EVALUATION OF AGGREGATES FOR BASE COURSE CONSTRUCTION

FINAL REPORT

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EXECUTIVE SUMMARY

An investigation of limestone base course aggregates was performed to ascertain if strength and stiffness changes in carbonate aggregates could be evaluated for the purpose of quantifying their effects on the base structural layer coefficient (a_2) used in pavement design. One of the goals of this approach was to develop a laboratory test or series of tests, which the FDOT might use to quantify or predict strength and stiffness gains, that could be generally applied to a range of materials types given field operating conditions. Materials of varying carbonate content were selected, prepared at optimum moisture content and compacted by modified proctor for testing at different ages after curing by two methods (soak and moisture room). Replicate specimens were prepared with 1.0 percent lime and tested for the purpose of accelerating cementation or modifying clay contained in the aggregate to simulate observed increases in field based strength performance. Limerock Bearing Ratio, cohesion and angle of internal friction, triaxial resilient modulus (M_R), and gyratory shear (G_s) tests were performed and evaluated.

Based on the data accumulated with this study, carbonate content does not necessarily relate to higher strength gain. This does not mean that high carbonate content materials cannot achieve cementation and greater strength, rather that the series of tests included in this report were unable to quantify and/or accurately reproduce the effect of cementation within a curing time of 60 or less days. However, it does suggest that use of a higher layer coefficient for high carbonate aggregates strictly based on percent carbonates may not be appropriate.

Several key complications in ascertaining the relationship between carbonate content and potential strength gain were identified as a result of this study. First, the use of the term carbonate content alone as an aggregate descriptor is problematic. Variations in aggregate carbonate mineralogy (low-Mg calcite, high-Mg calcite, aragonite, and dolomite) and crystallite/particle size among the various lithologies used in this study should have a significant impact on cementation potential, based on both kinetic and thermodynamic constraints. As a result, in order to fully ascertain the importance of aggregate carbonate content to strength gain potential, aggregates may need to be evaluated on a lithological basis, as the character of carbonate mineralogy varies among the aggregate sources employed as base course in Florida. Second, test variables other than carbonate content were found to have a major impact on strength gain, particularly dry density (γ_d) and aggregate gradation, impacting test ability to elucidate the role of carbonate content. Lastly, poor test precision added further to the difficulty in identifying a relationship, if any, between carbonate content and strength gain in the materials tested.

Lime addition (1.0 percent) produced both increases and decreases in strength-associated properties depending upon the material source. Results also varied among the different tests employed with this study for individual sources, and under different curing conditions. Triaxial M_R values gave a fairly consistent range in values. Computation of a mean layer coefficient from the M_R of the different aggregates indicated that an average a_2 value of 0.18 was typical for both limestone and bank-run shell aggregates. A relationship between G_s and M_R was developed to facilitate the computation of a_2 using G_s data.

An attempt was made to develop a rapid and practical method to accelerate cementation of base course materials in order to predict increases in field-based strength. Both untreated and treated (1% hydrated lime) samples from several pit locations, representing both high carbonate and low carbonate aggregate sources were prepared using a variety of experimental procedures, and then tested using an unconfined compression test in order to determine the unconfined shear

strength of the materials. Although it was believed that a controlled environment of some combination of variable humidity and variable CO_2 pressure would result in the conditions necessary to accelerate cementation, the experiments failed to produce the desired results. Apparently, we have been unable to mimic the proper natural field conditions over a short time span that will accelerate the increases in observed field-based strength performance.

INTRODUCTION

Research into the characterization of carbonate materials used for highway construction in Florida is of great interest to the Florida Department of Transportation (FDOT). As new quarry locations are opened, and new materials are used, it becomes more and more important to carefully monitor these materials to insure that proper specifications are being met. Recent studies of base course materials have been one of many areas of focus. The research outlined in this report was undertaken to evaluate the engineering properties of limestone base course materials for the potential assessment of their structural properties for use in pavement design.

The FDOT requires that aggregates to be used for base course meet the following specification requirements for approval with designated layer coefficients as outlined in Table 1.

Table 1. Standard FDOT specifications for materials used in base course construction

MATERIAL TYPE	STANDARD SPECIFICATION	MINIMUM LBR	MINIMUM CARBONATES (%)	LAYER COEFFICIENT (STD. INDEX)
Limerock	911	100	70	0.18
Shell	913	100	50	0.18
Shell-Rock	913A	100	50	0.18
Cemented Coquina	915	100	45	0.18
Graded Aggregate	204	100	0	0.15

In 1961, the AASHO Committee on Design of Flexible Pavements first proposed structural layer coefficients for base course materials (Zimpfer et al., 1973). These coefficients, adopted at the time by the FDOT, were based on the AASHO Road Test, which began in 1958, and used local Illinois base materials for the study. As part of the recommendations of the AASHO Committee on Design, utilization of satellite test pavements by the states was suggested as a means of supplementing and adjusting the AASHO Road Test findings to local conditions. During the 1960's many states followed this suggestion, including Florida (Schrivner and Moore, 1968). Zimpfer et al. (1973) were the first to point out that a combination of (1) AASHO coefficients, (2) Florida satellite studies, (3) field performance studies, (4) laboratory and test pit studies, and (5) research by other agencies was most likely required to develop reasonable estimates for structural layer coefficients that can account for environmental and material factors unique to Florida.

The AASHO Road Test coefficients initially were established as interim values based on the materials used in the study. In that study, the base materials included crushed stone, gravel, cement-treated gravel, and bituminous-treated gravel. The crushed stone base was a well-graded crushed dolomitic limestone with an approximate LBR value of 140. A structural coefficient of 0.14 was established for this material based on the AASHO Road Test. Based on a comparison of Florida limestones to the AASHO crushed limestone (Zimpfer et al., 1973), the FDOT established a layer coefficient of 0.15 for limerock materials used in the state, and a minimum LBR strength requirement of 100. This coefficient was correlated to an LBR value of 140, and was approximately the mid-range of materials tested. Furthermore, it was recognized that the FDOT required AASHTO T-180 density requirements for limerock base course construction. A review of the approach to this conclusion is documented in Research Report 177, "Structural Layer Coefficients for Flexible Pavement Design", August, 1973. With the concurrence of the Federal Highway Administration (FHWA), the FDOT later raised the structural layer coefficient of limerock from 0.15 to 0.18 in accordance with recommendations of a 1981 FDOT research report FL/DOT/OMR-235/81 entitled "Pavement Design Coefficients, A Reevaluation of Florida Base Materials" (Smith and Lofroos, 1981). This report studied the strength and stiffness increase over a five, six, and nine year period of three roads constructed with limerock bases. The study showed that field plate moduli increased significantly to levels above 40,000 psi, which exceeded a structural coefficient of 0.18 denoted in the AASHO Design nomograph from NCHRP Report 128. Potential reasons for the strength and stiffness increase were suggested, but no attempt was made to establish a method of predicting these increases.

A potential problem arises because the FDOT cannot evaluate a new material and assign a layer coefficient equivalent to limerock, based on equivalent performance in the FDOT's test pit and/or a test road section (per FDOT Procedure 675-000-004-a) without significant time delay. The decision cannot be made on the basis of the new material's initial performance, without understanding its potential strength gain or the field conditions that may contribute to strength gain.

The issue of strength and stiffness gain also highlights the controversial issue of minimum required carbonates. It has been suggested that strength and stiffness gains may be caused by cementation of base course aggregate, and that a minimum carbonate requirement is essential to achieve this result. In fact, high carbonate content aggregates (especially, high-CaO) have for some time been known to exhibit long-term gains in strength due to cementing action (Gartland, 1979; Zimpfer, 1981; Graves, 1987). In these earlier studies, the materials used were mixtures of pure limestone ($CaCO_3$) with varying amounts of quartz sand. However, this is not fully representative of the various lithologies employed as base material in Florida. From the previous table (Table 1), it is evident that some disparities appear to exist between the required minimum carbonate content of various aggregates, with no clear correlation to layer coefficient. It should be noted for Table 1 that graded aggregate may use either Group 1 aggregates (limestone, marble, or dolomite) or Group 2 aggregates (granite, gneiss, or quartzite), and as such, the minimum carbonate content of the material may be 0 % if Group 2 aggregates are employed.

Based solely on the disparities seen in Table 1, it is evident that there is a need to verify the validity of the carbonate strength gain hypothesis and to determine whether it is a relevant specification for assigning a structural number. Part of the problem with deciphering this relationship is the present terminology used with the study of high versus low carbonate base materials. The term high carbonate historically has been used by the FDOT for materials high in carbonates of calcium and/or magnesium. Whether the material in question is a limestone ($CaCO_3$), a dolomitic limestone ($CaCO_3$ and $CaMg(CO_3)_2$), or a dolostone ($CaMg(CO_3)_2$) will have a significant impact on the likelihood for strength gain derived through cementation based on kinetic considerations. Furthermore, even the mineral speciation within various limestones ($CaCO_3$ as low-Mg calcite, high-Mg calcite, and/or aragonite) should have an impact on cementation potential for the same reason. Therefore, one must consider the source lithology of base materials in question in order to fully ascertain the likelihood for strength gain via carbonate cementation.

Currently, no laboratory tests are used by the FDOT to quantify or predict strength and stiffness gains that could be generically applied to a range of material types. There is a need to quantify potential increase in performance characteristics of an aggregate base, and to identify the causal physical/chemical characteristic of the aggregate. There also is a need to investigate other laboratory test procedures that might be useful in supplementing the LBR test. These tests could be used on low-cohesive materials or on water-sensitive materials to estimate constructability or durability issues to which the LBR test may not be adequately sensitive.

Objectives

1. To develop and evaluate test procedures for the evaluation of base course materials (not currently specified) based on generic, measurable engineering properties and not based on limited chemical or mineralogical criteria. These measured properties will include aggregate properties and predictions of strength gains over varying time periods using methodologies reported in the technical literature and of practical use to the FDOT.

2. To evaluate the performance of these new tests on current and proposed aggregate sources and aggregate substitutes, including recycled products, to determine the acceptance of these materials for use as base materials in traditional roadway designs, specifically to ensure conformance to AASHTO design requirements.

3. To select materials being used or having been used in current and previous field construction projects.

Both high carbonate and low carbonate (high-SiO_2) aggregates from different quarries (pits) that conformed to FDOT base course specifications were selected for this study and tested using Limerock Bearing Ratio (LBR), triaxial shear, repeated triaxial resilient modulus (M_R), gyratory shear (G_S), and unconfined compression (UCT) tests. These aggregates were prepared with and without one (1.0) percent lime for the purpose of accelerating strength gain and/or cementation of carbonate materials. High carbonate content aggregates (both high-CaO and low-CaO) selected for the study came from both limestone lithologies (Suwannee Limestone, Ocala Limestone, Tamiami Formation, etc.) and dolostone/limestone lithologies (Avon Park Formation), while low carbonate content aggregates (high-SiO_2) came from limestone lithologies known for a high silica sand content (Ft. Thompson Formation, Anastasia Formation, etc.).

Results

Results of the study are as follows:

(1) The test results indicated that variability in LBR values over various time periods up to 60 days impacted the analyses and consequently, dry density (γ_d) was the only significant factor affecting the LBR values, primarily with the untreated samples, in Part 1 of the LBR study. In Part 2 of the LBR study, the only correlation observed with LBR data seemed to be material gradation, however, that was found to be a statistical artifact of the gradation of MX411. When MX411 was excluded from analysis, no correlation was found to exist among the Florida materials tested. Dry density was held more constant for the samples used in Part 2, and therefore was not

found to impact LBR results as much as was observed in Part 1. LBR data for treated samples (1 percent lime) from both Part 1 and Part 2 also showed the most statistically significant correlations to gradation, although the correlations in Part 2 were again an artifact of MX411. The effect of strength gain by cementation (carbonate content versus LBR) was not statistically significant in either part of the LBR portion of this study, and no equations predicting LBR results based on carbonate content were produced which were statistically significant.

(2) Triaxial shear tests were inconclusive. The effect of time on strength gain of lime treated aggregates was minor although the lime treatment appeared to produce a small increase in angle of internal friction (Φ). Tangent moduli derived from these tests gave no indication of time dependent effects although the moduli for lime treated aggregates were in all cases slightly greater than for untreated aggregate.

(3) The Resilient Moduli (M_R) test results were very consistent with aging time having no apparent effect on the test results for aggregate from all the pit locations tested. These results combined with FDOT data from prior tests on seven other aggregates were analyzed to determine AASHTO structural design coefficient a_2 for sum of principal stresses (Θ) equal to 137.9 kPa (20 psi). Values of a_2 ranging from 0.15 to 0.22 were obtained which were similar to the range (0.16 to 0.23) of 10 different bank-run shell specimens.

(4) Limited tests performed using the Gyratory Testing Machine (GTM) equipped with air roller gave lower gyratory shear (G_s) strength with lime treated Pit 36-246 high carbonate aggregate than the untreated aggregate. Conversely, low carbonate (44%) aggregate from Pit 70-279 produced higher shear strength for the lime treated aggregate. The effect of density was not apparent except for lime treated aggregates from Pit 56-465 which showed a substantial increase in shear strength with densification. Apparently, this material most likely contained clay, which may have reacted to the lime treatment. A tentative relationship between the G_s and the M_R values was developed and used to establish a prediction equation for a_2 based upon this relationship.

(5) Unconfined compression tests (UCT) performed on both high carbonate (Pit 36-246 and Pit 56-465) and low carbonate (Pit 70-279 and Pit 93-406) materials was undertaken as a means of developing a practical method to accelerate cementation of limestone base course materials in order to predict increases in field based strength performance. Through experimenting with a total of eleven autoclave-based treatments of prepared test specimens, it was hoped that a rapid and reliable technique could be developed. However, average failure stress values showed no correlation to either aggregate carbonate content or to the other engineering parameters measured in this study over the short time spans tested. Untreated samples did, however, show greater strength gains in almost all experiments.

The ensuing sections of this report present the test conditions, testing procedures, analysis, and the results of the various tests conducted on base course aggregates from a variety of quarries (pits) located around the state of Florida.

TESTING AND EVALUATION OF LIMEROCK BEARING RATIO AND MOISTURE-DENSITY DATA

Materials, Test Specimen Preparation, and LBR Testing (Part 1)

For the first stage of this study (Part 1), base course aggregates from seven (7) sources (pits) were selected and used to prepare lime treated and untreated test specimens for the purpose of evaluating strength gain effects on the Limerock Bearing Ratio (LBR). Two (2) separate splits from pit 93-406 were examined in this part of the study, resulting in a total of eight (8) samples. Initially, four to five specimens, each at different moisture contents, were compacted according to AASHTO Method T-180 to establish moisture-density curves. The optimum moisture content was determined from these curves for each source (pit) of aggregate. Treated aggregate samples were prepared by the addition of one (1.0) percent of lime (by weight) prior to the addition of water. Table 2 presents basic information on the aggregate and optimum moisture content for each source of material, while Table 3 outlines the material type, lithology, and mineralogy of the materials studied. The quantitative X-ray diffraction (XRD) data outlined in Table 3 was determined using a Rietveld refinement technique.

Table 2. Composition and optimum moisture contents for base materials (Part 1)

PIT NO.	PERCENT CARBONATES	% PASSING 4.75 mm	% RETAINED 4.75 mm	OPTIMUM MOISTURE CONTENT (%)	
				Untreated	Treated
36-246	98	82	18	10.0	11.0
56-465	77	74	26	8.0	9.0
12-008	70	49	51	7.0	8.0
87-090	70	66	34	6.0	7.0
17-091	52	80	20	8.0	9.0
93-406	47	73	27	7.0	7.0
93-406	40	64	36	7.0	8.0
70-279	40	78	22	7.0	7.0

Five samples of untreated and lime treated materials were prepared for each aggregate source. Moisture-density data for the compacted LBR test samples are given in Tables A-1 and A-2 of Appendix A. The dry density (γ_d) values were based upon the test specimen volume, sample weight, and moisture content after LBR testing at the different ages (3, 7, 14, 28, and 60-day).

LBR tests were initially conducted using a modification of Florida test method FM-515, for which samples were continually soaked in plain tap water during curing. Continuous soaking was performed for several reasons. This is the standard method for LBR testing used at the FDOT (although normally for 2 days), and Gartland (1979) showed that continuous soaking in plain water resulted in some of the largest strength gains compared to other methods of curing

Table 3. Lithology and mineralogy of base course materials (Part 1)

PIT NO.	MATERIAL TYPE	FORMATION	Calcite (%)	Dolomite (%)	Quartz (%)	Aragonite (%)	R (%)*
36-246	Limerock	Ocala	100	---	---	---	5.9
56-465	Limerock	Avon Park	73.6	1.8	12.6	11.9	9.1
12-008	Limerock	Tamiami	61.5	36.2	2.3	---	12.1
87-090	Limerock	Ft. Thompson	81.5	---	18.5	---	15.8
17-091	Shell	Tamiami	22.2	---	41.9	35.9	18.5
93-406	Shell-rock	Anastasia	38.1	---	37.4	24.6	34.7
70-279	Coquina	Anastasia	31.2	---	58.4	10.4	26.2

* R-values are residuals from quantitative Rietveld refinement of XRD data

Table 4. LBR values of untreated and treated aggregates (Part 1)

PIT NO. (% CARB.)	36-246 (98%)	56-465 (77%)	12-008 (70%)	87-090 (70%)	17-091 (52%)	93-406 (47%)	93-406 (40%)	70-279 (40%)
3-Day:								
Untreated	75*	(27)*	174	119	143	138	160	129
Treated	99*	158	165	199	132	138	205	140
% Change	32	485	-5	67	-8	0	29	8
7-Day:								
Untreated	(66)*	(44)*	137	124	137	135	171	122
Treated	168	178	143	210	160	155	217	165
% Change	154	305	4	69	44	15	27	35
14-Day:								
Untreated	(50)*	(12)*	150	130	122	124	196	116
Treated	166	199	199	202	150	192	186	160
% Change	232	1558	33	55	23	55	-5	38
28-Day:								
Untreated	(71)*	(6)*	173	130	114	161	169	132
Treated	165	158	232	238	179	129	233	183
% Change	132	2533	34	83	57	-20	38	39
60-Day:								
Untreated	(57)*	(29)*	119	109	153	156	150	137
Treated	174	129	256	209	163	170	215	191
% Change	205	345	115	92	6	13	43	39

* Fails FDOT requirement for minimum LBR of 100.
( ) Denotes very low LBR values and significant improvement with the addition of 1.0% lime.

involving wetting and drying cycles or CO_2 treatment. Since temperature remains fairly constant over the soaking time intervals, it was believed that carbonate material would dissolve and precipitate as cement due to changes in atmospheric pressure causing pore water CO2 partial pressures to fluctuate (Graves, 1987).

Current FDOT specifications require a minimum LBR of 100 for compacted base course materials. Test results for the untreated and treated base course aggregates at the different ages are given in Table 4. LBR values for all untreated materials except those from Pits 36-246 and 56-465 exceeded 100, and on the average ranged between 127 and 169 (Fig. 1). None of the samples exhibit any discernable trend with age. The low values for 36-246 and 56-465 may have been due to relatively low dry density/high moisture content or perhaps relatively high clay content (56-465). The dry density for these two samples averaged nearly 200 kg/m^3 less than that of the other samples studied, and the moisture content averaged approximately 3% more. However, the same differences in dry density and moisture content occur with the lime treated samples, but without the poor LBR results.

As outlined by Graves (1987), addition of lime to the dry base course materials before compaction and soaking was done in an attempt to enhance cementation and therefore strength gain variation with differences in composition. Lime treated aggregates on the average varied between an LBR of 154 and 212 (Fig. 2). Treated aggregates from Pit Nos. 12-008, 87-090, and 93-406 (40% carbonates) provided the highest mean LBR values (199 to 212). Unlike the lack of any discernable trends seen with the untreated aggregates, treated samples from Pit Nos. 36-246, 12-008, 17-091, and 70-279 appear to show an increasing trend with age. However, as with 36-246, most of the increase occurs early, suggesting that cementation is completed, the lime is depleted early, or the lime acted as a modifier/stabilizing agent. For most of the materials tested, the lime treated samples consistently show higher LBR values (Fig. 3). This is particularly noted with 36-246 and 56-465. However, there appeared to be no differences between untreated and treated materials from Pit Nos. 17-091 and 93-406 (47% carbonates). This is probably due to either test variability (e.g. dry density and moisture content) or a mineralogical control. The latter explanation may be associated with the high aragonite content of 17-091 (35.9%) and 93-406 (24.6%) being the primary cementing agent, thereby limiting the lime treatment to having little additional effect.

As noted previously, the most noticeable increase in LBR values for treated aggregates occurred with materials from Pit Nos. 36-246 and 56-465. The mean LBR values for the untreated materials, as given in Table 4, were extremely low, indicating substandard quality which could be attributed to moisture-density, gradation, excessive soak time during curing, and/or mineral composition (e.g. clay content). The effect of lime treatment on the LBR values of Pit No. 56-465 aggregate was extremely high. The mean LBR values increased almost 700 percent over those for the untreated material. As will be demonstrated in a subsequent section of this report, the gyratory shear strength of the treated 56-465 material increased substantially with densification whereas the untreated material had much lower strength, which did not change appreciably with densification. Undoubtedly the lime produced the improvement in properties. It is believed that chemical interactions such as the stabilization of clay minerals altered the behavior of the aggregate from Pit No. 56-465.

A scatter plot showing strength change of treated base course samples versus carbonate content was prepared for the total data set (Fig. 4). The plot suggests that base materials with higher carbonate content show greater strength gain with lime addition, as indicated by the positive slope of the fitted linear regression curves. However, the linear regression curves exhibit fair to good correlation for 7- and 60-day curing times (R^2 = 0.37 and 0.55, respectively) only, and no correlation for 3-, 14-, and 28-day curing times (R^2 = 0.12, 0.17, and 0.11,

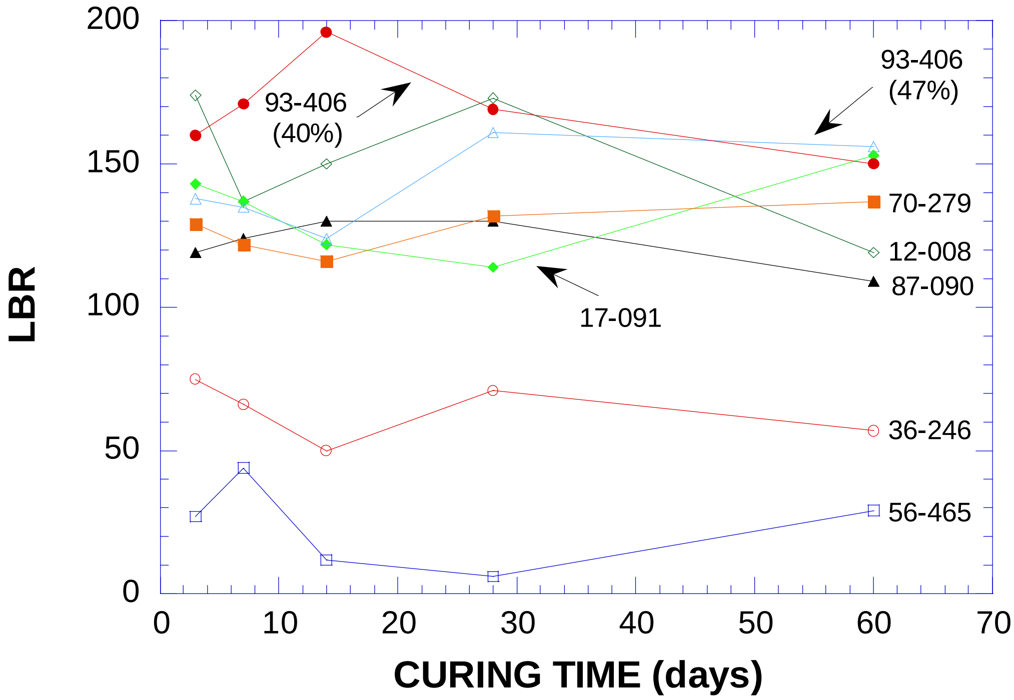

Figure 1. Plot of LBR data for untreated base course materials (Part 1).

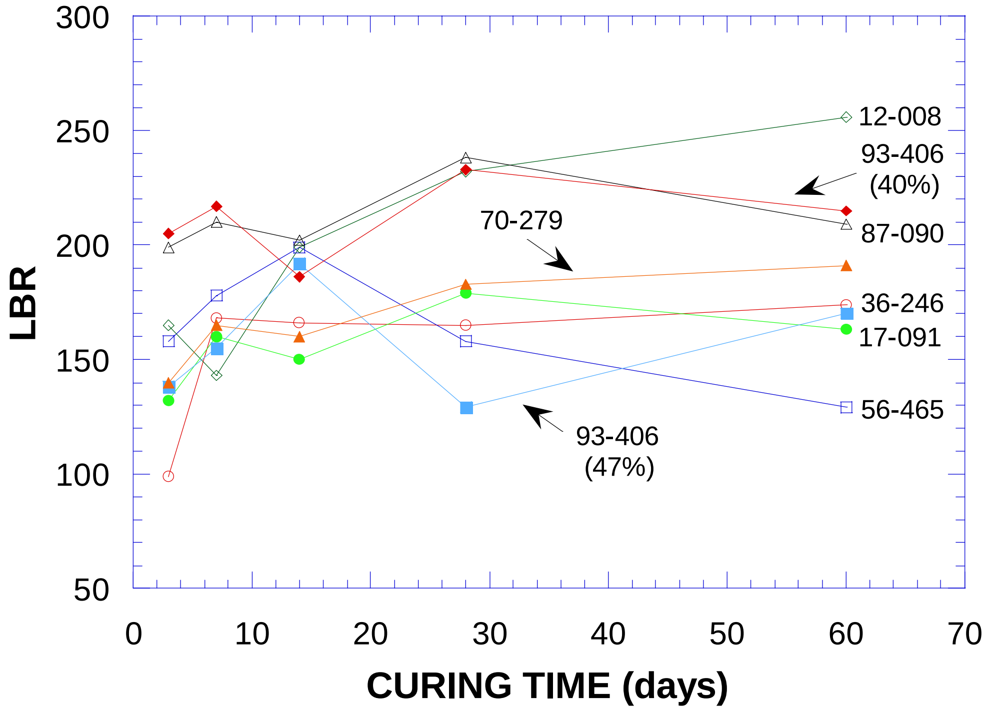

Figure 2. Plot of LBR data for treated base course materials (Part 1).

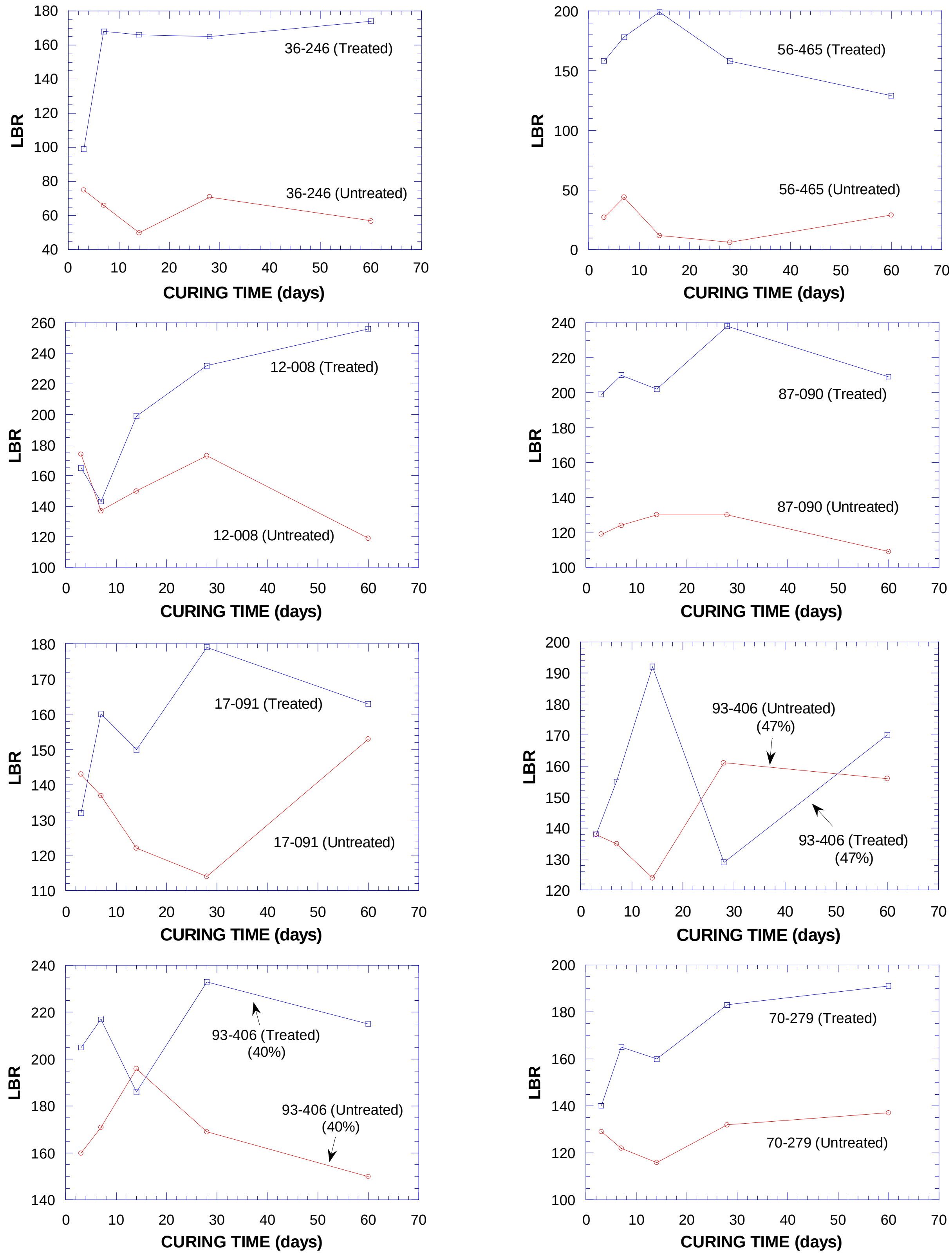

Figure 3. Plots illustrating the differences in LBR test results between untreated and treated base course materials (Part 1).

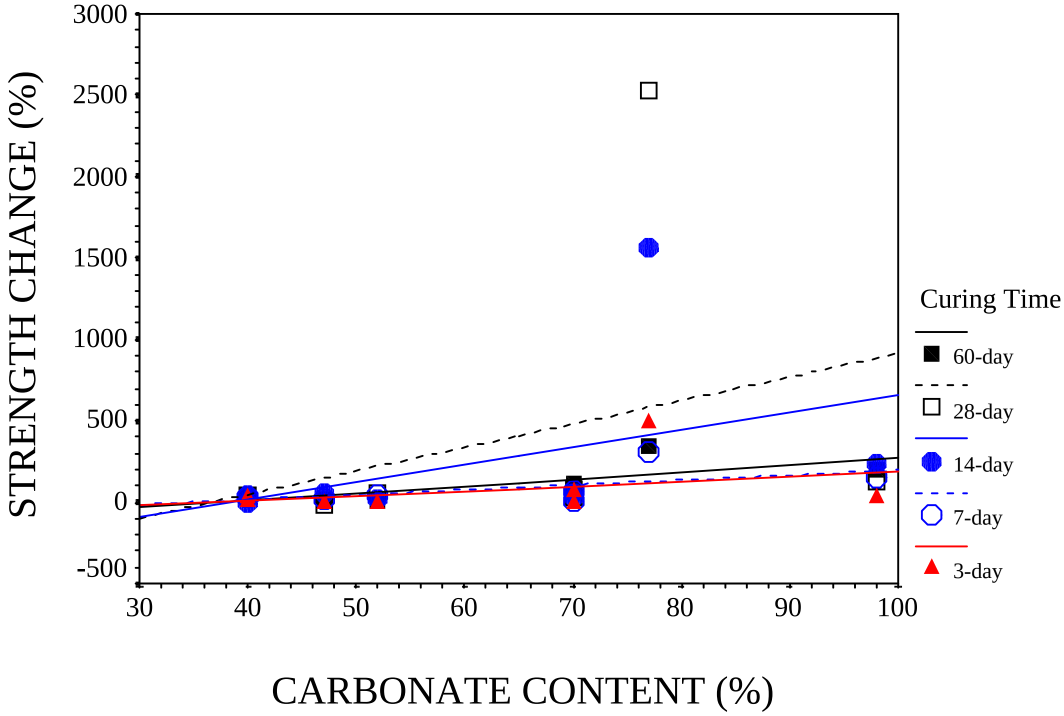

Figure 4. Scatter plot of strength change and carbonate content illustrating the relationship between curing time and the strength difference observed for treated versus untreated samples (Part 1).

respectively). This latter observation is most likely the result of the extreme LBR improvement seen with the samples from Pit No. 56-465 (77% carbonates) causing the poor curve fit.

Analysis of Variables Affecting LBR Values (Part 1)

Untreated Aggregates

In an effort to define the influence of density, moisture content, gradation, and carbonate content on the Limerock Bearing Ratio (LBR) of untreated base course materials, statistical procedures were used to produce graphs of LBR versus carbonate content for use in regression analyses. As a first step in this process, a bivariate correlation matrix which included mineralogical parameters was prepared for both untreated and treated aggregate LBR test variables (Tables 5 and 8). Only correlations possessing a Pearson correlation coefficient ≥ 0.6 were considered significant for this study.

Examination of Table 5 shows that LBR values for untreated aggregate samples exhibit a positive correlation to dry density (0.870) and negative correlations to both carbonate content (-0.679) and moisture content (-0.753). LBR also correlates negatively to calcite content (-0.602), but as calcite is the dominant mineral phase in most of the samples studied, it acts as a proxy for carbonate content. Therefore, LBR-calcite content correlations will not be examined further for this study. Of note, however, is the positive correlation between quartz and aragonite content (0.654), and the negative correlations they have with carbonate content (-0.897 and –0.659, respectively). This suggests that quartz acts as the primary diluting phase for carbonate content, and that samples containing quartz also tend to be more enriched in aragonite relative to calcite as the carbonate phase. This is of interest, as increased carbonate content under these test conditions is associated with an overall decrease in LBR values. Such an observation is in conflict with the hypothesis proposed by this study that high carbonate materials should exhibit greater strength gain due to cementation. A major cause for this conflicting observation is the exceptionally poor test results acquired for 36-246 and 56-465, the materials possessing the highest carbonate contents (98% and 77%, respectively) of those studied. Furthermore, as none of the untreated samples showed any discernable increase in strength with age, it is unlikely that the test parameters employed with this phase of the study (e.g. soaked curing) accurately reproduced the field conditions necessary for cementation.

Scatter plots of dry density, moisture content, carbonate content, and minus #4 (used as a proxy for gradation) versus LBR further illustrate the correlations of these variables for the total data set (Fig. 5). It can be seen that dry density and moisture content mirror one another, reflecting the fact that dry density decreases with increased moisture content. This relationship is driven, in part, by the dry density/moisture content correlation seen with samples from 36-246 and 56-465, which consistently gave poor results in this part of the study. Simple linear regression models for these variables are given in Table 6, and include models derived for the total data set, as well as models derived for the individual curing times of 3-, 7-, 14-, 28-, and 60-days. Regression equations were developed according to the following format:

$$LBR = a + b(var) \qquad \text{eqn. 1}$$

where, LBR = Limerock Bearing Ratio
var = γ_d (Dry density, kg/m^3), MC (Moisture Content, %), CA (Carbonate Content, %), or M4 (Minus #4, %)

The strongest correlation to LBR tests in the regression models remains to be dry density, for both the total data set and the individual curing times, excluding the model for the 7-day curing time. Moisture content shows the strongest correlation for that curing time and is consistently the second strongest correlation other than for the 60-day curing time, for which carbonate content is the second strongest correlation. The content of minus #4 material consistently exhibits the poorest correlation to LBR of any of the other variables. Although the specific gravity of the aggregates from different pits may influence dry density, it is likely that gradation may be a primary reason for the range of dry density values observed with these LBR tests.

Examining the scatter plot for LBR versus dry density in more detail shows that data from individual pits appear to exhibit a positive correlation (Fig. 6). In fact, several of the individual pits tested, including Pit Nos. 36-246 (R^2 = 0.66), 56-465 (R^2 = 0.78), 12-008 (R^2 = 0.76), and 93-406 (47% carbonates) (R^2 = 0.76), show strong correlation to linear regression modeling of this relationship. If not for the variability in test specimen dry density among individual pits, dry density and LBR results would likely not have such an important correlation as seen with this data set.

Table 5. Bivariate correlation matrix for untreated aggregate samples (Part 1)

	CARB. CONT.	DRY DEN.	MOIST. CONT.	LBR	MINUS #4	CALC. CONT.	DOLO. CONT.	QTZ. CONT.	ARAG. CONT.	CURING TIME
CARB. CONT.										
DRY DEN.	-.666** (.000)									
MOIST. CONT.	.577** (.000)	-.840** (.000)								
LBR	-.679** (.000)	.870** (.000)	-.753** (.000)							
MINUS #4	.067 (.680)	-.513** (.001)	.543** (.000)	-.449** (.004)						
CALC. CONT.	.920** (.000)	-.626** (.000)	.385* (.014)	-.602** (.000)	-.048 (.769)					
DOLO. CONT.	.179 (.270)	.334* (.035)	-.230 (.154)	.235 (.144)	-.810** (.000)	.097 (.550)				
QTZ. CONT.	-.897** (.000)	.454** (.003)	-.377* (.016)	.445** (.004)	.346* (.029)	-.858** (.000)	-.477** (.002)			
ARAG. CONT.	-.659** (.000)	.262 (.103)	.010 (.953)	.320* (.044)	.324* (.042)	-.803** (.000)	-.402* (.010)	.654** (.000)		
CURING TIME	.000 (1.000)	-.003 (.985)	.002 (.991)	-.029 (.860)	.000 (1.000)	.000 (1.000)	.000 (1.000)	.000 (1.000)	.000 (1.000)	

Note: Shaded cells indicate correlations considered to be statistically significant for this study (Pearson correlation coefficient ≥ 0.6).

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

( ) sig. (2-tailed), n = 40.

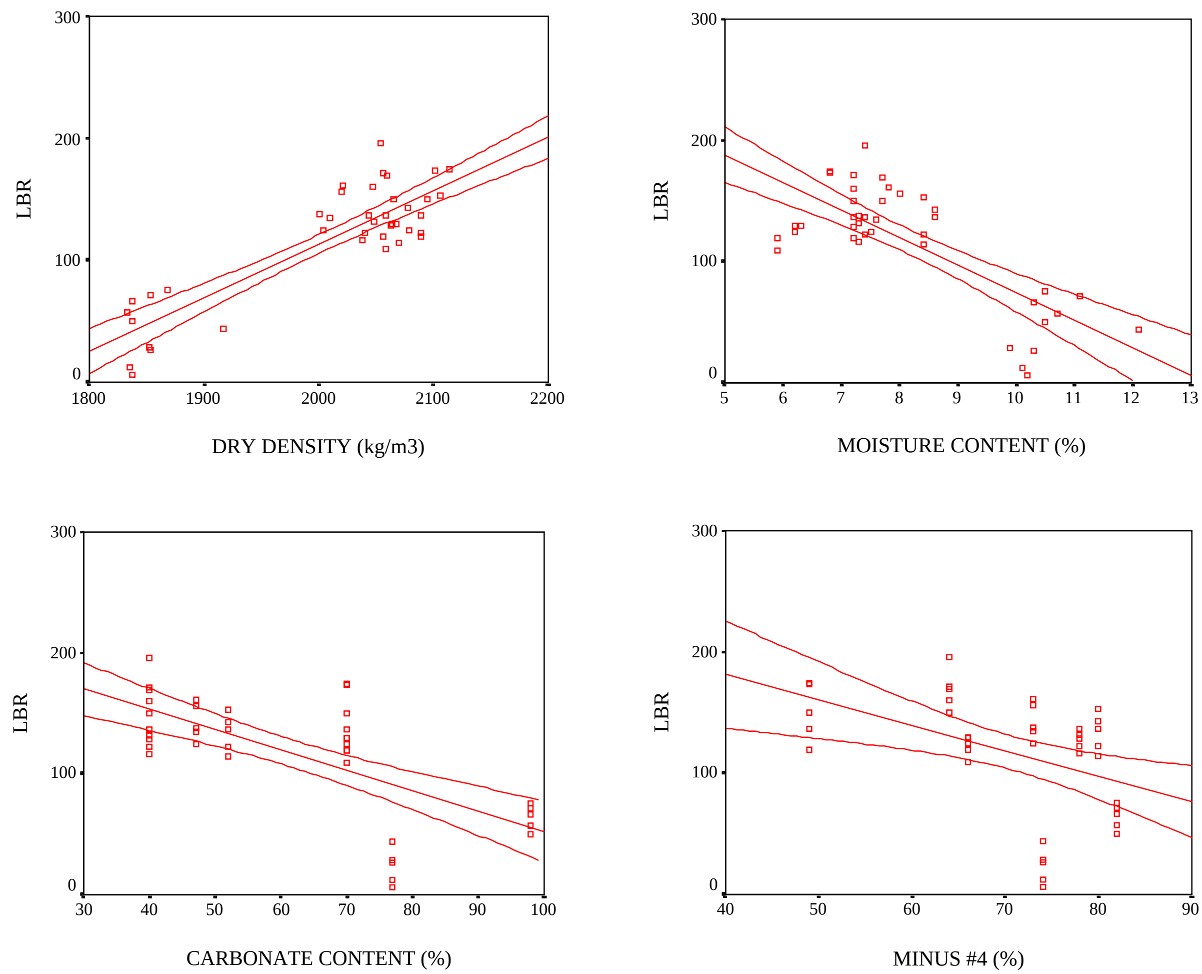

Figure 5. Scatter plots of variables thought to affect LBR test results of untreated aggregate samples (Part 1). (*Note*: Lines surrounding linear regression curves define the 95% confidence interval)

Table 6. LBR linear regression models for untreated aggregate samples (Part 1)

LINEAR REGRES. MODEL	R^2	STD. ERROR OF EST.	UNSTANDARDIZED COEFFICIENTS			
			CONSTANT	STD. ERROR	INDEPENDENT VARIABLE	STD. ERROR
TOTAL						
Dry Den.	0.76	23.98	-763.17	81.11	0.44	0.04
Moist. Cont.	0.57	32.00	302.00	26.79	-22.75	3.23
Carb. Cont.	0.46	35.66	220.23	19.01	-1.68	0.29
Minus #4	0.20	43.41	265.10	48.41	-2.10	0.68
3-DAY						
Dry Den.	0.83	21.26	-780.67	165.60	0.45	0.08
Moist. Cont.	0.58	33.62	295.11	61.84	-21.88	7.61
Carb. Cont.	0.37	41.26	208.12	49.20	-1.42	0.76
Minus #4	0.28	43.95	286.82	109.59	-2.35	1.53
7-DAY						
Dry Den.	0.69	25.13	-662.99	215.92	0.39	0.11
Moist. Cont.	0.74	22.98	270.57	38.33	-18.39	4.49
Carb. Cont.	0.57	29.47	211.11	35.14	-1.52	0.54
Minus #4	0.19	40.25	236.02	100.36	-1.68	1.40
14-DAY						
Dry Den.	0.75	30.77	-823.60	219.62	0.47	0.11
Moist. Cont.	0.65	36.74	360.21	75.87	-30.68	9.26
Carb. Cont.	0.45	45.91	227.94	54.73	-1.87	0.85
Minus #4	0.29	51.94	315.15	129.52	-2.86	1.81
28-DAY						
Dry Den.	0.77	29.36	-855.40	217.26	0.49	0.11
Moist. Cont.	0.61	38.12	339.50	72.52	-26.83	8.69
Carb. Cont.	0.36	49.18	221.69	58.63	-1.66	0.91
Minus #4	0.29	51.58	320.08	128.62	-2.84	1.80
60-DAY						
Dry Den.	0.76	24.79	-669.02	177.80	0.39	0.09
Moist. Cont.	0.40	39.62	270.39	79.98	-19.28	9.69
Carb. Cont.	0.69	28.28	232.26	33.71	-1.92	0.52
Minus #4	0.03	50.27	167.45	125.35	-0.76	1.75

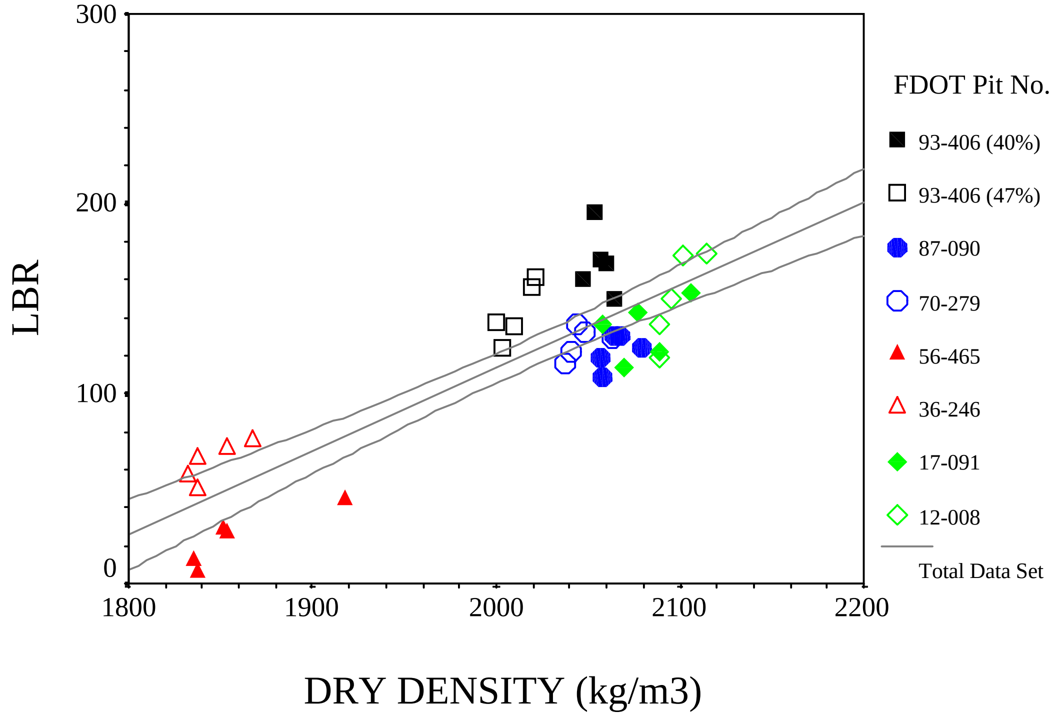

Figure 6. Scatter plot of LBR and dry density illustrating the relationship between pit source and location on the plot for untreated aggregate samples (Part 1).

In an effort to quantify the correlations between LBR values and the variables of dry density, moisture content, and carbonate content, a multiple regression approach was attempted, even though several of the variables appear to be cross-correlated (e.g. dry density and moisture content). Regression analyses for the different curing times (3-, 7-, 14-, 28-, and 60-day) were performed and regression equations developed according to the following equation format:

$$LBR = a + b(\gamma_d) + c(MC) + d(CA) \qquad \text{eqn. 2}$$

where, LBR = Limerock Bearing Ratio
γ_d = Dry density, kg/m^3
MC = Moisture Content, %
CA = Carbonate Content, %

Table 7 presents a comparison of the measured values of untreated samples at different ages with those values predicted by the regression equations. In general, the predicted values are good estimates of the measured LBR values even though the coefficients of determination (R^2) values are not exceptionally good. As seen previously with bivariate correlation and simple regression, dry density has the greatest effect on the LBR values whereas moisture content and percent carbonates have almost no influence on the LBR (probably statistically insignificant).

Table 7. Comparison of measured and predicted LBR values - untreated (Part 1)

PIT NO. (%CARB.)	3-DAY[(a)]		7-DAY[(b)]		14-DAY[(c)]		28-DAY[(d)]		60-DAY[(e)]	
	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.
36-246 (98%)	75	55	66	54	50	25	71	46	57	37
56-465 (77%)	27	51	44	56	12	38	6	35	29	58
12-008 (70%)	174	165	137	128	150	144	173	164	119	127
87-090 (70%)	119	138	124	141	130	140	130	143	109	107
17-091 (52%)	143	153	137	124	122	143	114	154	153	160
93-406 (47%)	138	118	135	136	124	124	161	126	156	131
93-406 (40%)	160	139	171	149	196	144	169	147	150	151
70-279 (40%)	129	146	122	145	116	139	132	139	137	140

Regression Equations:
(a) LBR (3-d) $= -781.97 + 0.4483(\gamma_d) + 1.24(MC) - 0.14(CA)$
$n = 8, R^2 = 0.83$
(b) LBR (7-d) $= 108.61 + 0.0730(\gamma_d) - 11.50(MC) - 0.70(CA)$
$n = 8, R^2 = 0.85$
(c) LBR (14-d) $= -449.92 + 0.3222(\gamma_d) - 6.46(MC) - 0.49(CA)$
$n = 8, R^2 = 0.78$
(d) LBR (28-d) $= -991.69 + 0.5382(\gamma_d) + 4.36(MC) - 0.08(CA)$
$n = 8, R^2 = 0.77$
(e) LBR (60-d) $= -595.75 + 0.3515(\gamma_d) + 7.61(MC) - 0.94(CA)$
$n = 8, R^2 = 0.87$

In an effort to relate LBR values to carbonate content, the multiple regression equations for 3- and 60-days were used to prepare LBR prediction lines using moisture content values of 6% and 12%, and dry density (γ_d) values of 1840 kg/m^3 and 2080 kg/m^3 (Fig. 7). The resulting figure illustrates that moisture content and carbonate content appear to have less affect on LBR results than dry density. As noted before, variations in gradation are believed to be an important factor in producing the range of dry density values encountered with this study. In an effort to reproduce field-like conditions for this study, gradation was not held as a constant, complicating the ability of the LBR tests to elucidate the role of carbonate content in predicting strength gain. Furthermore, as shown in Figure 7, both 3-and 60-day prediction lines indicate that LBR values decrease with an increase in carbonate content. As noted previously, this observation is opposite of what was expected, with the magnitude of the relationship due, in part, to the poor test results achieved for Pit Nos. 36-246 and 56-465. Furthermore, the 3- and 60-day prediction lines overlap, illustrating the lack of an observed strength gain that was expected with this test. This supports the contention that employing a continuous soak method of curing the LBR samples did

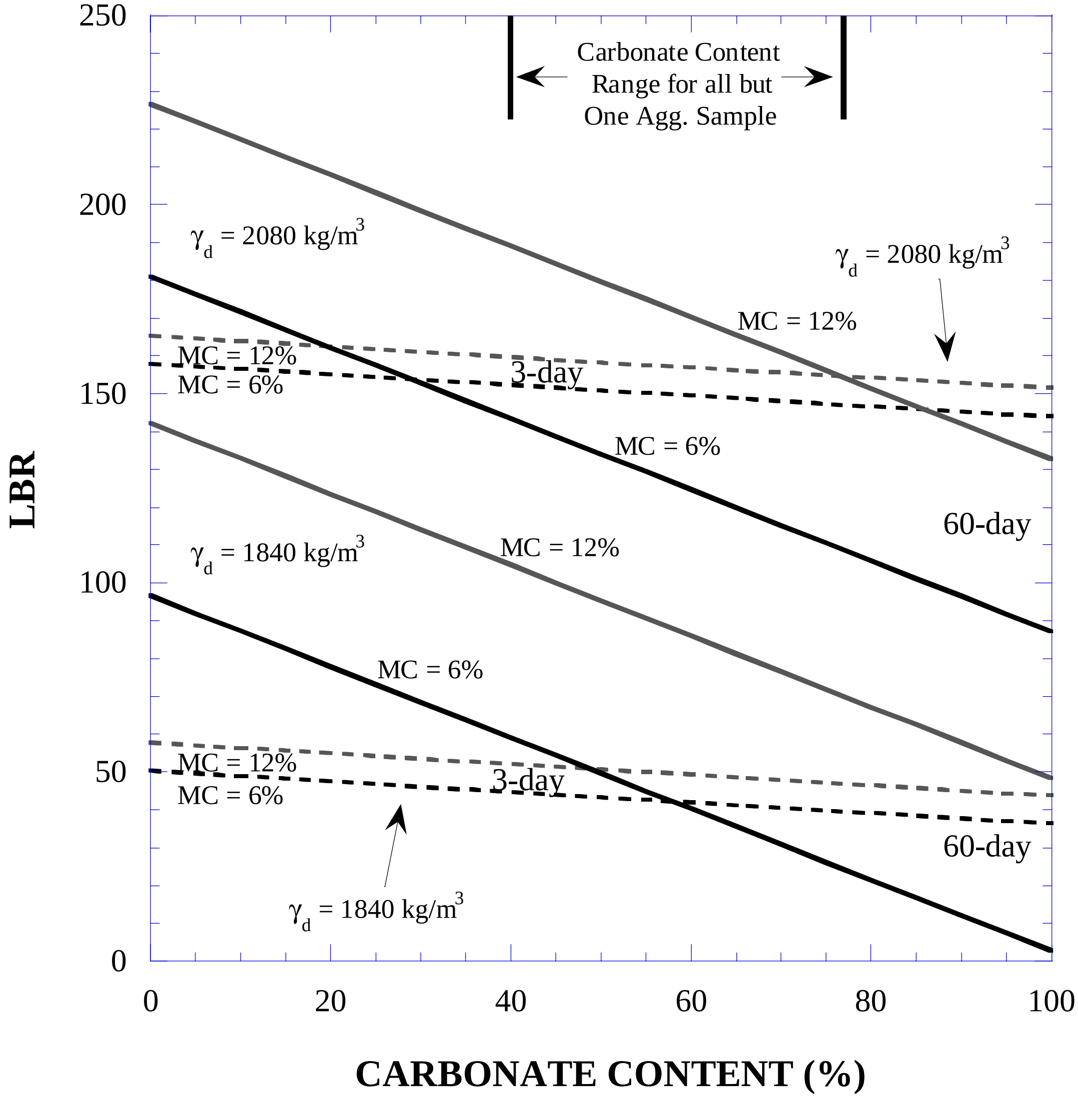

Figure 7. Prediction plot of LBR value as a function of carbonate content for untreated aggregate samples (Part 1). (*Note*: Prediction lines were generated using the 3- and 60 -day regression equations shown in Table 7)

not produce the conditions necessary for subsequent cementation after initial compaction of the samples, or that lithological variability among the samples used in the study prevented observation of this phenomenon. As a result, the prediction lines shown in Figure 7 should not be used to predict LBR test results based on carbonate content for the purpose of estimating field performance.

Treated Aggregates

Specimens prepared with 1.0 percent lime for the purpose of accelerating and/or enhancing the cementing of high carbonate aggregates also were evaluated to assess the effects of dry density, moisture content, carbonate content, and gradation on LBR test results. As outlined in the previous section, the first step was the production of a bivariate correlation matrix (Table 8).

Examination of Table 8 shows no significant correlations (Pearson correlation coefficient ≥ 0.6) between LBR and the variables of interest. The best correlation for LBR is with minus #4 (-0.541), but is insufficient to require detailed discussion other than the observation that an increase in fines appears to accompany a decrease in LBR values. This seems to suggest that either test variability was excessive or there is no relationship between these variables (including carbonate content) and LBR test results.

For the purpose of comparison, scatter plots of dry density, moisture content, carbonate content, and minus #4 versus LBR for the total data set are included (Fig. 8). In agreement with the bivariate correlation matrix, the scatter plots show no visual evidence for correlation of the variables of interest with LBR results. Linear regression models for these variables also are included for comparison to the untreated aggregate sample data (Table 9). As before, they include models according to the format of equation 1 for the total data set, as well as the individual curing times (3-, 7-, 14-, 28-, 60-days).

A review of Table 9 shows that minus #4 correlates best with LBR test results in the 3-day ($R^2 = 0.42$), 14-day ($R^2 = 0.47$), 28-day ($R^2 = 0.47$) and 60-day ($R^2 = 0.65$) regression analyses. Dry density also shows some evidence of correlation to LBR data during later curing times of 28-days ($R^2 = 0.47$) and 60-days ($R^2 = 0.65$). The similarity in coefficients of determination (R^2) for the 28- and 60-day curing times lends further credence to the interpretation that gradation has a major impact on dictating dry density values. There appears to be absolutely no relationship between carbonate content and LBR data for this part of the study.

For comparison to the data calculated for the untreated aggregates, multiple regression analyses were once again performed for the different curing times, although they lack any real statistical significance. Using the same format illustrated with equation 2, these regression equations were used to calculate predicted LBR values (Table 10). A review of Table 10 shows that the predicted values are poor estimates of the measured LBR values, an observation in keeping with the poor statistical basis for the multiple regression analyses.

As with the untreated aggregates, the multiple regression equations for 3- and 60-days were used to prepare LBR prediction lines (Fig. 9). Although they illustrate nothing of statistical significance, the 60-day prediction lines do show a positive correlation between LBR and carbonate content, suggesting that longer curing times may permit high carbonate aggregates to undergo greater strength gain exceeding the LBR values of aggregates with lower carbonate contents, even if the lower carbonate content aggregates have greater initial LBR values. Furthermore, it is still evident that dry density has a major impact on LBR test results, and that gradation plays a significant role in dry density variability. This suggests that greater emphasis should be placed upon selecting suitable gradations to attain a high dry density, which consequently will yield higher LBR values.

If LBR is considered as a relative indicator of base course aggregate strength, then the use of high carbonate aggregates is not necessarily beneficial if low density is achieved. This is clearly illustrated by the LBR test results for Pit No. 56-465, which group into two distinctly different density levels. As a result the 7- and 14-day LBR values are greater than the 28- and 60-day values even though the aggregate contains 77 percent carbonates. Another condition that

Table 8. Bivariate correlation matrix for treated aggregate samples (Part 1)

	CARB. CONT.	DRY DEN.	MOIST. CONT.	LBR	MINUS #4	CALC. CONT.	DOLO. CONT.	QTZ. CONT.	ARAG. CONT.	CURING TIME
CARB. CONT.										
DRY DEN.	-.263 (.101)									
MOIST. CONT.	.667** (.000)	-.426** (.006)								
LBR	-.116 (.478)	.232 (.149)	-.299 (.061)							
MINUS #4	.067 (.680)	-.404** (.010)	.413** (.008)	-.541** (.000)						
CALC. CONT.	.920** (.000)	-.213 (.187)	.479** (.002)	.065 (.690)	-.048 (.769)					
DOLO. CONT.	.179 (.270)	.298 (.062)	-.143 (.379)	.234 (.146)	-.810** (.000)	.097 (.550)				
QTZ. CONT.	-.897** (.000)	.146 (.369)	-.511** (.001)	-.093 (.569)	.346* (.029)	-.858** (.000)	-.477** (.002)			
ARAG. CONT.	-.659** (.000)	-.069 (.672)	-.058 (.724)	-.207 (.201)	.324* (.042)	-.803** (.000)	-.402* (.010)	.654** (.000)		
CURING TIME	.000 (1.000)	-.003 (.984)	-.060 (.715)	.270 (.092)	.000 (1.000)	.000 (1.000)	.000 (1.000)	.000 (1.000)	.000 (1.000)	

Note: Shaded cells indicate correlations considered to be statistically significant for this study (Pearson correlation coefficient ≥ 0.6).

* Correlation is significant at the 0.05 level (2-tailed).

** Correlation is significant at the 0.01 level (2-tailed).

( ) sig. (2-tailed), n = 40.

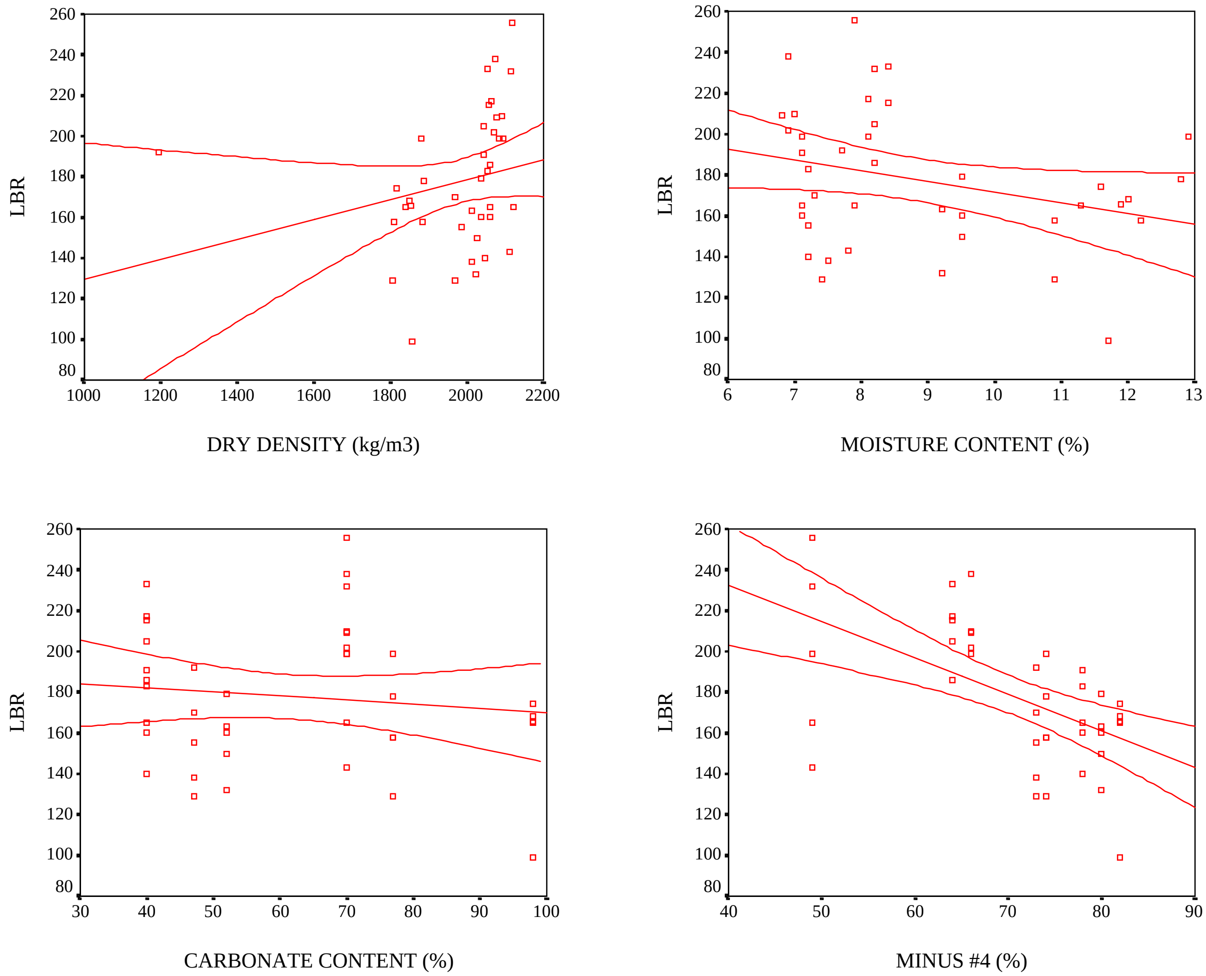

Figure 8. Scatter plots of variables thought to affect LBR test results of treated aggregate samples (Part 1). (*Note*: Lines surrounding linear regression curves define the 95% confidence interval)

is unexplained is why some of the 3-day LBR values for the lime treated aggregates are substantially greater than untreated. Does the addition of lime have an initial modification effect (change in surface chemistry) that alters the LBR values or is this indicative of testing variability? It is the prediction of these strength gain phenomena that was one of the main goals of this research.

Table 9. LBR linear regression models for treated aggregate samples (Part 1)

LINEAR REGRES. MODEL	R^2	STD. ERROR OF EST.	UNSTANDARDIZED COEFFICIENTS			
			CONSTANT	STD. ERROR	INDEPENDENT VARIABLE	STD. ERROR
TOTAL						
Dry Den.	0.05	33.41	80.74	66.08	0.05	0.03
Moist. Cont.	0.09	32.77	224.58	24.78	-5.30	2.74
Carb. Cont.	0.01	34.12	190.21	18.19	-0.20	0.28
Minus #4	0.29	28.89	304.17	32.22	-1.79	0.45
3-DAY						
Dry Den.	0.34	31.01	-291.23	254.74	0.22	0.13
Moist. Cont.	0.21	33.86	226.01	57.65	-8.06	6.35
Carb. Cont.	0.13	35.57	192.81	42.40	-0.62	0.66
Minus #4	0.42	28.92	304.70	72.13	-2.12	1.01
7-DAY						
Dry Den.	0.02	28.03	103.59	221.03	3.53	0.11
Moist. Cont.	0.01	28.19	182.22	42.73	-0.86	4.65
Carb. Cont.	0.01	28.07	183.70	33.47	-0.15	0.52
Minus #4	0.00	28.24	181.30	70.43	-0.10	0.99
14-DAY						
Dry Den.	0.03	21.54	202.36	51.89	-0.01	0.03
Moist. Cont.	0.01	21.74	188.91	34.08	-0.79	3.67
Carb. Cont.	0.04	21.44	170.40	25.56	0.18	0.40
Minus #4	0.47	15.90	272.14	39.65	-1.28	0.56
28-DAY						
Dry Den.	0.47	31.78	-302.32	213.12	0.25	0.11
Moist. Cont.	0.14	40.65	266.75	81.07	-8.84	9.15
Carb. Cont.	0.01	43.58	198.61	51.95	-0.15	0.80
Minus #4	0.47	31.76	371.07	79.20	-2.57	1.11
60-DAY						
Dry Den.	0.65	24.54	-342.17	157.96	0.27	0.08
Moist. Cont.	0.30	34.86	290.89	64.97	-11.85	7.38
Carb. Cont.	0.02	41.23	205.51	49.16	-0.28	0.76
Minus #4	0.65	24.65	391.65	61.48	-2.87	0.86

Table 10. Comparison of measured and predicted LBR values - treated with 1.0 percent lime (Part 1)

PIT NO. (%CARB.)	3-DAY[(a)]		7-DAY[(b)]		14-DAY[(c)]		28-DAY[(d)]		60-DAY[(e)]	
	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.
36-246 (98%)	99	118	168	167	166	181	165	172	174	161
56-465 (77%)	158	132	178	173	199	180	158	141	129	140
12-008 (70%)	165	178	143	177	199	193	232	242	256	241
87-090 (70%)	199	168	210	174	202	190	238	218	209	227
17-091 (52%)	132	165	160	178	150	185	179	205	163	190
93-406 (47%)	138	161	155	171	192	180	129	159	192	170
93-406 (40%)	205	171	214	178	186	184	233	190	215	194
70-279 (40%)	140	169	165	176	160	184	183	186	191	189

Regression Equations:

(a) $LBR\ (3\text{-d}) = -290.45 + 0.2235(\gamma_d) + 2.19(MC) - 0.33(CA)$
$n = 8,\ R^2 = 0.37$

(b) $LBR\ (7\text{-d}) = 42.10 + 0.0599(\gamma_d) + 2.03(MC) - 0.11(CA)$
$n = 8,\ R^2 = 0.02$

(c) $LBR\ (14\text{-d}) = -2.62 + 0.0837(\gamma_d) + 0.86(MC) + 0.19(CA)$
$n = 8,\ R^2 = 0.25$

(d) $LBR\ (28\text{-d}) = -740.11 + 0.4121(\gamma_d) + 6.65(MC) + 0.81(CA)$
$n = 8,\ R^2 = 0.65$

(e) $LBR\ (60\text{-d}) = -533.89 + 0.3409(\gamma_d) + 0.22(MC) + 0.73(CA)$
$n = 8,\ R^2 = 0.76$

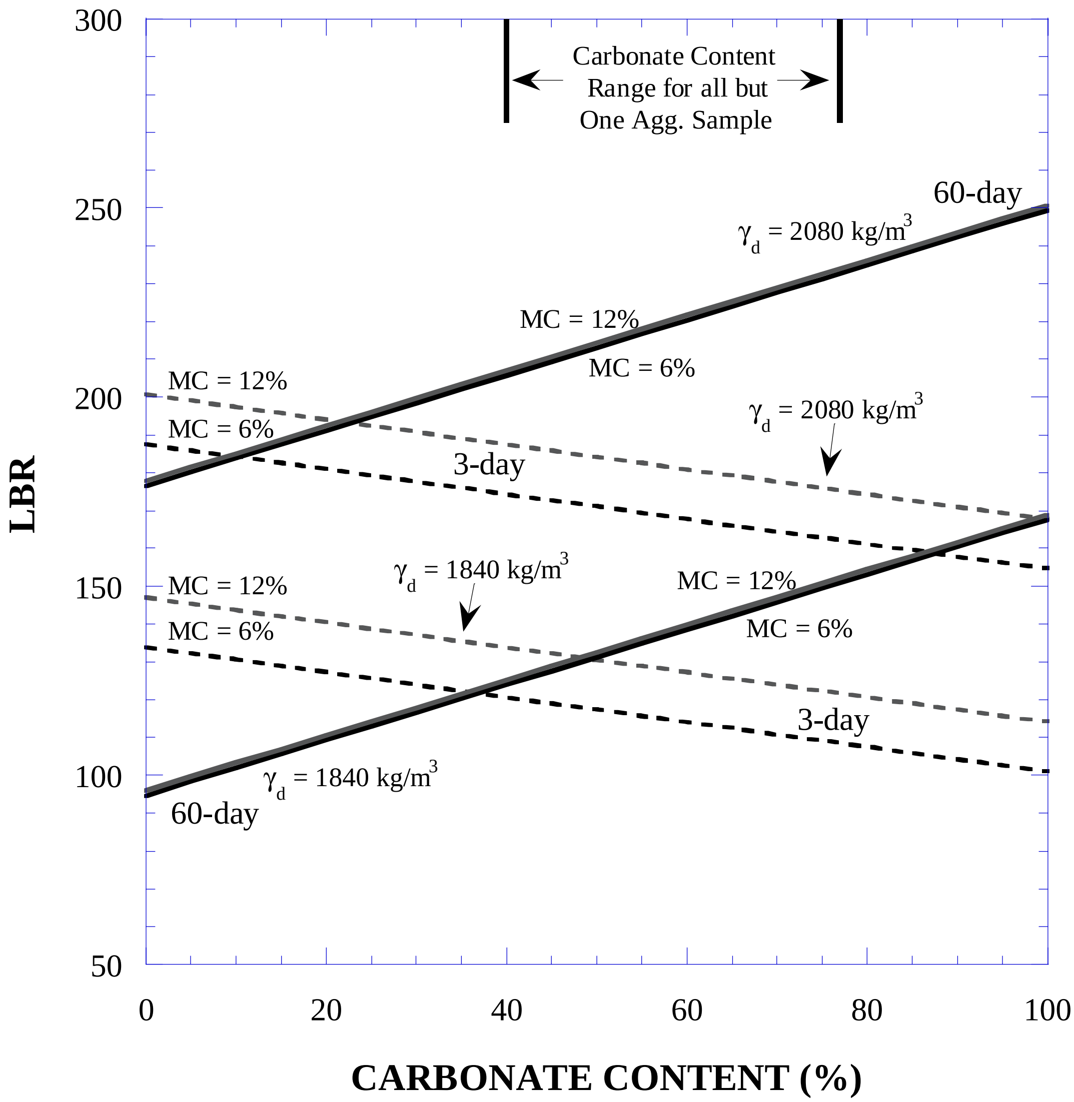

Figure 9. Prediction plot of LBR value as a function of carbonate content for treated aggregate samples (Part 1). (*Note*: Prediction lines were generated using the 3- and 60-day regression equations shown in Table 10)

Materials, Test Specimen Preparation and LBR Testing (Part 2)

For the second part of the LBR study (Part 2), base course aggregates from nine (9) sources (pits) were selected and used to prepare lime treated and untreated test specimens for the purpose of evaluating strength gain effects on the Limerock Bearing Ratio (LBR), as was done in Part 1 of the study. Included with these samples were one (1) sample of recycled crushed concrete aggregate (58-486) and two (2) samples from outside of Florida; MX411 from Mexico and AL-149 from Calera, Alabama. As with the initial set of samples tested, four to five specimens, each at different moisture contents, were compacted according to AASHTO Method T-180 to establish moisture-density curves. The optimum moisture content was determined from these curves for each source (pit) of aggregate. Treated aggregate samples were prepared by adding one (1.0) percent of lime prior to the addition of water. Table 11 presents basic information on the aggregate and optimum moisture content for each source of material, while Table 12 outlines the material type, lithology and mineralogy of the materials studied. Again, the quantitative X-ray diffraction (XRD) data outlined in Table 12 was determined using a Rietveld refinement technique.

Table 11. Composition and optimum moisture contents for base materials (Part 2)

PIT NO.	PERCENT CARBONATES	% PASSING 4.75 mm	% RETAINED 4.75 mm	OPTIMUM MOISTURE CONTENT (%)	
				Untreated	Treated
36-246	98	82	18	12.0	12.0
56-465	77	74	26	12.0	13.0
26-001	99	77	23	12.0	12.0
17-091	52	80	20	9.0	10.0
93-406	47	73	27	7.0	7.0
70-279	40	78	22	7.0	8.0
58-486	---	42	58	10.0	11.0
MX411	99	42	58	8.0	8.0
AL-149	99	51	49	6.0	6.0

For this phase of LBR testing, six samples of untreated and 1.0 percent lime treated materials were prepared for each aggregate source. Pit Nos. 36-246 and 70-279 were an exception, having eight samples of untreated and 1.0 percent lime treated materials prepared. Moisture-density data for the compacted LBR test samples are given in Tables B-1 and B-2 of Appendix B. The dry density (γ_d) values were based upon the test specimen volume, sample weight, and moisture content after LBR testing at the different ages (1, 7, 14, and 28-day). Whereas all samples were tested after curing times of 1, 14, and 28-days, Pit Nos. 36-246 and 70-279 also were tested at a 7-day curing interval.

LBR tests for this second phase of testing were conducted using a modification of Florida test method FM-515, for which samples were placed in a moisture room for curing rather than soaked. This method of curing was used after the techniques applied in Part 1 of the LBR study failed to produce expected results. Current FDOT specifications require a minimum LBR of 100 for compacted base course materials. Test results for the untreated and treated base course

Table 12. Lithology and mineralogy of base course materials (Part 2)

PIT NO.	MATERIAL TYPE	FORMATION	Calcite (%)	Dolomite (%)	Quartz (%)	Aragonite (%)	R (%)*
36-246	Limerock	Ocala	100	---	---	---	5.9
56-465	Limerock	Avon Park	73.6	1.8	12.6	11.9	9.1
26-001	Limerock	Ocala	100	---	---	---	7.7
17-091	Shell	Tamiami	22.2	---	41.9	35.9	18.5
93-406	Shell-rock	Anastasia	38.1	---	37.4	24.6	34.7
70-279	Coquina	Anastasia	31.2	---	58.4	10.4	26.2
58-486	N/S	----------	---	---	---	---	---
MX411	Limerock	----------	100	---	---	---	5.4
AL-149	Limerock	Calera	45.8	53.5	0.7	---	30.0

* R-values are residuals from quantitative Rietveld refinement of XRD data
(a) Sample 58-486 consists of crushed recycled concrete (N/S - no sample analyzed by XRD)

Table 13. LBR values of untreated and treated aggregates (Part 2)

PIT NO. (% CARB.)	36-246 (98%)	56-465 (77%)	26-001 (99%)	17-091 (52%)	93-406 (47%)	70-279 (40%)	58-486 (---)	MX411 (99%)	AL-149 (99%)
1-Day:									
Untreated[a]	128	91*	120	131	161	127	148	218	171
Treated[a]	174	133	155	135	155	148	234	233	193
% Change	36	46	29	3	-4	17	58	7	13
7-Day:									
Untreated[a]	104	---	---	---	---	112	---	---	---
Treated[a]	172	---	---	---	---	150	---	---	---
% Change	65	---	---	---	---	34	---	---	---
14-Day:									
Untreated[a]	111	117	(59)*	(82)*	119	114	207	188	182
Treated[a]	151	176	141	164	204	141	234	232	200
% Change	36	50	139	100	71	24	13	23	10
28-Day:									
Untreated[a]	126	108	113	110	137	123	228	193	145
Treated[a]	152	156	166	158	230	166	243	217	193
% Change	21	44	47	44	68	35	7	12	33

[a] Values are an average of 2 replicate tests.
* Fails FDOT requirement for minimum LBR of 100.
( ) Denotes very low LBR values and significant improvement with the addition of 1.0% lime.

aggregates at the different ages are given in Table 13. Listed LBR values in Table 13 are an average of two tests. Average LBR values for all untreated materials except from Pit 26-001 exceeded 100 and on the average ranged between 105 and 200 (Fig. 10). It should be noted that materials, which produced LBR values below the minimum of 100 from Part 1 of this study (36-246 and 56-465), performed better under the Part 2 testing protocol (36-246: LBR = 118, 56-465: LBR = 105). Only Pit No. 58-486 shows any increased strength trend with age (Fig. 10). All three of the non-Florida samples (58-486, MX411, and AL-149) possess higher LBR values than the Florida samples which are the focus of this study.

Lime treated aggregates on the average varied between an LBR of 149 and 237. Treated aggregates from Pit Nos. 58-486, MX411, AL-149, and 93-406 (47% carbonates) provided the highest mean LBR values (195 to 237). Treated aggregate samples from Pit Nos. 58-486 and 93-406 exhibit increased LBR values with age (Fig. 11). There appears to be only a minor increase in LBR values between untreated and treated materials from Pit Nos. MX411 and AL-149 (Fig. 12). This may be due to test variability (e.g. dry density) masking significant strength gain with age, or due to lithological characteristics causing lime addition to have little effect on strength gain for these materials. All other treated samples show obvious LBR increases with the addition of lime.

The most noticeable increase in LBR values for treated aggregates occurred with materials from Pit Nos. 26-001 and 17-091 (averaging 72% and 49%, respectively), although the magnitude of these increases are not comparable to those observed for Pit Nos. 36-246 and 56-465 (242% and 697%, respectively) in Part 1 of the study. The LBR values for the untreated materials, as given in Table 13, were extremely low, similar to observations for untreated materials in Part 1 of the study. This suggests substandard quality of many of these materials, which could be attributed to moisture-density, gradation, and/or mineral composition (e.g. clay content). It should be noted that the effect of lime treatment on the LBR values for Pit. No. 56-465 were not as dramatic as observed in Part 1 of the study. This might be attributed to a lower clay content in the split used in this phase of the study, or a problem with sample protocol in Part 1 with respect to preparation and curing of untreated Pit No. 56-465 samples.

A scatter plot showing strength change of treated base course samples versus carbonate content was prepared for the total data set (Fig. 13), as was done in Part 1. Linear regression curves fit to the data exhibit fair correlation for the 28-day curing time ($R^2 = 0.32$), and poor to no correlation for the 1- and 14--day curing times ($R^2 = 0.25$ and 0.01, respectively). The lack of correlation seen with the 14-day curing time data is likely due, in part, to the relatively extreme strength gain observed with the samples from Pit Nos. 26-001 (99% carbonates) and 17-091 (52% carbonates). The negative slope observed for the samples cured for 28-days (the only significant correlation) is in conflict with the curve slopes seen in Part 1 of the study, and suggests an overall decrease in strength gain with lime addition for materials with higher carbonate content. The differences in these observations may be due to the different curing protocols used in the two parts of the study, or due to lithological/mineralogical variables (aragonite content) impacting the comparison of test results.

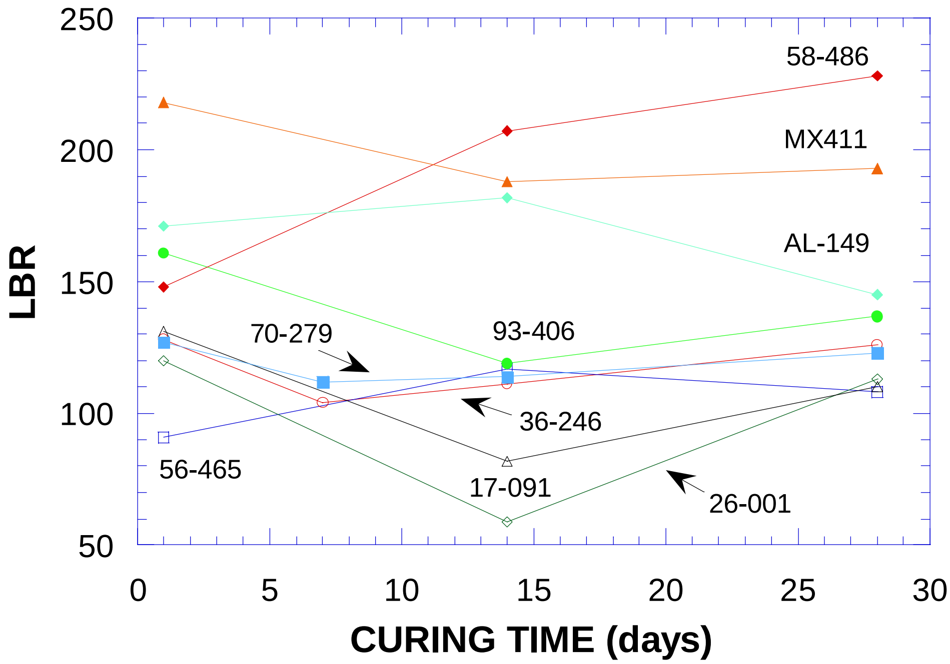

Figure 10. Plot of LBR data for untreated base course materials (Part 2).

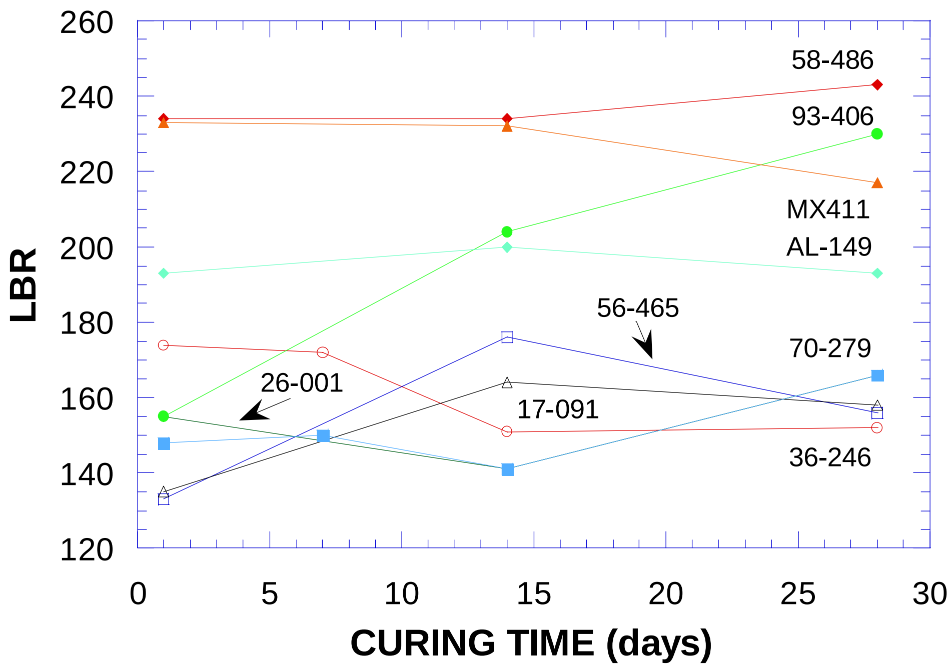

Figure 11. Plot of LBR data for treated base course materials (Part 2).

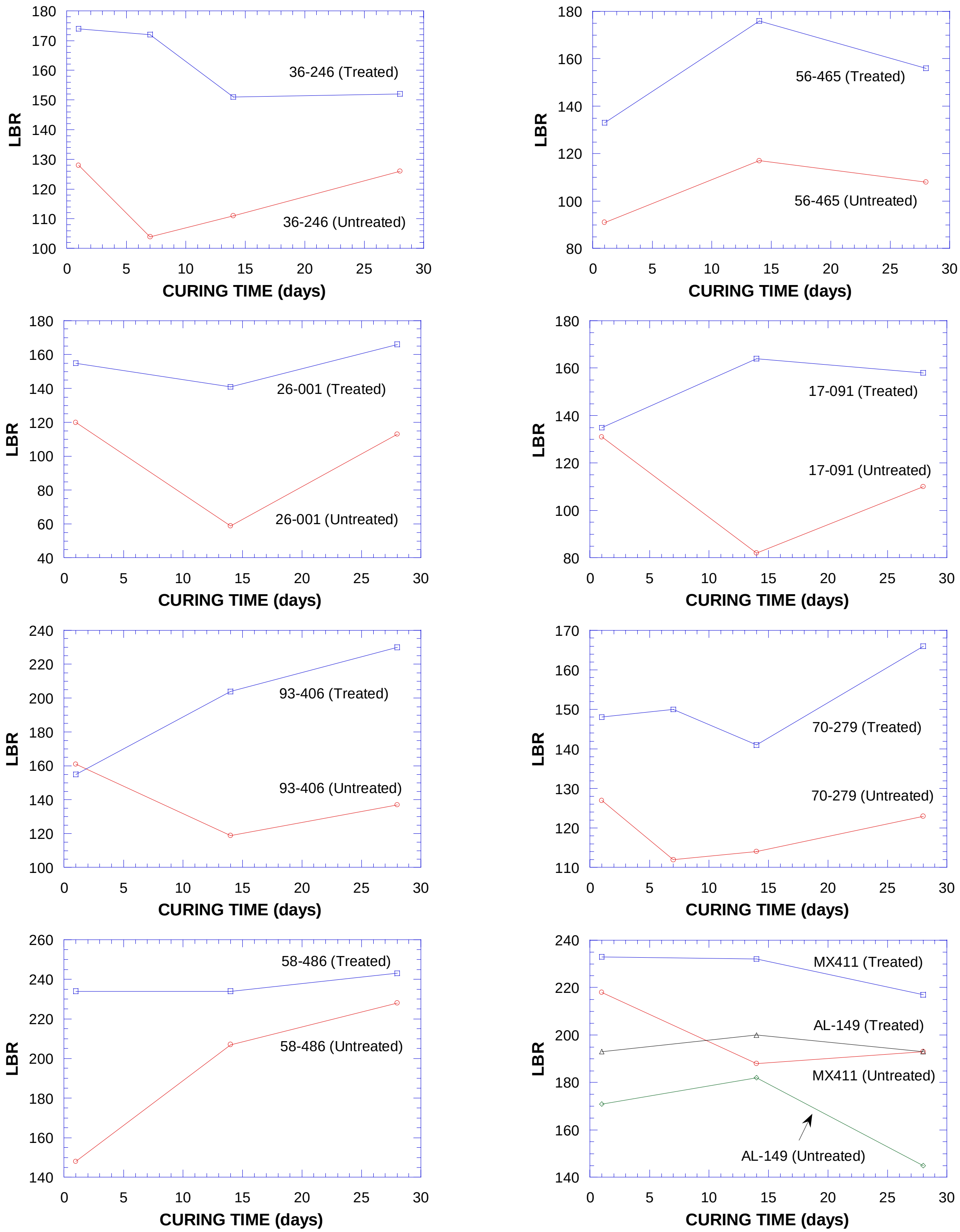

Figure 12. Plots illustrating the differences in LBR test results between untreated and treated base course materials (Part 2).

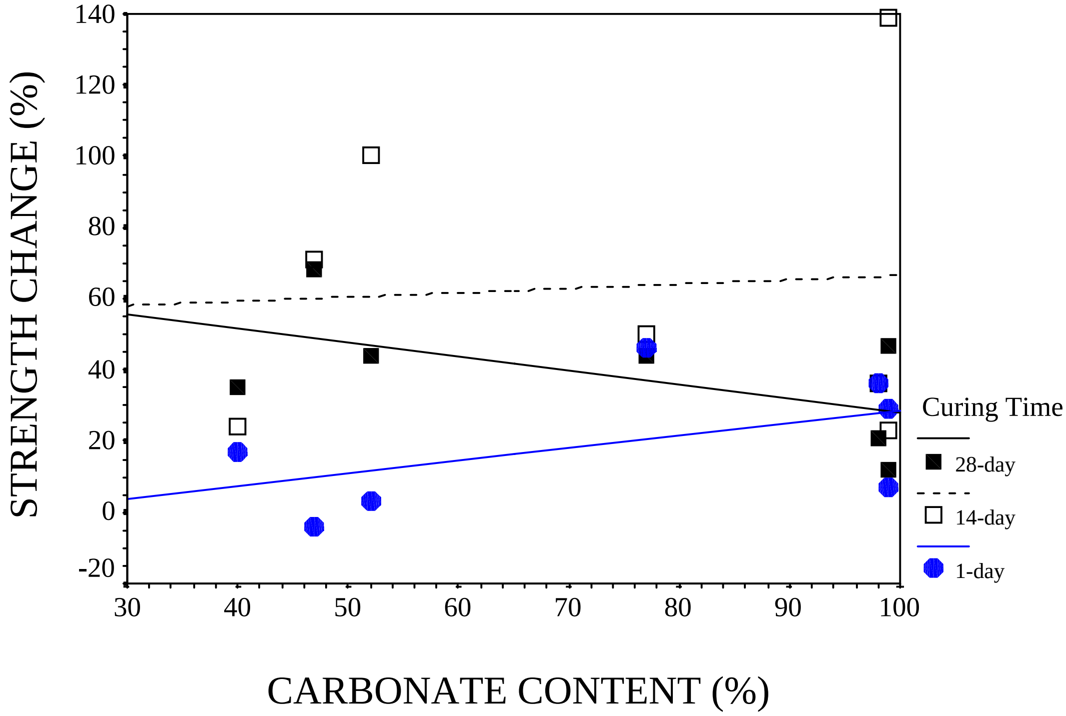

Figure 13. Scatter plot of strength change and carbonate content illustrating the relationship between curing time and the strength difference observed for treated versus untreated samples (Part 2).

Analysis of Variables Affecting LBR Values (Part 2)

Untreated Aggregates

As in Part 1 of this study, an effort was made to define the influence of density, moisture content, and carbonate content on the Limerock Bearing Ratio (LBR) results. For this purpose, these and other variables (gradation, mineralogy, and curing time) were selected for statistical analysis, and used to develop regression equations for comparison to the results obtained in Part 1 of the LBR study. Since Pit No. AL-149 represents a hard Paleozoic age dolomitic limestone significantly different in density and lithology from the "soft" limestones of Florida, it and the recycled crushed concrete sample (Pit No. 58-486) were ignored in the statistical analysis. Pit No. MX411, a "soft" limestone from Mexico, more closely resembles Florida limestone lithologies and was included in the data set. As in Part 1 of the LBR portion of this study, a bivariate correlation matrix, including mineralogical parameters, was prepared for both untreated and treated aggregate materials (Tables 14 and 17). Once again, only correlations possessing a Pearson correlation coefficient ≥ 0.6 were considered significant for this study.

Examination of Table 14 shows that LBR values for untreated aggregate samples exhibit a negative correlation to minus #4 (-0.780), but do not show correlations to dry density (0.518), moisture content (-0.463), and certainly not carbonate content (0.164) that fall within the significance threshold defined for this study (≥ 0.6). This is a significantly different outcome from that seen in Part 1 of the study, where LBR values of untreated samples exhibited fair to good correlation with percent carbonates, moisture content, and dry density. However, in agreement with observations from Part 1, quartz and aragonite content exhibit a positive correlation (0.662), and correlate negatively to carbonate content (-0.980 and –0.743, respectively). Again, this suggests that quartz is the primary diluting phase for carbonate content, and that samples containing quartz also tend to be enriched in aragonite.

As aragonite is metastable with respect to calcite, it is likely to undergo cementation reactions more rapidly than calcite, aiding in the strength gain observed for some aragonite-rich samples. Since overall carbonate content tends to decrease with increasing aragonite content in the samples tested, this confounds our attempt at observing strength gain as a function of carbonate content. This suggests that not only is the carbonate content of a base course material likely of importance in predicting strength gain, but also the knowledge of which carbonate mineral species are present and their relative abundances. Within a single lithology (e.g. Anastasia Formation), one is likely to find that carbonate content does relate to LBR strength gain (Graves, 1987), as long as the relative abundance of carbonate mineral species stay roughly constant. If the relative abundance of aragonite, calcite, and/or dolomite varies, a relationship between carbonate content and strength gain likely will not hold.

Scatter plots of dry density, moisture content, carbonate content, and minus #4 versus LBR for the total data set further illustrate the poor correlations for all variables other than minus #4 (Fig. 14). Dry density and moisture content remain mirror images, due to a strong negative correlation (-0.882) also observed in Part 1 of the LBR study. Linear regression models for these variables are given in Table 15 using the equation 1 format, and include models derived for the total data set, as well as models derived for the individual curing times of 1-, 14-, and 28-days. The only correlation of note remains minus #4, for the total data set and the individual curing times.

A more detailed examination of the scatter plots for minus #4 (Fig. 15) and dry density (Fig. 16) versus LBR gives further insight into these test results. It is evident from the minus #4 versus LBR scatter plot that the strong correlation (R^2 = 0.61) is a direct result of the extreme difference in gradation between MX411 and all other samples tested. As this effectively generates a two-point curve for the regression analysis, the data were examined, excluding MX411, to determine if a correlation exists for the remaining data set. As a result, the remaining data shows no correlation for minus #4 and LBR (R^2 = 0.02). The dry density versus LBR scatter plot shows two important observations. First, the data for Pit Nos. MX411 (R^2 = 0.41) and 93-406 (R^2 = 0.53) do show a correlation for dry density and LBR, and second, these are the two pits that show the greatest variation in dry density data. This latter observation illustrates that the correlations discussed for dry density and LBR in Part 1 of this study are primarily a result of poor sample preparation. Without a wide range in dry density of the samples prepared for testing, this variable would not be of importance. As a result, it is apparent that dry density must be held fairly constant for individual pits if one is to quantify the effects on LBR testing of other variables such as carbonate content.

In an effort to relate the data acquired in this part of the study to that of Part 1, multiple regression analyses were again performed for the different curing times (1-, 14-, and 28-days) in order to quantify the relationship between LBR and the variables of dry density, moisture content, and carbonate content. Although of no statistical significance to this part of the study, the equation 2 format was used to calculate predicted LBR values (Table 16). A review of Table 16 shows that the predicted values are fairly poor estimates of the measured LBR values, in agreement with the poor statistical basis for the multiple regression analyses. Although the coefficient of determination (R^2) is quite good for each of the regression equations derived, this parameter is a poor indicator of the relationship between LBR and the independent variables

Table14. Bivariate correlation matrix for untreated aggregate samples (Part 2)

	CARB. CONT.	DRY DEN.	MOIST. CONT.	LBR	MINUS #4	CALC. CONT.	DOLO. CONT.	QTZ. CONT.	ARAG. CONT.	CURING TIME
CARB. CONT.										
DRY DEN.	-.603** .000									
MOIST. CONT.	.644** .000	-.882** .000								
LBR	.164 .276	.518** .000	-.463** .001							
MINUS #4	-.324* .028	-.505** .000	.383** .009	-.780** .000						
CALC. CONT.	.975** .000	-.622** .000	.592** .000	.189 .208	-.336* .002					
DOLO. CONT.	.065 .665	-.225 .133	.484** .001	-.215 .152	.033 .829	.086 .572				
QTZ. CONT.	-.980** .000	.587** .000	-.672** .000	-.161 .286	.321* .030	-.957** .000	-.160 .289			
ARAG. CONT.	-.743** .000	.552** .000	-.332* .024	-.186 .215	.283 .057	-.851** .000	.020 .895	.662** .000		
CURING TIME	.009 .953	-.009 .954	.003 .986	-.065 .669	-.034 .823	.001 .993	.023 .879	-.018 .905	.029 .850	

Note: Shaded cells indicate correlations considered to be statistically significant for this study (Pearson correlation coefficient ≥ 0.6).
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
( ) sigma (2-tailed), n = 46.

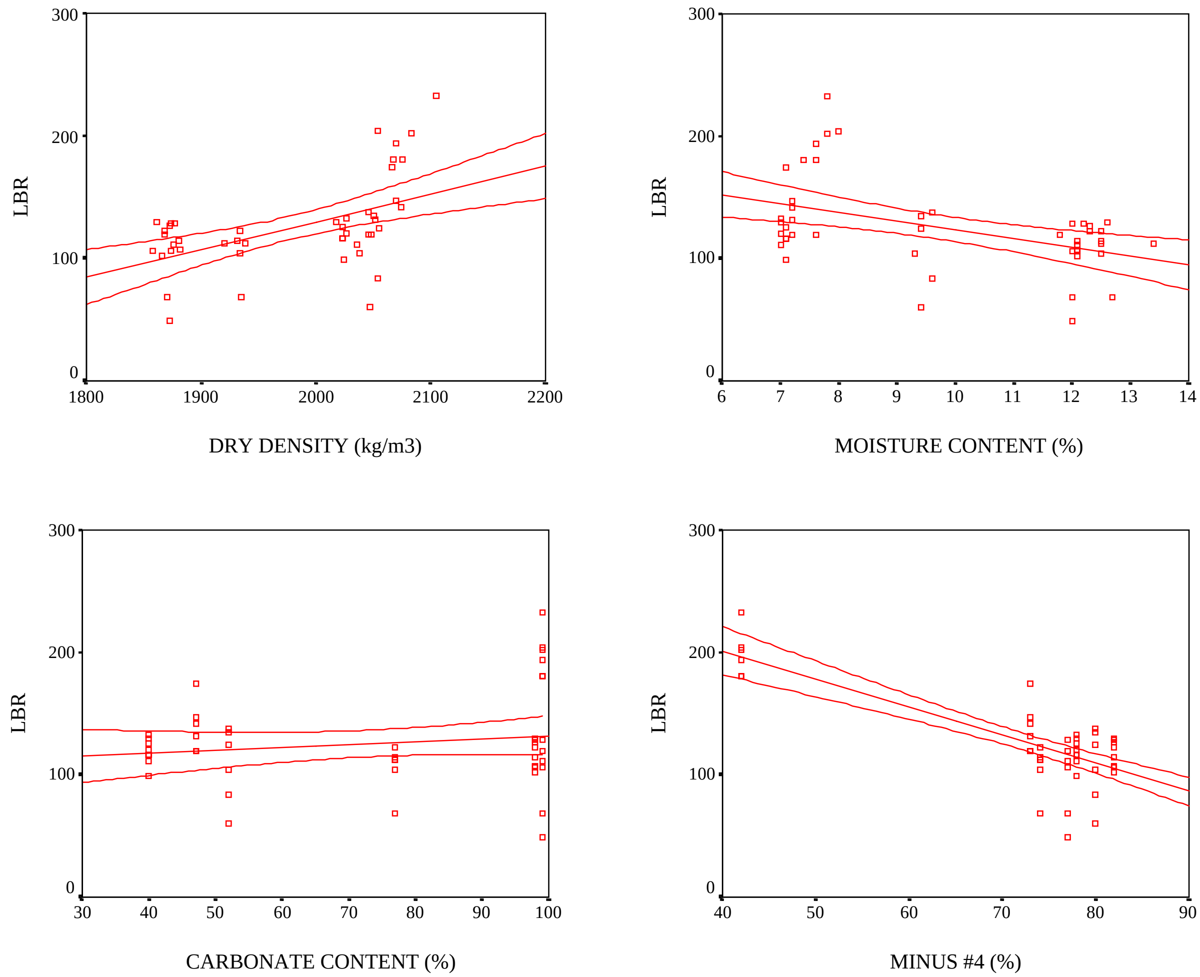

Figure 14. Scatter plots of variables thought to affect LBR test results of untreated aggregate samples (Part 2). (*Note*: Lines surrounding linear regression curves define the 95% confidence interval)

used to construct the equations. Similar to what was observed with Part 1, the overall poor result is most likely a consequence of the small data set (n = 14 for individual curing times), lithological variability among the samples, and internal inconsistencies in the data collected.

Similar to Part 1, the multiple regression equations for 1- and 28-days were used to prepare LBR prediction lines (Fig. 17). As before, moisture content values of 6% and 12%, and dry density (γ_d) values of 1840 kg/m^3 and 2080 kg/m^3 were used in the calculation of the prediction lines. Although the figure illustrates nothing of statistical significance, it suggests there is little to no effect of curing time on the LBR test, and that samples with a low moisture content and high dry density and carbonate content consistently give higher LBR results. As noted previously, dry density plays an important role in the LBR test results, and correspondingly, so does gradation.

Table 15. LBR linear regression models for untreated aggregate samples (Part 2)

LINEAR REGRES. MODEL	R^2	STD. ERROR OF EST.	UNSTANDARDIZED COEFFICIENTS			
			CONSTANT	STD. ERROR	INDEPENDENT VARIABLE	STD. ERROR
TOTAL						
Dry Den.	0.27	31.88	-323.04	111.83	0.23	0.06
Moist. Cont.	0.22	33.02	195.66	20.80	-7.19	2.07
Carb. Cont.	0.03	36.76	108.08	16.72	0.24	0.22
Minus #4	0.61	23.33	293.46	20.62	-2.30	0.28
1-DAY						
Dry Den.	0.41	32.42	-443.84	200.65	0.29	0.10
Moist. Cont.	0.36	33.85	238.05	39.04	-10.12	3.89
Carb. Cont.	0.03	41.77	120.03	35.16	0.26	0.46
Minus #4	0.63	25.63	316.75	39.58	-2.46	0.54
14-DAY						
Dry Den.	0.28	34.94	-395.00	234.06	0.26	0.12
Moist. Cont.	0.20	36.83	183.91	42.13	-7.30	4.19
Carb. Cont.	0.02	40.79	95.98	34.33	0.23	0.45
Minus #4	0.66	23.95	289.39	36.98	-2.45	0.50
28-DAY						
Dry Den.	0.17	29.16	-165.67	187.28	0.15	0.09
Moist. Cont.	0.23	28.14	189.46	32.52	-6.12	3.24
Carb. Cont.	0.08	30.69	104.32	25.84	0.35	0.34
Minus #4	0.72	16.82	273.48	25.98	-1.99	0.35

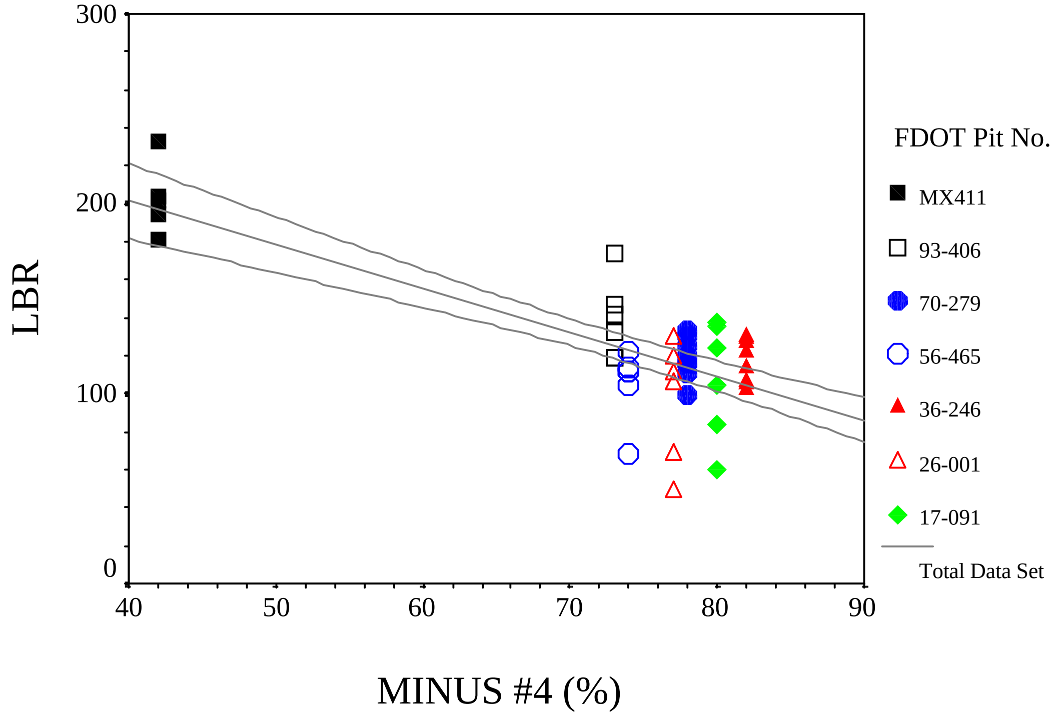

Figure 15. Scatter plot of LBR and minus #4 illustrating the relationship between pit source and location on the plot for untreated aggregate samples (Part 2).

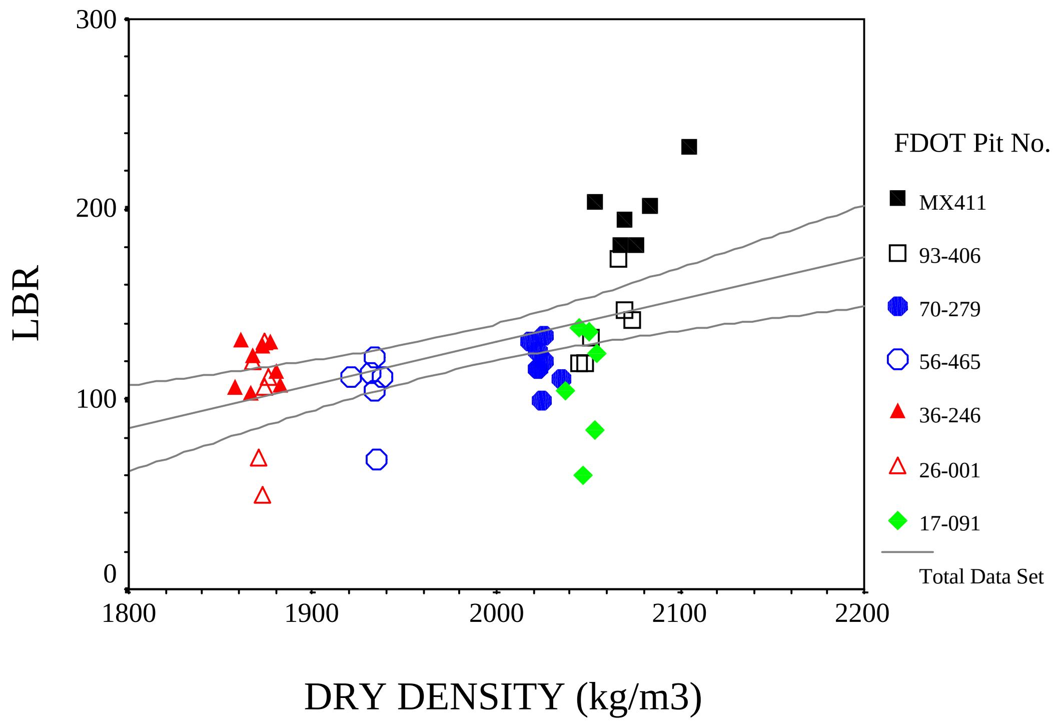

Figure 16. Scatter plot of LBR and dry density illustrating the relationship between pit source and location on the plot for untreated aggregate samples (Part 2).

Table 16. Comparison of measured and predicted LBR values - untreated (Part 2)

PIT NO. (%CARB.)	1-DAY[(a)]		1-DAY[(a)]		14-DAY[(b)]		14-DAY[(b)]		28-DAY[(c)]		28-DAY[(c)]	
	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.
36-246 (98%)	127	117	129	119	107	96	114	95	122	119	130	115
56-465 (77%)	114	98	68	97	122	94	112	87	112	101	104	101
26-001 (99%)	129	122	111	122	68	93	49	93	106	124	119	125
17-091 (52%)	124	128	138	123	104	114	60	118	135	116	84	115
93-406 (47%)	147	151	174	151	119	115	119	116	132	132	142	135
70-279 (40%)	133	135	120	135	111	104	116	99	130	121	116	121
MX411 (99%)	233	222	202	218	194	180	181	182	181	193	204	185

Regression Equations:

(a) $LBR\ (1\text{-d}) = -264.83 + 0.212(\gamma_d) - 12.14(MC) + 1.37(CA)$
$n = 14, R^2 = 0.87$

(b) $LBR\ (14\text{-d}) = -749.86 + 0.404(\gamma_d) - 1.51(MC) + 1.06(CA)$
$n = 14, R^2 = 0.59$

(c) $LBR\ (28\text{-d}) = -116.37 + 0.128(\gamma_d) - 9.63(MC) + 1.17(CA)$
$n = 14, R^2 = 0.79$

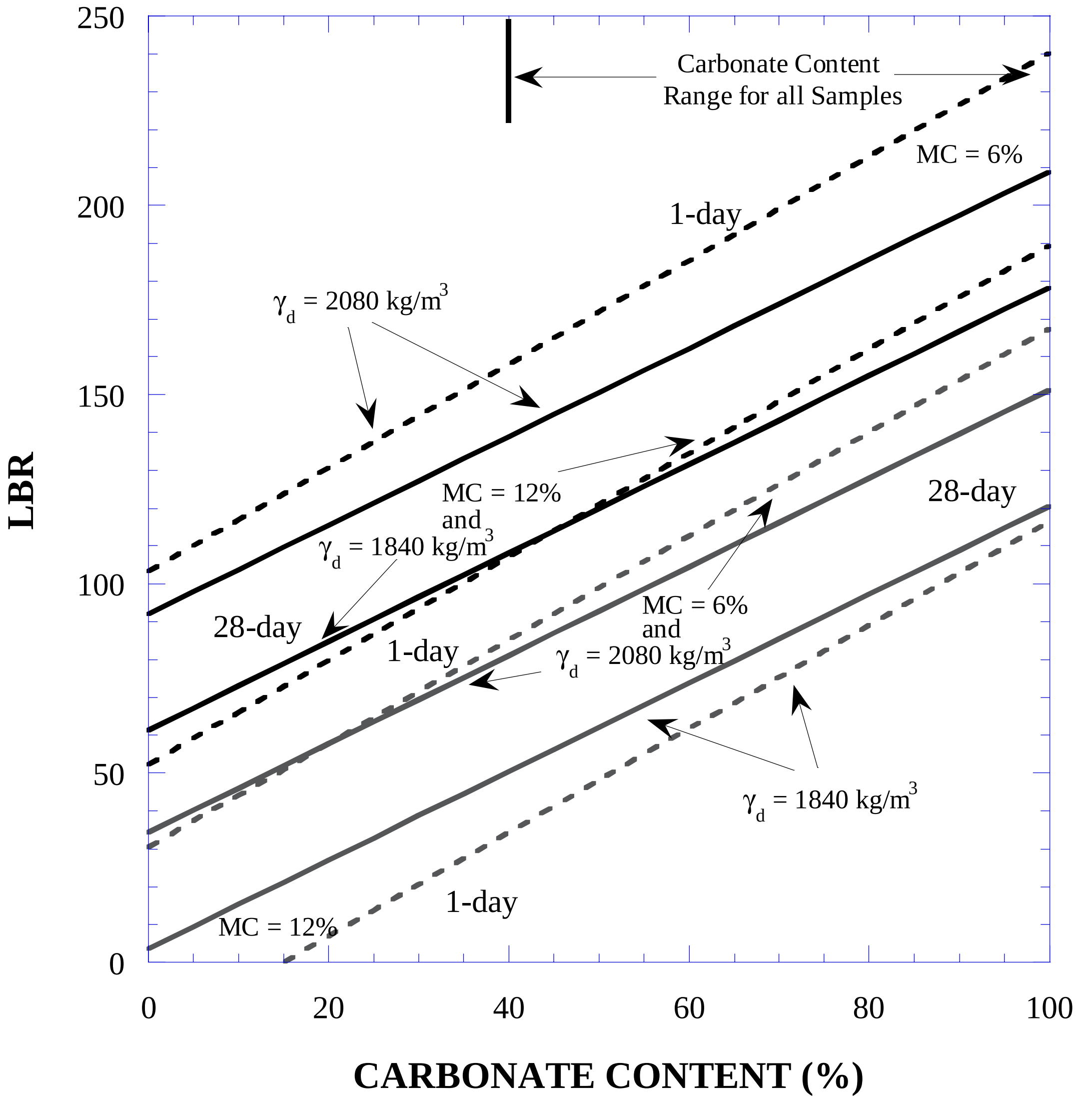

Figure 17. Prediction plot of LBR value as a function of carbonate content for untreated aggregate samples (Part 2). (*Note*: Prediction lines were generated using the 1- and 28-day regression equations shown in Table 16)

Treated Aggregates

As in Part 1 of the study, specimens prepared with 1.0 percent lime for the purpose of accelerating and/or enhancing the cementing of high carbonate aggregates also were evaluated to assess the effects of dry density, moisture content, carbonate content, and gradation on LBR test results. Again, the first step was production of a bivariate correlation matrix (Table 17).

Examination of Table 17 shows that LBR values for treated aggregate exhibit a negative correlation to minus #4 (-0.703), but do not show correlations to dry density (0.342), moisture content (-0.476), or carbonate content (0.199) that are significant (Pearson correlation coefficient ≥ 0.6). For comparison to the untreated aggregate data and data from Part 1 of this study, scatter plots of these variables are included for review (Fig. 18). In agreement with the bivariate correlation matrix, these plots illustrate the same relationships outlined for the untreated samples, with only minus #4 showing any visual evidence of correlation to LBR data. Linear regression models prepared according to that illustrated by equation 1 are included for comparison to the untreated aggregate data and the data from Part 1 (Table 18). As previously, they include models for the total data set, as well as the individual curing times employed with this part of the study (1-, 14-, and 28-days).

A review of Table 18 shows that the correlation for minus #4 remains the only relationship of note for the total data set and the individual curing times. However, one must consider the observation discussed for MX411, where an extreme difference in gradation produces the apparent correlation between minus #4 and LBR values. Again, if the data for MX411 are excluded from the analysis, it is apparent that there is actually no correlation for minus #4 and LBR ($R^2 = 0.08$) for the remaining data set. This suggests that there is either no relationship between these variables, or that lithological and/or test variables preclude identification of these statistical relationships.

In an effort to relate this data to other data in the study, multiple regression analyses were performed for the different curing times (1-, 14-, and 28-days) in order to quantify the relationship between LBR and the variables of dry density, moisture content, and carbonate content. Although of no statistical significance, the equation 2 format was used to calculate predicted LBR values (Table 19). As was observed with the untreated aggregate samples, a review of Table 19 shows that the predicted values are again fairly poor estimates of measured LBR values. Again, although the coefficient of determination (R^2) is quite good for the derived regression equations, the equations lack a good statistical basis.

As with the untreated aggregate samples, multiple regression equations for 1- and 28-days were used to prepare LBR prediction lines (Fig. 19). Although the figure illustrates nothing of statistical significance, it suggests observations similar to those outlined for the untreated aggregate samples, except that with lime treatment, carbonate content seems to have far less effect on strength gain of samples cured for longer periods (28-day), and that the lower dry density samples seem to exhibit greater LBR values with longer curing times (28-day) as well. This latter observation may be related to the effect of lime addition to the high carbonate base materials from Pit Nos. 36-246, 56-465, and 26-001, which possess relatively low dry densities. As discussed in the work of Graves (1987), lime addition was found to have the greatest effect for strength gain in high carbonate base course materials versus what was observed with lower carbonate materials containing a greater percentage of quartz sand.

As suggested in Part 1 of the study, if LBR is considered as a relative indicator of base course aggregate strength, then the use of high carbonate aggregates is not necessarily beneficial based on this data set. However, carbonate content has been documented to effect strength gain in both the laboratory and field by cementation (Gartland, 1979; Zimpfer, 1981; Graves, 1987). In the research done by Graves (1979), samples of cemented coquina base course quarried from

Table 17. Bivariate correlation matrix for treated aggregate samples (Part 2)

	CARB. CONT.	DRY DEN.	MOIST. CONT.	LBR	MINUS #4	CALC. CONT.	DOLO. CONT.	QTZ. CONT.	ARAG. CONT.	CURING TIME
CARB. CONT.										
DRY DEN.	-.676** .000									
MOIST. CONT.	.515** .000	-.891** .000								
LBR	.199 .186	.342* .020	-.476** .001							
MINUS #4	-.324* .028	-.414** .004	.462** .001	-.703** .000						
CALC. CONT.	.975** .000	-.673** .000	.451** .002	.221 .139	-.336* .002					
DOLO. CONT.	.065 .665	-.322* .029	.544** .000	-.174 .248	.033 .829	.086 .572				
QTZ. CONT.	-.980** .000	.687** .000	-.530** .000	-.236 .114	.321* .030	-.957** .000	-.160 .289			
ARAG. CONT.	-.743** .000	.506** .000	-.230 .124	-.132 .382	.283 .057	-.851** .000	.020 .895	.662** .000		
CURING TIME	.009 .953	-.050 .740	.014 .925	.202 .178	-.034 .823	.001 .993	.023 .879	-.018 .905	.029 .850	

Note: Shaded cells indicate correlations considered to be statistically significant for this study (Pearson correlation coefficient ≥ 0.6).
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
( ) sigma (2-tailed), n = 46.

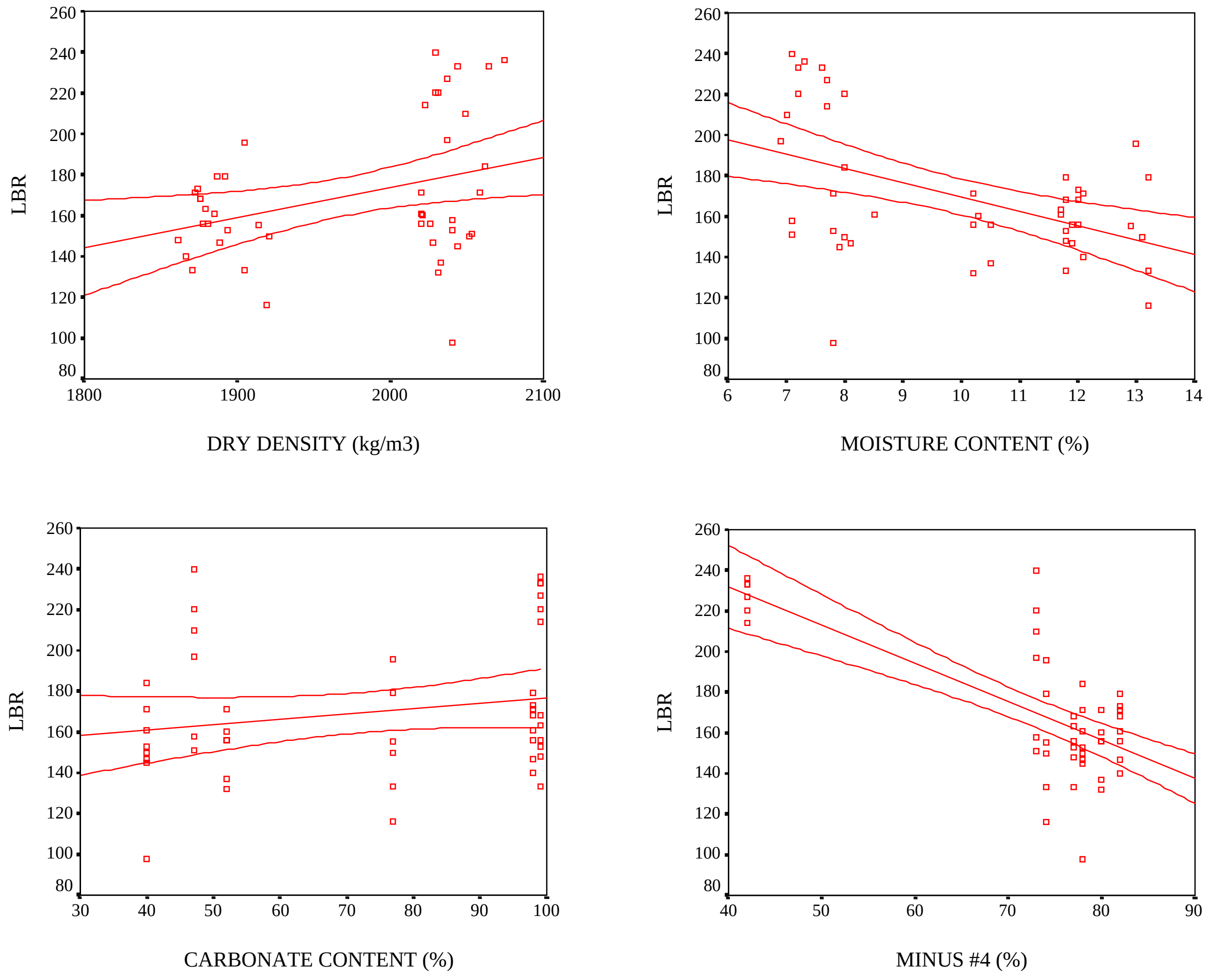

Figure 18. Scatter plots of variables thought to affect LBR test results of treated aggregate samples (Part 2). (*Note*: Lines surrounding linear regression curves define the 95% confidence interval)

the Anastasia Formation were cored from in-service highways (3-5 years) in southeast Florida, and showed strong evidence for cementation in the materials as a function of carbonate content. Furthermore, these observations agreed with cementation effects observed for LBR tests performed to illustrate strength gain due to the cementation phenomenon, and agreed with the laboratory based observations of both Gartland (1979) and Zimpher (1981). Based on these observations, it is likely that this database does not allow for the quantification of the effect that carbonate content has on strength gain due to the many competing variables observed in the data, including dry density, moisture content, gradation, carbonate content, carbonate mineralogy, quartz sand content, and general lithological variability. If more variables were held constant, it might be more probable to quantify the role of carbonate content.

Table 18. LBR linear regression models for treated aggregate samples (Part 2)

LINEAR REGRES. MODEL	R^2	STD. ERROR OF EST.	UNSTANDARDIZED COEFFICIENTS			
			CONSTANT	STD. ERROR	INDEPENDENT VARIABLE	STD. ERROR
TOTAL						
Dry Den.	0.12	31.80	-121.32	120.44	0.15	0.06
Moist. Cont.	0.23	29.76	240.20	20.12	-7.07	1.97
Carb. Cont.	0.04	33.17	150.48	15.09	0.26	0.20
Minus #4	0.49	24.06	307.23	21.27	-1.89	0.29
1-DAY						
Dry Den.	0.05	34.38	-23.85	242.23	0.09	0.12
Moist. Cont.	0.19	31.69	223.42	37.88	-6.22	3.71
Carb. Cont.	0.30	29.40	107.95	24.75	0.73	0.32
Minus #4	0.70	19.30	316.64	29.81	-2.15	0.41
14-DAY						
Dry Den.	0.23	35.01	-264.20	229.03	0.22	0.12
Moist. Cont.	0.21	35.52	246.73	42.72	-7.51	4.20
Carb. Cont.	0.01	39.80	162.07	33.50	0.14	0.43
Minus #4	0.52	27.68	324.20	42.75	-2.10	0.58
28-DAY						
Dry Den.	0.29	28.48	-277.43	208.36	0.23	0.11
Moist. Cont.	0.57	22.10	285.73	27.77	-10.76	2.70
Carb. Cont.	0.01	33.47	188.12	28.17	-0.14	0.37
Minus #4	0.39	26.40	287.86	40.77	-1.52	0.56

Table 19. Comparison of measured and predicted LBR values – treated with 1.0 percent lime (Part 2)

PIT NO. (%CARB.)	1-DAY[(a)]		1-DAY[(a)]		14-DAY[(b)]		14-DAY[(b)]		28-DAY[(c)]		28-DAY[(c)]	
	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.
36-246 (98%)	168	161	179	164	161	160	140	152	147	166	156	167
56-465 (77%)	150	131	116	129	155	155	196	151	179	138	133	136
26-001 (99%)	153	167	156	164	133	154	148	150	163	172	168	170
17-091 (52%)	137	136	132	138	171	174	156	174	156	161	160	160
93-406 (47%)	151	159	158	157	197	169	210	174	240	211	220	210
70-279 (40%)	150	142	145	141	98	165	184	176	171	193	161	187
MX411 (99%)	233	234	233	227	227	224	236	240	214	216	220	209

Regression Equations:

(a) $LBR\ (1\text{-d}) = -214.62 + 0.177(\gamma_d) - 7.89(MC) + 1.41(CA)$
$n = 14, R^2 = 0.91$

(b) $LBR\ (14\text{-d}) = -870.22 + 0.478(\gamma_d) + 2.49(MC) + 1.02(CA)$
$n = 14, R^2 = 0.50$

(c) $LBR\ (28\text{-d}) = 652.26 - 0.164(\gamma_d) – 16.96(MC) + 0.26(CA)$
$n = 14, R^2 = 0.67$

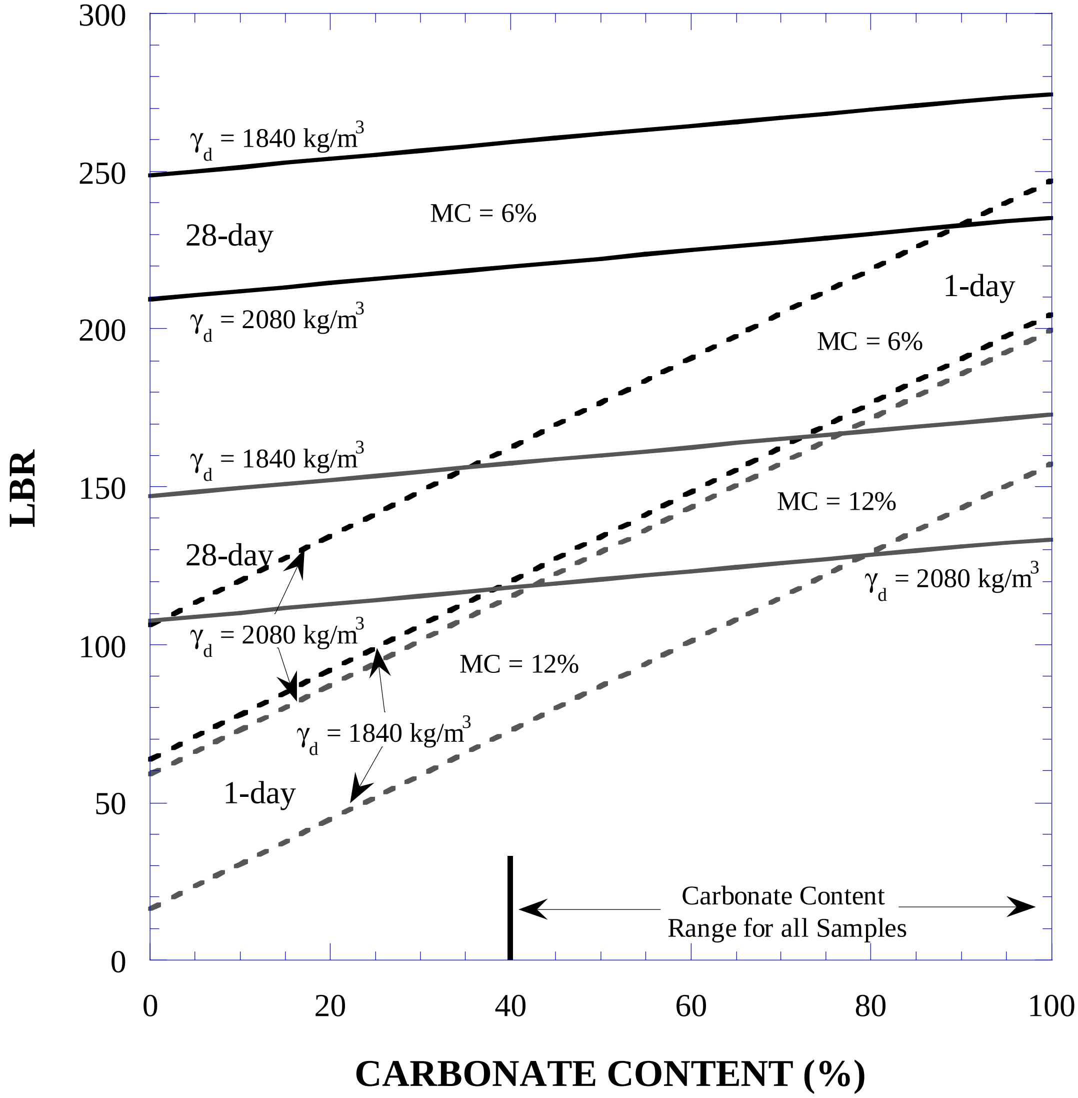

Figure 19. Prediction plot of LBR value as a function of carbonate content for treated aggregate samples (Part 2). (*Note*: Prediction lines were generated using the 1- and 28-day regression equations shown in Table 19)

TRIAXIAL SHEAR TESTS, RESULTS AND ANAYSIS

Test Specimen Preparation and Testing

In this phase of the study, one high carbonate (36-246) and one low carbonate (70-279) base course sample was selected to determine if the shear strength parameters of cohesion (C) and angle of internal friction (Φ) would identify differences in aggregate properties and degree of cementation. Modified Proctor compacted samples were prepared with and without 1.0 percent lime at optimum moisture content using granular base materials from Pit Nos. 36-246 and 70-276 which had 98 percent and 44 percent carbonates of calcium and magnesium, respectively. Six samples were prepared from each pit as both untreated and 1.0 percent lime treated (12 total samples). Two replicate samples were tested at each time period (1-, 7-, and 30-days). Triaxial compression tests were performed at confining pressures of 34.5 kPa and 138 kPa (5 and 20 psi, respectively). Test data report sheets are given in Appendix C.

Test Results and Analyses

A summary of the test results is presented in Table 20. The only sample to show a consistent increase in cohesion (C) with an increase in curing time was the untreated material from Pit No. 70-279 (Fig. 20). All other samples exhibited inconsistent cohesion data. Moreover, the treated samples from both pits exhibit a consistent slight increase in Φ with an increase in curing time (Fig. 21). The data not only suggest that the lime addition improves Φ with time, but also that the lime treated aggregate specimens achieved higher Φ values than the untreated materials. The low carbonate material from Pit No. 70-279 appeared to benefit more from lime treatment than the Pit No. 36-246 aggregates. The mean Φ value increased about 6 degrees with the addition of lime as compared to about 4 degrees for the high carbonate aggregates. This may be due to the reduction in dry density (γ_d) obtained with the lime treatment of Pit No. 36-246 samples. Conversely, material from Pit No. 70-279 increased in γ_d when lime was added.

A plot comparing the percentage of change in the values for both cohesion (C) and the angle of internal friction (Φ) between untreated and treated samples was prepared for Pit Nos. 36-246 and 70-279 (Fig. 22). The figure suggests that the majority of change caused by lime treatment for values of cohesion occur early during curing, while the majority of change observed for values of Φ seems to be concentrated more in the 30-day curing time values. Only the line illustrating the change in Φ values for 36-246 shows a consistent trend, exhibiting an increase in change with increased curing time.

Triaxial shear test data for Pit Nos. 36-246 and 70-279 were analyzed and tangent moduli computed for confining pressures of 34.5 kPa and 138 kPa (5 and 20 psi, respectively). Values for treated and untreated base materials were determined for the 1, 7, and 30 day tests (Appendix D). The results in Table 21 are somewhat difficult to interpret, probably due to the combination of test variability and data interpretation. In general, time (age) effects were not noticeable. The mean values indicate a slight increase in tangent modulus with increasing confining pressure and for treated versus untreated materials. These moduli are exceedingly low in relation to values obtained in the field from plate bearing and nondestructive tests (e.g. Dynaflect or FWD),

Table 20. Summary of shear strength parameters from triaxial tests

PIT NO./ CONDITION	AGE (days)	MOISTURE CONTENT w %	DRY DENSITY γ_d (kg/m^3)	SHEAR STRENGTH PARAMETERS	
				C (kPa)	Φ (degrees)
36-246/untreated	1	10.0	1899		
	1	10.3	1890	81.4	48.0
	7	10.4	1893		
	7	10.2	1893	69.6	46.2
	30	10.4	1866		
	30	10.4	1882	125.5	46.9
	Mean	10.3	1887	92.2	47.0
36-246/treated	1	10.0	1869		
	1	10.2	1856	131.0	49.0
	7	10.2	1857		
	7	10.1	1866	63.4	51.1
	30	10.1	1860		
	30	9.9	1861	118.6	53.3
	Mean	10.1	1861	104.3	51.1
Change (%)	1	---	---	60.9	2.1
	7	---	---	-8.9	10.6
	30	---	---	-5.5	13.7
	Mean	---	-1.4	13.12	8.7
70-279/untreated	1	7.1	2022		
	1	7.1	2026	60.0	42.5
	7	7.1	2036		
	7	7.1	2026	64.8	45.0
	30	7.2	2039		
	30	7.0	2036	83.4	39.4
	Mean	7.1	2031	69.4	42.3
70-279/treated	1	7.0	2053		
	1	7.2	2049	56.5	47.7
	7	7.1	2043		
	7	7.2	2042	102.0	48.8
	30	7.2	2037		
	30	7.2	2042	55.2	49.5
	Mean	7.2	2044	71.2	48.7
Change (%)	1	---	---	-5.8	12.2
	7	---	---	57.4	8.4
	30	---	---	-33.8	25.6
	Mean	---	0.6	2.6	15.1

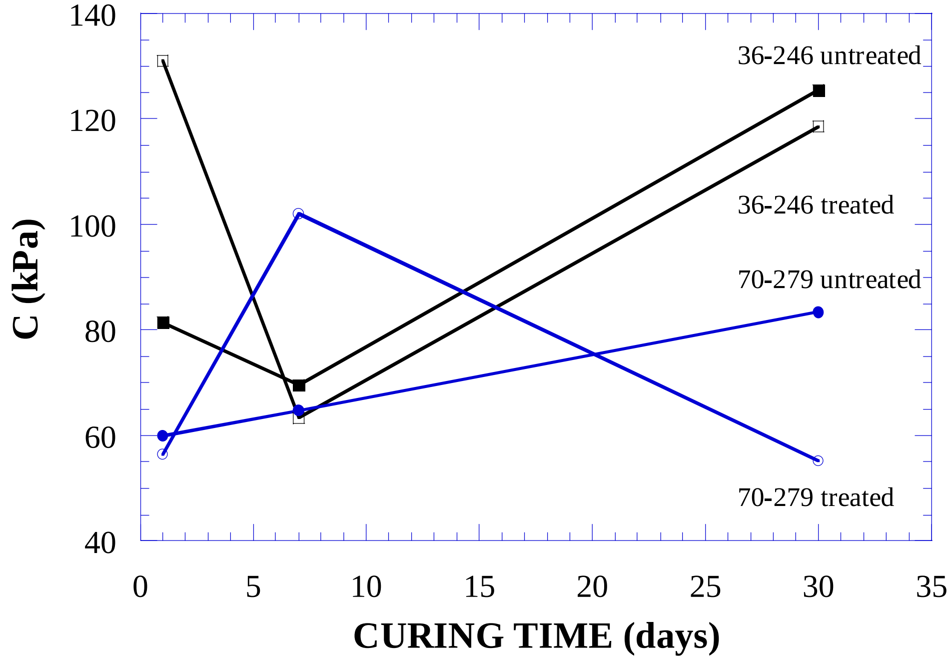

Figure 20. Plot of cohesion (C) versus curing time for both untreated and treated base course materials from Pit Nos. 36-246 and 70-279.

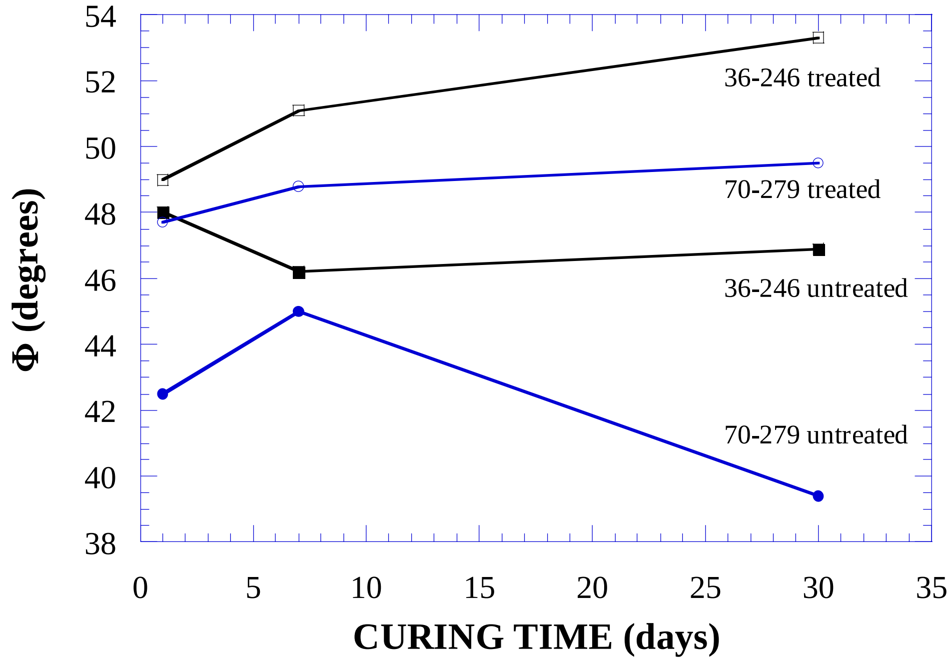

Figure 21. Plot of angle of internal friction (Φ) versus curing time for both untreated and treated base course materials from Pit Nos. 36-246 and 70-279.

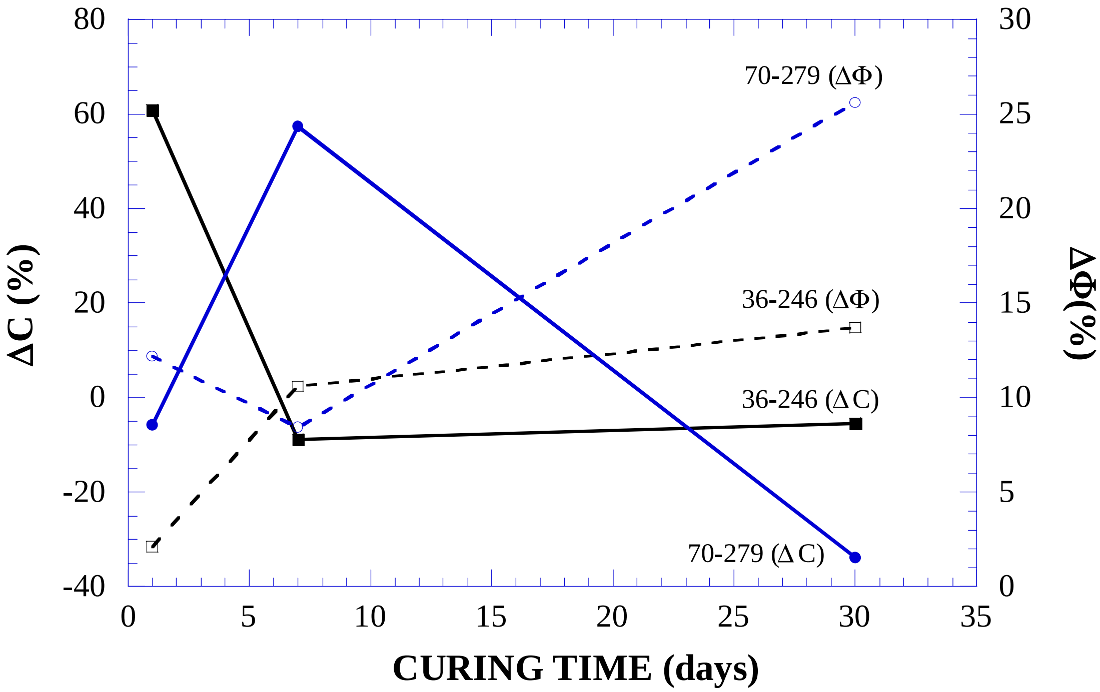

Figure 22. Plot of the percentage change in cohesion (C) and angle of internal friction (Φ) versus curing time for base course materials from Pit Nos. 36-246 and 70-279.

although it is difficult to compare these tests to the triaxial shear test results due to differences in strain conditions.

Table 21. Tangent moduli derived from triaxial shear tests

TIME (days)	CONFINING PRESSURE	PIT 36-246 UNTREATED Modulus (psi)	PIT 36-246 TREATED Modulus (psi)	PIT 36-246 CHANGE (%)	PIT 70-279 UNTREATED Modulus (psi)	PIT 70-279 TREATED Modulus (psi)	PIT 70-279 CHANGE (%)
1	5 psi	8125.0	12216.7	50.4	5990.9	6426.4	7.3
	20 psi	15930.0	18714.3	17.5	10975.0	11175.0	1.8
7	5 psi	7890.9	9633.3	22.1	7518.2	8440.0	12.3
	20 psi	11612.5	12807.1	10.3	12083.3	13083.3	8.3
30	5 psi	11514.3	12971.4	12.7	7391.7	11814.3	59.8
	20 psi	13976.9	15511.8	11.0	9336.4	13961.5	49.5
Mean	5 psi	9176.7	11607.1	26.5	6966.9	8893.6	27.6
	20 psi	13839.8	15677.7	13.3	10798.2	12739.9	18.0

TRIAXIAL RESILIENT MODULUS TESTS, RESULTS AND ANALYSIS

Test Specimen Preparation and Testing

Resilient modulus (M_R) tests were performed at the FDOT Office of Materials on limestone base course aggregates from Pit Nos. 36-246, 70-279, 56-465, 17-091, 93-406, 26-001, 58-486 (crushed concrete), MX411, and AL-149. Test specimens were prepared and compacted according to T180, modified proctor. Test procedures conforming to AASHTO T294-92 were used to obtain M_R values at three different axial stress conditions and at confining stresses of 20.7 kPa (3 psi), 34.5 kPa (5 psi), 69.0 kPa (10 psi), 103.4 kPa (15 psi), and 137.9 kPa (20 psi). In the case of Pit Nos. 36-246 and 70-279, two replicated tests were performed at 1-, 7-, 14-, and 28-days for lime treated and untreated materials. Based on the initial results acquired with tests for Pit Nos. 36-246 and 70-279, only 1- and 28-day tests were selected in order to save time for the remainder of the materials studied. Both external and internal LVDT measurements of deformation were obtained and used to define the resilient modulus values for all samples.

Test Results and Analyses

Test results summarizing mean triaxial resilient modulus (M_R) values for both internal and external deformation at 20 psi confining horizontal stress are given in Table 22. Data include M_R values for both untreated and treated base course materials, as well as the change in M_R values (ΔM_R) for both internal and external deformation after lime treatment. It is evident from examination of Table 22 that there are no distinct trends in M_R values with curing time. This observation is further illustrated by the plot of internal and external M_R values for Pit Nos. 36-246 and 70-279 (Fig. 23). There is little increase or decrease in the M_R data, the one exception being the treated sample from Pit No. 56-465 which shows a significant increase in M_R (internal), likely due to the clay stabilization phenomenon previously discussed for this material in the LBR section of this report.

Lime treatment of base course materials appears to generate both strength gain and loss in different pit samples. This is illustrated in both Table 22 and Fig. 23, as Pit Nos. 70-279, 56-465, 17-091, 93-406, and MX411 exhibit strength improvement, while Pit Nos. 36-246, 26-001, 58-486, and AL-149 exhibit a reduction in M_R values. In fact, some of the materials with the highest carbonate contents (36-246 and 26-001) show the worst declines in strength. In order to quantify this relationship, scatter plots of M_R versus carbonate content for both internal and external deformation were prepared for the total data set (Figs. 24 and 25). Linear regression curves fit to the data exhibit good to poor correlation for the 1-day curing time on both graphs (R^2 = 0.50 and 0.22, respectively), but show poor to no correlation for the 28-day curing time (R^2 = 0.06 and 0.20, respectively) and the total data set (R^2 = 0.15 and 0.21, respectively). However, if the 28-day data point for Pit No. 56-465 is removed due to the unusual phenomenon responsible for its strength gain, both the 28-day curing time data (R^2 = 0.63 and 0.68, respectively) and total data set data (R^2 = 0.66 and 0.53, respectively) exhibit good correlations between M_R values and carbonate.

Table 22. Mean triaxial resilient modulus test results for both untreated and treated base course samples at 20 psi confining horizontal stress

PIT NO.	CURING TIME (days)	M_R (20psi)* UNTREATED		M_R (20psi)* TREATED		Δ M_R (20psi)	
		Internal (psi)	External (psi)	Internal (psi)	External (psi)	Internal (%)	External (%)
36-246	1	85424	60366	70361	54274	-17.6	-10.1
	7	87604	59835	77891	56909	-11.1	-4.9
	14	88038	62123	77443	57460	-12.0	-7.5
	28	87988	62614	81801	60117	-7.0	-4.0
70-279	1	110243	71677	122044	76404	10.7	6.6
	7	104030	69190	128454	78306	23.5	13.2
	14	103301	68781	131688	81255	27.5	18.1
	28	103588	67234	129670	80689	25.2	20.0
56-465	1	64867	42682	74078	50987	14.2	19.5
	28	61648	30938	130475	51356	111.6	66.0
17-091	1	94833	65096	102457	68834	8.0	5.7
	28	86190	58807	95386	59604	10.7	1.4
93-406	1	104297	64097	114969	71731	10.2	11.9
	28	105712	51437	134614	70229	27.3	36.5
26-001	1	88954	61516	73057	53344	-17.9	-13.3
	28	89656	63149	75753	56278	-15.5	-10.9
MX411	1	109620	57686	113978	64059	4.0	11.0
	28	111710	72955	126607	66469	13.3	-8.9
58-486	1	86611	54336	86247	44998	-0.4	-17.2
	28	129526	61216	122889	59394	-5.1	-3.0
AL-149	1	128529	77889	120933	71910	-5.9	-7.7
	28	---	---	107984	44711	---	---

* Values are an average of two replicate tests.
(a) $M_R = a(\Theta)^b$, psi (Θ = sum of principal stresses). To convert to kPa multiply by 6.895.
Note: M_R results from Internal deformation measurements are considered more representative than External measured values because of end restraint conditions.

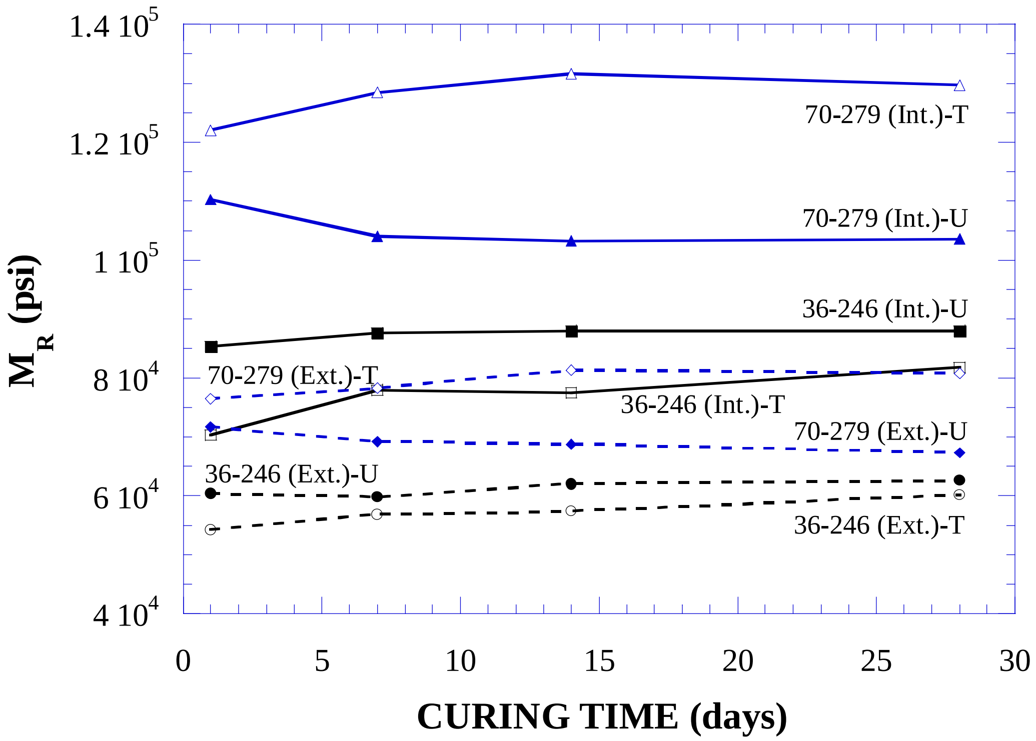

Figure 23. Plot of triaxial resilient modulus (M_R) data as a function of curing time for Pit Nos. 36-246 and 70-279 (untreated and treated samples).

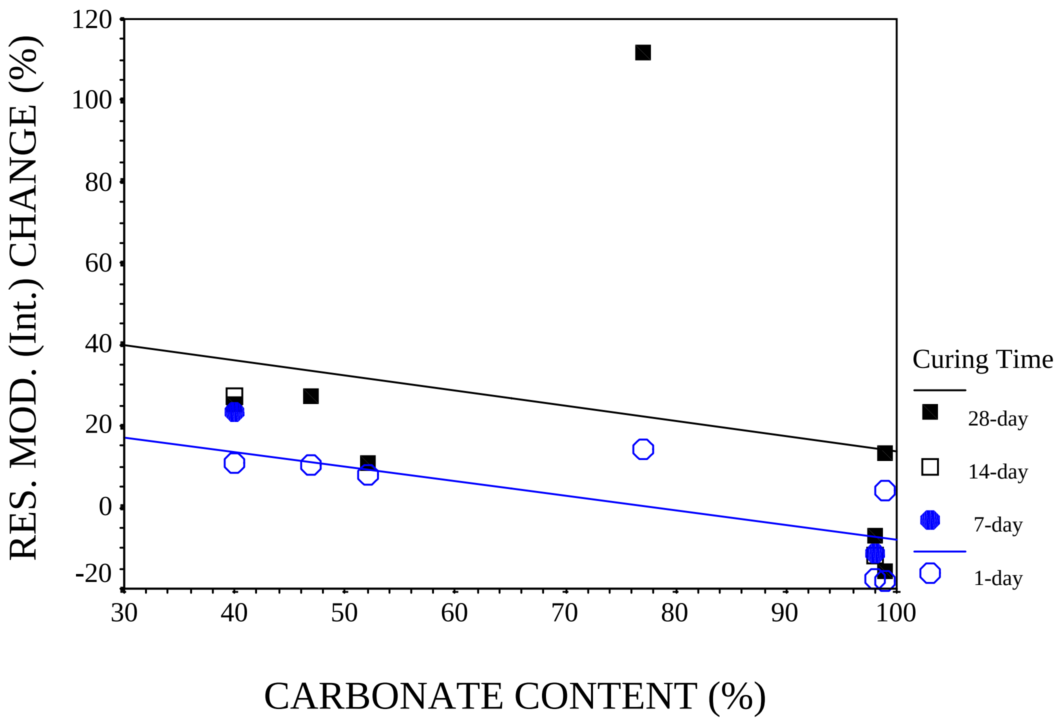

Figure 24. Scatter plot of M_R change (internal) and carbonate content illustrating the relationship between curing time and the strength difference for treated versus untreated samples.

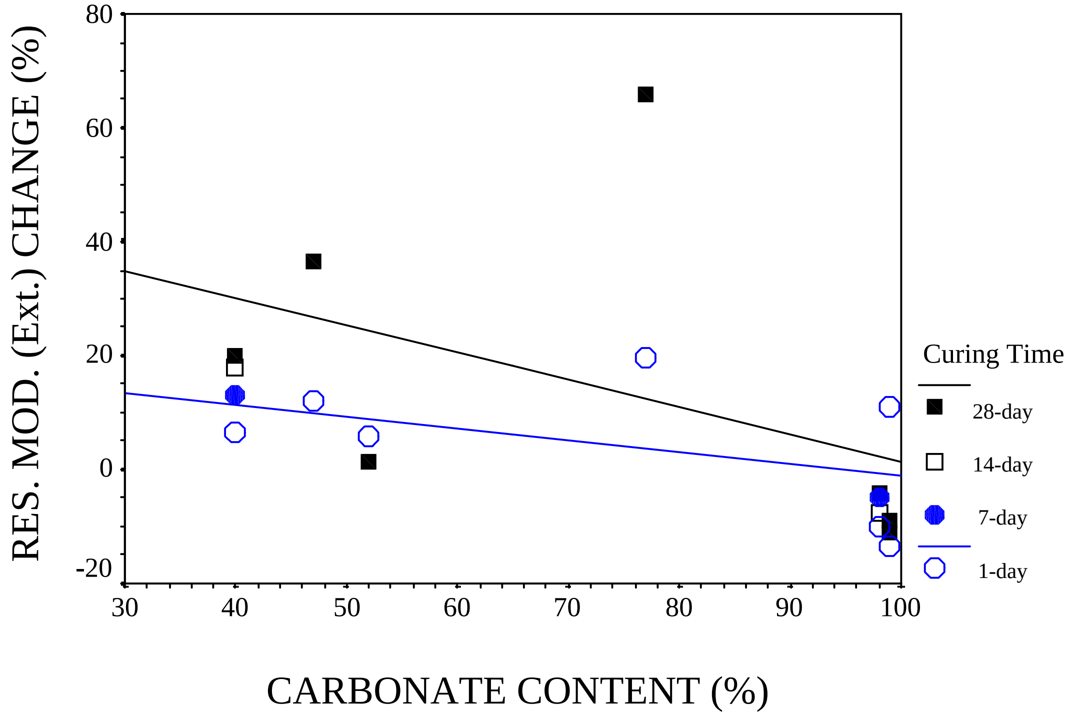

Figure 25. Scatter plot of M_R change (external) and carbonate content illustrating the relationship between curing time and the strength difference for treated versus untreated samples.

Data reduction and computation of resilient moduli values were very time-consuming due to the lack of computer software to facilitate computations. Fifteen M_R values were computed for each test specimen and plots of these M_R values versus the sum of principal stresses (Θ) were prepared for both internal and external deformation measurements. Power law regression analyses were performed to establish relationships according to the following equation:

$$M_R = a(\Theta)^b$$

where: M_R = modulus of resilience, psi
a = coefficient
b = exponent
Θ = sum of principal stresses, psi

or

$$M_R\ (\text{kPa}) = a(\Theta)^b * 6.895 \qquad \text{eqn. 3}$$

Tables 23 through 31 present a listing of the results derived from the regression analyses for materials from each pit. It should be noted that M_R results from internal deformation measurements are considered more representative than external measured values because of end restraint conditions. Furthermore, moisture content and density values for the tested specimens also are given in Tables 32 through 34 for comparison purposes. Appendix E contains the complete test data.

The regression equations for Pit Nos. 36-246 and 70-279 (Tables 23 and 24) were used to compute moduli values at Θ of 10 and 100 psi (68.95 and 689.5 kPa, respectively). These values were then subjected to additional regression analyses to obtain master equations for each material assuming that age (time) had no effect on the M_R. The results in Table 35 show a negligible increase in slope (exponent b) for treated 36-246 aggregate and a more substantial decrease in slope for treated 70-279 as compared to that for the untreated aggregates. Data from the other sources were not analyzed in this manner.

Since both slope (b) and coefficient (a) interchange in magnitude between treated and untreated, M_R values were computed using different stress conditions (Θ). These results gave 13 to 15 percent reduction in M_R regardless of stress level for the treated 36-246 material as compared to the untreated. Conversely, M_R for the untreated 70-279 aggregate was 21 to 23 percent less than the treated. The improvement in M_R for 70-279 is believed to be related to the presence of lime improving cementation, and correspondingly strength gain, due to the presence of aragonite in the sample. As seen in the LBR part of this study, samples containing aragonite show potential for strength gain often greater than materials that are 100% carbonate. Apparently, the testing procedure used in this part of the study favored strength gain of base course materials containing aragonite (70-279: 10.4%, 56-465: 11.9%, 17-091: 35.9%, and 93-406: 24.6%) over materials without aragonite. A comparison of the M_R values for materials from Pit Nos. 36-246 and 70-279 with and without lime treatment is presented in Fig 26.

Table 23. Regression equations derived from triaxial M_R tests for Pit No. 36-246

CONDITION	CURING TIME (days)	INTERNAL[(a)]			EXTERNAL[(a)]		
		a	b	R^2	a	b	R^2
Untreated	1	6612.8	0.5859	0.904	586.68	—	—
	1	5999.5	0.5732	0.925	3389.1	0.6326	0.949
	7	5977.8	0.5974	0.947	2760.6	0.6877	0.972
	7	4637.9	0.6379	0.963	2107.3	0.7361	0.977
	14	4994.9	0.6239	0.9469	2333.3	0.7193	0.971
	14	8648.2	0.5122	0.908	3819.6	0.6251	0.960
	28	5610.1	0.6178	0.950	2378.9	0.7263	0.970
	28	5696.2	0.5846	0.939	2998.6	0.6701	0.962
	Mean	6022.2	0.5916		2826.8	0.6853	
Treated	1	4704.6	0.5913	0.938	2743.6	0.6585	0.969
	1	4700.0	0.5912	0.955	3063.6	0.6325	0.960
	7	4204.8	0.6406	0.968	2771.1	0.6704	0.970
	7	4767.0	0.6123	0.957	2688.1	0.6708	0.974
	14	4762.8	0.6249	0.970	2509.7	0.6902	0.979
	14	4495.6	0.6126	0.948	2836.0	0.6683	0.971
	28	5302.4	0.5996	0.952	2761.9	0.6773	0.975
	28	6460.8	0.5537	0.913	3612.4	0.6241	0.964
	Mean	4924.8	0.6033		2873.3	0.6615	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 24. Regression equations derived from triaxial M_R tests for Pit No. 70-279

CONDITION	CURING TIME (days)	INTERNAL[(a)]			EXTERNAL[(a)]		
		a	b	R^2	a	b	R^2
Untreated	1	7382.9	0.6068	0.971	3279.2	0.6884	0.979
	1	8907.8	0.5603	0.959	3406.8	0.6865	0.981
	7	7041.6	0.6093	0.983	2858.2	0.7151	0.985
	7	8162.4	0.5637	0.965	3066.3	0.6975	0.982
	14	6997.0	0.6175	0.972	3016.6	0.7056	0.980
	14	6143.0	0.6168	0.960	2776.5	0.7187	0.983
	28	7023.0	0.6005	0.970	3103.6	0.6894	0.981
	28	7147.8	0.5962	0.969	2980.9	0.6988	0.982
	Mean	7350.7	0.5964		3061.0	0.7000	
Treated	1	9217.0	0.5849	0.966	3619.0	0.6857	0.981
	1	6591.5	0.6447	0.977	3123.5	0.7187	0.981
	7	11575.0	0.5368	0.936	4506.7	0.6361	0.975
	7	8865.8	0.5958	0.9644	4102.6	0.6610	0.979
	14	13147.0	0.5172	0.925	4563.5	0.6446	0.976
	14	9590.2	0.5757	0.959	4796.1	0.6300	0.972
	28	12720.0	0.5132	0.929	3965.6	0.6741	0.973
	28	13162.0	0.5074	0.936	5651.8	0.5943	0.967
	Mean	10608.6	0.5595		4291.1	0.6556	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 25. Regression equations derived from triaxial M_R tests for Pit No. 56-465

CONDITION	CURING TIME (days)	INTERNAL[(a)]			EXTERNAL[(a)]		
		a	b	R^2	a	b	R^2
Untreated	1	3503.1	0.6542	0.933	1352.7	0.7755	0.967
	1	3325.2	0.6607	0.893	1616.6	0.7375	0.953
	28	4729.8	0.5946	0.955	1869.7	0.6488	0.968
	28	2459.9	0.6972	0.946	1260.2	0.7030	0.976
	Mean	3504.5	0.6517		1524.8	0.7162	
Treated	1	3025.8	0.7401	0.936	1285.3	0.8374	0.957
	1	896.44	0.9685	0.971	738.59	0.9368	0.984
	28	107672	0.0054	0.000	4268.8	0.5665	0.951
	28	175977	-0.0730	0.143	2616.0	0.6747	0.967
	Mean	71892.8	0.4103		2227.2	0.7539	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 26. Regression equations derived from triaxial M_R tests for Pit No. 17-091

CONDITION	CURING TIME (days)	INTERNAL[(a)]			EXTERNAL[(a)]		
		a	b	R^2	a	b	R^2
Untreated	1	7058.0	0.5702	0.927	3882.8	0.6265	0.961
	1	6655.2	0.5964	0.929	3419.2	0.6594	0.957
	28	3350.2	0.7386	0.954	1899.6	0.7721	0.977
	28	3396.9	0.7117	0.960	2166.3	0.7372	0.974
	Mean	5115.1	0.6542		2842.0	0.6988	
Treated	1	8874.2	0.5319	0.885	4858.8	0.5895	0.934
	1	8436.2	0.5515	0.884	4631.2	0.5938	0.936
	28	7156.9	0.5711	0.894	3271.5	0.6391	0.953
	28	7629.9	0.5595	0.880	3945.6	0.6103	0.942
	Mean	8024.3	0.5535		4176.8	0.6082	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 27. Regression equations derived from triaxial M_R tests for Pit No. 93-406

CONDITION	CURING TIME (days)	INTERNAL[(a)]			EXTERNAL[(a)]		
		a	b	R^2	a	b	R^2
Untreated	1	7738.0	0.5973	0.961	4630.3	0.5940	0.959
	1	8251.7	0.5675	0.960	3252.3	0.6731	0.977
	28	5769.6	0.6524	0.971	753.99	0.9408	0.980
	28	4872.2	0.6911	0.969	1066.5	0.8781	0.985
	Mean	6657.9	0.6271		2425.8	0.7715	
Treated	1	7535.7	0.5984	0.935	5445.6	0.5792	0.953
	1	9967.8	0.5412	0.896	5399.2	0.5655	0.946
	28	16066.0	0.4543	0.952	1842.2	0.8398	0.987
	28	16487.0	0.4641	0.832	1183.7	0.8928	0.981
	Mean	12514.1	0.5145		3467.7	0.7193	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 28. Regression equations derived from triaxial M_R tests for Pit No. 26-001

CONDITION	CURING TIME (days)	INTERNAL[a]			EXTERNAL[a]		
		a	b	R^2	a	b	R^2
Untreated	1	6383.3	0.5786	0.920	4255.7	0.5983	0.949
	1	4847.7	0.6354	0.960	2542.2	0.6930	0.967
	28	5115.0	0.6300	0.939	3577.6	0.6375	0.969
	28	5192.6	0.6205	0.951	2568.1	0.7084	0.983
	Mean	5384.7	0.6161		3235.9	0.6593	
Treated	1	4839.8	0.6027	0.953	2833.3	0.6464	0.967
	1	4665.0	0.5951	0.950	3194.0	0.6221	0.963
	28	3683.3	0.6624	0.972	2369.2	0.7049	0.981
	28	3739.6	0.6666	0.971	2639.0	0.6751	0.982
	Mean	4231.9	0.6317		2758.9	0.6621	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 29. Regression equations derived from triaxial M_R tests for Pit No. 58-486

CONDITION	CURING TIME (days)	INTERNAL[a]			EXTERNAL[a]		
		a	b	R^2	a	b	R^2
Untreated	1	6374.2	0.5832	0.981	975.2	0.8872	0.988
	1	8264.4	0.5127	0.946	1234.6	0.8624	0.986
	28	—	—	—	—	—	—
	28	9242.5	0.9763	0.976	1481.2	0.8358	0.987
	Mean	7960.4	0.6907		1230.3	0.8618	
Treated	1	6736.9	0.5952	0.994	908.9	0.8865	0.989
	1	5140.0	0.6059	0.989	1341.1	0.7906	0.989
	28	18348.0	0.4326	0.938	1096.5	0.9153	0.984
	28	12164.0	0.4714	0.875	1009.2	0.9074	0.983
	Mean	10597.2	0.5263		1088.9	0.8750	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 30. Regression equations derived from triaxial M_R tests for Pit No. MX411

CONDITION	CURING TIME (days)	INTERNAL[(a)]			EXTERNAL[(a)]		
		a	**b**	**R^2**	**a**	**b**	**R^2**
Untreated	1	7886.8	0.5906	0.948	1112.4	0.8474	0.968
	1	14299.0	0.4243	0.863	2154.7	0.7450	0.978
	28	9540.4	0.5594	0.976	1255.4	0.9161	0.983
	28	9872.7	0.9272	0.927	1451.7	0.8794	0.985
	Mean	10399.7	0.6254		1493.6	0.8470	
Treated	1	23110.0	0.3557	0.802	1065.4	0.9247	0.981
	1	14312.0	0.4351	0.866	3169.9	0.6694	0.958
	28	16077.0	0.4542	0.949	1841.2	0.8399	0.987
	28	28662.0	0.3152	0.841	1437.6	0.8288	0.986
	Mean	20540.3	0.3901		1878.5	0.8157	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 31. Regression equations derived from triaxial M_R tests for Pit No. AL-149

CONDITION	CURING TIME (days)	INTERNAL[(a)]			EXTERNAL[(a)]		
		a	**b**	**R^2**	**a**	**b**	**R^2**
Untreated	1	10392.0	0.5654	0.976	1011.8	0.9689	0.988
	1	8222.9	0.5876	0.957	1299.8	0.9342	0.989
	28	—	—	—	—	—	—
	28	—	—	—	—	—	—
	Mean	9307.5	0.5765		1155.8	0.9516	
Treated	1	6322.3	0.6409	0.982	1122.5	0.9355	0.990
	1	9892.6	0.5645	0.978	947.1	0.9766	0.986
	28	5914.0	0.6581	0.985	828.4	0.9012	0.987
	28	8809.1	0.5460	0.982	961.1	0.8563	0.990
	Mean	7734.5	0.6024		964.8	0.9174	

(a) $M_R = a(\Theta)^b$, psi. To convert to kPa multiply by 6.895.

Table 32. Moisture-density of resilient modulus test specimens 36-246 and 70-279

CONDITION	CURING TIME (days)	PIT NO. 36-246		PIT NO. 70-279	
		w (%)	γ_d (kg/m^3)	w (%)	γ_d (kg/m^3)
Untreated	1	12.0	1874.0	7.1	2031.0
	1	12.2	1862.8	7.2	2027.8
	Mean	12.1	1868.4	7.2	2029.4
	7	12.1	1883.6	7.2	2026.1
	7	12.0	1865.0	7.1	2023.0
	Mean	12.1	1874.8	7.2	2024.6
	14	12.0	1864.4	7.1	2027.8
	14	12.0	1862.8	7.2	2021.3
	Mean	12.0	1863.6	7.2	2024.6
	28	12.0	1866.0	7.2	2031.0
	28	12.0	1872.4	7.0	2031.0
	Mean	12.0	1869.2	7.1	2031.0
Treated	1	12.1	1856.4	8.0	2040.6
	1	11.9	1862.8	8.1	2042.2
	Mean	12.0	1859.6	8.1	2041.4
	7	12.0	1858.0	8.0	2042.2
	7	12.0	1853.2	7.5	2047.0
	Mean	12.0	1855.6	7.8	2044.6
	14	11.9	1862.8	7.9	2045.4
	14	11.9	1856.4	8.1	2043.8
	Mean	11.9	1862.6	8.0	2044.6
	28	11.9	1854.8	8.0	2042.2
	28	12.0	1859.6	8.0	2035.8
	Mean	12.0	1857.2	8.0	2039.0

Table 33. Moisture-density of resilient modulus test specimens 56-465, 17-091, 93-406 and 26-001

CONDITION	CURING TIME (days)	PIT NO. 56-465		PIT NO. 17-091		PIT NO. 93-406		PIT NO. 26-001	
		w (%)	γ_d (kg/m^3)	w (%)	γ_d (kg/m^3)	w (%)	γ_d (kg/m^3)	w (%)	γ_d (kg/m^3)
Untreated	1	12.4	1925.2	9.3	2024.5	7.3	2050.2	12.1	1856.4
	1	12.4	1934.8	9.5	2021.3	7.0	2051.8	12.0	1853.2
	Mean	12.4	1930.0	9.4	2022.9	7.2	2051.0	12.1	1854.8
	28	12.1	1926.8	9.4	2026.1	7.3	2051.8	12.0	1858.0
	28	12.4	1926.8	9.2	2037.4	7.2	2045.4	12.0	1858.0
	Mean	12.3	1926.8	9.3	2031.8	7.3	2048.6	12.0	1858.0
Treated	1	13.7	1877.2	10.4	2005.3	7.0	2027.7	11.9	1851.6
	1	13.4	1900.0	10.2	2016.5	7.1	2018.1	11.7	1854.8
	Mean	13.6	1888.6	10.3	2010.9	7.1	2022.9	11.8	1853.2
	28	13.3	1894.8	10.4	2005.3	7.1	2002.1	11.8	1850.0
	28	13.0	1891.6	10.1	2003.7	6.9	2029.3	11.8	1850.0
	Mean	13.2	1893.2	10.3	2004.5	7.0	2015.7	11.8	1850.0

Table 34. Moisture-density of resilient modulus test specimens 58-486, MX411 and AL-149

CONDITION	CURING TIME (days)	PIT NO. 58-486		PIT NO. MX411		PIT NO. AL-149	
		w (%)	γ_d (kg/m^3)	w (%)	γ_d (kg/m^3)	w (%)	γ_d (kg/m^3)
Untreated	1	11.5	1915.6	7.9	2002.1	5.7	2280.8
	1	13.1	1910.8	7.9	2034.1	5.9	2268.0
	Mean	12.3	1913.2	7.9	2018.1	5.8	2274.4
	28	12.1	1893.2	8.4	2034.1	—	—
	28	11.5	1920.4	7.9	2022.9	—	—
	Mean	11.8	1906.8	8.2	2028.5		
Treated	1	12.0	1925.2	8.0	2034.1	5.8	2279.2
	1	12.4	1918.8	7.7	2003.7	6.3	2245.6
	Mean	12.2	1922.0	7.9	2018.9	6.1	2262.4
	28	12.9	1906.0	7.7	2022.9	5.7	2277.6
	28	12.4	1922.0	7.7	2003.7	5.7	2272.8
	Mean	12.7	1914.0	7.7	2013.3	5.7	2275.2

Table 35. Result of regression analyses for Pit Nos. 36-246 and 70-279 assuming no effect of time

PIT NO./ CONDITION	a*	b*	# VALUES	R^2
36-246 / Untreated	5924.8	0.5916	16	0.986
36-246 / Treated	4886.6	0.6033	16	0.990
70-279 / Untreated	7310.3	0.5964	16	0.990
70-279 / Treated	10349.2	0.5595	16	0.981

*$M_R = a(\Theta)^b$, psi or
$M_R = a(\Theta)^b \times 6.895$ = kPa

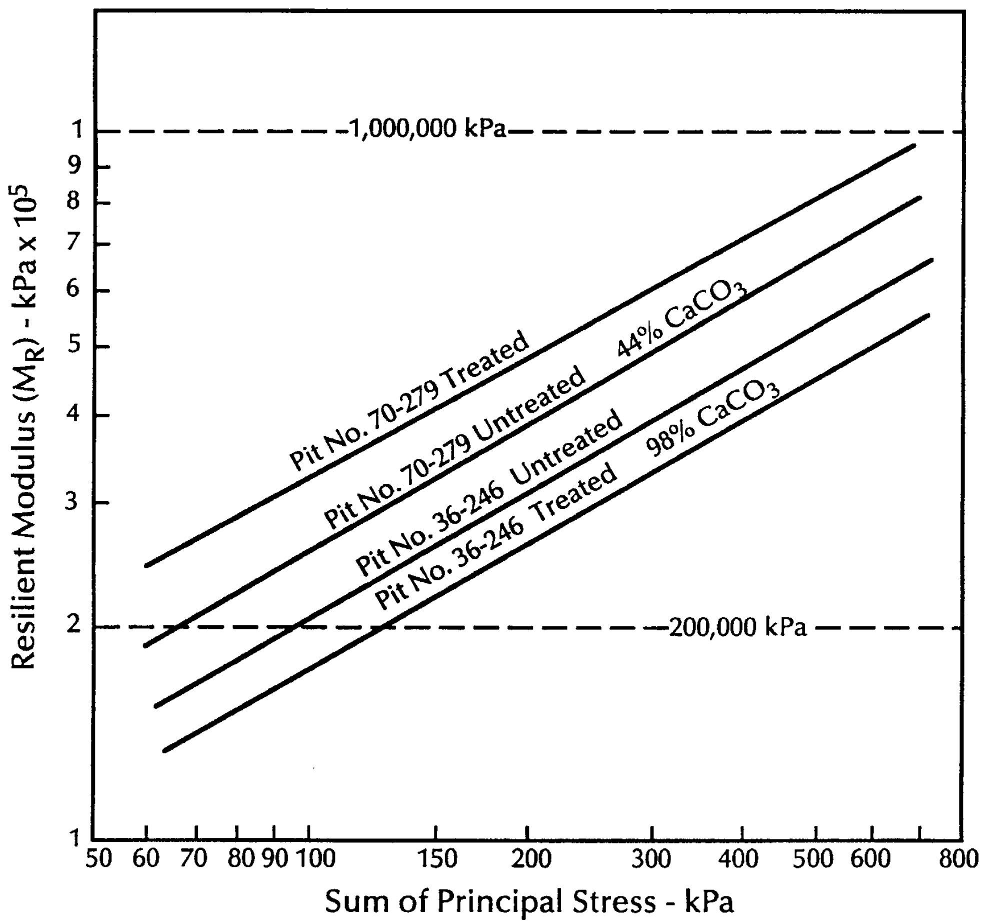

Figure 26. Comparison of predicted resilient moduli for Pit Nos. 36-246 and 70-279.

Analysis of Variables Affecting M_R Values

Untreated Aggregates

As was done in the LBR portion of this study, an effort was made to define the influence of relevent test variables on the triaxial resilient modulus test. For this purpose, the variables of dry density, moisture content, gradation, carbonate content, mineralogy, and curing time were selected for statistical analysis, and analyzed following a methodology similar to that employed in the LBR part of this study. As before, data from Pit Nos. 58-486 and AL-149 were excluded from these analyses.

A bivariate correlation matrix, including mineralogical parameters, was first prepared for both untreated and treated aggregate materials (Tables 36 and 37). Once again, only correlations possessing a Pearson correlation coefficient ≥ 0.6 were considered significant for this study. As noted previously, internal deformation M_R values will be stressed, as they are considered more representative than external measured values.

Examination of Table 36 shows that M_R (int.) values for untreated aggregate samples exhibit a negative correlation to moisture content (-0.792) and a fair to poor positive correlation to dry density (0.585) that falls below the ≥ 0.6 significance threshold used for this study.

Table 36. M_R correlation matrix for untreated aggregate samples

	CARB. CONT.	DRY DEN.	MOIST. CONT.	M_R INT.	M_R INT.	MINUS #4	CALC. CONT.	DOLO. CONT.	QTZ. CONT.	ARAG. CONT.	CURING TIME
CARB. CONT.											
DRY DEN.	-.777** (.000)										
MOIST. CONT.	.743** (.000)	-.921** (.000)									
M_R INT.	-.318 (.063)	.585** (.000)	-.792** (.000)								
M_R EXT.	-.172 (.323)	.253 (.142)	-.484** (.003)	.752** (.000)							
MINUS #4	-.266 (.116)	-.360* (.031)	.329 (.050)	-.392* (.020)	-.052 (.769)						
CALC. CONT.	.978** (.000)	-.779** (.000)	.694** (.000)	-.271 (.115)	-.159 (.362)	-.275 (.104)					
DOLO. CONT.	.066 (.702)	-.163 (.342)	.413* (.012)	-.743** (.000)	-.827** (.000)	.000 (1.000)	.079 (.648)				
QTZ. CONT.	-.982** (.000)	.754** (.000)	-.760** (.000)	.386* (.022)	.296 (.084)	.267 (.116)	-.958** (.000)	-.154 (.369)			
ARAG. CONT.	-.711** (.000)	.630** (.000)	-.396* (.017)	-.001 (.994)	-.126 (.470)	.218 (.202)	-.821** (.000)	.046 (.791)	.624** (.000)		
CURING TIME	.009 (.957)	.030 (.864)	.000 (.998)	-.040 (.821)	-.118 (.500)	-.038 (.828)	.001 (.993)	.026 (.881)	-.018 (.916)	.032 (.855)	

Note: Shaded cells indicate correlations considered to be statistically significant for this study (Pearson correlation coefficient ≥ 0.6).
*   Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
( ) sigma (2-tailed), n = 36.

M_R (ext.) values show no significant correlations to the variables in question. Mineralogical relationships are similar to those outlined in the LBR part of the study, and require no further discussion. However, the negative correlation between M_R (int.) and dolomite (-0.743) is unlike LBR observations, but since only one sample contains significant dolomite, this relationship will be ignored.

Scatter plots of dry density and moisture content versus M_R (int.) for the total data set further illustrate the correlations previously discussed (Fig. 27). As noted in the LBR portion of the study, these two variables are negatively cross-correlated. Simple linear regression of these data sets exhibit coefficient of determination (R^2) values of 0.34 and 0.63, respectively. No further statistical analysis of the untreated sample data set was performed as a result of these observations.

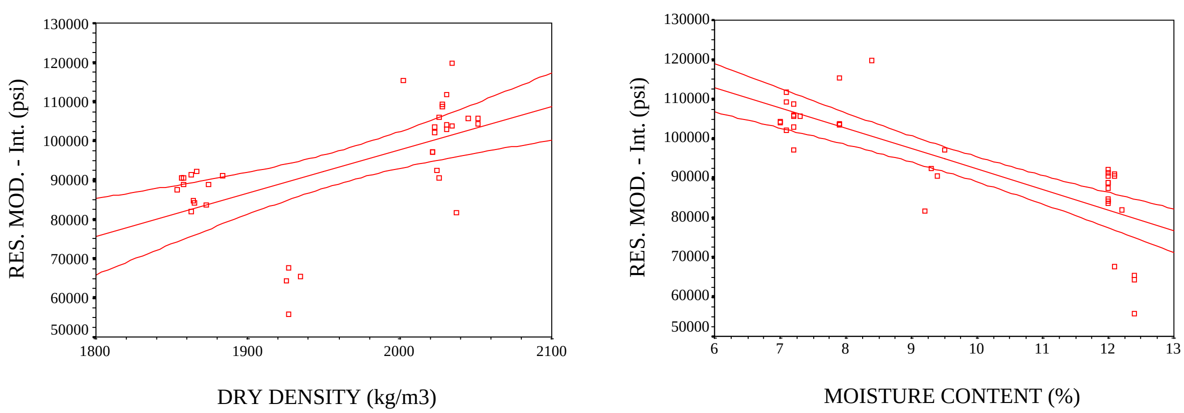

Figure 27. Scatter plots of variables thought to affect triaxial resilient modulus test results of untreated aggregate samples. (*Note*: Lines surrounding linear regression curves define the 95% confidence interval)

Treated Aggregates

As in the first part of the triaxial resilient modulus study, specimens prepared with 1.0 percent lime for the purpose of accelerating and/or enhancing the cementing of high carbonate aggregates were evaluated to assess the effects of the same variables studied for untreated samples. As with the untreated samples, the first step was production of a bivariate correlation matrix (Table 37).

Examination of Table 37 shows that M_R (int.) values for treated aggregate exhibit negative correlations to moisture content (-0.755) and carbonate content (-0.662), and a positive correlation to dry density (0.823). Mineralogically, M_R (int.) values exhibit a positive correlation to quartz content (0.651). M_R (ext.) values also exhibit similar correlations to moisture content (-0.827), carbonate content (-0.747), dry density (0.827), and quartz (0.800), but also possess a negative correlation to calcite content (-0.680). The relationships to dry density and moisture content are similar to correlations observed with LBR data. However, the negative correlations between M_R values and carbonate content are contradictory to what was expected, as high carbonate aggregates were expected to show the greatest strength gain potential. This observation is further supported by the quartz and calcite correlations, and further

Table 37. M_R correlation matrix for treated aggregate samples

	CARB. CONT.	DRY DEN.	MOIST. CONT.	M_R INT.	M_R INT.	MINUS #4	CALC. CONT.	DOLO. CONT.	QTZ. CONT.	ARAG. CONT.	CURING TIME
CARB. CONT.											
DRY DEN.	-.784** (.000)										
MOIST. CONT.	.599** (.000)	-.889** (.000)									
M_R INT.	-.662** (.000)	.823** (.000)	-.755** (.000)								
M_R EXT.	-.747** (.000)	.827** (.000)	-.827** (.000)	.706** (.000)							
MINUS #4	-.266 (.116)	-.334* (.047)	.411* (.013)	-.351* (.036)	-.056 (.744)						
CALC. CONT.	.978** (.000)	-.772** (.000)	.541** (.001)	-.597** (.000)	-.680** (.000)	-.275 (.104)					
DOLO. CONT.	.066 (.702)	-.274 (.107)	.531** (.001)	-.016 (.927)	-.450** (.006)	.000 (1.000)	.079 (.648)				
QTZ. CONT.	-.982** (.000)	.798** (.000)	-.613** (.000)	.651** (.000)	.800** (.000)	.267 (.116)	-.958** (.000)	-.154 (.369)			
ARAG. CONT.	-.711** (.000)	.526** (.001)	-.278 (.101)	.329* (.050)	.278 (.101)	.218 (.202)	-.821** (.000)	.046 (.791)	.624** (.000)		
CURING TIME	.009 (.957)	-.014 (.937)	-.017 (.923)	.262 (.123)	.007 (.969)	-.038 (.828)	.001 (.993)	.026 (.881)	-.018 (.916)	.032 (.855)	

Note: Shaded cells indicate correlations considered to be statistically significant for this study (Pearson correlation coefficient ≥ 0.6).
* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
( ) sigma (2-tailed), n = 36.

illustrates the greater strength gain seen with this test for low carbonate/high SiO_2/high aragonite samples.

For comparison to untreated sample data, scatter plots were prepared for the variables of dry density, moisture content, and carbonate content versus M_R (int.) (Fig. 28). Simple linear regression of these scatter plots exhibits coefficient of determination (R^2) values of 0.68, 0.57, and 0.44, respectively. More complete linear regression models prepared according to equation 1 are included for the total data set and 1- and 28-day curing times (Table 38). Review of Table 38 shows that dry density consistently exhibits the strongest correlation to M_R (int.) values, followed by moisture content and carbonate content, respectively.

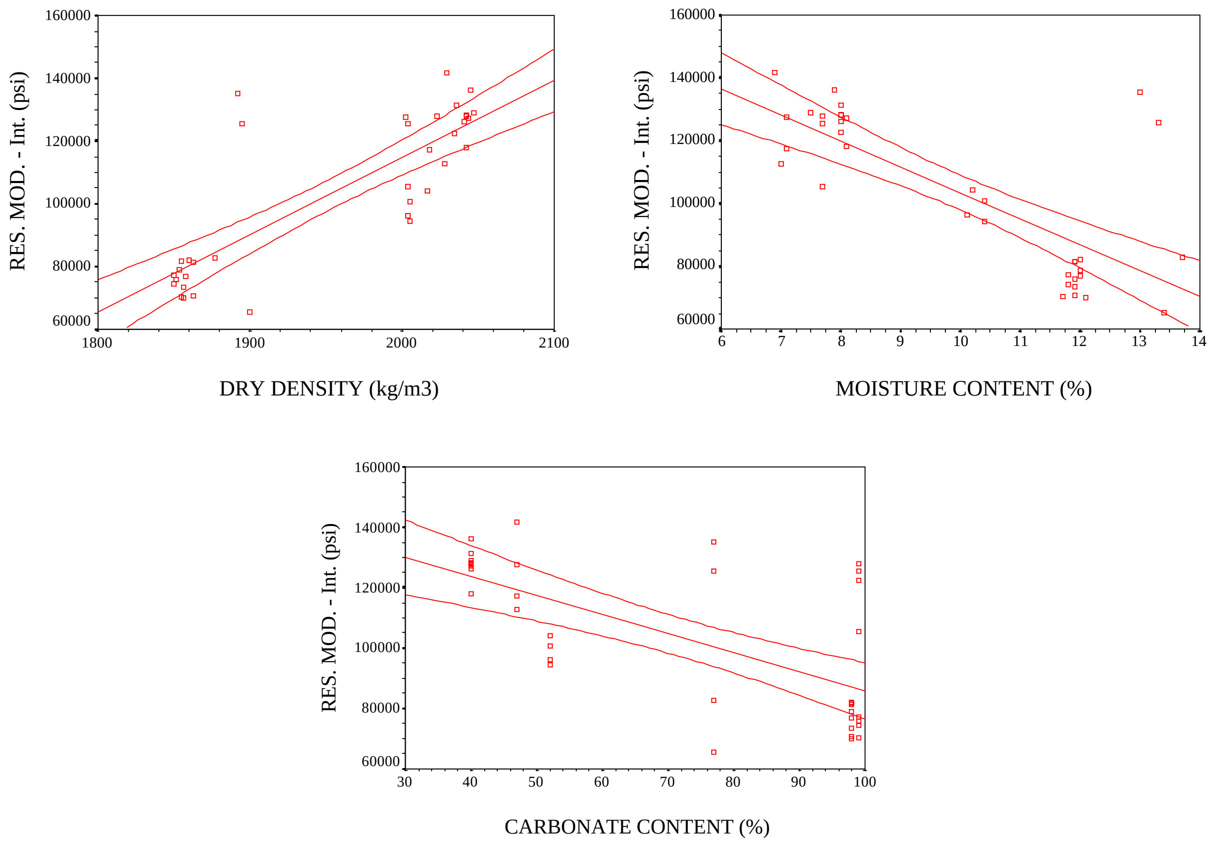

Figure 28. Scatter plots of variables thought to affect triaxial resilient modulus test results of treated aggregate samples. (*Note*: Lines surrounding linear regression curves define the 95% confidence interval)

Table 38. M_R (internal) linear regression models for treated aggregate samples

LINEAR REGRES. MODEL	R^2	STD. ERROR OF EST.	UNSTANDARDIZED COEFFICIENTS			
			CONSTANT	STD. ERROR	INDEPENDENT VARIABLE	STD. ERROR
TOTAL						
Dry Den.	0.68	14301.17	-377789	57110.47	246.24	29.20
Moist. Cont.	0.57	16495.67	186240.0	12655.15	-8282.07	1234.60
Carb. Cont.	0.44	18850.18	148962.3	9397.04	-631.23	122.63
1-DAY						
Dry Den.	0.90	7226.86	-412033	47937.41	259.59	24.48
Moist. Cont.	0.80	10315.13	180471.0	12390.02	-8390.30	1197.68
Carb. Cont.	0.40	17975.46	136713.5	15130.30	-558.70	196.16
28-DAY						
Dry Den.	0.45	18985.26	-295472	129169.70	207.90	66.08
Moist. Cont.	0.31	21275.98	169472.3	25874.02	-5898.39	2529.57
Carb. Cont.	0.26	22104.04	146578.1	18605.41	-491.69	241.21

In an effort to use the variables examined to predict M_R (both internal and external) values for treated samples, multiple regression analyses were performed for the different curing times (1- and 28-days) and for the total data set. The variables of dry density and carbonate content were used according to the following format:

$$M_R = a + b(\gamma_d) + c(CA) \qquad \text{eqn. 4}$$

where: M_R = modulus of resilience, psi
γ_d = dry density, kg/m^3
CA = carbonate content, %

Moisture content was not included in the equation as it is cross-correlated with dry density. A review of Table 39 shows that the predicted values are a fair estimate of the measured M_R for both internal and external values.

Similar to the LBR study, the multiple regression equations derived to produce Table 39, as well as the equations for the total data set were used to prepare M_R prediction lines for both internal (Fig. 29) and external measurements (Fig. 30). As seen previously, the figures show that dry density variation can have a large effect on M_R results, and that overall, (except for M_R (int.) data for a 1-day curing time) treated samples with higher carbonate contents tend to under perform treated materials that had lower carbonate contents, higher quartz, and higher aragonite. This latter observation was somewhat unexpected, although the presence of aragonite may be an important factor in generating the strength gain observed with this data set.

Table 39. Comparison of measured and predicted M_R values (psi) - treated

PIT NO. (%CARB.)	1-DAY[(a)] – INT.		1-DAY[(b)] – EXT.		28-DAY[(c)] – INT.		28-DAY[(d)] – EXT.	
	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.	MEAS.	PRED.
36-246 (98%)	70054	70011	54068	51559	81566	89411	59156	54653
36-246 (98%)	70667	71738	54480	52089	82035	90340	61077	55043
70-279 (40%)	126040	116974	76496	73729	128071	129307	79709	71946
70-279 (40%)	118048	117406	76311	73861	131268	128069	81669	71425
56-465 (77%)	82796	74635	54401	55786	125637	98468	52333	58647
56-465 (77%)	65359	80786	47572	57674	135313	97849	50378	58387
17-091 (52%)	100723	108016	69822	69375	94416	121415	58072	68521
17-091 (52%)	104191	111037	67845	70302	96356	121105	61136	68390
93-406 (47%)	112645	113823	73984	71826	127581	121110	75796	68436
93-406 (47%)	117293	111234	69477	71031	141646	126372	64662	70650
26-001 (99%)	75807	68764	52893	51043	74311	88420	56995	54227
26-001 (99%)	70306	69627	53794	51308	77194	88420	55560	54227
MX411 (99%)	122584	117995	64357	66156	127787	121869	75805	68299
MX411 (99%)	105371	109794	63760	63638	125426	118155	57132	66737

Regression Equations:

(a) M_R - int. (1-d) = $-435379 + 269.76(\gamma_d) + 47.02(CA)$
$n = 14, R^2 = 0.91$

(b) M_R - ext. (1-d) = $-90483.5 + 82.81(\gamma_d) - 119.24(CA)$
$n = 14, R^2 = 0.88$

(c) M_R - int. (28-d) = $-263266 + 193.76(\gamma_d) - 62.78(CA)$
$n = 14, R^2 = 0.45$

(d) M_R - ext. (28-d) = $-92860.8 + 81.39(\gamma_d) - 35.19(CA)$
$n = 14, R^2 = 0.47$

* Regression equations for total data set are:

M_R - int. = $-354780 + 236.00(\gamma_d) - 41.59(CA)$
$n = 36, R^2 = 0.68$

M_R - ext. = $-83486.7 + 79.47(\gamma_d) - 103.15(CA)$
$n = 36, R^2 = 0.71$

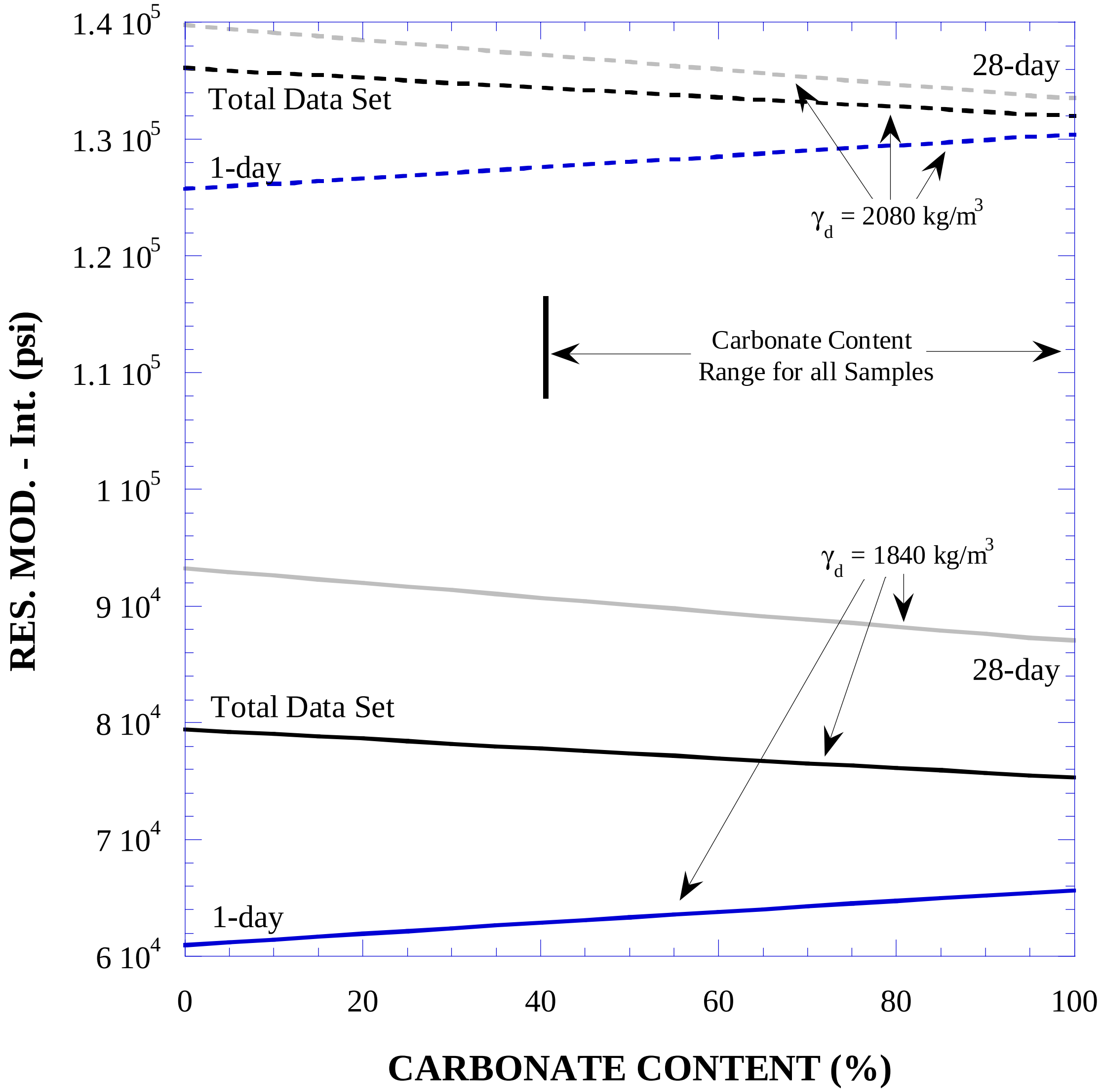

Figure 29. Prediction plot of M_R (int.) value as a function of carbonate content for treated aggregate samples. (*Note*: Prediction lines were generated using the 1- and 28-day regression equations shown in Table 39)

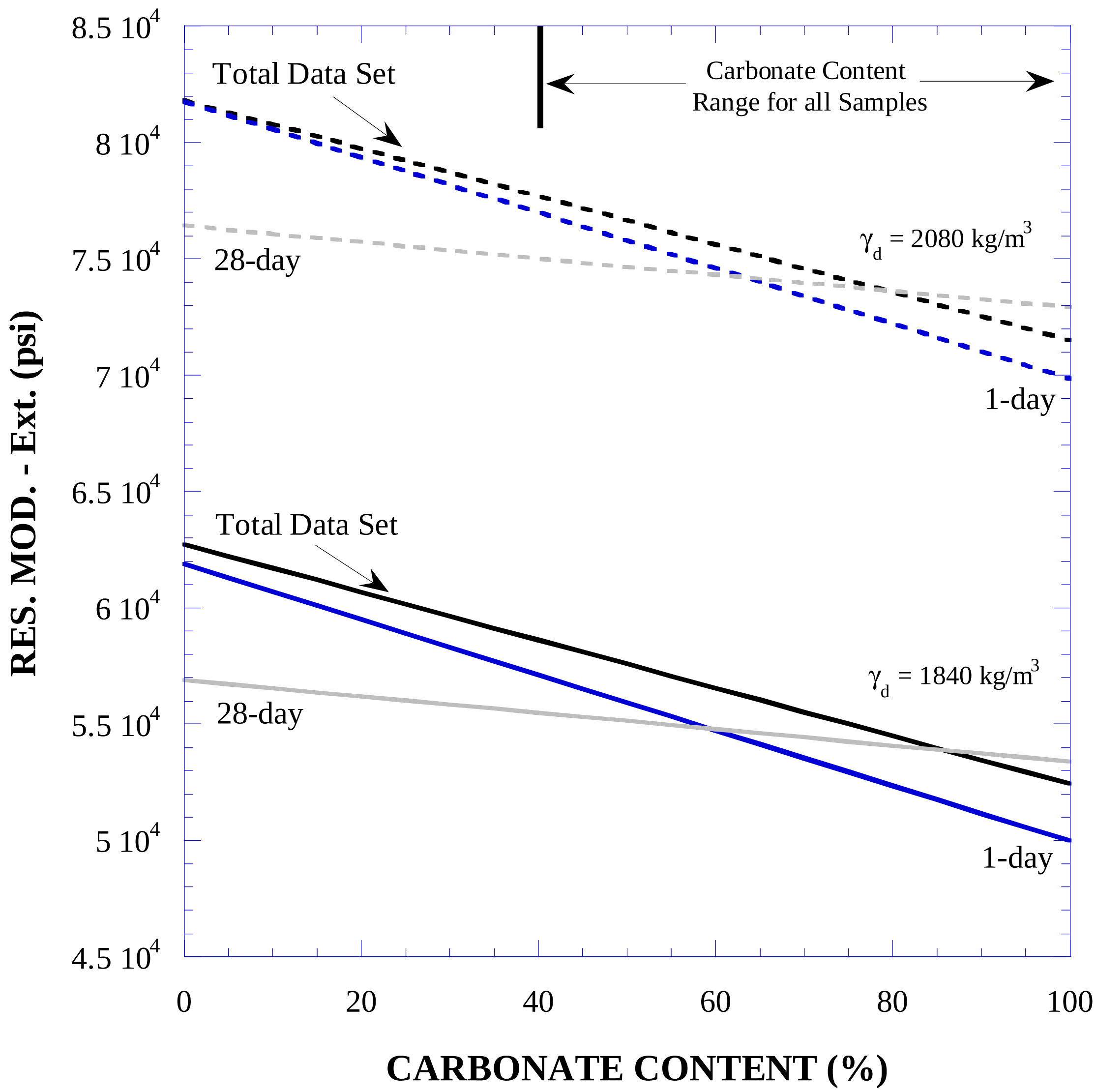

Figure 30. Prediction plot of M_R (ext.) value as a function of carbonate content for treated aggregate samples. (*Note*: Prediction lines were generated using the 1- and 28-day regression equations shown in Table 39)

ANALYSIS OF DATA COMBINED WITH PREVIOUS FDOT RESILIENT MODULUS TRIAXIAL TEST RESULTS

Methods of Data Analysis

Data from an FDOT report by Susan A. Moore was used in combination with the test results for base course aggregates from Pit Nos. 36-296 and 70-279. Initially the M_R values were computed using the k_1 and k_2 values derived from regression analysis at a Θ value of 50 psi (345 kPa). Table 40 gives these results along with moisture content, dry density, and percent passing the # 4 sieve. An effort was made to develop prediction equations using these parameters. Regression analyses were performed according to each of the following models:

$$M_R = a + b(w) + c\,(\gamma_d) \qquad \text{eqn. 5}$$

$$M_R = a + b(w) + c(\gamma_d) + d\,(<\#4) \qquad \text{eqn. 6}$$

where:
M_R = modulus of resilience, psi
w = moisture content, percent
γ_d = dry density, pcf
<#4 = percent passing # 4 sieve
a, b, c, and d = constant and coefficients

The results of these analyses are also given in Table 40.

Discussion of Results

The coefficients of determination (R^2) were 0.89 and 0.93 for eqns. 5 and 6, respectively. Predicted M_R values (eqn. 5) were within 9 percent of the measured values except for Pit Nos. 16-231 and 38-036 that differed by about 16 percent. The resulting regression equation predicted a reduction in M_R due to moisture content that conforms with the anticipated behavior of the materials. Normally an increase in dry density would produce an increase in M_R, not a reduction as given in these equations. This is probably a direct effect of testing at optimum moisture content where higher density could produce a greater degree of saturation and lower M_R or shear strength. In retrospect, the testing program should have included specimens at several moisture contents below optimum. Similarly, an increase in the percent passing the #4 sieve increased the M_R, which may or may not be logical. The lack of data for a wide range of percent passing values and the slight improvement in R^2 suggests that this parameter is not significant.

M_R values were also computed for four lower stress states (Θ) that were considered typical by AASHTO for the testing of base course materials. Table 41 lists these Θ values. The values of k_1 and k_2 derived from repetitive triaxial tests and the M_R values computed for the different Θ values are presented in Table 42. Several of the k_1 and k_2 values fell outside those considered typical by AASHTO.

Table 40. Prediction of M_R values @ Θ = 50 psi

PIT NO.	MOISTURE CONTENT (w %)	DRY DENSITY γ_d, pcf	% PASSING #4 SIEVE	M_R (Θ = 50 psi) – psi[e]		
				Meas.[a]	Eqn. 5[b]	Eqn. 6[c]
36-246	12.0	116.7	82	59,950	55,997	61,690
70-279	7.2	126.6	78	75,370	72,301	75,815
12-008[d]	8.3	128.2	—	60,937	50,725	—
16-231[d]	10.5	120.7	63	48,857	56,913	54,093
08-015[d]	13.5	113.5	64	51,211	51,393	50,808
08-050[d]	12.0	117.5	69	53,958	52,308	52,072
26-096[d]	11.0	113.0	44	84,597	85,966	85,612
26-100[d]	12.1	116.2	60	54,366	57,012	55,011
38-036[d]	10.3	119.8	64	69,808	63,645	63,016

(a) Based on k_1 and k_2 from regression analyses of triaxial test data according to $M_R = k_1\Theta^{k2}$

(b) M_R (psi) = 749015 – 12907.2(w) – 4611.23(γ_d)
n = 8, R^2 = 0.89

(c) M_R (psi) = 922233 – 15670.9 (w) – 6022.0(γ_d) + 369.21(<#4)
n = 8, R^2 = 0.93

(d) Data from an FDOT report by Susan A. Moore entitled "A Determination of Resilient Modulus and Permanent Deformation of Bank-Run Shell and Limerock Using Repetitive Triaxial Testing", April 1985.

(e) M_R (psi) × 6.895 = M_R (kPa)

Table 41. Typical values of Θ for base course

ASPHALT CONCRETE THICKNESS IN (mm)	M_R SUBGRADE (psi)		
	3000	7500	15000
	Θ (sum of principal stresses)		
< 2 (50)	20	25	30
2-4 (50 to 100)	10	15	20
4-6 (100 to 150)	5	10	15
> 6 (150)	5	5	5

1.0 psi = 6.895 kPa

Table 42. Resilient moduli for different limestones

PIT NO.	k_1	k_2	M_R (psi)[c] @ DIFFERENT Θ			
			5 psi	**10 psi**	**15 psi**	**20 psi**
(a) 36-296	5924.8	0.5916	15,353	23,135	29,407	34,863
(a) 70-279	7310.3	0.5964	19,090	28,863	36,758	43,638
(b) 12-008	21,357.7*	0.268*	32,876	39,587	44,131	47,668
(b) 16-231	9338.2	0.423	18,447	24,732	29,360	33,759
(b) 08-015	9598.5	0.428	19,114	25,716	30,589	34,597
(b) 08-050	15,191.0*	0.324*	25,589	32,032	36,529	40,098
(b) 26-096	26,574.1*	0.296*	42,791	52,536	59,235	64,500
(b) 26-100	9722.6	0.440	19,739	26,778	32,008	36,328
(b) 38-036	32,809.6*	0.193*	44,761	51,168	55,333	58,492

(a) Results from this investigation

(b) Data from an FDOT report by Susan A. Moore entitled "A Determination of Resilient Modulus and Permanent Deformation of Bank-Run Shell and Limerock Using Repetitive Triaxial Testing", April 1985.

(c) M_R (psi) × 6.895 = M_R (kPa)

* Values of k1 and k2 fall outside typical AASHTO values:

k_1 (dry) = 6000 to 10000 and k_2 (dry) = 0.4 to 0.7
k_1 (damp) = 4000 to 6000 and k_2 (damp) = 0.4 to 0.7
k_1 (wet) = 2000 to 4000 and k_2 (wet) = 0.4 to 0.7

Regression analyses were performed using the parameters and measured M_R data given in Table 43. The results were not as good ($R^2 = 0.70$) as previously developed using a greater Θ value. The M_R data trends illustrated in Fig. 31 suggest that M_R at Θ values between 40 psi (276 kPa) and 100 psi (690 kPa) tend to merge even though the slopes as defined by k_2 are substantially different. At Θ equal to 50 psi (345 kPa), M_R values ranged between 50,000 psi (345 MPa) and 85,000 psi (586 MPa), about a 70 percent increase over the low value. Similarly, at Θ of 20 psi (138 kPa), M_R was between 33,800 and 64,500 psi (233 to 445 MPa), an increase of about 90 percent. Again, the dispersion in test results cannot be assigned to material quality or characteristics because of an insufficient range in moisture contents and dry density for M_R test data.

Tables 44 and 45 list the AASHTO structural coefficients for base (a_2) and subbase (a_3) computed for limestone and bank-run shell materials, respectively, for a Θ of 20 psi (138 kPa). In consideration of the mean a_2 values and the range in these values for both types of materials, a larger coefficient of 0.18 (FDOT for LBR > 100) seems appropriate for both limestone and bank-run shell materials. The critical aspects of M_R evaluation and determination of a_2 and a_3 are related to moisture content, dry density, and probably gradation of the coarse aggregate relative to the amount and type of fine aggregate. Also, it should be recognized that regardless of layer coefficient, its behavior and performance in the pavement may be significantly altered due to moisture content fluctuations relative to clay content, mineralogy, etc.

Table 43. Prediction of M_R values @ Θ = 20 psi

PIT NO.	MOISTURE CONTENT (w %)	DRY DENSITY γ_d, pcf	% PASSING #4 SIEVE	M_R (Θ = 20 psi) – psi		
				Measured	Predicted[a]	± % Diff.
36-296	12.0	116.7	82	34,863	35,884	+ 2.9
70-279	7.2	126.6	78	43,638	47,168	+ 8.1
12-008	8.3	128.2	—	47,688	—	—
16-231	10.5	120.7	63	33,759	39,802	+ 17.9
08-015	13.5	113.5	64	34,597	36,548	+ 5.6
08-050	12.0	117.5	69	40,098	35,700	- 11.0
26-096	11.0	113.0	44	64,500	65,544	+ 1.6
26-100	12.1	116.2	60	36,328	41,051	+ 13.0
38-036	10.3	119.8	64	58,495	44,579	- 23.8

(a) $M_R = 567547 - 9317.7(w) - 3458.1(\gamma_d) - 198.6(<\#4)$
$n = 8,\ R^2 = 0.70$

Table 44. AASHTO base and subbase coefficients for limestone aggregates

PIT NO.	M_R @ Θ = 20 psi	BASE COURSE COEFF., a_2*	SUBBASE COEFF., a_3**
36-296	34,863	0.15	0.19
70-279	43,638	0.18	0.21
12-008	47,688	0.19	0.22
16-231	33,759	0.15	0.19
08-015	34,597	0.15	0.19
08-050	40,098	0.17	0.21
26-096	64,500	0.22	0.25
26-100	36,328	0.16	0.20
38-036	58,495	0.21	0.24
Mean	43,774	0.176	0.211
Range	33,759 to 64,500	0.15 to 0.22	0.19 to 0.25

* $a_2 = 0.249(\log E_2) - 0.977$, (Moore, 1985)
** $a_3 = 0.227(\log E_3) - 0.839$, (Moore, 1985)

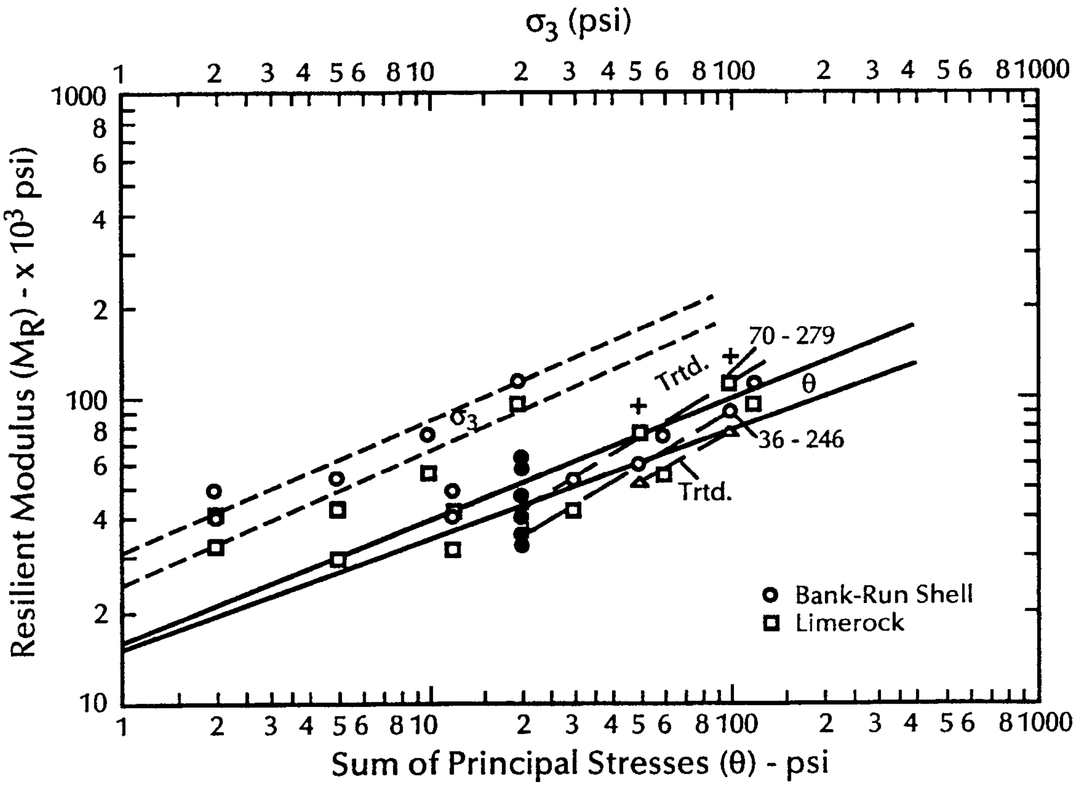

Figure 31. Average M_R versus Θ and σ_3.

Table 45. AASHTO base and subbase coefficients for bank-run shell[(a)]

BANK-RUN SHELL	M_R @ Θ = 20 psi	BASE COURSE COEFFICIENT, a_2*	SUBBASE COEFFICIENT, a_3**
10-285	47,825	0.19	0.22
17-087	50,143	0.19	0.23
17-197	45,962	0.18	0.22
17-091	38,856	0.17	0.20
10-217	41,058	0.17	0.21
10-052	62,270	0.22	0.25
01-274	44,286	0.18	0.22
05-238	66,804	0.22	0.26
01-220	50,385	0.19	0.23
12-249	67,226	0.23	0.26
Mean	47,057	0.194	0.230
Range	38,856 to 67,226	0.17 to 0.23	0.20 to 0.26

(a) M_R Data from a FDOT report by Susan A. Moore entitled "A Determination of Resilient Modulus and Permanent Deformation of Bank-Run Shell and Limerock Using Repetitive Triaxial Testing", April 1985.

* $a_2 = 0.249(\log E_2) - 0.977$, (Moore, 1985)

**$a_3 = 0.227(\log E_3) - 0.839$, (Moore, 1985)

GYRATORY TESTING, DATA ANALYSIS AND COMPARISONS

Gyratory (GTM) compaction and shear tests were performed on aggregates from Pit Nos. 36-246, 70-279, and 56-465. Initially, specimens were compacted to different numbers of GTM revolutions (15 to 25) to produce approximately the same dry density (γ_d) as was previously obtained with modified Proctor compaction. Subsequently, 18 revolutions, considered as typical of asphalt concrete paving compaction, were used to compact the specimens. After compaction, the specimens in the molds were placed in sealed plastic bags with wet paper towels for 14 days of curing. Then the specimens were tested in the GTM for 50 revolutions to obtain the gyratory shear strength and density. The GTM test conditions used were:

Initial angle of gyration:	3-degrees
Initial air-roller pressure:	62 kPa
Ram Pressure:	690 kPa
Compaction revolutions:	18 (except where otherwise noted)
Densification after 14-days:	zero to 50 with data recorded at various increments of revolutions

Upon completion of these tests the samples were extruded, broken down in pans and placed in a 105ºC oven for removal of moisture. Moisture contents and dry densities were then calculated using these data and volumetric information from the GTM.

Table 46 Gives the dry densities (γ_d) for the compacted and densified specimens. Samples prepared at different times are designated as DS1 through DS4, which denotes Data Set 1, etc. Since a few grams of material were lost during compaction, the sample height at zero revolutions prior to densification to 50 revolutions was used with extruded sample weights to calculate γ_d. There was little difference between the untreated and treated (1.0% hydrated lime) γ_d values for Pit 36-246 or Pit 70-279. However, untreated γ_d values for Pit 56-465 were approximately 65 kg/m^3 (3 pcf) greater than the treated samples.

Figures 32, 33, and 34 illustrate the G_s trends for aggregates from Pit Nos. 36-246, 70-279 and 56-465, respectively. Also shown on the figures are linear regression equations conforming to the following format:

$$G_s = a + b\,(\text{Rev.})$$

where G_s = Gyration shear, kPa
a = constant
b = coefficient
(Rev.) = Number of revolutions

The trends depicted in the figures conform to the regression equations except for the treated aggregate for Pit No. 56-465 which is shown as a power law trend according to the equation:

$$G_s = a(\text{Rev.})^b$$

Table 46. GTM dry density results

	Sample No.	Moisture Content, %	GTM Compaction – Densification				
			No. Rev.	Density (γ_d)		Density @ 50 Revolutions	
				Kg/m^3	pcf	Kg/m^3	pcf
Pit 36-246 (98% $CaCO_3$)							
Untreated	1 (DS1)	9.90[b]	20	1784	111.3	1933	120.6
"	2 (DS1)	10.48[b]	20	1827	114.0	1922	119.9
"	1 (DS4)	7.51	18	1710	106.7	1819	113.5
"	2 (DS4)	7.49	18	1805	112.6	1879	117.2
"	3 (DS4)	7.70	18	1783	111.3	1848	115.3
Treated	3 (DS1)[a]	11.16[b]	20	1808	112.8	1869	116.6
"	4 (DS1)	10.16[b]	25	1799	112.3	1888	117.8
"	4 (DS4)	7.69	18	1773	110.6	1860	116.1
"	5 (DS4)	7.83	18	1775	110.8	1875	117.0
Pit 70-279 (44% $CaCO_3$)							
Untreated	5 (DS2)	7.05	21	1999	124.7	2084	130.0
"	6 (DS2)	7.07	15	1854	115.7	2020	126.0
Treated	7 (DS2)	7.00	21	1958	122.2	2032	126.8
"	8 (DS2)	6.91	21	1859	116.0	1989	124.1
Pit 56-465 (77% $CaCO_3$)							
Untreated	6 (DS3)	11.07	18	1860	116.0	1987	124.0
"	7 (DS3)	11.05	18	1859	116.0	1974	123.2
Treated	8 (DS3)	11.10	18	1735	108.2	1813	113.2
"	9 (DS3)	11.15	18	1768	110.3	1837	114.7
"	1 (DS5)	10.77	18	1868	116.5	1931	120.5
"	2 (DS5)	11.10	18	1859	116.0	1904	118.8
"	3 (DS5)	10.76	18	1892	118.0	1929	120.4
"	4 (DS5)	11.04	18	1845	115.1	1900	118.6

[a] Error - sample weight 100g low, therefore higher w%
[b] Moisture Content reduced for Data Set 4 (DS4).

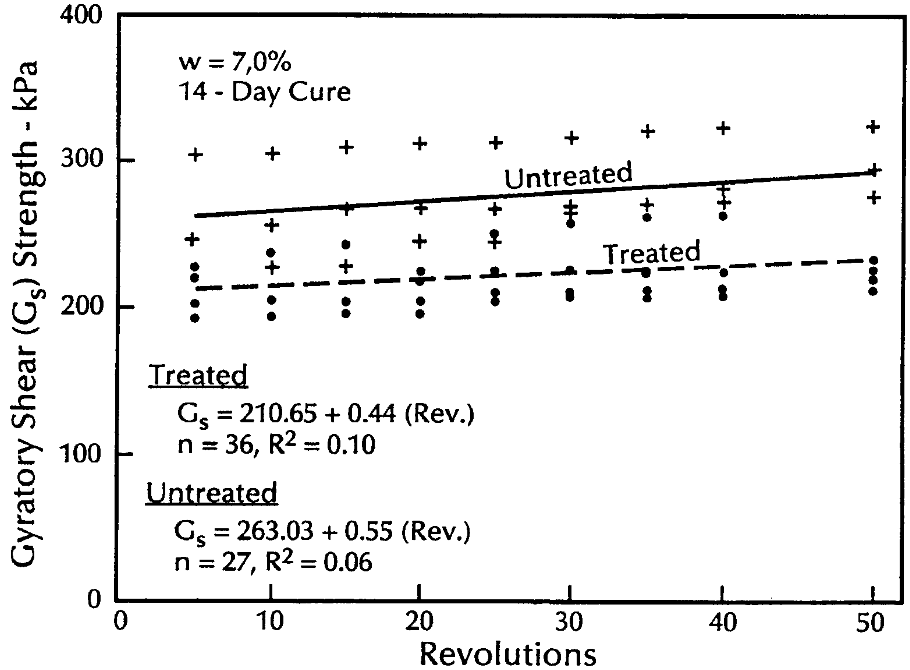

Figure 32. Gyratory shear strength for Pit No. 36-246.

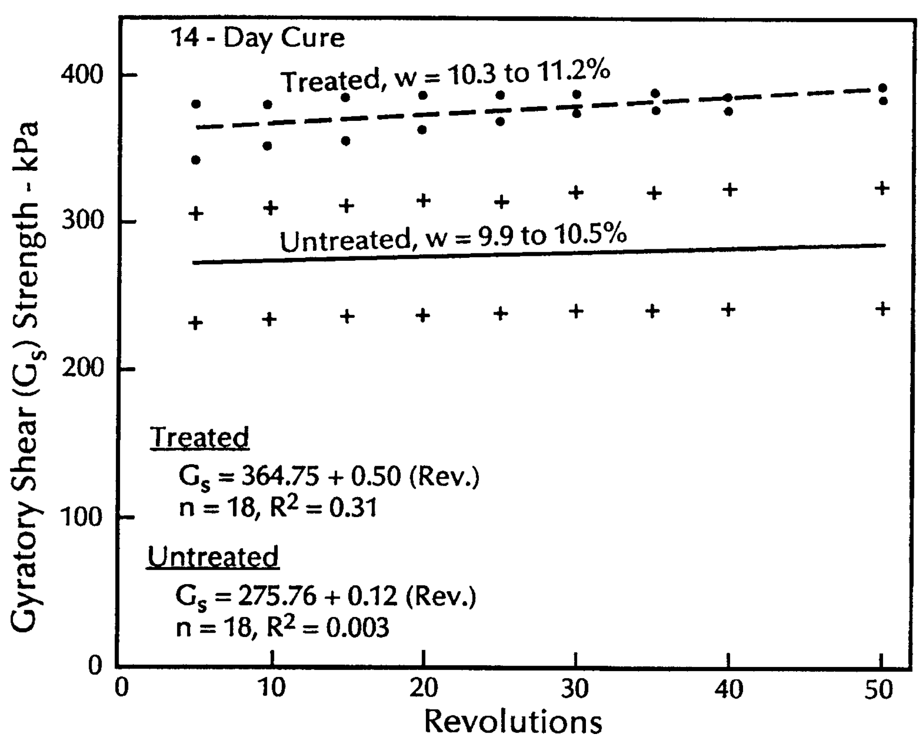

Figure 33. Gyratory shear strength for Pit No. 70-279.

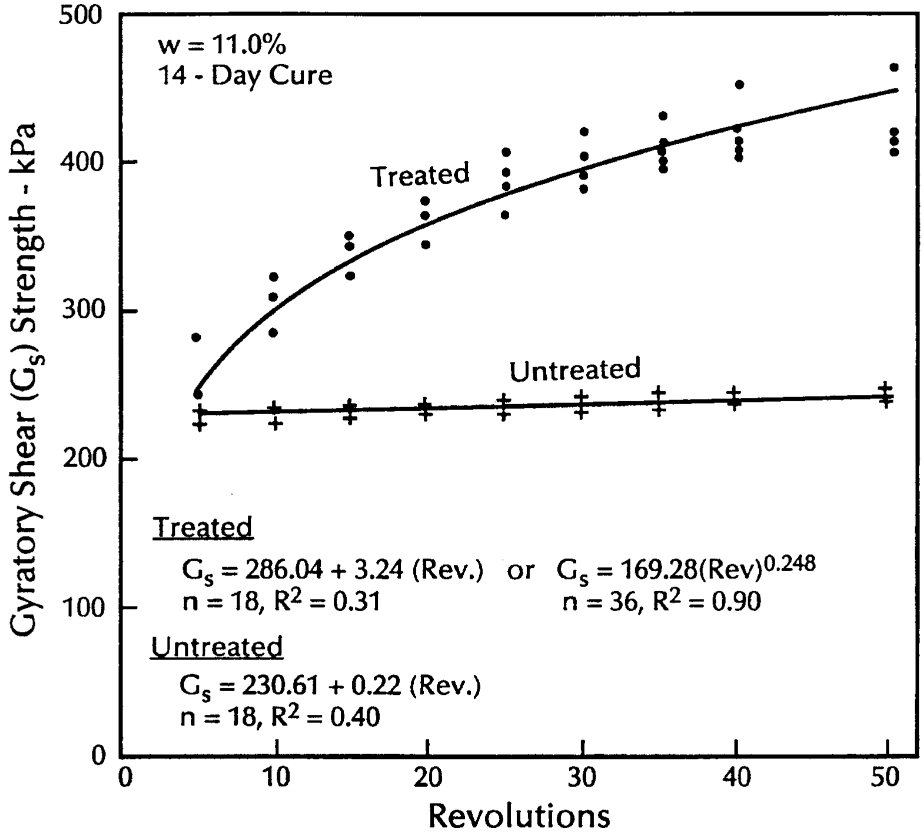

Figure 34. Gyratory shear strength for Pit No. 56-465.

The linear trends are compared in Figure 35. The G_s values for untreated aggregate from the three pits are very similar except that Pit 56-465 has a slightly lower shear resistance. In all cases the shear resistance increased only slightly with densification. Treated aggregate for Pit 36-246 appears similar to the untreated material but the addition of lime reduced its shear resistance. Pit 70-279 aggregate treated with one percent lime almost doubled its G_s values as compared to the untreated material. Only the treated aggregate from Pit 56-465 showed substantial increase in G_s with densification. All other materials were insensitive to densification above that produced using 18 revolutions for compaction.

The effect of density was evaluated for each test specimen by regression analysis according to the following linear model:

$$G_s = a + b(\gamma_d)$$

where: G_s = Gyratory shear, kPa
γ_d = Dry density, kg/m^3

The results given in Table 47 indicate only slight increases in shear resistance except for treated Pit 56-465 material. Table 48 presents a comparison of measured and predicted G_s values at different γ_d values. Untreated materials from all three pits gave densified G_s values at 14 days less than the 18 revolution compacted values. There was very little difference in G_s between

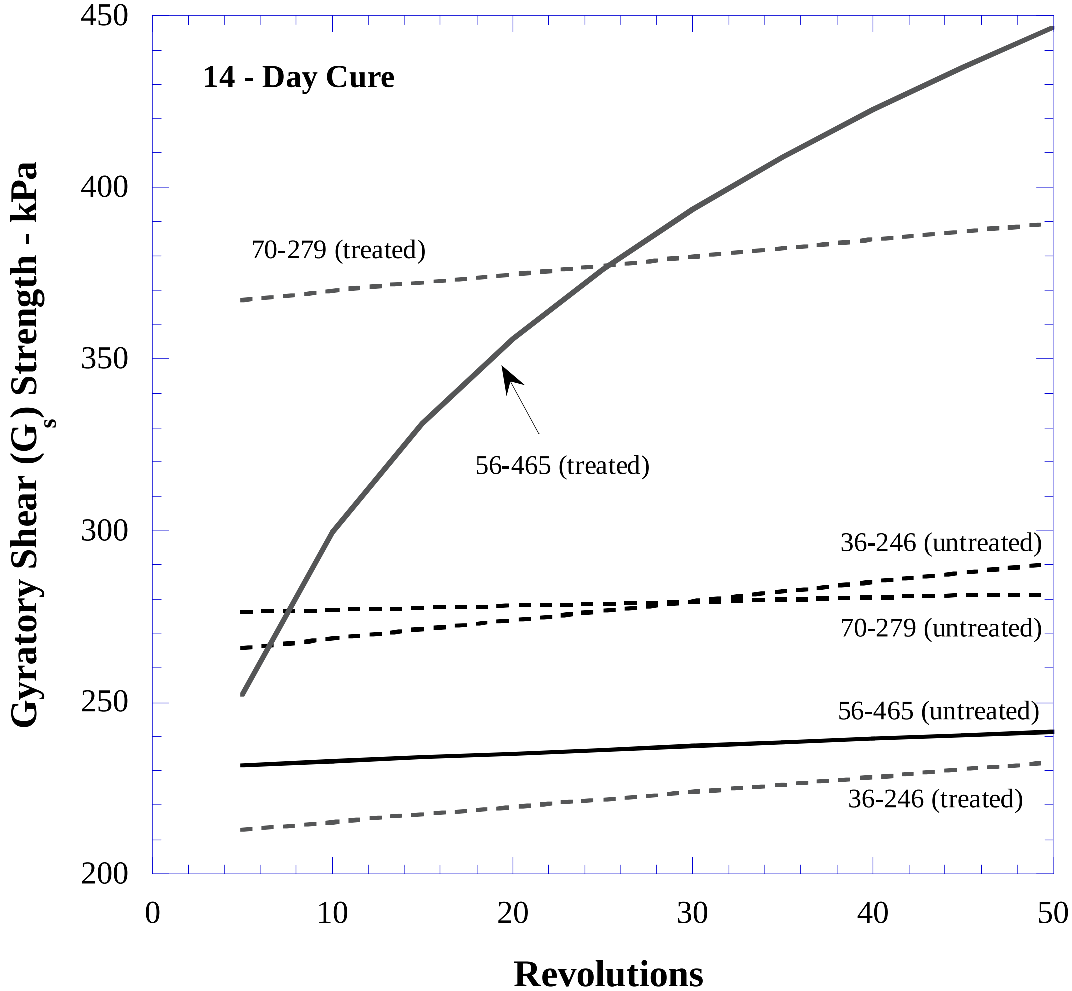

Figure 35. Comparison of gyratory shear trends for aggregates from Pit Nos. 36-246, 70-279, and 56-465.

Table 47. Results of regression analyses

	Sample No.	n	R^2	a*	b*
Pit 36-246					
Untreated	1 (DS1)**	9	0.95	-1387.2	0.9168
"	2 (DS1)	9	0.85	-462.3	0.3839
"	1 (DS4)	9	0.99	-0.05	0.1750
"	2 (DS4)	9	0.98	-2259.7	1.3565
"	3 (DS4)	9	0.88	-647.3	0.4877
Treated	3 (DS1)	9	0.98	-3.9	0.1235
"	4 (DS1)	9	0.96	-845.6	0.5897
"	4 (DS4)	9	0.72	-109.2	0.1737
"	5 (DS4)	9	0.88	-286.8	0.2670
Pit 70-279					
Untreated	5 (DS2)	9	0.91	-356.2	0.3269
"	6 (DS2)	9	0.99	-29.7	0.1357
Treated	7 (DS2)	9	0.96	-1.1247	0.7428
"	8 (DS2)	9	0.79	-4.4	0.1986
Pit 56-465					
Untreated	6 (DS3)	9	0.04	+232.1	0.0000
"	7 (DS3)	9	1.00	-0.62	0.1242
Treated	8 (DS3)	9	0.98	-3246.3	1.9865
"	9 (DS3)	9	0.92	-605.7	0.4436
"	1 (DS5)	9	0.99	-6251.8	3.4745
"	2 (DS5)	9	0.99	-4453.1	2.5575
"	3 (DS5)	9	0.98	-7852.3	4.2921
"	4 (DS5)	9	1.00	-5142.3	2926.1

*Regression Equation: $G_s = a + b(\gamma_d)$

where: G_s = Gyratory shear, kPa

γ_d = Dry density, kg/m^3

**Data Set 1, etc.

Table 48. Summary of gyratory shear results

Pit No.	Sample No.	Gyratory Shear (G_s) – kPa						
		Compacted	Densified		Predicted @ γ_d =			
		18 Rev.	5 Rev.	50 Rev.	1800	1850	1900	1950
36-246/Un	1 (DS1)	402	322	393	263	309	—	—
	2 (DS1)	289	249	272	228	248	—	—
	1 (DS4)	441	305	318	315	324	—	—
	2 (DS4)	279	196	290	182	250	—	—
	3 (DS4)	293	221	257	231	255	—	—
Mean		341	(259)	306	(244)	277	—	—
36-246/Tr	3 (DS1)*	286	221	227	218	225	—	—
	4 (DS1)	362	228	265	216	245	—	—
	4 (DS4)	311	202	220	204	212	—	—
	5 (DS4)	348	194	213	194	207	—	—
Mean		327	(211)	231	(217)	237	—	—
70-279/Un	5 (DS2)	365	309	325	232	249	—	281
	6 (DS2)	338	233	244	215	221	—	235
Mean		352	(271)	285	224	235	—	(258)
70-279/Tr	7 (DS2)	376	347	382	212	249	—	324
	8 (DS2)	348	382	391	353	363	—	383
Mean		362	(365)	387	283	306	—	(354)
56-465/Un	6 (DS3)	303	226	237	232	232	—	232
	7 (DS3)	356	234	245	223	229	—	242
Mean		330	(230)	241	(228)	231	—	237
56-465/Tr	8 (DS3)	388	216	346	329	429	528	627
	9 (DS3)	398	182	208	193	215	237	259
Mean		393	(199)	277	(261)	322	382	443
	1 (DS5)	417	218	462	—	176	345	523
	2 (DS5)	434	283	407	—	278	406	534
	3 (DS5)	355	230	412	—	88	303	517
	4 (DS5)	393	244	416	—	271	417	564
Mean		400	(244)	424	—	(203)	368	535

( ) represent values at 5 revolutions and at constant density within the range γ_d test results.

*Error - sample weight 100g low

treated and untreated materials for the compacted condition, however, as illustrated in Fig. 35, both Pit 70-279 and 56-465 exhibited substantially higher G_s for the treated aggregate than untreated material. The test results for the high carbonate (98%) limestone aggregate from Pit 36-246 did not produce any noticeable differences in shear resistance between treated and untreated materials.

Relationships between G_S and Φ

A comparative analysis of G_s and Φ is presented in Table 49. Individual and mean γ_d values from triaxial shear tests were used to predict G_s values. Then regression analyses were performed to determine if relationships between G_s and angle of internal friction (Φ) from the triaxial shear tests could be established to verify the shear strength trends. Table 50 presents results from regression analyses for Pits 36-246 and 70-279. The coefficient of determination (R^2) was poor ($R^2 < 0.55$) except for Pit 70-279 where average G_s and Φ values were used in the analysis. In this case the effect of lime treatment appeared to be substantial and verified by both GTM and triaxial shear tests.

In summary, the test results generally indicated very little difference between the untreated and treated shear resistance (G_s) of the different aggregates. Only the aggregate from Pit 70-279 uniformly gave a substantial increase in G_s for the lime treated material.

Relationships between G_S and M_R

A relationship was developed between Gs and MR using values corresponding to similar moisture content and density for test samples. Table 51 indicates that the GTM sample densities were almost the same as produced by Modified Proctor for MR triaxial tests. Also, moisture contents were the same except for untreated Pit 36-296 aggregates. The Gs and MR values given in Table 51 were subjected to regression analyses and plotted as shown in Fig. 36. Regression analysis of data for treated materials for Pits 36-296 and 70-279 provided the following results,

$$M_R = -121.33 + 1.3366(G_s)$$
$$n = 8, \quad R^2 = 0.92$$

where M_R = Resilient Modulus, MPa
G_s = Gyratory Shear, kPa

The number of values used in the analysis was increased from four as given in Table 51 to eight by using each of the two G_s values with each M_R value in an effort to give representative results. The regression line depicted in Figure 36 also intersects the data for untreated samples. The dispersion of this data and the lack of range in G_s and M_R prevented the development of any meaningful relationship.

Table 49. Comparative analyses of G_s and Φ

PIT NO.	CURING TIME (days)	w%	γ_d		Φ	GTM @ γ_d [(a)]				PREDICTED G_s using regression eqns. & γ_d [(b)]
			pcf	kg/m^3		REV.	G_s, kPa	REV.	G_s, kPa	
36-246										
Untreated	1	10.0	118.03	1891.5	48.0	15	344	20	268	
	7	10.4	118.2	1894.2	46.2	15	344	20	268	
	30	10.4	119.3	1911.9	46.9	35	372	40	271	
Mean		10.3	118.5	1899.2	47.0		353		269	354/267
Treated	1	10.0	116.7	1870.2	49.0	50	227	30	260	
	7	10.2	115.9	1857.4	51.1	35	225	20	245	
	30	10.1	116.1	1860.6	53.3	40	226	25	252	
Mean		10.1	116.2	1862.7	51.1		226		252	226/253
70-279										
Untreated	1	7.1	126.3	2024.0	42.5	5	309	40	244	
	7	7.1	127.1	2036.9	45.0	10	311	50	244	
	30	7.2	127.3	2040.1	39.4	10	311	50	244	
Mean		7.1	126.9	2033.7	42.0		310		244	309/246
Treated	1	7.0	128.2	2054.5	47.7	50	382	50	391	
	7	7.1	127.2	2043.3	49.5	50	382	50	391	
	30	7.2	127.2	2038.5	48.8	50	382	50	391	
Mean		7.1	127.6	2045.4	48.7		382		391	395/402

(a) G_s values (14-day) at γ_d corresponding to triaxial shear test specimens. Values may be slightly low where G_s at 50 revolutions is given since γ_d may occur at > 50 revolutions.
(b) Prediction eqn. format: $G_s = a + b(\gamma_d)$

Table 50. Relationships between G_s and Φ

Pit No.	Φ (avg.)	Gs @ γ_d (avg.)	n	R^2	N = a + bG_s	
					a	b
#36-246 (98% $CaCO_3$)	47.0	345/267	4	0.55	57.76	-0.032
	51.1	266/253				
	( )	( )	12	0.41	58.04	-0.0326
#70-279 (44% $CaCO_3$)	42.0	309/246	4	0.90	27.57	+0.052
	48.7	395/402				
	( )	( )	12	0.33	26.76	+0.054

( ) Φ and G_s values correspond to γ_d

Table 51. G_s and M_R data at 14-days

Pit No.	Condition	w%[(a)]	Gyratory @ 14-Day		M_R Triaxial Data @ 14-Day	
			kg/m^3 @ 50 Rev.	G_s, kPa	γ_d, kg/m^3	M_R, MPa[(b)]
36-246	Untreated	7.5/12.0	1879	290	1864	223.2
		7.7/12.0	1848	257	1863	276.6
	Treated	11.2/11.9	1869	227	1863	213.5
		10.2/11.9	1888	265	1856	194.2
70-279	Untreated	7.0/7.1	2084	325	2028	306.8
		7.1/7.1	2020	244	2021	321.7
	Treated	7.0/7.9	2032	382	2045	426.8
		6.9/8.1	1989	391	2044	371.0

(a) Moisture Content - Gyratory/Proctor for M_R
(b) M_R computed using k_1 and k_2 for 14-day test specimens and Θ = 137.9 kPa (20 psi)

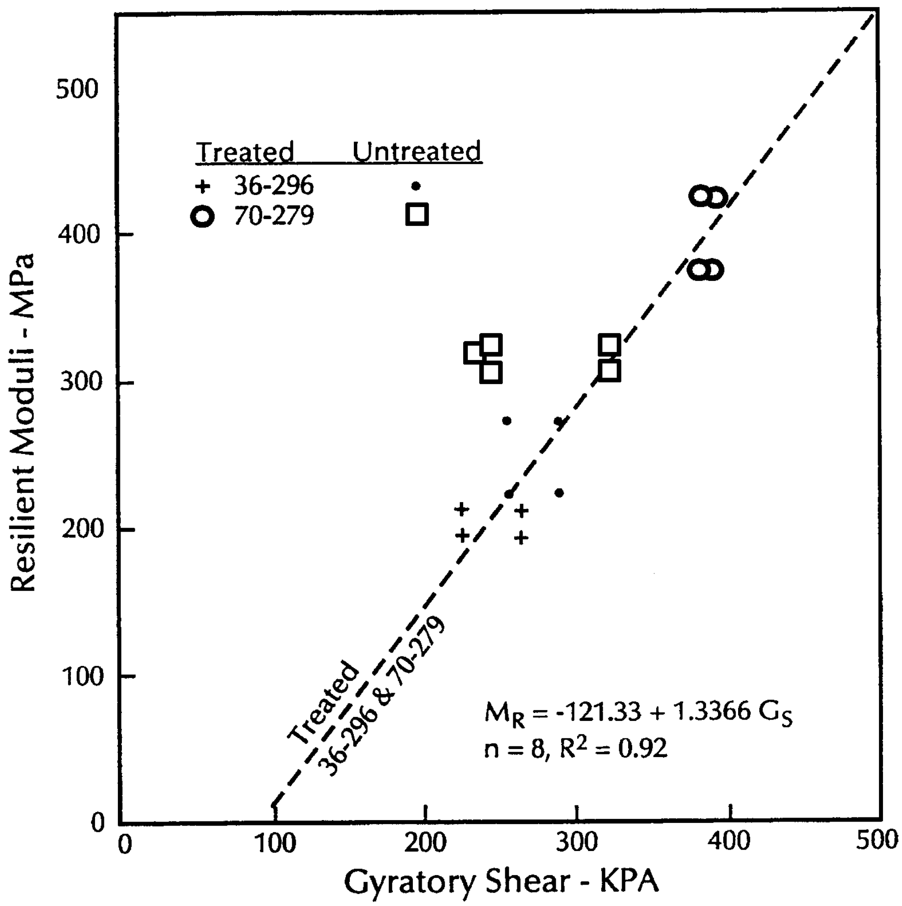

Figure 36. Correlation of G_s and M_R at $\Theta = 138$ kPa.

The correlation should not be used without verification or modification by additional data from other pits. However, it does appear that the GTM offers a fairly fast and perhaps reliable assessment of M_R. The following equation incorporates the M_R prediction equation into the AASHTO Base Coefficient equation for a_2:

$$a_2 = 0.249 \text{ Log } ((-121.33 + 1.3366G_s)/6895 \text{ E-6}) - 0.977$$

The predicted a_2 values for G_s of 200, 300, and 400 kPa are 0.10, 0.17, and 0.21, respectively. Mean values of G_s for 14-day tests were used to predict the M_R values for Pits. 36-296 and 70-279. These results are given in Table 52.

Table 52. a_2 predictions from G_s

Pit No.	Condition	Predicted M_R, MPa
36-296	Untreated	0.16
	Treated	0.14
70-279	Untreated	0.16
	Treated	0.21

TESTING AND EVALUATION OF RAPID PROCEDURES TO DETERMINE RECEMENTATION POTENTIAL

The cementation potential of carbonate base course materials is of major importance to highway construction. Although both limestones and dolomites used for base course material in Florida possess relatively low physical strength properties, their potential for cementation after initial compaction is great, favoring notable strength increases with time. The beneficial effects of permanent strength gain, associated with carbonate bases has been recognized for years (Graves, 1987; Gartland, 1979), yet development of a rapid means of predicting such gains has not been developed.

Previous research aimed at evaluating the cementation potential of Florida carbonate base course materials has primarily focused on chemical and mineralogical characterization (Graves, 1987; Gartland, 1979), rather than engineering properties (Zimpfer, 1989). Several factors that influence these engineering properties include grain size distribution, shape, and mineral composition (Graves, 1987). All play some role in the cementation of base course carbonates, yet understanding the interaction between these factors and the environmental conditions which drive the dissolution and recrystallization reactions responsible for strength gains remains unclear. For this portion of the study, our focus is on the evaluation and development of a practical method, particularly one with measurable parameters, that accelerates the cementation of limestone base course materials in order to predict increases in field based strength performance.

Materials, Test Specimen Preparation and UCT Testing

Analysis using an unconfined compression test (UCT) based on a modified Proctor approach was selected as a rapid means of measuring the unconfined shear strength of base course materials. Samples were subjected to a variety of additives and pretreatments (hydrated lime, CO_2 saturation, elevated humidity, etc.) at various pressures and temperatures with the ultimate goal of evaluating the effect of these additives and pretreatments on the cementation potential of base course materials. The eleven (Series A-K) procedures followed were:

Series A:	H_2O saturated atmosphere at 100ºC for 72 hours
Series B:	CO_2 (15 lbs.) saturated atmosphere at 100ºC for 72 hours
Series C:	CO_2 (15 lbs.) and H_2O saturated atmosphere at 100ºC for 72 hours
Series D:	CO_2 (15 lbs.) and H_2O saturated atmosphere at room temp. for 72 hours
Series E:	CO_2 (15 lbs.) and H_2O saturated atmosphere (24 hour cycle) at room temp. for 96 hours
Series F:	CO_2 (110 lbs.) and H_2O saturated atmosphere at room temp. for 96 hours
Series G:	CO_2 (110 lbs.) and H_2O saturated atmosphere (24 hour cycle) at room temp. for 96 hours
Series H:	CO_2 (100 lbs.) and H_2O saturated atmosphere at room temp. for 48 hours, followed by 96 hours at 100ºC with no CO_2
Series I:	CO_2 (100 lbs.) and H_2O saturated atmosphere at room temp. for 48 hours, followed by 7 days at 60ºC

Series J:	CO_2 (100 lbs.) and H_2O saturated atmosphere at room temp. for 48 hours, followed by 96 hours at 60ºC to 10ºC (24 hour cycle)
Series K:	CO_2 (100 lbs.) and H_2O saturated atmosphere at room temp. for 72 hours, followed by 7 days in a dessicator under natural barometric pressure

Materials selected for analysis included two high carbonate (Pit 36-246 and Pit 56-465) and two low carbonate (Pit 70-279 and Pit 93-406) samples. Samples from each pit were first split into 150 g subsamples and placed in plastic bags. To each sample, D.I. water was added to achieve optimum moisture as determined by LBR testing, and the samples agitated to insure an even moisture content. Both untreated and treated samples (containing 1% hydrated lime - $Ca(OH)_2$) from each quarry were prepared in this manner.

Core samples for unconfined strength tests were prepared in a 1.25" by 2.75" mold using a modified Proctor approach to sample preparation. Approximately 50 ml of sample was placed in the mold and compacted using a hammer with a 1 ft throw. Three layers were compacted in this manner, employing 5 drops of the hammer for each layer, producing a 6 ft lb/in^2 compactive effort per layer. After each core was completed, it was wrapped in a moist paper towel until placed into an autoclave

The autoclave was prepared with a custom built rack allowing 12 samples to be analyzed simultaneously in 3 levels containing 4 samples each. Prior to the day samples were placed in the autoclave, the temperature was preset and a CO_2 cylinder attached which would allow for pressurization of the autoclave to levels desired for each experiment.

Test Results and Analyses

Two cores each of both untreated and treated base course material (4 total) from each of the pit locations were analyzed according to each of the eleven experimental conditions outlined. Table 53 summarizes the results for this part of the study, with the complete data for each experiment included in Appendix F. The percent carbonate and optimum moisture content of each sample is that given in Table 2. Percent fines (passing 200 mesh) for each material were 37.0% (Pit 36-246), 13.0% (Pit 70-279), 29.4% (Pit 56-465), and 15.7% (Pit 93-406).

In almost all of the experiments the untreated samples showed greater strength (gain?). This may be due to the hydrated lime acting as a fine lubricant, reducing the internal friction of the base course mixes, as well as reducing the dry density, over the short time span confined by these experiments. No correlation is observed between these experiments and the LBR data for these materials, nor does there appear to be any correlation to carbonate content, % fines, or any of the other engineering parameters measured in this study. Although it was believed that a controlled environment of some combination of variable humidity and variable CO_2 pressure would result in the conditions necessary to accelerate cementation, the experiments failed to produce the desired results. Apparently, we have been unable to mimic the proper natural field conditions over a short time span that will facilitate acceleration of the cementation process observed in the field.

Table 53. Unconfined compression test results								
	36-246	36-246	56-465	56-465	70-279	70-279	93-406	93-406
	Untreated	Treated	Untreated	Treated	Untreated	Treated	Untreated	Treated
Series A	73.24	72.84	192.11	112.10	29.48	53.99	82.66	59.32
Series B	108.86	46.21	128.84	66.64	60.17	51.95	106.78	89.25
Series C	44.50	64.62	142.78	136.61	41.72	36.39	99.39	97.35
Series D	71.04	63.02	160.31	107.18	47.06	35.18	67.09	49.91
Series E	174.30	53.18	110.46	51.14	40.91	18.01	56.47	50.74
Series F	85.51	47.05	101.47	38.06	28.24	24.95	48.66	50.33
Series G	53.99	29.88	95.74	39.67	36.31	33.13	53.59	30.69
Series H	45.44	45.00	86.32	49.50	29.48	27.40	73.64	46.65
Series I	70.38	40.48	98.18	32.33	59.72	47.89	84.67	51.54
Series J	37.53	38.43	119.85	71.19	37.66	35.61	107.20	60.56
Series K	65.05	42.52	94.09	58.11	65.99	46.65	53.41	33.57

* Values of average failure stress are in psi.

CONCLUSIONS AND RECOMMENDATIONS

Evaluation of the results from the testing of base course aggregates provided the following specific conclusions for each of the tests conducted in the research.

Limerock Bearing Ratio (LBR)

1. Density, moisture content, carbonate content, and perhaps gradation were found to have variable statistical significance on LBR values throughout the LBR study. Dry density appears to be the most significant variable if test samples vary in dry density within the constraints of the sample protocol that is employed.

2. Regression analyses indicted that high carbonate content aggregates are not necessarily beneficial (part 1), and regression equations developed to give an estimate of the effect of the different variables on LBR should not be used as predictors. The variability in equation constants at different ages combined with the relatively low R^2 values preclude their use except as supplemental information to actual test data. The collection of additional data for analysis in the future may yield a more reliable prediction equation for LBR that may be dependent on lithology. Observations suggest that aragonite content may be of importance in the final assessment of the role of carbonate content to strength gain potential.

3. The effect of lime on accelerating cementation and increasing LBR was only slightly apparent with most materials when considering high variability in test data. However, lime treated aggregates from Pit. No. 56-465 produce a 400 percent or more increase in LBR over that for the untreated aggregate that was attributed to the influence of lime on possible clays contained in the aggregate.

Triaxial Shear

1. The angle of internal friction (Φ) was on the average 4 to 6 degrees greater for lime treated aggregates than the untreated aggregates from Pits 36-246 and 70-279.

2. Increases in Φ with time (1, 7, and 30-days) were very small and probably not significant.

3. Tangent moduli derived from the tests were in the range of 69 to 110 MPa (10 to 16 ksi) which is exceedingly lower than typical results from plate bearing tests or FWD back calculated moduli, although comparison at different strain conditions is problematic.

Triaxial Resilient Modulus (M_R)

1. Low carbonate (44%) aggregate from Pit 70-279 treated with lime provided about a 20 to 30 percent increase in M_R values over that of the untreated aggregates, but Pit No. 36-246 (98% carbonate) gave about a 20 percent reduction in M_R when treated with lime.

2. Aging of specimens up to 28-days had no observable effect on M_R. The effect of lime appeared to be almost immediate within less that 1-day.

3. M_R data from the total data set suggests that lime treatment produces the greatest strength gain in materials possessing low carbonate contents. However, this observation is complicated by the presence of aragonite in the low carbonate samples, and its likely importance as a cementing phase responsible for observed strength gain.

4. Regression analyses show M_R data to correlate with the variables of dry density, moisture content, and carbonate content in the treated samples. This permitted development of prediction curves for treated sample M_R values, which are a fair estimate of measured M_R data.

Gyratory Shear (G_S) Testing

1. The G_s results from the Gyratory Testing Machine verified the relative effect of lime treatment on the two aggregates (i.e. treated gave lower G_s for Pit No. 36-246 and higher for Pit No. 70-279).

2. Densification had little effect on G_s except for treated aggregate from Pit No. 56-465. In this case the G_s increased substantially with density.

Development of M_R and a_2 Predictions

AASHTO base coefficients, a_2, that were computed at a Θ = 138 kPa (20 psi) for nine limestone aggregates and ten bank-run shell materials suggests there is very little difference between the materials. The a_2 values ranged between 0.15 and 0.23. A mean value of 0.18 was selected as being a typical or acceptable value.

A relationship was developed to predict M_R from G_s values. This was substituted in the AASHTO equation for calculation of a_2. G_s predictions of a_2 for 36-246 and 70-279 were 0.14 and 0.21 for the lime treated aggregate, respectively and 0.16 for both of the untreated materials.

Unconfined Compression Test (UCT)

The only noticeable observation from these experiments was the greater strength associated with the untreated samples over that observed for samples treated with 1% hydrated lime. No other correlations were observed between these experiments and either measured physical parameters (carbonate content, % fines, etc.) or engineering parameters determined as a part of this study. These experiments failed to produce the desired results of producing a rapid means of determining the cementation potential of base course materials. Apparently, we were unable to produce the conditions, over a short time span, necessary to accelerate the cementation process observed in the field.

Summary of Conclusions

The differences in aggregate gradation, particle shape and texture, clay and silt content, moisture content, and compacted or in-place density precludes the use of generalized characterization for determination of structural coefficients or behavior. The triaxial resilient modulus is a time consuming but reliable test method. The GTM has the advantage of providing G_s data throughout a range in density thus making it a quick and efficient method for testing aggregates at different moisture contents.

It is recommended that the FDOT consider an investigation to verify or modify the M_R and a_2 prediction equations based upon G_s test values. This will require a comprehensive test program involving aggregates from different pits, modification of aggregate blends and gradations, different moisture contents, and different density levels to ascertain the effect of variables and to develop a reliable relationship using G_s or perhaps other aggregate characterization variables.

In the interim, it is suggested that aggregates having long term strength gain potential be considered on the basis of as placed, short-term properties. Test results imply that carbonate content is not necessarily the parameter that relates to the strength gain in structural properties or bearing capacity of limestone base course aggregates. If it is assumed that M_R calculation of a_2 is reliable, then to what degree will testing variability and differences in density/moisture content affect this value and behavior of the pavement? Consequently until further research is performed, it is suggested that an a_2 value of 0.18 for $\Theta = 138$ kPa be used for these materials conforming to FDOT specifications.

LBR testing also may offer a good method of eventually evaluating the importance of carbonate content to base course strength gain phenomena. However, test variables observed in this study may require that individual lithologies be independently evaluated, as carbonate content has a variable meaning in different materials around the state. It also is of importance to evaluate the role of aragonite content and gradation within the context of cementation and/or base course strength gain.

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APPENDICES

APPENDIX A: MODIFIED PROCTOR MOISTURE-DENSITY DATA FOR UNTREATED AND TREATED BASE COURSE AGGREGATES (PART 1)

Table A-1. Modified proctor moisture/density data for untreated base course aggregates (part 1)

Pit No. (% Carbonates)	3-day		7-day		14-day		28-day		60-day	
	w%	γ_d	w%	γ_d	w%	γ_d	w%	γ_d	w%	γ_d
36-246 (98%)	10.5	1867.6	10.3	1837.1	10.5	1837.1	11.1	1853.2	10.7	1832.3
56-465 (77%)	10.3	1853.2	12.1	1917.2	10.1	1835.5	10.2	1837.1	9.9	1851.6
12-008 (70%)	6.8	2114.2	7.4	2088.6	7.2	2095.0	6.8	2101.4	7.2	2088.6
87-090 (70%)	5.9	2056.5	6.2	2079.0	6.2	2064.5	6.3	2067.8	5.9	2058.2
17-091 (52%)	8.6	2077.4	8.6	2058.2	8.4	2088.6	8.4	2069.4	8.4	2106.2
93-406 (47%)	7.3	2000.5	7.6	2010.1	7.5	2003.7	7.8	2021.3	8.0	2019.7
93-406 (40%)	7.2	2047.0	7.2	2056.6	7.4	2053.4	7.7	2059.8	7.7	2064.6
70-279 (40%)	7.2	2063.0	7.4	2040.6	7.3	2037.4	7.3	2048.6	7.2	2043.8

(a) Percent moisture by weight of dry aggregate
(b) Specimen dry density - kg/m^3

Table A-2. Modified proctor moisture/density data for lime treated base course aggregates (part 1)

Pit No. (% Carbonates)	3-day		7-day		14-day		28-day		60-day	
	w%	γ_d	w%	γ_d	w%	γ_d	w%	γ_d	w%	γ_d
36-246 (98%)	11.7	1858.0	12.0	1848.4	11.9	1851.6	11.3	1838.7	11.6	1816.3
56-465 (77%)	12.2	1883.6	12.8	1886.8	12.9	1878.8	10.9	1809.9	10.9	1806.7
12-008 (70%)	7.9	2122.3	7.8	2111.0	8.1	2095.0	8.2	2114.2	7.9	2117.4
87-090 (70%)	7.1	2085.4	7.0	2091.8	6.9	2071.0	6.9	2075.8	6.8	2077.4
17-091 (52%)	9.2	2022.9	9.5	2035.8	9.5	2027.8	9.5	2037.4	9.2	2011.7
93-406 (47%)	7.5	2011.7	7.2	1984.5	7.7	1192.5	7.4	1970.0	7.3	1970.0
93-406 (40%)	8.2	2042.2	8.1	2064.6	8.2	2061.4	8.4	2053.4	8.4	2056.6
70-279 (40%)	7.2	2047.0	7.1	2061.4	7.1	2061.4	7.2	2053.4	7.1	2042.2

(a) Percent moisture by weight of dry aggregate
(b) Specimen dry density - kg/m^3

APPENDIX B: MODIFIED PROCTOR MOISTURE-DENSITY DATA FOR UNTREATED AND TREATED BASE COURSE AGGREGATES (PART 2)

Table B-1. Modified proctor moisture/density data for untreated base course aggregates (part 2)

Pit No. (% Carbonates)	1-day w%	1-day γ_d	1-day w%	1-day γ_d	7-day w%	7-day γ_d	7-day w%	7-day γ_d	14-day w%	14-day γ_d	14-day w%	14-day γ_d	28-day w%	28-day γ_d	28-day w%	28-day γ_d
36-246 (98%)	12.3	1872.4	12.2	1877.2	12.1	1858.0	12.1	1866.0	12.1	1882.0	12.1	1880.4	12.3	1867.6	12.6	1861.2
70-279 (40%)	7.0	2026.1	7.0	2026.1	7.1	2022.9	7.1	2024.5	7.0	2035.8	7.1	2022.9	7.0	2018.1	7.1	2022.9
56-465 (77%)	12.5	1931.6	12.7	1934.8	----------		----------		12.5	1933.2	13.4	1920.4	12.5	1938.0	12.5	1933.2
17-091 (52%)	9.4	2055.0	9.6	2045.4	----------		----------		9.3	2037.4	9.4	2047.0	9.4	2050.2	9.6	2053.4
93-406 (47%)	7.2	2069.4	7.1	2066.2	----------		----------		7.2	2045.4	7.6	2048.6	7.2	2051.8	7.2	2074.2
26-001 (99%)	12.0	1874.0	12.1	1875.6	----------		----------		12.0	1870.8	12.0	1872.4	12.0	1874.0	11.8	1867.6
58-486 (-- %)	10.9	1901.2	11.5	1902.8	----------		----------		10.7	1957.3	11.5	1965.3	10.7	1965.3	11.4	1957.3
MX411 (99%)	7.8	2104.6	7.8	2083.8	----------		----------		7.6	2069.4	7.6	2075.8	7.4	2067.8	8.0	2053.4
AL-149 (99%)	5.9	2280.8	5.9	2290.4	----------		----------		5.9	2298.4	5.8	2332.1	5.7	2303.2	5.8	2277.6

(a) Percent moisture by weight of dry aggregate
(b) Specimen dry density - kg/m^3

Table B-2 Modified proctor moisture/density data for lime treated base course aggregates (part 2)

Pit No. (% Carbonates)	1-day w%	1-day γ_d	1-day w%	1-day γ_d	7-day w%	7-day γ_d	7-day w%	7-day γ_d	14-day w%	14-day γ_d	14-day w%	14-day γ_d	28-day w%	28-day γ_d	28-day w%	28-day γ_d
36-246 (98%)	12.0	1875.6	11.8	1886.8	12.1	1872.4	12.0	1874.0	11.7	1885.2	12.1	1866.0	11.9	1888.4	12.0	1877.2
70-279 (40%)	8.0	2051.8	7.9	2043.8	8.1	2027.7	7.8	2040.6	7.8	2040.6	8.0	2061.4	7.8	2058.2	8.5	2019.7
56-465 (77%)	13.1	1920.4	13.2	1918.8	----------		----------		12.9	1914.0	13.0	1904.4	13.2	1891.6	13.2	1904.4
17-091 (52%)	10.5	2032.5	10.2	2030.9	----------		----------		10.2	2019.7	10.5	2019.7	10.2	2026.1	10.3	2021.3
93-406 (47%)	7.1	2053.4	7.1	2040.6	----------		----------		6.9	2037.4	7.0	2048.6	7.1	2029.3	7.2	2029.3
26-001 (99%)	11.8	1893.2	11.9	1880.4	----------		----------		11.8	1870.8	11.8	1861.2	11.7	1878.8	11.8	1875.6
58-486 (-- %)	12.7	1947.7	12.6	1957.3	----------		----------		12.9	1949.3	13.2	1952.5	13.0	1950.9	12.5	1947.7
MX411 (99%)	7.2	2064.6	7.6	2043.8	----------		----------		7.7	2037.4	7.3	2074.2	7.7	2022.9	8.0	2030.9
AL-149 (99%)	6.4	2282.4	5.6	2332.1	----------		----------		6.1	2332.1	5.8	2296.8	5.8	2292.0	5.9	2314.4

(a) Percent moisture by weight of dry aggregate
(b) Specimen dry density - kg/m^3

APPENDIX C: RESULTS FROM TRIAXIAL SHEAR TESTS

APPENDIX D: STRESS-STRAIN CURVES FROM TRIAXIAL SHEAR TESTS FOR MODULUS COMPUTATIONS

APPENDIX E: TEST DATA AND ANALYSES FOR REPEATED LOAD TRIAXIAL RESILIENT MODULUS

APPENDIX F: RESULTS FROM UNCONFINED COMPRESSION TESTS