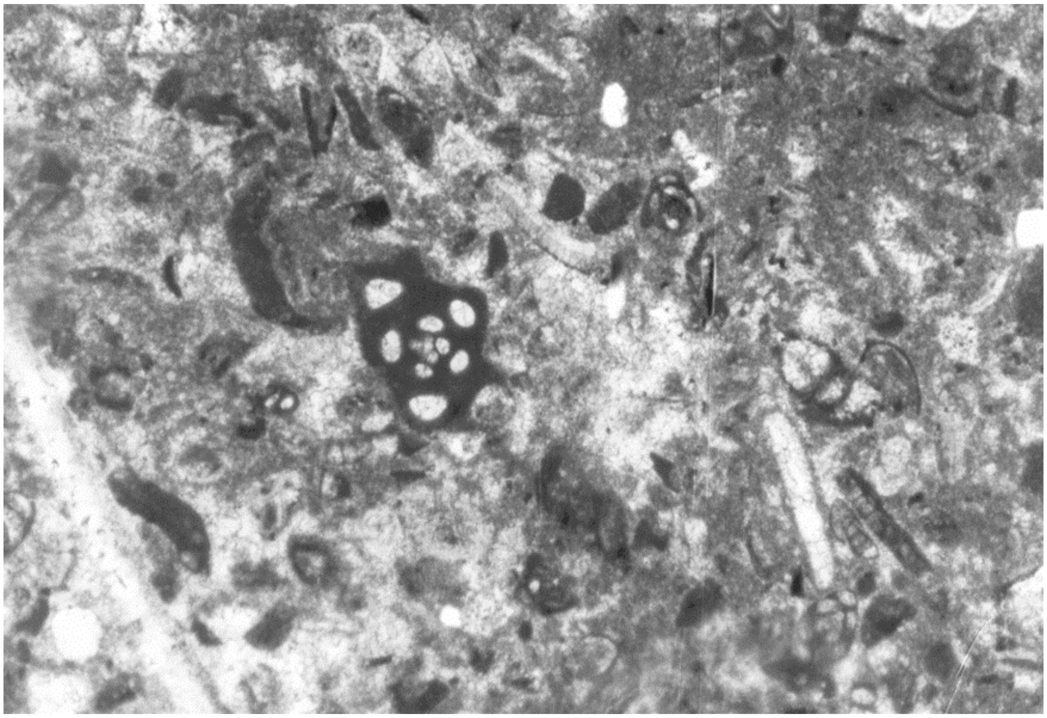


Figure 4-1: Petrographic photograph (cross polarized light) showing fossils typical of the Suwannee Limestone. Scale: 1mm = 50mm on image.

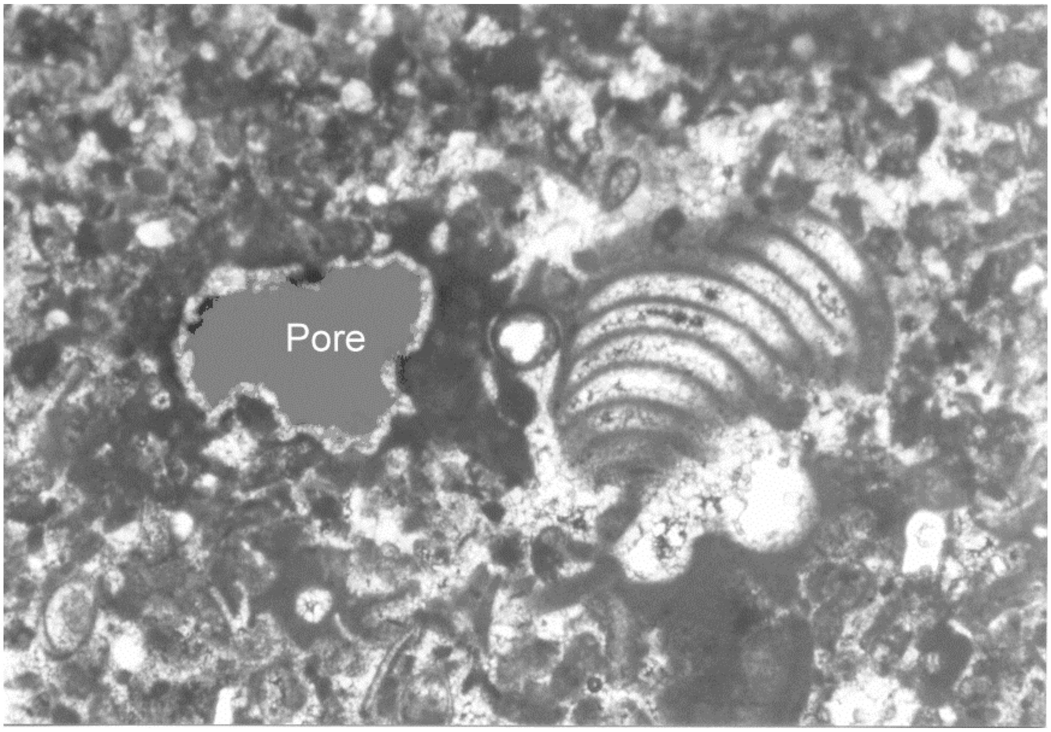


Figure 4-2: Petrographic photographic (cross polarized light) showing a gastropod fossil and a pore space in a Suwannee Limestone sample. Scale: 1mm = 50mm on image.

Interparticle porosity is the pore space between individual allochems and can be large in size. As a result, interparticle porosity also is assigned a FW of 3.0. Intraparticle pores and intercrystalline pores, pores that are found within individual particles and between crystals, respectively, are typically very small and were thus assigned FWs of 2.0 (Figure 4-7).

The final grains addressed by Oyen et al (1998) were the noncarbonate grains. These include chert, quartz, clays and opaque minerals. With the exception of chert and quartz, all other noncarbonate grains were assigned a FW of 6.0. This designation was given because opaque minerals can cause substantial physical weakening from oxidation and clays can cause weakening via expansion (Figure 4-8). In the PN system used by Oyen et al (1998), quartz and chert were quantified based on crystallinity indices made on the acid-insoluble residue of the aggregate source. FWs were assigned based on this quantification. Because quartz and chert grains typically have good strength values and because alkali-silica reactivity is not a problem with rip rap, they have been assigned a FW of 1.0.

A total of 20 thin sections, four of each evaluated material, were studied in this project using the methodology of Oyen et al (1998). A point count analysis was performed on each thin section and recorded on petrographic data sheets (Figure 4-9). This analysis used an automatic point counting stage to systematically move the thin section below the objective of the petrographic microscope. Each point measurement consisted of determining the nature of the grain located in the center of field of view and recording it on an electromechanical device. A total of 100 points were counted from each thin section using this method. The percent totals of each grain type were subsequently recorded on the data sheet and multiplied by the FWs to determine the PNs. This analysis takes 1.5-2 hours to complete.

Calculation of average PN values for five Florida aggregates shows a limited range of values (Table 4-1); from 111.5 for the Avon Park Limestone to 139.5 for the Key Largo Limestone.

Rhodamine Epifluorescent Microscopy

In addition to the petrographic study of the five Florida stones, the application of the rhodamine epifluorescent microscopy technique outlined by Soeder (1990) to rip rap microporosity analysis was evaluated. Rhodamine epifluorescent microscopy (REFM) is a commonly used biological technique. The equipment used was accessible at the Computerized Image Analysis Laboratory, School of Veterinary Medicine, University of Florida.

Ten REFM thin sections, two from each aggregate type, were prepared for study. Thin section preparation involved the vacuum impregnation of samples with an epoxy resin that was mixed with a hardener containing dissolved rhodamine B and a non-fluorescent blue dye. This mixture allowed a comparison of microporosity using both REFM and standard blue dye by plane polarized light microscopy. The impregnated samples were prepared as an ultrathin section (~ 15 microns thick) to minimize overlapping pore spaces. The desired result of the REFM technique involves the reddish orange fluorescence of the impregnated rhodamine B under excitation of green light at a wavelength of 540 nanometers, thereby indicating impregnated pore spaces and microcracks in the aggregate (Thompson and Meletiou, 1992).

While the REFM technique has been used in other applications with great success, the technique presented two problems that proved difficult to resolve. The first problem manifested itself as a general fluorescent background glow in the samples that prevented the delineation of microstructural details. One possible source of this problem may have been the migration of

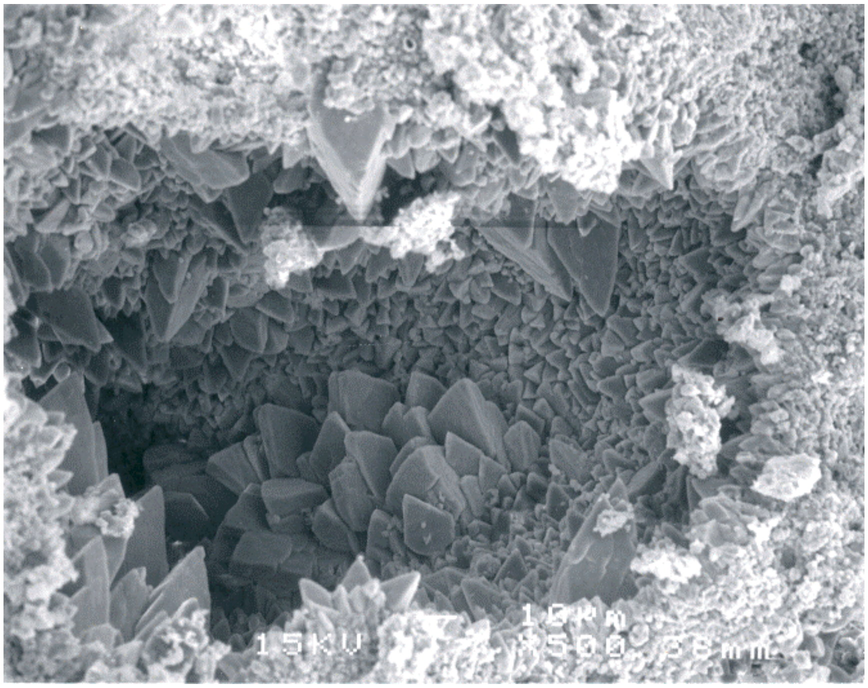


Figure 4-3: Scanning electron micrograph showing an intermediate sized pore in a sample of Ocala Limestone.

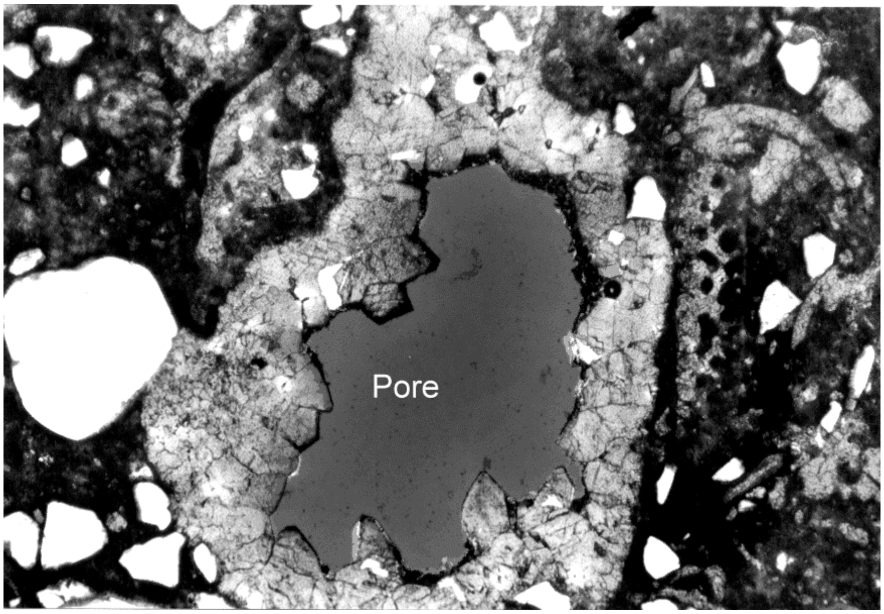


Figure 4-4: Petrographic photograph (plane polarized light) showing a large moldic pore in a sample of Key Largo Limestone. Scale: 1mm = 50mm on image.

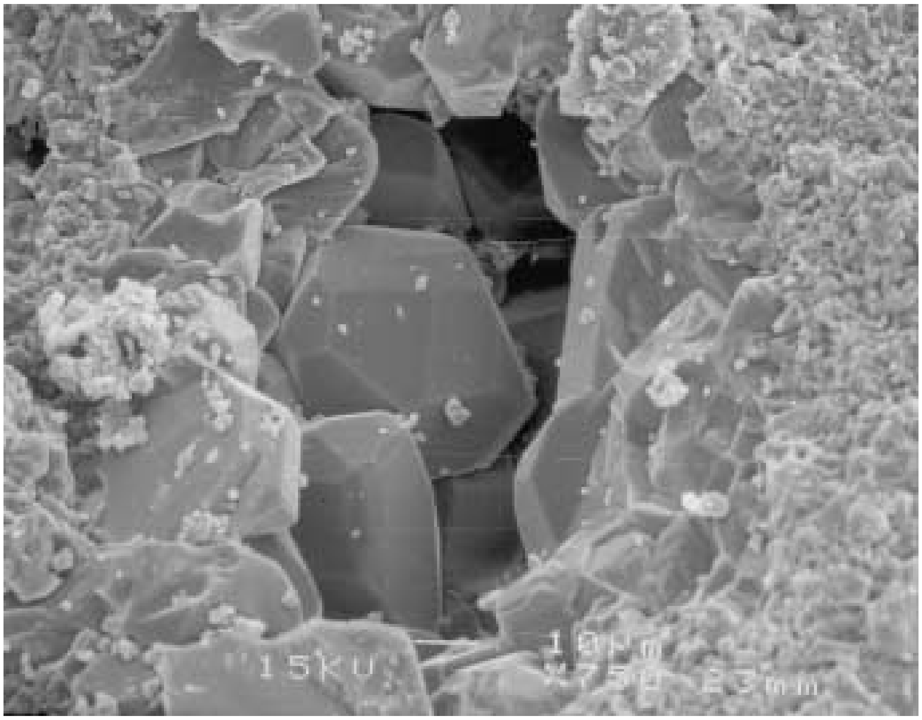


Figure 4-5: Scanning electron micrograph showing an intermediate sized moldic pore in a sample of Suwannee Limestone.

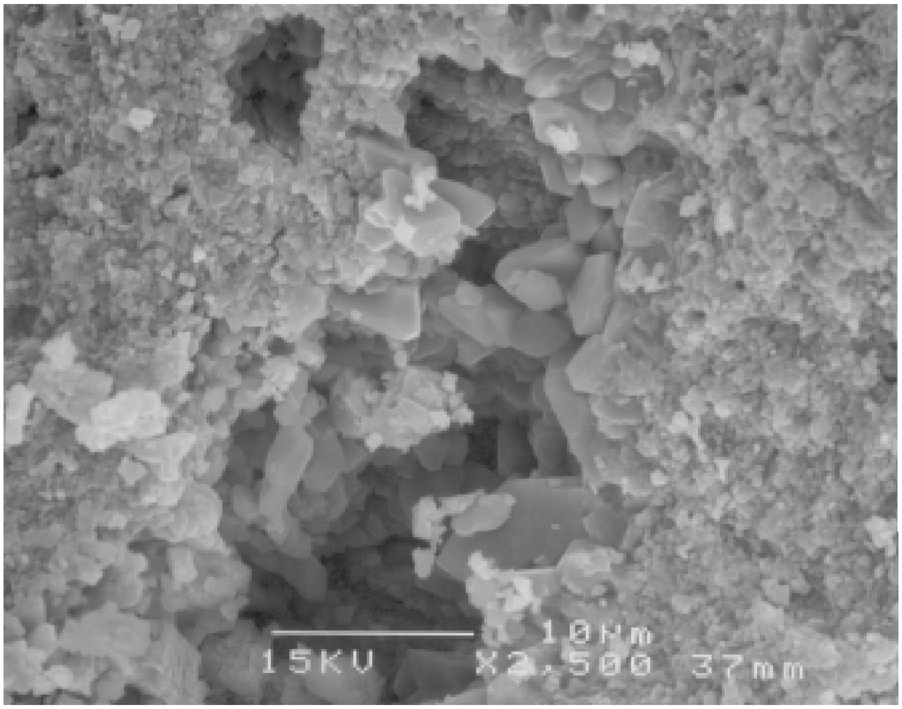


Figure 4-6: Scanning electron micrograph showing a very fine moldic pore (dissolution of a fossil) in a sample of Key Largo Limestone.

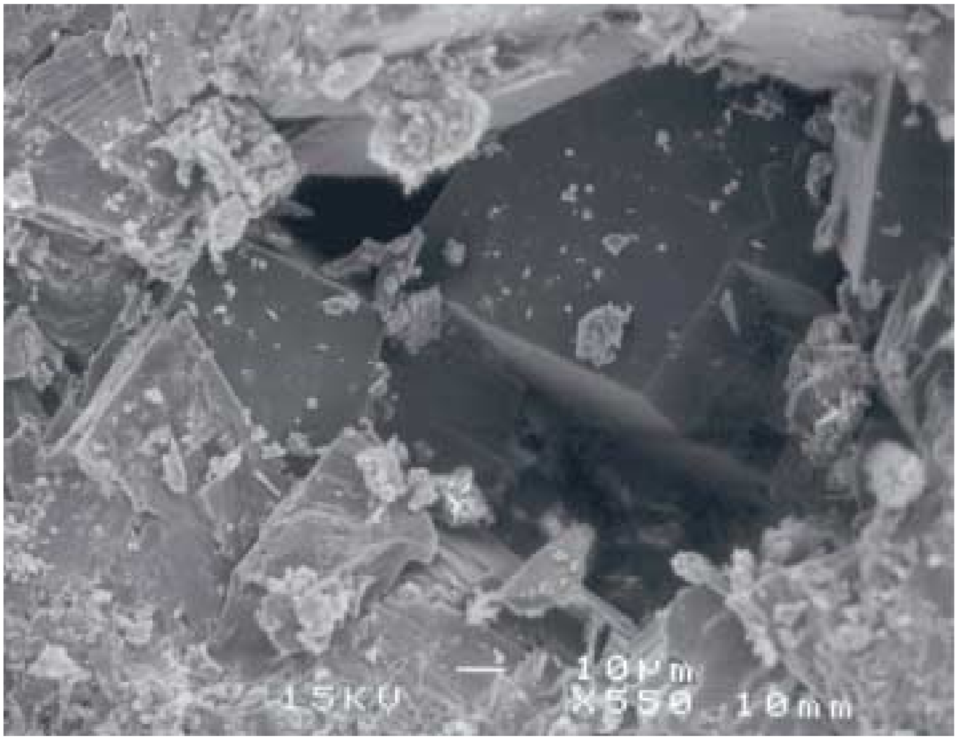


Figure 4-7: Scanning electron micrograph showing an intercrystalline pore typical of the Avon Park Limestone.

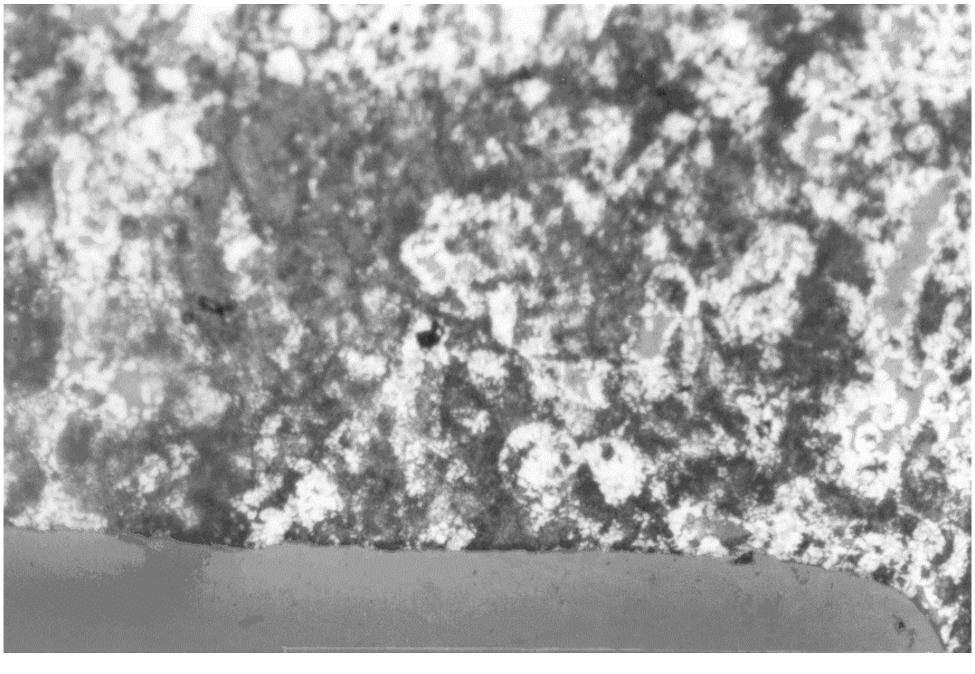
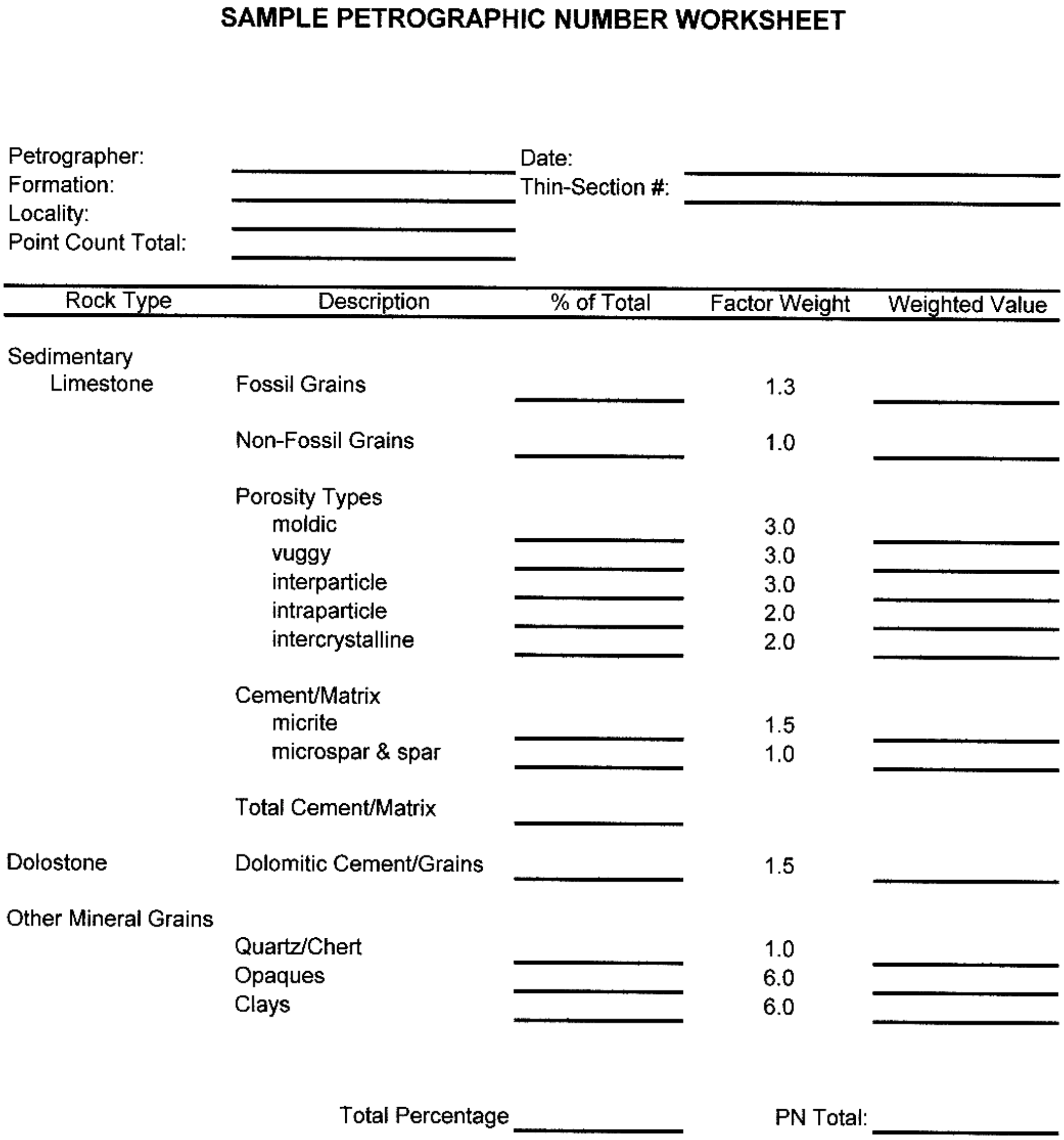


Figure 4-8: Petrographic photograph (plane polarized light) showing an opaque grain in a sample of Avon Park Limestone. Scale: 1mm = 25mm on image.



SAMPLE PETROGRAPHIC NUMBER WORKSHEET

Petrographer: ____________ Date: ____________

Formation: ____________ Thin-Section #: ____________

Locality: ____________

Point Count Total: ____________

Rock Type	Description	% of Total	Factor Weight	Weighted Value
Sedimentary				
Limestone	Fossil Grains		1.3	
	Non-Fossil Grains		1.0	
	Porosity Types			
	moldic		3.0	
	vuggy		3.0	
	interparticle		3.0	
	intraparticle		2.0	
	intercrystalline		2.0	
	Cement/Matrix			
	micrite		1.5	
	microspar & spar		1.0	
	Total Cement/Matrix			
Dolostone	Dolomitic Cement/Grains		1.5	
Other Mineral Grains				
	Quartz/Chert		1.0	
	Opaques		6.0	
	Clays		6.0	

Total Percentage ____________ PN Total: ____________

Figure 4-9: Sample petrographic number worksheet.

Table 4-1. Petrographic number values.

Key Largo Limestone	
Slide #1 PN	145.90
Slide #2 PN	137.90
Slide #3 PN	138.50
Slide #4 PN	135.50
Average PN	139.45
Standard Deviation	4.49

Avon Park Limestone	
Slide #1 PN	109.90
Slide #2 PN	125.80
Slide #3 PN	106.00
Slide #4 PN	104.30
Average PN	111.50
Standard Deviation	9.82

undissolved rhodamine in the hardener prior to impregnation. Because rhodamine is hydrophilic, water used during thin section preparation can cause this undissolved rhodamine to migrate into the sample, resulting in this background fluorescent glow. A second problem encountered during this research was an overall difficulty in resolving the REFM images. The clarity of the images under the green light was poor, preventing the assessment of microporosity. The images appeared dark with a general background glow (previously discussed) and limited, distorted reddish-orange pore spaces. Because image clarity is necessary to utilize this technique, microstructural assessment proved to be impossible. Representatives of the School of Veterinary Medicine suggested that the source of the problem may lie in the preparation of the thin sections. The dark, distorted images likely resulted from thin sections that were prepared in excess of 15 microns, resulting in pore space impregnation difficulty.

CHAPTER 5

INTRUSION POROSIMETRY

Porosity and pore size distribution are parameters that are fundamentally related to physical properties such as absorption and density. As a result, these two physical parameters are very important in determining the soundness of stones. Mercury intrusion porosimetry (MIP) is a convenient and rapid method for measuring pores between 100 micrometers and 10 nanometers. MIP theory is based on the physical principle that a non-reactive, non-wetting liquid will not penetrate pores until sufficient pressure is applied to force its entrance. The relationship between the applied pressure and the pore size into which mercury will intrude is stated in the Washburn equation:

$$\mathbf{PD = -4\,\gamma \cos\theta}$$

Where P is the applied pressure

D is the pore diameter

γ is the surface tension of mercury (480 dyne cm^{-1})

θ is the contact angle between mercury and the pore wall (140°).

As the pressure increases, the instrument senses the intrusion volume of mercury by the change in capacitance between the mercury column and a metal sheath surrounding the stem of the sample cell. As the mercury column shortens, the pressure and volume data are continuously acquired and displayed on a computer monitor.

For this project, duplicate samples from each of the five aggregate types were tested using an Autoscan-60 porosimeter located at the Research Center for Particle Science and Technology, University of Florida, Gainesville, Florida. Each sample was tested according to

ASTM D 4404-84 Standard Test Method for Determination of Pore Volume and Pore Volume Distribution of Soil and Rock by Mercury Intrusion Porosimetry. Oven-dried 5 to 6 gram samples of minus 3/8” material were used in testing. All samples were analyzed over a range of 0 to 60,000 pounds per square inch (psi) using the MIP.

The computer program that supports the porosimeter allows the results of each test to be displayed in a variety of ways, however, the most common is a cumulative distribution of pore sizes. Plots of the pore size distribution for each aggregate type (Figures 5-1 through 5-5) show several interesting features. The gray chert from the Suwannee-Hawthorn unconformity has almost no measurable porosity as shown by the flat curve at the bottom of Figure 5-5. The Suwannee Limestone (Figure 5-1) and Avon Park Limestone (Figure 5-2) have most of their porosity occurring in the fine pores (below 0.1 micrometers), but their total porosity is relatively low. The porosity data for the Key Largo (Figure 5-3) Limestone and Ocala Limestone (Figure 5-4) are the greatest measured in this sample group (note the change in scale in the last two figures), and most of their porosity occurs in the larger sizes (greater than 0.1 micrometers).

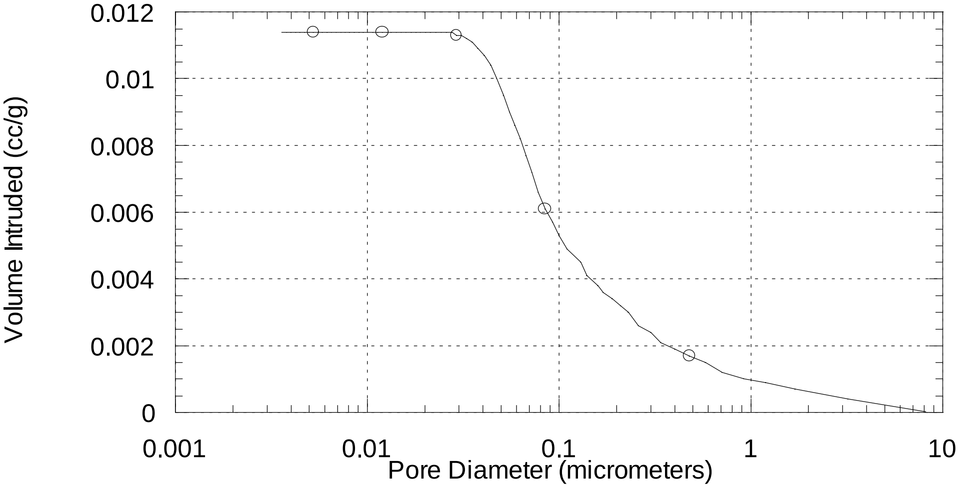


Figure 5-1: Mercury intrusion porosimetry curve for Suwannee Limestone.

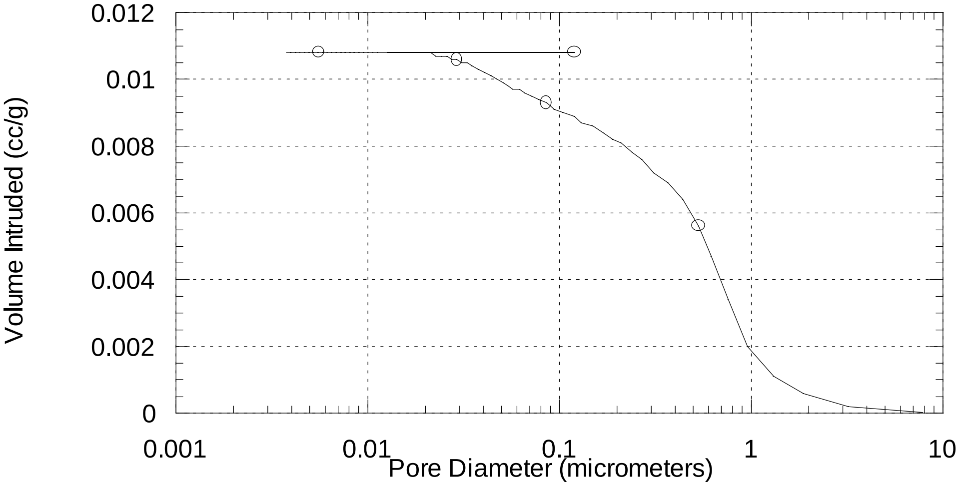


Figure 5-2: Mercury intrusion porosimetry curve for Avon Park Limestone.

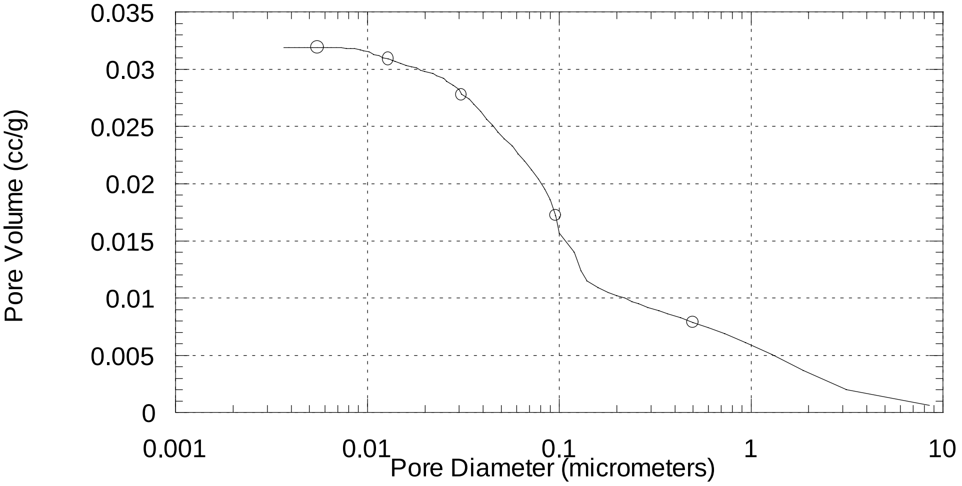


Figure 5-3: Mercury intrusion porosimetry curve for Key Largo Limestone.

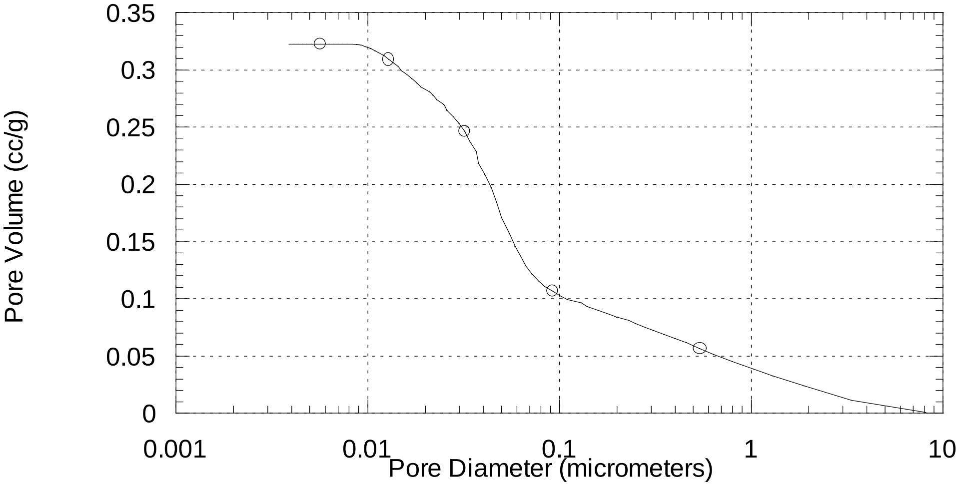


Figure 5-4: Mercury intrusion porosimetry curve for Ocala Limestone.

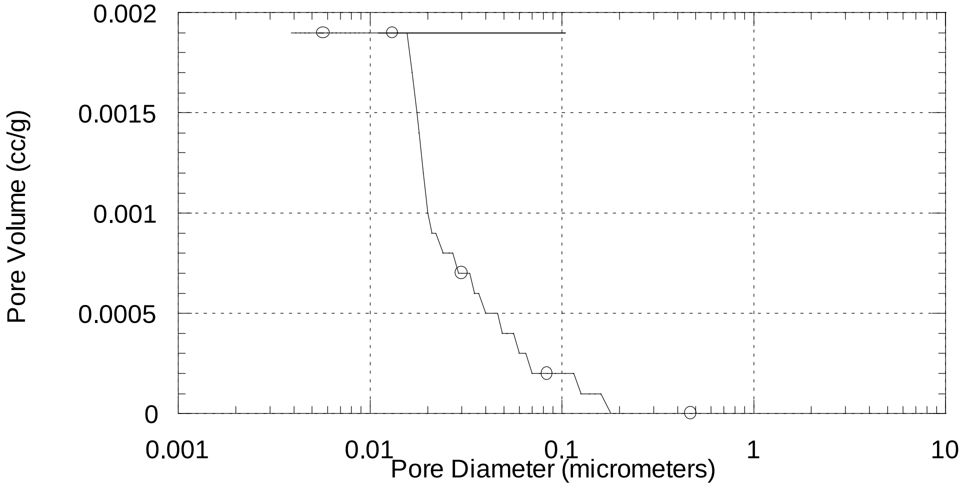


Figure 5-5: Mercury intrusion porosimetry curve for Gray Chert.

CHAPTER 6
GYRATORY TESTING MACHINE AND UNCONFINED COMPRESSIVE STRENGTHS

Gyratory Testing

The FDOT currently uses the Los Angeles Abrasion test to evaluate physical degradation potential in stones used for rip rap. The Los Angeles Abrasion test possesses numerous qualities that affect its usefulness as an index test for evaluating potential rip rap aggregates. This research used a gyratory testing because this method produces degradation due to aggregate particle interaction (autogenous effects) and does not cushion tested materials with fines generated during testing. The Gyratory Testing Machine (GTM) Model 6C/4C was used to test the five Florida aggregate types selected for this study.

The standard sample size for each test was 1000 grams of oven-dried stone. Each 1000 gram sample consisted of 500 grams of 1/4"-3/8" material and 500 grams of 3/8”–1/2” material. This gradation was selected because it is the largest particle size material that can be effectively tested with the GTM. This sample size provided a sample height of approximately three inches in the 4-inch diameter compaction mold. A total of 10 samples, duplicate samples of each aggregate type under wet conditions, were prepared and tested as part of this research. Because wet tests were performed on the samples to approximate in-service rip rap conditions, each sample was soaked in tap water for a minimum of 1.5 hours and a maximum of 4 hours prior to compaction. The samples were free drained and allowed to air dry for approximately 15 minutes prior to placement in the GTM compaction mold.

Prior to sample compaction, the GTM settings were verified and adjusted as needed. The operational aspects of the GTM have been thoroughly discussed in the literature (Ruth and Schaub, 1965; 1968: Ruth and Tia, 1994) leading to the selection of the test settings used in this research. The ram pressure was set at 100 psi, air roller pressure set to 9 psi, and the gyratory angle was set to 3°. The height dial gauge was calibrated using a 2.5-inch test block.

Testing consisted of placing each sample in the gyratory compactor and compacting it to the desired number of revolutions. Duplicate samples of the materials were tested at levels of 25, 50 and 100 revolutions. Also, the air roller pressure and sample height were recorded during compaction in order to calculate the gyratory shear during the test. After compaction, each sample was removed from the GTM and a wet sieve analysis was performed to obtain the post-test gradation. The wet sieve analysis (FM 1-T-030) consisted of the washing and subsequent drying of the degraded aggregate prior to the mechanical separation by sieve. This completed the compaction testing procedure for one sample.

Initial degradation percent passing values for the Hawthorne-Suwannee unconformity chert at 25 revolutions for the 1/2" sieve was 58.17 percent and 15.09 percent for the 3/8" sieve (Figures 6-1 to 6-3). These values increased to 58.76 percent and 19.26 percent, respectively at 200 revolutions. It appears the majority of the chert degradation takes place between 50 and 100 revolutions. There was, however, very little increase in minus 200 material produced after breakdown of the initial sized material.

Initial degradation values for the Avon Park Limestone at 25 revolutions were 61.85 percent passing the 1/2" sieve and 25.75 percent passing the 3/8" sieve. These values increased to 68.12 percent and 37.63 percent, respectively, at 200 revolutions. Degradation of the Avon Park Limestone appears to be evenly distributed from 25 to 100 revolutions. There is, however, an increase in minus 200 material from 1.93 percent to 2.87 percent from 50 to 100 revolutions.

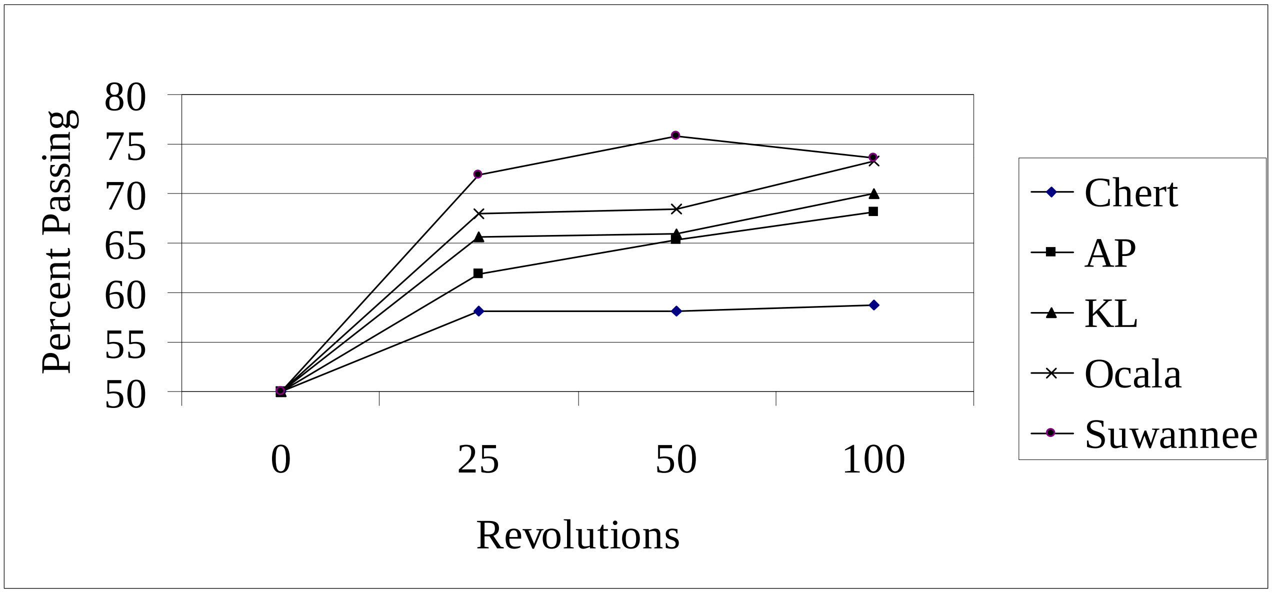


Figure 6-1: Wet aggregate comparison: passing 1/2" sieve.

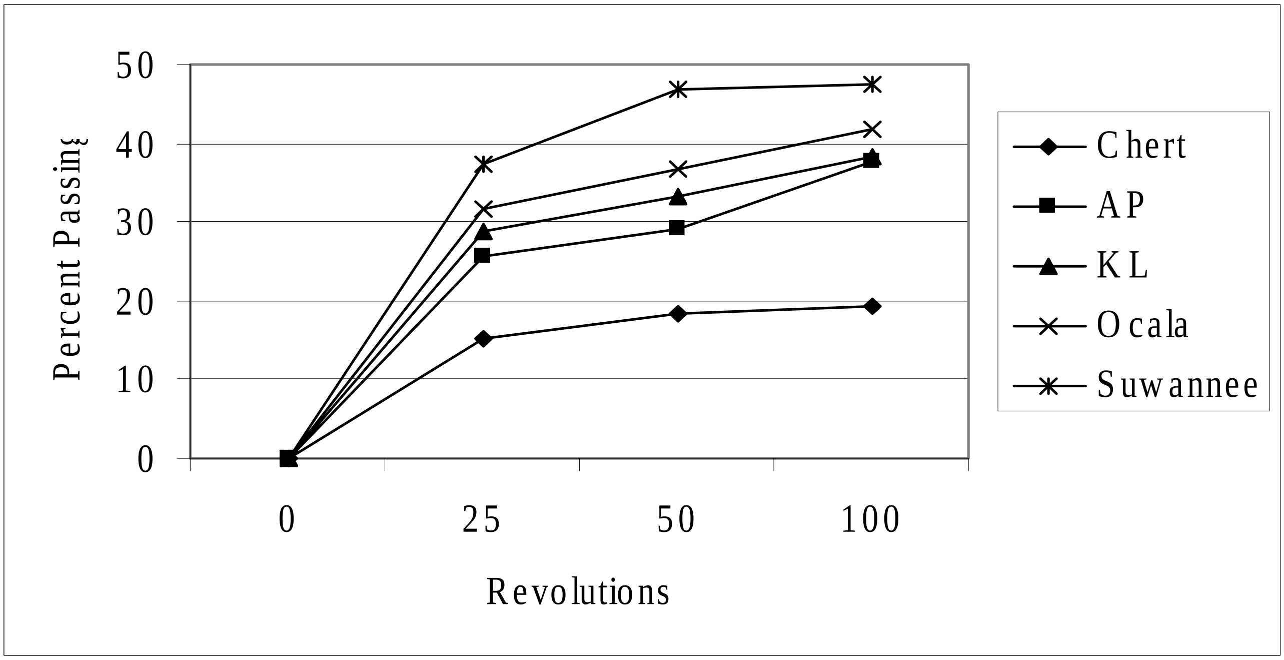


Figure 6-2: Wet aggregate comparison: passing 3/8" sieve.

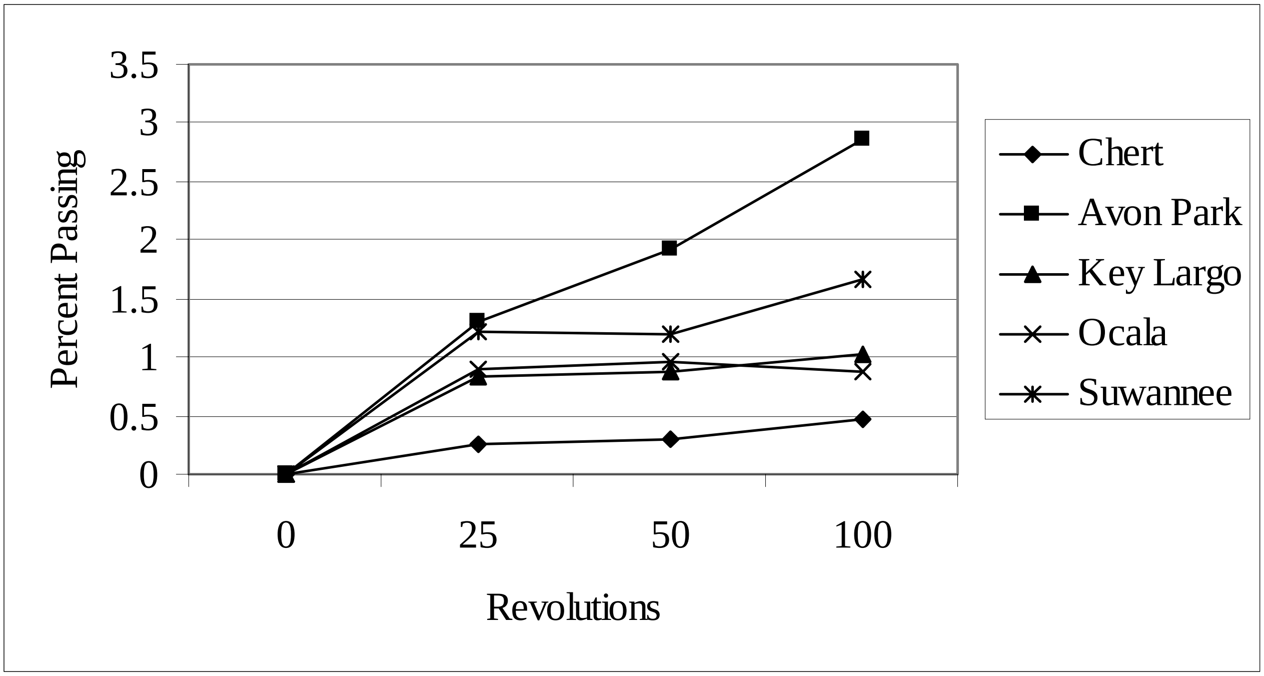


Figure 6-3: Wet aggregate comparison: passing 200-mesh sieve.

The percent passing values for the Key Largo Limestone at 25 revolutions were 65.69 percent for the 1/2” sieve and 28.77 percent for the 3/8” sieve. These values increased to 70.07 percent and 38.24 percent, respectively, at 200 revolutions. The majority of the Key Largo Limestone degradation appears to occur between 50 and 100 revolutions. There is a slight increase in the amount of minus 200 material produced as revolutions increased.

Initial degradation values for the Ocala Limestone at 25 revolutions were 67.91 percent passing the 1/2” sieve and 31.75 percent passing the 3/8” sieve. These values increased to 73.29 percent and 41.63 percent, respectively, at 200 revolutions. The majority of aggregate degradation for the Ocala Limestone occurs between 50 and 100 revolutions. There is a slight increase in the amount of minus 200 material produced as revolutions increased.

The percent passing values for the Suwannee Limestone at 25 revolutions were 71.86 percent passing the 1/2” sieve and 37.33 percent passing the 3/8” sieve. These values increased to 75.83 percent for the 1/2” sieve at 50 revolutions and 47.52 percent for the 3/8” sieve at 100 revolutions. Since the largest amount passing the 1/2” sieve occurs at 50 revolutions, it appears that the majority of the degradation of the Suwannee Limestone occurs between 25 and 50 revolutions. There is a nominal increase in minus 200 material produced as revolutions are increased. The summarized average results for the gyratory testing are presented in Tables 6-1 through 6-5

The Suwannee-Hawthorn unconformity chert showed the least amount of degradation at 25 revolutions for the 1/2” and 3/8” material. In both sizes the Suwannee Limestone exhibited the most breakdown at 25 revolutions. At 200 revolutions the chert sample also showed the least amount of breakdown. The highest degradation at 200 revolutions occurred in the Suwannee Limestone for both sizes, but was equivalent with the Ocala Limestone for the 1/2” material. At 25 revolutions, the chert also showed the best performance with 0.26 percent passing the No. 200 sieve.

Table 6-1. Suwannee Limestone Average GTM Test Results

% Retained				
Sieve Size	0	25	50	100
1/2	50	28.15	24.17	26.34
3/8	50	34.53	29.06	26.15
#4	0	21.26	24.24	23.01
#10	0	7.27	9.31	9.99
#40	0	5.27	8.23	8.47
#80	0	1.24	2.19	2.51
#200	0	1.09	1.60	1.89
Pan	0	1.19	1.44	1.66

% Passing				
Sieve Size	0	25	50	100
1/2	50	71.86	75.83	73.67
3/8	0	37.33	46.77	47.52
#4	0	16.07	22.53	24.52
#10	0	8.80	13.22	14.53
#40	0	3.54	4.99	6.06
#80	0	2.30	2.80	3.55
#200	0	1.21	1.20	1.66
Pan	0	0.00	0.00	0.00

Table 6-2. Avon Park Limestone Average GTM Test Results

% Retained				
Sieve Size	0	25	50	100
1/2	50	38.16	34.71	31.88
3/8	50	36.10	36.27	30.50
#4	0	15.75	16.88	20.43
#10	0	4.87	5.35	7.11
#40	0	2.76	3.43	5.13
#80	0	0.56	0.74	1.14
#200	0	0.51	0.71	0.96
Pan	0	1.27	1.90	2.85

% Passing				
Sieve Size	0	25	50	100
1/2	50	61.85	65.30	68.12
3/8	0	25.75	29.03	37.63
#4	0	10.00	12.15	17.20
#10	0	5.13	6.80	10.09
#40	0	2.37	3.38	4.97
#80	0	1.82	2.64	3.83
#200	0	1.30	1.93	2.87
Pan	0	0.00	0.00	0.00

Table 6-3. Key Largo Limestone Average GTM Test Results

% Retained				
Sieve Size	0	25	50	100
1/2	50	34.31	34.14	29.94
3/8	50	36.92	32.74	31.83
#4	0	17.77	20.49	22.12
#10	0	5.08	5.74	7.19
#40	0	3.30	3.89	5.07
#80	0	0.94	1.15	1.56
#200	0	0.86	0.99	1.26
Pan	0	0.82	0.89	1.03

% Passing				
Sieve Size	0	25	50	100
1/2	50	65.69	65.86	70.07
3/8	0	28.77	33.12	38.24
#4	0	11.01	12.63	16.12
#10	0	5.93	6.89	8.93
#40	0	2.63	3.01	3.86
#80	0	1.69	1.85	2.31
#200	0	0.83	0.87	1.05
Pan	0	0.00	0.00	0.00

Table 6-4. Ocala Limestone Average GTM Test Results

% Retained				
Sieve Size	0	25	50	100
1/2	50	32.10	31.56	26.71
3/8	50	36.16	31.69	31.66
#4	0	20.32	22.44	24.60
#10	0	5.11	6.63	7.67
#40	0	3.27	4.30	5.53
#80	0	1.18	1.36	1.70
#200	0	0.98	1.07	1.26
Pan	0	0.89	0.96	1.12

% Passing				
Sieve Size	0	25	50	100
1/2	50	67.91	68.44	73.29
3/8	0	31.75	36.75	41.63
#4	0	11.43	14.32	17.03
#10	0	6.33	7.69	9.36
#40	0	3.06	3.39	3.83
#80	0	1.88	2.03	2.14
#200	0	0.90	0.96	0.88
Pan	0	0.00	0.00	0.00

Table 6-5. Chert Average GTM Test Results

% Retained				
Sieve Size	0	25	50	100
1/2	50	41.84	41.94	41.25
3/8	50	43.08	39.63	39.50
#4	0	10.34	13.64	12.46
#10	0	2.73	2.73	3.50
#40	0	1.37	1.38	2.16
#80	0	0.24	0.23	0.39
#200	0	0.17	0.17	0.29
Pan	0	0.24	0.24	0.42

% Passing				
Sieve Size	0	25	50	100
1/2	50	58.17	58.07	58.76
3/8	0	15.09	18.44	19.26
#4	0	4.76	4.80	6.80
#10	0	2.03	2.07	3.30
#40	0	0.67	0.69	1.15
#80	0	0.43	0.47	0.76
#200	0	0.26	0.30	0.47
Pan	0	0.00	0.00	0.00

Unconfined Compressive Strength

Unconfined compressive strength of rock is often used as an index property indicative of the mechanical durability of an aggregate type. Each of the rock cores that were created as part of the modified absorption testing was subsequently subjected to compressive strength testing. The Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens (ASTM D 2938) was the general guideline used for conducting the testing. The ends of each rock core were machined flat using a rock saw and lapping wheel. The cores were subsequently dried to constant weight and placed in the loading device. A constant axial load was placed on each core and continuously increased until peak load and failure values were obtained. All data was collected by a personal computer that was attached to the loading device platens.

The compressive strength from each test specimen was calculated from the maximum compressive load on the rock core and the initial computed cross-sectional area as follows:

$$\boldsymbol{\sigma = P / A}$$

where: σ = Compressive strength

P = Maximum load

A = Cross-sectional area

Based upon this formula, the unconfined compressive strength was computed for each tested rock core. The results are tabulated in Table 6-6.

Table 6-6. Unconfined compression strength results.

Sample ID	Rock Type	Maximum Load (lbs)	Cross-Sectional Area (in^2)	Compressive Strength (psi)
AP-1	Avon Park Limestone	1,804	0.785	2,297
AP-2	Avon Park Limestone	4,228	0.785	5,383
AP-3	Avon Park Limestone	5,133	0.785	6,536
AP-4	Avon Park Limestone	3,068	0.785	3,906
O-1	Ocala Limestone	2,751	0.785	3,503
O-2	Ocala Limestone	1,313	0.785	1,672
O-3	Ocala Limestone	2,746	0.785	3,496
O-4	Ocala Limestone	3,579	0.785	4,557
O-7	Ocala Limestone	2,739	0.785	3,487
S-1	Suwannee Limestone	1,855	0.785	2,362
S-2	Suwannee Limestone	3,981	0.785	5,069
S-4	Suwannee Limestone	3,090	0.785	3,934
KL-1	Key Largo Limestone	1,723	0.785	2,194
KL-2	Key Largo Limestone	2,295	0.785	2,922
KL-3	Key Largo Limestone	2,009	0.785	2,558
KL-4	Key Largo Limestone	1,750	0.785	2,228
C-2	Chert	>10,000	0.785	>12,732

CHAPTER 7
SLAKE DURABILITY TESTING

Slake durability refers to the resistance of a stone to weakening and disintegration from a standard cycle of wetting and drying (Franklin and Chandra, 1972). This test evaluates the slaking resistance of clay-bearing rocks and predicts deterioration potential due to cyclic wetting and drying. This test was developed in 1972 by Franklin and Chandra and is the accepted method of determining slake durability. The test aims to accelerate physical breakdown of test material by combining the processes of slaking and sieving. As the samples disintegrate, the new surfaces that are formed are immediately subjected to additional slaking. Each of the five stones in this study was tested, in triplicate, using this test apparatus.

The slake durability test apparatus consists of two, 100-mm wide, 140-mm diameter, 2-mm standard mesh test cylinders, each equipped with a solid fixed base and a solid removable lid. The test cylinders are supported along a horizontal axis inside a trough. The trough is filled with a slaking fluid to a level 20-mm below the cylinder axes. The cylinders are mounted to allow 40-mm of unobstructed clearance between the trough and the base of the mesh. The horizontal axes of the test cylinders are in turn connected to a motor drive capable of rotating the cylinders at a speed of 20 revolutions per minute (rpm).

Sample preparation for the slake durability test consists of selecting approximately 10 aggregate lumps, each weighing 40 to 60 grams, for a total sample weight of 450 to 550 grams. The selected samples were roughly spherical in shape and rough edges were rounded prior to testing. Samples were placed inside a clean test cylinder and dried to constant weight. The weight of the drum and the sample was recorded. The lid was then placed on the test cylinder, and it was coupled to the motor. The trough was filled to a level 20-mm below the test cylinder with synthetic seawater at a temperature of 20° C to approximate rip rap field conditions. The cylinders were subsequently rotated at 20 rpm for a period of 10 minutes. Following the first test cycle, the cylinders were removed from the trough, the lids removed, and the samples dried to constant weight. The weight of the cylinder and the retained material was recorded and the procedure repeated. After two cycles, the weight of the cylinder and the retained material was recorded. Finally, the cylinders were cleaned and the empty weights recorded. After testing was completed, the slake durability index for two cycles was calculated as the percentage ratio of final to initial dry sample weights as indicated below:

$$\textbf{Slake durability index, } I_{d2} = (C - D / A - D) \times 100\%$$

where: A = Initial dry weight of sample and cylinder

C = Second cycle dry weight of sample and cylinder

D = Dry weight of clean, empty cylinder

The results of the slake durability testing are shown in Table 7-1.

Because the primary purpose of a slake durability test is to evaluate the breakdown resistance of clay-bearing rocks, acid insoluble residue testing and petrographic assessments also were performed on the stones included in this study. Petrographic assessments were performed in conjunction with the aforementioned development of a PN system for rip rap aggregates. Clays were assigned a FW of 6.0 due

Table 7-1. Slake durability results.

Sample Type	Slake Durability Index
Ocala #1	97.35
Ocala #2	98.66
Ocala #3	99.17
Ocala (Mean)	98.39
Key Largo #1	99.08
Key Largo #2	98.98
Key Largo #3	98.51
Key Largo (Mean)	98.86
Avon Park #1	99.45
Avon Park #2	98.09
Avon Park #3	99.14
Avon Park (Mean)	98.89
Suwannee #1	98.99
Suwannee #2	99.29
Suwannee #3	99.40
Suwannee (Mean)	99.23
Chert #1	99.68
Chert #2	99.76
Chert #3	99.52
Chert (Mean)	99.65

to their deleterious impact on durability; however, no clays were identified during the PN point counts. The petrographic assessment was further validated by acid insoluble residue testing. Insoluble residues of limestones and dolomites are the non-carbonate materials that remain behind after dissolving the rock in hydrochloric acid. The most common residues are quartz, chert, clay and pyrite.

The procedure for acid insoluble residue testing involved soaking an approximately 20 gram sample for 24 hours in a solution of 2 N hydrochloric acid. After the soaking cycle, the acid was decanted and the sample was transferred to a plastic bottle and filled with distilled water. The residue sample was then centrifuged for a period of 10 minutes to separate the solid and liquid phases of the sample. After the centrifuge cycle, the liquid was decanted and the residue was washed with distilled water. Washing and centrifuging was repeated three times for each sample. After the final washing cycle, the insoluble fraction was transferred to a drying dish, dried at 110 °C for 8 hours, cooled to room temperature, and weighed. The percent of acid insolubles was calculated using the weight of the insoluble fraction divided by the starting weight. The results are shown in Table 7-2.

Table 7-2. Acid insoluble residue testing results.

Sample Type	Sample Weight (g)	Residue Weight (g)	Percent Insolubles
Ocala Limestone	20.00	0.35	1.75
Key Largo Limestone	20.00	3.94	18.8
Avon Park Limestone	20.00	0.33	1.65
Suwannee Limestone	20.00	0.13	0.65
Gray Chert	20.00	15.37	76.5

CHAPTER 8

MODIFIED SODIUM SULFATE SOUNDESS TESTING

Sodium sulfate soundness testing is performed by repeated immersions of aggregate samples in a saturated solution of sodium sulfate alternating with oven drying to precipitate the salt in permeable pore spaces. This test method is considered a simulation of the action of freeze-thaw cycles, and is used to characterize the physical and chemical durability of aggregates. The primary method of failure is internal tensile stress that develops during wetting and drying of the surfaces of the aggregate particles (Minty and Smith, 1980). This internal tensile force is thought to result from the step-wise rehydration of salt precipitated in the permeable pore spaces upon re-immersion in a saturated solution (Minty and Smith, 1980; Ping and Beaudoin, 1992; Forster, 1994).

One problem associated with sodium sulfate soundness testing is the precision of test results. The failure to achieve good precision may result from differences in materials and/or procedures used to conduct the tests. Some of these factors are listed below, illustrating a lack of ruggedness of the sodium sulfate soundness procedure.

1. Temperature of the solution; the solubility of $NaSO_4$ is very temperature dependent.
2. Temperature variation of the solution during testing.
3. Temperature of samples at time of immersion after oven drying.
4. Temperature variation and rate of drying oven.
5. Design of containers used for immersing samples.
6. Age of the sodium sulfate solution
7. Chemical grade of sulfate used to create solution.
8. Purity of water used to create solution.

9. Reactivity of the tested aggregate with sodium sulfate solution

In response to many of these problems, the Illinois Department of Transportation (IDOT) conducted an evaluation program to identify and correct major problem areas of the ASTM/AASHTO test methods (Sheftick, 1989). The IDOT testing program revealed temperature control during all phases of testing to be the most important problem area. This is, however, the most difficult variable to control. The IDOT research showed the effect of temperature on the saturation curve of sodium sulfate. The soaking solution used for testing is saturated at 21 °C with no additional sodium sulfate present. As a result, any rise in soaking temperature causes the solution to lose saturation and may result in the dissolution of sodium sulfate crystals already deposited in the pores of aggregate samples. Temperature variations can occur with natural temperature fluctuations within the room used for testing or from placing samples that have not cooled to 21 °C back into the soaking the solution. The result is the reduction in sample breakdown with a resulting decrease in soundness values (Sheftick, 1989).

In an effort to reduce the time required for testing and to improve precision, this research evaluated some modifications of the Florida Method of Test for Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate (FM 1-T 104). The first modification involved the construction of an accelerated wet-dry test device (Figures 8-1 and 8-2). This device consisted of a 14-inch diameter plastic wheel equipped with eight testing axles. The wheel was horizontally mounted over a stainless steel trough that contained the immersion solution. The wheel was connected to a one-revolution-per-hour clock motor. High-intensity heat lamps were located around the exposed portion of the wheel for sample drying between immersion cycles. The 24 wet/dry cycles per day

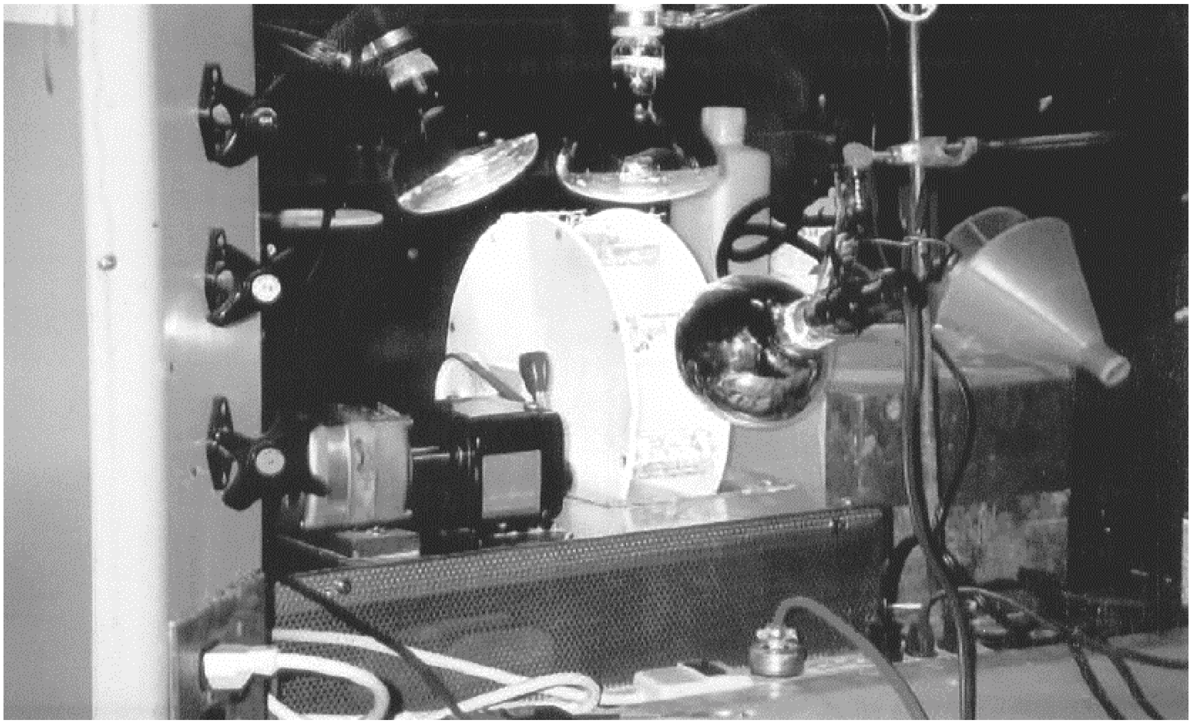


Figure 8-1: View of accelerated weathering tester in operation.

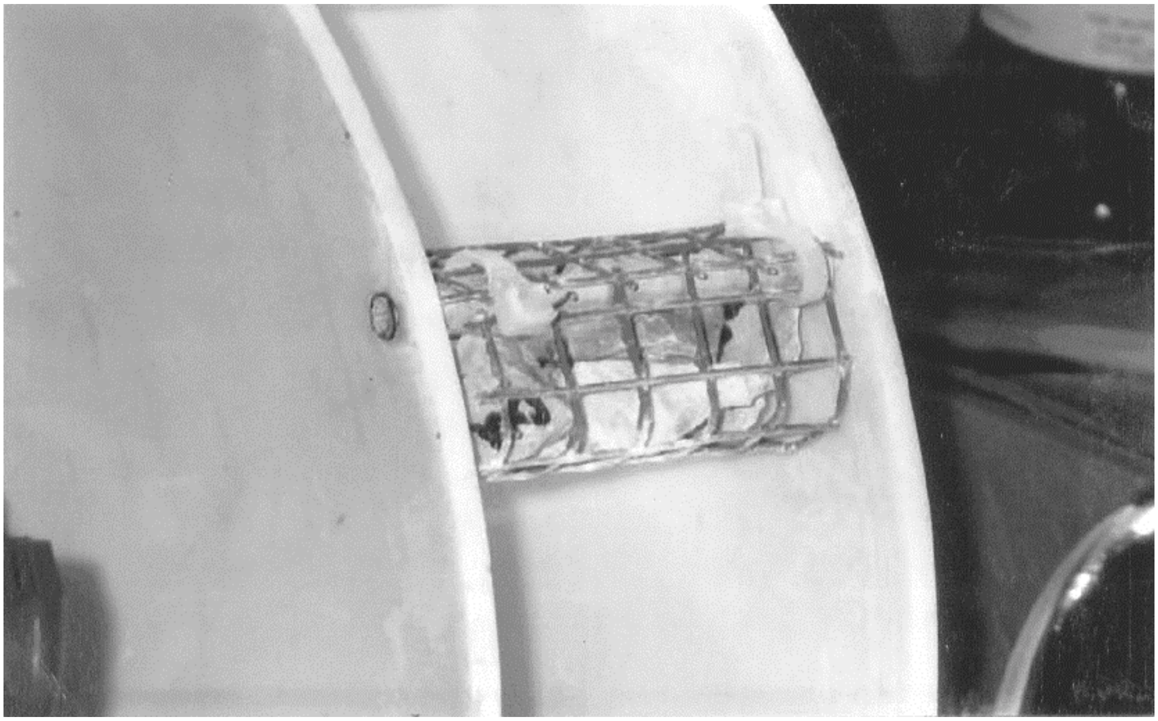


Figure 8-2: Close up view of aggregate samples mounted on accelerated weathering tester.

allowed the equivalent of approximately one month of exposure to be simulated in one day.

The first modified soundness test evaluated with the accelerated weathering test device involved the use of a saturated solution of synthetic seawater in the immersion trough of the device. An excess of salt crystals was maintained in the bottom of the immersion tank to ensure saturation of the solution throughout the testing cycle. Synthetic seawater was chosen to replace sodium sulfate because of its lack of temperature sensitivity and its greater crystallization energy. Seawater is also more representative of in-service conditions encountered by rip rap materials.

Replicate tests were made on portions of the five tests stones resulting in thirty one tests (Table 8-1). Representative stone sub-samples were attached to the testing axles using plastic-coated screen mesh and plastic cable ties. The samples ranged in size from approximately 5 to 20 grams in weight. Duplicate tests were conducted, each lasting 30 days. This testing length simulated almost two years of exposure time. Results from this testing appear in Table 8-1. After synthetic seawater testing in the accelerated weathering device, sodium sulfate solution was used in the immersion tank of the test device. A saturated solution of sodium sulfate was placed in the testing tank; crystals were maintained in the bottom of the tank to ensure saturation maintenance throughout the testing cycle. As with the synthetic seawater testing, duplicate tests of 31 aggregate samples were performed for a period of 30 days. The aggregate samples, from each of the five tested materials, ranged in size from approximately 5 to 20 grams in weight. The results of this testing effort appear in Table 8-2.

Table 8-1. 30-Day saturated synthetic seawater accelerated weathering test results.

Sample ID	Dry Weight (before testing)	Dry Weight (after testing)	Percent Loss
AP-1	12.94	12.94	0.00
AP-2	11.19	11.19	0.00
AP-3	8.38	7.59	9.43
AP-4	8.28	8.28	0.00
KL-1	11.65	11.59	0.52
KL-2	10.64	10.51	1.22
KL-3	11.44	11.18	2.27
KL-4	9.78	9.78	0.00
S-1	16.93	16.91	0.12
S-2	15.86	14.89	6.12
S-3	11.64	11.64	0.00
S-4	14.54	13.83	4.88
S-5	8.96	8.96	0.00
OI-1	14.97	14.97	0.00
OI-2	5.56	5.56	0.00
OI-3	5.04	5.03	0.20
OI-4	8.69	8.66	0.35
OU-1	8.82	8.64	2.04
OU-2	6.98	6.98	0.00
OU-3	7.16	7.16	0.00
OU-4	12.38	12.38	0.00
PC-1	14.13	14.13	0.00
PC-2	11.78	11.78	0.00
PC-3	7.86	7.86	0.00
PC-4	6.63	6.63	0.00
PC-5	8.85	8.85	0.00
BC-1	10.60	10.60	0.00
BC-2	21.83	21.83	0.00
BC-3	15.34	15.34	0.00
BC-4	22.31	22.31	0.00
GC-1	20.19	20.19	0.00

KEY:
AP = Avon Park
KL = Key Largo
S = Suwannee
OI = Ocala (indurated)
OU = Ocala (unindurated)
GC = Gray Chert
PC = Pink Chert
BC = Blue Chert

Table 8-2. 30-Day saturated $NaSO_4$ accelerated weathering test results.

Sample ID	Dry Weight (before testing)	Dry Weight (after testing)	Percent Loss
AP-1	12.94	12.78	1.24
AP-2	11.19	11.12	0.63
AP-3	7.59	7.59	0.00
AP-4	8.28	8.28	0.00
KL-1	11.59	11.33	2.24
KL-2	10.51	10.51	0.00
KL-3	11.18	11.16	0.18
KL-4	9.78	9.75	0.31
S-1	16.91	16.77	0.83
S-2	14.89	14.89	0.00
S-3	11.64	11.64	0.00
S-4	13.83	13.83	0.00
S-5	8.96	8.95	0.11
OI-1	14.97	14.97	0.00
OI-2	5.56	5.49	1.26
OI-3	5.03	5.02	0.20
OI-4	8.66	8.61	0.58
OU-1	8.64	8.64	0.00
OU-2	6.98	6.98	0.00
OU-3	7.16	7.11	0.70
OU-4	12.38	12.33	0.40
PC-1	14.13	14.13	0.00
PC-2	11.78	11.78	0.00
PC-3	7.86	7.86	0.00
PC-4	6.63	6.63	0.00
PC-5	8.85	8.85	0.00
BC-1	10.60	10.60	0.00
BC-2	21.83	21.79	0.18
BC-3	15.34	15.28	0.39
BC-4	22.31	22.31	0.00
GC-1	20.19	20.19	0.00

KEY:
AP = Avon Park
KL = Key Largo
S = Suwannee
OI = Ocala (indurated)
OU = Ocala (unindurated)
PC = Pink Chert
BC = Brown Chert
GC = Gray Chert

The second modification of the sodium sulfate soundness test involved an attempt to streamline the testing process and eliminate many of the complexities associated with testing. The first change involved a modification of aggregate sample size. FM 1-T 104 requires a total of 7,800 grams of sample, ranging in size from 3/8” to 2-1/2”, for each testing trial. Because this test is for rip rap, this research selected a reduced size range from 3/4” to 2-1/2”. The sample set was composed of a total of 2,000 grams of sample. Each sample set was composed of 500 grams of 1” to 3/4” material, 500 grams of 2-1/2” to 1-1/2” material and 1,000 grams of 1-1/2” to 1” material. The second major modification involved the testing procedure itself. Because temperature and humidity-controlled testing cabinets are not readily available, this research used large coolers to accommodate the sodium sulfate solution and the sample sets. Each testing cooler was filled with enough sodium sulfate solution to cover the aggregate samples by approximately 1/2". Temperature checks conducted throughout testing of the solution in the coolers revealed good temperature control to ± 2.8 °C (5°F). In addition, excess sodium sulfate crystals were placed into the testing coolers throughout the test procedures to ensure maintenance of a supersaturated solution regardless of temperature variation. Also, oven dried samples were allowed to cool to a temperature of 70°F (21°C) before re-immersion in the test solution. This prevented warm samples from raising the temperature of the test solution above 70° F.

Three separate trials were conducted of each of the five tested aggregate materials. The averaged results are presented in Table 8-3.

Table 8-3. Modified sodium sulfate soundness results.

Material	Soundness Loss	Standard Deviation
Ocala Limestone	12.72	3.8
Key Largo Limestone	13.40	2.2
Avon Park Limestone	4.91	0.7
Suwannee Limestone	10.17	2.8
Chert	4.68	2.4

CHAPTER 9
RIP RAP RATING SYSTEM

The process involved in evaluating a potential source of rip rap of good quality is a complex process. Steps in the process may involve evaluation of a quarry, production methods, laboratory and field testing of the processed stone, mode and distance of transportation, and placement methods (Lienhart, 1998). This process can be viewed as a rock engineering system. In 1998, D.A. Lienhart developed a rock engineering interaction matrix in order to simplify an understanding of how various factors affecting the quality of a potential rip rap source were interrelated. The result was a weighted rock engineering rating system to determine the suitability of various rip rap sources.

Lienhart's rock engineering rating system was designed with three interaction matrices for the geological processes, production/construction processes and in-service processes that affect rip rap quality. Because a detailed quarry evaluation and construction processes were beyond the scope of this project, only in-service processes (durability tests) have been evaluated here.

In order to create a rock engineering rating system, Lienhart first examines principal factors affecting rip rap quality in terms of an interaction matrix. Hudson (1989) first proposed the use of an interaction matrix to recognize interrelationships. The interaction matrix developed for in-service (durability) properties is depicted in Figure 9-1. The site conditions process is located at the bottom right hand corner of the matrix and the principal factors that influence the process are located along the diagonal (Lienhart, 1998). The principal factors of the in-service process identified by Lienhart are petrographic features (mineral composition, grain size, texture, genetic history, presence

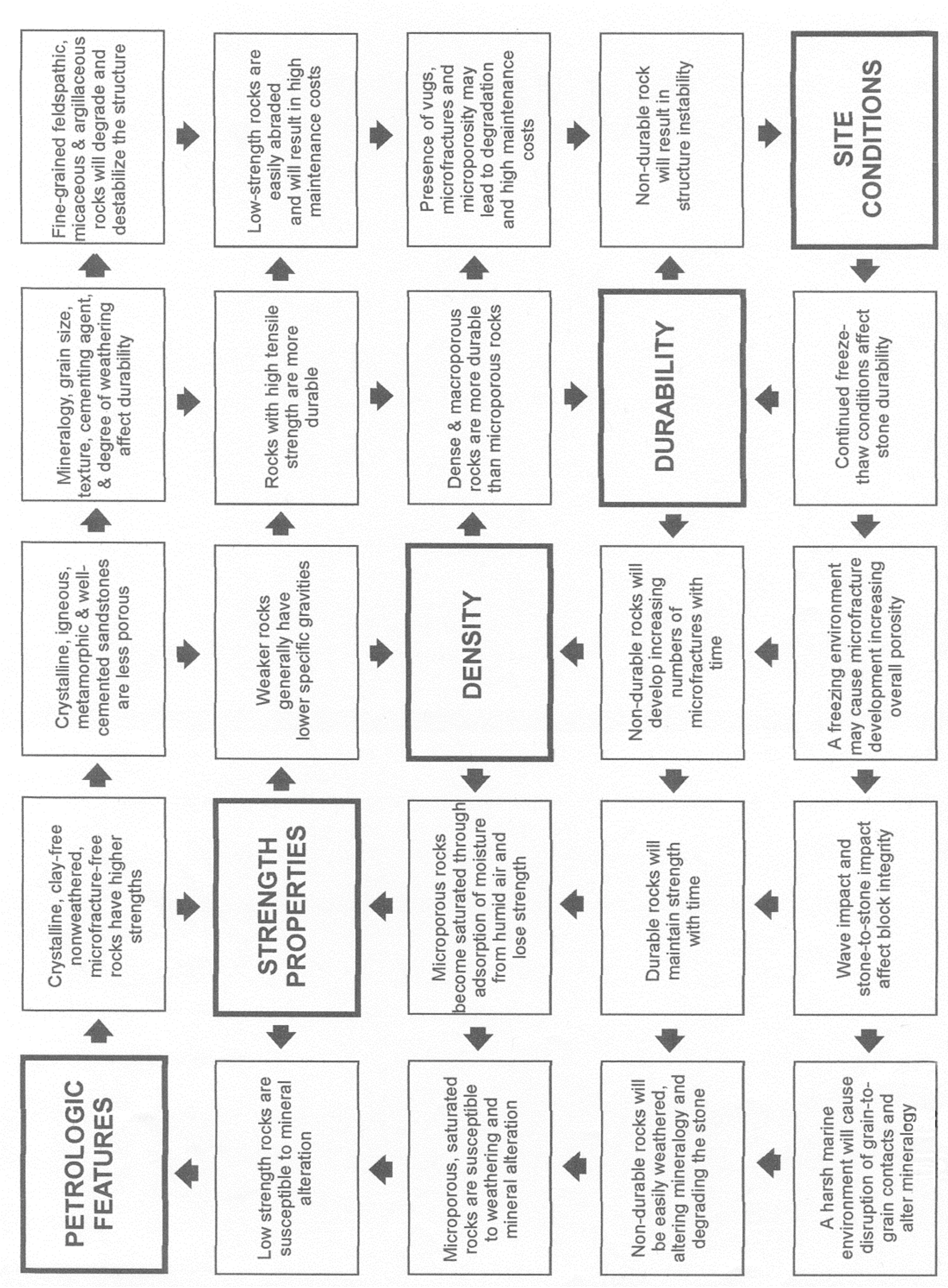


Figure 9-1. Interaction matrix for in-service properties (Lienhart, 1998)

of microfractures); strength properties (compressive strength, tensile strength, and abrasion resistance); density properties (specific gravity, absorption and microporosity) and rock durability (susceptibility to weathering action). The mechanisms of interaction affecting the principal factors have been established in the remaining portion of the matrix and the influence of an interaction of one principal factor on another is in the direction of the arrows (Lienhart, 1998).

The in-service matrix was coded using the “expert semi-quantitative” method promulgated by Hudson (1989). The system is dependent on the totals for the columns and rows, not on the specific codes. Therefore, a specific code is not critical to the evaluation of a principal factor (Hudson, 1989; Lienhart, 1998). Lienhart uses the following as a key to the specific codes: 0 = no interaction; 1 = weak interaction; 2 = medium interaction; 3 = strong interaction; and 4 = critical interaction. The interaction codes are subsequently added by rows to determine a “cause” value for each principal factor. The “effect” value for each principal factor is determined by adding the specific codes for each column (Lienhart, 1998). The result of this procedure is a relative cause- and-effect (C-E) value that is plotted as coordinate values on a cause-effect plot for in-service processes. “C” represents the method by which a principal factor affects in-service processes while “E” represents the manner in which in-service processes affect the principal factors (Lienhart, 1998). The overall result depicts the relative importance of each principal factor. The cause-effect plot for in-service processes, as determined by Lienhart, appears as Figure 9-2. Lienhart’s coding of the in-service processes is depicted in Figure 9-3. The relative importance of a principal factor can be assessed by the factor’s position on the cause-effect plot in the following manner. Factor dominance is determined by scaling the

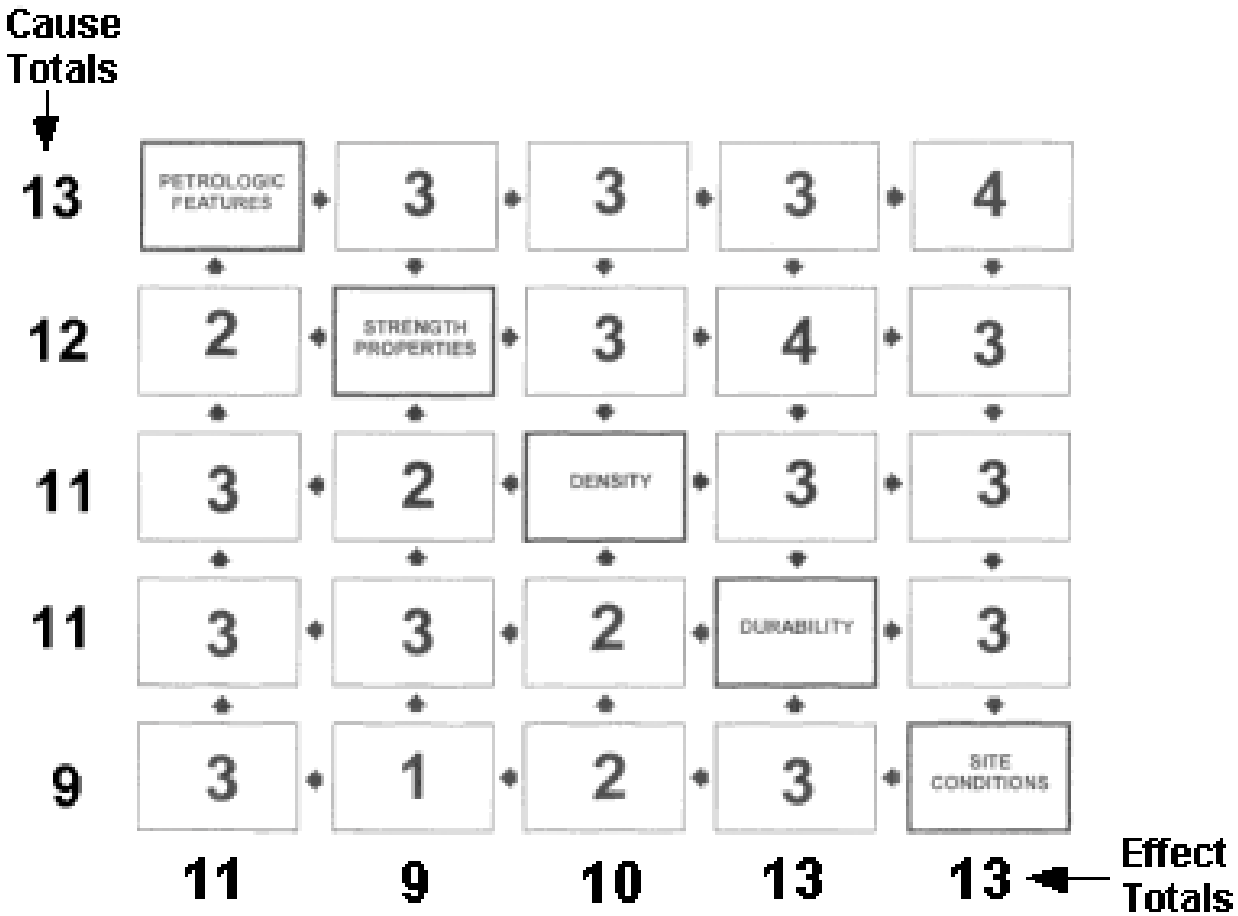


Figure 9-2. Coding of the in service properties (Lienhart, 1998).

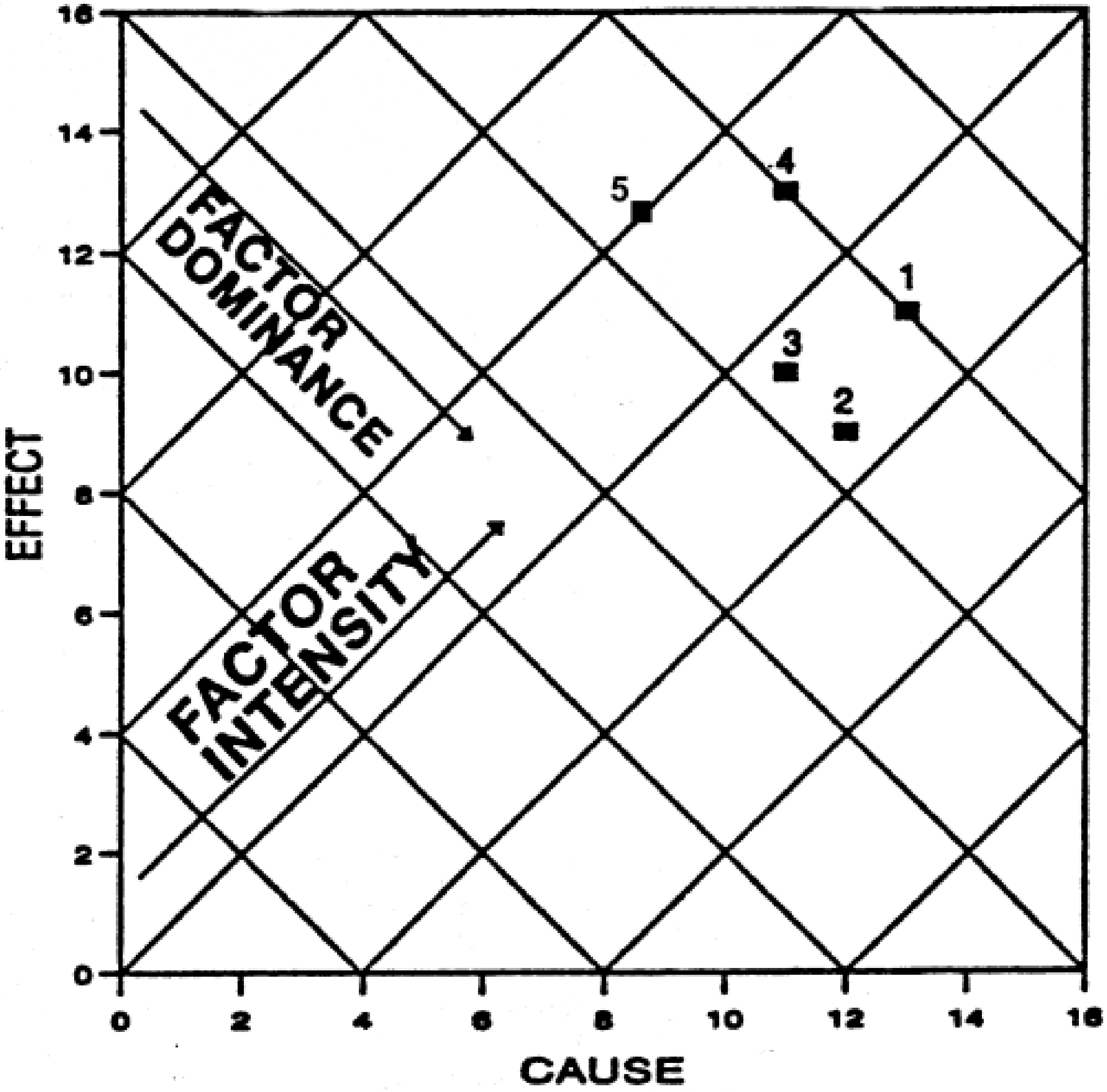


Figure 9-3. Cause-effect plot for in-service processes.

perpendicular distance from the factor point to the factor intensity line. This distance is equal to $(C - E) / 2^{½}$. If the factor line lies to the right of the factor intensity line, the factor dominance value will be positive. Conversely, if the factor line lies to the left of the factor intensity line, then the factor dominance will be negative and the factor will only affect in-service processes indirectly (Lienhart, 1998). If a point lies on the factor intensity line, cause and effect are equal. Factor intensity is measured by scaling the distance from the origin to the point at which the perpendicular from the factor point intersects the factor intensity line. This distance is equal to $(C + E) / 2^{½}$. The total vector distance (factor intensity plus factor dominance) is the factor's relative importance. This is reduced to the following equation:

$$\mathbf{(C + E) / 2^{½} + (C - E) / 2^{½} = \text{factor importance}}$$

Based upon the cause-effect plot determined for in-service processes, Lienhart determined principal factor ratings for the in-service processes affecting rip rap quality. These ratings appear in Table 9-1. According to Lienhart, the in-service processes principal factors generally show equal variation in factor intensity and dominance. Petrologic features, strength properties and density properties directly affect the performance of a potential rip rap source while durability and site conditions indirectly affect the aggregate's performance (Lienhart, 1998). In order to develop the specification system for the assessment of the potential quality of a rip rap source, Lienhart developed specific information related to rock properties that may affect performance and limits for the various qualities (excellent, good, marginal and poor) of the rock. This research has attempted to establish quality specifications for the alternative test methods evaluated as part of this study. These specifications are depicted in Table 9-2. The alternative testing standards can be divided into four groups. The first group considers the

Table 9-1. Ratings of matrix parameters: in-service processes (after Lienhart, 1998).

Matrix Parameters	Rating from Cause-Effect Plot $[(C + E) / 2^{1/2}] + [(C - E) / 2^{1/2}]$
Petrologic Features	18.38
Strength Properties	16.97
Density Properties	15.56
Durability	15.56
In-service Conditions	12.72

petrographic properties of the aggregate, the second group is related to strength properties, the third group considers density/porosity properties and the fourth group encompasses accelerated weathering durability tests.

Lienhart's proposed quality rating assessment worksheet for in-service process, modified to reflect the alternative testing procedures evaluated as part of this project, appears as Figure 9-4. Column A lists the specification criteria from Table 9-2. Column B consists of the four quality ratings where the appropriate rating is entered with a symbol based upon observations, testing or other evaluation relative to the specifications contained in Table 9-2. It should be noted that a value of zero may be entered for a particular criteria that will be especially detrimental to the long-term performance of a potential rip rap source. Column C is reserved for the appropriate numerical average of each set of quality values. Column D displays the relative importance of each criterion developed in Figure 9-1 and Table 9-1. An index based on column D values is contained in Column E. Finally, Column F contains weighted ratings of each criterion (Column c X Column e) (Lienhart, 1998).

As part of this research, the five evaluated rock types were classified using this proposed rock engineering rating system. The ratings for each stone studied are summarized in Figures 9-5 through 9-9. Examination of these ratings tables reveals a range of rating values from 2.40 to 3.44. According to these ratings, all five of the aggregate types would make marginal to good rip rap materials.

Table 9-2. Quality specifications based on rock property factor criteria.

	Quality Specification			
Criteria	Excellent	Good	Marginal	Poor
Petrographic Evaluation	*	*	*	*
Compressive Strength (psi)	> 10,000	6,000 - 10,000	6,000 - 2,000	< 2,000
Gyratory Testing	**	**	**	**
Specific Gravity	> 2.9	2.60 - 2.90	2.50 - 2.60	< 2.50
Absorption (%)	< 0.5	0.5 - 2.0	2.0 - 6.0	> 6.0
Mercury Intrusion Porosimetry	**	**	**	**
Sodium Sulfate Soundness (% loss)	< 2	2 - 10	10 - 30	> 30
Slake Durability Index (%)	95 - 100	75 - 95	25 - 75	0 - 25

NOTES:
* The petrographer must assign
aggregate to one of the categories
** Requires development of standards.
Rating is currently subjective.

Figure 9-4. Quality rating assessment worksheet: in-service processes.

(a) Criteria	(b) Quality Rating				(c) Rating Value	(d) Cause-Effect Rating	(e) Index (d/d_{mean})	(f) Weighted Rating (c) X (e)
	Excellent (=4)	Good (=3)	Marginal (=2)	Poor (=1)				
Petrographic Evaluation						18.38	1.2	
Compressive Strength Gyratory Testing						16.97	1.11	
Specific Gravity Absorption Mercury Intrusion						15.56	1.02	
Sulfate Soundness Slake Durability						15.56	1.02	

Overall Rating=	

Figure 9-5. Quality rating assessment worksheet: Suwannee Limestone

.

(a) Criteria	(b) Quality Rating				(c) Rating Value	(d) Cause-Effect Rating	(e) Index (d/d_{mean})	(f) Weighted Rating (c) X (e)
	Excellent (=4)	Good (=3)	Marginal (=2)	Poor (=1)				
Petrographic Evaluation		✓			3	18.38	1.2	3.8
Compressive Strength		✓	✓		2.5	16.97	1.11	2.78
Gyratory Testing								
Specific Gravity				✓	1.67	15.56	1.02	1.7
Absorption			✓					
Mercury Intrusion			✓					
Sulfate Soundness			✓		3	15.56	1.02	3.06
Slake Durability	✓							

Overall Rating=	2.78

Figure 9-6. Quality rating assessment worksheet: Avon Park Limestone.

(a) Criteria	(b) Quality Rating				(c) Rating Value	(d) Cause-Effect Rating	(e) Index (d/d_{mean})	(f) Weighted Rating (c) X (e)
	Excellent (=4)	Good (=3)	Marginal (=2)	Poor (=1)				
Petrographic Evaluation		✓			3	18.38	1.2	3.6
Compressive Strength		✓	✓		2.5	16.97	1.11	2.78
Gyratory Testiing								
Specific Gravity			✓		2.33	15.56	1.02	2.39
Absorption			✓					
Mercury Intrusion		✓						
Sulfate Soundness		✓			3.5	15.56	1.02	3.57
Slake Durability	✓							

Overall Rating=	3.08

Figure 9-7. Quality rating assessment worksheet: Key Largo Limestone.

(a) Criteria	(b) Quality Rating				(c) Rating Value	(d) Cause-Effect Rating	(e) Index (d/d_{mean})	(f) Weighted Rating (c) X (e)
	Excellent (=4)	Good (=3)	Marginal (=2)	Poor (=1)				
Petrographic Evaluation			✓		2	18.38	1.2	2.40
Compressive Strength			✓		2.5	16.97	1.11	2.78
Gyratory Testing		✓						
Specific Gravity				✓	1.33	15.56	1.02	1.37
Absorption			✓					
Mercury Intrusion				✓				
Sulfate Soundness			✓		3	15.56	1.02	3.06
Slake Durability	✓							

Overall Rating=	2.40

Figure 9-8. Quality rating assessment worksheet: Ocala Limestone.

(a) Criteria	(b) Quality Rating Excellent (=4)	Good (=3)	Marginal (=2)	Poor (=1)	(c) Rating Value	(d) Cause-Effect Rating	(e) Index (d/d_{mean})	(f) Weighted Rating (c) X (e)
Petrographic Evaluation			✓		3	18.38	1.2	2.4
Compressive Strength Gyratory Testing			✓		2.5	16.97	1.11	2.78
		✓						
Specific Gravity Absorption Mercury Intrusion		 ✓ 	✓ ✓		1.67	15.56	1.02	2.39
Sulfate Soundness Slake Durability	 ✓		✓ 		3	15.56	1.02	3.06

Overall Rating=	2.66

Figure 9-9. Quality rating assessment worksheet: Gray Chert.

(a) Criteria	(b) Quality Rating Excellent (=4)	Good (=3)	Marginal (=2)	Poor (=1)	(c) Rating Value	(d) Cause-Effect Rating	(e) Index (d/d_{mean})	(f) Weighted Rating (c) X (e)
Petrographic Evaluation			✓		2	18.38	1.2	3.6
Compressive Strength	✓				2.5	16.97	1.11	3.89
Gyratory Testing		✓						
Specific Gravity				✓	1.67	15.56	1.02	2.72
Absorption		✓						
Mercury Intrusion	✓							
Sulfate Soundness		✓			3	15.56	1.02	3.57
Slake Durability	✓							

Overall Rating=	3.44

CHAPTER 10
DISCUSSION OF RESULTS

Results of the modified absorption testing indicate that significant increases in absorption values are realized when using the vacuum extraction method. As a result, absorption values more representative of the maximum absorption values desired for rip rap can be obtained without significantly altering the time or expense required for testing. A comparison between values obtained from the current absorption test method and the alternative vacuum extraction method is shown in Table 3-3.

Results of the synthetic seawater testing indicate lower average absorption values for the current and modified test methods. The vacuum extraction method, however, did produce significantly higher average absorption values than the soak-only test method. A comparison of the two methods (Table 3-6) shows lower average absorption values for tests using synthetic seawater compared to results using distilled water (with or without vacuum treatment). This is likely the result of the dissolved solids in the synthetic seawater increasing the viscosity of the fluids attempting to enter the smaller pore spaces of the rock samples. Although synthetic seawater testing closely approximates field conditions, its does not result in the low moisture absorption values thought to be indicative of durability in the testing of rip rap stones destined for use in engineered structures. Physical properties of the synthetic seawater, such as increased viscosity, may decrease its access to small pores. Therefore, in order to produce data to be used in engineering designs, absorption testing with synthetic seawater is not recommended.

Absorption tests made with distilled water/methanol testing produced the lowest average values of the methods evaluated (Table 3-9). It was anticipated that decreasing the surface tension would increase the pore velocity of the test solution, resulting in an increase in average absorption values. Methanol has a low surface tension and is completely miscible in water. Surface tension is a condition existing at the free surface of a liquid, resembling the properties of an elastic membrane under tension. The tension is the result of intermolecular forces exerting an unbalanced inward pull on the individual surface molecules. The tendency of any liquid surface is to become as small as possible as a result of this tension. The addition of liquid soap, which has a surface tension comparable to methanol, to water reduces the overall surface tension. Since water molecules do not bond as strongly with soap molecules as they do with themselves, the bonding force that enables the molecules to behave like an elastic membrane is weaker. The addition of methanol to distilled water should decrease the overall surface tension of the liquid, thereby allowing the solution to fully penetrate more of the pore spaces of the stones. Test results, however, did not confirm this result. Possible weaknesses of this method may be stereochemical effects between the larger methanol and the smaller water molecules, differences in charge distribution across two dipolar molecules, formation of methanol vapors under vacuum resulting in blocked pores, and competing methods of absorption between the two different molecules (i.e., electrostatic for water and dielectric for methanol).   A series of additional tests using ethanol, propanol, and butanol and water might clarify the mechanism. The methanol-water testing procedure is not recommended for rip rap aggregate testing.

The FDOT has a bulk specific gravity specification (2.3) for materials used on banks and shores. The results reported here place the five stones tested in this study in the fair to poor category established by Lienhart et al. (1995). These authors evaluated 125 samples of limestone and dolomite, and proposed the following index property specification for the specific gravity of limestone:

Poor: < 2.50 Fair: 2.50 – 2.65 Good: >2.6

Florida materials tested appear in the lower categories of this classification scheme. Because specification limits based on index properties can often vary according to rock type, these preliminary results should be viewed only as a first step (Lienhart et al., 1995). Additional testing of full broad range of stones subsamples (rather than individual cores) should be completed to develop a complete specific gravity database for Florida materials. Only after the development of such a database can a specification for specific gravity be proposed for Florida materials to be used as rip rap.

Petrographic studies showed that Suwannee Limestone, Avon Park Limestone, and chert from the Suwannee-Hawthorn unconformity had the lowest porosity values, and the lowest PN values, ranging from 111.5 to 118.2, of the stones in this study (Table 4-1). Conversely, more porous Ocala Limestone and Key Largo Limestone had much higher PN values of 135.2 and 139.5, respectively. PN results indicate that stones with PN values less than 120 would be expected to have generally good field performance, while those aggregates with PN values greater than 130 would be expected to perform poorly under field conditions. Aggregates having PN values between 120 and 130 would require some additional testing before being accepted or rejected for use as rip rap.

It should be noted that these PN performance ranges are intuitive values that are not based upon actual field performance measurements. This is because the FDOT commonly uses non-Florida aggregates for rip rap applications. As a result, there may be an inadequate base of field performance data for Florida materials to correlate with the results of this study.

Additional studies will be required to develop the database necessary to establish relationships between field performance and the PN test procedure. In addition, this represents the application of a relatively new PN technique that had been previously developed to assess the durability of Florida aggregates used in concrete. Therefore, as more field performance data is generated, factor weight (FW) and related PN values can be refined, resulting in greater reliability of PN values.

Rhodamine epifluorescence microscopy was unsuccessfully applied to these stones. The problems were related to an inadequate sample preparation technique which failed to reveal detailed porosity. The fact that this technique works on other materials, but was not useful here, indicates more work may be needed if detailed study of the porosity of stones is identified as a major quality factor.

While mercury intrusion porosimetry (MIP) is an inexpensive and relatively fast test method, it is limited to very small sample sizes, limiting the amount of sampled material to less than 10 grams. This does not allow for assessment of sample heterogeneities that are commonly seen macroscopically and microscopically in Florida stones. This raises the question as to how representative the data are for any given material. This problem can be overcome by performing multiple analyses to determine the range of values and an average and standard deviation for each stone. This, however, would be time consuming and would negate the use of MIP as a “quick and dirty” index test for aggregate durability. The Iowa Pore Index test, which is performed on 9,000-gram samples, is more likely to be representative of bulk aggregate materials, and would be recommended for evaluation in any future rip rap stone porosity assessment.

In the gyratory crushing machine, the performance of the Key Largo Limestone and Ocala Limestone was comparable at 25 revolutions with 0.83 and 0.90 percent, respectively, passing a 200-mesh screen. The highest values at 25 revolutions occurred in the Suwannee Limestone and the Avon Park Limestone with 1.21 and 1.30 percent, respectively, passing 200-

mesh. This grouping is maintained at 50 and 100 revolutions with the chert producing the least minus 2--mesh materials and the Avon Park Limestone producing the most (Figures 6-1 to 6-3).

These results show the varying degree of GTM soundness results that is present within the tested stones. For example, the Suwannee-Hawthorn unconformity chert and Avon Park Limestone have excellent degradation patterns (yield low percentages of minus 1/2" and minus 3/8" materials) yet they have not been recognized as viable rip rap aggregates by the FDOT. Conversely, the Suwannee Limestone and Key Largo Limestone, which are recognized as potential rip rap aggregates, have much less desirable degradation patterns.

One major advantage that gyratory testing possesses is the ability to incorporate water susceptibility into the degradation testing. This is particularly advantageous when testing potential rip rap aggregates since rip rap will be constantly exposed to water throughout its service life. Based upon this preliminary research, it appears that this test method could be implemented either in place of or in conjunction with Los Angeles Abrasion testing to evaluate rip rap aggregate soundness.

Unconfined compression is fairly simple to perform and the equipment is readily available. Test results (Table 6-6) indicate a very wide range of values for each material tested. For example, of the five tested Ocala Limestone rock cores, the unconfined compressive strength values range from 1,672 psi to 4,557 psi. It is evident that there is significant sample variability that can only be overcome by the replicate testing and analysis of rock cores and statistical analysis of the data. As a result, unconfined compressive strength testing is not viewed as a viable index test for mechanical durability of potential rip rap stones. In future work, sawn rock samples of larger cross-sectional areas could be substituted for the rock cores. This might simplify sample preparation and allow for the testing of larger, more representative samples.

The results of the slake durability testing (Table 7-1) show very little variability within the five stones tested. Indices range from 98.39 for the Ocala Limestone to 99.65 for the Suwannee-Hawthorn unconformity chert. These values, however, place all five aggregate types in the "Extremely High" classification proposed by Franklin and Chandra, meaning that these materials have extremely high slake durabilities. All of the tested stones are very durable under conditions of wetting and drying after exposure to sea water.

Acid insoluble residue testing (Table 7-2) shows the Suwannee Limestone had the least amount of insoluble material at 0.64 percent. Conversely, the chert from the Suwannee-Hawthorn unconformity had the most insolubles at 76.47%. X-ray diffraction analysis of the insoluble residue confirmed the chert and the four silicified carbonates consisted primarily of carbonate material with silica being the most common insoluble component of the rock types. Negligible amounts of clay were observed in each of the five stones.

Results of the synthetic seawater testing in the accelerated aging device resulted in negligible soundness losses over the testing period. An explanation would be that sodium chloride, the principal salt in seawater does not form hydrates. Repetitive, step-wise hydration occurs when sodium sulfate is used in soundness testing. With sodium chloride, the crystallization pressure against pore walls is a one-time process; whereas crystallization and hydration pressures are cumulative in multiple cycle sodium sulfate soundness testing (Winkler and Wilhelm, 1970). The multiple-hydration steps observed in sodium sulfate may better represent field conditions where time and climatic factors are important. Thus, without the benefit of multiple steps of hydration to add to the deterioration effects on aggregate samples, it appears that sodium chloride is unable to produce measurable results on a time scale suitable for use in the laboratory.

When sodium sulfate solutions were used in the accelerated weathering device, no significant losses were measured over the testing period. Since excess crystals were continually maintained in the solution, saturation does not appear to be an issue. A possible explanation for the absence of positive results with this testing could be inadequate drying from the lamps used in this experiment. Each sample set has approximately 30 minutes under the drying lamps to achieve complete drying along with the resulting hydration of the sodium sulfate salt. The standard sodium sulfate soundness test involves drying samples after the immersion cycle to constant mass at 110°C. This drying time typically takes between four and six hours. The temperature recorded beneath the drying lamps reached 110°C, and tests showed the specimens had come to a constant weight. However, inadequate duration of drying times may not have allowed the samples to achieve the hydration and crystallization energies required for stone deterioration.

While the accelerated weathering device did not produce the expected results in the research, it appears to hold promise for future testing. In the event that a more concentrated drying device that is capable of delivering greater temperatures can be developed, this device can simulate long-term exposures in a limited amount of time under controlled laboratory conditions. As a result, the accelerated weathering device may have unrealized test potential that may benefit from additional improvements.

Using the modified sulfate soundness testing procedure (2 kilogram quantities of coarser materials, an excess of sodium sulfate crystals in the solutions, and large insulated coolers to contain the materials), all five of the stone samples (Table 8-3) would pass the currently accepted FDOT standard of 12%. Some materials, such as the Ocala Limestone (soundness = 12.7), are believed to be poor materials for rip rap and are not even considered by the FDOT. The standard deviation for all the trials appears to be good, ranging from 0.7 to 3.8. It should be noted, however, that statistical significance may be affected by the small number of tests completed. The soundness result for the Key Largo Limestone, 13.40%, is consistent with published FDOT data. An inspection of the limited FDOT data revealed that the Key Largo Limestone and Suwannee Limestone, of the aggregates tested, have been used by the FDOT for marine rip rap applications, produced results ranging from 10 to 18%. This may indicate a good correlation between the results of the modified testing procedure and the standard FDOT procedure.

Numerous workers have stated that the factors involved with poor accuracy and precision of the sodium sulfate soundness test are too numerous and varied to allow for improvement of the procedure (Aubertin and LaRochelle, 1984; Sheftick, 1989).

This research did not attempt to improve accuracy or precision. Instead, it focused on developing an easier, less costly and less time-consuming test method. Evidence suggests that there are many other forces acting on aggregate particles, other than those exerted by crystal growth. As a result, it is virtually impossible to account for all of these processes. Thermal stresses related to internal gradients and volumetric variations, movements of adsorbed fluids and cycles of alternate wetting and drying are all responsible for a substantial portion of the destructive effects seen in sodium sulfate soundness testing (Bloem, 1966; Aubertin and LaRochelle, 1984; Ping and Beaudoin, 1992). In addition, there is an absence of any strict relationship between the sulfate soundness test and the actual field performance of aggregates exposed to in-service conditions. Therefore, it has been suggested that sodium sulfate soundness testing be used as a general index property in combination with other aggregate properties such as absorption, abrasion and petrography. The modified sulfate soundness testing has accomplished the following:

1. Eliminated the need for costly humidity and temperature-controlled cabinets.
2. Eliminated the stringent need for temperature control due to the constant addition of excess crystals to maintain solution saturation.
3. Eliminated the need for excessive cooling times of dried aggregate.

Based upon the preliminary results, the modified sodium sulfate soundness testing protocol appears promising. Additional research should be completed to expand the testing database, to evaluate apparent gains in accuracy and precision, and to evaluate the potential impact of the reduced sample size on testing results.

These results appear to reflect the FDOT's concern in using these Florida materials for rip rap applications. While this preliminary rating system for Florida's potential rip rap stones appears promising, it should be noted that this study evaluated only the in-service processes aspect of a potential source.

For a more complete rock engineering rating, geological processes and construction/placement processes must also be evaluated. This generally occurs during a detailed quarry evaluation of potential aggregate sources. In addition, this rock engineering rating system must be approximated with actual rip rap field performance to further refine multifactorial weightings as well as validate the ratings system. Preliminary field evaluations conducted by Lienhart (1998) indicate that the ratings system has resulted in a close approximation of the actual field performance of rip rap.

CHAPTER 11
CONCLUSIONS

This report allows several conclusions to be drawn relevant to soundness testing as a method of field performance and to the preliminary evaluation of alternative test methods for rip rap aggregate materials. These conclusions are:

1. Modified absorption testing indicates that more accurate absorption results can be obtained by placing test samples in a plastic dessicator and subsequently removing air entrained in sample pore spaces under a vacuum. Comparisons between vacuum extraction and standard absorption testing showed significant increases in average absorption values with the vacuum extraction method. Distilled water, synthetic seawater and a distilled water/methanol mixture were evaluated as test solutions for standard and modified absorption testing. Of these, distilled water demonstrated the most consistent and highest average absorption results. While these results are preliminary, vacuum extraction absorption testing appears to be an excellent alternative to standard testing in order to produce more accurate test results.

2. Specific gravity testing of the five Florida aggregate types indicate that all five stones appear to be of good to marginal quality for rip rap according to the classification scheme devised by Lienhart et al., 1995. A complete aggregate sample set, however, should be completed to develop a specific gravity database for Florida aggregate materials. As a result, these results should be considered preliminary until a database expansion can be performed to provide a basis for comparison.

3. Application of a modified Petrographic Number (PN) method, based on the method used by Oyen et al., 1998, to the five aggregates showed that the stones would be expected to have generally good to poor field performance properties. Specifically, the Avon Park Limestone, Suwannee Limestone and Hawthorne-Suwannee unconformity chert would be expected to have good field performance. Conversely, the higher porosity Ocala Limestone and Key Largo Limestone would be expected to demonstrate poor field performance based upon the fact that porosity plays a major role in aggregate failure in rip rap. These results remain preliminary and will evolve as weighting factors used to score the stones becomes better defined.

4. Rhodamine epifluorescent microscopy (REFM) represents a relatively new, inexpensive technique for evaluating microstructural detail in aggregate thin sections. Results of this study, however, were affected by two problems that proved difficult to overcome. The first problem was a general fluorescent background glow in the samples that could not be corrected by light filtration. This background glow prevented the delineation of microstructural details. A second problem involved a difficulty in resolving the REFM images. The clarity of the images was poor, much of it due to the background glow, preventing assessment of microporosity. As a result of these problems, REFM was eliminated from the alternative testing protocol. This, however, does not diminish the potential applicability of this method to aggregate evaluation. This method will become more viable as thin section preparation methods are further refined for the REFM method.

5. Mercury Intrusion Porosimetry (MIP) testing was performed on the five aggregates as a method for quantitatively evaluating pore size distribution. Results of this testing indicate that chert from the Hawthorne-Suwannee unconformity has almost no measurable porosity. The Suwannee Limestone and Avon Park Limestone have most of their porosity occurring in the fine pores (< 0.1 micrometers), but their total porosity is relatively low. Conversely, the Ocala Limestone and Key Largo Limestone have a relatively high overall porosity, but the majority of the porosity occurs in the larger sizes (> 0.1 micrometers). While MIP testing is inexpensive and readily accessible, it suffers a major drawback from small sample size. This small sample size does not allow the method to account for sample heterogeneities commonly seen in Florida aggregates. As a result, the Iowa Pore Index (IPI), a porosity assessment method developed by the Iowa Department of Transportation, appears to hold more promise that MIP testing. IPI testing, while not evaluated as part of this study, is performed on a 9,000-gram sample that is more representative of bulk aggregate materials. As a result, IPI testing is recommended for evaluation as an alternative test rather than MIP testing.

6. The Gyratory Testing Machine (GTM) was evaluated as a potential alternative to the currently accepted Los Angeles Abrasion test. GTM was selected because this method can easily be performed on wet aggregate, produces degradation due to aggregate particle interaction and does not cushion tested materials with fines. GTM results indicate that the Hawthorne-Suwannee unconformity chert exhibited the least amount of degradation while the Suwannee Limestone produced the greatest amount of aggregate breakdown. Based upon this preliminary research, it appears that the GTM method

could be utilized either in place of or in conjunction with the Los Angeles Abrasion test. Additional research and in-service data, however, are required to establish suitable specification limits and to determine whether modifications to the GTM method are required. Additional testing should also be conducted to determine potential correlation of the GTM method with other index tests for rip rap durability.

7. Unconfined compressive strength testing was conducted for rock cores prepared for each of the five aggregate types. Results of this testing indicate that, while unconfined compression testing is a readily accessible and simple test to perform, there is a wide range of values for unconfined compressive strength. This is due to the significant sample variability that is associated with Florida aggregate heterogeneities. Testing and analysis of multiple rock cores and the subsequent statistical treatment of the resulting data can overcome this problem. Because this would be a very time consuming effort, unconfined compressive strength testing is not considered a useful index test for mechanical durability of potential rip rap aggregates.

8. Slake durability testing results of the five aggregate types indicate that they are all in the “Extremely High” classification as determined by Franklin and Chandra. This classification means that the stones slake to a negligible extent and, as a result, are very durable under atmospheric conditions of wetting and drying.

9. Acid insoluble residue testing of the five aggregate types indicates that silica is the most common non-carbonate component of the aggregates. Very minor amounts of clay were

observed. The relative absence of clay validates the results of the slake durability testing because the slaking test is primarily designed to evaluate the weathering resistance of clay-bearing rocks.

10. Modified soundness experiments performed using an accelerated weathering device produced negligible soundness losses over a one-month testing period (equivalent to 2 years of field testing) using both synthetic seawater and saturated sodium sulfate solutions. The absence of positive results with the synthetic seawater could be attributed to a lack of hydration pressures associated with sodium chloride. The absence of positive soundness loss results associated with the sodium sulfate testing could be attributed to inadequate drying times or drying lamp intensity that resulted in incomplete drying of aggregates that did not allow the formation of hydrates in the pore spaces of the samples. The accelerated weathering test device shows a great deal of promise due to ease of use and the ability to generate long-term data over a relatively short testing period. Before this method can be fully utilized, a more concentrated drying device must be devised so that complete hydrates may form in the pore spaces of the tested samples and produce positive soundness loss values.

11. Modified sodium sulfate soundness testing was performed using smaller sample sets that were tested in coolers containing supersaturated sodium sulfate solutions. Results of this modified testing indicate values that appear to be relatively consistent with published FDOT data. While this testing did not attempt to improve accuracy or precision, it appears that many of the problems associated with standard sodium sulfate soundness

testing can be eliminated by simply maintaining a saturated solution in the testing vessel. While further investigation is required to fully evaluate this alternative method, it appears promising based upon the preliminary results of this study.

12. This research attempted to produce a rip rap engineering rating system based upon the system created by Lienhart, 1998. Because this study focused on aggregate durability, the ratings system involved the evaluation of in-service processes. The five tested aggregate types were classified using this rock engineering system using the results of the durability tests as input. According to the quality ratings produced by this system, all five aggregate types would make marginal to good rip rap materials. This classification appears to reflect the FDOT’s current unwillingness to use these Florida materials for marine rip rap applications. While the preliminary ratings system results are encouraging, in order to refine the ratings system, geological processes and quarry evaluations should be incorporated with the in-service processes to provide a three-tiered interaction matrix.

CHAPTER 12
SUPPLEMENTAL TESTS

In cooperation with the staff of the FDOT Materials Office staff, additional testing was undertaken as part of the project. These supplemental tests were to expand the database to include some new materials, to test a new sample preparation technique, and to further evaluate the equipment and procedures developed in an accelerated weathering test.

The materials tested in this series included the five used in the original test sequence plus five additional samples (Table 12-1). The materials added to the test list include three limestones (Ft. Thompson, a second sample of Key Largo, and Tamiami), one Georgia granite, and samples from cement filled sand bags from Ft. Lauderdale.

In an effort to simplify sample preparation techniques, the materials were cut to 1" X 1" X 2" rectangular prisms using a rock saw equipped with a diamond blade. This technique is more flexible and simpler to do than rock coring, does not require as much specialized equipment, produces larger test units than were available with coring, and provides samples with uniform geometric shapes. In both coring and sawing, rather large field collected pieces are required for sampling, but the larger specimens produced are likely to be more representative of rip rap stones than the small rock chips used in most laboratory testing.

The test procedures used were the same as those previously discussed. The specimens were placed on a test device that rotates at 1 revolution per hour. The samples pass through a tank containing the test solution (i.e., either a solution of synthetic seawater or a saturated solution of sodium sulfate). The samples then are dried on the apparatus using heat lamps before being reimmersed. Test periods ranged from 3 to 28 days. When a test period was completed, the sample was cleaned of any adhering salt, and weighed. The differences in the starting and final weights were recorded. In addition, any material left in the basket containing the specimens was screened to determine the particle sizes. In some case, the samples failed completely during testing (Table 11-2), and no material was left for screening.

Tests with sodium sulfate solution (Table 11-2) showed the Ft. Thompson and granite samples losing weight after only 3 days. At 7 days, the cement filled bags and one specimen of the Tamiami Limestone began to change. Those specimens that had begun to change at 7 days showed further losses at 14 days. By 28 days, several specimens had completely disintegrated (noted by zeros in the percent retained on the 4-mesh screen). Specimens of Key Largo Limestone, Suwannee Limestone, Gray Chert, Avon Park Limestone, and Ocala Limestone persisted for 28 days and showed a range of losses (54% to none).

Tests of these materials in synthetic seawater were unsuccessful (Table 11-3). None of the materials showed any significant changes in 14 days of testing.

These tests reinforce the observations made in the initial series that used smaller, cored samples. Sodium sulfate causes some materials to begin losing weight (i.e., starting to fail) as early as 3 days into the test cycle. After 14 days of exposure, the materials that are going to perform poorly in this test are clearly identified. After 28 days, the durability of some materials is so poor that the specimens actually disintegrated and were lost from their enclosures. Selected examples of materials that were failing at 14 days in sodium sulfate are shown in Figures 12-1 and 12-2.

The differences in results between sodium sulfate and synthetic seawater have been discussed in the main body of this report. While the salts in synthetic seawater may have higher energies of crystallization, the persistent pressure resulting from the systematic rehydration of sodium sulfate in the pores of the stones is more damaging to the rock's fabric.

This accelerated weathering procedure offers several advantages over the conventional sulfate soundness test. Specimens of various sizes and shapes can be tested which is advantageous when dealing with very coarse materials where changes in shape or non-homogeneous failure may be important. Intermediate stage test results at 3, 7, or 14 days are easily obtained. Testing of materials with various solutions (for example, $MgCl_2$) is facilitated. The use of open solution containers simplifies the maintenance of saturated solutions and minimizes the effects of temperature on solution composition. Some of these benefits of an alternative, accelerated weathering procedure were demonstrated in this test program. Additional work on the effects of variables and test procedures and close correlation with in-service field performance will be necessary before a final recommendation for acceptance should be made.

Table 12-1. Sample identifications.

FDOT ID	LOCATION	GEOLOGIC UNIT	GEOLOGIC AGE
08-005*	Brooksville, FL	Suwannee Limestone	Oligocene
08-005*	Brooksville, FL	Hawthorne-Suwannee Unconformity Chert	Miocene-Oligocene
87-090*	Miami, FL	Key Largo Limestone	Pleistocene
26-098*	Newberry, FL	Ocala Limestone	Eocene
34-106*	Gulf Hammock, FL	Avon Park Limestone	Eocene
94-209**	St. Lucie Co., FL	Ft. Thompson Fm.	Pleistocene
87-339**	Dade Co., FL	Key Largo Fm.	Pleistocene
01-495**	Charlotte Co., FL	Tamiami Fm.	Pliocene
GA-327**	Georgia	Alleghenian Granite	Permian
FT**	Ft. Lauderdale, FL	cement filled sand bags	Recent

*Sample set collected by Scott Gregory.
**-Sample set collected by the FDOT.

Table 12-2. Results of accelerated weathering using sodium sulfate.

Retained on screen, percent

Sample #	Screen No.4				Screen No.40				Screen No.200				Fines (Minus-200 Mesh)			
Days	3	7	14	28	3	7	14	28	3	7	14	28	3	7	14	28
FT	0.98	0.50	0.46	0.00*	0.00	0.10	0.14	0.00	0.01	0.35	0.34	0.00	0.01	0.05	0.05	1.00
FT	0.99	0.88	0.62	0.00*	0.00	0.03	0.15	0.00	0.01	0.07	0.22	0.00	0.01	0.03	0.02	1.00
O1-495	1.00	0.99	0.84	0.46	0.00	0.00	0.11	0.42	0.00	0.00	0.03	0.11	0.00	0.01	0.02	0.01
O1-495	1.00	0.89	0.53	0.57	0.00	0.33	0.08	0.36	0.00	0.13	0.03	0.07	0.00	0.08	0.01	0.00
87-090	1.00	0.98	1.00	0.94	0.00	0.01	0.00	0.03	0.00	0.00	0.00	0.03	0.00	0.01	0.00	0.00
87-090	0.99	0.99	1.00	0.77	0.00	0.00	0.00	0.10	0.00	0.00	0.00	0.12	0.01	0.01	0.00	0.01
87-339			1.00	0.00*			0.00	0.00			0.00	0.00			0.00	1.00
87-339			1.00	0.00*			0.00	0.00			0.00	0.00			0.00	1.00
94-209	0.92	0.92	0.73	0.00*	0.05	0.10	0.18	0.00	0.03	0.02	0.09	0.00	0.00	0.00	0.00	1.00
94-209	0.92	0.77	0.56	0.00*	0.26	0.03	0.06	0.00	0.17	0.06	0.02	0.00	0.02	0.00	0.00	1.00
GA-327	0.90	0.56	0.00*	0.00*	0.05	0.00	0.68	0.00	0.04	0.16	0.31	0.00	0.01	0.01	0.02	1.00
GA-327	0.90	0.57	0.31	0.00*	0.10	0.33	0.44	0.00	0.00	0.03	0.23	0.00	0.00	0.25	0.02	1.00
8-005Ls			1.00	0.99		0.01	0.00	0.00			0.00	0.00			0.00	0.00
8-005Ls			0.98	0.98		0.00	0.01	0.01			0.01	0.01			0.00	0.00
8-005C			1.00				0.00				0.00				0.00	
8-005C			1.00				0.00				0.00				0.00	
34-106			0.98	0.79			0.01	0.07			0.01	0.09			0.01	0.06
34-106			1.00	1.00			0.00	0.00			0.00	0.00			0.00	0.00
26-098			0.98	0.80			0.01	0.15			0.01	0.04			0.00	0.00
26-098			1.00	0.98			0.00	0.01			0.00	0.01			0.00	0.00

*Specimen failed or was 100% passing the screen.

Table 12-3. Accelerated weathering test results using synthetic seawater.

Retained on screen, percent

Sample #	Screen No.4			Screen No.40			Screen No.200			Minus 200-Mesh		
Days	3	7	14	3	7	14	3	7	14	3	7	14
FT	0.99	0.99	0.99	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.00	0.00
FT	1.00	0.94	0.99	0.00	0.02	0.00	0.00	0.02	0.01	0.00	0.01	0.00
O1-495	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
O1-495	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87-090	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87-090	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87-339	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
87-339	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
94-209	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
94-209	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GA-327	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GA-327	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8-005Ls	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8-005Ls	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8-005C	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8-005C	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34-106	1.00	0.97	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.00
34-106	0.99	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
26-098	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
26-098	1.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Figure 12-1A. Tamiami Limestone before exposure to accelerated weathering.

Figure 12-1B. Sand cement mixture before exposure to accelerated weathering.

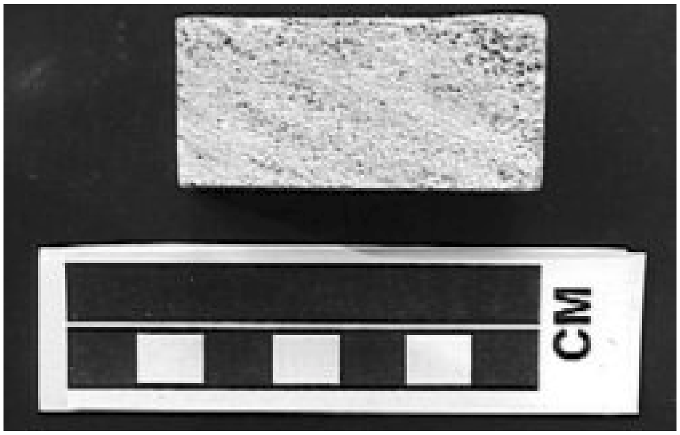


Figure 12-1C. Georgia granite before exposure to accelerated weathering.

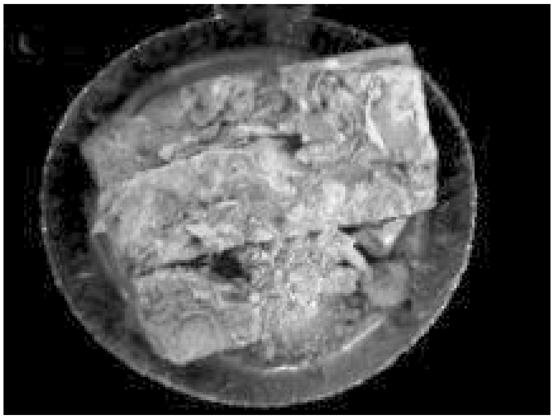


Figure 12-2A. Tamiami Limestone after 14-day accelerated weathering in sodium sulfate. Pan diameter is 6.0 cm.

Figure 12-2B. Sand cement mixture after 14-day accelerated weathering in sodium sulfate. Pan diameter is 6.0 cm.

Figure 12-2C. Georgia granite after 14-day accelerated weathering in sodium sulfate. Pan diameter is 6.0 cm.

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