Case Study for Implementing RECIPPE as a Quality Control in Construction Projects

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16. Abstract

The quality of construction is a very important factor in the life-cycle performance of flexible pavements. This is particularly true of the individual characteristics of construction and their relative effect on life-cycle performance of the pavement. It is crucial to determine both what these characteristics are and, to what degree their variability from the desired value affects the life-cycle performance of pavements. Knowing this will enable a transportation agency to apply its limited inspection resources in the most effective manner. Therefore, the goal of this research was to identify construction parameters that have the greatest impact on the life-cycle performance of the pavement. In the long term, the results of this research should enable agencies like TxDOT to write more effective performance-based specifications for construction of pavements and determine the cost effectiveness of innovations in construction practices.

The implementation of an effective performance-based construction quality management requires a tool for determining impacts of construction quality on the life-cycle performance of pavements. This report presents case studies on the pilot implementation of RECIPPE.

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by

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Performed in cooperation with

The Texas Department of Transportation and
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CHAPTER ONE - INTRODUCTION

The quality of construction is a very important factor in the life-cycle performance of flexible pavements. This is particularly true of the individual characteristics of construction and their relative effect on life-cycle performance of the pavement. It is crucial to determine both what these characteristics are and, to what degree their variability from the desired value affects the life-cycle performance of pavements. Knowing this will enable a transportation agency to apply its limited inspection resources in the most effective manner. Therefore, the goal of this research was to identify construction parameters that have the greatest impact on the life-cycle performance of the pavement. In the long term, the results of this research should enable agencies like TxDOT to write more effective performance-based specifications for construction of pavements and determine the cost effectiveness of innovations in construction practices. This research was carried out in three phases.

Phase I consisted of determining the characteristics of construction processes that have a significant effect on the life-cycle performance of pavements, and whether these characteristics are observable and measurable.

The second phase consisted of predicting how the variability of these construction characteristics affects the life-cycle performance of pavements by using mechanistic analysis. The mechanistic analysis should enable the engineers to predict the life-cycle performance of the pavement as these characteristics are varied.

The third phase consisted of field measurements to verify the predictions of the second phase. A list of characteristics of construction process and the methodology to measure and analyze these characteristics available to TxDOT were developed.

The first two years of the research, which are documented in Research Report 0-4046-1 (Abdallah et al., 2004a) were focused on addressing the following items:

a) An information search was carried out on ways that existing mechanistic models can be used in developing an algorithm to relate the impact of construction parameters to performance. After a national search, several material models were identified, and feasible models were selected. Several popular and well-established performance-based models were also selected.

b) A probabilistic analysis tool was developed. The probabilistic approach differs from a deterministic approach by explicitly accounting for the variability of a parameter. A random parameter can take a range of values and can be represented by different types of probability distributions. The Monte Carlo simulation method, a common probabilistic method for simulating and accounting for the variability of a parameter, was used. Since many parameters are used in the analysis, the two-point mass method (TPM, Rosenblueth, 1981) was combined with the Monte Carlo method to accelerate the process. The TPM method can be used to approximate mean and standard deviation of random variables. The detail of both methods is provided in Chapter 2 of Report 0-4046-1 (Abdallah et al., 2004a).

c) Once the models were selected and the flow of probabilistic algorithm was defined, a prototype algorithm was developed. Figure 1.1 shows the general flow of information used in the mechanistic algorithm with the probabilistic methods. The detail and a case study of how to use the program were also provided in (Abdallah et al., 2004a).
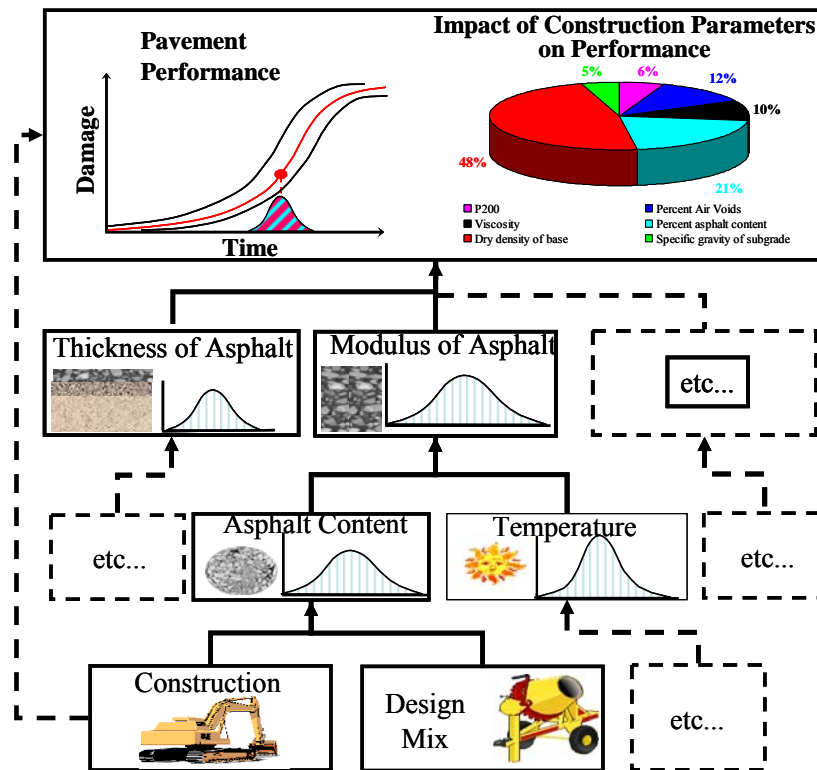
Figure 1.1 - Flowchart Depicting the Process of Utilizing A Probabilistic Approach in a Mechanistic Analysis.

d) The mechanistic models selected provide a number of parameters that are used as a measure of construction practices. To optimize the process, a sensitivity analysis was conducted to primarily identify the relative importance of construction parameters on performance indicators. The results of this study, as presented in Abdallah et al. (2004a), provided an indication of important parameters for pavements with different traffic levels.

e) Based on the results of the sensitivity study, a search to document methods on measuring important parameters was carried out. The document was embedded into software package

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RECIPPE. In that manner, the users can easily access the different ways to measure any given parameter. Another advantage of including the document into the program is that when new parameters are added, the document can be easily amended or updated. This document is included in Appendix A of Research Report 0-4046-2 (Abdallah et al, 2004b).

The third year of the research effort focused on developing a document for validation using few of construction parameters and demonstrating the validation process using selected parameters. The details of these tasks were documented in Research Report 0-4046-2 (Abdallah et al, 2004b). The efforts are summarized below:

a) A validation of the algorithm to quantify the impact of construction parameters on performance is the initial step before being able to utilize RECIPPE with confidence. Three types of models make up the mechanistic algorithm developed: a) the material models, b) the structural models and c) the performance models. The material models were calibrated with information from existing databases and from field data collected at several sites in Texas. The structural and performance models incorporated into the algorithm are well-established. The structural model is based on a nonlinear model using equivalent linear algorithm. The equivalent linear model was developed under TxDOT Project 0-1780 (Ke et al., 2000, and Abdallah et al., 2003). The calibration and validation of these models are outside the scope of this project. Research Report 4046-2 (Abdallah et al, 2004b) provides the validation strategy to calibrate and validate the material models that are being incorporated into RECIPPE. The efforts in extracting data from the Long-Term Pavement Performance (LTPP) database for the asphalt-concrete (AC) layer material model were discussed. The protocol for targeting sites and collecting data for base and subgrade material models were presented. The calibration of the AC material model using data extracted from LTPP database for Texas sites was also presented in that report.

b) The probabilistic process to obtain the variability of performance on the uncertainty in construction parameters using mechanistic analysis was also validated. Two techniques were used in the probabilistic process. The advantages and disadvantages of each technique and a comparison of their effect on producing the Impact Chart (a chart used to identify significant parameters) were documented in that report.

c) The calibration of the AC material model using data collected from Texas sites was performed in three different ways. The first method was based on least squares single variable calibration. The second equation was based on modifying the existing coefficients of the current Witczak equation. The final approach was to develop a new model using similar parameters used by the Witczak equation. Summary of the results are presented in Research Report 0-4046-2 (Abdallah et al, 2004b).

d) A case study showing a limited implementation of the validation process was also presented in Research Report 0-4046-2 (Abdallah et al, 2004b). The validation process is presented by demonstrating the impact variability of one construction variable on the variability of performance.

The fourth year of the research effort focused on adjustments to be made to the prototype of RECIPPE to provide optimal results. This includes:

a) enhancing the reliability analysis process,
b) automating the optimization algorithm,
c) incorporating a sampling frequency algorithm (including control charts),
d) incorporating a cost allocation algorithm and
e) incorporating a cost allocation equation.

These efforts also included replacing the programming platform from MS Excel to Borland C++.

In the fourth year of the project, new material models were developed and the existing models were calibrated. Data from sites collected throughout the research efforts of this project and from databases of previous research such as 0-1336 were used to calibrate existing models or to develop new base and subgrade material models. The outcomes of the fourth year efforts of this project were documented in Research Report 0-4046-3 (Haggerty et al., 2005).

The final report was Research Report 0-4046-4 (Abdallah et al., 2005) documented implementation strategies and several scenarios for utilizing the program.

Also, accompanying the RECIPPE program is a user's manual that briefly goes over the background and methodology behind RECIPPE. It also, includes the strategy of utilizing RECIPPE for quality management. The appendix in this manual provides several exercises that illustrate the use of this program. Also, a website allows users to go step by step through various exercises on how to use this program. At the end of the tutorial the RECIPPE program can be downloaded. The latest version of the software can be downloaded from ***http://ctis.utep.edu/training/***

Once the research was complete the project was selected for pilot implementation. This report contains the implementation of the tool or program called RECIPPE that was developed under this project. The program was used to shadow the current quality management practices on several sites.

ORGRANIZATION OF REPORT

Chapter 2 provides case studies where demonstrating the capabilities of RECIPPE. Three sites are documented in this report. Chapter 6 contains the summary and conclusion for this project. The appendices included in this report provide pertinent information such as the methodology, the models, and the strategy for RECIPPE. Appendix A provides a recap of the methodology that illustrates the use of construction parameter variability to estimate variability on pavement performance. Appendix B has the models for pavement performance and the material models that were identified in the literature and that were used in the software. Appendix C covers the strategy to utilize RECIPPE for quality management. Appendix D includes a protocol that was used to help identify and test site with RECIPPE. Finally Appendix E and Appendix F contain the results of the field and laboratory tests for two case studies.

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CHAPTER TWO – CASE STUDY

RECIPPE is a software tool developed to optimize the effectiveness of inspection and testing resources during construction, by:

1. Estimating whether the variability of construction parameters meets TxDOT's expectations for a reasonably uniform pavement life.
2. Identifying the construction parameters to focus inspection on during construction, in order to reduce the pavement life variance and increase the reliability of the pavement performance.
3. Tracking and identifying out-of-control procedures during construction.
4. Improving construction practices through process control.

This tool was used to shadow current specifications at several sites to establish whether RECIPPE is effective in optimizing the inspection and testing resources during construction. In an effort to locate test sites, a plan based on the protocol in Appendix D was established as summarized in Figure 2.1.
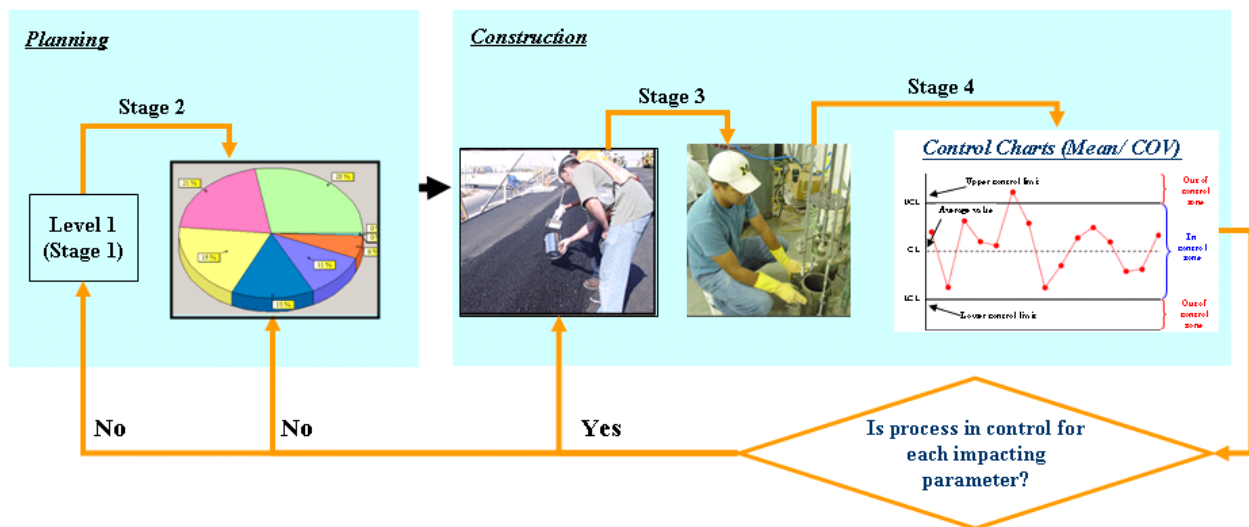
Figure 2.1 – Steps used in RECIPPE to Optimize the Effectiveness of Inspection and Testing.

The first stage was to carry out a Level 1 analysis in RECIPPE to establish the structural adequacy of the section. The results of Level 1 analysis assisted in identifying which layer modulus and thickness impact the performance the most.

For either Level 2 or Level 3 analysis, Stage 2 consisted of identifying the parameters that impacted the variability in performance the most. Depending on the acceptable variability specified by the user on the life on the pavement, the optimization process in RECIPPE estimated the allowable COV for each parameter. Based on the level of impact and the allowable COVs, the initial sample size for each relevant parameter was established. In cases when the sample size was less than the value specified in the minimum guide schedule, the initial sample size was set to that of the minimum guide schedule. Also developed for this stage were the impact charts, which are used as an indication of the level of impact of each parameter on the overall performance. This completed the planning stage, and transitioned RECIPPE into the construction stage.

In Stage 3, the important parameters selected were sampled. Sampling was carried out either from trucks as they left the plant or from materials delivered to the site or measured directly on the finished product. Laboratory tests, when appropriate, were then carried out on each batch of samples to determine the average and COV of each parameter.

In Stage 4, these averages and COVs were then compared with the corresponding criteria for means and COVs established in Stage 1 using control charts. It is very important to evaluate both the mean and COV control charts. If a process was in-control, the sample size was reduced. On the other hand, if a process was out-of-control, either the sample size was increased or the process should have been stopped and adjusted.

Three sites were identified for the pilot implementation of RECIPPE. Several more districts responded and were interested. Due to reasons, such as weather, scheduling, lack of personnel, and construction delays, several commitments did not materialize.

The results from two of the three sites are included in this report. Results from the third site will be included in the final version of this report. The two sites that were selected for scheduling and testing were located in Odessa and Austin Districts.

CASE 1 - IH-20, ODESSA DISTRICT

The site in the Odessa District was located on IH-20 in Reeves County. Figure 2.2 shows the location of the construction site. The project length was 8.5 miles. The construction activity monitored was a 1.5-in.-thick Superpave-C overlay.

Because this was a rehabilitation section, a Level 1 analysis was carried out by considering the overlay as the critical layer. In RECIPPE, the COV's of the other layers were set at zero to focus on the overlay. Also, since this was a field validation exercise, both the Level 2 (monitoring thickness and modulus of the overlay) and Level 3 (monitoring thickness and mix parameters of the overlay) were used in quality management.

a) Location of the site   b) Coring and PSPA Testing
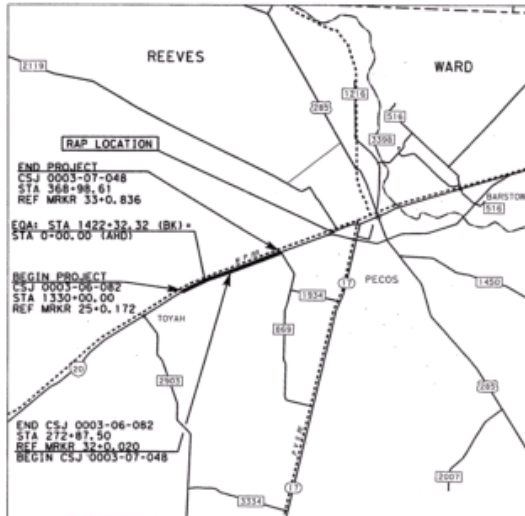
Figure 2.2 – Location of the section on IH20 section in Reeves County.

For Level 2 quality management, the two critical parameters were the thickness of the layer which was determined based on cores and the modulus of the layer which was measured directly using the PSPA. The model parameters that were most impacting performance were the thickness with an Impact Value (IV) of 66% followed by the modulus with an IV of 34% (see Figure 2.3a). In this case, the thickness is more critical to performance than the modulus. The performance model that was critical was the fatigue cracking.

For Level 3, the calibrated version of the Witczak model shown in Equation B.5 was selected. The calibration was essentially a multiplication factor of 2.34 (documented in Research Report 0-4046-3). For the modulus, the three parameters that impacted the performance the most were the asphalt content with IV of 41%, the air voids with an IV of 39% and the percent passing No. 200 with an impact value of 20% (see Figure 2.3b).

The next step was to set the initial sampling frequency for each parameter. Table 2.1 provides the sampling frequency based on both the minimum guide schedule and on RECIPPE for Level 2 and Level 3 quality management. For Level 2, the sampling frequency based on RECIPPE was three measurements per lot for thickness, and 26 samples or locations per lot for the modulus. There are no specifications in the minimum guide schedule for measuring either of the two parameters for Level 2 for the ACP layer.

For Level 3, other than the thickness, TxDOT specifies a minimum sampling for the other three parameters (see Table 2.1). The relevant protocol and sample size for each of the three parameters and the minimum frequency of sampling are compared to the sampling frequency determined by RECIPPE in Table 2.1. The frequency of sampling for the asphalt content and gradation are higher for RECIPPE than the guide schedule. The sampling frequency is equal for the air voids.

a) Design Parameters
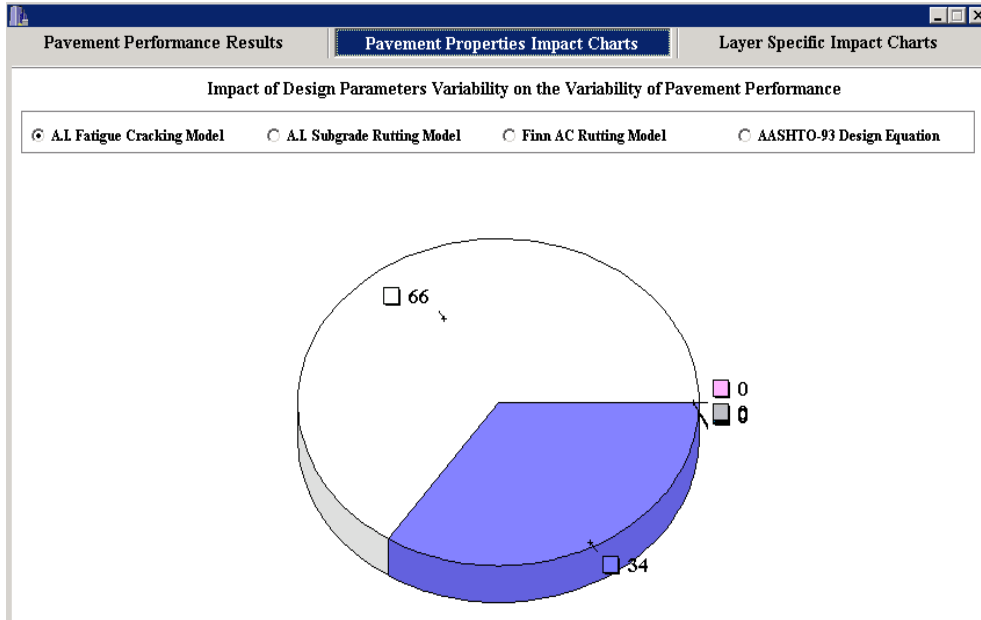
b) Construction Parameters
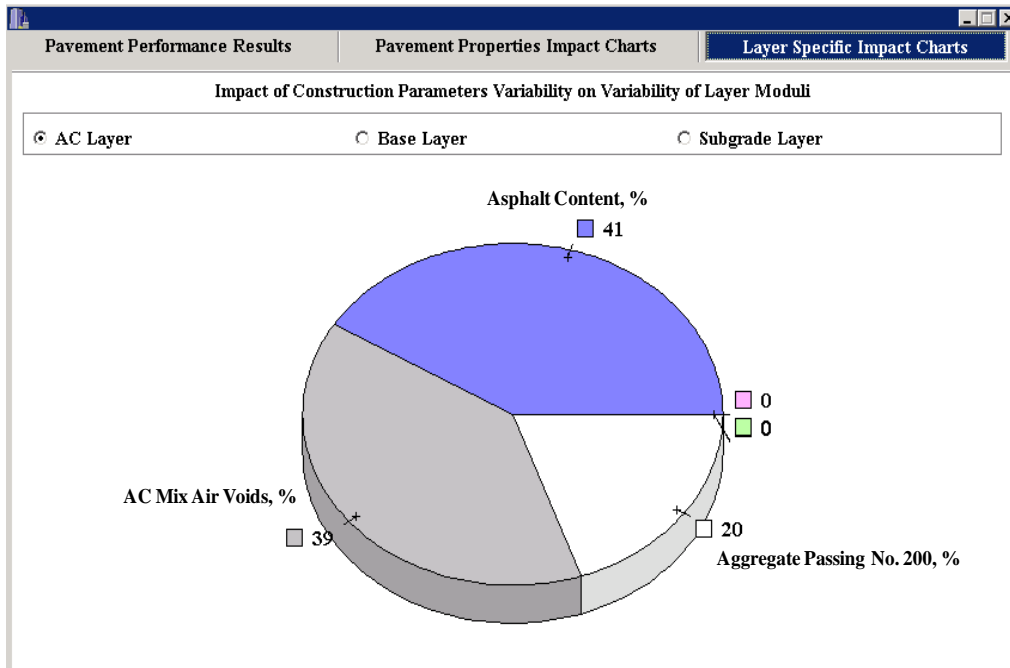
Figure 2.3 – Impact Charts for Design and Construction Parameters.

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Table 2.1 – Initial Frequency of Sampling for IH-20.

| Analysis Level | Parameter | Location or Time of Sampling | Minimum Guide Schedule | | RECIPPE |
			Test Number	Frequency of Sampling	Frequency of Sampling
Level 2	Thickness	Roadway	-	-	3 samples per lot
	Modulus	Roadway	-	-	26 samples per lot
Level 3	Thickness	Roadway	-	-	3 samples per lot
	Asphalt content (%)	Engineer Truck Sample	Tex-236-F	Minimum of 1 sample per Lot	3 samples per lot
	Gradation	Engineer Truck Sample	Tex-236-F	Minimum of 1 sample per 12 sublots	8 samples per lot
	In-Place Air Voids	Roadway	Tex-207-F	1 core per sublot	4 cores per lot

Data Collection

A meeting with the field personnel involved in the project was held to coordinate the sampling process. Concurrent with the TXDOT operation, the sampling of the materials from trucks as they left the plant was divided into four sublots (for this site the hot mix plant was setup next to the site). The sampling was carried out for this project when TxDOT personnel sampled materials for their QA. This minimized the additional man power and any impact on construction or inspection operations.

The amount of sampling for the first period was known as shown in Table 2.1. The appropriate way of data collection and interpreting the control charts would be to investigate all parameters for each period and determine the proper action to take. Appropriate actions would be either to change the sample size for the next period for important parameters or stop construction in the case of an out-of-control process. To expedite the process and to minimize the burden to the TxDOT personnel, each parameter was heavily oversampled for four consecutive days. The laboratory tests were then performed at UTEP to develop the control charts and estimate the number of data necessary for the next period. A random number generator was then used to select the number of representative samples for each parameter from the oversampled population.

For evaluating the Level 2 procedure, the coring operation and PSPA testing were performed 24 hours after the placement of the HMA. This was possible since lane closures continued to the next day until coring operations were completed. TXDOT provided the cores in conjunction

with their regular sampling operation. The PSPA testing was rapid and was performed by UTEP students alongside the coring operation (see Figure 2.2b). In total 12 cores per lot was sampled and thirty points per lot were tested with the PSPA.

The PSPA test provides a direct measurement of the layer moduli. Traditionally, the seismic moduli are low-strain high-strain-rate values. Vehicular traffic causes high strain deformation at low strain rates. To remedy this issue the master curve concept was used which tracks the modulus over wide frequency range and temperature.

Tandon et al. (2006) and Kim and Kweon (2006) have shown that the seismic modulus and the master curve from dynamic modulus can be combined together. The moduli from the two tests complement one another in defining a master curve. As such, the results of the combined seismic/dynamic modulus tests can be used with confidence in the structural design.

The ratio of moduli at 10 Hz (typical of an FWD) and 10 KHz (typical for seismic) from the master curve is used to adjust the modulus from seismic tests such as the PSPA. In the absence of mix-specific dynamic modulus test results, either the Witzcak equation (see Equation B.5) or the empirical relationship developed by Aoud and Stokoe (1993) can be used instead.

For the purpose of research and to compare the dynamic modulus with the modulus from PSPA and the modulus estimated from the material model in Level 3, an extra sample of 18 lb (8000g) was collected from trucks on the last sampling batch of the day. This was used to perform the dynamic modulus test and obtaining the master curve.

For evaluating the Level 3 procedure using RECIPPE, in addition to the cores, 10 lb (4500g) hot mix material was repeatedly sampled from trucks before they left the plant. This process was repeated for a total of four days.

At the completion of the four days of testing, all samples were brought back to UTEP and the appropriate tests for each parameter were conducted.

Presentation of Test Results

The first set of data presented is the direct measurement of the modulus collected using the PSPA. Thirty locations at each lot were tested. The moduli from the PSPA are presented in Table 2.2. Included with thirty samples are the overall mean, standard deviation, and coefficient of variation. If more than thirty samples were required, these statistical values were used to simulate the additional number of samples per parameter using the Monte Carlo simulation. In practice, more than 30 samples are associated with a significantly out of control process.

The dynamic modulus tests were performed on four specimens, one from each lot. Specimens were tested over a wide range of frequency and temperature as shown in Figure 2.4a. In addition to the dynamic modulus test results, the laboratory seismic test with a V-meter was used to determine the modulus at high frequencies. The moduli at different frequencies and

Table 2.2 – Moduli Based on PSPA Testing at IH-20 Section.

Sample #	Lot 1	Lot 2	Lot 3	Lot 4
1	522	679	714	682
2	772	665	676	691
3	666	525	622	685
4	525	694	662	651
5	619	694	665	648
6	631	639	659	565
7	636	608	691	485
8	654	659	554	559
9	642	659	648	499
10	694	731	685	534
11	619	739	739	511
12	664	682	731	642
13	494	731	591	525
14	619	676	671	679
15	614	648	625	548
16	651	688	696	480
17	659	676	739	619
18	582	702	668	534
19	617	639	597	619
20	679	708	611	548
21	617	582	594	514
22	505	628	685	557
23	477	711	716	554
24	402	651	665	597
25	636	631	711	519
26	508	642	648	628
27	636	773	631	577
28	702	682	619	614
29	708	793	704	562
30	565	691	568	554
Average	**611**	**674**	**659**	**579**
Std. Dev.	**80**	**54**	**50**	**63**
COV	**13%**	**8%**	**8%**	**11%**

temperatures were shifted as shown in Figure 2.4b and fitted using a sigmoid curve described in Equation 2.1.

$$Log \ (E^*) \ = \ \delta \ + \ \frac{\alpha}{1 \ + \ e^{[\beta \ + \ \gamma \ \log(\ Tr \ )]}} \tag{2.1}$$

where E* is the dynamic modulus, *Tr* is the reduced time, δ is considered the minimum value of dynamic modulus, δ + α is the maximum value of dynamic modulus, and β, γ are the sigmoid function shape parameters. The values of the fit parameters in Equation 2.1 are shown in Table 2.3.

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a) Frequency Results
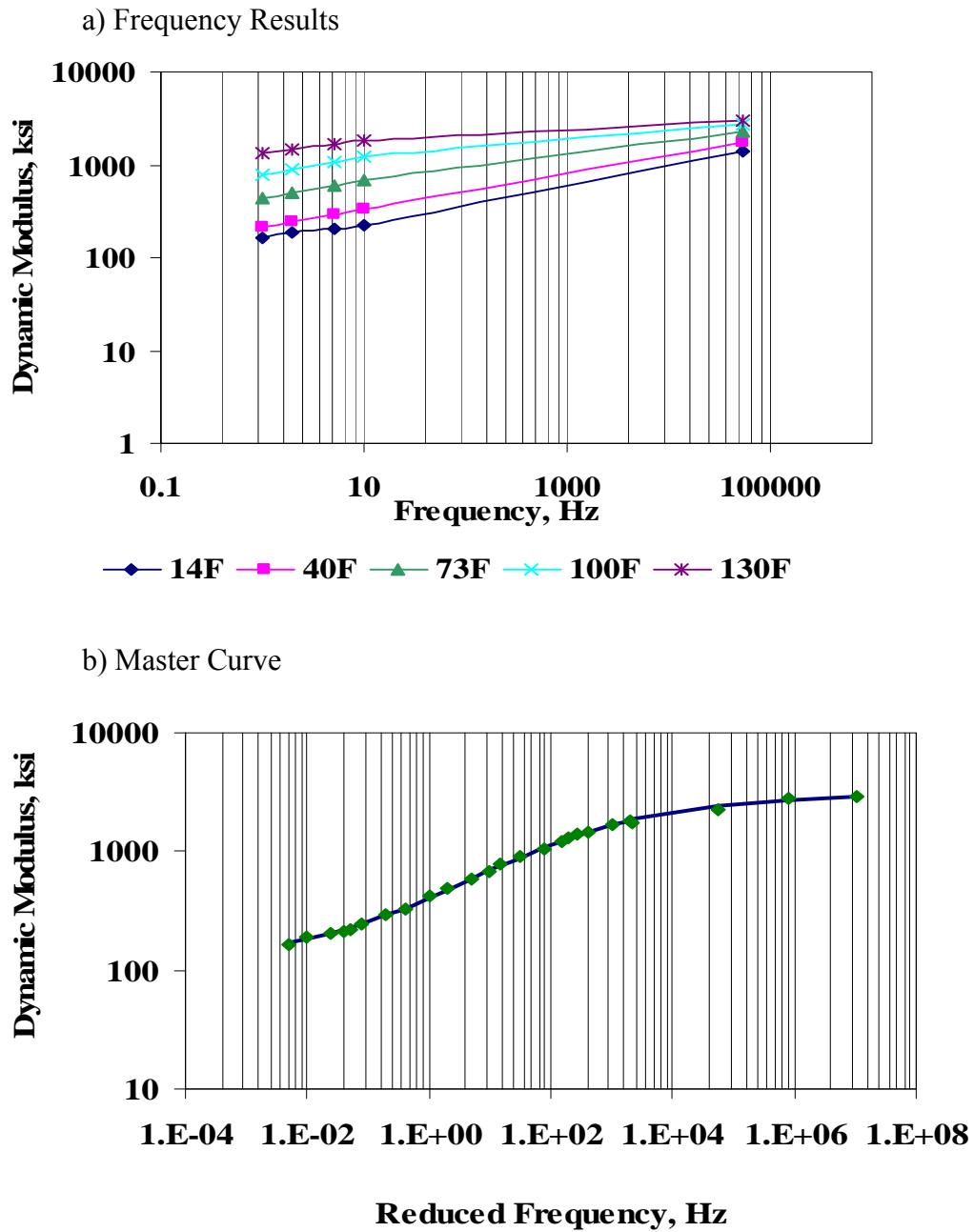
b) Master Curve

Figure 2.4 – Results of the Master Curve for IH-20 Section.

Table 2.3 – Results of Master Curve Parameters for IH-20 Section.

Master Curve Parameter	Delta	Alpha	Beta	Gamma
	2.04	1.44	0.43	0.65

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The master curve parameters presented in Table 2.3 are the average of four master curves developed. The ratio of the modulus at high frequency (10 kHz), which represents measurements from seismic testing, over low frequency (10 Hz), which represents design frequency, was calculated to be 3.1. Since the dynamic modulus was not part of the methods for testing the modulus in RECIPPE and was not sampled according to RECIPPE, a typical factor of 3.2 (recommended by Aouad and Stokoe, 1993) was used to adjust the PSPA moduli.

The next sets of data presented in Tables 2.4 through 2.7 are the thickness and the mix parameters used for Level 3. Samples were randomly selected out of the daily batches and tested for the asphalt content and gradation.

These inputs are the thickness of the ACP measured from cores, the asphalt content determined from loose material using an ignition oven, gradation based on the residue after the ignition oven, and air voids based on the bulk specific gravity (G_{mb}) of the cores. Twelve samples were tested for each lot to obtain overall mean, standard deviation, and coefficient of variation. Again the statistical sampling could be performed if more samples than twelve samples were required.

The gradations for cumulative retained materials on 3/4-in., 3/8-in. and #4 sieves and the percent passing # 200 sieve are included in the tables. Even though only the percent passing sieve No. 200 was used in the quality management, the other gradation parameters are input to Witczak material model.

Table 2.4 – Summary of Test Results from Data Collected in Lot 1 of the IH-20 Section.

Sample No.	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.59	5.82	7.25	0	14.4	46.4	6.4
2	1.57	5.75	8.10	0	11.4	44.2	6.8
3	1.56	5.65	7.38	0	10.5	43.8	6.4
4	1.43	5.84	7.89	0	12.3	46.4	6.3
5	1.26	5.75	6.19	0	14.3	46.6	6.6
6	1.35	5.79	6.87	0	12.9	45.2	6.0
7	1.44	5.54	9.25	0	15.6	48.9	5.5
8	1.37	5.59	8.74	0	11.2	44.5	6.6
9	1.56	5.57	9.58	0	14.7	47.1	5.5
10	1.25	5.54	6.83	0	11.5	46.0	5.9
11	1.14	5.59	6.40	0	12.7	46.9	5.7
12	1.34	5.57	7.93	0	14.3	48.9	5.6
Average	**1.40**	**5.67**	**7.70**	**0**	**12.98**	**46.24**	**6.10**
Std. Dev.	**0.15**	**0.11**	**1.09**	**-**	**1.65**	**1.65**	**0.46**
COV	**10.3%**	**2.0%**	**14.1%**	**-**	**12.7%**	**3.6%**	**7.5%**

[1]- Core Samples, [2]- Loose material from hot mix

Table 2.5 – Summary of Test Results from Data Collected in Lot 2 of the IH-20 Section.

Sample No.	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.65	5.62	8.06	0	12.1	46.7	6.7
2	1.79	5.53	8.52	0	11.1	43.4	7.4
3	1.67	5.62	8.82	0	8.6	41.8	6.9
4	1.83	5.52	8.27	0	11.3	45.2	6.7
5	1.57	5.47	8.78	0	14.9	46.0	6.3
6	1.79	5.59	8.61	0	11.3	45.2	6.0
7	1.74	5.69	9.88	0	10.7	45.7	5.8
8	1.39	5.71	8.95	0	9.4	43.6	5.8
9	1.51	5.83	9.20	0	8.8	41.9	5.8
10	2.22	5.46	11.58	0	13.1	47.4	6.7
11	2.16	5.55	11.32	0	11.8	45.4	5.7
12	2.20	5.60	10.52	0	11.7	46.0	6.3
Average	**1.79**	**5.60**	**9.38**	**0**	**11.24**	**44.85**	**6.33**
Std. Dev.	**0.27**	**0.11**	**1.18**	**-**	**1.77**	**1.80**	**0.53**
COV	**15.2%**	**1.9%**	**12.6%**	**-**	**15.7%**	**4.0%**	**8.4%**

[1]- Core Samples, [2]- Loose material from hot mix

Table 2.6 – Summary of Test Results from Data Collected in Lot 3 of the IH-20 Section.

Sample No.	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.36	5.91	10.64	0	9.3	43.8	6.8
2	1.37	5.95	10.35	0	7.8	42.4	6.8
3	1.36	5.93	10.22	0	9.4	44.0	7.1
4	1.18	5.76	8.95	0	9.0	40.7	6.5
5	1.34	5.78	8.27	0	9.5	40.6	6.0
6	1.20	5.71	7.12	0	8.4	39.5	5.7
7	1.82	5.88	8.48	0	11.8	45.4	5.7
8	1.87	5.88	8.31	0	8.8	37.9	6.0
9	2.00	5.54	9.08	0	10.4	47.3	6.5
10	1.96	5.77	8.93	0	9.9	42.4	6.3
11	1.95	5.81	9.54	0	7.6	39.4	5.8
12	1.34	5.57	7.93	0	12.2	45.4	6.8
Average	**1.56**	**5.79**	**8.98**	**0**	**9.50**	**42.40**	**6.33**
Std. Dev.	**0.32**	**0.13**	**1.06**	**-**	**1.41**	**2.88**	**0.48**
COV	**20.7%**	**2.3%**	**11.8%**	**-**	**14.9%**	**6.8%**	**7.5%**

[1]- Core Samples, [2]- Loose material from hot mix

Table 2.7 – Summary of Test Results from Data Collected in Lot 4 of the IH-20 Section.

Sample No.	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.36	5.79	7.38	0	13.1	41.8	7.1
2	1.91	5.73	7.50	0	11.6	42.9	6.9
3	1.36	5.73	7.25	0	10.9	39.7	7.3
4	1.76	5.97	7.04	0	8.7	40.7	6.6
5	1.39	5.91	7.59	0	11.1	41.7	6.7
6	1.65	5.78	6.57	0	11.1	42.3	6.4
7	1.84	5.94	7.29	0	11.8	42.0	7.3
8	1.85	5.96	7.21	0	11.1	41.7	6.7
9	1.58	5.72	11.03	0	8.8	41.1	7.0
10	1.31	5.92	10.09	0	10.9	41.5	6.9
11	1.41	5.89	11.20	0	9.5	40.6	6.0
12	1.52	5.78	9.41	0	12.3	42.4	7.2
Average	**1.58**	**5.84**	**8.30**	**0**	**10.91**	**41.53**	**6.85**
Std. Dev.	**0.22**	**0.10**	**1.66**	**-**	**1.32**	**0.89**	**0.38**
COV	**13.9%**	**1.7%**	**20.0%**	**-**	**12.1%**	**2.1%**	**5.6%**

[1]- Core Samples, [2]- Loose material from hot mix

Results Based on Level 2

The results from the evaluation of thickness and PSPA modulus for the four periods are presented in Figure 2.5. On the left side of the figure, the control chart for the mean value of each parameter is presented. For the mean control chart, the data for four periods is compared to the mean values (expected value) and the upper and lower limits. On the right side of the figure, the control chart for the COV value of each parameter is presented. The variability of the data for the four periods is compared to the required COV value and the upper limit. For the COV control chart the lower limit is zero. Also included in the COV control charts are the sample size for each period.

Figure 2.5a and 2.5b contains the results for the thickness. The sample size for the first period of testing was four according to RECIPPE. For the first period, the mean value is close to the lower limit; however it is still in-control. On the other hand, the first period's COV is slightly above the upper limit. The results indicate that the thickness measured for the first period has higher variability than allowable which signifies that the thickness parameter for Level 2 is out-of-control. In this case, the choice is to either stop construction and address the problem or increase sampling for the next period. The increased sampling suggested by RECIPPE for the second period was 10.

In the second period, the results again show that the mean thickness is in-control and close to the upper limit. However, the COV increased for this period as well. Again the consequence is to increase the sample size for Period 3 to 17 samples.
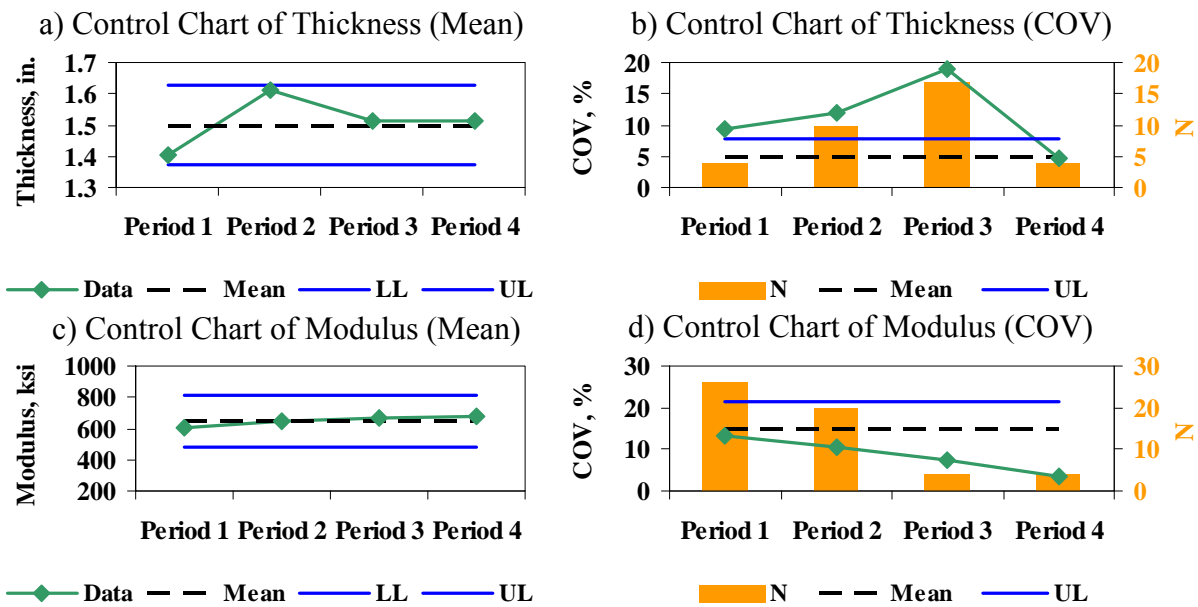
Figure 2.5 – Control Chart Results Using Level 2 Data for IH-20.

For the third period, the thickness is close to the allowable mean. However, the COV is still increasing. In this case, the recommendation is to stop the construction process until the contractor addresses the problem. Once the problem is fixed, the construction can resume. The sample size for the fourth period was set to the initial sampling size of four since the assumption is that the problem has been fixed.

In the last period, the mean and COV are in-control. Therefore, the sample size could be either maintained for one more period to verify that the process is truly in-control or to reward the contractor and decrease the sample size based on the reduced variability.

The second set of control charts in Figure 2.5, represent the results for the modulus measured using PSPA. The sample size for the modulus is initially set at 26 as indicated in Figure 2.5d. Since the mean and COV for period one are in-control, the sample size is decreased to 20 for the second period, and three for the subsequent periods.

Results Based on Level 3

Figure 2.6a and 2.6b presented the results for the overlay thickness. The sample size for the first period of testing was three according to RECIPPE. However, since five cores were extracted for computing the air voids (see Table 2.1), five measurements of thickness were used as an initial sample size (see Figure 2.6b). The trends for thickness are discussed above.

In the case of the percent passing #200 sieve, the process was in-control for all periods and as such the sampling size decreases for each consecutive period (see Figure 2.6c and 2.6d). If TxDOT would like to enforce the minimum guide schedule, four samples will be the minimum sampling recommended if the process is in-control.

Figures 2.6e and 2.6f present the results for the air voids. From the first period, both the mean and COV were out-of-control. Therefore, the sample size was increased from 5 to 12 for the second period. For the next three periods the process was in-control and therefore the sample size was reduced.

The last parameter is the asphalt content. The results from the control charts show that the process was in-control for all four periods (see Figures 2.6g and 2.6h). This suggests that the contractor was doing a good job controlling the binder as specified in the mix design, and the sample size can be even reduced further.

Comparison of Modulus for Level 2 and Level 3

The average moduli from Level 2 (direct measurement) and Level 3 (using the calibrated Witczak model from Haggerty et al., 2005) are compared in Figure 2.7. The Level 3 moduli are slightly higher than the moduli directly measured using the PSPA. For this site, it would be more prudent to run Level 2 (PSPA testing) instead of the Level 3 due to limited resources needed to carry out the sampling and laboratory testing. The average moduli at 10 Hz from the dynamic modulus test and the Witczak model before calibration are also shown in Figure 2.7. The modulus from the dynamic modulus tests is fairly similar to the Level 2 and Level 3 moduli.

CASE 2 – LOOP 1, AUSTIN DISTRICT

The map in Figure 2.8 shows the location of construction located along Loop 1 in Austin, Texas. The proposed construction was placing 2 in. of SMA-C over 5.5 in. of base over subgrade.

Similar to Case 1, the 2 in. ACP layer was assumed as the critical layer because this was a rehabilitation project. Again, both Level 2 and Level 3 processes were used. In Level 2, the thickness and the modulus of the layer were monitored. For the modulus, in Level 3, the three parameters that were impacting most were again the asphalt content, the air voids, and the percent passing No. 200. The data collection and laboratory testing process were carried out similar to the previous site. Table 2.8 provides the sampling frequency based on both the minimum guide schedule and based on RECIPPE for both Level 2 and Level 3. Since the structural system, the pavement design life and the assigned variability for Case 1 and Case 2 were different, the impact value of Level 2 and Level 3 parameters were different. As such the amount of variability for each parameter is different and follows that the sample size for Case 2 will be different than that of Case 1.

The same process used for gathering the data for the first case was also used here. The one difference was that construction was performed at night and the coring and PSPA testing were performed few hours after pouring compared to the standard 24 hours after laying down the hot mix.

a) Control Chart of Thickness (Mean)

b) Control Chart of Thickness (COV)

c) Control Chart of P200 (Mean)

d) Control Chart of P200 (COV)

e) Control Chart of Air Voids (Mean)

f) Control Chart of Air Voids (COV)

g) Control Chart of AC Content (Mean)

h) Control Chart of AC Content (COV)
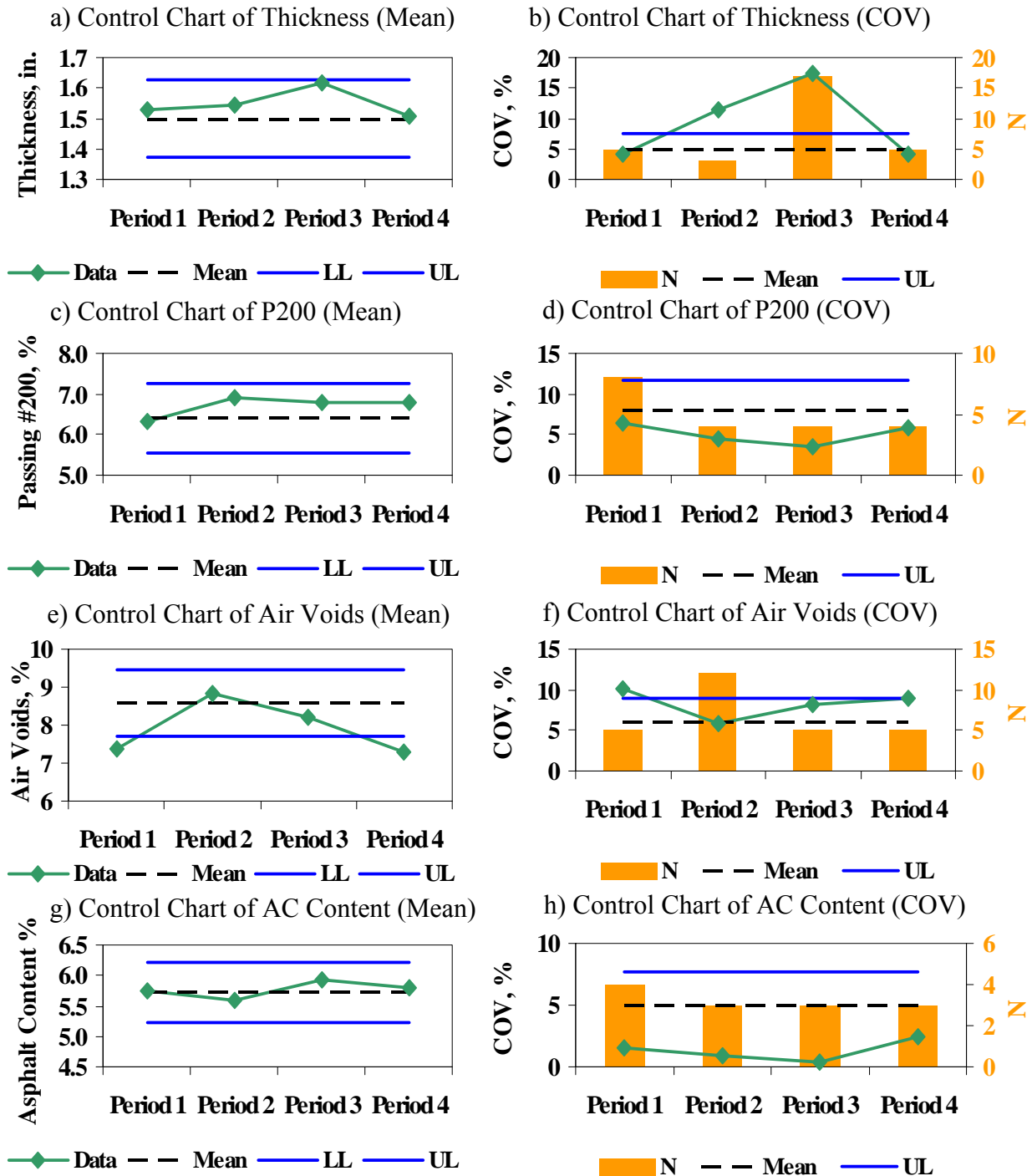
Figure 2.6 – Control Chart Results for with RECIPPE Using Level 3 Data for IH-20.
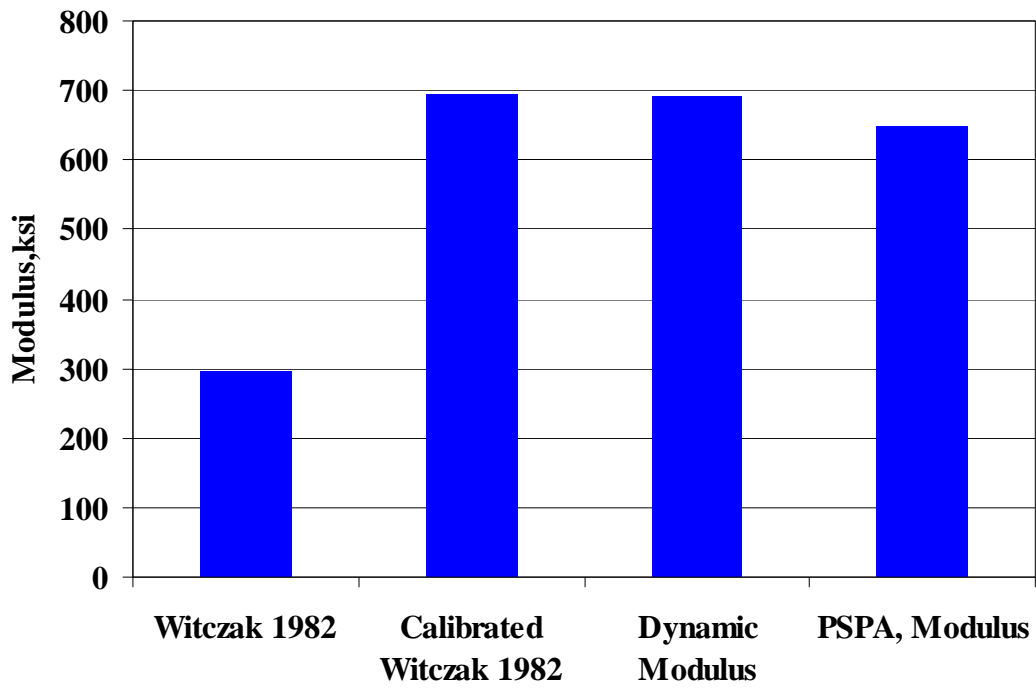
Figure 2.7 – Comparison of Modulus Results with Different Measurements for IH-20.

Figure 2.8 – Location of the section on Loop 1 in Austin.

Table 2.8 – Initial frequency of Sampling for Loop 1.

| Analysis Level | Parameter | Location or Time of Sampling | Minimum Guide Schedule | | RECIPPE |
			Test Number	Frequency of Sampling	Frequency of Sampling
Level 2	Thickness	Roadway	-	-	6 samples per lot
	Modulus	Roadway	-	-	14 samples per lot
Level 3	Thickness	Roadway	-	-	8 samples per lot
	Asphalt content (%)	Engineer Truck Sample	Tex-236-F	Minimum of 1 sample per Lot	8 samples per lot
	Gradation	Engineer Truck Sample	Tex-236-F	Minimum of 1 sample per 12 sublots	8 samples per lot
	In-Place Air Voids (A)	Roadway	Tex-207-F	1 core per sublot	5 cores per lot

At the completion of the four days of testing, all materials were brought back to UTEP and the appropriate tests for each parameter were conducted. Again, the appropriate numbers of samples were randomly selected for the relevant parameters. The results from laboratory and field tests are included in Appendix E.

Results Based on Level 2

Figure 2.9a and 2.9b presented the results for the thickness. The initial number of samples recommended was six. Based on the first period results, the mean was on target, but the COV was above the upper limit. Sampling was increased for the next period to 20. The mean thickness was on target for the second period, and the COV decreased from 15% to 10% close to the upper limit. Based on the COV of 10%, the reduced sample size of 12 was used for the next period. The COV value for Period 3 was still close to the upper limit but in-control. The control charts show that, for the last period, the thickness is in-control based on a sample size of 12.

Figures 2.9c and 2.9d present the control charts for the modulus measured using the PSPA. The first period mean modulus was lower than the Level 1 lower limit, and the COV was at the border line of the upper limit. Since the two control parameters were marginally acceptable, the sample size for the second period was maintained as the first period to carefully monitor the quality before taking any action. In the second period, the mean modulus was in-control, but the COV increased slightly above the upper limit. For the next period, the sample size was increased to 33. For the third period, the COV increased to 30%. At this time the recommendation would

be to stop the production and make adjustment to the construction process for a more uniform layer. Once the changes are in affect with the construction process, the construction would resume and sampling continues. At this stage, the sample size would be the initial sampling from Level 1 (assuming the problem is fixed) or continue with the sample size of Period 3. Since the data collection with PSPA was rapid, the sample size of 33 maintained. The COV is now in-control.

a) Control Chart of Thickness (Mean)   b) Control Chart of Thickness (COV)

c) Control Chart of Modulus (Mean)   d) Control Chart of Modulus (COV)
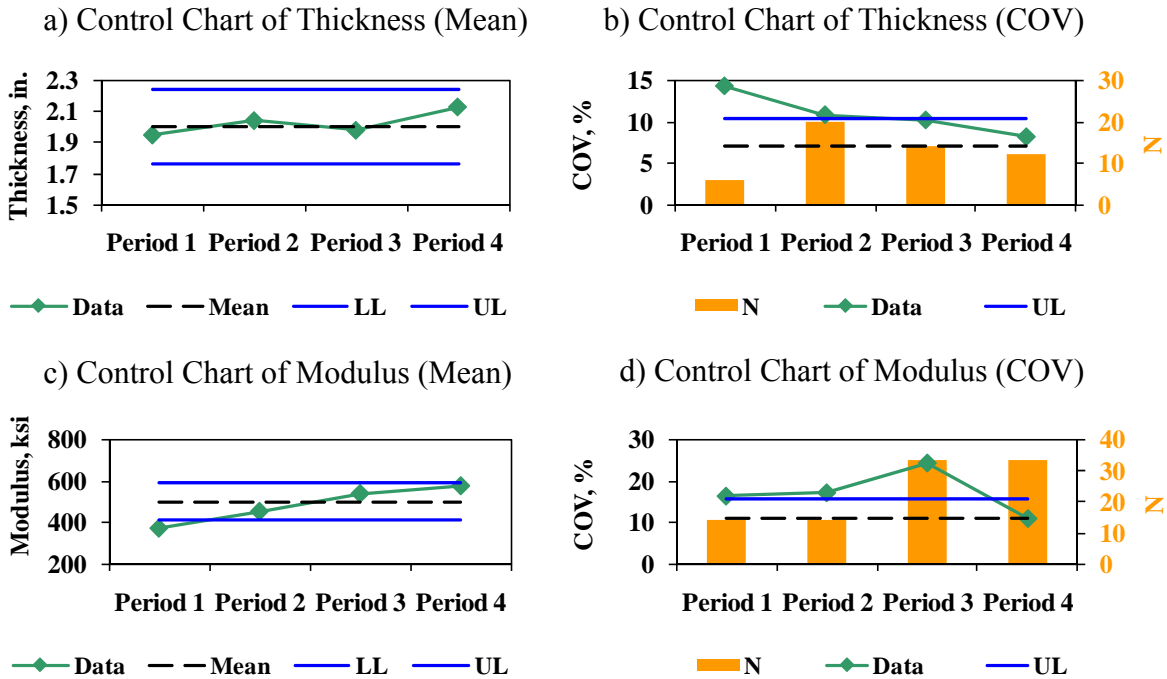
Figure 2.9 – Control Chart Results for with RECIPPE Using Level 2 Data for Loop 1.

Results Based on Level 3

Figures 2.10a and 2.10b contain the results for the thickness of the 2in. SMA-C. This parameter was discussed for level 2.

The control charts for the percent passing #200 sieve show that this parameter had COVs close to the upper acceptable limit for three periods. The mean value is in control except for the last period.

The last two parameters are the air voids and the asphalt content. The results from the control charts show that the processes are in-control for all four periods (see Figures 2.10e - 2.10h). This suggests that the contractor is doing a good job in compaction and in-controlling the binder as specified in the mix design.
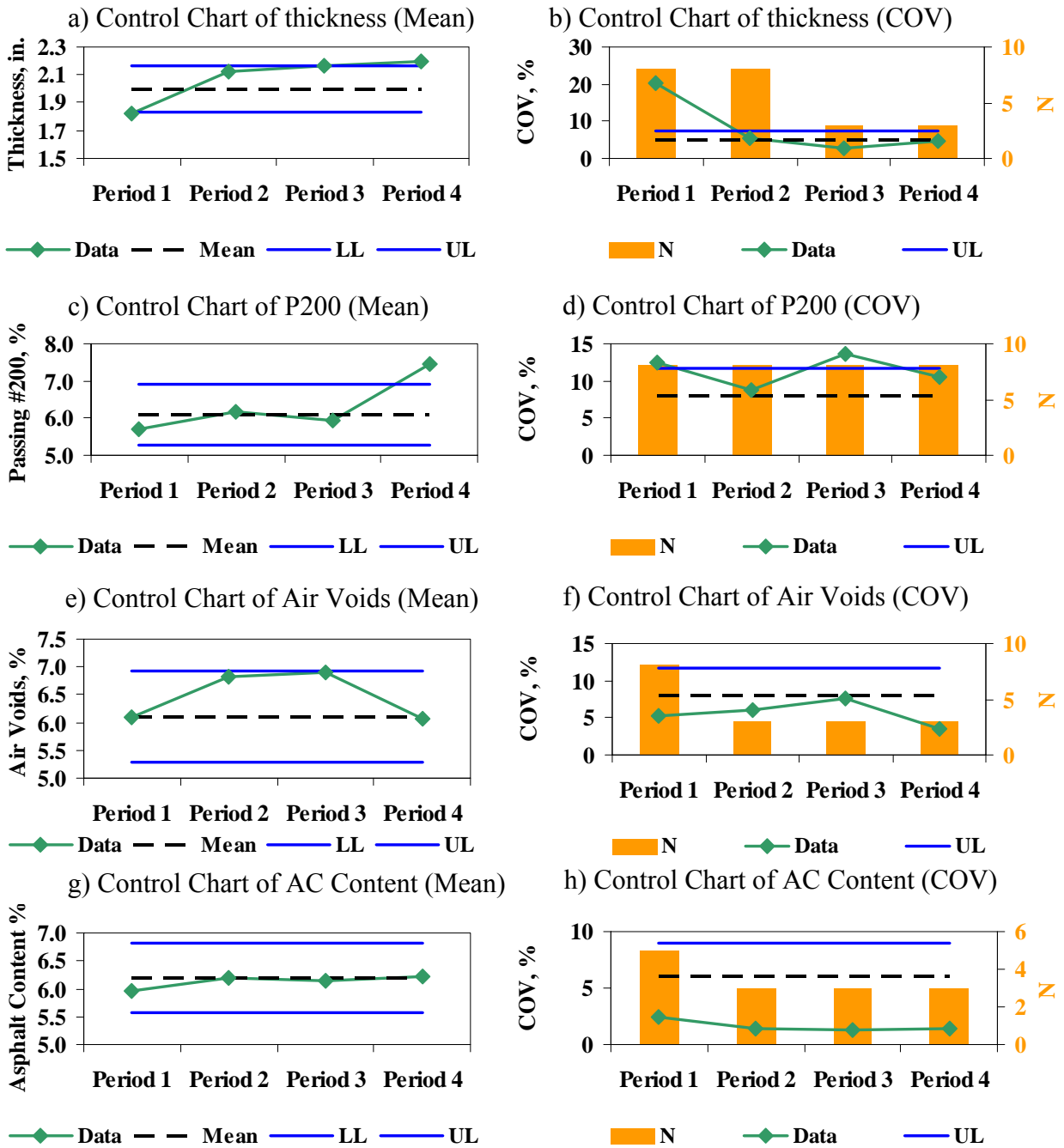
Figure 2.10 – Control Chart Results for with RECIPPE Using Level 3 Data for Loop 1.

Comparison of Modulus for Level 2 and Level 3

The moduli from Level 2 and Level 3 data are compared if Figure 2.11. The moduli from Level 3 are computed using the calibrated 1982 Witczak model. For this site, the moduli based on the material model were greater than the PSPA moduli for all four period.

Again the dynamic modulus test was used as a benchmark to compare the moduli from the material model and from PSPA. Figure 2.12 shows that the dynamic modulus was closer to the PSPA as compared to the calibrated Witczak model.
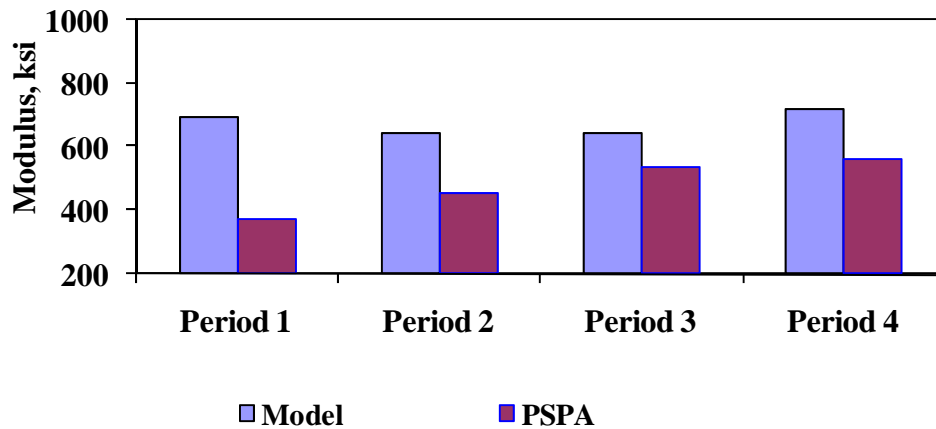
Figure 2.11 – Comparison of Modulus Results Using Level 3 and Level 2 Data for Loop1.
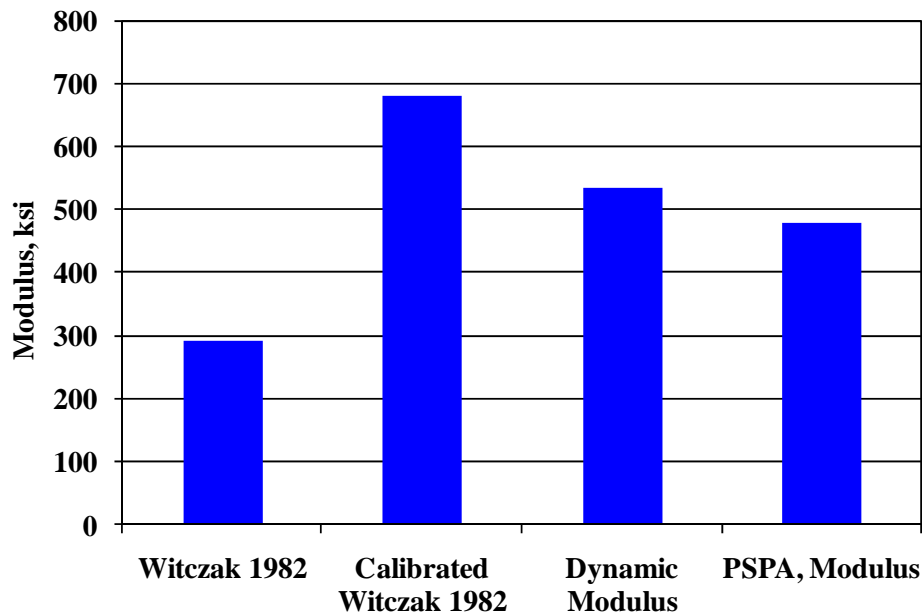
Figure 2.12 – Comparison of Modulus Results with Different Methods for Loop1.

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CASE 3 – IH-35, AUSTIN DISTRICT

As shown in Figure 2.13, the construction site located along IH-35 in Austin, Texas. The proposed construction was to mill and replace the top 2 in. of the existing pavement with a Type SMA-D mix.

Figure 2.13 – Location of the section on IH-35 in Austin.

As in the previous case study, the 2 in. ACP layer was assumed as the critical layer because this was a rehabilitation project. Again, both Level 2 and Level 3 processes were used. In Level 2, the thickness and the modulus of the layer were monitored. For the modulus, in Level 3, the three parameters that were impacting the most were the asphalt content, the air voids, and the percent passing No. 200. The data collection and laboratory testing process were carried out similar to the previous sites. Table 2.9 provides the sampling frequency based on both the minimum guide schedule and based on RECIPPE for both Level 2 and Level 3.

The same process used for gathering the data for the first two cases was also used here. Again, as with the second site, construction was performed at night and the coring and PSPA testing were performed about an hour after placement as compared to the standard 24 hours after laying down the hot mix. The main reason for this action was that the completed overlay section would be opened to traffic around 6:00 AM. Von Quintus et al (2007) performed tests with the PSPA shortly after and after 24 hours after the placement of the hot mix in several projects. They concluded that the design modulus obtained from shifting the master curve to the temperature at which the PSPA measurements are carried out would provide results that are comparable to those from dynamic modulus tests performed on the specimens from the same mix at the average

Table 2.9 – Initial Frequency of Sampling for IH-35.

| Analysis Level | Parameter | Location or Time of Sampling | Minimum Guide Schedule | | RECIPPE |
			Test Number	Frequency of Sampling	Frequency of Sampling
Level 2	Thickness	Roadway	-	-	8 samples per lot
	Modulus	Roadway	-	-	20 samples per lot
Level 3	Thickness	Roadway	-	-	8 samples per lot
	Asphalt content (%)	Engineer Truck Sample	Tex-236-F	Minimum of 1 sample per Lot	12 samples per lot
	Gradation	Engineer Truck Sample	Tex-236-F	Minimum of 1 sample per 12 sublots	12 samples per lot
	In-Place Air Voids (A)	Roadway	Tex-207-F	1 core per sublot	8 cores per lot

in-place air voids. As such, the PSPA moduli were adjusted to an average temperature of 140°F which was the average temperature of the mat at the time of the PSPA tests.

At the completion of the four days of testing, all materials were brought back to UTEP and the appropriate tests for each parameter were conducted. Again, the appropriate numbers of samples were randomly selected for the relevant parameters. The results from laboratory and field tests are included in Appendix F.

Results Based on Level 2

Figures 2.14a and 2.14b present the results for the thickness measurements. The initial number of samples recommended was eight. Based on the first period results, the mean thickness was close to the lower bound of acceptable thickness. The COV was close to the acceptable limit and within the thickness tolerances acceptable for the layer. As such, the sampling was maintained at the same frequency as Period 1. The mean thickness for Period 2 was less than the target value while the COV increased. Based on field observation, Period 2 encountered several construction problems. For purposes of this exercise, an assumption was made that these problems were investigated and fixed in the field and the original target sampling recommended by RECIPPE is used for Period 3. The results for Period 3 show that the thickness was still less than specified 2 in. with a COV value of 9%. For the final period the mean thickness stayed the same. However, the COV value improved to 6%.

a) Control Chart of Thickness (Mean)

b) Control Chart of Thickness (COV)

c) Control Chart of Modulus (Mean)

d) Control Chart of Modulus (COV)
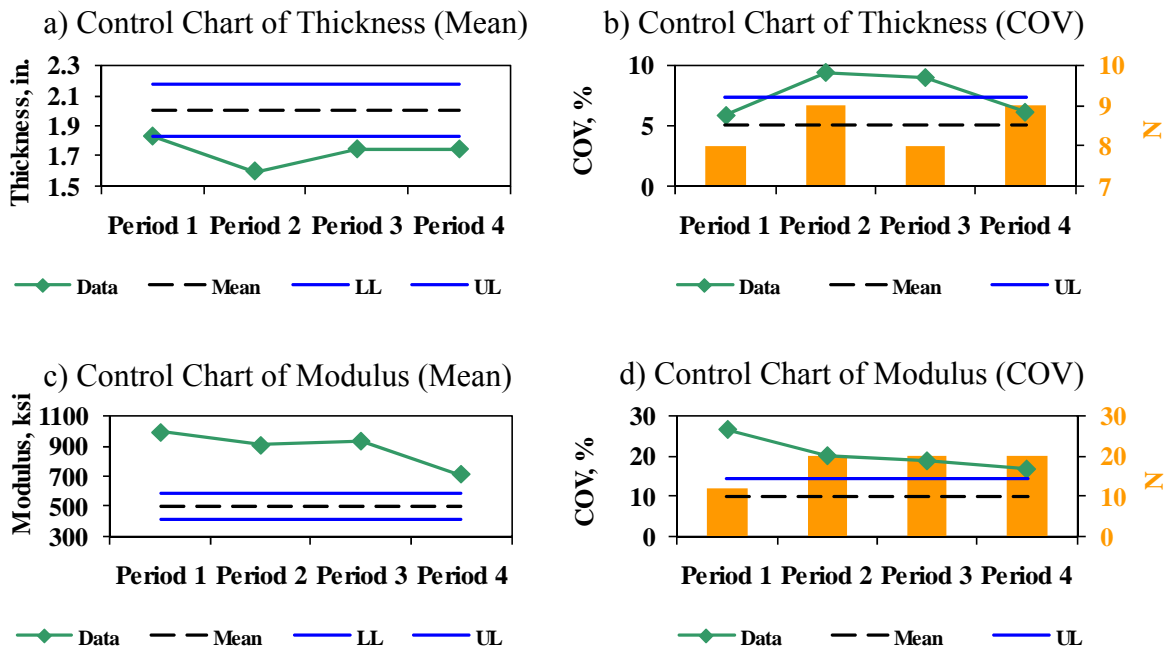
Figure 2.14 – Control Chart Results for with RECIPPE Using Level 2 Data for IH35.

Figures 2.14c and 2.14d present the control charts for the modulus measured using the PSPA. For all four periods, the value of the PSPA was greater than the typical 500 ksi considered in the design. The first period mean modulus was 990 ksi, and the COV was significantly greater than the proposed upper limit. Based on that the sample size for the second period was increased to 20 (maximum sample size). In the second period, the mean modulus was similar to the first period but the COV decreased but was still above the upper limit. For the next two periods, the sample size was maintained to the maximum sample size. The COV values decreased. Based on the history of this site and from talks with the officials on the site, a tool such as RECIPPE could have really helped in reducing cost, reducing time and improving construction quality. The inspectors also mentioned that there were a lot of construction delays on this site due to mix design problems.

Results Based on Level 3

Figures 2.15a and 2.15b contain the results for the thickness of the 2in. SMA-D. This parameter was discussed in detail in for Level 2.

The control charts for the percent passing #200 sieve show that this parameter had COVs close to mean value and acceptable COV for all four periods.

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a) Control Chart of thickness (Mean)

b) Control Chart of thickness (COV)

c) Control Chart of P200 (Mean)

d) Control Chart of P200 (COV)

e) Control Chart of Air Voids (Mean)

f) Control Chart of Air Voids (COV)

g) Control Chart of AC Content (Mean)

h) Control Chart of AC Content (COV)
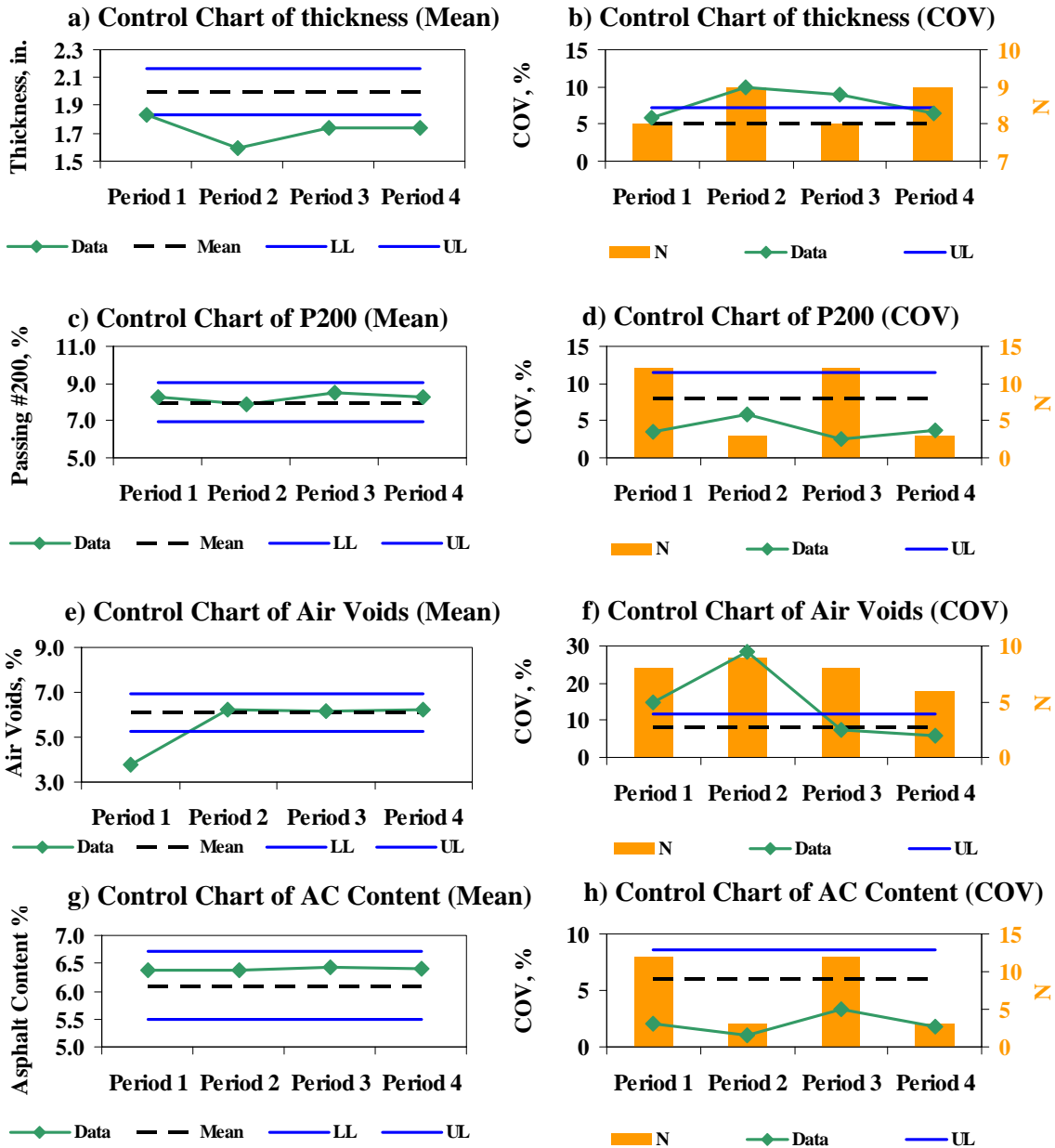
Figure 2.15 – Control Chart Results for with RECIPPE Using Level 3 Data for IH-35.

The last two parameters are the air voids and the asphalt content (see Figures 2.15e through 2.15h). The results overall show that the air voids were quite low for Period 1 and the COV value was larger than the upper limit for the first two periods but improved and decreased to acceptable range for the last two periods. This could explain the results from Level 2 and verifies the discussion of the contractor using different binder. The results for the asphalt content although was within the limits, it was consistently higher than the mean value.

Comparison of Modulus for Level 2 and Level 3

The moduli from Level 2 and Level 3 data are compared if Figure 2.16. The moduli from Level 3 are computed using the calibrated 1982 Witczak model. For this site, the moduli based on the material model were much greater than the PSPA moduli for all four period.

Again the dynamic modulus test was used as a benchmark to compare the moduli from the material model and from PSPA. Figure 2.17 shows that the dynamic modulus, in this case, was closer to the Calibrated Model as compared to the PSPA results. However, these moduli may not be reflective of the construction problems encountered.
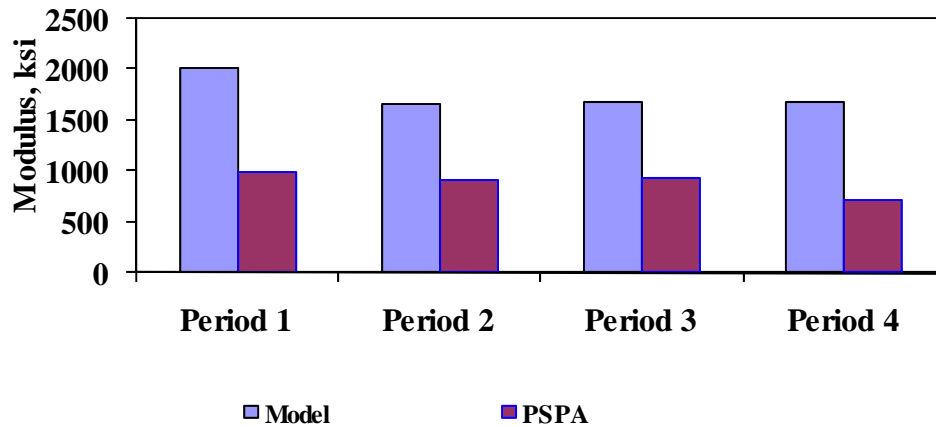
Figure 2.16 – Comparison of Modulus Results Using Level 3 and Level 2 Data for IH-35.
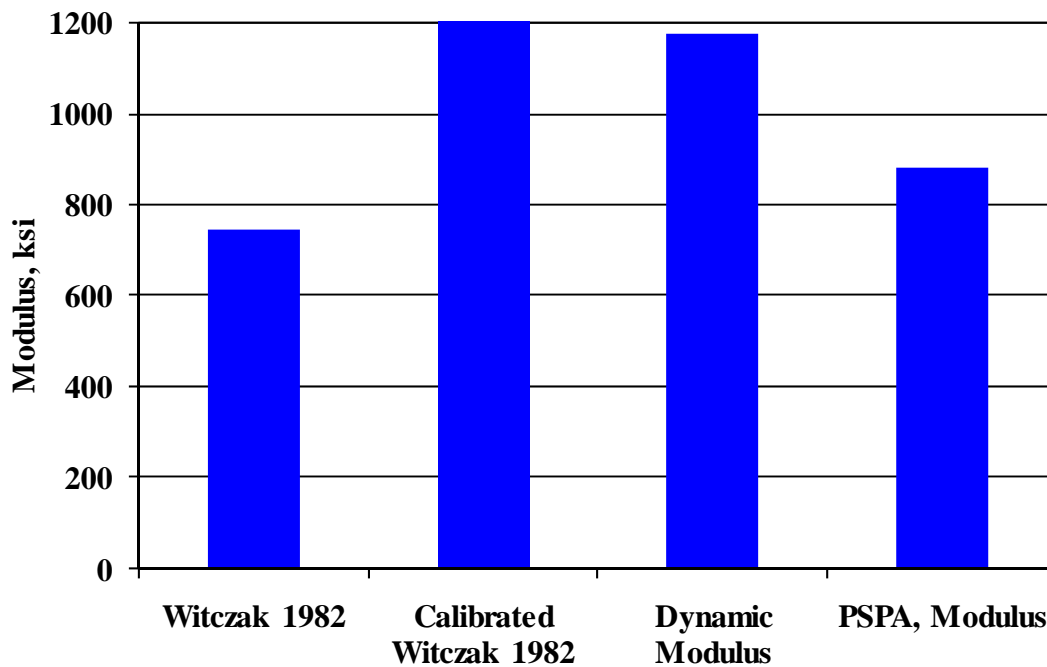
Figure 2.17 – Comparison of Modulus Results with Different Methods for IH-35.

CHAPTER THREE – SUMMARY AND CONCLUSION

SUMMARY

The goal of this project was to develop a rational algorithm that can be used in practice for the quality control of construction of pavements. As such, a method was developed, which for a given project, will guide TxDOT personnel to determine what parameters would significantly impact the performance, what parameters will moderately impact and those that are of small importance. The level of acceptable deviations from the target design value for each parameter is established based on quantification of the variability of the construction parameters introduced by: (a) the construction processes, (b) the material properties, (c) the models used to predict pavement performance and those used for data analysis, and (d) the resolution of the procedures used in the field for quality control.

The software developed utilizing the algorithm is called Rational Estimation of Construction Impact on Pavement Performance (RECIPPE). It can be used to reconcile the results from pavement-performance models used in the state of practice, or those widely accepted by state agencies, with statistical process control techniques and uncertainty analysis methods, to determine project-specific parameters that should be used in construction quality management.

CONCLUSIONS

RECIPPE presents a process that can be used in a practical manner to optimize construction quality control. Furthermore, the latest version of the process is versatile and avails complete modularity, which allows for new material and performance models to be inputted and/or calibrated as needed. Even though a limited number of sites were used to develop calibrated material models the results from RECIPPE and the methodology presented in this study is a step towards a more rational estimation of pavement remaining life from construction parameters.
The current RECIPPE program can be used to:

- Generate construction parameter values that will meet owner's needs for pavement life
- Identify the construction parameters to focus on, in order to reduce pavement life variance and increase reliability
- Track and identify out-of-control procedures during construction
- Reduce sampling costs by optimizing the frequency of testing

- Create databases that can be used in future projects
- Lower variability of construction practices
- Perform quality control and/or quality assurance of construction practices
- Focus manpower on specific parameters and reduce costs

Based on the pilot implementation work using RECIPPE, the recommendations are the following:

- For large scale projects such as design build or new construction a combination of Level 2 and Level 3 can be used in the analysis for both surface and subsurface layers. The main concern is the accuracy and validity of the material models. Also, on large scale projects, enough man power and larger on site facilities are available to carry out laboratory testing for the number of sampling that could be required for the different parameters.
- For small scale projects or rehabilitation type projects, Level 2 is good enough for surface and subsurface layers. An example of surface layer analysis based on the direct measurement of the modulus using the PSPA and thickness with either coring and or GPR is enough as presented in the case studies presented in Chapter 2. This expedites the QC process and maximizes resources with diminishing the value of the QC process.

APPENDIX A – METHODOLOGY

The methodology developed under this research provides a link between construction and performance. Figure A.1a shows a conceptual representation of the methodology starting from the center, or inner circle and moving to the outer circle. The three circles presented in the figure represent the main features in the methodology. The process starts from construction parameters, which is represented by the inner circle. These parameters are used to estimate the layer moduli via material models for the different layers of a pavement system. The material characteristic models, represented by the middle circle, are the links between the construction and pavement performance. Pavement performance is represented by the outer circle, which is based on the layer moduli and other pavement properties so that the pavement system performance can be determined.

In Figure A.1b the process is further explained. The core of this methodology is based on mechanistic analysis. The structural model is based on a nonlinear model using equivalent-linear algorithm. The equivalent-linear model was developed under TXDOT Project 0-1780 (Ke et al. 2000, and Abdallah et al., 2003). The structural model, designated as *(1)* in Figure A.1b serves as the engine that performs all numerical calculations such as determining the nonlinear layer moduli and appropriate stresses and strains in the pavement analysis process. The next process illustrates the link of the inner circle and the middle circle *(2)*. Construction parameters are used in material models to determine the moduli of the layers. For example, the modulus of ACP is estimated using a model that incorporates as input construction parameters such as air voids, asphalt content, asphalt viscosity, etc. The last step illustrated in the process shows the link between the middle circle, material models, and the outer circle, performance models *(3)*. This step depicts the process of estimating the critical strains based on the layer properties (thickness, modulus, etc…) to determine performance of the pavement using the structural model. The process described thus far allows the estimation of pavement performance based on construction parameters. As such, this analysis only represents a deterministic analysis. The uncertainties that are associated with the input parameters are not accounted for. However, engineering measurement associated with a construction parameter demonstrates a certain variation. Therefore, a probabilistic approach is a more rational approach and was incorporated into the process.

a) Conceptual framework of Methodology

b) Process

(1) Equivalent linear analysis is used as the structural model to analyze the pavement system

AC
Base
Subgrade

(2) Regression equations relate construction parameters to estimate layer moduli

(3) Critical structural responses such as critical strains are used to estimate remaining life

Construction & Process Control Parameters

Example: Asphalt content, compaction, dry density, moisture content, Aagg. passing #200

Material Model

Example: Witczak or Hirsch model for moduli of asphalt layer and constitutive model for base and subgrade

Pavement Performance

Example: Rutting, Fatigue Cracking

$$N_d = f4 / (\varepsilon_c)^{f5}$$

$$N_f = f1 / (\varepsilon_t)^{f2} / (E_{AC})^{f3}$$
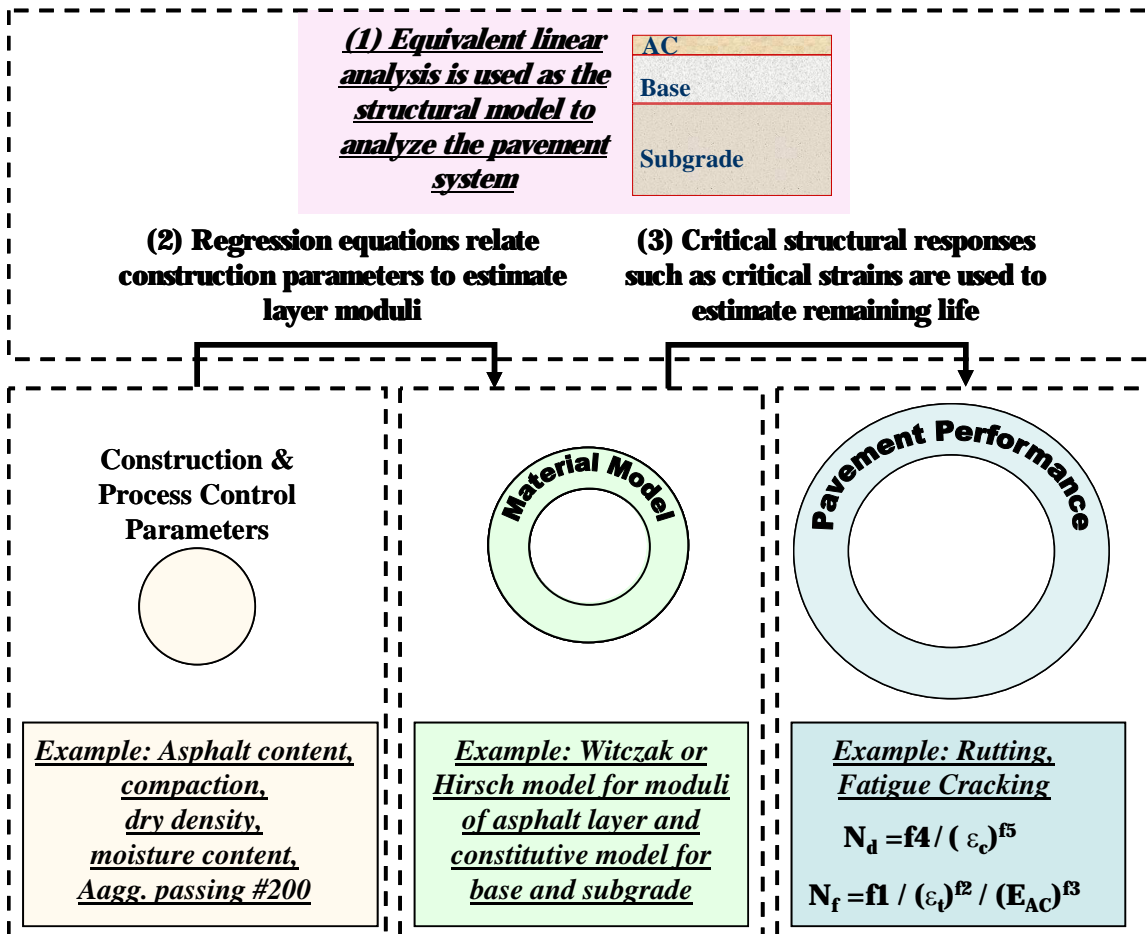
Figure A.1 - Conceptual Framework of Methodology and Process for Determining Pavement Performance from Construction Parameters

Probabilistic Approach and Generation of Impact Chart

For practical consideration, all input parameters are assumed to be normally distributed. Once variability of input parameters is incorporated into the system, performance outputs will also retain variability. By accounting for variability in the analysis, the impact of construction variability on the variability of pavement performance is determined. This impact is estimated using an "impact chart". The impact chart compares the influence of each construction parameter on the remaining life. The probabilistic analysis employed in this project is based on two methods: 1) Monte Carlo Simulation and 2) Two Point Mass (TPM) Simulation.

Monte Carlo simulations technique randomly generates values to represent variables with uncertainty. For this case, the construction parameters are randomly created multiple times to simulate a continuous model. Similarly, the TPM simulation is used to approximate low-order moments of functions (e.g., mean and coefficient of variation, COV) for construction parameters (Rosenblueth, 1981). This is achieved by replacing continuously randomly-generated values with two discrete values.

The major difference between the Monte Carlo and TPM simulations is the number of iterations it takes to complete a simulation. With a Monte Carlo simulation, 500 simulations are considered adequate enough to model a normal distribution in this study (Abdallah et al., 2004a), while the number of iterations for TPM varies with the number of random variables represented by:

$$\text{Iterations}_{\text{TPM}} = 2^{\textit{Number of Random Variables}} \tag{A.1}$$

For the algorithm developed in this research, two types of statistical analyzes are performed: 1) varying values for a single construction parameter and 2) varying all parameters at once. Figure A.2 illustrates the concept of the simulation process. Any input parameter is described with a normal distribution represented by a mean and a coefficient of variation (COV). As illustrated in part one of Figure A.2, each parameter is simulated individually and is processed through the system to determine its impact on the variation of pavement performance. This process is repeated for each parameter, and as such, for each construction parameter, the impact of that parameter can be determined.

The impact of each parameter does not account for the joint effect of all parameters impacting performance. Therefore, processing of all input parameters simultaneously through the system is required (the second part illustrated in Figure A.2). The program developed in this project uses Monte Carlo simulation and TPM simulations in unison. The TPM simulations can be used to calculate the variance of the remaining life when one parameter is varied, and the Monte Carlo simulations can be used when all of the construction parameters are varied together.

The last part of the figure depicts the use of the impact values to develop the impact chart. To prioritize the significance of different construction parameters relative to one another, the approach described next is followed. When the simulation is carried out for a single construction parameter, it is possible to create pie charts showing how each parameter impacts the variability
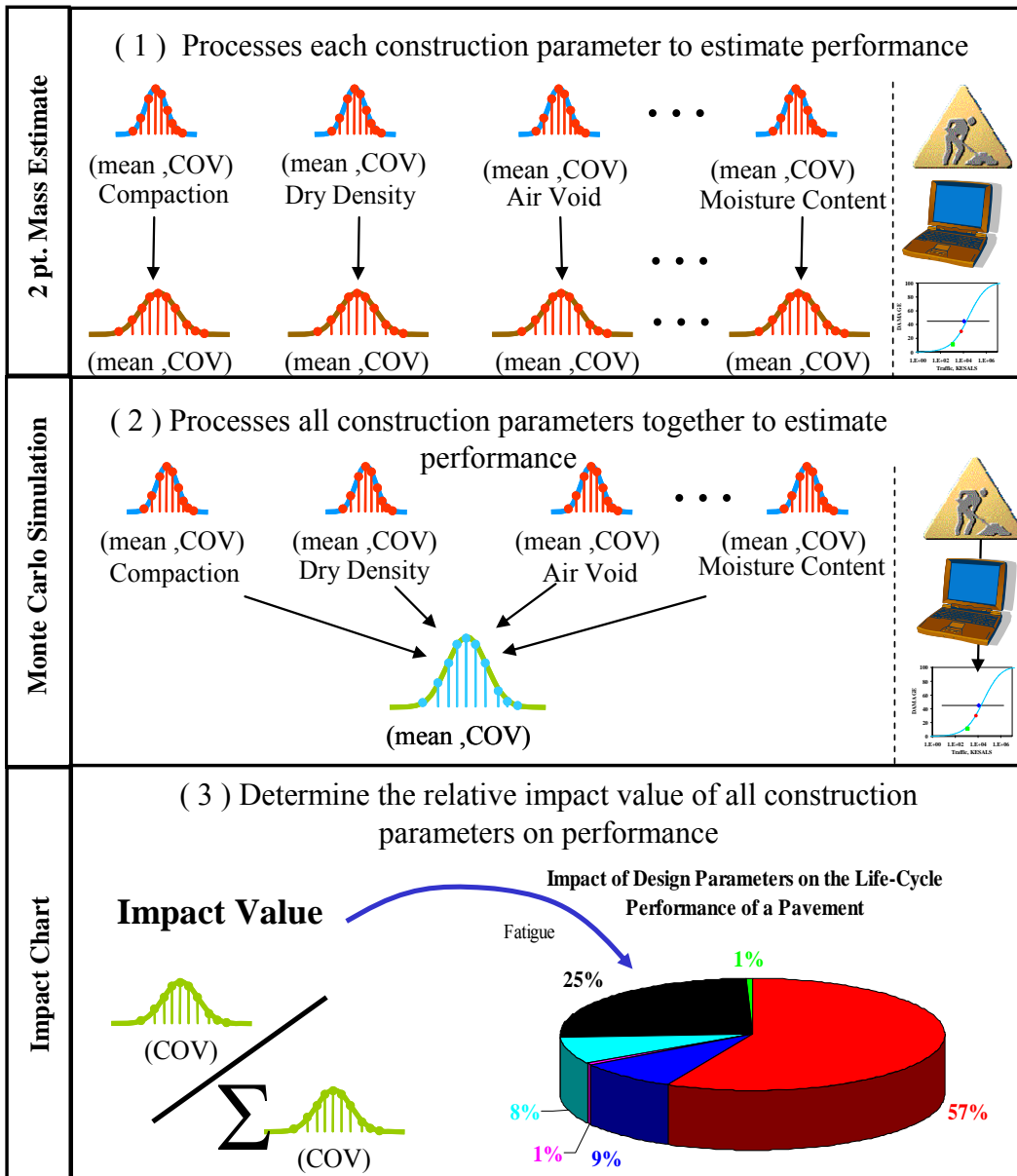
Figure A.2 - Probabilistic Analysis Process used in Developing the Impact Chart

of a performance model with respect to the other construction parameters. The values that are entered into the pie charts are called normalized impact values, shown in Equation A.2:

$$NIV_i = \frac{COV_i}{\sum_{i=1}^{n} COV_i} \tag{A.2}$$

where *NIV* is the normalized impact value for construction parameter *i* and the COV_i is the coefficient of variation of the pavement performance model for construction parameter *i*. By

placing all of the *NIV*s in a pie chart, an impact chart can be created to identify significant construction parameters. The figure in the last part of Figure A.2 is a representation of an impact chart, where each parameter is represented by an impact value. Parameters with large impact values indicate significant parameters and should be focused on in-controlling performance. However, parameters with very low impact values indicate no significance, and resources for controlling variability should be focused elsewhere. If one is interested in changing the mean and COV of the performance indicator associated with these parameters, she/he should focus on reducing the COV for those parameters with significant impact values, therefore reducing performance variance.

Planning Process - Optimization Process to Identify Significant Parameters

The process presented thus far illustrates the procedure to determine the impact of construction variability on the variability of performance using the impact chart. The next step is to demonstrate the optimization process in the program.

Figure A.3 illustrates the use of the impact chart to identify significant parameters through an optimization process. Initially, input information, as shown in Figure A.3, is based on the mean and variance of each construction constituent found either in historical data or required specifications. These constituents are then simulated in the statistics-based algorithm by varying the inputs according to a normal distribution and using the simulated values in material models to estimate layer moduli. The results from the material models are then used to estimate pavement performance. The output is the pavement performance based on the input values and the performance variance based on the variability of the input. If the simulated pavement life meets the design specifications, the algorithm terminates and significant impact values are
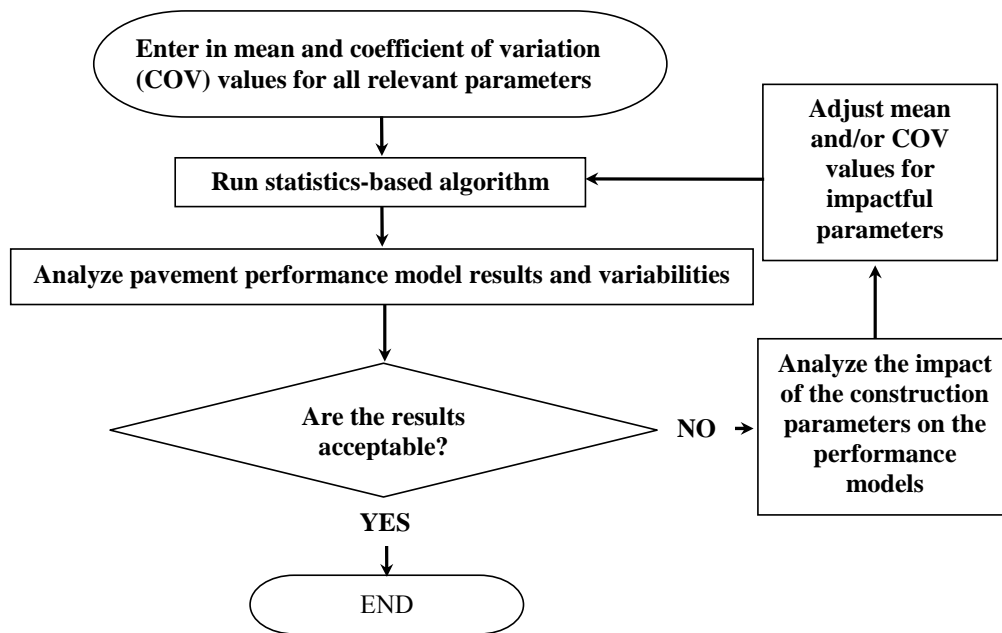
Figure A.3 - General Flow of Optimization Process

identified from the impact chart, and provided to those involved in the construction and inspection. If the variability in the performance is larger than specified, the COV values for parameters that are identified as significant are reduced, and the analysis is repeated. This process continues until the pavement performance specifications are met. The program provides means to adjust the number of significant parameters that are reduced, the increment of reduced variability after each iteration, and constraint of the minimum value of variability. The process is part of the planning phase of this program. The next phase is construction.

Construction Process - Quality Control Process

In planning, the optimization process identifies the significant parameters for inspectors to focus on. Along with identifying significant parameters, the number of necessary samples for each parameter is determined based on the optimization process.

Number of Samples and Sampling Frequencies

The process of developing the number of samples based on the COV of each parameter is thoroughly documented in Research Report 0-4046-3 (Haggerty et al., 2005). Equation A.3 represents the sample size equation used in the program.

$$n = \left(\frac{(Z_\alpha + Z_\beta) \times COV}{e} \right)^2 \tag{A.3}$$

where *n* is the sample size, *e* represents the tolerable error or tolerance, *COV* represents the coefficient of variation for an individual construction parameter, Z_α defines the normalized standard deviation value based upon the level of significant (α), and Z_β defines the normalized standard deviation value based upon the level of significant (β) found as the standard deviation divided by the mean.

For the purpose of this report, α and β are related to confidence level of the seller (contractor) and buyer (TxDOT), respectively. Zhang et al. (2001) presents definitions of those parameters as follows:

- Seller's Risk (α): The risk of rejecting "good" material. In highway construction this is associated with the risk of a contractor having good material rejected by the owner.
- Buyer's Risk (β): The risk of accepting "bad" material at reduced or full payment. In highway construction, this risk is associated with the owner's risk of accepting what is actually bad material.

The α-risk affects the contractor because it is probable that the agency may reject, what is in fact, acceptable work. The β-risk affects the agency because it is probable that the agency may accept, what is in fact, unacceptable work. The true meaning of risk is how much one is willing to lose in terms of dollars if an action is taken.

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After determining the sample size, the testing frequencies can be determined. Zhang et al. (2001) shows example of two ways of determining testing frequency:

a) *Time-based testing frequency:* TF = daily production / sample size
b) *Quantity-based testing frequency:* TF = batch quantity / sample size

Once the testing frequency is determined, control charts can be used to provide quality control by the inspector.

Control Charts

Control chart is one way of conducting inspection. Control charts help identify instability and unusual circumstances in production processes. This implies that, based upon allowable variances, inspectors can randomly sample road specimens and determine whether or not the pavement, statistically, will be stable over time (in-control or out-of-control, respectively).

To assist in monitoring the important parameters during construction, the program provides control charts (CC) for the mean and COV of a specified parameter. The CC based on the mean has three limits: a) the center line (CL) defined by the mean and b) upper and lower control limits (UCL, LCL) defined by one deviation from the mean. The CC for the COV shows the trend of the QC variability with respect to the allowable COV value specified in planning. Research Report 0-4046-3 (Haggerty et al., 2005) depicts the development, rules and examples of using control charts.

Cost Analysis

With the information that has been described, thus far, a quantitative value can be provided for inspection costs, which will be discussed in this section. Production expenditures, due to rehabilitation and maintenance, are intuitively calculated in a qualitative manner, because the basic concept of the program is to minimize variability thereby increasing the longevity of pavement.

The program estimates the minimum number of tests to be run for inspecting a single parameter. Hence, for each test run there is a corresponding cost, which can be related as a unit price (i.e. \$10.00/Nuclear Density Gauge). If the unit price is known for each test to be run, then the total inspection costs can be found using a simple mathematical operation:

$$TotalCost_{inspection} = \sum_{i=1}^{m} C_i n_i \qquad (A.4)$$

where C_i is the unit price for parameter i and n_i is the sample size for parameter i. Typical costs for some parameters of ACP, base and subgrade layers in Texas are shown in Table A.1. These costs are estimated for the entire state of Texas. The program can modify this program if necessary.

Table A.1 - Typical Inspection Tests & Costs for Texas Pavements

STANDARD		TEST	Unit	STATEWIDE AVG.		2 Year Avg.
				FY 2002	FY 2003	
Tex	103	Moisture Content	each	$6.00	$27.00	$16.50
Tex	106	Plasticity Index	each	$33.75	$71.00	$52.38
Tex	110, Pt1	Gradation	each	$32.50	$60.00	$46.25
Tex	110, Pt2	Gradation	each	-	$150.00	$150.00
Tex	113	M-D Curve for Base	each	$162.50	$330.00	$246.25
Tex	114	M-D Curve for Base	each	$155.00	$330.00	$242.50
Tex	115	Nuclear Density	hour	$31.50	$37.50	$34.50
Tex	116	Wet Ball	each	$135.00	$200.00	$167.50

APPENDIX B – MODELS USED IN RECIPPE

PERFORMANCE MODELS

The three performance models investigated in the study were:

1) Permanent deformation in the ACP layer (Finn et al., 1984):

   ACP layers that are less than 6 in. thick

$$\log RR = -5.617 + 4.343 \log w_0 - 0.167 \log(N_{18}) - 1.118 \log \sigma_c \qquad \text{(B.1)}$$

   ACP layers equal to or greater than 6 in. in thickness:

$$\log RR = -1.173 + 0.717 \log w_0 - 0.658 \log(N_{18}) + 0.666 \log \sigma_c \qquad \text{(B.2)}$$

where RR is the rate of rutting in micro-inches (1 μin. =10^{-6} in.) per axle load repetition, w_0 is the surface deflection in mil (1 mil=10^{-3} in.), σ_c is the vertical compressive stress within the AC layer in psi, and N_{18} is the equivalent 18-kip single-axle load in 10^5 ESALS.

2) Permanent deformation in the subgrade (Huang, 1993):

$$N_d = f_4 (\varepsilon_c)^{-f_5} \qquad \text{(B.3)}$$

where N_d is the allowable number of load repetitions to prevent rutting, ε_c is the compressive strain at the top of subgrade and parameters f_4 and f_5 are design constants.

3) Pavement failure as a result of fatigue cracking (Huang, 1993):

$$N_f = f_1 (\varepsilon_t)^{-f_2} (E_{ACP})^{-f_3} \qquad \text{(B.4)}$$

where N_f is the allowable number of load repetitions to prevent fatigue cracking, ε_t is the tensile strain at the bottom of the ACP layer, E_{ACP} is the elastic modulus of asphalt-concrete layer (in psi), and parameters f_1 through f_3 are design constants.

Table B.1 provides a list of coefficients for performance models in Equations B.3 and B.4. These models can be used in the mechanistic analysis developed for this project and can be incorporated into the program. The calibration and validation of these models are outside the scope of this project.

MATERIAL MODELS

As illustrated in Appendix A, the methodology of the program depends on the material characteristics models and pavement performance models. Throughout the research of this project, several material models were identified that could be used in the program.

ACP Models

The material models selected for the ACP layer are summarized in Table B.2. The Witczak 1982 model presented in Equation B.5, was first used in the study to determine the feasibility in the use of the methodology developed in this project.

Table B.1- Fatigue Cracking Model and Rutting Model Parameters used to Determine Remaining Life of a Flexible Pavement

Model	Fatigue Cracking Model $N_f = f_1 (\varepsilon_t)^{-f_2} (E_{AC})^{-f_3}$			Subgrade Rutting Model $N_d = f_4 (\varepsilon_c)^{-f_5}$	
	f_1	f_2	f_3	f_4	f_5
Asphalt Institute	0.0796	3.291	0.854	1.365×10^{-9}	4.477
Shell	0.0685	5.671	2.363	6.15×10^{-7}	4.0
Shell (50% reliability)	-	-	-	6.15×10^{-7}	4
Shell (85% reliability)	-	-	-	1.94×10^{-7}	4
Shell (95% reliability)	-	-	-	1.05×10^{-7}	4
Illinois Dept. of Transportation	5E-6	3	-	3	-
Transport and Road Research Laboratory	1.66×10^{-10}	4.32	-	4.32	-
U.K Research & Road Research Laboratory (85% reliability)	-	-	-	6.18×10^{-8}	3.95
University of Nottingham	-	-	-	1.13×10^{-6}	3.571
Belgian Road Research Center	4.92×10^{-14}	4.76	-	3.05×10^{-9}	4.35
New Mechanistic Design Guide (MDG) (National Calibration Factors[1]) for top –bottom cracking $$k^*_1 = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{(11.02 - 3.49 h_{AC})}}}$$ for bottom-top cracking, $$k^*_1 = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{(15.676 - 2.8186 h_{AC})}}}$$ h_{AC} is thickness of ACP layer and C is laboratory to field adjustment factor	$0.00432 k^*_1 C$	3.9492	1	-	-

Note: constants are for US customary units

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Table B.2 - Summary of Material Models for ACP Layer

Witczak 1982 Model (Asphalt Institute, 1982)	$\log E_{AC} = 5.553833 + 0.028829 \dfrac{P_{200}}{f^{0.17033}} - 0.03476 V_V$ $+ 0.070377 \eta + 0.000005 t_p^{(1.3+0.49825 \log f)} P_{ac}^{0.5} -$ $0.00189 t_p^{(1.3+0.49825 \log f)} \dfrac{P_{ac}^{0.5}}{f^{1.1}} + 0.931757 f^{-0.02774} + \text{э}$ E_{AC} = dynamic modulus of AC mix (in psi), η = bitumen viscosity (in 10^6 poise) at 70°F, f = load frequency (in Hz), V_v = percent air voids in the mix by volume, P_{ac} = percent effective bitumen content by volume, and P_{200} = percent passing No. 200 sieve by total aggregate weight.
Witczak 1995 Model (Ayres and Witczak, 1998)	$\log \mid E_{AC} \mid = -1.249937 + 0.029232 P_{200} - 0.001767 (P_{200})^2$ $+ 0.002841 P_4 - 0.058097 V_a - 0.808808 \dfrac{V_{beff}}{(V_{beff} + V_a)}$ $+ \dfrac{\left[3.871977 - 0.0021 P_4 + 0.003958 P_{38} - 0.000017 (P_{38})^2 + 0.00547 P_{34}\right]}{1 + e^{(-0.603313 - 0.31335 \log(f) - 0.393532 \log(\eta))}}$ E_{AC} = dynamic modulus of AC mix (in 10^5 psi), η = bitumen viscosity (in 10^6 poise) at 70°F, f = load frequency (in Hz), V_a = percent air voids in the mix by volume, V_{beff} = percent effective bitumen content by volume, and P_{200} = percent passing No. 200 sieve by total aggregate weight, P_4 = cumulative percent retained No. 4 sieve by total aggregate weight, P_{34} = cumulative percent retained No. 3/4 sieve by total aggregate weight, and $P_{3/8}$ = cumulative percent retatined No. 3/8 sieve by total aggregate weight.
Witczak Model 2000 (Witczak, 2003)	$\log \mid E_{AC} \mid = -0.261 + 0.008225 P_{200} - 0.00000101 (P_{200})^2$ $+ 0.00196 P_4 - 0.03157 V_a - 0.415 \dfrac{V_{beff}}{(V_{beff} + V_a)}$ $+ \dfrac{\left[1.87 + 0.002808 P_4 + 0.00000404 P_{38} - 0.0001786 (P_{38})^2 + 0.0164 P_{34}\right]}{1 + e^{(-0.716 \log(f) - 0.7425 \log(\eta))}}$
Hirsch Model (Bonaquist, R., 2005)	$\mid E^* \mid_{mix} = P_c \left[4{,}200{,}000 \left(1 - \dfrac{VMA}{100}\right) + 3 \mid G^* \mid_{binder} \left(\dfrac{VFA \, x VMA}{10{,}000}\right) \right] + \dfrac{1 - P_c}{\left[\dfrac{\left(1 - \dfrac{VMA}{100}\right)}{4{,}200{,}000} + \dfrac{VMA}{3 VFA \mid G^* \mid_{binder}} \right]}$ $P_c = \dfrac{\left(20 + \dfrac{VFA \, x 3 \mid G^* \mid_{binder}}{VMA}\right)^{0.58}}{650 + \left(\dfrac{VFA \, x 3 \mid G^* \mid_{binder}}{VMA}\right)^{0.58}}$ VMA = Voids in mineral aggregates (%), VFA = Voids filled with asphalt (%), and $\mid G^* \mid_{binder}$ = shear complex modulus of binder (psi)

$$\log E_{AC} = 5.553833 + 0.028829 \frac{P_{200}}{f^{0.17033}} - 0.03476 V_V$$
$$+ 0.070377 \eta + 0.000005 t_p^{(1.3+0.49825 \log f)} P_{ac}^{0.5} -$$
$$0.00189 t_p^{(1.3+0.49825 \log f)} \frac{P_{ac}^{0.5}}{f^{1.1}} + 0.931757 f^{-0.02774} + \ni \qquad (B.5)$$

where E_{AC} = dynamic modulus of AC mix (in psi), η = bitumen viscosity (in 10^6 poise) at 70°F, f = load frequency (in Hz), V_v = percent air voids in the mix by volume, P_{ac} = percent effective bitumen content by volume, and P_{200} = percent passing No. 200 sieve by total aggregate weight.

The model was calibrated based on limited Texas sections. Research Report 0-4046-3 provides detail on the models and calibration process. The other models were subsequently identified and any of these which can be used in RECIPPE.

Base and Subgrade Models

Several material models were discovered during the literature review phase of this project for the base and subgrade layers. Some of the models are summarized in Table B.3. All these models can be generalized by the following constitutive model:

$$M_R = k_1 P_a \left[\frac{\theta}{P_a}\right]^{k_2} \left[\frac{\tau_{oct}}{P_a}\right]^{k_3} \qquad (B.6)$$

where $\theta = \sigma_1 + \sigma_2 + \sigma_3$ = bulk stress; τ_{oct} = octahedral shear stresses; P_a = atmospheric pressure, and k_1, k_2 and k_3 are multiple regression constants evaluated from resilient modulus test data from equations developed from a regression procedure that relate the regression constants to construction parameters.

One of the biggest challenges in this study was finding regression constants that relate construction parameters. The first success in finding such parameters was from a study carried out for Georgia DOT. Santha (1994) presented equations for regression constants defined for both granular and cohesive soils. Those equations were used in most part of the research study and are set as the default values in the program. At the latter part of the study, regression equations from Minnesota and Indiana DOTs were found. The regression equations for the material model parameters are summarized in Tables B.4 and B.5.

Table B.3 - Summary of Material Models
for Base and Subgrade Layers

K - Θ Model	$M_R = k_1 \theta^{k_2}$
Uzan Model	$M_R = k_1 \theta^{k_2} \sigma_d^{k_3}$ $\sigma_d = \sigma_1 - \sigma_3 =$ deviator stress
Octahedral Shear Stress Model	$M_R = k_1 P_a \left[\dfrac{\theta}{P_a} \right]^{k_2} \left[\dfrac{\tau_{oct}}{P_a} \right]^{k_3}$
Itani Model	$M_R = k_1 P_a \left[\dfrac{\theta}{3} \right]^{k_2} \sigma_d^{k_{3a}} \sigma_3^{k_{3b}}$ where $\sigma_3 =$ confining stress; k_{3a} and k_{3b} are multiple regression constants
UTEP Model	$M_R = k_1 \theta^{k_2} (\varepsilon_a)^{k_3}$ $\varepsilon_a =$ induced resilient axial strain
UT-Austin Model	$M_R = k_1 \theta^{k_2} \sigma_3^{k_3}$ $\sigma_3 =$ confining stress
Bilinear Approximation (Arithmetic Model)	$M_R = k_1 + k_{3a} (k_2 - \sigma_d)$ when $\sigma_d < k_2$ $M_R = K_1 + k_{3b} (\sigma_d - k_2)$ when $\sigma_d > k_2$

Granular Soils	$Log(k_1) = 3.479 - 0.07MC + 0.24MCR + 3.681COMP + 0.011SLT + 0.006CLY$ $$-0.025SW - 0.039DEN + 0.004\left(\frac{SW^2}{CLY}\right) + 0.003\left(\frac{DEN^2}{S40}\right)$$ MCR represents the ratio of moisture content (MC) to optimum moisture content, COMP is the degree of compaction and SATU is the degree of saturation, S40 represents the percent passing sieve #40, SLT is the percent of silt, CLY is the percent of clay, SW is the percent of swell value, SH is the percent of shrinkage, DEN is the maximum dry density (in pcf) and CBR is the California bearing ratio
	$k_2 = 6.044 - 0.053OMC - 2.076COMP + 0.0053SATU - 0.0056CLY + 0.0088SW$ $$-0.0069SH - 0.027DEN + 0.012CBR + 0.003\left(\frac{SW^2}{CLY}\right) - 0.31\frac{(SW+SH)}{CLY}$$ OMC is the optimum moisture content
	$k_3 = 3.752 - 0.068MC + 0.309MCR - 0.006SLT + 0.0053SLY + 0.026SH$ $$-0.033DEN - 0.0009\left(\frac{SW^2}{CLY}\right) + 0.00004\left(\frac{SATU^2}{SH}\right) - 0.0026CBR(SH)$$
Cohesive Soils	$Log(k_1) = 19.813 - 0.045OMC - 0.131MC - 9.171COMP + 0.0037SLT + 0.015LL$ $$-0.016PI - 0.021SW - 0.052DEN + 0.00001S40(SATU)$$ PI and LL values, which stand for the plasticity index and liquid limit, respectively
	$k_2 = 0$
	$k_3 = 10.274 - 0.097*MOIST - 1.06*MCR - 3.471COMP + 0.0088S40$ $$-0.0087PI + 0.014SH - 0.046*DEN$$

Table B.5 - Regression Equations of Material Models for Subgrade Layers Developed Based on Research of Transportation Agencies of Minnesota and Indiana

Minnesota DOT (Uzan Model)	**Cohesive Soils**	$k_1 = 5770.8 - 520.98DEN^{0.5} - 3941.8MC^{0.5} + 33.1PI - 36.62LL - 17.93P200$ MC is the moisture content, DEN is the maximum dry density (in pcf), P200 represents the percent passing sieve #200, PI and LL values stand for the plasticity index and liquid limit, respectively
		$k_2 = 5409.9 - 306.18DEN^{0.1} - 82.63MC + 0.033PI + 0.138SAND - 0.041LL$ SAND is the percent of SAND
		$k_3 = -5.334 + 0.000316DEN^3 + 9.686MC - 0.054PI + 0.046LL + 0.022P200$
Indiana DOT (Equation 3.10)	**Fine-grained Soils**	$Log(k_1) = 6.660876 - 0.22136OMC - 0.04437MC - 0.92743MCR - 0.06133DEN$ $+ 10.64862COMP + 0.328465SATU - 0.04434SAND - 0.04349SLT$ $- 0.01832CLY + 0.027832LL - 0.01665PI$ MCR represents the ratio of moisture content (MC) to optimum moisture content (OMC), COMP is the degree of compaction and SATU is the degree of saturation, SLT is the percent of silt, CLY is the percent of clay, and SW is the percent of swell value
		$k_2 = 3.952635 - 0.33897OMC + 0.076116MC - 2.45921MCR - 0.06462DEN$ $+ 6.012966COMP + 1.559769SATU + 0.020286SAND + 0.002321SLT$ $+ 0.011056CLY + 0.077436LL - 0.05367PI$
		$k_3 = 2.634084 + 0.12447OMC - 0.09277MC + 0.366778MCR - 0.01168DEN$ $- 1.32637COMP + 1.297904SATU - 0.01226SAND - 0.00512SLT$ $+ 0.00492CLY - 0.05083LL + 0.018864PI$

**APPENDIX C – STRATEGY TO UTILIZE RECIPPE FOR QUALITY ASSURANCE**

The methodology presented in this research provides a means of assessing construction consistency for a flexible pavement system. Thus far, the methodology and the algorithms were discussed and documented. Also, material models were presented. To assist in utilizing RECIPPE, a strategy is provided in this chapter. This strategy has been discussed in the previous reports, but since this reports focus on implementation, the content is repeated in this chapter.

The main purpose of this research was developing a tool to ultimately optimize effectiveness of inspection and testing resources during construction given TxDOT limited resources by:

1. Estimating if variability of construction parameters meets the owner's expectations for a reasonably uniform pavement life.
2. Identifying the construction parameters to focus on during construction inspection, in order to reduce pavement life variance and increase reliability.
3. Tracking and identifying out-of-control procedures during construction.
4. Improving construction practices through process control.

Figure C.1 outlines the overall purpose of RECIPPE. The first part of the figure shows a representation of pavement performance. Pavement performance can be specified based on the level of distress with time. Therefore, for a certain specified time period, a pavement is designed to withstand a certain level of distress caused be traffic loading and environmental factors. However, due to variability in construction practices along the length of the pavement, the pavement quality varies from one section to the next, and as a result damage is accumulated faster than estimated in the inferior sections, and therefore, the life of the pavement is shortened.

The primary objective for this research was to develop a tool to minimize variability of performance to ensure that pavement life is achieved based on design specification (listed in the right side of Figure C.1). To address this objective, the strategy was to develop a tool that can be used to identify and track pavement properties for quality control. In this case, pavement properties are the layer thickness and layer moduli. These parameters are the main components used in estimating the pavement performance. For each of these parameters, certain variability exists, and depending on the pavement system, these parameters can contribute differently to performance. This means that by identifying which of these parameters is significant and by controlling the variability of those parameters, variability of performance can be managed. To implement this strategy to meet the objective, RECIPPE was developed to identify significant pavement properties and provide a process control tool for quality assurance.
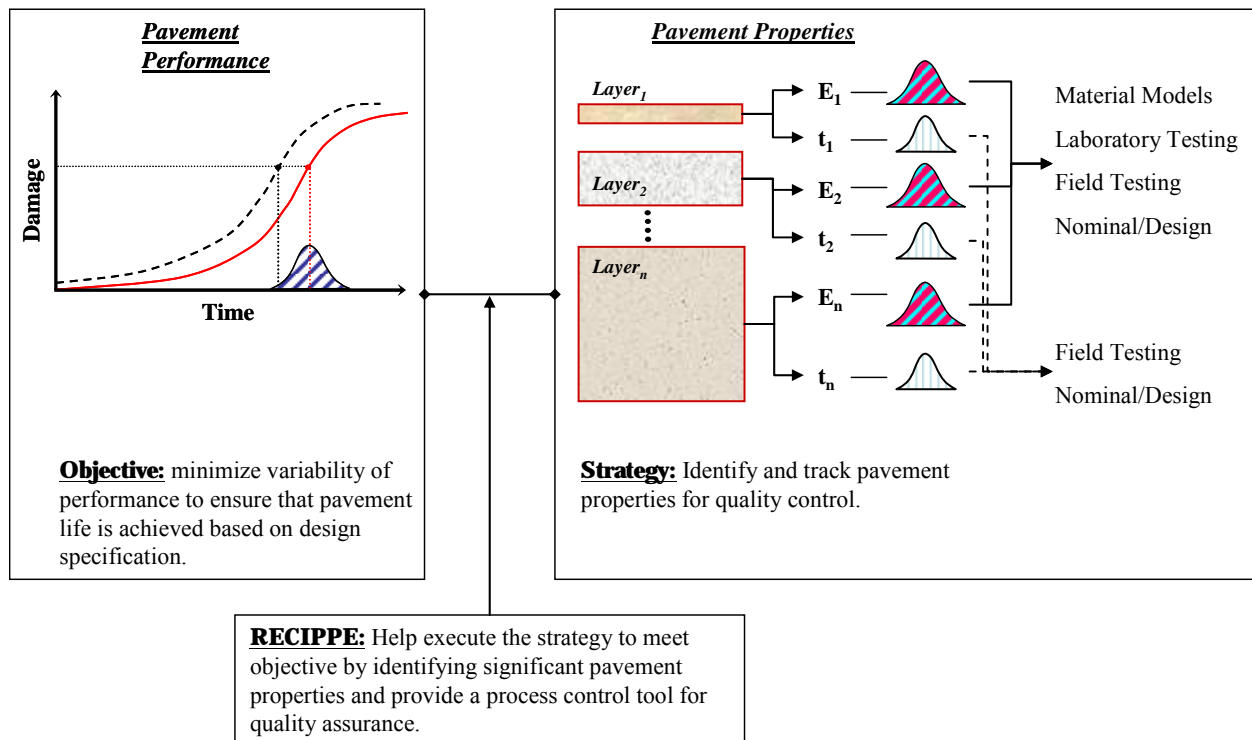
Figure C.1 - Process of using RECIPPE to Ensure Uniform Pavement by Monitoring Pavement Layer Information

In order to present different ways that RECIPPE can be utilized, it is beneficial to first summarize the different types and levels of input that can be incorporated into the program. Table C.1 provides a summary of inputs categorized by levels according to the type of data used. In this table the input levels are divided into three categories for each of the pavement layer properties. Level 1 is designated for design values. This is data that is easily obtainable and requires neither field nor laboratory efforts. This type of input is best used when no other information is provided or to supplement the input to RECIPPE since pavement layer information for all layers is required to carryout the analysis. Level 2 and Level 3 inputs require field and laboratory measurements. Both these levels of input are necessary when a significant pavement property is identified. In most cases, Level 2 input indicate direct measurements of layer property and Level 3 input requires the use of material models that is based on construction parameters to estimate layer properties.

For the layer thickness, the ACP layer can be measured from cores and or Ground Penetrating Radar (GPR), and the base and subgrade layer can be measured form cores or Dynamic Cone Penetrometer (DCP). For the ACP modulus the information can be provided based on V-meter test using cores and or PSPA field measurements (Level 2) and material model such as those presented in Table B.2. Finally, the base and subgrade modulus can be measured using devices such as the Dirt Seismic Pavement Analyzer (DSPA) or an equivalent system in the field and or laboratory testing such as resilient modulus with in-situ material from the field (Level 2). The DSPA is one tool that can be used for quality control to measure the elastic moduli of base and

Table C.1 - Input Levels for Estimating Pavement Layer Properties

Material Property	Input	Type of Data	Methods
ACP Thickness	Level 1	Design	Nominal
	Level 2	Measured	Cores
	Level 3		GPR
Base and Subgrade Thickness	Level 1	Design	Nominal
	Level 2	Measured	Cores
	Level 3		DCP
ACP Modulus	Level 1	Design	Nominal
	Level 2	Measured	Cores (V-Meter)
			PSPA
	Level 3	Material Model	Construction parameters such as Gradation and volumetric information
Base and Subgrade Modulus	Level 1	Design	Nominal
	Level 2	Measured	DSPA
		Material Model	DSPA and assumed material parameters
		Measured & Material Model	DPSA & Resilient Modulus
	Level 3	Material Model	Construction parameters such as Gradation and volumetric information

subgrade layers. For Level 3 input, material models, such as those presented in Figures B.3 through B.5, can be used for estimating the layer moduli.

RECIPPE is separated into two phases: planning and construction. Figure C.2 is a flowchart of the progression of utilizing different levels of inputs in RECIPPE. For the planning phase, a dry-run can be initially carried out based on Level 1 input. Level 1 input is based on the pavement system design values with their associated variability, which can be assumed base on experience or historical information. Based on the results of the dry-run, significant pavement parameters can be identified. This allows users to decide on the input levels to use when starting the analysis is planning mode. Level 1 inputs can be used for the parameters not found significant. The inputs for the more significant parameters can be measured based on the Levels 2 and 3 protocols. Once the levels of inputs are defined, RECIPPE can be processed in planning mode followed by construction mode.

In the construction phase, the parameters that are identified as significant are used to determine a set of sampling frequencies for inspectors to use in control charts to ensure quality of the construction process in an optimized manner.

Dry Run		
Inputs Based on Level 1 with assumed variability	Identify Significant Pavement Layer Properties	Decide on Levels of Input for Significant Pavement Layer Properties (Levels 1, 2 & 3)

Planning Phase
(Identify Most Impactful Construction Parameters)

Construction Phase
(Quality assurance using Control Charts)
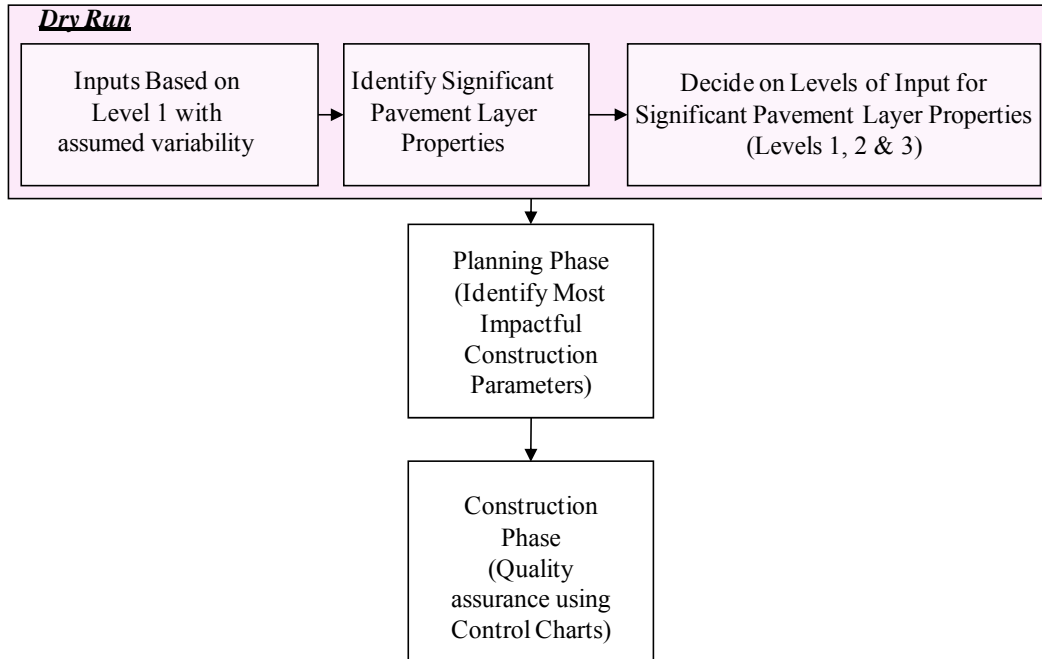
Figure C.2 - Flowchart of RECIPPE to Ensuring Uniform Pavement Construction

Three general scenarios are presented to illustrate how RECIPPE can be used at different stages and with different levels of input. Table C.2 presents a general scenario for a pavement where the subgrade layer properties were identified as significant. The information in the table presents the levels of input for the layer moduli. For this scenario, the input to the RECIPPE for the top layers can be provided as Level 1 input. However, the input for the subgrade layer moduli can be provided either based on Level 2 input or Level 3 input. Based on Table C.2, Level 2 input could be a direct field measurement using a device such as the DSPA. This would measure the elastic modulus of the layer and thereby uses the linear elastic algorithm in the program for the subgrade layer. The other Level 2 option is to combine the field measurements from DSPA with laboratory tests such as the resilient modulus test that is used for determining the k-parameters of the nonlinear model. The modulus from the DSPA can be used to calculated k_1 and the results of the resilient modulus for k_2 and k_3 parameters. This allows the constitutive model listed in Table C.2 as the material model for the analysis. The last input level is Level 3, which requires the use of constitutive models that uses regression equations to estimate the k-parameters. These regression equations are functions of construction parameters. Appendix B provides a list of regression equations from various regions in the country that can be used to estimate the k-parameters. At the present time, due to the lack of comprehensive models for Texas, it is not recommended to use Level 3 input.

The next scenario is for a pavement system where base layer properties were identified as significant. In this case, the input to RECIPPE for the top layer can be provided as Level 1 input, and input to the subgrade layer could be the results from scenario one represented as a mean and standard deviation. For the base layer moduli (significant parameter) information from either Level 2 input or Level 3 input can be used. The information in Table C.3 presents the levels of

Table C.2 - Input Levels of Design Parameters for Subgrade Layer

Parameter	Input	Material Type	Methods
Thickness	Level 3	-	Cores
Modulus	Level 2	Linear Elastic	DSPA used in the field for quality control to measure layer moduli directly
		Nonlinear based on Constitutive Model	- DSPA is used to Estimate k_1 - k_2, and k_3 are assume from literature based on material quality
		$M_R = k_1 P_a \left[\dfrac{\Theta}{P_a} \right]^{k_2} \left[\dfrac{\sigma_d}{P_a} \right]^{k_3}$	- DSPA is used to Estimate k_1 - Resilient Modulus performed in the laboratory on in-situ material to determine k_2, and k_3
	Level 3	Nonlinear based on Constitutive Model (same as equation in Level 2)	k_1, k_2, k_3 are estimated based on regression equations that are functions of construction parameters

Note: 1) ACP and Base layer information are based on design values.

Table C.3 - Input Levels of Design Parameters for Base Layer

Parameter	Input	Material Type	Methods
Thickness	Level 2	-	Cores
	Level 3		DCP can be used to estimate thickness value
Modulus	Level 2	Linear Elastic	DSPA used in the field for quality control to measure layer moduli directly
		Nonlinear based on Constitutive Model	- DSPA is used to Estimate k_1 - k_2, and k_3 are assume from literature based on material quality
		$M_R = k_1 P_a \left[\dfrac{\Theta}{P_a} \right]^{k_2} \left[\dfrac{\sigma_d}{P_a} \right]^{k_3}$	- DSPA is used to Estimate k_1 - Resilient Modulus performed in the laboratory on in-situ material to determine k_2, and k_3
	Level 3	Nonlinear based on Constitutive Model (same as equation in Level 2)	k_1, k_2, k_3 are estimated based on regression equations that are functions of construction parameters

Note: 1) ACP layer information are based on design values.
2) Subgrade layer information is based on either design values or actual field data estimated in Scenario 1 from either level 2 or level 3 inputs.

input for both the layer thickness and the layer moduli. The two main properties for the base layer are the thickness and layer moduli. For the base layer thickness, the monitoring tool can either be to measure cores directly (Level 2) or DCP field testing (Level 3).

Based on Table C.3, Level 2 input for the base layer moduli is similar to the Level 2 input for the subgrade layer. This can be a direct field measurement using DSPA (or an equivalent device) or a combined field measurements from DSPA and laboratory tests using the resilient modulus results. Also, Level 3 input is same as that presented in for Level 3 input of the subgrade layer, which is to use regression equations to estimate the k-parameters of the constitutive model.

Table C.4 - Input Levels of Design Parameters for ACP Layer

Parameter	Input	Material Type	Methods
Thickness	Level 2	-	Cores
	Level 3		GPR
Modulus	Level 2	Linear Visco-elastic	V-Meter to measure layer elastic moduli directly from cores Lab testing to determine the viscous properties of the material
			PSPA used in the field for quality control to measure layer moduli directly Lab testing to determine the representative viscous properties of the material
	Level 3	Linear Visco-elastic (Material Model such as regression equations based on Master Curve)	Construction parameters such as Gradation and volumetric information

Note: 1) **Base and subgrade layer information is based on either design values, level 1input, or actual field data estimated in Scenarios 1 and 2 from either level 2 or level 3 input.**

The last scenario presented involves an analysis where ACP layer properties were identified as significant. Input levels for the top layer are summarized in Table C.4. The thickness of the top layer can be monitored either by cores or GPR, which are designated as Levels 2 and 3, respectively. For the layer moduli Level 2 input, two options are presented: a) V-meter measurements of cores to estimate layer moduli directly and b) direct measurement of the modulus in the field using the PSPA or an equivalent system. For Level 3 input the material models listed in Table B.2 can be selected to estimate the layer moduli based on construction parameters. The input for the lower layers in this scenario can be provided as Level 1 input. If any parameter of the lower layers was found significant, then the statistics from that analysis can be incorporated into this scenario.

As demonstrated from the three scenarios presented, RECIPPE can be used at different stages of a construction project and at different levels of input to monitor variability of construction. At this stage of the program, a combination of Level 1 and Level 2 inputs are recommended in the analysis until more elaborate material models can be developed and calibrated for Texas.

However, Level 3 inputs provided in the program should be investigated further since for that level, construction parameters can be related directly to performance. A training web site located at *__http://ctis.utep.edu__* makes available training modules for the program.

APPENDIX D – PROTOCOL

Protocol and Testing Process

The initial strategy was to target several sites at different districts throughout the state. For each site identified, a planning stage was setup to establish a connection with the project engineers and project managers in the district. As it turned out, the sites identified through the help from district personnel. The person from the district identified the site and gathered necessary information such as:

- The status of the project
- Test sections that will be evaluated with RECIPPE
- The level of quality management (QM) that will be carried out
- The pavement properties that will be focused on
- A time schedule to coordinate testing efforts
- The type of NDT and other testing equipment that will be used at the site
- The sampling process for laboratory testing
- The coordination of tests that will be carried out by UTEP and the test that will be handled by TXDOT

All these tasks were coordinated between engineers from TxDOT and UTEP researchers. The next aspect was to coordinate access to the site. Since several field tests were performed at each site during construction practices. A time frame was to be coordinated with the contractor given that weather permitted. Once the time frame and site specifics are set the next step was quality management.

TXDOT was to follow their current procedures for QM. UTEP was to follow QM process based on RECIPPE. Since this required extra sampling, UTEP and TxDOT coordinated the quality management process to accommodate the extra sampling required.

TxDOT's current process, of ensuring proper construction of any pavement system is based on the "Minimum Guide to Sampling and Testing." TxDOT currently tests materials at the corresponding frequencies such as those listed in Table D.1 for bases. These are the minimum sampling required. As an example, the in- place density as per Tex-115-E will be carried out in the field at locations determined by the engineer. The frequency of testing is at a minimum, each 3,000 yd^3 or 3000 lin-ft. with a minimum of 1 test per lift. This conventional method is static, and does not change depending on the type of pavement section being built. Comparatively, the number of tests provided in RECIPPE is based on the parameters that are important to the

integrity of each pavement section. Simply put, the inspector will focus on layers and construction practices that matter the most to achieve a long lasting pavement.

Table D.1 – Sample of the Minimum Sampling and Testing Recommended in the Guide Schedule for Untreated Base

Test	Test Number	Location or Time of Sampling	Frequency of Sampling	Remarks
Moisture/ Density	Tex-113-E	During stockpiling operations, from completed stockpile, or windrow (B)	Each 20,000 cu. yd.	As required by the plans.
Triaxial (A)	Tex-117-E	During stockpiling operations, from completed stockpile, or windrow (B)	Each 20,000 cu. yd.	As required by the plans. When base material is from a source where the District has a record of satisfactory triaxial results, the frequency of testing may be reduced to one per 30,000 C.Y. If any one test fails below the minimum value required, the frequency of testing will return to the original frequency of 20,000 C.Y.
In-place Density (A)	Tex-115-E	As designated by the Engineer	Each 3,000 cu. yd. or 3000 lin. ft.,min 1 per lift.	Correct the moisture contents measured by nuclear density gauge in Tex-115-E with the moisture contents determined in accordance with Tex-103-E for each different material or notable change in material and adjust the density accordingly. Materials such as RAP, gypsum and iron ore tend to bias the counts for nuclear density gauges.
Moisture Content	Tex-103-E	As designated by the Engineer	Each 3,000 cu. yd.	
Thickness	Tex-140-E	As designated by the Engineer	Each 3,000 cu. yd.	Not required where survey grade control documents compliance.

A - When this project acceptance test fails but the product is accepted, document the reasons for acceptance on the Letter of Certification of Materials Used or in the SiteManager Remarks Field.
B – Engineer will select any of these location or any combinations thereof with the provision that at least one out of ten consecutive samples will be taken at the project site (from the windrow for treated and untreated bases and embankments when possible).

The criterion that RECIPPE uses to determine the sampling number for parameters that are found important is based on the pavement design life. RECIPPE operates in two modes: a) Planning and b) Construction. The planning phase is used to select the layers and construction practices that need to be focused on during construction. The initial numbers of samples are greater for layer parameters that are identified to be most critical. The number of samples is tracked with RECIPPE in the construction mode to access the condition of the pavement during construction and to flag any parameter that may fall out of specification. If the contractor can provide a uniform and high quality product during the construction, the number of samples can be reduced. On the other hand, if the quality of the product is not reasonably uniform or if the final product is of low quality, the number of samples will increase, or in the worst case scenario, the construction will stop until the problems are resolved.

Figure D.1 provides a list of pavement layer parameters that are considered in evaluating the remaining life of the flexible pavement. For each of the pavement parameter a list of tests that can be carried out to obtain information from the laboratory or field regarding that parameter is provided.
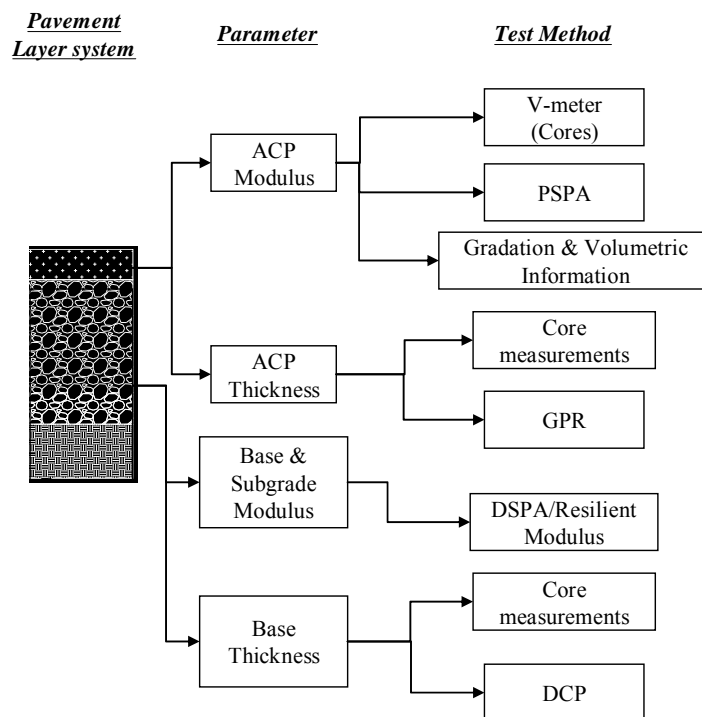
Figure D.1 – Pavement Layer Properties and Their Corresponding Test Methods

For the modulus of the ACP layer, three test methods can be used: a) direct measurement of the modulus from core specimens using a) V-meter, b) MTS testing of cores, c) direct measurement of the modulus in the field using a PSPA, and d) use gradation and volumetric information to estimate the modulus value. The last option requires measuring parameters such as a) asphalt content, b) air void content, and c) gradation. TxDOT carries out most of these tests as listed in Table D.2.

Table D.2 – Sample of the Minimum Sampling and Testing Recommended in the Guide Schedule for Asphalt-Concrete

Test	Test Number	Location or Time of Sampling	Frequency of Sampling	Remarks
Asphalt content (%) (A)	Tex-236-F	Engineer Truck Sample	Minimum of 1 per Lot	Determine correlation factors for ignition oven use at a minimum of one per project.
Voids in Mineral Aggregates (VMA)	Tex-207-F	Truck Sample Plant Produced	1 per Sublot	Does not apply to Item 342 Permeable Friction Course.
Gradation	Tex-236-F	Engineer Truck Sample	Minimum of 1 per 12 Sublots	Determine correlation factors for ignition oven use at a minimum of one per project.
Moisture Content	Tex-212-F Part II	Engineer Truck Sample	1 per project	
Lab Molded Density (A)	Tex-207-F	Truck Sample	1 per Sublot 1 per Lot for Item 342	
In-Place Air Voids (A)	Tex-207-F	Roadway	1 cores per Sublot	Two cores taken per Sublot and averaged. Does not apply to Item 342 Permeable Friction Course.

A - When this project acceptance test fails but the product is accepted, document the reasons for acceptance on the Letter of Certification of Materials Used or in the SiteManager Remarks Field.

The next parameter provided in Figure D.1 is the thickness of the ACP layer. This parameter will be measured using cores or GPR (if thickness is found as a crucial parameter by RECIPPE). Coring is a regular part of the quality management process for TxDOT, so the same equipment will be used to core any additional specimens that may be required. Plans can be made to have TxDOT's GPR available for testing.

The base and subgrade layer moduli, can be measured directly in the field with a DSPA. Alternatively, the DSPA in conjunction with the resilient modulus test can also be used to estimate the modulus value using a constitutive model incorporated into RECIPPE. Both DSPA and the resilient modulus testing can be performed by UTEP.

The last parameter listed in Figure D.1 is the thickness of the base layer. Two alternatives are provided for measuring this parameter: a) core measurements and b) DCP testing. If coring is used, then plans to have TxDOT on site to core required number of samples will be made. Alternatively, if DCP is used, then UTEP with help from TxDOT will carryout the tests.

Since this exercise is to evaluate the usefulness of RECIPPE, the frequency of testing for all parameters will be based on the project size and time on the construction site. At the time of coordinating the access to the site and based on the tests that will be carried out, a time span will be set (usually a week) where daily testing will be carried out by UTEP with minimal help from

TXDOT where appropriate. The number of testing or sampling is based on the recommendation of RECIPPE.   RECIPPE provides a set of initial and final number of sampling for each parameter identified as impacting to the remaining life of the pavement system.

Again, UTEP will coordinate the acquisition and operation of any equipment for any testing that is not carried out by the districts or is cumbersome to perform by TxDOT personnel. This will be coordinated with the Project Manager. Also, a charge number will be available under this project for any additional sampling and testing carried out both at the site and in the lab by TxDOT.

APPENDIX E – RESULTS FROM CASE STUDY 2

Table E.1 – Modulus Results Based on PSPA Testing at Loop 1 Section.

Sample Number	Lot 1	Lot 2	Lot 3	Lot 4
1	329	741	410	510
2	339	445	540	430
3	311	789	530	520
4	393	801	460	470
5	364	569	460	440
6	402	638	530	225
7	419	685	490	560
8	486	406	350	450
9	688	467	520	390
10	490	508	420	450
11	249	757	440	265
12	336	567	580	460
13	330	650	470	350
14	322	778	390	610
15	303	812	400	480
16	283	720	480	530
17	340	696	470	650
18	444	592	480	490
19	586	745	480	560
20	368	579	480	670
21	310	378	400	350
22	402	335	420	440
23	344	508	560	390
24	370	455	270	400
25	344	358	340	380
26	724	569	285	470
27	480	487	400	350
28	560	429	380	370
29	540	343	390	340
30	370	498	460	500
Average	**407**	**674**	**443**	**450**
Std. Dev.	**116**	**54**	**75**	**103**
COV	**28%**	**8%**	**17%**	**23%**

Table E.2 – Results of Master Curve Parameters for Loop 1 Section.

Master Curve Parameter	Delta	Alpha	Beta	Gamma
	1.75	1.3	-0.24	0.87

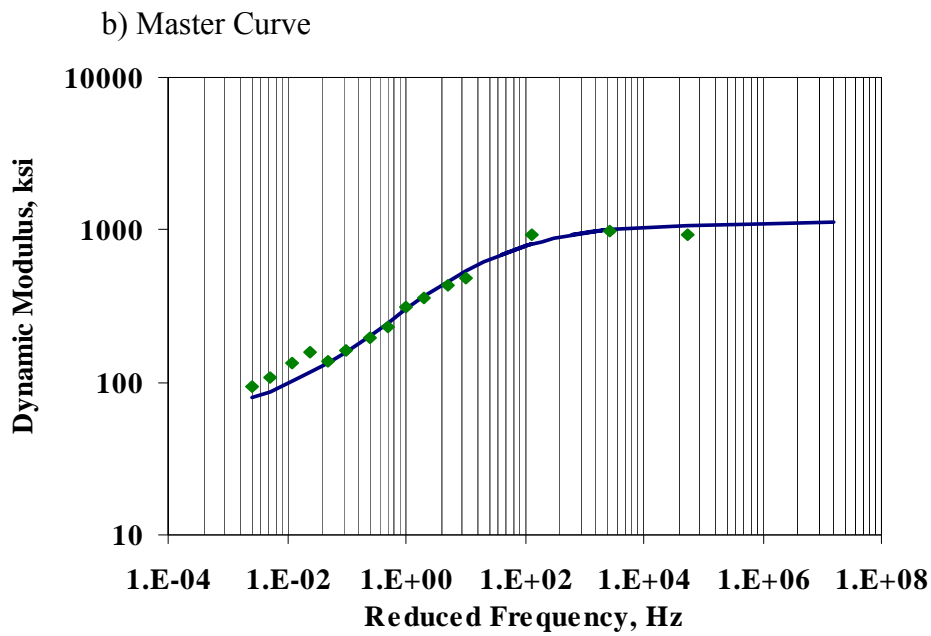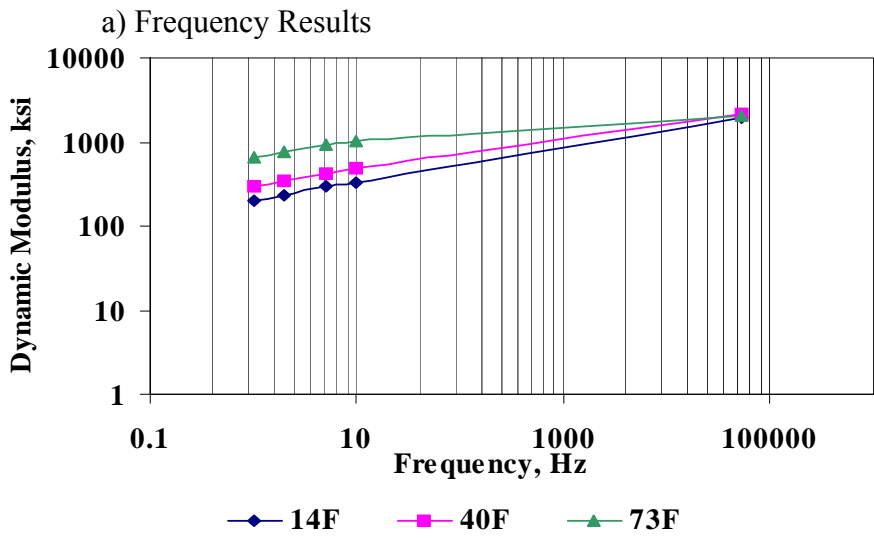a) Frequency Results

b) Master Curve

Figure E.1 – Results of the Master Curve for Loop 1 Section.

Table E.3 – Summary of Test Results from Data Collected in Lot 1 of Loop1 Section.

Sample Number	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	2.30	6.13	5.80	0	45.4	74.5	4.8
2	2.03	6.23	6.40	0	47.4	72.3	8.9
3	1.56	6.28	6.30	0	48.7	75.7	3.7
4	1.25	6.07	5.70	0	52.1	74.0	6.5
5	2.30	6.20	6.30	0	49.6	76.1	5.3
6	2.21	6.06	6.10	0	49.2	76.0	4.9
7	2.19	6.09	5.78	0	50.7	78.5	5.1
8	1.51	6.19	6.42	0	45.2	74.2	5.2
9	1.55	6.01	5.80	0	50.0	74.0	6.7
Average	**1.88**	**6.14**	**6.07**	**0**	**48.68**	**75.04**	**5.67**
Std. Dev.	**0.41**	**0.09**	**0.30**	**-**	**2.34**	**1.76**	**1.51**
COV	**21.7%**	**1.5%**	**4.9%**	**-**	**4.8%**	**2.4%**	**26.6%**

[1]- Core Samples, [2]- Loose material from hot mix

Table E.4– Summary of Test Results from Data Collected in Lot 2 of Loop 1 Section.

Sample Number	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.70	6.23	7.90	0	56.6	77.5	5.1
2	2.28	6.10	7.80	0	51.9	75.6	5.7
3	1.90	5.93	4.50	0	49.1	73.7	6.6
4	2.20	5.93	4.40	0	52.7	76.1	5.3
5	1.63	5.93	4.70	0	54.2	76.2	6.6
6	2.01	6.07	4.80	0	46.3	70.6	8.5
7	1.87	6.21	6.20	0	45.3	71.7	6.7
8	2.15	6.03	6.20	0	50.1	71.8	8.5
9	2.29	6.26	7.40	0	48.5	73.9	5.5
Average	**2.00**	**6.08**	**5.99**	**0**	**50.53**	**74.12**	**6.51**
Std. Dev.	**0.24**	**0.13**	**1.45**	**-**	**3.68**	**2.39**	**1.27**
COV	**12.1%**	**2.2%**	**24.2%**	**-**	**7.3%**	**3.2%**	**19.5%**

[1]- Core Samples, [2]- Loose material from hot mix

Table E.5 – Summary of Test Results from Data Collected in Lot 3 of Loop 1 Section.

Sample Number	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	2.00	6.24	7.50	0	50.1	73.7	7.1
2	1.60	6.33	6.60	0	43.9	71.2	7.7
3	1.40	6.22	7.30	0	48.9	74.5	7.8
4	2.00	6.14	6.50	0	50.5	74.5	5.9
5	2.33	6.30	6.70	0	49.0	75.2	7.9
6	2.21	6.21	7.50	0	47.9	72.5	6.5
7	2.18	6.06	7.80	0	48.4	73.3	8.1
8	2.10	6.14	7.20	0	50.3	74.4	6.7
9	2.01	6.01	7.10	0	47.6	72.7	5.8
Average	**1.98**	**6.18**	**7.13**	**0**	**48.51**	**73.54**	**7.05**
Std. Dev.	**0.30**	**0.11**	**0.45**	**-**	**2.02**	**1.27**	**0.89**
COV	**15.1%**	**1.7%**	**6.3%**	**-**	**4.2%**	**1.7%**	**12.6%**

1- Core Samples, [2]- Loose material from hot mix

Table E.6 – Summary of Test Results from Data Collected in Lot 4 of Loop 1 Section.

Sample Number	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.70	6.17	5.10	0	48.7	73.1	7.5
2	2.25	6.05	4.90	0	51.8	74.8	7.4
3	2.30	5.99	5.10	0	52.6	77.5	5.3
4	2.10	5.92	6.00	0	46.5	72.9	5.0
5	2.20	6.21	6.30	0	48.3	72.8	7.7
6	2.00	6.33	5.90	0	47.7	74.0	5.3
7	2.03	6.15	5.60	0	48.1	73.2	8.0
8	2.23	6.21	5.10	0	50.6	75.4	4.5
9	2.40	6.17	5.00	0	45.9	69.9	7.5
Average	**2.13**	**6.13**	**5.44**	**0**	**48.91**	**73.72**	**6.47**
Std. Dev.	**0.21**	**0.13**	**0.52**	**-**	**2.31**	**2.10**	**1.39**
COV	**9.7%**	**2.0%**	**9.5%**	**-**	**4.7%**	**2.8%**	**21.5%**

[1]- Core Samples, [2]- Loose material from hot mix

APPENDIX F – RESULTS FROM CASE STUDY 3

Table E.1 – Modulus Results Based on PSPA Testing at IH-35 Section.

Sample Number	Lot 1	Lot 2	Lot 3	Lot 4
1	987	868	928	617.0
2	675	1185	696	685.6
3	675	835	793	651.3
4	1135	903	716	874.1
5	1563	724	580	857.0
6	1168	773	1064	718.7
7	707	740	1006	641.0
8	1218	707	1199	757.6
9	905	740	812	660.5
10	823	1185	1045	582.8
11	1053	691	832	621.6
12	971	773	870	660.5
13	1415	1069	716	679.9
14	543	773	1118	660.5
15	921	1201	968	641.0
16	691	823	968	602.2
17	921	1152	968	660.5
18	740	1119	1085	1077.7
19	839	888	1102	793.3
20	736	921	1168	758.0
Average	**934**	**904**	**932**	**710**
Std. Dev.	**263**	**180**	**174**	**118**
COV	**28%**	**20%**	**19%**	**17%**

Table E.2 – Results of Master Curve Parameters for Loop 1 Section.

Master Curve Parameter	Delta	Alpha	Beta	Gamma
	1.85	1.62	-0.24	0.88

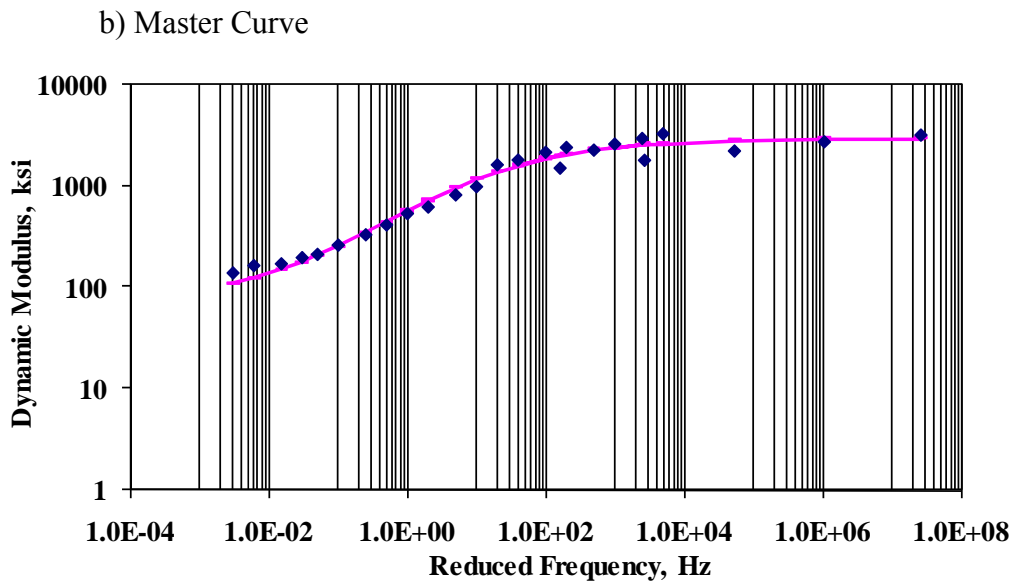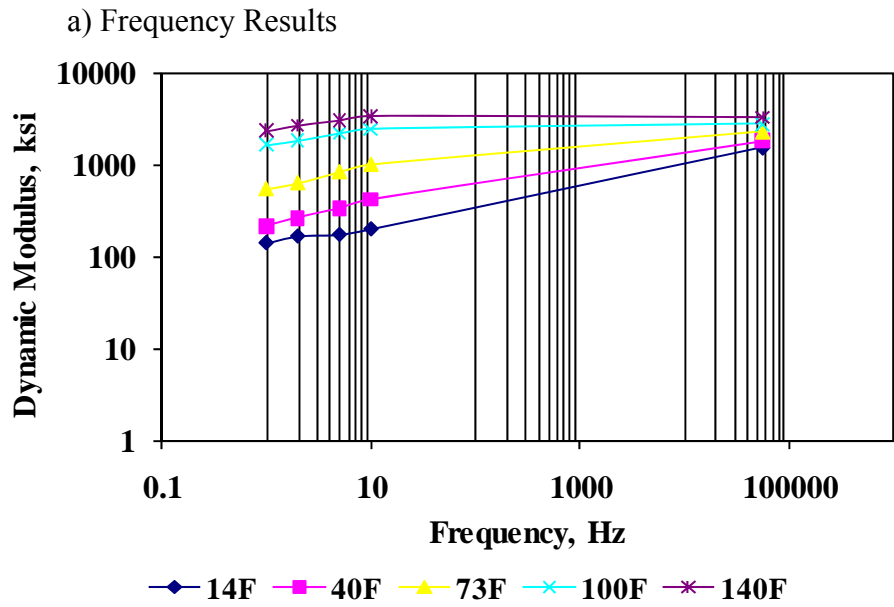a) Frequency Results

b) Master Curve

Figure E.1 – Results of the Master Curve for Loop 1 Section.

Table E.3 – Summary of Test Results from Data Collected in Lot 1 of IH-35 Section.

Sample Number	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.82	6.21	3.50	0	39.3	72.2	7.9
2	1.64	6.64	3.18	0	36.4	70.1	8.5
3	1.86	6.33	4.39	0	36.6	71.1	8.4
4	2.00	6.45	3.30	0	32.4	70.0	8.3
5	1.82	6.36	4.01	0	34.8	71.0	7.8
6	1.92	6.59	3.30	0	32.3	69.0	8.1
7	1.77	6.25	4.72	0	37.5	71.8	8.0
8	1.80	6.43	4.01	0	33.0	70.0	8.5
9	1.83	6.39	3.30	0	34.1	73.9	8.9
10		6.35		0	37.8	71.5	8.2
11		6.27		0	35.4	71.0	8.2
12		6.61		0	33.1	70.3	8.2
13		6.47		0	33.6	72.3	9.0
14		6.37		0	35.1	71.2	9.0
15		6.67		0	32.0	70.3	8.9
Average	**1.83**	**6.43**	**3.75**	**0**	**34.91**	**71.05**	**8.40**
STD Dev	**0.10**	**0.15**	**0.56**	**-**	**2.25**	**1.20**	**0.39**
COV	**5.4%**	**2.3%**	**14.9%**	**-**	**6.5%**	**1.7%**	**4.7%**

[1]- Core Samples, [2]- Loose material from hot mix

Table E.4– Summary of Test Results from Data Collected in Lot 2 of IH-35 Section.

Sample Number	Thickness1, in.	Asphalt Content2, %	Air Voids1, %	Cumulative Retained, %			Percent Passing #2002
				3/4"2	3/8"2	#42	
1	1.82	6.33	4.00	0	38.6	72.9	7.6
2	1.36	6.35	4.05	0	36.3	72.1	7.6
3	1.55	6.45	5.64	0	34.4	71.5	8.4
4	1.55	6.35	5.56	0	37.4	72.1	8.0
5	1.65	6.44	5.50	0	35.1	70.9	8.6
6	1.80	6.68	7.94	0	34.3	70.5	8.4
7	1.54	6.51	8.15	0	34.3	70.9	8.5
8	1.46	6.41	8.90	0	35.2	71.3	8.5
9	1.65	6.46	6.10	0	35.3	69.6	8.8
10		6.31		0	35.6	70.3	8.3
11		6.60		0	32.7	70.2	8.3
12		6.33		0	35.6	69.9	8.6
13		6.41		0	37.1	37.1	8.2
14		6.21		0	37.7	37.7	8.3
15		6.77		0	34.6	34.6	8.0
Average	**1.60**	**6.44**	**6.20**	**0**	**35.62**	**64.11**	**8.27**
STD Dev	**0.15**	**0.15**	**1.76**	**-**	**1.56**	**14.36**	**0.35**
COV	**9.4%**	**2.3%**	**28.4%**	**-**	**4.4%**	**22.4%**	**4.2%**

[1]- Core Samples, [2]- Loose material from hot mix

Table E.5 – Summary of Test Results from Data Collected in Lot 3 of IH-35 Section.

Sample Number	Thickness[1], in.	Asphalt Content[2], %	Air Voids[1], %	Cumulative Retained, %			Percent Passing #200[2]
				3/4"[2]	3/8"[2]	#4[2]	
1	1.66	6.76	6.64	0	35.8	67.9	8.8
2	1.60	6.89	6.52	0	29.8	67.2	8.5
3	1.60	6.43	6.60	0	33.7	69.5	8.8
4	1.81	6.15	6.10	0	36.1	70.4	8.5
5	1.69	6.26	6.00	0	37.1	71.1	8.3
6	1.67	6.39	6.27	0	35.2	70.1	8.2
7	1.89	6.35	5.85	0	34.4	69.7	8.3
8	1.70	6.33	5.18	0	33.5	70.0	8.1
9	2.08	6.35	6.31	0	37.3	70.1	8.3
10		6.31		0	37.5	69.7	8.4
11		6.61		0	31.7	68.1	8.7
12		6.41		0	33.1	69.1	8.6
13		6.22		0	36.8	70.1	8.6
14		6.46		0	34.8	69.6	8.4
15		6.41		0	35.4	69.9	8.0
Average	1.74	6.42	6.16	0	34.82	69.49	8.45
STD Dev	0.16	0.20	0.46	-	2.18	1.03	0.23
COV	8.9%	3.1%	7.4%	-	6.2%	1.5%	2.7%

1- Core Samples, 2- Loose material from hot mix

Table E.6 – Summary of Test Results from Data Collected in Lot 4 of IH-35 Section.

Sample Number	Thickness1, in.	Asphalt Content2, %	Air Voids1, %	Cumulative Retained, %			Percent Passing #2002
				3/4"2	3/8"2	#42	
1	1.61	6.55	6.31	0	33.8	68.8	8.6
2	1.60	6.34	5.64	0	36.6	70.1	8.3
3	1.77	6.35	6.10	0	36.8	70.6	8.0
4	1.85	6.33	6.48	0	32.6	69.5	8.1
5	1.65	6.47	6.51	0	36.4	69.1	8.4
6	1.72	6.35	6.39	0	33.4	68.8	8.7
7	1.90	6.36	4.22	0	32.1	60.5	7.1
8	1.80	6.62	5.56	0	35.5	69.3	8.6
9	1.79	6.34	6.44	0	32.3	68.4	8.7
10		6.33		0	35.4	69.4	8.5
11		6.58		0	32.4	67.6	8.9
12		6.39		0	32.6	68.2	8.9
13		6.16		0	37.2	69.5	8.5
14		6.41		0	35.3	69.0	8.8
15		6.32		0	35.2	68.6	8.9
Average	1.74	6.39	5.96	0	34.50	68.50	8.46
STD Dev	0.11	0.12	0.74	-	1.84	2.32	0.48
COV	6.1%	1.8%	12.5%	-	5.3%	3.4%	5.7%

1- Core Samples, 2- Loose material from hot mix

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