RMRC Project 6 - Evaluation of Tests for Recycled Material Aggregates for Use in Unbound Applications

Final Report

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Section 1 – Introduction

As may often be the case, the soil at a given site may be less than ideal for engineering purposes. In order to improve the soil to a point adequate for geotechnical applications, the soil needs to be stabilized. The most common method of treatment is through compaction using various techniques. Compaction can be applied to both fill and in situ materials, and the methods for these are quite different.

To simulate field compaction in the laboratory, different techniques must be used depending on soil type. For cohesive soils, the laboratory methods such as the Proctor tests are quick, easy to conduct and work quite well. But for cohesionless soils, an ideal test method has yet to be developed. The current American Society for Testing and Materials (ASTM) test procedure for cohesionless soils, ASTM D 4253-00: *Standard Test Methods for Maximum Index Density and Unit Weight of Soils Using a Vibratory Table*, is far too cumbersome and time consuming. In many instances this test method is disregarded and the Proctor tests are performed in place of this due to ease and familiarity.

It has been widely know for several decades that the most efficient means for densifying cohesionless materials is through the application of vibration. The current ASTM specification mentioned above is a vibratory-based test, which is difficult to perform. Alternatives to this test method have been considered and much research has focused upon the use of a modified demolition hammer for laboratory compaction of granular materials. Past experiences with demolition hammers have shown great promise and have resulted in the publication or drafting of several standard test specifications in Europe and in the United States.

There are three primary objectives of this research. The first goal is to determine the feasibility of using a modified demolition hammer for laboratory soil compaction purposes. This would be accomplished by showing that the hammer test method was repeatable, non-destructive, not operator dependent, and achieved higher maximum dry unit weights with minimal particle degradation when compared to current accepted test methods. Another goal for this research is to acquire enough data from various measurements to model and understand the compaction process. These laboratory measurement devices were also utilized to help in determining repeatability. The third goal of this work is to improve the understanding on the behavior of recycled materials aggregates. By developing an understanding of these materials behaviors, it is hoped to promote their use for fill materials.

The testing for this research was divided into four phases. The first phase was conducted upon a control aggregate to establish the repeatability of the test method. In unison with the first phase, the second phase focused upon data acquisition for modeling of the compaction process. Measurements from Linear-Variable-Differential-Transducers (LVDT's) and piezoelectric accelerometers were used for modeling. After establishing that the test method was repeatable, the third and fourth phases of testing were conducted. The third phase centered upon expanding the testing program to include additional aggregates, including two recycled materials aggregates. Some limited data acquisition was conducted during this phase as well to determine if the compaction process was affected by material. The fourth phase of testing was primarily concerned with calibration and standardization of the test method. This phase dealt predominantly with the determination of the energy being imparted into the soil specimen through the use of several laboratory instruments, in particular the use of LVDT's, accelerometers and strain gages. This phase of testing also introduced Ottawa sand to the testing program as a means for standardization and calibration. In addition, the final phase of testing also attempted to model the vibratory hammer setup as a vibrating footing. An analysis of this was conducted that sought to predict the behavior of the control aggregate during the compaction process.

Section 2 of this work provides some general background about the compaction process and the different compaction techniques utilized in both field and laboratory settings. In Section 3, the materials that were used over the course of this research are presented, including descriptions of soil properties. Section 4 describes the equipment and testing procedure used in this research. Results from the testing program are presented in Section 5.

Section 2 – Background

More and more commonly, areas that were at one time thought of as undesirable are required for use in construction applications. The use of this land requires substantial amounts of improvement to increase the engineering properties to a point suitable for construction. Several of the most commonly used forms of soil improvement include dewatering, pre-consolidation, and compaction. Perhaps the most widely used method of improvement is compaction, which is most commonly defined as any of the means of mechanical improvement of the engineering properties of a soil. Through the use of laboratory testing a series of key relationships can be developed and then used as guidelines for compaction in the field. These relationships include the moisture-density relationship for the material, the optimum moisture content (OMC), and the factors influencing the behavior of materials during compaction.

In order to achieve compaction of a material, water is almost always required in the densification process regardless of material type or gradation. This additional water is used to fill pore spaces in the soil skeleton once occupied by air. As water is denser than air, this results in an increase in unit weight for the material. The additional water also acts as a lubricant for the soil particles, allowing them to slide past each other into denser configurations (Hilf, 1991). As would be imagined, there is a limit to this phenomenon. Eventually a point will be reached where the addition of water begins replacing soil particles. As soil solids have higher unit weights, the loss of soil particles decreases the specimen unit weight. Graphically, this creates a curve. The point of interest on the curve is at the apex, a point defined as the maximum unit weight, γ_{max}. This point is the maximum achievable dry unit weight for the given soil sample for a particular compactive effort.

This moisture-density relationship works well in describing the behavior of cohesive soils but does not apply to granular materials. Granular materials do not absorb moisture in the same fashion as cohesive soils, and are thus rather non-responsive to the addition of water. There is no clearly defined peak for the curve corresponding to a maximum dry unit weight as seen with cohesive soils. From the curve, it is evident that the same unit weight at nearly 100 % saturation can be achieved at an air-dried condition. The slight decrease in maximum achievable dry unit weight with intermediate water contents is described with the phenomena of bulking. As noted by Hilf (1992), the partially saturated material develops capillary stresses that counteract the compactive effort being put forth. Bulking only occurs in partially saturated materials and is not present in either completely dry or saturated testing. The water content corresponding to the maximum achievable dry unit weight is known as the optimum moisture content, or OMC. Usual practice for compaction dictates that field compaction be conducted over a range of the OMC plus or minus several percent. While clearly defined for a cohesive soil, the OMC for a cohesionless soil is very poorly defined.

There are numerous factors that must be considered when choosing a method for compaction. In his original work, Proctor stated that there were four main factors that influence compaction: 1) dry density, 2) water content, 3) compactive effort, and 4) soil type (Holtz and Kovacs, 1981, Bergado et al., 1996, and Mehdiratta, 1974). The first two were discussed previously. The latter two, compactive effort and soil type, are best treated as one factor due to their complex interconnected relationship. The method of compaction used on a project is determined only after the soil at the site has been classified. For this reason, one of the most important considerations when choosing a compaction method is soil type. Compaction methods will have very different results when used upon cohesive soils versus cohesionless granular soils. It is for this reason that soil type and compactive effort are of great importance. Even owing to their importance, these two factors are often either overlooked or neglected in considerations.

Section 3 –Materials

Sand was used as the baseline control. A sample of the sand can be seen in Figure 1. The values for D_{60}, D_{30}, and D_{10}, from the grain size distribution curve, were estimated to be 0.37, 0.26, and 0.16 mm, respectively. For this material the values for C_c and C_u were determined to be 1.14 and 2.31, respectively. As more than 50% of the material passes the #4 sieve, the material is sand. Using the guidelines for USCS classification, the values of C_c and C_u can be used to determine the gradation of the material. The material was classified as a poorly-graded sand, SP. The specific gravity for this sand was found to be 2.67. The natural water content of the material was determined to be approximately 0.3 %. The average unit weight of this material was determined to be approximately 95 pcf.

Figure 1
Sand

Material: *Play Sand*								
D_{60} (mm)	**D_{30} (mm)**	**D_{10} (mm)**	**C_c**	**C_u**	**USCS Designation**	**Water Content, %**	**Specific Gravity**	**Unit Weight, pcf**
0.37	0.26	0.16	1.14	2.31	SP	0.28%	2.67	95.18

Quartz Monzonite is an igneous plutonic rock found commonly throughout Southern Maine and New Hampshire. A sample of the Quartz Monzonite can be seen in Figure 2. Visual inspection of the aggregate shows very angular particles with a maximum particle size of approximately ¾". From the grain size distribution curve, values for D_{60}, D_{30}, and D_{10} were approximated at 10.40, 7.90, and 5.50 mm, respectively. As more than 50 % of the material is greater than the #4 sieve, the material is classified as gravel. For this particular material, the values for c_c and c_u were determined to be 1.10 and 1.89, respectively. Using the guidelines set out by the USCS for well-graded gravel, this material was seen to be poorly graded gravel, GP. The specific gravity of the material was determined to be 2.57. The true natural water content of this material was somewhat difficult to determine, due to storage issues. The quartz monzonite aggregate had an average unit weight of about 93.4 pcf.

Figure 2
Quartz Monzonite

***Material**: Quartz Monzonite Aggregate*								
D_{60} (mm)	**D_{30} (mm)**	**D_{10} (mm)**	**C_c**	**C_u**	**USCS Designation**	**Water Content, %**	**Specific Gravity**	**Unit Weight, pcf**
10.40	7.95	5.50	1.10	1.89	GP	1.00%	2.57	93.41

Limestone is a sedimentary rock that can be created through a variety of processes. The most common form of limestone is created by marine biochemical process, and this type of limestone was used. The limestone consists of angular particles with a maximum particle size of ¾" as seen in Figure 3. From the grain size distribution, values of D_{60}, D_{30}, and D_{10} were estimated to be 10.9, 7.8, and 5.2 mm respectively. Values for the coefficients of curvature and uniformity were calculated as being 1.07 and 2.10, respectively. As more than 50 % of the material is retained on the # 4 sieve, the material is obviously considered a gravel. In accordance with the USCS system, the material is classified as poorly graded gravel with little to no fines, GP. The limestone aggregate was determined to have a specific gravity of 2.74. The natural water content for this aggregate was somewhat difficult to determine, due to storage issues. The resulting water content for the aggregate was estimated to be no greater than 0.03 %. It cannot be stated with 100% confidence that there even was water present in the material. The average unit weight of the limestone was calculated to be 103 pcf.

Figure 3
Limestone

Material: *Limestone Aggregate*								
D_{60} (mm)	**D_{30} (mm)**	**D_{10} (mm)**	**C_c**	**C_u**	**USCS Designation**	**Water Content, %**	**Specific Gravity**	**Unit Weight, pcf**
10.90	7.80	5.20	1.07	2.10	GP	0.03 %	2.74	102.35

The glass gravel was purchased from Conigliaro Industries based in Framingham, Massachusetts. Visual inspection of the material revealed dirty, angular particles as seen in Figure 4 intermixed with miscellaneous debris. Also of note is the presence of a stale odor upon opening the 55-gallon drum that the sample was stored in as well as a heavy condensation buildup inside the drum. Maximum particle size appears to be on the order of ½". From the grain size distribution curve, the key parameters of D_{60}, D_{30}, and D_{10} are estimated as 8.2, 6.9, and 5.5 mm respectively. As more than 50 % of the material is retained on the # 4 sieve, the material is classified as gravel. From the calculation of C_c and C_u, with values of 1.05 and 1.50 respectively,

Figure 4
Glass Gravel Aggregate

the material is classified as poorly graded. The USCS classification for this material would then be poorly graded gravel with little to no fines, GP. The specific gravity was determined to be 2.47. The average water content was approximately 0.66 %. The unit weight of the glass gravel was approximately 89 pcf.

Material: *Glass Gravel Aggregate*								
D_{60} (mm)	**D_{30} (mm)**	**D_{10} (mm)**	**C_c**	**C_u**	**USCS Designation**	**Water Content, %**	**Specific Gravity**	**Unit Weight, pcf**
8.25	6.90	5.50	1.05	1.50	GP	0.66 %	2.47	89.08

Recycled concrete aggregate was also chosen for testing. This aggregate was created through the destruction/breakup of a series of concrete sidewalk slabs. The estimated strength of the concrete used in the construction of the sidewalk slabs to be approximately 3500 psi. Visual inspection of the concrete revealed a very wide range of particle sizes, from the 1" maximum to very fine powder, as seen in Figure 5. From the grain size analysis of the aggregate, the values of D_{60}, D_{30}, and D_{10} were estimated as 13.0, 11.0, and 6.8 mm respectively. With these values, the coefficients of curvature and uniformity were calculated to be 1.37 and 1.91, respectively. For classification of the material, more than 50 % was retained on the # 4 sieve, indicating gravel. As the coefficient of uniformity is less than 4, the material is poorly graded. The specific gravity was determined to be an average value of 2.26. The water content of the aggregate was determined to be 3.68 %. The unit weight of the concrete aggregate was determined to be 82.1 pcf

Figure 5
Recycled Concrete Aggregate

Material: *Recycled Concrete Aggregate*								
D_{60} (mm)	**D_{30} (mm)**	**D_{10} (mm)**	**C_c**	**C_u**	**USCS Designation**	**Water Content, %**	**Specific Gravity**	**Unit Weight, pcf**
13.00	11.00	6.80	1.37	1.91	GP	3.68%	2.26	82.10

Section 4 – Description of Testing Apparatus

The most common laboratory test method used for the definition of a moisture-density relationship is the Proctor Test. The Proctor test was first introduced by R.R. Proctor in 1933 and has become the basis for standard compaction testing. The original test, often referred to as the standard Proctor test, uses a 5.5-pound hammer with a 12-inch drop height to compact a specimen in three equal lifts. The current ASTM specification for this test method is D 698-00a. With the improvement and design of newer and heavier aircraft during World War II, compaction techniques for runway design needed to be modified. The standard Proctor test was modified with a series of changes, including increased hammer weight and drop height. This test method, known as the modified Proctor test, is defined in ASTM specification D 1557-00. It has been widely shown that the Proctor tests give quite reasonable results for cohesive soils, but perform less than adequately upon cohesionless materials. For many cohesionless materials, the impact procedure results in significant particle degradation. The current ASTM procedures recommend a modification of the current procedure for “fragile” materials susceptible to degradation by conducting a series of one-point tests.

Vibration was first used as a means for densifying cohesionless soil in Germany during the 1930’s and has been widely recognized as the most efficient means for densifying cohesionless soil in both the field and in a laboratory setting (Moorhouse and Baker 1969, D’Appolonia, Whitman and D’Appolonia 1969). Through a long experimentation process, the current ASTM procedure for determination of a maximum and minimum density for cohesionless soils, D 4253-00, was created. This test method specifies the use of an electric powered vertically vibrating table that uses either electromagnetic or eccentric cam-driven means to create vibration. The current test specification is not without difficulties. Although intended to resolve difficulties in densification of granular materials, D 4253-00 has not been widely accepted for a variety of reasons. Calibration and operation of the vibratory table is difficult for even an experienced operator, and vibratory tables have been plagued by mechanical difficulties from their introduction (Benavidez and Young, 1992). Also of note is that the vibratory table is not portable. While not crucial to laboratory testing, the ability to conduct compaction testing in the field is a much sought after feature (Fohs, Blystone and Smith, 1972).

An alternative compaction method in use in Japan for the specific problem of densification of cohesionless sands is in existance. The Japanese standard for maximum density of granular soils, JIS 1224-2000, is applicable only to fine grained sands, rather than all cohesionless materials. The test procedure uses vibration to achieve the maximum dry unit weight for clean uniform sand. The vibration is applied through repeated blows of a hammer to the side of the small mold, 100 blows per lift for 10 lifts. This test specification has one severe limitation, that being the restriction on maximum particle size. Only materials with 100 % passing the 2-millimeter sieve are applicable to reduce boundary effects.

Previous attempts to create a new standard specification for densification of granular cohesionless materials have been undertaken with varying success. Several standards are in existence that use a modified demolition hammer for laboratory densification: The British Standards Institute's BS 1377, 1924 and 5835 and the USBR's 5535. These tests are suited for use upon cohesionless granular materials with a maximum particle size no greater than 37.5-mm (1.5-inch) and have been proven to provide reliable results. A new vibratory hammer test procedure was developed, based upon USBR 5535. The test setup and procedure were adopted from USBR 5535, using two equal lifts vibrated for one minute each. The vibratory hammer was modified from its original state with several additions made to the tamper foot and shank, including a Linear-Variable-Displacement-Transformer (LVDT) with 2.5-inch of stroke, a shock accelerometer rated to 10,000 g's, and a series of strain gages. These modifications were added to further understand the behavior of the soil specimen during testing and to provide a means for standardization and calibration of test equipment.

Section 5 – Results

A series of Proctor tests, both standard and modified method, were conducted upon all materials for this research. This testing was conducted in accordance with current ASTM procedures, utilizing the one-point method of testing as recommended for use with "fragile" materials susceptible to degradation. The one-point method of testing utilizes fresh material for each test rather than reuse material from one test to another. During testing it was observed that even with the use of the one-point method there was still significant particle degradation. To determine the extent, a grain size analysis was conducted for all materials at the conclusion of a compaction test. The results were then compared to the baseline curve established during index property testing.

Material	Method	Average Dry Unit Weight	Standard Deviation
-	-	(pcf)	(pcf)
Play Sand	Standard	103.3	2.72
	Modified	105.2	2.38
Quartz Monzonite	Standard	104.0	0.38
	Modified	127.7	0.66
Limestone	Standard	109.8	1.87
	Modified	129.9	0.41
Glass Gravel	Standard	99.7	1.01
	Modified	116.9	1.01
Recycled Concrete	Standard	98.3	0.38
	Modified	116.2	0.76

Table 1: Proctor test results for five test aggregates

All vibratory table testing was conducted at the USBR laboratories in Denver, Colorado, due to the unavailability of a vibratory table at the University of New Hampshire. Due to several factors, the limestone aggregate was not sent for testing. Testing was conducted according to USBR 5530, which is similar to the current ASTM D 4253.

Material	Method	Average Dry Unit Weight	Standard Deviation
-	-	(pcf)	(pcf)
Play Sand	Vibratory Table	107.8	0.14
Quartz Monzonite	Vibratory Table	96.4	0.42
Limestone	Vibratory Table	-	-
Glass Gravel	Vibratory Table	95.1	0.14
Recycled Concrete	Vibratory Table	86.3	0.78

Table 2: Vibratory table results

A series of tests were run in accordance with JIS 1224 to determine the maximum and minimum achievable dry unit weights for the play sand. This test is only valid for use upon sands, and was not conducted upon any of the other materials. As recommended by the specification, both minimum and maximum unit weights were determined.

Trial #	Method	Material	Dry Unit Weight
-	-	-	(pcf)
1	Japanese Minimum	Play Sand	86.9
2	Japanese Minimum	Play Sand	86.8
3	Japanese Minimum	Play Sand	86.6
4	Japanese Minimum	Play Sand	86.7
5	Japanese Minimum	Play Sand	86.6
6	Japanese Minimum	Play Sand	86.6
7	Japanese Minimum	Play Sand	86.7

Table 3: Japanese compaction minimum unit weight results

Results from testing using JIS 1224 gave an average achievable maximum dry unit weight for the play sand of 105.4 pcf, with a standard deviation of 0.72 pcf. The average minimum dry unit weight results for this same material were determined to be 86.7 pcf, with a 0.12 pcf standard deviation.

Trial #	Method	Material	Dry Unit Weight
-	-	-	(pcf)
1	Japanese Maximum	Play Sand	105.5
2	Japanese Maximum	Play Sand	104.4
3	Japanese Maximum	Play Sand	106.1
4	Japanese Maximum	Play Sand	105.7

Table 4: Japanese maximum compaction results

The testing program for the vibratory hammer was conducted in four phases. The first, and most important phase, was to prove that the vibratory hammer test was repeatable and an improvement upon the current test methods. The second phase of testing intended to provide insight and understanding into the hammer-specimen interaction during the compaction process. Once the test had been proven repeatable and the dynamics were understood, the testing program would move to the third phase, which involved expanding the testing program to include the use of additional aggregates deemed “fragile” by current ASTM standards. Also included in this third phase was testing examining the moisture-density relationships for the aggregates. The fourth and final phase of testing was created out of the results of the second phase. The fourth phase involved the determination of the energy exchanged during the compaction process as a means of calibration for the test hammer and providing additional insight into the compaction process. The results from each of these phases will be discussed in further detail in the following sections.

The intent of the first phase of testing was to prove that the vibratory hammer test method was repeatable and a marked improvement over current alternatives. All testing during this phase was carried out upon an established control aggregate, the play sand. The average maximum achievable dry unit weight for the play sand was approximately 109.9 pcf with a standard deviation of 0.60 pcf. Particle degradation was also of interest during testing and was closely monitored. After testing, the material was sieved and compared against the baseline grain size distribution curve established during index property testing.

Trial #	Method	Material	Dry Unit Weight
-	-	-	(pcf)
1	Vibratory Hammer	Play Sand	109.8
2	Vibratory Hammer	Play Sand	111.4
3	Vibratory Hammer	Play Sand	110.8
4	Vibratory Hammer	Play Sand	110.1
5	Vibratory Hammer	Play Sand	109.9
6	Vibratory Hammer	Play Sand	109.4
7	Vibratory Hammer	Play Sand	109.6
8	Vibratory Hammer	Play Sand	109.7
9	Vibratory Hammer	Play Sand	110.7
10	Vibratory Hammer	Play Sand	110.4
11	Vibratory Hammer	Play Sand	110.1
12	Vibratory Hammer	Play Sand	109.8
13	Vibratory Hammer	Play Sand	109.7
14	Vibratory Hammer	Play Sand	109.5
15	Vibratory Hammer	Play Sand	109.0
16	Vibratory Hammer	Play Sand	109.7
17	Vibratory Hammer	Play Sand	109.4
18	Vibratory Hammer	Play Sand	109.3

Table 5: First phase results

Second phase testing was intended to provide insight and understanding into the compaction process with the additions of several laboratory measurement devices. The additions of an LVDT and accelerometer to the system allowed detailed measurements of displacement and acceleration of the tamper foot to be recorded during testing. Second phase testing was conducted using the control sand, with the majority of second phase testing occurring simultaneously with first phase testing.

The third phase of testing expanded the testing program to include four additional materials: two natural aggregates, quartz monzonite and limestone, and two recycled materials aggregates, a glass gravel and recycled concrete aggregate. All four of these materials are currently classified by ASTM standards as aggregates susceptible to degradation. Material properties for these aggregates were previously described. The moisture-density relationship for all five of the test materials was also established during this phase of testing. The average dry unit weights and standard deviations for these materials were: 108.6 pcf and 0.10 pcf for quartz monzonite, 116.2 pcf and 0.44 pcf for limestone, 105.0 pcf and 0.25 pcf for glass gravel, and 100.3 pcf and 0.30 pcf for the recycled concrete aggregate. Particle degradation of the additional materials was checked during this phase of testing in a fashion similar to that conducted in first phase testing. Particle degradation of these materials using the vibratory hammer test is clearly seen to be minimal.

Trial #	Method	Material	Dry Unit Weight
-	-	-	(pcf)
1	Vibratory Hammer	Quartz Monzonite	108.7
2	Vibratory Hammer	Quartz Monzonite	108.5
3	Vibratory Hammer	Quartz Monzonite	108.6
1	Vibratory Hammer	Limestone	115.7
2	Vibratory Hammer	Limestone	116.4
3	Vibratory Hammer	Limestone	116.5
1	Vibratory Hammer	Glass Gravel	105.0
2	Vibratory Hammer	Glass Gravel	104.8
3	Vibratory Hammer	Glass Gravel	105.3
1	Vibratory Hammer	Recycled Concrete	100.3
2	Vibratory Hammer	Recycled Concrete	100.6
3	Vibratory Hammer	Recycled Concrete	100.0

Table 6: Results from expanded testing program

For the third phase of testing, several tests were conducted with the LVDT in place to record displacement data. No useable data was gathered from the recycled concrete aggregate tests due to severe amounts of twisting and rotation of the hammer. No additional acceleration data was taken for these materials. As with the LVDT curve from the control sand, the LVDT curve here again shows the displacement time history of the specimens during the compaction process.

Material	Method	D_{60}	D_{30}	D_{10}	C_c	C_u
-	-	(mm)	(mm)	(mm)	-	-
Quartz Monzonite	Pre-Compaction	10.4	8.0	5.5	1.10	1.89
	Post-Compaction	13.0	8.3	6.5	0.82	2.00
Limestone	Pre-Compaction	10.9	7.8	5.2	1.07	2.10
	Post-Compaction	13.0	9.0	7.0	0.89	1.86
Glass Gravel	Pre-Compaction	8.3	6.9	5.5	1.05	1.50
	Post-Compaction	8.3	6.4	5.4	0.91	1.54
Recycled Concrete	Pre-Compaction	13.0	11.0	6.8	1.37	1.91
	Post-Compaction	13.0	11.0	6.7	1.39	1.94

Table 7: Grain size distribution analysis for additional materials

Also conducted during this phase of testing was a study into the moisture-density relationship for the materials. Following standard procedure for determination of this relationship (as outlined by the Proctor tests), each material was tested at varying water contents to determine the maximum achievable dry unit weight and optimum moisture content. As would be expected, very little change in the dry unit weight was actually seen in the four third phase materials. There was some effect seen in the control sand, which showed a defined OMC and maximum dry unit weight. The control sand showed a maximum achievable dry unit weight of approximately 104.5 pcf could be achieved at a moisture content anywhere in the range of 12 and 20 %.

The fourth and final phase of testing was designed to determine the energy output by the hammer during the compaction process. This energy would provide a means of standardization and calibration of the system for testing as well as provide additional insight into the compaction process. As was previously described, this was indirectly accomplished by using a series of strain gages mounted upon the shank of the tamper foot. All testing for this phase was conducted upon the control aggregate with no additional measurements being taken. The force could be used in conjunction with the acceleration data previously gathered to determine the energy input into the system.

A vibratory footing analysis was conducted for this research to determine if it would be possible to accurately model the compactive behavior of the control aggregate during testing. The modeling of the footing was conducting using the simplified analog method put forth by Lysmer and Richart (1966). After several iterations using the vibrating footing analysis devised by Lysmer and Richart, it was found that the specimen behavior could be predicted with a high degree of precision. In any future attempts for modeling a specimen in such a means, it would be wise to conduct a more thorough and detailed investigation into the test material's properties.