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16. Abstract In Test Methods Tex-113-E and Tex-114-E, the Texas Department of Transportation (TxDOT) employs an impact hammer method of sample compaction for laboratory preparation of road base and subgrade materials for testing. In this third and final report documenting efforts to improve the relationship between laboratory material compaction and field construction, Texas Transportation Institute (TTI) researchers present results from efforts to identify whether TxDOT should require Modified Proctor compaction for bases, and whether TxDOT should modify its existing laboratory compaction methods to improve the state-of-the-art. Efforts to evaluate whether a shift to Modified Proctor was warranted proved unfruitful due primarily to a lack of interest and lack of participation from field offices. However, prior work in this project and prior in-house investigations by TxDOT indicate little incentive exists for TxDOT to require Modified Proctor for its base materials. An immediate technique to enhance the state-of-the-art of sample compaction within TxDOT is to implement the Soil Compactor Analyzer (SCA) system developed in this project. The SCA permanently installs onto the laboratory automatic tamper and enables calibration of the applied compaction energy along with real-time monitoring of the important operating parameters of the tamper during the sample construction process.					
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**IMPROVING LAB COMPACTION SPECIFICATIONS FOR
FLEXIBLE BASES WITHIN THE TEXAS DOT**

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EXECUTIVE SUMMARY

In Test Methods Tex-113-E and Tex-114-E, the Texas Department of Transportation (TxDOT) employs an impact hammer method of sample compaction for laboratory preparation of road base and subgrade materials for testing. Tex-113-E applies to base materials and requires approximately 41 percent of the compactive energy specified by ASTM D 1557, or “Modified Proctor.” This third and final report documents efforts to validate and finalize recommendations for improving the laboratory compaction methods TxDOT uses for aggregate base materials. Specifically, this report describes efforts to finalize recommendations on whether TxDOT should require Modified compaction energy for its base materials, and this report describes recommendations on how TxDOT should modify its laboratory methods to improve the quality of lab compaction results.

Prior work to evaluate the need for specifying Modified compaction instead of Tex-113-E energy did not provide compelling evidence to warrant the change. Similarly, the additional efforts described in Chapter 1 of this report did not yield results suggesting TxDOT should initiate an across-the-board shift to Modified Proctor.

For improving lab compaction methods, Chapter 2 of this report describes alternative techniques investigated. Of available methodologies studied, implementation of the Soil Compactor Analyzer (SCA) provides the most immediate method for improving TxDOT’s laboratory compaction procedure. The SCA can quantify the applied compaction energy and produce a record of the compactor’s operation for each lab sample constructed, making the system applicable for both calibration and quality control of the automatic tampers employed by the test procedure. Chapter 3 summarizes some initial data collected with the SCA from compactors used in industry. The amount of energy imparted by the automatic tampers ranged from 81 to 94 percent of the energy specified by Tex-113-E.

Based upon these current results and the findings already published in Reports 0-5135-1 and 0-5135-2, Chapter 4 summarizes the findings from this project. In summary, TxDOT should:

- Implement the use of the slide hammer finishing tool in Tex-113-E.
- Continue separating out the plus 7/8-inch aggregate in Tex-113-E.
- Consider using the SCA for establishing and monitoring proper operation of automatic laboratory tampers.
- Conduct further investigation into threshold values for applied compaction effort.
- Conduct a new interlaboratory study to develop new precision statistics for compaction effort, sample dry density, and strength after Tex-117-E Part II.

CHAPTER 1

EVALUATING THE NEED FOR MODIFIED PROCTOR COMPACTION FOR TEXAS BASE MATERIALS

SUMMARY

In the course of this project, questions arose regarding whether the energy required by Tex-113-E was too low for today's construction equipment. Specifically, the concern existed that TxDOT was not maximizing the structural benefit of its base materials while simultaneously allowing contractors to achieve target density too easily. For reference, the compaction energy required by Tex-113-E is only approximately 41 percent of the energy required by ASTM D 1557.

At an earlier phase of this project, detailed in Report 0-5135-2, Texas Transportation Institute (TTI) researchers conducted a small-scale study, which revealed that requiring Modified compaction energy may improve mechanical properties of some, but not all, Texas base materials, and that in the field with equipment and placement lift thicknesses common to TxDOT projects, Modified density was not achieved. To follow up on this work, the researchers sought to evaluate four additional Texas base materials in a construction setting to better define where, if at all, Modified compaction was warranted. These follow-up efforts proved unfruitful due primarily to a lack of interest and lack of participation from field offices. However, work in this project and prior in-house investigations by TxDOT indicate little incentive exists for TxDOT to require Modified Proctor for its base materials.

FIELD EFFORTS TO INVESTIGATE COMPACTIVE ENERGY

Efforts to secure field projects where Modified compaction would be required only produced one participant. This project was FM 899 in Titus County. This project used a Grade 4 base with a gradation as Table 1.1 shows. The TxDOT District Lab performed both Tex-113-E and Modified compaction curves on the base as Figure 1.1 illustrates. The results show that the increased lab compaction effort did indeed lower the optimum water content; however, the resultant dry density did not increase. For this base material, Tex-113-E produced essentially the same dry density as Modified compaction energy. Therefore, research work on FM 899 was suspended since no incentive exists to specify increased compaction energy when the resultant dry density is unchanged.

Table 1.1. Gradation of FM 899 Base.

Sieve Size	Individual Percent Retained
1 3/4	6.70
1 1/4	8.70
7/8	7.47
5/8	6.58
3/8	9.07
#4	10.96
#10	10.13
Passing #10	40.39

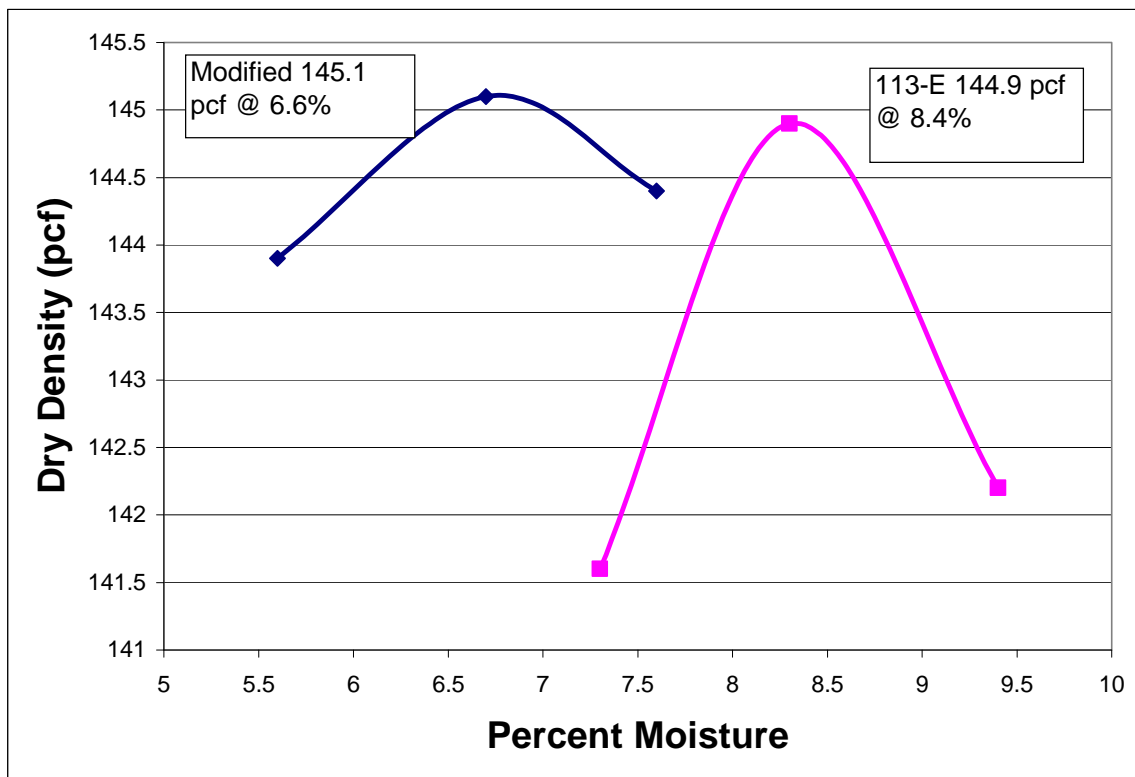


Figure 1.1. Moisture-Density Curves for FM 899 Base.

HISTORICAL PERSPECTIVE ON THE DEVELOPMENT OF TEX-113-E

Due to the lack of field projects for examining the applicability of Modified compaction on Texas base materials, TTI researchers undertook a review of literature highlighting the development of Tex-113-E. While ASTM D 1557 requires 56,000 ft-lbf/ft³, Tex-113-E only requires 13.26 ft-lbf/in³, or approximately 22,913 ft-lbf/ft³. In cooperation with TxDOT's Construction Division, TTI performed a review of records illustrating the initial reasoning for adopting the energy level specified by Test Method Tex-113-E. The story of development follows.

R.R. Proctor first suggested a method for evaluating the compactability of fill materials in 1933 (1). By 1941, the Texas Highway Department (THD) included a compaction test in its *Testing Procedures* as THD-84, “Standard Proctor Test” (2). THD-84 was essentially identical to ASTM D 698 42T and was intended for use on materials passing the ¼-inch sieve. Already in 1941, THD-108, “Testing and Controlling the Compaction of Roadbeds,” discussed the fact that field variables (such as number of passes, weight of equipment, placement lift thickness, etc.) and material variables (such as the presence of large aggregate) influence the relevancy of the Proctor lab test result to the field (3).

In 1946, Chester McDowell presented to the Highway Research Board (HRB) several changes to laboratory compaction methods that THD proposed for use in preparing subgrade and base materials for testing (4). Major dimensions of these proposed changes included:

- Size of material used in lab specimens: THD proposed using the entire gradation in lab specimens, not just the material passing the ¼-inch sieve.
- Size of lab sample: THD proposed 6-inch diameter, 8-inch tall specimens, compacted in 2-inch layers. The 2-inch layer thickness was selected because most standard flexible base specifications at the time required all material to pass the 2-inch sieve. The sample diameter of 6 inches was deemed practical for general use.
- Amount of compactive effort: THD proposed using the Modified hammer (10-lb hammer with an 18-inch drop) to produce a compactive effort of approximately twice that of the Standard Proctor procedure. Use of the Modified hammer was suggested to improve the precision of the test, and selection of the amount of compactive effort was based upon correlation with densities obtained in the normal field construction process. To quote Mr. McDowell from the 23rd annual Highway Short Course, “An investigation showed that approximately 50 blows per layer...of the ‘Modified Proctor’ hammer applied to layers two inches thick and six inches in diameter would produce densities comparable to those produced by normal rolling for granular materials and very heavy rolling for highly plastic clays.”
- “Remolding” used material: THD proposed to not remold material during construction of moisture-density curves because of cases of soft aggregates breaking down, or clay soils where residual lumps exist as a result of the remolding.

By 1953, THD included these recommended practices in its *Soil Testing Procedures* as THD-83, “General Laboratory Test for Moisture-Density Relations for Soils” (5). THD-83 specified variable compactive effort dependent upon the material, where 50 blows per layer were prescribed for flexible base materials and select, non-shrinking or swelling soils. “Moderately active” soils were prescribed 25 blows per layer, and plastic clays were prescribed 15 to 20 blows per layer. By 1960, THD-83 had been slightly tweaked and renamed Tex-113-E, “Determination of Moisture-Density Relations of Soils and Base Materials.” The basic procedure, however, remained unchanged, still

employing variable compactive effort depending on the material, and prescribing a 6×8-inch specimen compacted with the 10-lb, 18-inch drop hammer in 2-inch lifts.

This test procedure remained virtually intact until the 1997 TxDOT *Manual of Testing Procedures*, when Tex-113-E was specifically designated for base and cohesionless sand, eliminating the application to higher plasticity materials and eliminating the variable compactive effort element of the procedure. Instead, Tex-114-E, which essentially mirrors ASTM D 698, was prescribed for determining the moisture-density relationship of subgrades and embankments (6).

CONCLUSIONS

With a lack of conclusive evidence indicating a need for enforcement of higher levels of compaction energy for Texas base materials, and a long history of base performance under the current prescribed level of compaction energy, the researchers do not believe justification exists for a statewide mandate of Modified Proctor energy for Texas base materials. The researchers would instead suggest that if an office experiences pavement failure attributable to a lack of strength in the base, despite documentation of achieving Tex-113-E compaction in the field, that office could consider examining the possibility of higher compaction requirements for that particular material. At this time, however, the researchers are not aware of forensic results indicating such occurrences.

CHAPTER 2

IMPROVING LABORATORY COMPACTION METHODS WITH THE AUTOMATIC TAMPER

SUMMARY

Impact hammer compaction methodology is one of many approaches to fabricating laboratory test specimens. For compaction of flexible bases, the researchers believed that vibratory compaction of lab specimens could better replicate the field structure of compacted base materials. Although vibratory compaction did result in improved measured properties, the potential implementation challenge led to focusing the final efforts of this project on improving the operation of the existing impact hammer compactors used in Tex-113-E. Specifically, TTI developed a Soil Compactor Analyzer, which determines the energy produced by the impact hammer at the point of impact with the sample surface.

ALTERNATIVE METHODS TO 113-E COMPACTION

Previously, Report 0-5135-2 determined the role soil fabric can have in producing results that correlate to field compaction. In addition to impact hammer, other lab approaches include static compaction, vibratory, kneading, and gyratory. Certain compaction approaches may be more appropriate to mimic field compaction because they may better replicate the spatial variability and soil fabric that field compaction produces. A prototype vibratory lab compactor, shown in Figure 2.1, was used as an alternative to impact hammer compaction. Results already presented in Report 0-5135-2 showed that lab vibratory compaction produced improved triaxial classification in Tex-117-E, improved moisture susceptibility rankings in Tex-144-E, and improved rutting properties as analyzed with the VESYS pavement performance model.



Figure 2.1. Prototype Lab Vibratory Compactor.

These triaxial, moisture susceptibility, and rutting results were based upon tests with both a TxDOT Grade 1 and Grade 2 flex base. Follow-up work was planned to further validate these initial findings concurrently with the additional investigations of using Modified effort for flexible base compaction. However, as explained in Chapter 1, these follow-up efforts proved unfruitful due primarily to a lack of interest and lack of participation from field offices. Therefore, the researchers re-visited the prior-collected computed-axial-tomography (CAT) scanning data that were presented in Report 0-5135-2 to conduct further analysis. The purpose of this further analysis was to identify if vibratory compaction produced a different sample structure and fabric than impact hammer compaction. Due to the observed differences in strength and moisture susceptibility, efforts focused on evaluating air voids and took the prior analysis one step further by developing three-dimensional plots of the air voids in the specimens. Figures 2.2 and 2.3 show these plots for the Groesbeck and Spicewood materials, respectively. These data seem to indicate that indeed the improved performance in specimens prepared with the vibratory method of lab compaction results from a difference in spatial variability within the samples. Specifically, the air void distribution in vibratory-prepared specimens differs substantially from the air void distribution in samples prepared with the impact hammer. The data seem to support the hypothesis that the vibratory compaction mechanism produces fewer interconnected voids. For reference, with over 20 samples with each compaction method molded, Table 2.1 shows the average dry density and standard deviation for each base material based upon gravimetric analysis.

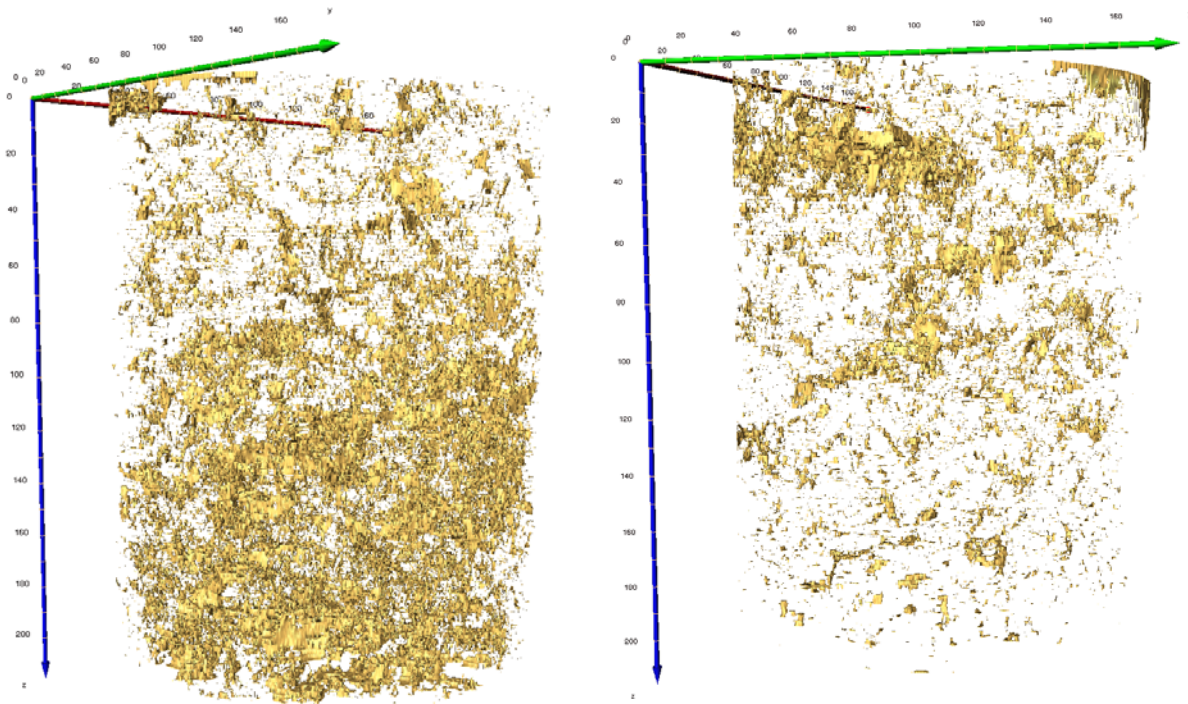


Figure 2.2. Air Voids in Groesbeck 113-E (Left) and Vibratory (Right) Specimens.

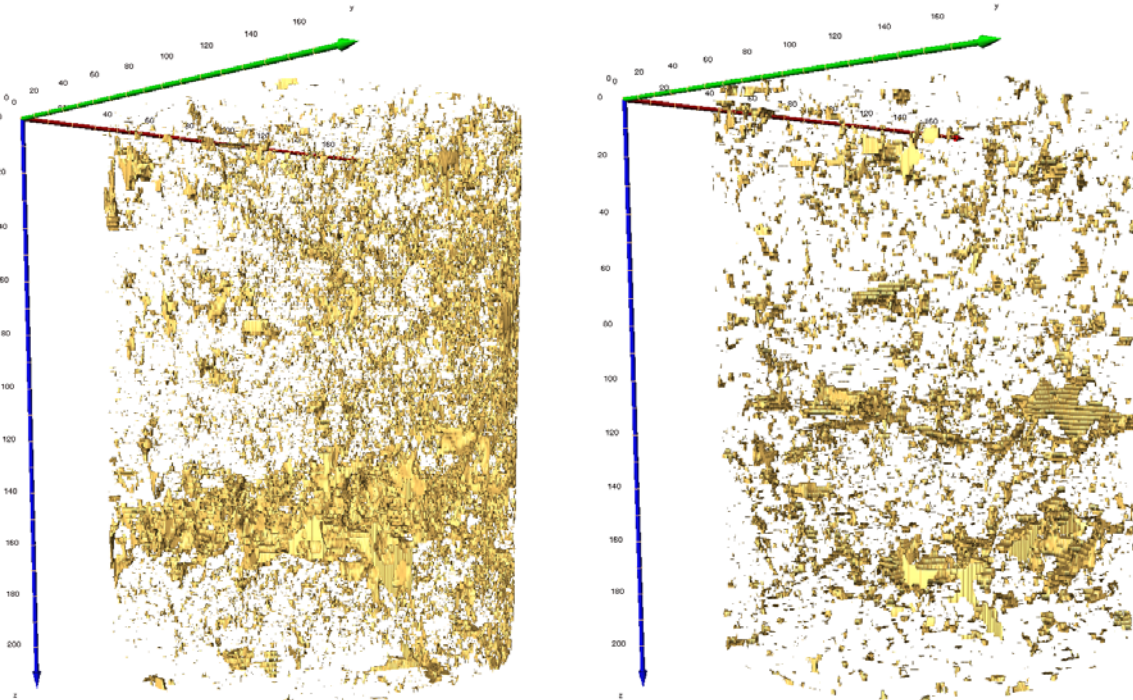


Figure 2.3. Air Voids in Spicewood 113-E (Left) and Vibratory (Right) Specimens.

Table 2.1. Gravimetric Density Analysis from Groesbeck and Spicewood Flex Bases.

Aggregate	Groesbeck		Spicewood	
	113-E	Vibratory	113-E	Vibratory
Average Dry Density (pcf)	132.7	133.7	148.4	149.2
Standard Deviation (pcf)	0.84	0.50	0.64	1.34

After the researchers concluded evaluating the vibratory lab compaction method, the project director shifted the focus of the remainder of this project to improving the operations of the Tex-113-E compactors by developing a reliable and robust method to measure the energy produced by the hammer during sample fabrication.

IMPROVING TEX-113-E WITH THE SOIL COMPACTOR ANALYZER

The most immediate technique to improve the quality of results from lab-compacted specimens is to better calibrate and monitor the operation of the automatic tampers used in Texas. Currently the calibration of the apparatus is checked by determining the mass of the hammer and manually measuring the drop height. However, the true desired specification parameter for the hammer is compaction energy. Additionally, current methods for evaluating the operation of the tamper do not provide any quality control during the sample compaction process.

To address these problems, TTI researchers developed an instrumentation system, called the Soil Compactor Analyzer, which uses rapid sampling of the hammer displacement to measure the impact velocity. With the known mass of the hammer and the determined velocity, energy can be determined. Figure 2.4 shows an example waveform of the hammer's operation, and Figure 2.5 shows the primary components of the SCA.

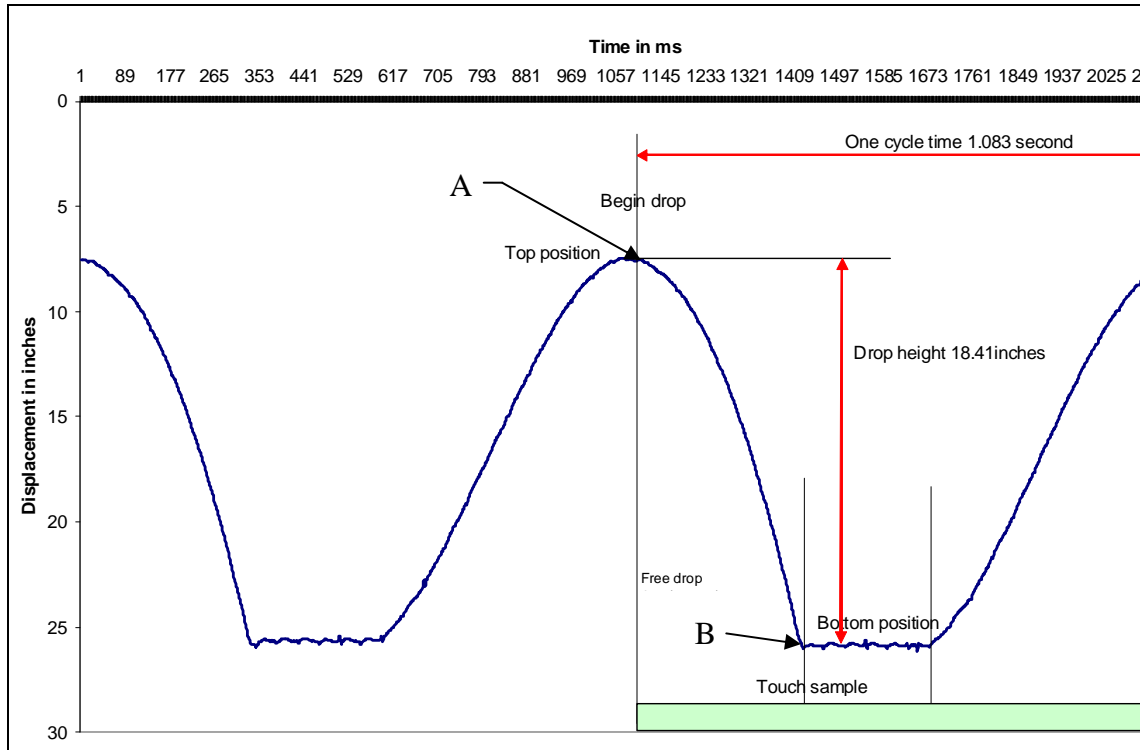


Figure 2.4. Example Displacement Waveform from Automatic Tamper Operation.

Note: Velocity measured from point A to B.



Figure 2.5. Primary Components of the Soil Compactor Analyzer.

In addition to quantifying energy for purposes of calibration, the SCA has the added benefit of providing continuous monitoring of the tamper operation, which allows the system to also quantify operational variability and document the hammer operation during the sample construction process. Key parameters recorded by the SCA for each lift during laboratory sample compaction include:

- velocity – the hammer impact velocity upon striking the soil surface,
- raise time – the time the hammer takes to be raised from the specimen surface to its highest position prior to dropping,
- drop height – the distance the hammer falls from its highest point to the sample surface,
- bounce – the amount of bounce of the hammer off of the sample surface after the impact,
- compaction – the amount of deformation of the sample from the hammer impact,
- sample height – the total height of the sample,
- hammer raise height – the height the hammer is lifted from the surface of the sample to its highest point prior to dropping,
- lift height – the height of the current lift, and
- energy – the kinetic energy produced by the hammer's fall.

The SCA system can display the above parameters for every drop of each lift, or alternatively the user may view average values from each of the four lifts in either graphical or tabular formats. Figures 2.6 and 2.7 illustrate the locations on the waveform used by the SCA to determine the hammer raise height, drop height, raise time, compact, and bounce values. Product 0-5135-P6 contains complete details of the SCA.

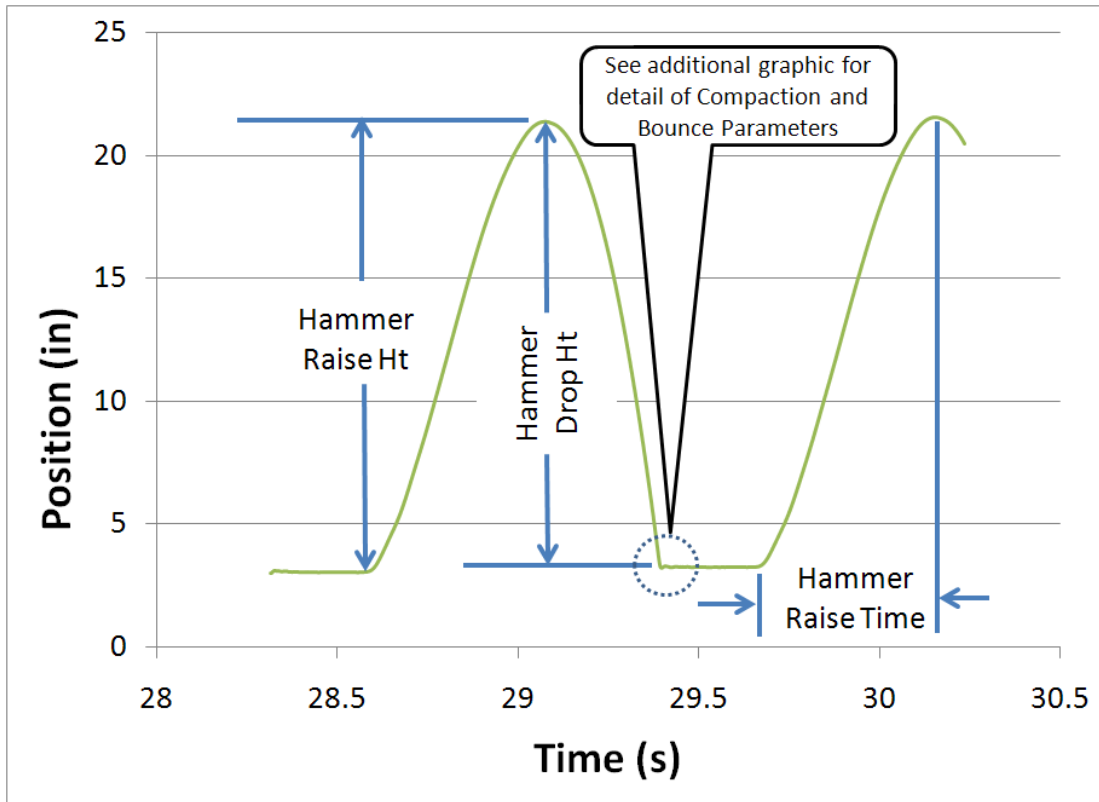


Figure 2.6. Hammer Parameters Annotated on Hammer Waveform.

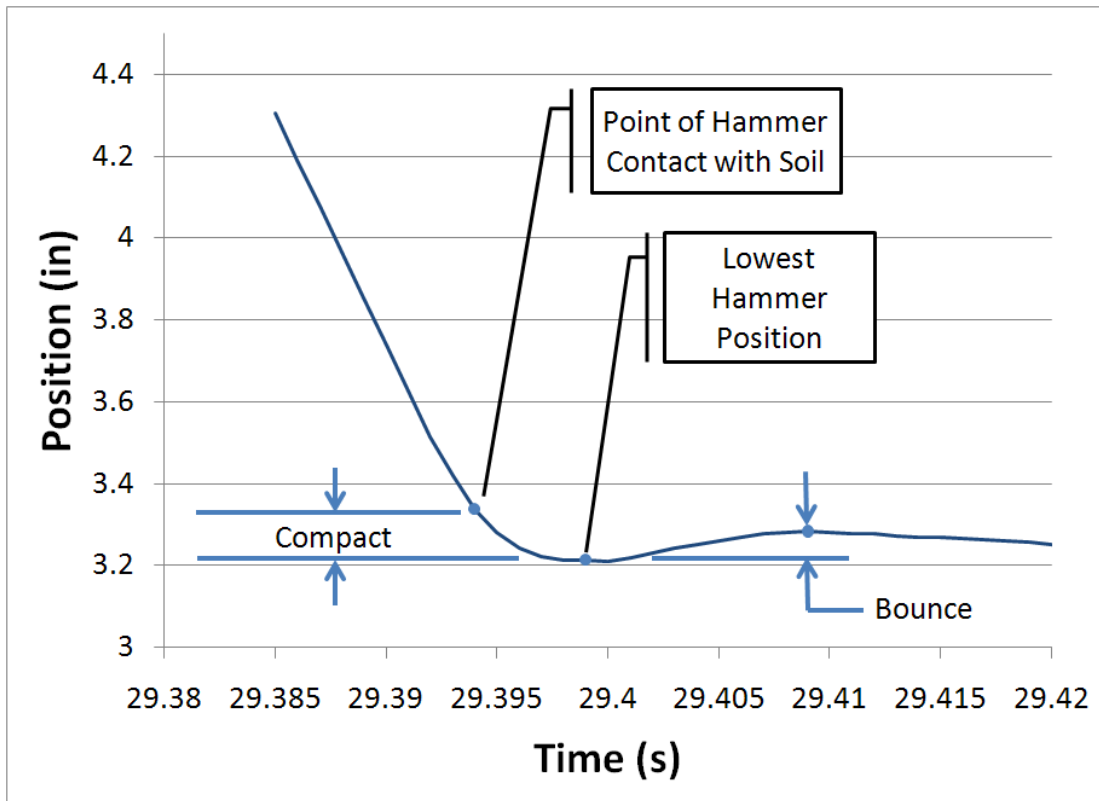


Figure 2.7. Compact and Bounce Determination from Hammer Waveform.

CONCLUSIONS

While alternative laboratory compaction means such as vibratory compaction would seem to better mimic field methodology, compelling evidence currently does not exist that such a shift in laboratory methodology is currently warranted. The most immediate technique available to improve TxDOT's laboratory compaction methodology is to implement the Soil Compactor Analyzer to calibrate and monitor operation of the automatic tampers. The SCA can quantify the applied compaction energy and produce a record of the compactor's operation for each lab sample constructed.

CHAPTER 3

EVALUATING COMPACTORS WITH THE SCA

SUMMARY

TTI conducted testing with the Soil Compactor Analyzer at four commercial testing laboratories to measure the operation of their automatic tampers used in Test Method Tex-113-E. Each lab fabricated two specimens with the SCA installed. The results showed that, on average, all of the machines operated with a drop height quite near 18.0 inches, with the minimum average drop height being 17.92 and the maximum 18.18 inches. The amount of energy imparted by the automatic tampers ranged from 81 to 94 percent of the energy specified by Tex-113-E.

A key concern for TxDOT and commercial laboratories is reproducibility of results. Using the SCA to establish operation of machines within TxDOT specifications could be a first step toward this common goal.

DATA FROM MULTIPLE LABS

Tex-113-E specifies a compactive effort of 13.26 lb-ft/in³, which for an 8.00-inch tall specimen equates to 750 lb-ft of energy for each of the four lifts, for a cumulative total of 3000 lb-ft. As a percent of the specification energy, the commercial lab's compactors applied from 81.0 percent to 94.39 percent of the specification energy. For comparison, TTI's compactor applies approximately 89.5 percent of the specification energy on average.

Figures 3.1 and 3.2 summarize the results from the four commercial labs and include results from TTI's machine for comparison. Figure 3.1 displays the overall average applied total energy to a sample as a percent of the Tex-113-E specification energy along with the overall average drop height. Figure 3.2 illustrates the average applied energy as a percent of the specification energy for each of the four lifts.

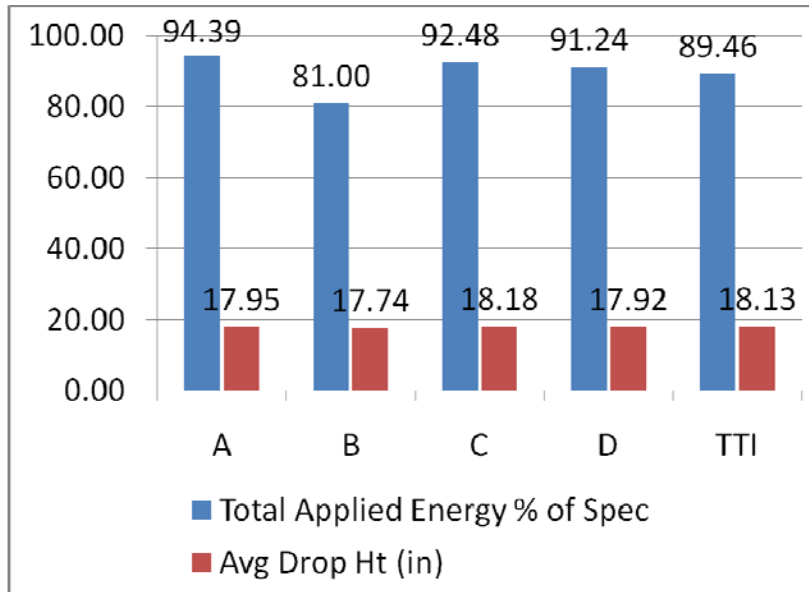


Figure 3.1. Average Applied Energy and Drop Height for Five Labs.
Note: Specification = 3000 lb-ft per sample

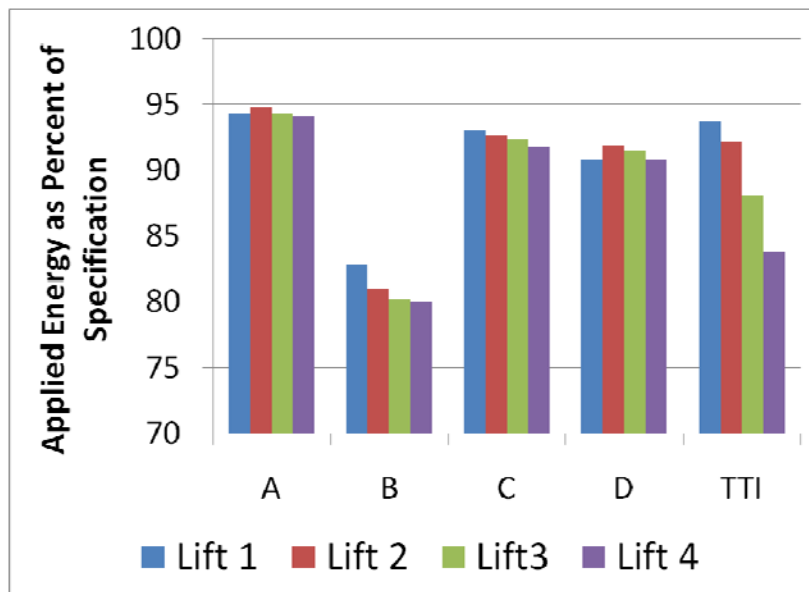


Figure 3.2. Average Applied Energy for Each Lift from Five Labs.
Note: Specification = 750 lb-ft per lift

These results seem to show: 1) the energy applied by the machine at lab B clearly is not consistent with the other compactors measured, and 2) the machine at lab B and particularly TTI's machine exhibit poor reproducibility in applied energy from lift to subsequent lift. Essentially the machines appear to lose more energy to friction while operating in the range of motion that compacts the upper lifts of the sample.

To evaluate whether these differences in applied energy are meaningful, and in an attempt to determine what range of energies are permissible, TTI first compacted a series of specimens with the automatic tamper and with the manual hammer. Additionally, a set of specimens was compacted in the automatic tamper with the SCA removed to make sure installation of the SCA did not detrimentally impact the resultant sample dry densities. To perform these tests, TTI used the Frost limestone flexible base. This material has a Tex-113-E maximum density of 134.1 pcf at 7.0 percent water. Table 3.1 summarizes the results.

Table 3.1. TTI's Results from Frost Base.

	Sample	%M	Ht (in)	Dry Density pcf	AVG % M	AVG pcf	Lift 1 lb-ft applied	Lift 2 lb-ft applied	Lift 3 lb-ft applied	Lift 4 lb-ft applied	Total lb-ft applied	Total Energy applied (lb-ft/in ³)	% of Spec Energy**
With SCA	1	7.0	7.95	134.7			701	*	663	636	*		
	2	7.0	7.94	134.7			711	695	655	636	2697	12.01	90.60
	3	7.0	8	134.3	7.03	134.7	707	689	663	627	2686	11.87	89.55
	4	7.0	7.94	134.8			690	689	662	621	2662	11.86	89.42
	5	7.1	7.95	134.9			701	680	652	605	2638	11.74	88.51
Without SCA	6	7.0	8	133.6									
	7	7.2	7.95	134.7									
	8	7.1	8	134	7.11	134.3	Not available - SCA removed for construction of these specimens						
	9	7.2	7.95	134.5									
	10	7.1	7.95	134.7									
Manual Hammer	11	7.1	7.95	134.8									
	12	7.1	7.95	134.8	7.09	134.8	Not available - samples molded with manual hammer						
	13	7.1	7.95	134.7									

*Not available as data was not collected on Lift 2 of this sample

**Spec = 13.26 lb-ft/in³

The results in Table 3.1 show that: 1) the presence of the SCA had no impact on the specimen dry densities, and 2) the maximum difference between the automatic tamper and manual hammer dry densities was 1.2 pcf. This is a maximum difference of 0.9 percent, which is within the 2 percent difference allowed by ASTM D 2168. Additionally, the difference in average density between the automatic and manual hammer was 0.3 pcf, or 0.2 percent.

After determining that TTI's compactor, which on average produces approximately 89.5 percent of Tex-113-E specification energy, passes the ASTM criteria for a mechanical compactor, TTI next purposefully varied the compaction energy and tested specimens in duplicate both for dry density and unconfined compressive strength (UCS) after Tex-117-E Part II. For simplicity, TTI varied the compaction energy by varying the number of drops per lift. Table 3.2 presents the dataset, and Table 3.3 summarizes the results.

Table 3.2. Dataset of Varying Effort on Frost Base.

Sample	Molded Volume (in ³)	Total Energy Applied (lb-ft)	Total Effort Applied (lb-ft/in ³)	% of 113-E Spec Effort	Molded Moisture Content (%)	Molded Dry Density (pcf)	Moisture Content After Soak (%)	UCS After Soak (psi)
F70-1	229.0221	1992.8	8.70	65.62	6.771988	132.53	7.71	19.63
F70-2	227.60839	2025.4	8.90	67.11	6.758784	133.57	7.40	32.28
F75-1	227.60839	2146.7	9.43	71.13	7.03659	133.04	7.39	39.91
F75-2	226.19467	2156.5	9.53	71.90	6.894487	134.16	7.52	39.97
F80-1	226.19467	2317	10.24	77.25	7.093092	133.55	7.38	34.45
F80-2	226.19467	2308	10.20	76.95	7.013695	134.51	7.29	31.67
F85-1	226.19467	2479.1	10.96	82.65	6.994833	133.89	7.13	41.09
F85-2	226.19467	2478.3	10.96	82.63	6.985178	134.08	7.39	49.67
F90-1	224.78095	2568.4	11.43	86.17	6.74265	135.27	7.14	55.58
F90-2	224.78095	2584.9	11.50	86.72	6.730459	134.92	7.24	34.91
F95-1	224.78095	2719.8	12.10	91.25	7.068015	135.07	7.46	32.16
F95-2	225.48781	2743.5	12.17	91.76	6.745363	134.02	7.34	39.78
F100-1	226.19467	2894.8	12.80	96.51	6.860173	134.86	7.36	39.04
F100-2	224.78095	2889.3	12.85	96.94	6.930288	135.11	7.26	27.82

Table 3.3. Summary of Varying Compactive Effort on Frost Base.

Avg % Effort	Avg Dry Density (pcf)	Avg M.C. after Soak (%)	Avg UCS after Soak (psi)
66.36	133.05	7.55	25.95
71.51	133.60	7.45	39.94
77.10	134.03	7.34	33.06
82.64	133.98	7.26	45.38
86.45	135.10	7.19	45.24
91.50	134.55	7.40	35.97
96.73	134.99	7.31	33.43

An analysis of these data shows:

- Percent effort positively correlated with sample dry density (Figure 3.3).
- Percent effort showed a weak negative correlation to the moisture content after soaking.
- Percent effort did not correlate to UCS.
- Dry density negatively correlated to the moisture content after soaking (Figure 3.4).
- Dry density did not correlate to strength.
- Moisture content after soaking negatively correlated to UCS.

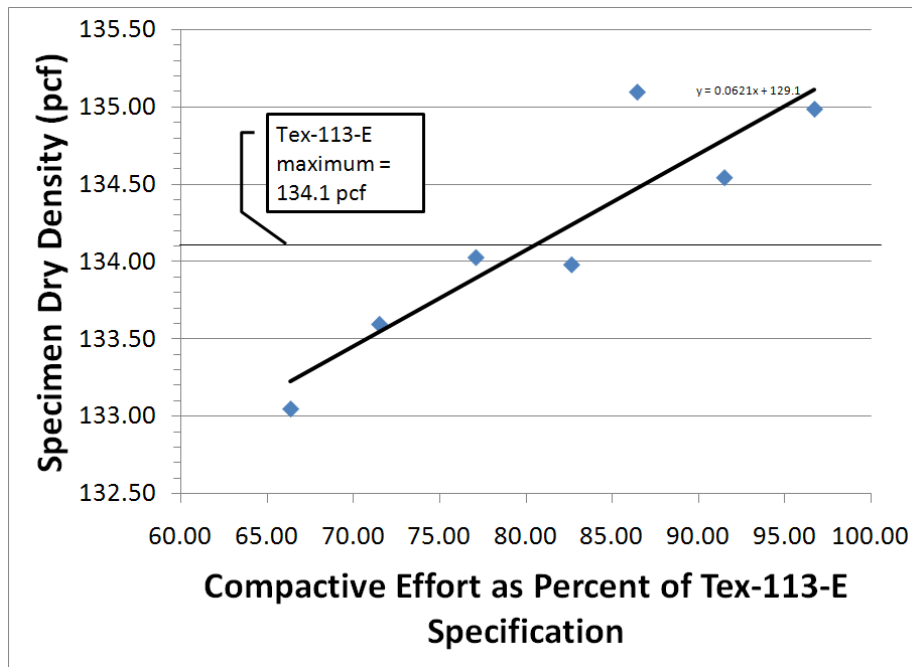


Figure 3.3. Frost Dry Density vs. Compactive Effort.

Note: All specimens compacted at ~ 7.0 percent water.

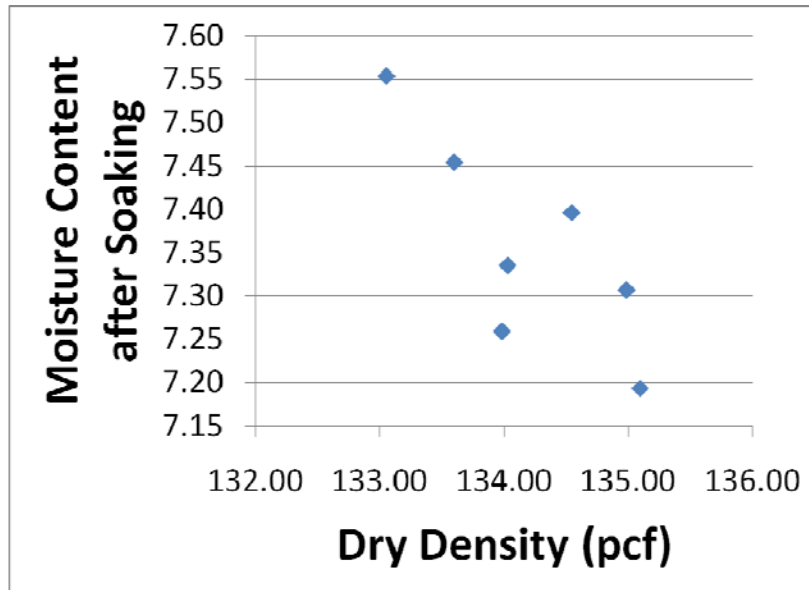


Figure 3.4. Moisture Content after Soaking vs. Dry Density.

DISCUSSION

The results obtained showed that, while substantial variability in energy applied may exist among automatic tampers used in industry, the factor most impacted by varying operation of the compactor is the resultant dry density. When effort fell below 81 percent of Tex-113-E specifications, the 113-E maximum density was no longer obtained.

Despite subtle changes, dry density was a causal factor in the amount of moisture after the capillary soak, with higher densities resulting in lower moisture contents. In turn, the moisture content after soak negatively correlated with UCS. Since the dry density showed an increasing trend with increasing compaction effort, one would deduce that compaction effort should relate to the strength, although this dataset did not show a significant correlation between these two variables. Furthermore, analysis of the strength data is compounded by poor reproducibility of the UCS data.

Interestingly, the lowest moisture contents after soaking, and the peak average UCS values, occurred at energies between 83 and 86 percent of the 113-E specification. It is unknown if this is coincidental, or if this occurrence may relate back to the amount of energy produced by the compactor used to run the original 113-E. Unfortunately, no SCA data exist for the compactor used to perform the original Tex-113-E moisture-density relationship.

Another factor that may impact these results is the method chosen to vary the compaction effort. For simplicity, these experiments varied the number of drops to change the effort. In reality, Tex-113-E requires 50 drops per lift, and the number of drops applied is easy to control in practice. A better experimental approach would be to maintain the 18-inch drop height and 50 drops per lift, and vary the mass of the hammer. This approach would alter the energy

imparted by each drop, which would be more representative of a machine with varying amounts of frictional forces acting on the hammer as it falls.

RECOMMENDATION

Based upon tolerances for mold diameter, hammer mass, and sample height, current TxDOT flexible base compaction procedures allow compaction effort to vary from 12.57 to 13.79 lb-ft/in³. This equates to 94.9 to 104 percent of the 13.26 lb-ft/in³ specified in Tex-113-E. This range means each drop of the hammer should apply between 14.2 and 15.6 lb-ft of energy. Assuming all labs produced an 8.0-inch tall specimen, none of the machines tested would meet the current allowable range of compaction effort.

The data collected in this experiment gave indication that compaction effort potentially could vary significantly with minimal impact on test results. Test samples still met a prior-determined 113-E maximum density with compaction efforts as low as 10.7 lb-ft/in³, or 81 percent of the 113-E specification effort. However, the effort produced by the machine that performed the original moisture-density curve is unknown.

Some ideas to improve the agreement of results among multiple machines and to further develop guidelines on the acceptable range of compaction effort include:

- Service and adjust machines as necessary to establish compaction efforts meeting specifications. Adding hammer mass provides the easiest method to increase the compaction effort. The SCA can be used to evaluate when the machines meet the specification.
- Perform a new set of experiments investigating the impact of varying compaction effort on sample performance. Begin by establishing Tex-113-E optimum moisture content and maximum density on a machine operating as closely to 13.26 lb-ft/in³ as possible. Vary compaction effort by changing the hammer mass while maintaining a constant drop height of 18 inches and applying 50 drops per lift to the specimens. In addition to strength, consider performing Tex-144-E, since preliminary data indicate the varied compaction effort impacts the capillary absorption properties of the specimens. Instead of the unconfined compressive test, consideration should be given to performing a confined test so results may be more repeatable.
- Conduct an interlaboratory study to develop new precision statistics for compaction energy, sample dry density, and unconfined compressive strength after Tex-117-E Part II. The reproducibility study should involve at least six laboratories, a minimum of three materials, and three replicates per material.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

Based upon these current results and the findings already published in Reports 0-5135-1 and 0-5135-2, to improve the state-of-the-art with Tex-113-E compaction TxDOT should:

- Implement the use of the slide hammer finishing tool in Tex-113-E.
- Continue separating out the plus 7/8-inch aggregate in Tex-113-E.
- Consider using the SCA for establishing and monitoring proper operation of automatic laboratory tampers.

Results in this project did not substantiate the need for an across-the-board shift to Modified compaction effort for Texas flexible base materials.

CONCLUSIONS REGARDING LAB TECHNIQUES

Literature and results in this project indicate method of compaction largely contributes to differences between lab- and field-compacted materials. Different techniques of compaction produce different soil fabric, which can influence results. With flexible bases, lab vibratory compaction produced better triaxial classification, improved moisture susceptibility rankings, higher modulus results at most moisture contents, and an improved permanent deformation parameter μ . The most substantial differences existed in the rutting parameter μ .

To minimize the impacts of lab preparation on testing, results show that separating out the plus 7/8-inch aggregate fraction during the Tex-113-E procedure does produce more repeatable dry densities among multiple samples. To improve the correlation between the lab and the field, lab vibratory compaction may be warranted during sample preparation to obtain reasonable results for certain tests, particularly the permanent deformation test to obtain reasonable results for the μ parameter.

The focus of the final phases of this project became development and refinement of a method to measure the compaction energy produced by TxDOT's mechanical compactors. To accomplish this task, TTI developed a system called the Soil Compactor Analyzer that among other things can measure the hammer drop height and impact velocity. Using the determined impact velocity and the already-known hammer mass, the SCA calculates the kinetic energy of the hammer at the point of impact. In addition to serving as a calibration tool, the SCA can remain permanently installed on the compactor during sample production, which enables the lab to document proper operation of the compactor for each sample produced.

RECOMMENDED FUTURE EFFORTS

Data collected in this project indicate that compaction effort could fall as low as 81 percent of Tex-113-E specification effort and still achieve the peak density from the previously determined Tex-113-E moisture-density curve. This observation should be tested by conducting further investigation into threshold values for applied compaction effort, as Chapter 3 describes.

TxDOT should also consider using the SCA to validate proper operation of laboratory mechanical compactors and then conduct a new interlaboratory study to develop new precision statistics for compaction effort, sample dry density, and strength after Tex-117-E Part II.

Finally, TxDOT could consider further investigation into alternative lab compaction techniques such as vibratory compaction for flexible bases. This may be particularly important if TxDOT adopts mechanistic-empirical design approaches that include use of the VESYS rutting model.

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