

VARIABILITY OF AS-CONSTRUCTED PROPERTIES OF HMA

AND THEIR RELATION TO PAY FACTORS

AND RUTTING RESISTANCE:

A CASE STUDY

by

ROSARIO TRIPIANA MARTINEZ

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ABSTRACT

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Rosario Triplana Martinez

The University of Texas at Arlington, 2014

Supervising Professor: Stefan A. Romanoschi

During the last decade, Texas has undergone a huge reconstruction of its major and strategic highways in order to improve transportation and prepare for future population and traffic growth. The population is estimated to increase by 50% for 2035 for the North Texas Area.

Some of those highway reconstruction projects have asphalt pavements, and they utilize significant quantities of asphalt concrete. This study compiles the test results of As-Constructed properties for asphalt mixes for four different projects built in Texas. This data was statistically analyzed to obtain information on the variability of As-Constructed properties and study the effect of the current TxDOT specification requirement related payment factor. In addition, the analysis of the relation between rutting and As-Constructed HMA properties was studied.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Presently, there are 2.6 million miles of paved roads in the USA; about 93% of those are built with asphalt concrete. A significant proportion of roads and highways are full-depth asphalt pavements and others are merely asphalt overlays used to resurface existing concrete pavements in order to increase their bearing capacity and serviceability.

The largest use of asphalt cement, or bitumen, is in the production of Hot Mix Asphalt (HMA) (Roberts, 1996). There are about 4,000 asphalt mix plants in the United States that produce approximately 500 million tons of asphalt mixture per year. The asphalt industry records about 30 billion dollars in operating revenue in 2010 and it supports 300,000 jobs across the nation (NAPA, 2014)

HMA provides many advantages. It is very competitive in terms of initial cost and maintenance. A road built with an HMA surface layer can be opened to traffic almost immediately after the compaction is completed, a major advantage in urban projects with time constraints. An asphalt pavement surface offers a safe, quiet and smooth driving surface. In addition, HMA can be recycled and reused, which reduces environmental damage and cost.

The structural design of asphalt pavements is focused on the determination of the layer thicknesses, material selection, drainage design and pavement structure, all are important for a proper load distribution between pavement layers. The design of the

HMA mixture attempts to address some performance concerns in the laid product, such as: resistance to permanent deformation, fatigue and reflective cracking, resistance to moisture damage and low temperature cracking, workability and skid resistance. In order to control those performance characteristics, the management of HMA properties such as: gradation, aggregate texture, size or shape, binder selection, asphalt content, density, design voids and compaction, is essential. These properties are related to the HMA resistance to traffic load, the proper adhesion and coating of aggregates into the mixture, the permeability and the resistance of the surface to polishing.

Asphalt concrete pavements have been commonly used in Texas as pavement structures for many projects built during the last decades. These projects demand the production of a high tonnage of asphalt mixtures and consequently generate a large volume of test data for quality control and quality assurance purposes. The analysis of this available data allows the study of the variability of the as-constructed mix properties for projects built under the same specifications. The findings provide useful information related to variability of these properties or the effect of the application of the current specification on the quality of the HMA. These results can be useful for further research or evaluation of the current specifications.

1.2 Objectives

This research was initiated to perform a study of the as-constructed HMA properties. The main objectives of this research are:

- i. Compile the quality control data generated during the construction of the projects in order to study the variability of HMA properties during construction of asphalt pavement.
- ii. Evaluate the effects of the payment factors on the quality of a final asphalt pavement product.
- iii. Analyze the relationships between rutting and HMA properties.

CHAPTER 2

BACKGROUND

2.1 Aggregates and Hot Mix Asphalt

2.1.1 Aggregates in HMA Mixes

Aggregates have a very important role in asphalt mixtures, because they constitute about 85% of the total volume of mix in their different forms: Coarse, fine and mineral aggregates.

- Coarse Aggregates are the particles retained on a 2.36mm (#8) sieve. Usually gravels meet size requirements for coarse aggregates, but it is very important to guarantee that these aggregates are not round, flat and/or elongated. The ideal shape for a coarse aggregate is cubical and highly angular in order to provide greater strength and rut resistance to the asphalt mix.
- Fine Aggregates are the aggregates smaller than 2.36mm and retained on the 0.075mm (#200) sieve. Fine aggregates can be obtained from natural sources (river pits) or manufactured by crushing rocks into small particles, that have higher angularity.
- Filler or Mineral Aggregates are the particles passing the 0.075mm (#200) sieve. It is often called mineral dust. No more than 7% passing #200 is usually used in asphalt concrete.

The size distribution of aggregates or gradation is critical for the effectiveness of a mix design because it controls aggregate packing and therefore, the air voids and asphalt

content in the mix. The maximum size of aggregates is in accordance with the thickness of the asphalt lift and it should be no more than 1/2 of the lift thickness. In addition, the surface texture of the paved mix will be influenced in part by the gradation of the mix.

In order to determine the gradation, the aggregates are passed through a stack of sieves (Figure 2-1), and the percentage of the material retained by each sieve is calculated as a proportion of the total aggregate weight.



Figure 2-1: Stacked sieve for gradation (Pavement Interactive, 2014)

Additional characteristics of the aggregates are fundamental for the design and the volumetric properties of asphalt mixtures.

- Nominal Maximum Aggregate Size (NMAS): NMAS is defined as the smallest sieve size that retains (cumulatively) no more than the 10% of the aggregates by weight.

- Angular and Rough Textured Aggregate: These two properties of aggregates in an asphalt mix help prevent rutting and provide strength due to a better

interlock between particles. Table 2-1 shows the recommended percentages of fractured particles in a mix for coarse aggregates, depending on:

- The thickness of pavement layer
- The traffic volume during design life (ESALs)

Table 2-1: Coarse Aggregate Fractured Faces Requirements (Advanced Asphalt Technologies, LLC, 2011)

Design ESALs (millions)	% with at least one fractured faces		% with at least two fractured faces	
	Depth from Surface			
	≤ 100 mm (4 inches)	> 100 mm (4 inches)	≤ 100 mm (4 inches)	> 100 mm (4 inches)
< 0.3	55	-	-	-
0.3 to < 3	75	50	-	-
3 to < 10	85	60	80	-
10 to < 30	95	80	90	75
≥30	100	100	100	100

- Flat and elongates aggregates: Flat and/or elongated particles make the compaction of the mix difficult because they tend to break down. This can modify the gradation of the aggregates and affect volumetric properties of the asphalt mixture. Usually, flat and elongated particles must be less than 10% (Advanced Asphalt Technologies, LLC, 2011)

- Cleanliness and deleterious materials: Aggregate particles can be covered by clay materials, vegetation or friable particles. This causes a poor adhesion between the aggregate and the asphalt binder. The insufficient adhesion could produce distresses on the asphalt pavement such as potholes and reduce its service life.

- Toughness: Toughness and abrasion resistance of the particles facilitate the compaction process by reducing the chance of aggregate particles breaking down, and improve the durability of aggregates under the repeated loading from heavy vehicles. That helps reduce distresses related to aggregate problem close to the surface, such as raveling. In addition, it improves the skid resistance of surface mixes.

- Soundness refers to the resistance of aggregates to breakdown or disintegration into smaller size particles due to weather and particularly, due to freeze-thaw cycles. Low soundness value means low susceptibility to weathering and therefore is desirable (Advanced Asphalt Technologies, LLC, 2011). High values of soundness produce a disintegration of the aggregate particles with time and weather cycles, and therefore it reduces service life of asphalt pavement.

2.1.2 Hot Mix Asphalt (HMA)

Bituminous materials are defined as substances in which bitumen is presented or from which it can be derived (Goetz, 1960). Asphalt is considered a primary type of bituminous material for civil engineering applications. The American Society for Testing and Materials (ASTM) defines *Asphalt* as a dark, brown to black, cementitious material in which the predominant constituent is bitumen. It may occur in nature or it can be obtained in petroleum processing. *Natural asphalt* is present in some areas such as the Pitch Lake in the Caribbean Island of Trinidad. But the vast amount of asphalt used today is from petroleum asphalt. *Petroleum asphalt* is obtained from the heavy residue of the distillation of crude oil after removing fuel and lubricant.

The main usage of asphalt cement is as the binder in the Hot Mix Asphalt. HMA is a combination of aggregates and asphalt cement, heated and uniformly mixed. After cooling to ambient temperature, HMA becomes a strong material used for construction of pavement.

Today, approximately 93% of the paved roads in USA are asphalt pavements. This high utilization highlights the importance of these products to the economy. Its specific characteristics make asphalt somewhat challenging to control in order to ensure a good performance. For example, temperature is one of the properties that directly impacts the performance of an asphalt binder. High temperatures in an asphalt binder could lead to rutting or shoving of the mix. On the other hand, low temperatures can make the binder too stiff and generate distresses such as cracking during the service life. In addition, the oxidation process, either long-term or short-term process (during mixing, transportation and placement of a binder) can harden the asphalt binder and cause severe cracking.

HMAs are classified on three types:

- i.* Dense-Graded HMAs: High-quality HMA, well graded with high quality aggregate. According to TxDOT, they are classified by their Nominal Maximum Aggregate Size (NMAS) in type A, B, C, D and E, as shown in Table 2-2.
- ii.* Open-Graded HMAs: Designed to be water permeable. They are classified in two types. Open-Graded Friction Course, OGFC, is used as a surface layer only, and provides skid resistance, positive drainage and noise mitigation. Typically, they have 15% air voids. An Asphalt Treatment Permeable Base (ATPB) is used underneath other asphalt layers as a base drainage layer.

- iii. Stone Matrix Asphalt (SMA): It is a Gap-Graded HMA with a very good resistance to rutting due to the stone-to-stone contact provided by the proportion of mineral filler (10%), coarse aggregate (70-80%) and high asphalt content (over 6%), (The Asphalt Institute, 2007)

Table 2-2: Master Gradation Bands (% Passing by weight or volume) and Volumetric Properties (TxDOT, 2004)

Sieve Size	A Coarse Base	B Fine Base	C Coarse Surface	D Fine Surface	E Fine Mixture
1-1/2"	98.0-100.0	-	-	-	-
1"	78.0-94.0	98.0-100.0	-	-	-
3/4"	64.0-85.0	84.0-98.0	95.0-100.0	-	-
1/2"	50.0-70.0	-	-	98.0-100.0	-
3/8"	-	60.0-80.0	70.0-85.0	85.0-100.0	98.0-100.0
#4	30.0-50.0	40.0-60.0	43.0-63.0	50.0-70.0	80.0-86.0
#8	22.0-36.0	29.0-43.0	32.0-44.0	35.0-46.0	38.0-48.0
#30	8.0-23.0	13.0-28.0	14.0-28.0	15.0-29.0	12.0-27.0
#50	3.0-19.0	6.0-20.0	7.0-21.0	7.0-20.0	6.0-19.0
#200	2.0-7.0	2.0-7.0	2.0-7.0	2.0-7.0	2.0-7.0
Design VMA ¹ , % Minimum					
-	12.0	13.0	14.0	15.0	16.0
Plant-Produced VMA, % Minimum					
-	11.0	12.0	13.0	14.0	15.0

¹ Voids in mineral aggregates.

2.2 Volumetric Properties of HMA

Asphalt mixes have three main components: Aggregates, Asphalt and Air. Other additives that improve mix performance and workability could be presented in the mixes such as, mineral fibers or polymers; they represent just small proportions of the overall volume. The design procedure can be given in terms of both, weight or volume relations; the most common method has been the volumetric design method. Generally, aggregates

represent 84-90% of the compacted mix volume; asphalt binder 6-12% and air voids around 4% of the volume. Figure 2-2 presents a diagram showing the volumetric and mass relationship for asphalt mixture components.

Main asphalt properties that affect asphalt performance are: Density, Air Void, Asphalt Content and Voids in the Mineral Aggregated.

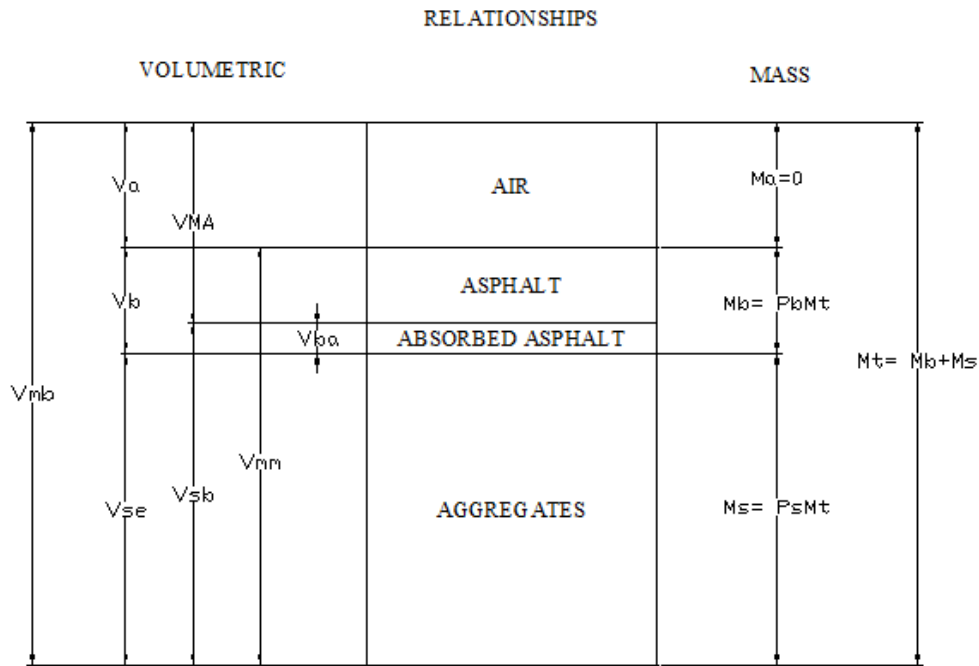


Figure 2-2: Mass and Volumetric relationship for asphalt mixture components

Some properties such specific gravity do not directly affect the performance of the asphalt mixture but are indispensable for determining other volumetric parameters such as VMA and air voids. For example, In-place Air Voids are calculated based on the ratio of Bulk Specific Gravity and Theoretical Maximum Gravity.

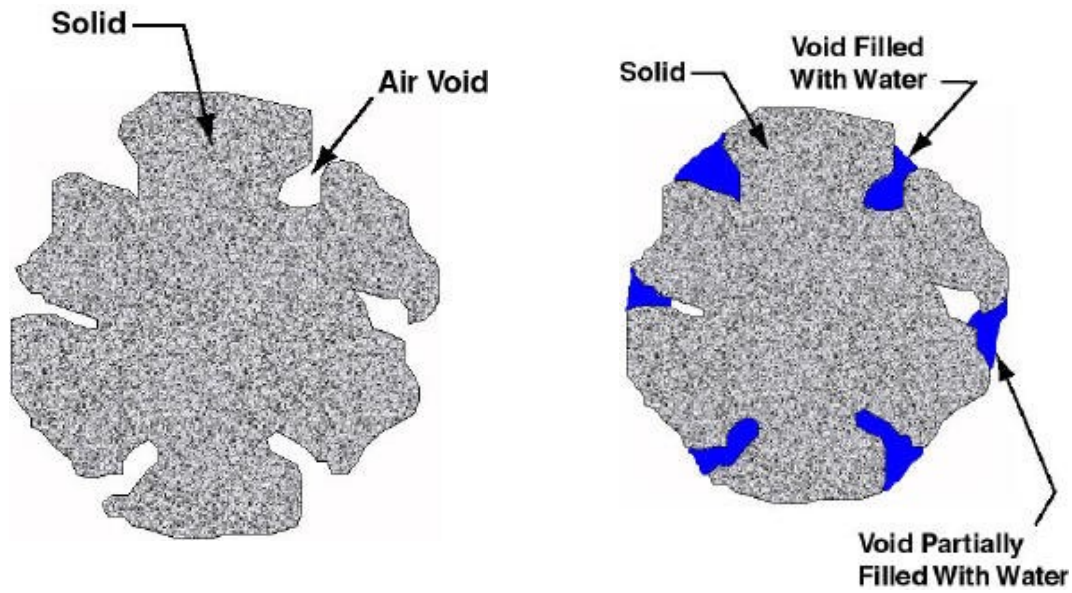


Figure 2-3: Dry and Wet Aggregate (Pavement Interactive, 2014)

Aggregate Bulk Specific Gravity (G_{sb})

$$G_{sb} = \frac{\text{Mass of oven Dry aggregate}}{\text{Bulk volume}} / 1000\text{g/cm}^3 \quad (2-1)$$

Bulk Volume = Volume of solid particles plus the volume of water permeable pores (See Figure 2-3)

Aggregate Apparent Specific Gravity (G_{sa})

Apparent Specific Gravity of the aggregates does not include the volume of the water permeable pores.

$$G_{sa} = \frac{\text{Mass of oven Dry aggregate}}{\text{Apparent volume}} / 1000\text{g/cm}^3 \quad (2-2)$$

Apparent Volume = Volume of Solid Aggregate particles only (See Figure 2-3)

Aggregate Effective Specific Gravity (G_{se})

$$G_{se} = \frac{\text{Mass of oven Dry aggregate}}{\text{Effective volume}} / 1000\text{g/cm}^3 \quad (2-3)$$

Effective Volume= Volume of solid particle plus the volume of water permeable pores not filled with asphalt (See Figure 2-3).

Bulk Specific Gravity of compacted HMA (G_{mb})

Bulk Specific Gravity gives weight per unit volume of compacted mixture and is used in the calculation of Air Voids.

The bulk specific gravity can be measure for a sample molded in the laboratory or from a core taken from a compacted HMA asphalt layer in the field.

$$G_{mb} = \frac{\text{Mass of Aggregates and Binder}}{\text{Bulk Volume}} = \frac{A}{(B-C)} \quad (2-4)$$

Bulk Volume= Volume of aggregates, binder and air voids

A=Mass of the compacted dry sample in air

B=Mass of Saturated Surface Dry (SSD): obtained by measuring sample mass after quickly blot the sample that was kept under water for 10 minutes.

C= Mass of sample under water (sample is placed directly in water bath) (The Asphalt Institute, 2007).

Theoretical Maximum Specific Gravity (G_{mm})

The Theoretical Maximum Specific Gravity is the specific gravity of a mixture containing no air voids.

$$G_{mm} = \frac{\text{Mass of Aggregates and Binder}}{\text{Volume of aggregates and Binder}} = \frac{A}{(A-C)} \quad (2-5)$$

It is also called Rice Specific Gravity or TMD (Theoretical Maximum Density).

2.2.1 Definition of Volumetric Properties

Mix Density

The density of paved mix is a measure of compaction quality. The ratio between the bulk density measured in field and the maximum theoretical density determined in laboratory is used as a reference for compaction level during the construction procedure. The Bulk Density will be used for calculating the density percentage during the construction procedure as a control measure.

$$\% \text{ Density} = \frac{G_{mb}}{G_{mm}} 100 \quad (2-6)$$

Where:

G_{mm} = Maximum Theoretical Specific Gravity of mixture (Rice density)

G_{mb} = Bulk Specific Gravity of mixture

Air Voids

Air voids represent small pockets of air between aggregates particles of a compacted asphalt mixture.

By definition:

$$V_a = \% \text{ Air voids} = \frac{V_v}{V_t} 100 = 100 - \% \text{ Density} \quad (2-7)$$

V_a =Percentage by volume of Air Voids

V_v =Volume of air voids

V_t =Total Volume of compacted specimen.

$$\% \text{ Air voids} = \left(1 - \frac{G_{mb}}{G_{mm}}\right) 100 \quad (2-8)$$

G_{mb} = Bulk Specific Gravity of mixture

G_{mm} = Maximum Specific Gravity of mixture

The proportion of air voids is very important for the stability and durability of the asphalt mixture. In-place air voids are obtained by measuring the average bulk specific gravity on core samples extracted directly from the compacted asphalt layer during construction. Low in-place air voids can result in an unstable mixture, which can develop typical performance issues related to high asphalt content, such as rutting. High in-place air voids can result in a water-permeable mixture with problems such as moisture damage.

In-place air voids are used as a measure of the compaction level, since compaction reduces the air voids proportion. When the in-place air voids decrease to less than 3%, rutting of the asphalt mixture is more likely to occur. When air voids are above 8%, the mix is permeable to air and water, and the rate of oxidation of the asphalt binder increases (Roberts, 1996).

Typical values for air voids are:

- Mix design values: Typically, the target value is 4% for a Superpave mix design, but it is expanded to 3-5% in Marshall Mix design.
- In-place air voids: 6-11% immediately after construction with median values of 8 and 9% (Advanced Asphalt Technologies, LLC, 2011).

TxDOT Specifications (Item 341) allow from 2.7%-9.9% for in-place air voids, applying a placement pay adjustment factor greater than 1.0 for values between 4.7%-8.5% (TxDOT, 2004). TxDOT requirements are described in Chapter 2.6.3.

Asphalt Content: AC

Asphalt content in the mixture is an important parameter to be evaluated because it directly affects mixture properties such as voids, stability, and flow or aggregated coat; Therefore, AC has to be determined accurately in the laboratory and controlled in the field to ensure a good performance of the mix.

Optimum asphalt content is directly dependent on aggregate characteristics, especially on gradation. Coarse aggregate particles have less specific exterior area per unit weight than fine aggregates and therefore, they require less asphalt for coating their surface.

High asphalt content leads to an unstable mixture that likely develops distresses such as rutting or shoving and low skid resistance. In addition, it increases the cost of the mixture because asphalt binder is the most expensive component of the mixture. Low asphalt content generates a stiff mixture with durability problems such as early cracking because of insufficient bond between the aggregate particles.

Another critical property related to AC is the aggregate absorption. AC needs to be sufficient to allow absorption by aggregates and permit bonding the aggregates. The *effective asphalt content*, the asphalt not absorbed by the aggregate, creates a film that coats the aggregate surface and bonds the particles.

Asphalt Binder content can be measured in several different ways:

- Total asphalt content by weight (P_b):

$$P_b = \left(\frac{M_b}{M_s + M_b} \right) 100 \quad (2-9)$$

M_b = Mass of asphalt

M_s = Mass of aggregate stone

- Total asphalt content by Volume (V_b):

$$V_b = \frac{P_b G_{mb}}{G_b} \quad (2-10)$$

P_b = Total asphalt binder content, % by mass

G_{mb} = Bulk Specific Gravity of mixture

G_b = Specific Gravity of asphalt binder

- Absorbed asphalt content by volume (VBA):

$$VBA = G_{mb} \left[\left(\frac{P_b}{G_b} \right) + \left(\frac{P_s}{G_{sb}} \right) - \left(\frac{100}{G_{mm}} \right) \right] \quad (2-11)$$

G_{mb} = Bulk Specific Gravity of asphalt mixture

P_b = Total asphalt binder content, % by mass

G_b = Specific Gravity of asphalt binder

P_s = Total aggregate percentage content. $P_s = P_b - 100$

G_{sb} = Bulk Specific Gravity of aggregate

G_{mm} = Maximum Specific Gravity of mixture

- Percent binder absorbed by weight (P_{ba}): Percentage of absorbed asphalt by mass of dry aggregate.

$$P_{ba} = \left(\frac{G_{se} - G_{sb}}{G_b G_{se}} \right) 100 \quad (2-12)$$

$$P_{ba} = P_b - P_{be} \quad (2-13)$$

G_{se} = Effective Specific Gravity of aggregate

G_{sb} = Bulk Specific Gravity of aggregate

G_b = Specific Gravity of asphalt binder

P_b = Total asphalt binder content, % by mass

P_{be} = Effective Asphalt content by weight

- Effective asphalt content by Volume (V_{be}):

$$V_{be} = V_b - V_{ba} \quad (2-14)$$

V_b = Total Asphalt content by Volume

V_{ba} = Absorbed Asphalt content by volume

- Effective asphalt content by weight (P_{be}): Mass concentration of asphalt not lost to absorption.

$$P_{be} = P_b \left(\frac{V_{BE}}{V_b} \right) \quad (2-15)$$

V_b = Total asphalt content by Volume

V_{BE} = Effective asphalt content by Volume

P_b = Total asphalt binder content, % by mass

Voids in the Mineral Aggregate (VMA)

Void in the Mineral Aggregate is the volume of intergranular void space between the aggregate particles of a compacted paving mixture. It includes the air voids and the volume of the asphalt not absorbed into aggregates (Roberts, 1996).

$$VMA = 100 - \frac{G_{mb}P_s}{G_{sb}} \quad (2-16)$$

G_{mb} = Bulk Specific Gravity

P_s = Percentage of Aggregate content

G_{sb} = Aggregate bulk specific gravity

VMA represents the space available for air voids and for effective asphalt content:

$$VMA = V_a + V_{be} \quad (2-17)$$

V_a = % Air Voids by volume

V_{be} = Effective asphalt binder content, % by total mixture volume

Minimum values for VMA are required to achieve a proper packing of the aggregate particles and guarantee a good performance of the asphalt mixture. These

values are determined depending on each type of material and mix design method (See Table 2-3, 2-4 and 2-5)

Table 2-3: VMA values for Marshall Method (Advanced Asphalt Technologies, LLC, 2011)

Marshall Method Mix Design		
NMAS	VMA	Air Content
9.5mm	14%	3%
	15%	4%
	16%	5%
12.5mm	13%	3%
	14%	4%
	15%	5%
19.0mm	12%	3%
	13%	4%
	14%	5%

Table 2-4: VMA values for Superpave Method (Advanced Asphalt Technologies, LLC, 2011)

Superpave Method Mix Design	
NMAS	VMA
9.5mm	15%
12.5mm	14%
19mm	13%
25mm	12%
37.5mm	11%

Table 2-5: VMA Minimum % (TxDOT, 2004)

Design VMA, % Minimum				
A Coarse Base	B Fine Base	C Coarse Base	D Fine Surface	E Fine Surface
12%	13%	14%	15%	16%

The control of VMA values and Air Voids (design and in-place values) are fundamental to ensure future performance of the asphalt binder. VMA values are related to rut resistance, fatigue resistance and permeability.

Important findings relating air voids and VMA are (Christensen, 2006):

- A dramatic decrease of rut resistance was observed for in-place air void values less than 2%. In order to achieve such a low air void percentage with conventional compaction equipment, the asphalt mix must have an excessive binder content, rounded aggregates or improper aggregate gradation. All these factors cause a significant reduction in the resistance to rutting. Therefore, values under 3% for in-place air voids should be avoided for intermediate and wearing layers to reduce the possibility of a poor rut resistance pavement.
- Many State Highway Agencies have modified air voids and VMA requirements. The three most common modifications are: (1) variation of design air void proportion from 4% to a range of 3 to 5%; (2) establish maximum VMA at 1.5% to 2.0% above minimum values and (3) increase of 0.5% in the minimum VMA values.
- A 1% decrease in VMA at constant air voids, increase 1% in air voids design at constant VMA or decrease 1% in field air voids at constant VMA increases rutting resistance by 20%.

Voids Filled with Asphalt (VFA)

Voids Filled with Asphalt is the percentage of the volume of the voids that is filled with asphalt cement (Roberts, 1996). Since VFA is related to VMA and air voids, by maintaining the VMA and air voids within the specified limits, the VFA requirements (Table 2-6) are also satisfied.

$$VFA = \frac{VMA - V_a}{VMA} 100 \quad (2-18)$$

V_a = % Air Voids by volume

VMA = Voids in the mineral aggregate, % by total mixture volume

Table 2-6: Minimum VFA Range Requirements (AASHTO, 2001)

Design ESALs (millions)	VFA (Range Percentage)
< 0.3	70-80
0.3 to < 3	65-78
3 to < 10	65-75
10 to < 30	
≥ 30	

2.3 Description of Asphalt Mix design Methods.

The design of the asphalt mixture is a critical process that affects the performance of asphalt pavement. The objective of the mix design is to obtain an economical mix that meets the requirements of the established design method and the necessities of the project in question.

Several mix design methods have been developed and improved with experiences and observations. Examples of design methods are the Pat Test, used from 1900 to early

1920s, The Bitulithic Pavement by Warren Brothers who had eight different patents of asphalt mixture by 1920. More recently methods are Marshall and Hveem, used till today, and the current Superpave Mix Design Method.

Francis Hveem from the California DOT developed the Hveem Mix design Method in late 1920. His method considered the asphalt absorption by aggregate, the durability of HMA structure based on thickness and mixture stability to resist traffic load. The Marshall Method was developed by Bruce Marshall of the Mississippi Highway Department in 1939 and improved years later, by the U.S. Army Corps of Engineering (USACE). During World War II, he conducted studies to redefine the method due to the increase in the wheel load and tire pressure. In 1950, the USACE modified the Marshall Method to incorporate additional variables such as weather or deformation measure device. This method tries to find the asphalt binder content at a desired density that satisfies minimum stability and a range of flow values (White, 1985). An extensive number of studies have been developed related to the Marshall Method, and, in consequence, many improvements and variations have been proposed from different engineers and organizations. For this and others mix design methods, the Asphalt Institute's publications are considered the best reference.

Other methods, such as German Compactor, French Roller, were also used in USA since the early 1990s, both developed and based on European Standards. Nowadays, in the USA, Superpave is the most widely used mix design method.

The Superpave Mix Design Method or Superior Performing Asphalt Pavement System was the result of the SHRP, Strategy Highway Research Program, approved by

the US Congress to improve the pavement condition on USA highways. The research was developed during the 1990s, and it has been implemented by most states since 2000.

2.3.1 Traditional Mix Design Methods

This subchapter briefly describes the traditional mix design methods such as Hveem, Marshall or Superpave Method. All of them follow the same steps for the design of the mixture. Some differences are found on proportioning and verification steps, as well as on the compactor used for sample preparation.

The basic four steps are:

- 1) Determination of requirements based on service life, agency and project specifications, workability, durability, moisture, fatigue, deformation resistance and skid resistance;
- 2) Selection of Materials: Aggregates and Binder selection based on the requirements determined on point one. In addition to weather, pavement temperature (for binder selection), sources, cost, location of the asphalt layer on the pavement structure (base, intermediate or surface).
- 3) Proportioning: During this process several samples will be prepared with different asphalt proportions in order to determine the optimum asphalt content based on different conditions and depending on the design method used.
- 4) Verification: This last step will confirm that the mix obtained from previous steps met the requirement.

Hveem Mix Design

The mix design is centered on the evaluation of a trial mixture aggregate-asphalt using a specimen of 100mm (4 inches) diameter by 70mm (2.5 inches) thick. The asphalt binder content for the trial mixture is estimated using a percentage of oil retained and the centrifuge kerosene equivalent (CKE). Several samples are prepared based on this asphalt content adding 0.5%, 1%, 1.5% and 2% of asphalt for different trials. These samples are compacted using a California Kneading Compactor.

Laboratory-compacted specimens must meet requirements for stabilometer and swell test (Table 2-7). After selection of the samples within those requirements, minimum 4% air-voids will be provided.

The principle of the Hveem method is to select the highest asphalt content to get highest durability ensuring minimum stability required (Roberts, 1996)

Table 2-7: Hveem Design Criteria (The Asphalt Institute, 2007)

Traffic Category	Heavy		Medium		Light	
Test Property	Min.	Max.	Min.	Max.	Min.	Max.
Stabilometer Value	37	-	35	-	30	-
Swell	less than 0.030 in (0.762 mm)					

Traffic Classifications:

Light - traffic conditions resulting in a Design ESAL $< 10^4$

Medium - traffic conditions resulting in a Design ESAL between 10^4 and 10^6

Heavy - traffic conditions resulting in a Design ESAL $> 10^6$

Marshall Mix Design

This mix design focus on the evaluation of trial mixture aggregate-asphalt, using typically 5 blends with 3 samples each for a total of 15 specimens. Specimens are 100mm (4 inches) diameter by 70 mm (2.5inches) thick, and are compacted using the Marshall Hammer. Samples are tested using the Marshall stability and flow device (Roberts, 1996).

The designed asphalt content is the average for the asphalt content at maximum stability, the asphalt content at maximum density and the asphalt content at 4% air voids. Then, this asphalt content will be used to calculate the stability, flow, VMA and VFA. All of them need to meet specific requirements (Table 2-8), which have varied over time and the agency.

Experience with the Marshall design indicated the need to modify the original method. Bruce Marshall recommended the lowest possible VMA values, because that gives the densest mixes, but experience revealed durability problems based on this criterion. Therefore, minimum values for VMA were established to avoid durability issues.

Superpave Mix Design

This method evaluates different trials of aggregate-asphalt based on number of gyrations (N), properties obtained for each blend for the three levels of N (Table 2-9) and in the volumetric properties obtained for each blend. Specimens are 150mm (6inches) diameter by 115mm (4.5inches) height. The compactor used in Superpave mix design is a Superpave Gyratory Compactor (SGC) (Figure 2-4).

Table 2-8: Marshall Design Criteria (The Asphalt Institute, 2007)

Marshall Method Mix Criteria	Light Traffic Surface & Base		Medium Traffic Surface & Base		Heavy Traffic Surface & Base	
	Min.	Max.	Min.	Max.	Min.	Max.
Compaction, number of blows each end of specimen		35		50		75
Stability, lb.	750		1200		1800	
(N)	(3336)	-	(5338)	-	(8006)	
Flow, 0.01 in (0.25 mm)	8	18	8	16	8	14
Percent Air-Voids	3	5	3	5	3	5
Percent Voids in Mineral Aggregate (VMA)	See Table 2-3					
Percent Voids Filled With Asphalt (VFA)	70	80	65	78	65	75

Notes

1. All criteria, not just stability value alone, must be considered in designing an asphalt paving mix. Hot mix asphalt bases that do not meet these criteria when tested at 140°F (60°C) are satisfactory if they meet the criteria when tested at 100°F (38°C) and are placed 4 in (100 millimeters) or more below the surface. This recommendation applies only to regions having a range of climatic conditions similar to those prevailing throughout most of the United States. A different lower test temperature may be considered in regions having more extreme climatic conditions.
2. Traffic Classifications:
 - Light - traffic conditions resulting in a Design ESAL $< 10^4$
 - Medium - traffic conditions resulting in a Design ESAL between 10^4 and 10^6
 - Heavy - traffic conditions resulting in a Design ESAL $> 10^6$
3. Laboratory compaction efforts should closely approach the maximum density obtained in the pavement under traffic.
4. The flow value refers to the point at which the load begins to decrease.
5. The portion of asphalt cement lost by absorption into the aggregate particles must be allowed for when calculating percent air-voids.
6. Percent voids in the mineral aggregate should be calculated on the basis of the ASTM bulk specific gravity for the aggregate.

Table 2-9: Superpave Gyratory Compactive Effort

Design ESALs ^a (million)	Compaction Parameters			Typical Roadway Applications
	N _{initial}	N _{design}	N _{maximum}	
< 0.3	6	50	75	Applications include roadways with very light traffic volumes, such as local roads, county roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special-purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to 3	7	75	115	Applications include collector roads or access streets. Medium-trafficked city streets and the majority of country roadways may be applicable to this level.
3 to < 30	8	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access highways. Among these are medium to heavily trafficked city streets, many state routes, U.S. highways, and some rural intersections.
> 30	9	125	205	Applications include the vast majority of the U.S. Interstate System, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.

^a The significant project traffic level expected on the design lane over a 20-year period. Regardless of the design life of the roadway, determine the design ESALs for 20 years.

Note: Initially Superpave Gyratory Compactive Effort was given in function of High Air Temperature. The combined matrix presented was developed in NCHRP 09-09 (NCHRP, 2000) and used by AASTHO



Figure 2-4: Superpave Gyratory Compactor (Pavement Interactive, 2014)

$N_{initial}$ (2-18) is a measure of compactability. The mixture should not be compacted too quickly because this can produce an unstable pavement when loaded with traffic. $N_{maximum}$ (2-19) gives the number of gyrations to produce a density that should never be exceeded in the field. Excessive compaction creates a low percentage of in-place air voids, and therefore, the pavement is more likely to have rutting.

$$N_{initial} = (N_{design})^{0.45} \quad (2-19)$$

$$N_{maximum} = (N_{design})^{1.10} \quad (2-20)$$

The design binder content is obtained by plotting VMA, VFA, Density, Air Voids, and Dust content versus the asphalt content. The asphalt content that corresponds to 4%

air voids at N_{design} is selected as the optimum value and has to meet the density requirements (Table 2-10) for a sample compacted at N design gyrations in addition to all other properties must be verified (Table 2-11).

Table 2-10: Required Densities for N_{initial} , N_{design} and N_{max} (AASHTO, 2001)

20-yr Traffic (in millions of	Required Density (% of Gmm)		
	N _{initial}	N _{design}	N _{max}
< 0.3	≤ 91.5	96	≤ 98.0
0.3 to < 3	≤ 90.5		
3 to < 10	≤ 89.0		
10 to < 30			
≥ 30			

Table 2-11: Minimum VMA Requirements and VFA Range Requirements
(AASHTO, 2001)

20-yr Traffic Loading	Minimum VMA (percent)					VFA Range (percent)	Dust-to- Binder
	9.5 mm	12.5 mm	19.0 mm	25.0 mm	37.5 mm		
	(0.375inch)	(0.5inch)	(0.75inch)	(1 inch)	(1.5inch)		
< 0.3	15	14	13	12	11	70 – 80	0.6-
0.3 to < 3						65 – 78	
3 to < 10						65 – 75	1.2
10 to < 30							
≥ 30							

A moisture sensitivity test will be used for the final acceptance or rejection of the mix. This test is used as a measure of possible stripping and as a measure of moisture susceptibility (The Asphalt Institute, 2007). The test is performed on two groups of samples, a moisture conditioned group and non moisture conditioned group. Both groups are tested for indirect tensile strength, and the ratio between the average group values gives the TSR (Tensile strength ratio). Superpave requirements have an 80% minimum TSR criterion.

2.3.2 Tex-204-F: Design of Bituminous Mixtures

Tex-204-F is the Method used by TxDOT for the design of Bituminous Mixtures. Dense-graded HMA mixture design will follow Tex-204-F typical weight design, as indicated on Item 341 of the TxDOT Specification. In addition, the TxDOT Pavement Design Guide specifies the use of a Texas Gyratory Compactor (TGC, Figure 2-5) for mix types A, B, C, D or F.



Figure 2-5: Texas Gyratory Compactor (TGC).

Tex-204-F using a TGC works with molded specimens of 4 inches diameter and a target height of 2.0 inches. Specimens are compacted using a combination of gyration and pressure. Different specimens with different asphalt content are prepared. Asphalt content is plotted against Density and VMA. The optimum AC is selected for a typical 96% lab-molded density. Some designs increase the target density as selection criteria for the AC percentage in the mix design in order to achieve higher asphalt content. Special care is needed to avoid a mixture susceptible to rutting. In all projects covered for this research, the laboratory-molded density was increased to 97% on the Project 1 and 96.5% in

Project 2, 3 and 4 in order to reduce the air voids content. For the verification process, the Hamburg Wheel and Indirect Tensile Strength test are performed.

Superpave Gyratory Compactor (SGC) is a modification of the Texas Gyratory Compactor (TGC). Several studies have been made related to the relationship between SGC and TGC. In 2004, The Texas Transportation Institute developed the Design of TxDOT Asphalt Mixtures Using the Superpave Gyratory Compactor (Joe W. Button, 2004). The Pavement Design Guide, (TxDOT, 2008) specifies the use of TGC or SGC depending on the mix type. TGC is used for design of Dense-graded mixture, and SGC is used for Open-graded and Stone Matrix Asphalt mixture designs.

2.4 Quality Control (QC) and Quality Assurance (QA)

Quality Control (QC) and Quality Assurance (QA) are essential to ensure a satisfactory product with an adequate performance during the design life. QC usually refers to the quality of the product being produced. QA refers to the acceptance of a product according with the owner's specifications.

AASHTO Standard Practice R10, (AASHTO, 2006) gives the following definitions:

Quality Assurances, QA: "all those planned and systematic actions necessary to provide confidence that a product or facility will perform satisfactorily in service".

Quality Control, QC: "The system used by a contractor to monitor, assess, and adjust their production or placement processes to ensure that a final product will meet the specified level of quality".

Acceptance: “The process whereby all factors used by the agency are evaluated to determine the degree of compliance with contract requirements and to determine the corresponding value for a given product”.

Independence Assurance: “Activities that are an unbiased and independent evaluation of all the sampling and testing (or inspection) procedure used in the quality assurance program”.

Nowadays, all state highway agencies use quality acceptance specifications for selecting and monitoring HMA construction procedures. Usually, the contractor is responsible for testing the HMA and quality control of the product while state highway agencies are responsible for material quality acceptance.

Control Properties, such as Gradation, Asphalt Content, Air Voids, VMA, Material Density are used to regulate the production and placement of the HMA process. A Quality Control plan establishes the frequency and minimum sampling needed to ensure the quality of the HMA pavement. Agencies must also set a minimum testing procedure and time of reporting from contractor to the agency.

2.5 TxDOT Specifications for Test Frequency

Transportation agencies establish their minimum sampling and testing standards to ensure a final product under their specifications. Item 341 Dense-Graded Hot-Mix Asphalt (QC/QA) of TxDOT Standard Specifications (TxDOT, 2004) establishes the frequency of the production tests (Table 2-12).

Frequency is given by project, lot or subplot. According to the TxDOT specification, a production lot will have a size between 1,000 and 4,000 tons or a production day and it consists of four equal sublots. It will be considered a small quantity when less than 500 tons are produced. Under this circumstance, QA/QC sampling and testing could be waived.

Table 2-12: Production and Placement Testing Frequency (TxDOT, 2004)

Description	Test Method	Minimum Contractor Testing Frequency	Minimum Engineer Testing Frequency
Individual % retained for #8 sieve and larger individual % retained for sieves smaller than #8 and larger than #200	Tex-200-F or Tex-236-F	1 per subplot	1 per 12 sublots
% passing the #200 sieve			
Asphalt content	Tex-236-F	1 per subplot	1 per lot
Laboratory-molded density VMA In-Place air voids Laboratory-molded bulk specific gravity	Tex-207-F	N/A	1 per subplot
Theoretical maximum specific (Rice) gravity	Tex-227-F	N/A	1 per subplot
Hamburg Wheel test	Tex-242-F	N/A	1 per project
Boil test ¹	Tex-530-C	1 per lot	1 per project
Moisture content	Tex-212-F, Part II	When directed	1 per project
Asphalt binder sampling and testing ¹	Tex-500-C	1 per subplot (sample only)	1 per project
Thermal profile	Tex-244-F	1 per subplot	1 per project
Segregation (density profile)	Tex-207-F, Part V	1 per subplot	1 per project
Longitudinal joint density	Tex-207-F, Part VII	1 per subplot	1 per project

¹ The Engineer may reduce or waive the sampling and testing requirements based on a satisfactory test history.

2.6 TxDOT Acceptance Criteria

Item 341 Dense-Graded Hot-Mix Asphalt (QC/QA) of the TxDOT Standard Specifications (TxDOT, 2004), specifies the acceptance criteria for HMA QC/QA during production and construction. The requirements for HMA properties that are related to this research are further discussed in this subchapter.

2.6.1 Gradation

Different types of mixture are classified in accordance with aggregate gradation (See Table 2-2). This classification (A, B, C, D, E or F) states the thickness of lift for layer construction, depending on the aggregate size and therefore the mixture type.

2.6.2 Laboratory-Molded Density

Laboratory-Molded Density requirement is 96%. Where possible, an increase of 1% in target laboratory-molded density is encouraged in order to increase the asphalt content into the mixture.

Lab-molded density, for as-constructed asphalt pavement will be determined from samples taken during construction, from trucks before placement and compaction. It is used as acceptance criteria for the as-constructed pavement. In addition, for laboratory-molded density, the Production Payment Factors given in Table 2-13 are applied to reward when a proper mixture for the HMA asphalt.

Table 2-13: Production Pay Adjustment Factors for Laboratory-Molded Density
(TxDOT, 2004)

Absolute Deviation from Target	Production Pay
0.0	1.050
0.1	1.050
0.2	1.050
0.3	1.044
0.4	1.038
0.5	1.031
0.6	1.025
0.7	1.019
0.8	1.013
0.9	1.006
1.0	1.000
1.1	0.965
1.2	0.930
1.3	0.895
1.4	0.860
1.5	0.825
1.6	0.790
1.7	0.755
1.8	0.720
> 1.8	Remove and replace

2.6.3 In-Place Air Voids

In-Place Air Voids are calculated from bulk specific gravity from a core taken out of compacted asphalt layer. It is used as a measure of good compaction during the construction process. Acceptance criteria are in the range of 2.7% to 9.9%, but, Placement Pay Factors (Table 2-14) are applied on Texas projects with a penalty for in-place air void outside a range of 4.7%-8.5%.

Table 2-14: Placement Pay Adjustment Factors for In-Place Air Voids (TxDOT, 2004)

In-Place Air	Placement Pay Adjustment Factor	In-Place	Placement Pay Adjustment Factor
< 2.7	Remove and	6.4	1.042
2.7	0.705	6.5	1.040
2.8	0.720	6.6	1.038
2.9	0.735	6.7	1.036
3.0	0.750	6.8	1.034
3.1	0.765	6.9	1.032
3.2	0.780	7.0	1.030
3.3	0.795	7.1	1.028
3.4	0.810	7.2	1.026
3.5	0.825	7.3	1.024
3.6	0.840	7.4	1.022
3.7	0.855	7.5	1.020
3.8	0.870	7.6	1.018
3.9	0.885	7.7	1.016
4.0	0.900	7.8	1.014
4.1	0.915	7.9	1.012
4.2	0.930	8.0	1.010
4.3	0.945	8.1	1.008
4.4	0.960	8.2	1.006
4.5	0.975	8.3	1.004
4.6	0.990	8.4	1.002
4.7	1.005	8.5	1.000
4.8	1.020	8.6	0.998
4.9	1.035	8.7	0.996
5.0	1.050	8.8	0.994
5.1	1.050	8.9	0.992
5.2	1.050	9.0	0.990
5.3	1.050	9.1	0.960
5.4	1.050	9.2	0.930
5.5	1.050	9.3	0.900
5.6	1.050	9.4	0.870
5.7	1.050	9.5	0.840
5.8	1.050	9.6	0.810
5.9	1.050	9.7	0.780
6.0	1.050	9.8	0.750
6.1	1.048	9.9	0.720
6.2	1.046	> 9.9	Remove and Replace
6.3	1.044		

2.6.4 Asphalt Content

Determination and ratification of a proper Asphalt Content is indispensable to ensure the quality of the lay down asphalt during the construction procedure.

For determination of asphalt content, the ignition method is used. The asphalt content is determined by burning samples at high temperatures and calculating the weight difference before and after calcinations. Correction factors are applied depending on the oven used, in addition to the gradation and origin of aggregates, since some aggregates could be affected by the high temperatures of the burning process.

TxDOT Specifications, (TxDOT, 2004) for asphalt content include:

- Operational tolerance of 0.3% allowable difference from target JMF
- Request to suspend production and shipment of mixture if asphalt content deviates from target JMF by more than 0.5%
- The rejection of the lot for 2 or more sublots outside operational tolerance.

2.6.5 Hamburg Wheel Test

The Hamburg Wheel Test is a measure of the combined effect of rutting resistance and moisture on a HMA mixture (The Asphalt Institute, 2007). The test simulates the effect of traffic loading by rolling a small loaded steel wheel at high temperature (55°C) (Figure 2-6). The number of passes applied will depend on the performance grade of the binder (Table 2-15). It provides a load and pressure similar to the field condition. As a drawback, this test does not provide results related to the long term aging and has a relatively high cost of operation. This test is used for verification during the mix design

procedure and as an indication of performance during pavement construction. This test is performed on asphalt samples taken from the truck delivering the mix to the construction site, before the placement and compaction of mix.



Figure 2-6: Hamburg Wheel Tracking Device (www.control-group.com)

Table 2-15: Hamburg Wheel Test Requirements (TxDOT, 2004)

High Temperature Binder Grade	Minimum # of Passes ² @ 0.5" Rut Depth Tested @ 122° F
PG 64 or lower	10,000
PG 70	15,000
PG 76 or higher	20,000

¹ HWT Tested in accordance with Tex-242-F.

² May be decreased or waived when shown on the plan.

2.6.6 Operational Tolerances

As previously described, operational tolerances are applied in addition to other requirements like Pay Adjustment Factor to guaranty the quality of the final HMA pavement. These tolerances are not applied as an isolated test result. They are analyzed with the complete lot with the purpose of ensuring the quality of the final product. Table 2-16 provided the requirements established by TxDOT as a base for QA/QC for HMA Dense-Graded pavement. Operational tolerances are a measure of acceptance, but additional parameters are applied in order to assure the quality of the final product. For example, if three consecutive lots are placed with an applicable payment factor below 1.0, production needs to stop and the paved mix must be removed.

Table 2-16: Operational Tolerances (TxDOT, 2004)

Description	Test Method	Allowable Difference from Current JMF Target	Allowable Difference between Contractor and Engineer ¹
Individual % retained for #8 sieve and larger	Tex-200-F or Tex-236-F	$\pm 5.0^2$	± 5.0
Individual % retained for sieves smaller than #8 and larger than #200		$\pm 3.0^2$	± 3.0
% passing the #200 sieve		$\pm 2.0^2$	± 1.6
Asphalt content, %	Tex-236-F	$\pm 0.3^3$	± 0.3
Laboratory-molded density, %	Tex-207-F	± 1.0	± 1.0
In-Place air voids, %		N/A	± 1.0
Laboratory-molded bulk specific gravity		N/A	± 0.020
VMA, %, min		Note 4	N/A
Theoretical maximum specific (Rice) gravity	Tex-227-F	N/A	± 0.020

¹ Contractor may request referee testing only when values exceed these tolerances.

² When within these tolerances, mixture production gradations may fall outside the master grading limits; however, the % passing the #200 will be considered out of tolerance when outside the master grading limits.

³ Tolerance between JMF1 and JMF2 may exceed $\pm 0.3\%$.

Test and verify that Table 2-2 requirements are met.

CHAPTER 3

CASE STUDY

3.1 Projects Description

This research uses data from four different asphalt pavement projects located in Texas (Table 3-1). All are important projects that improve mobility and are critical for their geographical areas. The four projects were built at different periods of time by different companies. The materials were from different sources and suppliers. Also, different contractors were in charge of production and construction of the asphalt mixtures, which provide variability to the data analysis in this research. The variability of data helps create a more accurate analysis and consequently, obtain more valid conclusions on the quality of the mix produced, placed and compacted. The complexity of creating a uniform database for a proper analysis and control of the data provided was a major challenge. Special care was taken with the data manipulation in order to minimize errors from data processing.

In addition to this variability, the construction process was not the same for all the projects. Three were urban projects built in different phases, which increase the complexity. They have a pavement asphalt structure design as a HMA base and intermediate layers plus a SMA surface layer. The fourth project was built in a rural area, as a full depth asphalt pavement. Its pavement asphalt structure was designed with different types of dense graded HMA for each layer.

The projects were built in different years, but no changes in the construction specifications were made during that period of time. Therefore, all of them were built

under the same specifications, since each QA/QC department followed TxDOT Standard Specification for Construction and Maintenance of Highways, Streets and Bridges, 2004.

No mention to the project names is made in this research, since data was provided under the consideration of confidentiality. In addition, this information is not relevant for the purpose of this study.

Table 3-1: Projects Description

Project	Length	Construction Cost (dollars)	Construction Time	Total Number of Lanes	Asphalt Laid (tons)	Asphalt Cost (dollars)
Project 1 (P1)	41 miles	\$1.4 billion	3 years	4	1.4 million	\$95.8 million
Project 2 (P2)	6.4 miles	\$1 billion	4 years	8	0.45 million	\$29.2 million
Project 3 (P3)	6.9 miles	\$1.05 billion	4 years	10	0.51 million	\$35.5 million
Project 4 (P4)	16.5 miles	\$2.6 billion	5 years	14	0.34 million	\$19.0 million

3.2 Description of HMA construction procedure

The construction sequence, for the projects evaluated in this report, was different due to the different constraints that each of them faced during construction, such as the phasing of the project.

Three of the projects were opened to traffic during construction. Therefore, smaller quantities of asphalt were placed during each phase. Only surface layers were placed with no traffic during operation, which allowed bigger asphalt tonnage for production and placement and continuity on the lay-down process. Differences in quantities are reflected

as well in plant production and consequently in asphalt properties. Asphalt plants were working with interruptions due to the small quantities required. They also had to change between different types of mix design to adjust their production to field requirements. These continuous changes could create a greater variability in the mix properties, especially, due to the short period of time for plant adjustment. Nevertheless, the placement operation for all four projects was similar, and specifications under which they were constructed were the same.

3.2.1 Placement Operation

HMA asphalt layers were placed over a proper compacted and uniform aggregate base layer. The total thickness of asphalt layers was distributed in different lifts depending on design specifications as well as on the mixture type. According to the TxDOT specification (TxDOT, 2004), the compacted lift thickness for a Type B mixture must be in a range of 2.50 to 5.00 inches, and a Type C mixture in a range of 2.00 to 4.00 inches. As a rule of thumb, the mixture layer thickness before compaction is 1.25 times the compacted thickness. Weather conditions are checked before planning a paving operation, which is canceled if the temperature is lower than 60° F, as directed per TxDOT specifications.

Before starting the lay-down operations, the surface was properly cleaned and finished. A tack coat was used between asphalt layers for a proper bonding between them (Figure 3-1).



Figure 3-1: Surface prepared with tack coat for paving operation

Visual inspections occur before starting the paving operation:

- The mixture temperature can be checked by observation- If blue smoke can be seen for the mixture usually indicates that the mix is overheated.
- Visually stiff or improper coating of aggregates could indicate a too cold mixture.
- Too much asphalt binder in the mix could be visually detected when the mixture arrives with a peak in the trucks and suddenly the load become flat.
- An excess of coarse aggregates will generate a visually appreciable workability problem, and excess of fine aggregate will be noticed in a different texture of a well graded mixture.
- Excess Moisture, can be detected if steam is rising from the mixture when is dumped in the spreader.
- Non-uniformity of the mixture can also be detected by visual inspection.

When problems are not detected before the paving operation, it will continue as a regular process.

3.2.1 Lay- Down

For the four project analyzed on this paper, HMA was brought to the construction sites in dump trucks, and deposited in a Material Transfer Device (MTD, see Figure 3-2, 3-3 and 3-4), which facilitates a continuous and smooth pavement operation. MTD remixes the asphalt mix in order to eliminate segregation that might occur during transport, and places the asphalt in the Paver (Figure 3-5, Figure 3-6). The asphalt paver spreads the materials according to the asphalt thickness layer established depending of the mixture type and design requirement (Figure 3-7).

Due to the project space constraints, especially on Projects 2, 3 and 4, the width of the layers was difficult to control. Usually, it was extended according to the necessary width for the next phase of the project. Surface layers were extended considering the final section of the roads, to make the longitudinal joint and the travel lane marking overlap. In addition, the paving operation for surface layers, where possible, were planned to avoid transverse joints, by fitting a production section between approach slabs on bridges, were joints are inevitable.

3.2.1 Compaction

The compaction of HMA asphalt layers, as well as for other components of the pavement such as the aggregate base, is a significant factor to guarantee a proper performance during the design life.



Figure 3-2: Asphalt Placement operation.



Figure 3-3: Material Transfer Device (MTD)



Figure 3-4: Truck discharging on MTD



Figure 3-5: Paver



Figure 3-6: MTD discharging material on paver



Figure 3-7: Paver spreading material



Figure 3-8: Asphalt layer before compaction

Problems related to a lack of compaction lead to early distresses on the pavement, such as cracking, water permeability, or future rutting on the wheel path due to mix densification during traffic load. Excessive energy used for compaction could lead to aggregates breaking during the process and durability problems later.

The compaction process is based on the application of external forces, which push together coated aggregates particles and reduce the air void volume of the HMA mixture in a proportion that allows the asphalt mix to expand and contract during temperature changes. It is affected by factors such as: temperature (ambient and mixture), asphalt binder, aggregates, mix type or confinement.

The four projects studied in this research used Vibratory Steel-Wheeled rollers and Pneumatic Tire rollers in conjunction for compaction operation. Vibratory steel

rollers are considered the most effective compactor for asphalt placement operation, while pneumatic tire rollers provide a more uniform degree of compaction, improve the seal near the surface and orientate aggregate for greater stability (The Asphalt Institute, 2007). A combination of both was used for HMA compaction.



Figure 3-9: Vibratory Steel-Wheeled rollers

For HMA compaction, roller operation starts on the low side of the layer with the vibratory-steel roller. This first step provides a greater increase in density for the compaction process. A secondary compaction phase with a pneumatic tire roller is performed to densify and seal the asphalt layer. The last phase is the finishing with the steel wheel roller but in a static mode for aesthetic improvement, to eliminate the marks from the pneumatic tire roller. In Figure 3-9, a water spread system cleans the steel roller to avoid material sticking on the wheel.

3.2.2 Sampling and Testing Frequency

The sampling and testing frequency is determined by the TxDOT specification (TxDOT, 2004). Table 3-2 is an example table for an IPP (Inspection Point Program). The Acceptance Criteria described in the IPPs are only a brief description of the recommendations included in the "TxDOT Standard Specification for construction and maintenance of Highways, Streets and Bridges 2004", but other requirements from the TxDOT Standard Specification not included in these IPPs were followed.

Additional tests, such as the Hamburg Wheel, were completed more frequently to ensure asphalt pavement performance. Ride Quality and Skid resistance tests were completed for the final acceptance of the entire project.

3.3 Data Description

All data were directly extracted from the QA/QC departments' logs and reports. Data were selected and combined to keep the same configuration. Therefore, this study takes the common data available for comparison and statistical analysis.

Some of the data was provided as raw data directly from test reports. This information was revised and entered into Microsoft Excel. Other information was provided as MS Excel logs used for the QA/QC department records. Several spread sheets were combined to obtain a full database to ease the statistical analysis. All these steps were meticulously processed to minimize the possibility of errors in the analysis due to data manipulation.

Table 3-2: Example of Inspection Point Program

	Test		TxDOT/Tests	Insp. Points			
Activity to Control	/Inspection	Frequency	Number	W.P	H.P	Responsible	Acceptance Criteria
SURFACE PREPERATION							
Survey stake out	Inspection	Previous		X		Subcontractor Surveyor (QC) or Contractor Surveyor (QA)	Design Project ± 1/4 in.
Surface conditions	Inspection	Each		X		Contractor Personnel (QA)/ Subcontractor Firm(QC)	Placement surface is free from dirt, pavement parkers, moisture, and other objectionable material. Surface is smooth and even.
Weather Conditions	Inspection	Each		X		Contractor Personnel (QA)/ Subcontractor Firm(QC)	Roadway surface meets the requirements in table 10A in 341.4.G.1 for HMA, and for SMA according to item 346.4.G TxDOT Standards.
Place Tack Coat	Inspection	Each		X		Contractor Personnel (QA)/ Subcontractor Firm(QC)	Tack coat applied uniformly at the rate directed by TxDOT Standards or the Plans and Project Standards.
HMA PLACEMENT							
Lift Thickness and layer placement	Inspection	Each		X		Contractor Personnel (QA)/ Subcontractor Firm(QC)	Lift thickness meets the requirements of plans and project Standards. Lift is placed at a steady rate without areas of uneven application
Vertical and Horizontal Alignment	Inspection	Each			X	Subcontractor Surveyor (QC) / Contractor Surveyor (QA)	Tolerance: +- 0.5 in. in 25 ft. measured longitudinally and +- 0.5 in. over the entire width of the cross section
QA TESTING							
Asphalt Content (%)	Sampling	Each Lot	Tex-236-F	X		QA Technician	Asphalt Content sample
Voids in Mineral Aggregates (VMA)	Sampling	Each Sublot	Tex-207-F	X		QA Technician	VMA sample
Gradation	Sampling	Each 12 Sublots	Tex-236-F	X		QA Technician	Gradation sample
Lab Molded Density	Sampling	Each Sublot	Tex-207-F	X		QA Technician	Lab Molded Density sample
In Place Air Voids	Sampling	Each Sublot	Tex-207-F	X		QA Technician	2 cores taken for in place air voids

Data availability

The available data was a vast quantity of tests and logs from each of the QA/QC departments. A total of 5,176 records, distributed as shown in Table 3-3, were available for the development of this research. Those records contained information related to mixture type, plant where mixture was produced, specific location of the mixture, tonnage of the lot, bulk specific gravity and rice specific gravity of the mixture, aggregate gradation, asphalt content, laboratory modeled density, in-place air voids, void in mineral aggregates (VMA), Hamburg wheel test, as-built layer thickness and width.

Some codes are used to identify the different mix designs, the project they belong to and mix number. For example, P2C3 is a mix design on Project 2; it is a type C and is the type C number 3 on this project.

Project 1 has a total number of 3,670 records distributed in six different mix designs. Five of them were a type B with a PG64-22 binder used for base and intermediate layers on the asphalt structure distribution and one type C (PG76-22) used for surface layers (See Figure 3-10).

Project 2 has 375 records distributed in 4 mix designs. One type B is a base layer and two types C (PG64-22) are intermediate layers. In addition to a type C (PG70-22), this works as a temporary surface layer during construction and as an intermediate layer for final pavement (See Figure 3-10)

Project 3 provided a total number of 968 records, distributed in six different mix designs. Three mixes type B (PG64-22) were used as base layers on the asphalt section distribution. One type C (PG64-22) was used as an intermediate layer and two types C

(PG70-22) served as a temporary surface layer during construction and as an intermediate layer for the final pavement, same as in Project 2 (See Figure 3-10).

Project 4 has 163 total records and two types of mix design. A type B PG64-22 was used for base layer of the asphalt section, and a type C PG70-22 was used as intermediate layer of asphalt (See Figure 3-10).

A SMA (Stone Matrix Asphalt) layer was placed as a final surface layer for Projects number 2, 3 and 4. It was not considered retained in the analysis since it is not the purpose of the study.

Table 3-3: Data availability

Project #	Mix Type	PG	CODE	# SAMPLES	Total
P1	B	64-22	P1B1	247	3,670
		64-22	P1B2	323	
		64-22	P1B3	1,231	
		64-22	P1B4	580	
		64-22	P1B5	314	
	C	76-22	P1C1	975	
P2	B	64-22	P2B1	231	375
	C	64-22	P2C1	20	
		70-22	P2C2	100	
		64-22	P2C3	24	
P3	B	64-22	P3B1	474	968
		64-22	P3B2	62	
		64-22	P3B3	134	
	C	70-22	P3C1	212	
		70-22	P3C2	58	
		64-22	P3C3	28	
P4	B	64-22	P4B1	140	163
	C	70-22	P4C1	23	

TOTAL # 5,176

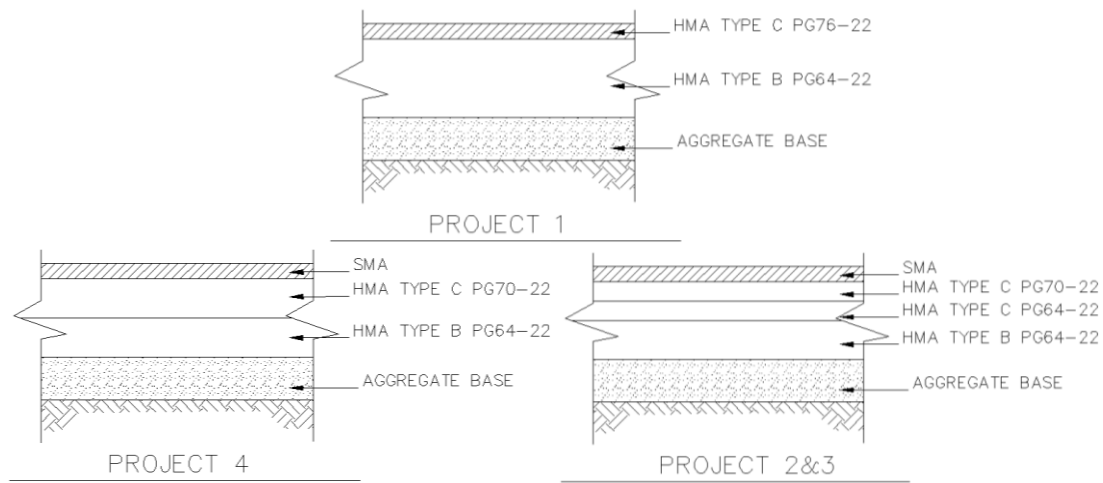


Figure 3-10: Pavement Structure

All this information was carefully analyzed and some records were removed for the study since they did not provide data on all asphalt properties relevant for this study. The data selection was made based on common information between projects or information with enough observations to guarantee the validity of the statistical analysis of the HMA asphalt properties.

The selected data for statistical analysis included:

1. Aggregate Gradation
2. Asphalt Content
3. Laboratory Modeled Density
4. In-Place Air Voids
5. Void in Mineral Aggregates (VMA)
6. Hamburg Wheel test (analysis for two of the projects).

The final total number of observations used for this study was 2,819 distributed as shown in Table 3-4. The observations kept from the original data included samples rejected during the acceptance process. These samples were not removed from the database if all property information were available. They were taken into account for variability analysis because they were part of the production and construction process.

3.1 Variability of As-Constructed HMA Properties

The purpose of this chapter is a basic statistical analysis of each of the mixtures available for this research. First, a mean close to the target value of JMF (Job Mix Formula) ensures the quality of the parameters. Secondly, the standard deviation gives an idea of the uniformity of the materials placed, since low values for standard deviation represents low variability in the test result. Thirdly, higher confidence levels provide the level of quality achieved in a project (The Asphalt Institute, 2007).

Standard deviation values can be compared with expected values given by past experiences. After collection of a good amount of data to evaluate the typical variability of pavement properties, some typical values for asphalt content and density are given in Table 3-5.

Other works indicated a standard deviation of 0.3 for asphalt content as a maximum value. Table 3-6 provides typical standard deviation values for Asphalt Content, Air Voids, VMA and VFA and Table 3-7 gives typical values for Standard Deviation on aggregate size.

Table 3-4: Data Selected for analysis

Project #	Mix Type	PG	CODE	# SAMPLES	Total
P1	B	64-22	P1B1	82	1,352
		64-22	P1B2	95	
		64-22	P1B3	455	
		64-22	P1B4	239	
		64-22	P1B5	109	
	C	76-22	P1C1	372	
P2	B	64-22	P2B1	223	355
	C	64-22	P2C1	17	
		70-22	P2C2	93	
		64-22	P2C3	22	
P3	B	64-22	P3B1	468	951
		64-22	P3B2	60	
		64-22	P3B3	133	
	C	70-22	P3C1	205	
		70-22	P3C2	58	
		64-22	P3C3	27	
P4	B	64-22	P4B1	138	161
	C	70-22	P4C1	23	

TOTAL # 2,819

Table 3-5: Typical Asphalt Content and Density Standard Deviation (Roberts, 1996)

Property	Standard Deviation
Asphalt Content, percentage by weight	0.2
Density of HMA, percentage of laboratory density	1.02

Table 3-6: Typical Overall Standard Deviation of mixture properties (Advanced Asphalt Technologies, LLC, 2011)*

Property	Typical Range for Overall Standard Deviation
Asphalt Content	0.15 to 0.30%
In-Place Air Voids	1.3 to 1.5%
Laboratory Air content	0.90%
VMA	0.90%
VFA	4.00%

Table 3-7: Typical Overall Standard Deviation values for Aggregate Gradation (Advanced Asphalt Technologies, LLC, 2011)*

Sieve Size		Typical Range for Overall Standard Deviation
mm	Number	
19	3/4	1.5 to 4.5%
12.5	1/2	2.5 to 5.0%
9.5	3/8	2.5 to 5.0%
4.75	# 4	2.5 to 5.0%
2.36	# 8	2.5 to 4.0%
1.18	#16	2.5 to 4.0%
0.6	# 30	2.0 to 3.5%
0.3	# 50	1.0 to 2.0%
0.15	# 100	1.0 to 2.0%
0.075	# 200	0.6 to 1.0%

* Advanced Asphalt Technologies, LLC. (2011). *NCHRP Report 673-A Manual for Design of Hot Mix Asphalt with Commentary*.

A first approach is based on the analysis of Basic Statistical Properties, for each project and for each mix design (Figure 3-11).

- 1) Calculation of mean and standard deviation for each mix design of each project.
- 2) Comparison with typical values obtained from a national report.
- 3) Conclusion related typical standard deviation.

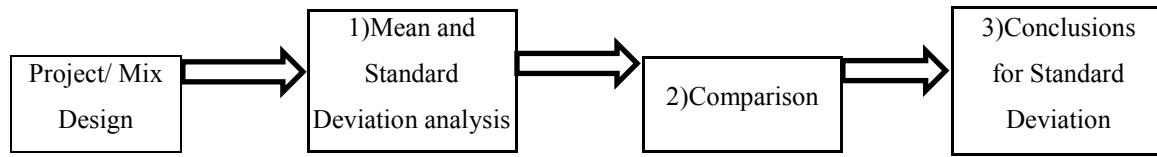


Figure 3-11: Steps for Variability Analysis

Statistical information available for existing projects helps on future research for analyzing common properties and gives information about typical variability.

3.1.1 Statistical Analysis

Mean and Standard Deviation were calculated for each of the projects and each of their mix designs. The results are presented in Tables 3-8, 3-9, 3-10 and 3-11 for Projects 1, 2, 3 and 4, respectively.

3.1.2 Commentary: Ranges for Standard Deviation

Common values for standards deviation were previously presented on Table 3-5, 3-6 and 3-7. This information will be used for comparison with the ranges obtained from the four projects studied above.

Projects and mix designs were analyzed in an independent way in order to keep consistency between properties from different mix designs, since each of them have different target values for each property. Maximum Standard Deviation values were combined and rounded to obtain a general table with a generic range of values.

Table 3-8: Basic Statistical Analysis. Project 1

		TYPE P1B1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	#200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	82	100.00	95.20	76.00	57.30	40.90	25.20	16.60	4.30		13.30	97.00	3.00	4.50
Mean		99.56	94.88	72.21	52.73	37.59	23.30	16.16	5.55	0.00	13.07	96.99	7.01	4.36
Standard Deviation		0.89	1.80	3.21	3.07	2.73	2.57	2.14	0.84	0.00	0.43	0.46	1.20	0.19
		TYPE P1B2												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	95	99.00	93.00	68.20	50.60	35.10	22.00	14.60	2.80		13.60	97.00	3.00	4.40
Mean		99.65	96.39	72.32	52.07	37.05	26.14	20.05	5.32	0.00	14.04	96.65	6.46	4.41
Standard Deviation		0.89	2.54	2.97	3.14	2.71	2.22	1.67	0.50	0.00	0.40	0.39	1.08	0.16
		TYPE P1B3												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	455	98.30	90.50	62.20	43.20	29.60	17.40	10.80	4.00		12.40	97.00	3.00	3.80
Mean		98.38	91.09	65.08	44.20	29.20	16.68	11.67	3.25	0.00	12.86	97.21	6.41	4.19
Standard Deviation		1.53	2.82	3.72	3.13	2.06	1.57	0.94	0.46	0.00	0.67	0.41	0.88	0.16
		TYPE P1B4												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	239	100.00	92.30	67.30	44.80	30.80	18.00	11.30	3.90		14.50	97.00	3.00	5.10
Mean		99.11	93.13	68.63	45.62	31.11	16.84	11.23	3.84	0.00	13.07	96.88	6.87	4.36
Standard Deviation		1.25	2.45	3.25	2.95	2.24	1.47	1.38	0.85	0.00	0.49	0.58	0.97	0.20

Table 3-8 - continued

		TYPE P1B5												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	109	99.90	94.90	71.40	45.90	29.90	13.40	9.10	3.60		13.70	97.00	3.00	4.70
Mean		99.67	94.59	71.73	45.48	29.58	12.71	8.77	3.65	0.00	13.68	96.90	6.48	4.67
Standard Deviation		0.70	2.30	3.44	2.87	1.90	2.47	1.55	0.73	0.00	0.56	0.60	0.97	0.24
		TYPE P1C1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	372	100.00	99.80	75.00	53.70	36.60	22.90	15.30	3.50		15.00	96.50	3.50	4.90
Mean		0.00	100.00	78.20	56.60	37.33	21.96	15.52	4.57	0.00	13.92	97.18	6.48	4.65
Standard Deviation		0.00	0.04	2.28	2.57	2.39	1.87	1.58	0.66	0.00	0.61	0.44	1.23	0.16

Table 3-9: Basic Statistical Analysis. Project 2

		TYPE P2B1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix	223	100.00	95.40	73.60	53.70	35.50	15.70	9.70	3.40		13.30	96.50	3.50	4.20
Mean		99.89	95.60	79.74	61.23	41.90	19.05	13.28	4.98	0.00	13.07	96.72	6.62	4.15
Standard Deviation		0.38	2.05	4.11	3.19	3.57	1.85	1.30	0.53	0.09	0.57	0.56	1.00	0.20
		TYPE P2C1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix	17	100.00	100.00	73.40	53.30	35.70	15.10	8.90	3.10		14.00	96.50	3.50	4.50
Mean		100.00	100.00	72.90	57.28	37.58	18.69	10.87	4.04	0.00	13.42	96.72	7.18	4.31
Standard Deviation		0.00	0.00	2.75	1.91	2.82	1.25	1.01	0.40	0.27	0.39	0.34	1.43	0.17
		TYPE P2C2												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix	93	100.00	100.00	73.40	53.30	35.70	15.10	8.90	4.22		14.10	96.50	3.50	4.50
Mean		100.00	99.96	78.49	62.34	41.34	17.71	11.92	4.22	0.00	13.66	96.69	7.65	4.38
Standard Deviation		0.00	0.35	4.73	3.97	4.50	2.19	1.63	0.71	0.47	0.48	0.55	1.21	0.18
		TYPE P2C3												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix	22	100.00	100.00	73.30	53.20	35.70	15.80	9.80	4.90		14.30	96.50	3.50	4.60
Mean		100.00	99.91	79.74	62.74	42.05	19.76	13.16	4.90	0.00	13.58	96.96	6.39	4.45
Standard Deviation		0.00	0.43	3.56	3.06	2.91	1.92	1.34	0.51	0.00	0.48	0.65	1.04	0.19

Table 3-10: Basic Statistical Analysis. Project 3

		TYPE P3B1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	468	100.00	96.80	77.60	56.20	38.90	19.80	12.20	3.40		13.70	96.50	3.50	4.30
Mean		99.92	95.97	79.44	58.55	32.30	14.48	11.09	5.54	0.06	13.31	96.79	6.91	4.20
Standard Deviation		0.33	2.01	3.37	2.69	2.60	1.60	1.25	1.05	0.69	0.53	0.50	1.03	0.17
		TYPE P3B2												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	60	100.00	99.30	79.50	56.60	39.10	19.60	14.00	3.40		14.00	96.50	3.50	4.30
Mean		98.81	93.38	80.52	60.70	35.40	17.88	13.35	4.10	0.00	13.60	96.80	6.46	4.22
Standard Deviation		1.48	2.55	3.30	2.50	2.50	1.76	1.39	0.96	0.00	0.63	0.58	1.08	0.17
		TYPE P3B3												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	133	100.00	96.80	77.60	56.20	38.90	19.80	12.20	3.40		13.50	96.50	3.50	4.30
Mean		99.93	95.99	81.69	60.01	33.83	15.83	11.06	4.94	0.14	13.33	96.74	6.90	4.29
Standard Deviation		0.34	2.13	3.15	2.63	2.61	1.87	1.52	0.89	0.79	0.46	0.52	1.28	0.17
		TYPE P3C1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	205	100.00	100.00	83.00	59.50	41.40	20.70	12.30	3.40		14.10	96.50	3.50	4.60
Mean		100.00	99.92	83.43	63.07	37.01	16.22	11.03	3.94	0.05	13.58	96.79	7.34	4.42
Standard Deviation		0.00	0.89	2.35	2.13	2.62	1.67	1.54	1.16	1.09	0.43	0.43	0.98	0.13

Table 3-10 - continued

		TYPE P3C2												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	58	100.00	100.00	82.40	58.20	39.70	19.40	13.70	3.20		14.50	96.50	3.50	4.60
Mean		100.00	99.99	83.00	63.23	37.99	19.18	13.44	2.97	0.00	14.32	96.52	6.89	4.40
Standard Deviation		0.00	0.11	2.22	1.96	3.07	2.13	1.62	0.53	0.21	0.42	0.45	0.89	0.11
		TYPE P3C3												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	27	100.00	100.00	82.90	59.10	40.90	20.80	12.70	3.50		14.30	96.50	3.50	4.50
Mean		100.00	100.00	83.54	62.00	36.01	15.01	10.26	4.78	0.00	13.86	96.88	6.80	4.46
Standard Deviation		0.00	0.00	1.95	2.00	2.48	1.36	1.14	0.57	0.00	0.41	0.40	1.13	0.14

Table 3-11: Basic Statistical Analysis. Project 4

		TYPE P4B1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	138	100.00	92.80	76.95	56.60	39.10	19.40	14.00	3.40		14.00	96.50	3.50	4.30
Mean		98.18	92.06	80.83	60.63	35.69	17.51	13.12	3.89	0.00	13.52	96.71	6.39	4.17
Standard Deviation		1.75	3.00	3.15	2.47	2.05	1.33	1.32	0.38	0.00	0.59	0.42	1.10	0.20
		TYPE P4C1												
		Gradation (% passing)									Volumetric properties			AC
	N	1"	3/4"	3/8"	# 4	# 8	# 30	# 50	# 200	Minus # 200	VMA	Lab Model Density	In place Air Voids	Asphalt Content
Mix Design	23	100.00	100.00	82.40	58.20	39.60	19.40	13.70	3.20		14.40	96.50	3.50	4.50
Mean		100.00	100.00	82.69	64.47	40.64	21.12	15.65	4.71	0.00	14.27	96.64	6.76	4.43
Standard Deviation		0.00	0.00	2.65	2.08	1.64	1.11	0.98	0.30	0.00	0.70	0.49	1.13	0.19

Table 3-12 gives the Maximum Standard Deviation obtained from the calculations on Project 1, 2, 3 and 4 in comparison with typical values of standard deviation for HMA properties given by NCHRP, 2011.

For aggregate gradation, the maximum standard deviations obtained at this study were smaller than the typical value, except for % passing #8 sieve. Other gradation properties such as for % passing #30, #50 and #200 sieve have values nearly the typical or lower.

The Voids in Mineral Aggregate has a maximum standard deviation of 0.7%, lower than the typical 0.9%. In-place air void has values lower than the typical. The maximum lab-molded density standard deviation is 1.1%, slightly greater than the typical 0.9%. The asphalt content has a maximum of 0.24%, nearly the typical value.

Table 3-12: Maximum Standard Deviation

	PROPERTY	Project 1	Project 2	Project 3	Project 4	Maximum of all Projects (1 to 4)	NCHRP Report 673
Gradation (% passing)	1"	1.53	0.38	1.48	1.75	1.75	
	3/4"	2.82	2.05	2.55	3.00	3.00	1.5 to 4.5
	3/8"	3.72	4.73	3.37	3.15	4.73	2.5 to 5.0
	# 4	3.14	3.97	2.69	2.47	3.97	2.5 to 5.0
	# 8	2.73	4.50	3.07	2.05	4.50	2.5 to 4.0
	# 30	2.57	2.19	2.13	1.33	2.57	2.5 to 3.5
	# 50	2.14	1.63	1.62	1.32	2.14	1.0 to 2.0
	# 200	0.85	0.71	1.16	0.38	1.16	0.6 to 1
	Minus # 200	0.00	0.47	1.09		1.09	
Volumetric Properties	VMA	0.67	0.57	0.63	0.70	0.70	0.9
	Lab Model Density	0.60	0.65	0.58	1.10	1.10	0.9
	In place Air Voids	1.23	1.43	1.28	1.13	1.43	1.3 to 1.5
AC	Asphalt Content	0.24	0.20	0.17	0.20	0.24	0.15 to 0.3

Variability during construction is affected by several factors from the construction procedure to testing personnel in the laboratory. Considering such variability, the standard deviation obtained in each of the four projects in Texas were inside or nearly the limits considered typical for HMA properties. Due to the amount of data and variability of the projects considered for this thesis, the maximum values presented on Table 3-12 can be considered as Typical Standard Deviation ranges for As-Constructed HMA pavements.

3.2 The Effect of Pay Adjustment Factor on As-Constructed HMA Properties

The analysis of the HMA properties was performed based on a database of 2,819 records. All properties analyzed were studied in comparison with Operational Tolerance specified on Table 2-16. Therefore, differences from current JMF target (test values-reference values) were calculated for all properties except for in-Place air voids (operational tolerance for in-place air voids is given by absolute values instead of deviation from the target). The purpose of using those differences is to obtain a measure that is comparable with TxDOT specification for comparison and to homogenize the results for all properties, independently on the type of mix design.

The steps followed for the analysis are (Figure 3-12):

- 1) Calculate descriptive statistics of HMA properties and analysis parameters.
- 2) Calculate frequency distributions for each property under study.
- 3) Analysis of histogram and normality plots for each property to determine if it resembles a normal distribution.

4) Conduct a Normality analysis to determine whether or not the property can be approximated to a normal distribution. The tests used were the Kolmogorov-Smirnov and Shapiro-Wilk for analysis of normality.

5) Study the confidence intervals for a common 95% significance level and compare with the operational tolerance ranges. In addition, calculate the probability of having HMA properties inside operational tolerances.

6) Analysis of the effect of the Pay Adjustment Factor on the data distribution.

7) Assessment of the relation between test results and applied payment factors.

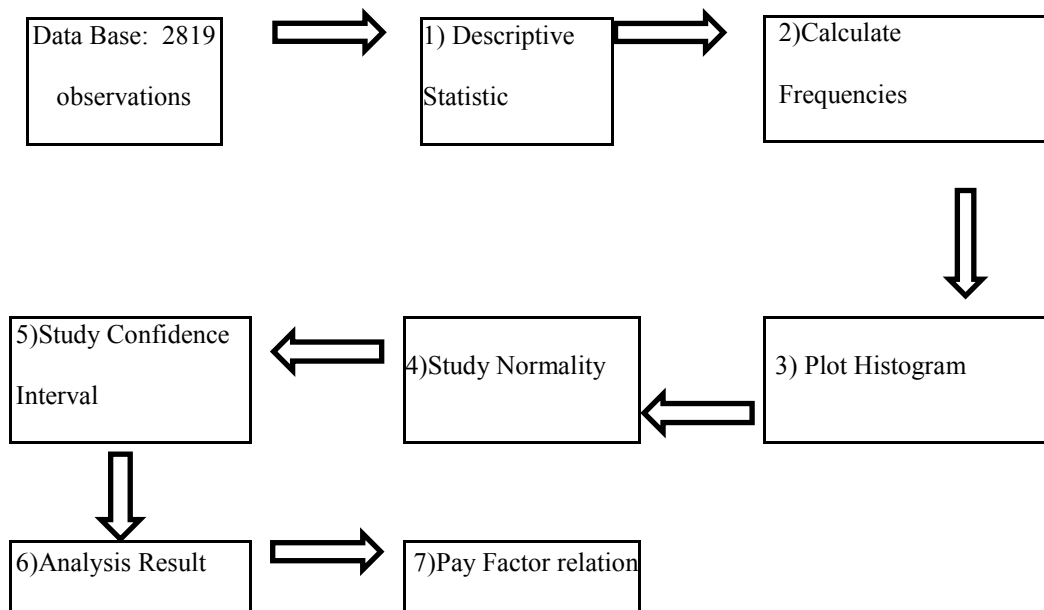


Figure 3-12: Steps for Analysis of Effect of Payment Factor

The process described on Figure 3-12 was performed for each of the HMA properties relevant for this research. The results are summarized on Table 3-13.

The decision if a distribution was a Normal distribution or not was based on the observation of the histogram and normality plots, in the analysis of kurtosis and skewness of the property distributions and in the normality tests.

The criteria followed for kurtosis and skewness analysis was:

- i. Kurtosis is a measure of “peakedness” of a distribution: When in comparison with a Normal distribution, negative values of kurtosis show a flatter shape while positive values show a more peaked shape.
- ii. Skewness: Positive values reveal right skewness with respect to a Normal distribution whereas negative values show left skewness. In addition, related to the symmetry of the distribution, it will be classified as follow:
 - Symmetric distribution between -0.5 and +0.5
 - Moderately Symmetric distribution between -1.0 and -0.5, and 0.5 and 1.0
 - Non Symmetric distribution: less than -1.0 or more than 1.0.

For the analysis of normality, the hypothesis test established was:

Ho: Data is Normally distributed

H1: Data is not Normally distributed

The confidence level considered was 95%, for the rejection or acceptance of the null hypothesis; two tests were performed using SSPS software:

- i. Kolmogorov-Smirnov test:

If $D < 0.05$, the distribution is not a Normal Distribution.

If $D > 0.05$, then we cannot reject the hypothesis that the distribution is a Normal Distribution

ii. Shapiro-Wilks' W test:

If $W < 0.05$, the distribution is not a Normal Distribution.

If $W > 0.05$, then we cannot reject the hypothesis that the distribution is a Normal Distribution

Deviation from Target Laboratory-Modeled Density

Deviation from the Target Laboratory-Modeled Density was analyzed in order to study the behavior of test results during the HMA production and their relation with the application of production pay factor shown in Table 2-13, as part of the QA/QC procedures.

The operational tolerance for laboratory-molded density is $\pm 1\%$ from the target JMF, as specified on Table 2-16. Although, production pay factors consider a valid tolerance of $\pm 1.8\%$. It will be considered a passing result but a penalty in payment will be applied. However, if the pay factor drops below 1.0 in three consecutive lots, the production needs to be stopped and the material needs to be removed (TxDOT, 2004).

Kurtosis and skewness values given in Table 3-13, suggest a symmetric distribution, left skewed, close in shape to the Normal distribution. The mean has a value close to -0.1% , which indicates a tendency of obtaining Laboratory-Molded Densities below the specified value on JMF.

Table 3-13: Descriptive Statistic for As-Constructed HMA Properties

	Deviation from target Lab-Molded Density	In-Place Air Voids	Deviation from target AC	Deviation from target VMA	Deviation from target %retained #8	Deviation from target %retained #30	Deviation from target %retained #50	Deviation from target %passing #200	Rut (HWT)
Mean	-0.098	6.730	-0.023	1.118	1.671	0.255	-1.791	0.788	5.856
Standard Error	0.010	0.021	0.005	0.011	0.042	0.042	0.029	0.023	0.444
Median	-0.100	6.700	-0.100	1.100	1.600	0.200	-1.500	0.700	4.880
Mode	0.100	6.600	-0.300	0.800	1.400	0.200	-1.100	0.200	3.760
Standard Deviation	0.526	1.089	0.263	0.582	2.214	2.244	1.554	1.197	3.106
Sample Variance	0.276	1.186	0.069	0.339	4.902	5.036	2.416	1.434	9.644
Kurtosis	-0.075	-0.038	-0.230	-0.023	0.171	0.488	-0.119	-0.411	-0.310
Skewness	-0.418	0.162	0.554	0.350	0.043	0.367	-0.305	0.231	0.787
Range	3.500	8.200	1.600	3.700	17.500	17.100	11.300	8.100	11.440
Minimum	-2.300	3.000	-0.800	-0.600	-8.000	-6.700	-6.000	-2.000	1.390
Maximum	1.200	11.200	0.800	3.100	9.500	10.400	5.300	6.100	12.830
Sum	-276.970	18965.800	-63.930	3142.440	4710.990	718.810	-5037.300	2215.490	286.950
Count	2819	2818	2817	2811	2819	2815	2812	2810	49
Kolmogorov- Smirnov	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.000	0.004
Shapiro-Wilk	0.000	0.000	0.000	0.009	0.000	0.000	0.000	0.000	0.001
95% CI	Min	-1.13	4.60	N/A	-0.02	-2.67	-4.14	N/A	N/A
	Max	0.93	8.86	N/A	2.26	6.01	4.65	N/A	N/A
Probability within tolerance limits	93.9%	91.7%	N/A	97.3%	93.2%	81.6%	N/A	N/A	N/A
Percentage within tolerance limits	95.7%	93.4%	84.7%	99.4%	92.8%	77.0%	78.0%	83.2%	98.0%

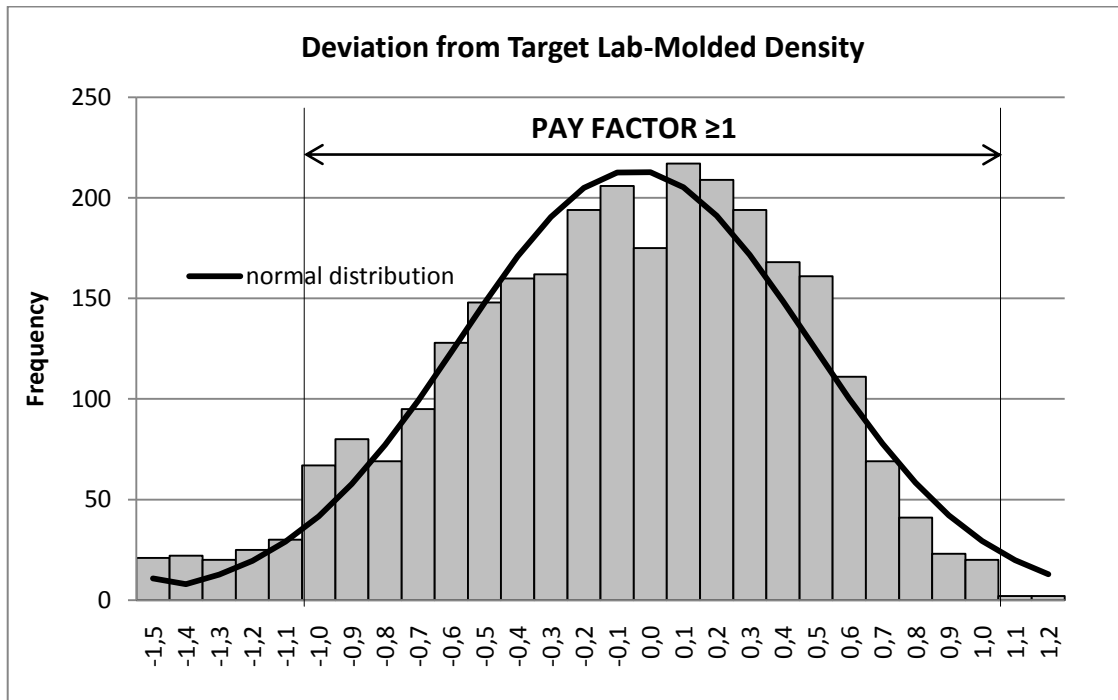


Figure 3-13: Histogram: Deviation from Target Lab-Molded Density

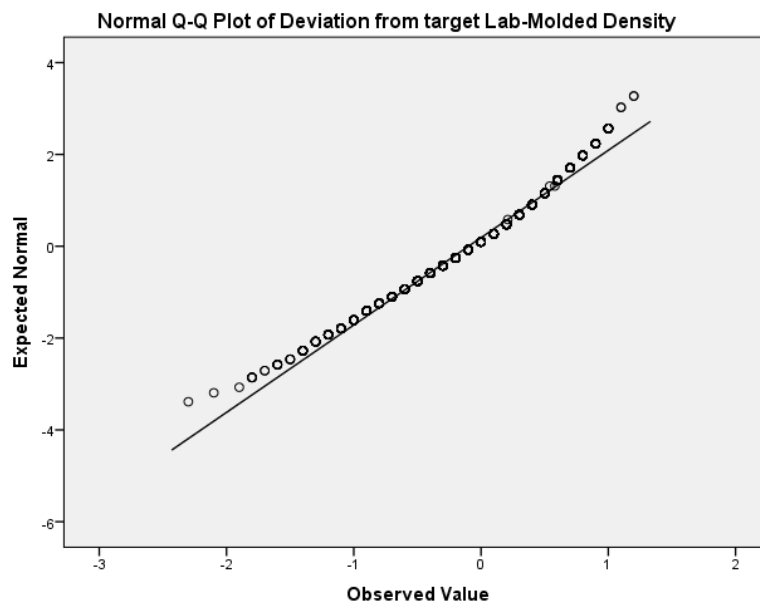


Figure 3-14: Normal Probability plot: Deviation from target Lab-Molded Density

Figure 3-13 shows a frequency distribution for deviation from target laboratory-molded density skewed to the left and close to the Normal distribution shape. Figure 3-13 and Figure 3-14 shows differences with the Normal distribution, and normality tests (Table 3-13) suggest that deviation from target laboratory-molded density is not normally distributed. Even though, since it is considered symmetric and not far apart from the Normal, for the purpose of this study, deviation from target laboratory-molded density is considered as approximately Normal distributed.

More than 95% of the results were within tolerance and with a production pay factor greater than 1.0. Based on the hypothesis of deviation from target laboratory-molded density being approximately Normal distributed, the confidence interval calculated for a 95% level of confidence was [-1.13% to 0.93%] (Table 3-13). This range is slightly wider than the 1% tolerance, but nearly the payment factor of 1.0. The payment factor for a deviation of -1.13% is 0.95 and for 0.93% is 1.007. In addition, the range is inside the 1.8% limits proposed by the TxDOT specification for removal and replace.

And, the probability of having deviation within pay factors greater to or equal 1.0% is a 93.85%. Therefore, the production payment factor applied to this property comprises values inside the operational tolerance range required by the specifications of the agency.

In-Place Air Voids

In-Place Air Voids is, in conjunction with deviation from target laboratory-modeled density, the property for which TxDOT standard specifications consider a Pay

Adjustment Factor, as shown in Table 2-14. No operational tolerances for in-place air voids are identified on the TxDOT Specifications. Therefore, the values analyzed in this research were the test result values, without calculation of deviation from the target since there was no value on the operational tolerance to compare.

A wide range between 2.7% and 9.9% is allowed for this property. However, a penalty for values outside the range of 4.75 to 8.5% is applied (inside this range, the pay factor applied is 1.0 or greater). In addition, if pay factor drops below 1.0 in three consecutive lots, the production needs to be suspended and lots need to be removed. Finally, as a second check for failing in-place air voids results, two additional core samples are taken within 3ft of the original core to obtain new payment factors and confirm the failure or goodness of the test data (TxDOT, 2004).

The results for descriptive statistics given in Table 3-13 suggest a shape similar to the Normal distribution in terms of “peakedness”. Skewness value indicates a right skewness and a symmetric distribution of the data. The same conclusion was obtained from the Histogram (Figure 3-15). Figure 3-16 presents the Normal Probability plot. The expected values are very close to the observed values. A symmetric distribution is shown with the majority of the data concentrated around the central values. Even though, a Normality test resulted in a conclusion of non-normality, after the plots and descriptive statistical analysis, the in-place air voids were considered approximately Normal distributed for the purpose of this study.

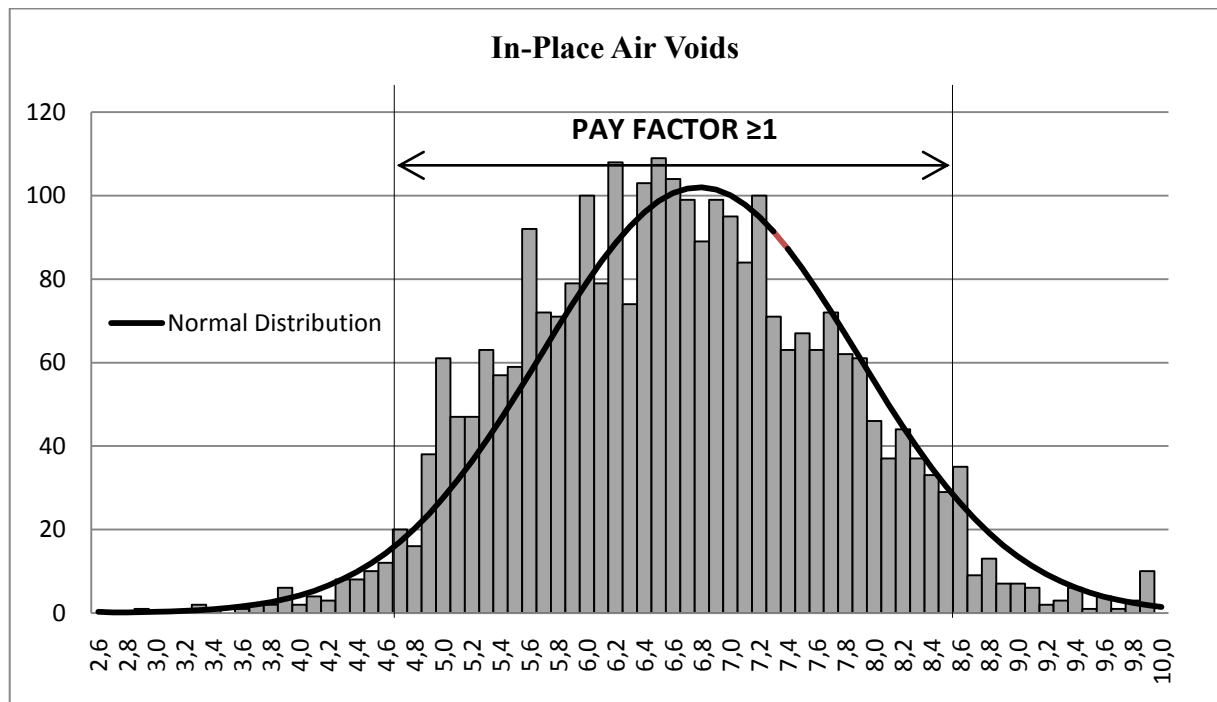


Figure 3-15: Histogram: In-Place Air Voids

The percentage of results within a payment factor equal or greater than 1.0 was 93.43%. Considering in-place air voids as Normally distributed, 95% confidence interval calculated was [4.6% to 8.86%]. This range is slightly wider than the 4.6% to 8.9% range for payment factor of 1.0, but still very close, the payment factor for 4.6% is 0.990 and for 8.86% is 0.993, and it is inside the 2.7 to 9.9% considered by the TxDOT specification (TxDOT, 2004) as acceptable. The probability of having these values inside tolerance limits with a pay factor greater or equal to 1.0 is a 91.68%. Therefore, the application of the payment factor embraces values inside the acceptable tolerance and pay factor equal or greater than 1.0.

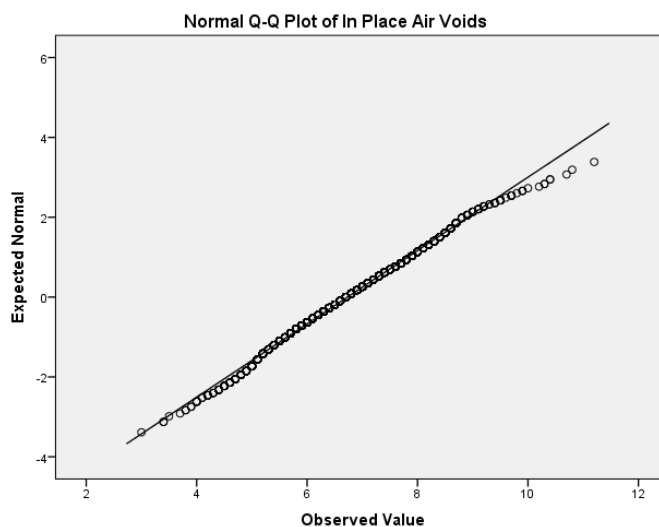


Figure 3-16: Normal Probability plot: In-Place Air Voids

In the following subchapter, other properties will be analyzed continuing with the same procedure. The next properties are not related to the Pay Factor and their analysis would help understand their effects and benefits on asphalt pavement properties.

Deviation from Target Asphalt Content

Asphalt Content on mixture is controlled by operational tolerance of deviation from the target JMF asphalt content as shown on Table 2-16. Operational tolerance for AC is within $\pm 0.3\%$ for the JMF AC.

An additional limit is established on the TxDOT Standard Specifications: the production must be suspended when the AC deviates for JMF by more than 0.5% (TxDOT, 2004). Furthermore, it is specified that no bonus would be applied when 2 or more cores for the same sublots are outside the operational tolerance. These two values will help in the analysis of test results for asphalt content.

The descriptive statistics were calculated and summarized in Table 3-13. A mean of -0.023% was obtained, this value is nearly zero, and negative, showing a tendency of obtaining no difference of asphalt content with respect to the JMF. In addition, the kurtosis and skewness values suggest a moderately symmetric distribution, right skewed and slightly flatter than the Normal distribution.

Figure 3-17 reflects the asymmetry of the data and the differences in shape from the Normal distribution. Figure 3-18 confirms the asymmetry of the results and the concentration of values on the left side of the distribution. In addition to the plot analysis, the Normality test indicates a non-normal distribution. Consequently, the deviation from target asphalt content will not be considered as Normally distributed for further analysis. Around 85% of the data analyzed were within the operational limits ($\pm 0.3\%$), and 97% are within $\pm 0.5\%$.

This is a difference from the results obtained when payment factors are applied. The analysis of deviation from target laboratory-modeled density and in-place air voids concluded that, when pay factors are applied:

- 95% confidence interval used to be within tolerance range
- Results are close to payment factor equal or greater than 1.0.
- Results are far apart from the suspended production factors.

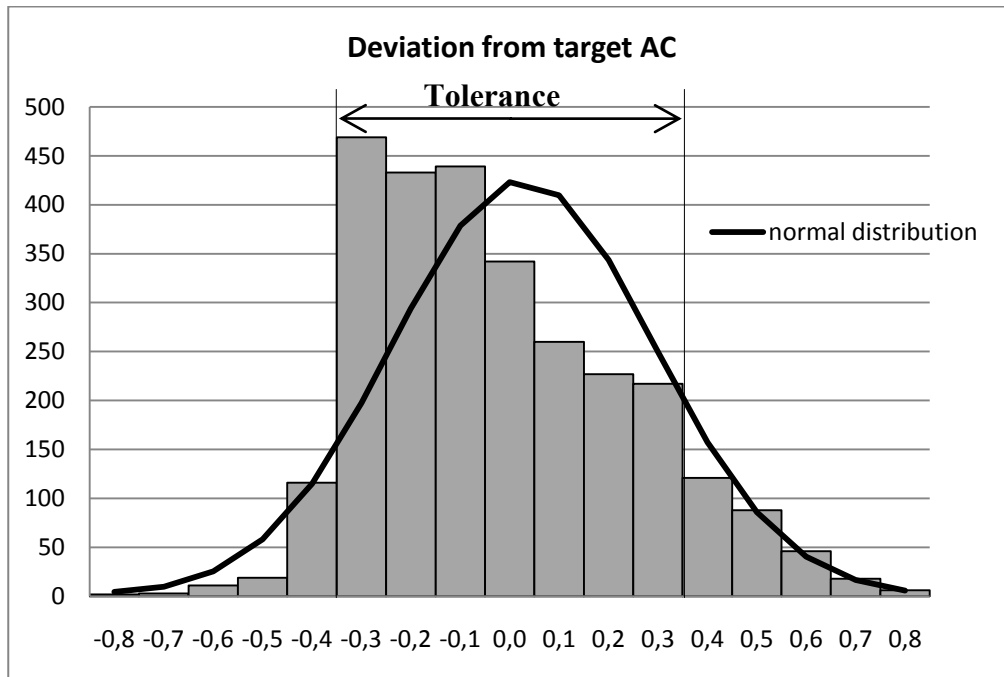


Figure 3-17: Histogram: Deviation from target Asphalt Content

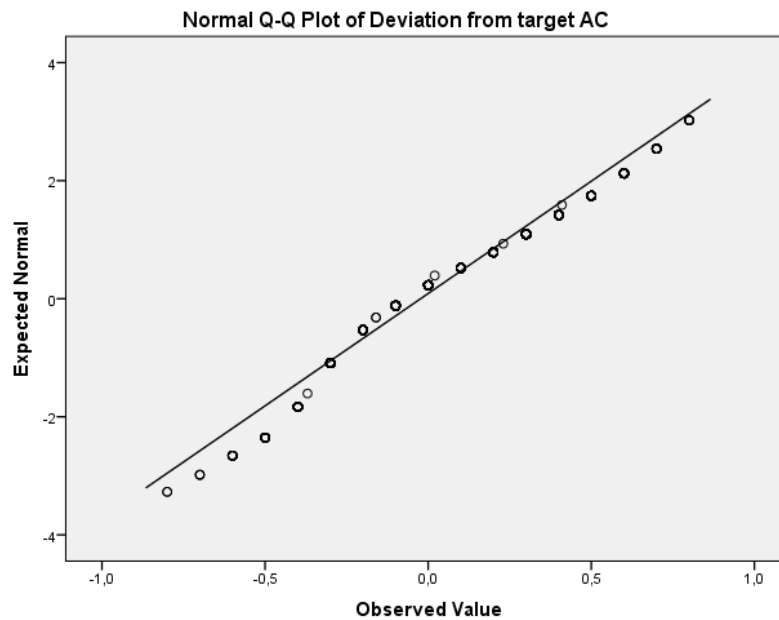


Figure 3-18: Normal Probability plot: Deviation from target AC

Deviation from target asphalt content has a significant proportion of data inside tolerance limits. However, the distribution reveals that no penalty on extreme limits increases the use of specification limits as the range for production (production takes advantage and operates within limits of the range). Indeed, data is concentrated on the -0.3% difference from JMF. Therefore, the majority of samples have a reduction on the asphalt content, inside tolerance but using extreme boundaries of 0.3% as a limit of production. The reduction of asphalt content highly reduces the cost of production since it is the most expensive component of the asphalt mixture.

Table 3-14: Proposal for Production Pay Adjustment Factor for Deviation from Target Asphalt Content

Deviation from target AC	Pay Adjustment Factor
0.0-0.1	1.05
0.1-0.2	1.03
0.2-0.3	1.00
0.3-0.4	0.8
0.4-0.5	0.7
>0.5	Remove and Replace

This result leads to the conclusion of recommending a production payment factor for the deviation from target Asphalt Content. Table 3-14 presents a recommendation for those factors. This recommendation considers a 5% bonus on the payment for asphalt content equal to the target, and a 30% penalty for values outside the acceptance limit. No further studies were done for this proposal; therefore, it is just an example for further investigation or specification revision.

Deviation from Target VMA

The requirements for tolerance of Void in Mineral Aggregate are indicated in Table 2-16. This value is a function of the HMA mixture type. For the cases under study, the minimum values used as tolerance limits are 12% for type B and 13% for a type C mixture.

Table 3-13 gives a summary of the descriptive statistics for deviation from target VMA. A mean of 1.18% was obtained, indicating the tendency of being over the minimum value given in the specification. From kurtosis and skewness values suggest a symmetric distribution, skewed to the right and a flatter shape than the Normal.

Figure 3-19 presents a symmetrical distribution with a shape very close to the Normal distribution. Figure 3-20 shows the Normal probability plot. The expected values are around observed values, with difference on boundary values. It is presented as a symmetric distribution with a majority of the data concentrated around the mean value. Consequently, for the purpose of this study, deviation from the target VMA was considered as a Normal distribution, although, the Normality test suggests that the distribution is not Normal.

Approximately 99.5% are over the minimum VMA values given in Table 2-16. In addition, at 95% confidence level, deviation from the target VMA will be between 0% and +2.26%. With a 97.27% of probability, VMA values will be greater than the minimum.

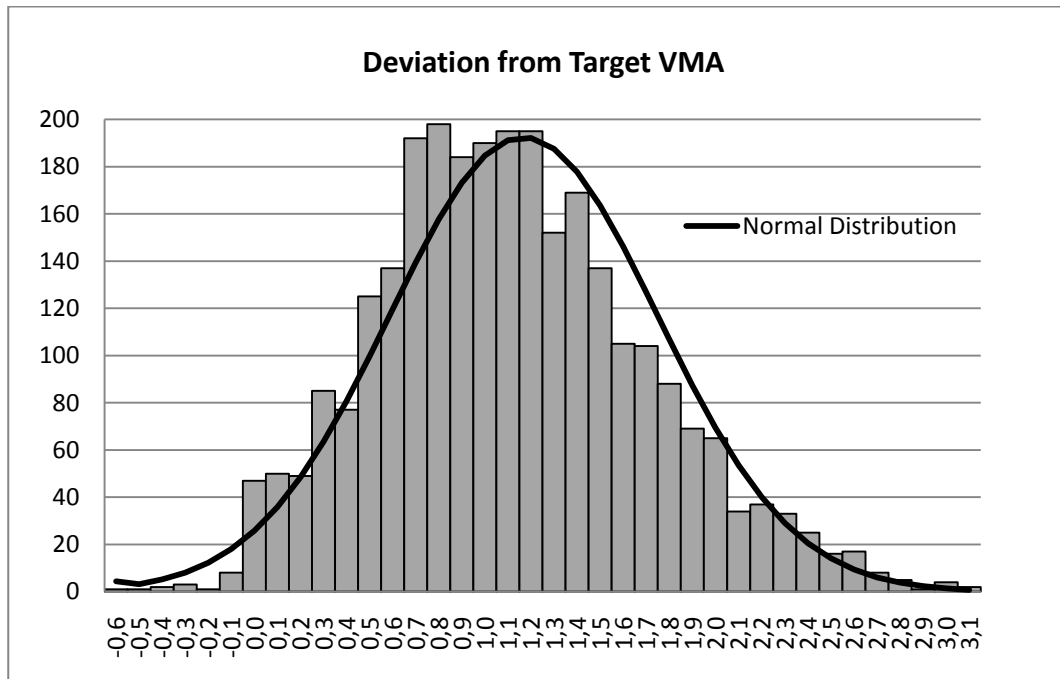


Figure 3-19: Histogram: Deviation from target VMA

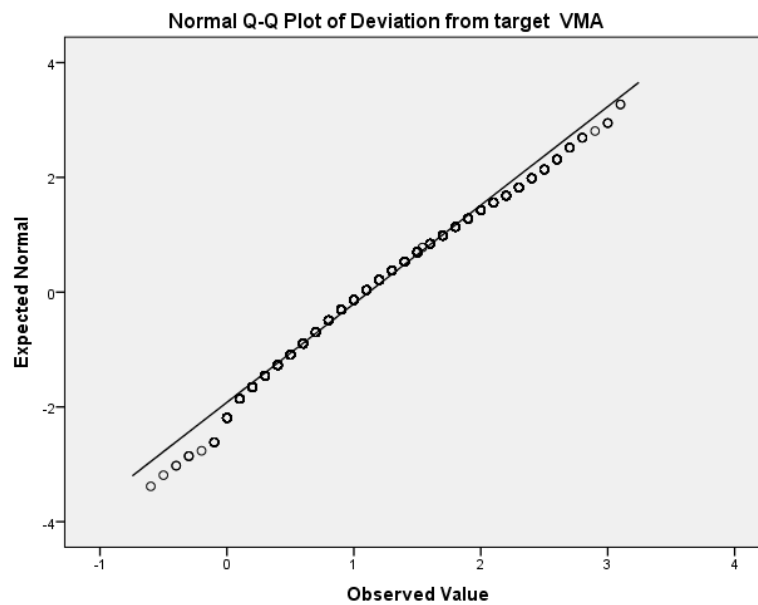


Figure 3-20: Normal Probability plot: Deviation from target VMA

This leads to the conclusion that even when Payment Factors were not applied to the VMA values, the results are similar to other properties that consider the application of those factors. In addition, VMA, per definition, is related to asphalt content and gradation. Therefore, by controlling these two properties, VMA will be controlled.

Deviation from Target Percentage Retained #8 Sieve (2.36mm)

Tolerance for Deviation from the Target percentage Retained on #8 Sieve given in Table 2-16 is +/-5% difference from the JMF. When within this tolerance, the mixture production gradation may fall outside the master gradation limits given in Table 2-2 (TxDOT, 2004).

The descriptive statistic was calculated and the results summarized in Table 3-13. A mean value of 1.67% indicates an increase on the percentage retained on #8 sieve with respect to the target. Kurtosis and skewness values indicate a more peaked distribution than the Normal distribution, but still very close, in addition to a symmetric and right skewed distribution.

Figure 3-21 shows a symmetrical distribution, with a shape similar to the Normal distribution. Figure 3-22 shows that the observed values are close to the expected from a Normal distribution. However, the Normality test performed suggests a non-normal distribution. The descriptive statistics and plots present similarities with the Normal distribution, and therefore, for the purpose of this study, it will be considered that the data fits approximately into a Normal distribution. Table 3-13 indicates that around 93% of the test results were within tolerance limits. Deviation from the target percentage retained

on #8 sieve will be in a range of [-2.67% to 6.0%] for a 95% level of confidence. Upper limit is slightly out of tolerance, and the lower range limit is inside tolerance and far apart from the 5%, that confirm the tendency of having a percentage for individual retained on sieve #8 greater than the target.

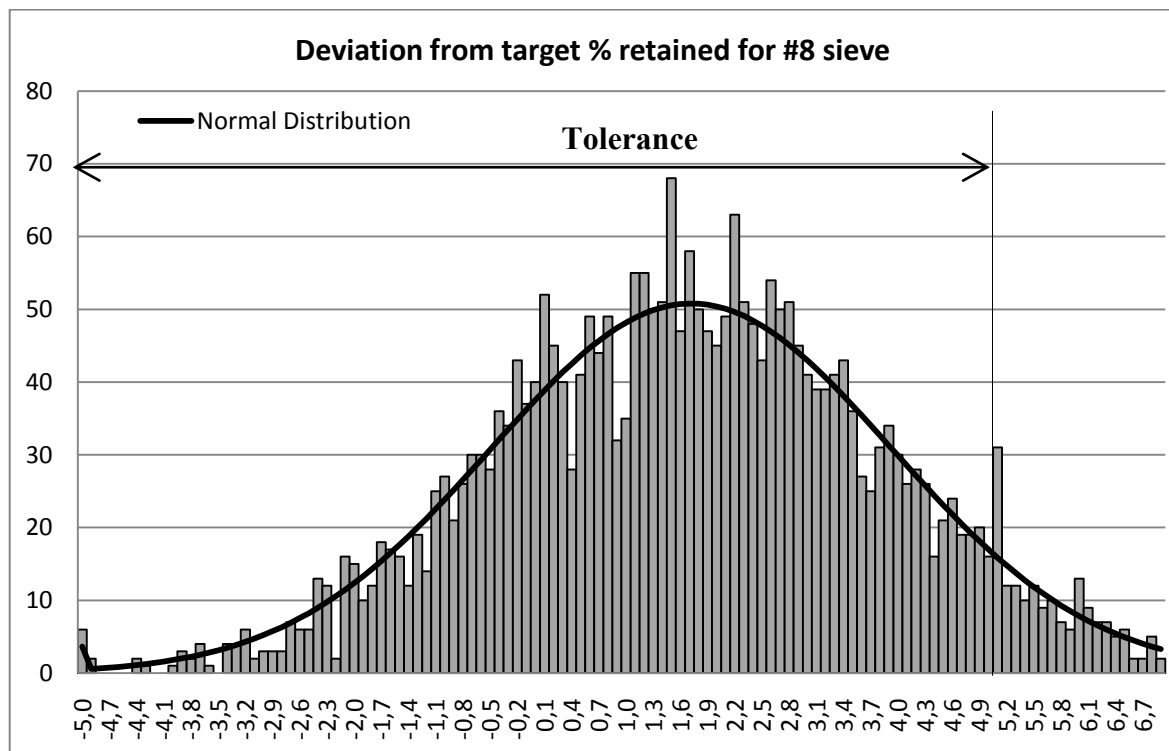


Figure 3-21: Histogram: Deviation from target % retained on #8 sieve.

In addition, the probability of having values within the tolerance limits is 93%. Consequently, for deviation from the target percentage retained on #8 sieve, values are comprised in a range near the acceptance limits. No payment factors are applied on this property, but in reality there appears to be no need for them due to the results range obtained in the analysis.

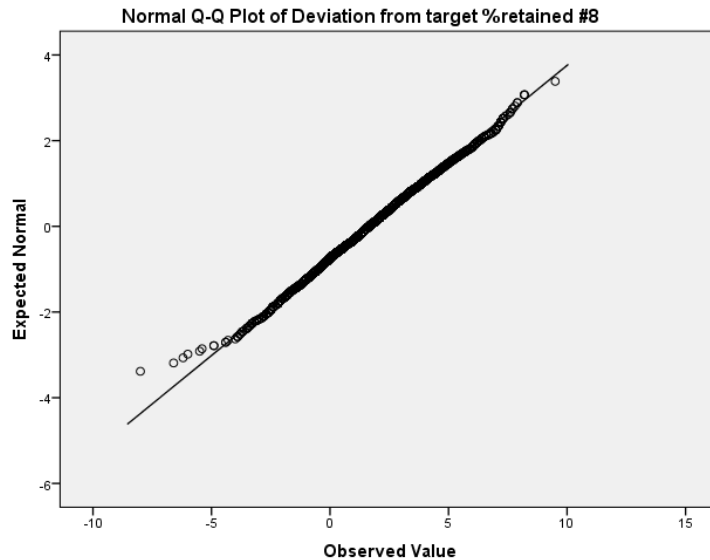


Figure 3-22: Normal Probability plot: Deviation from target % retained on #8 sieve

Deviation from Target Percentage Retained on #30 Sieve (0.6mm)

The operational tolerance for Deviation from Target percentage retained on #30 sieve is $\pm 3.0\%$ (Table 2-16). When within this tolerance, mixture production gradation may fall outside the master grading limits given on Table 2-2 (TxDOT, 2004) .

As for the other gradation properties, there is no payment factor applied to the percent retained on #30 sieve. The calculation of the descriptive statistics is given in Table 3-13. This table shows a positive kurtosis, so the distribution is sharper than the Normal distribution. In addition, it shows a right skewed and symmetric distribution. The mean is 0.25%, so, test results tend to have a percentage retained on a #.30 sieve slightly greater the JMF. Figure 3-23 shows the difference between the Normal distribution and property deviation. But it is still close to a Normal shape.

The distribution for this property is not considered Normally distributed when Normality test is performed (Table 3-13). From Figure 3-23 and 3-24, it is observed that

the distribution deviates from the Normal distribution on the right and left boundaries values. However, the observed and expected values from Normal are very close for central values. Therefore, for the purpose of this study, data is considered approximately Normal distributed.

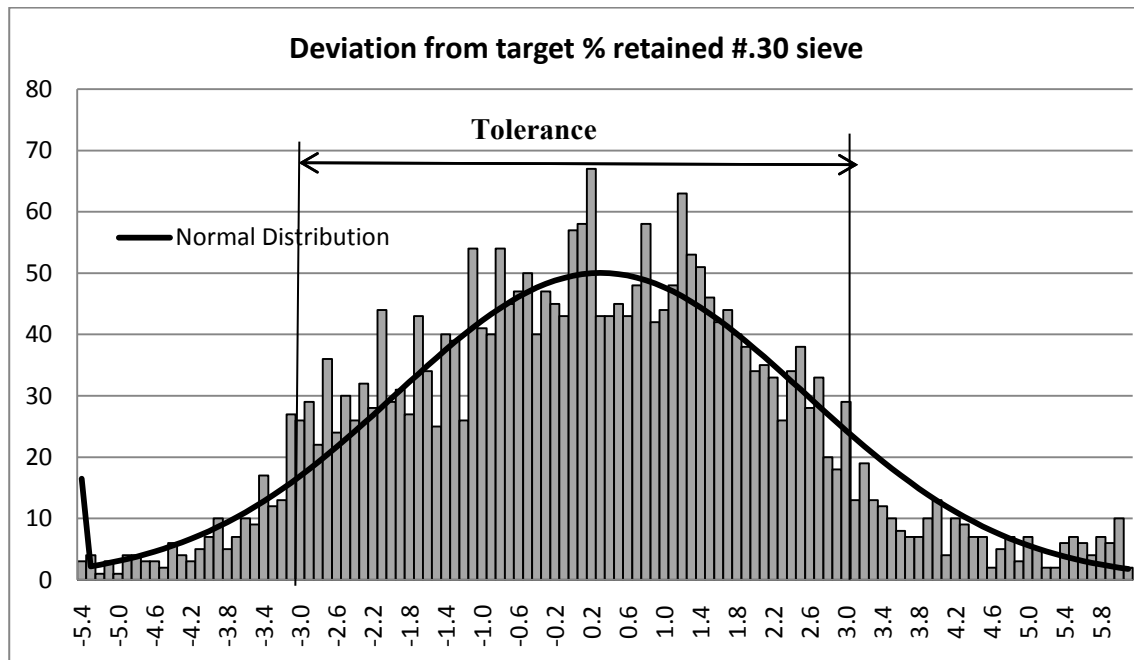


Figure 3-23: Histogram: Deviation from target % retained on #30 sieve.

The percentage of defective data for deviation from target percentage retained on #30 sieve is 23%. Assuming the Normality of the distribution, the interval obtained for a 95% level of confidence is $[-4.14\% \text{ to } 4.65\%]$. This range is wider than the $\pm 3\%$ interval required in the specifications. In addition, there is only an 81.6% probability of having the results inside the tolerance.

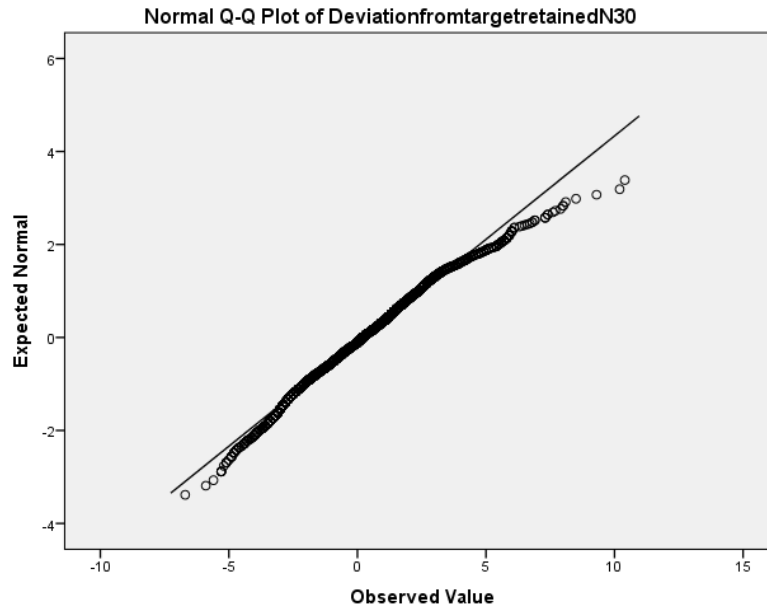


Figure 3-24: Normal Probability plot: Deviation from target % retained on #30 sieve

Due to the amount of defective results obtained, it is recommended the application of payments factors for deviation from the target percentage retained on #30 sieve. Those pay factors will help stimulate the contractor to keep material inside the tolerance limits. A proposal for those payment factors is defined on Table 3-15.

The payment factors recommended were based on a 5% bonus and 10% penalty on the production process. No additional studies were performed for this proposal, and it should be used just as an example.

Deviation from Target Percentage Retained on #50 Sieve (0.3 mm)

Deviation from target percentage retained on #50 sieve operational tolerance according to Table 2-16 is $\pm 3.0\%$. As for all sieves larger than #200, this range may fall outside the master grading limits specified on Table 2-2. Furthermore, no pay factors are applied during production of the asphalt mixture.

The descriptive statistics (Table 3-13) indicate a negative kurtosis with a value of approximately zero, so the shape should be close to the Normal distribution in terms of peakedness. The distribution is left skewed and it can be considered symmetric. The mean has a value of -1.79%, indicating the tendency of getting values with a smaller percentage retained on #50 sieve than the JMF values.

Figure 3-25 shows a clear deviation from the Normal distribution and the unsymmetrical characteristic of this property. From Figure 3-26, the same conclusion is obtained. Moreover, the Normality tests performed suggest a non Normal distribution. Therefore, deviation from target percentage remained on #50 sieve cannot be approximated to a Normally distributed.

No confidence interval is calculated since the distribution for this property is unknown. Approximately 77% of the results for this property were inside of the tolerance limits, but still 23% of the results are greater than tolerances. Furthermore, all defective results are values under the operational tolerance and then, percentages for the individual retained on #50 sieve tend to be smaller than the JMF value.

The spread distribution detected for this property and the percentage of defective values lead to the conclusion for the need of payment factors. As operational tolerances are in the same range than deviation from the target retained on #30 sieve, the production payments factors suggested are the same as those indicated in Table 3-15.

Table 3-15: Proposal for Production Pay Factors for Deviation from target percentage
retained on #30 & #50 sieves

Absolute Deviation from target % retained between #30 & #50 sieves	Pay Adjustment Factor	Absolute Deviation from target % retained between #30 & #50 sieves	Pay Adjustment Factor
0	1.050	1.7	0.965
0.1	1.044	1.8	0.959
0.3	1.039	1.9	0.954
0.4	1.034	2	0.949
0.5	1.028	2.1	0.944
0.6	1.023	2.2	0.938
0.7	1.018	2.3	0.933
0.8	1.012	2.4	0.928
0.9	1.007	2.5	0.922
1	1.002	2.6	0.917
1.1	0.997	2.7	0.912
1.2	0.991	2.8	0.906
1.3	0.986	2.9	0.901
1.4	0.981	3	0.900
1.5	0.975	>3	Additional investigation
1.6	0.970		

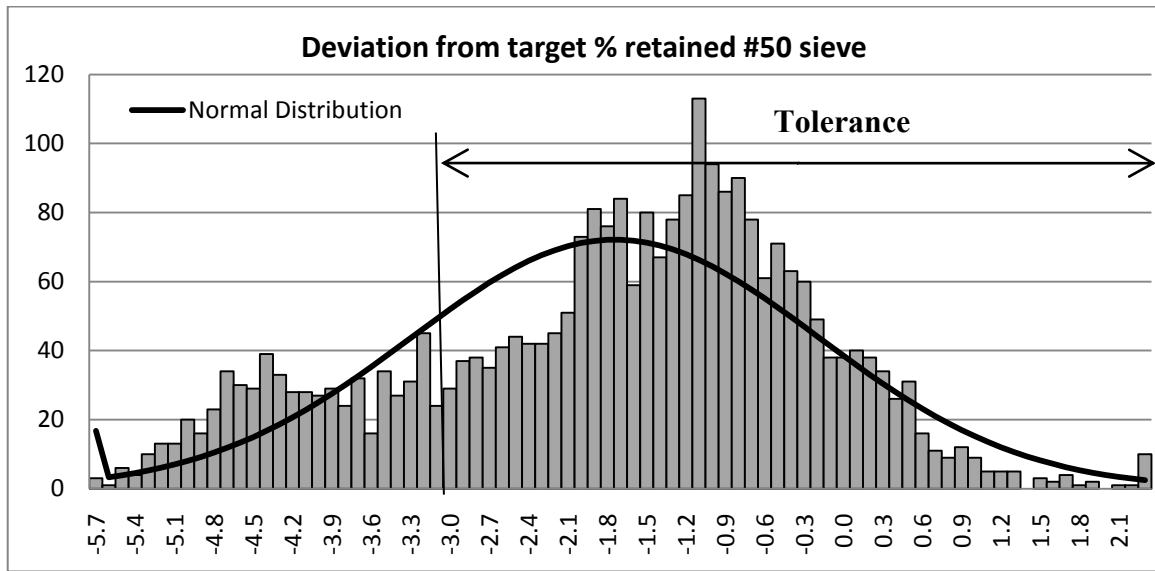


Figure 3-25: Histogram: Deviation from target % retained on #50 sieve

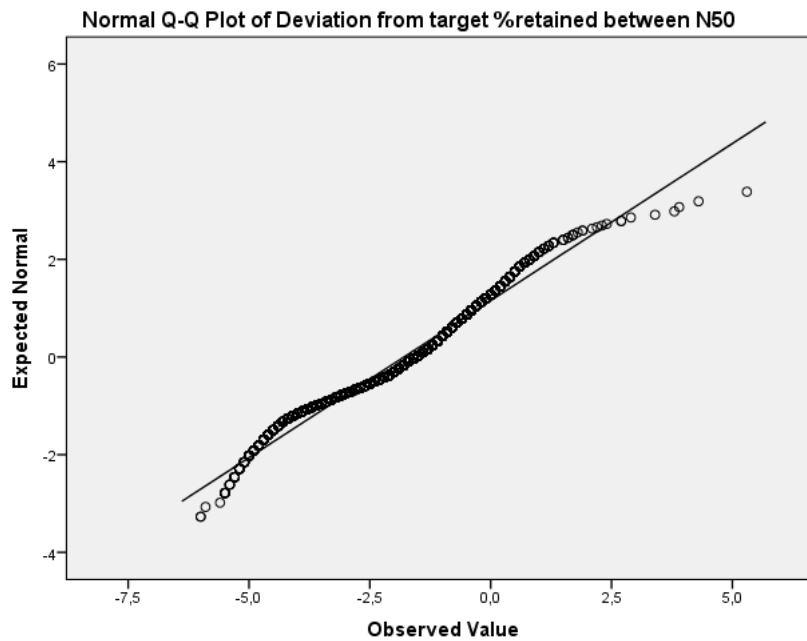


Figure 3-26: Normal Probability plot: Deviation from target % retained on #50 sieve

Deviation from Target Percentage Passing #200 Sieve (0.075 mm). Dust Material

The tolerance interval for Deviation from Target Percentage Passing on Sieve #200 is $\pm 2\%$ difference from JMF value and it is given in Table 2-16. As a difference with other gradation properties, when tolerance ranges given by Table 2-16 fall outside the master gradation bands provided on Table 2-2, the Percentage Passing #200 Sieve will be considered outside tolerances. There is no payment factor applied to this property as a requirement on TxDOT specification, same as other gradation properties.

The descriptive statistics table (Table 3-13) shows a flatter curve than the Normal and a right skewed and symmetric distribution. A 0.78% mean value was calculated, so, there is a tendency of obtaining results with a greater percentage of dust than the target. Figure 3-27 indicates a distribution that differs in shape from the Normal distribution shape, especially around the mean value.

Figure 3-28 shows differences from the Normal distribution in boundary values as well as the center of the distribution. The Normality tests presented in Table 3-13 suggest a non Normal distribution for this property. Therefore, deviation from the target percentage passing #200 sieve cannot be considered normally distributed.

Since the distribution of the property is unknown, confidence intervals were not calculated to study the data proximity to operational tolerance. From the data provided, approximately 17% defective results were obtained. The majority of the deviation from results tends to be greater than the zero. This indicates a greater percentage of dust on the mixture than specified in the JMF value.

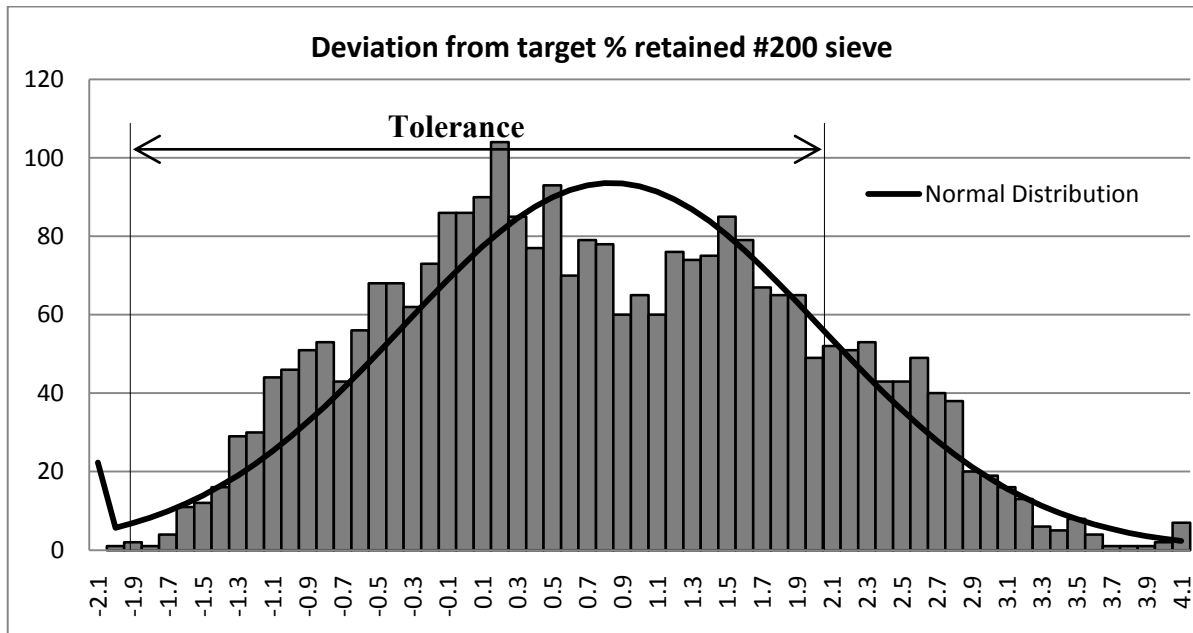


Figure 3-27: Histogram: Deviation from Target % passing #200 Sieve

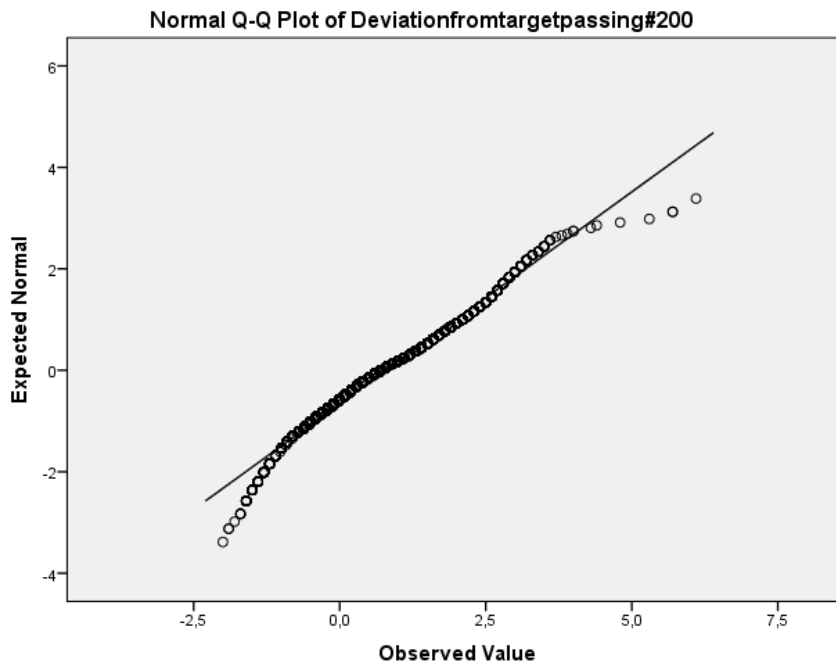


Figure 3-28: Normal Probability Plot: Deviation from target % passing #200 sieve

As has been done for other properties, in order to compute the deviation inside the operational tolerance, payment factors are recommended for deviation from target percentage passing #200 sieve. Table 3-16 is a recommendation of those payment factors. Production Payment Factors should be used just as an example because no further studies were performed for this proposal.

3.2.1 Commentary: Effect of Payment Factors

The application of payment factors for assurance of the quality of the As-Constructed HMA pavements and it is highly recommended during pavement production and construction operations in order to guarantee a high quality of final product.

Those properties with payment factors applied on the specifications have shown narrower ranges than properties without this requirement. In addition, 95% confidence intervals for those results are within tolerance, and a pay factor equal to or greater than 1.0. Those findings reveal the benefits of the application of payment factors on properties related to production and construction of asphalt pavement.

A recommendation for the application of payment factor was done for those properties with higher percentages of defective results: deviation from target asphalt content, deviation from target percentage retained on #30 sieve, deviation from target percentage retained on #50 sieve and deviation from target percentage passing #200 sieve.

Table 3-16: Proposal Production Pay Factors for Deviation from target percentage
passing #200 sieve

Absolute Deviation from target % Passing #200 Sieve	Pay Adjustment Factor
0.0	1.050
0.1	1.042
0.3	1.034
0.4	1.026
0.5	1.018
0.6	1.011
0.7	1.003
0.8	0.995
0.9	0.987
1.0	0.979
1.1	0.971
1.2	0.963
1.3	0.955
1.4	0.947
1.5	0.939
1.6	0.932
1.7	0.924
1.8	0.916
1.9	0.908
2.0	0.900
>2	Additional investigation

Special attention is required to asphalt content, since it is the most expensive material of the asphalt mixture. It was shown that a considerable amount of result in the limit of -0.3%, which is the minimum asphalt content allow in the specifications. A similar situation was observed for dust content. A reduction of the size of the material is

shown in comparison with the JMF. That is maybe part of the same purpose of the cost reduction in mixture production activities. Consequently, the application of a production payment factor for the asphalt mixture on asphalt content as well as on the gradation properties is highly recommended.

Additional information related to pay factor can be found on The Asphalt Handbook (The Asphalt Institute, 2007). It provides an example of the payment factor applied to several quality characteristic such as, Asphalt Content, Air Voids, and Passing #8 sieve, Passing #200 sieve or Compaction level. The proposed factors are based on statistical acceptance method considering the mean, standard deviation and percentage within the specification limits (PWL).

3.3 Relations between VMA and Gradation and Asphalt Content for As-Constructed HMA

By definition, void in the mineral aggregate is the ratio of voids volume and the total volume of the mix. That includes the air voids and the volume of the asphalt not absorbed into aggregates (Roberts, 1996).

Then, the VMA values will depend on the aggregate and on asphalt content. In addition, depending on the aggregate gradation, a different requirement for VMA is applied to the asphalt mixture (Table 2-2). This subchapter will study the relationship between those characteristics and VMA values.

The VMA is obtained from samples molded in the laboratory. It depends, in addition to gradation, on the compaction level of the mixture. Therefore, the Laboratory-

Molded Density is introduced in the analysis of VMA, since it is a property that depends on sample compaction.

A regression analysis was performed considering VMA (%) as dependent variable and Gradation, Asphalt Content (AC) and Laboratory-Molded Density (D) as independent variables. Gradation was divided in four different variables: percentage retained on #8 sieve (P8), percentage retained on #30 sieve (P30), percentage retained on # 50 sieve (P50) and percentage passing # 200 sieve (P200). All variables were introduced in the analysis in percentages (%).

The extreme values for all variables were removed from the database to avoid errors in the results, a total of 2,810 observations were used for the study. The database was split in 2 parts. A first part, containing 80% of the data (2,249 records) was used for the development of a model for estimating VMA using linear regression. A second part with 20% of the data (561 records) was used for model validation.

Plots of individual variables were analyzed to observe the tendency for the relation between the dependent variable VMA and each of the independent variables. No clear relationships were observed and therefore, no variable transformations were considered.

Table 3-17 shows the ANOVA table information obtained from MS Excel after the regression analysis for the 80% of the data considered for model estimation. This reveals that all independent variables considered on the regression are significant predictors of VMA, for a 95% confidence level. The estimated model gives a $R^2=0.90$. Therefore relation obtained can be considered strong since R-square is very close to 1.0.

$$\boxed{VMA = 86.37 + 1.96 * AC - 0.85 * D + 0.04 * P8 - 0.02 * P30 + 0.02 * P50 + 0.01 * P200} \quad (3-1)$$

From this relation observes that, VMA increases with the asphalt content, and decreases with the density. In addition, VMA depends on gradation parameters.

A validation analysis was performed with the 20% of the data remained. Model from Equation (3-1) was used for prediction of the VMA values. It obtained a mean of percentage of error equal to 0.32%, this value is positive and nearly zero, concluding that the model slightly overestimates the VMA, but due to the proximity to zero, this error can be considered negligible. In addition, the mean of absolute percentage of error was estimated having a value of 1.95%. Due to the small values of the error, the model for estimation of VMA values can be considered valid.

3.4 Relations between As-Constructed HMA Properties and Rutting Resistance

Additional data related to rut resistance was provided from two of the four projects studied in this report. As an additional measure of performance, Hamburg Wheel Test (HWT) was carried during the construction of asphalt layers. This test was used for mixture design acceptance. In addition, it was used as a measure of performance during construction.

The HWT was conducted on samples taken from asphalt trucks before lay-down and compaction. Most of the Hamburg Wheel Test performed passed the requirements. When samples failed, the pavement was removed and re-constructed.

Data from the HWT was given in millimeters. The Fail/Pass limit is 0.5inches, (12.7 mm). The acceptance limit for the data provided was established on 12.50 mm.

Table 3-17: Linear Regression Analysis Output: VMA vs Asphalt Content, Lab. Molded Density, Retained #8, Retained #30, Retained #50 and Passing #200.

<i>Regression Statistics</i>	
Multiple R	0.948690525
R Square	0.900013712
Adjusted R Square	0.89974613
Standard Error	0.194983535
Observations	2249

ANOVA					
	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	6	767.2557831	127.8759638	3363.512442	0
Residual	2242	85.23765435	0.038018579		
Total	2248	852.4934374			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	86.37407639	0.81566294	105.894325	0	84.7745429	87.9736099	84.7745429	87.9736099
Asphalt Content by Ignition	1.967460252	0.018930215	103.9322725	0	1.93033767	2.00458283	1.93033767	2.00458283
%retained #8	0.043858384	0.001810544	24.22386519	2.4241E-115	0.04030787	0.0474089	0.04030787	0.0474089
%retained between #30	-0.019538477	0.001206409	-16.19556388	7.09117E-56	-0.02190427	-0.01717268	-0.02190427	-0.01717268
%retained between #50	0.016782404	0.003173719	5.287929448	1.35708E-07	0.01055867	0.02300614	0.01055867	0.02300614
Lab. Molded Density	-0.847290501	0.00858342	-98.71245533	0	-0.86412278	-0.83045822	-0.86412278	-0.83045822
%passing #200	0.010793013	0.00395589	2.728340077	0.006415059	0.00303542	0.0185506	0.00303542	0.0185506

A total of 49 observations were used for this study. Data for properties studied in previous subchapters was also available for the 49 records used. Descriptive statistic data can be found on Table 3-13. It can be observed that 97.96% of samples had as Depth for the HWT lower than 12.50mm.

A regression analysis was performed considering rut depth as the independent variable and laboratory-molded density (D), percentage retained on #8 sieve (DP8), percentage retained on #30 sieve (DP30), percentage retained on #50 sieve (DP50), percentage passing #200 sieve (DP200), asphalt content (AC) and performance grade (PG) as the dependent variable. Since the performance grade is a qualitative variable, it assumes values of 0 from PG-64-22 and 1 for PG70-22.

This analysis considers only these properties whose values are calculated from laboratory-molded samples, since values available for rut depth are obtained from laboratory samples molded at a target air void of 7%. Therefore, the data related to the field condition such as in-place air voids is not relevant for this analysis. In addition, VMA was removed since it is correlated to AC, Gradation and Density as demonstrated before

Multilinear regression was done in MS Excel to obtain a model for rut depth. The result is given in Table 3-18. For a 95% confidence level, only three variables are related to the rut depth: asphalt content, percentage retained #50 sieve and percentage passing #200 sieve. A second trial with just the three of the significance variables is performed, and results are found on Table 3-19. From this table it is shown that asphalt content is not a significant variable for a 95% confidence level and was removed for the analysis. A

third regression with percentage retained #50 and percentage passing #200 is shown in Table 3-20.

The analysis reveals that the two variables considered are significant to the rut depth obtained, but the regression function result on this analysis has a $R^2 = 0.19$, which indicates that the model does not provided a good prediction of the rut depth.

Two conclusions can be made from this result:

- i. The variables considered for the estimation of the model are not all the significance variables that affect the results of Rut Depth obtained from the HWT. Additional variables, such as percentage of rounded sand used for the mix design, which can depend on the material source (river pits, or manufacture crushed aggregates), and likely influences the rutting potential of the mixes, were not included in the analysis of rutting depth due to a lack of data.
- ii. The poor relation between HMA Properties and rut depth values may be because almost all HMA properties are within the tolerance limits. Kim, (2012) also found that when volumetric properties are inside specification limits, no model to predict the rutting potential of mixes was found.

Table 3-18: Linear regression for Rut Depth vs D, AC, DP8, DP30, DP50, DP200, AC and PG

<i>Regression Statistics</i>	
Multiple R	0.54405234
R Square	0.29599295
Adjusted R Square	0.17579662
Standard Error	2.81935715
Observations	49

ANOVA

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	7	137.0214	19.5744857	2.462579	0.03320553
Residual	41	325.899763	7.948774717		
Total	48	462.921163			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	77.5356807	95.7160769	0.810059117	0.42258308	-115.766856	270.838217	-115.766856	270.838217
D	-0.87984488	1.04808876	-0.839475544	0.40607092	-2.99650306	1.23681329	-2.99650306	1.23681329
AC	6.0278008	2.95096153	2.042656516	0.04755178	0.06821315	11.9873885	0.06821315	11.9873885
P8	0.00671834	0.20526617	0.032729874	0.97404882	-0.40782511	0.42126178	-0.40782511	0.42126178
P200	-1.50739951	0.50492726	-2.985379544	0.00475974	-2.52712079	-0.48767824	-2.52712079	-0.48767824
P30	0.02710883	0.16798963	0.161372038	0.87259297	-0.31215311	0.36637077	-0.31215311	0.36637077
P50	-1.05619921	0.44632699	-2.36642471	0.02276693	-1.95757484	-0.15482358	-1.95757484	-0.15482358
PG	-2.03491215	1.59102876	-1.278991433	0.20809187	-5.24805987	1.17823557	-5.24805987	1.17823557

Table 3-19: Linear regression for Rut Depth vs AC, DP50, DP200

<i>Regression Statistics</i>	
Multiple R	0.49938558
R Square	0.24938596
Adjusted R Square	0.19934503
Standard Error	2.7787892
Observations	49

ANOVA

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	3	115.44604	38.4820133	4.98363906	0.00453487
Residual	45	347.475123	7.72166941		
Total	48	462.921163			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	2.26651501	7.41490645	0.30567007	0.76126546	-12.667873	17.200903	-12.667873	17.200903
AC	3.31299324	1.74728212	1.89608376	0.06438089	-0.20621354	6.83220002	-0.20621354	6.83220002
P200	-1.21259888	0.39525601	-3.06788216	0.00364343	-2.00868534	-0.41651241	-2.00868534	-0.41651241
P50	-0.99841142	0.30157239	-3.3106858	0.0018397	-1.60580938	-0.39101346	-1.60580938	-0.39101346

Table 3-20: Linear regression for Rut Depth vs DP50, DP200

<i>Regression Statistics</i>	
Multiple R	0.4352218
R Square	0.18941801
Adjusted R Square	0.15417532
Standard Error	2.85609781
Observations	49

ANOVA

	<i>df</i>	<i>SS</i>	<i>MS</i>	<i>F</i>	<i>Significance F</i>
Regression	2	87.6856066	43.8428033	5.37467443	0.00798601
Residual	46	375.235557	8.15729471		
Total	48	462.921163			

	<i>Coefficients</i>	<i>Standard Error</i>	<i>t Stat</i>	<i>P-value</i>	<i>Lower 95%</i>	<i>Upper 95%</i>	<i>Lower 95.0%</i>	<i>Upper 95.0%</i>
Intercept	15.2573232	2.91424868	5.23542253	3.9733E-06	9.39124495	21.1234015	9.39124495	21.1234015
%passing #200	-1.15760884	0.40515734	-2.85718346	0.00639779	-1.97314824	-0.34206943	-1.97314824	-0.34206943
%retained N50	-0.868556	0.30186379	-2.87731104	0.00606262	-1.47617628	-0.26093573	-1.47617628	-0.26093573

CHAPTER 4

CONCLUSIONS

This research compiled a vast amount of data provided by four different asphalt paving projects in Texas. The database created was used for performing a comparison between the Theoretical HMA properties for several mixes and the As-Constructed HMA Properties of the same mixes, from test results recorded during the production and construction of HMA pavements. The study was divided into three different parts: The analysis of variability of as-Constructed HMA properties and the comparison with typical values; the study of the relation of payment factor and test results; and the analysis of relationships between As-Constructed HMA properties and Rutting. The research performed led to the following conclusions:

- The Maximum Standard Deviation obtained for As-Constructed HMA Properties falls inside typical ranges reported in a national study (Advanced Asphalt Technologies, LLC, 2011). Due to the amount of data and variability of the projects used to develop this research, the values obtained for Maximum Standard Deviation could be used as a reference for typical values.
- The application of Payment Factor on production and construction of HMA pavement, concentrates the test results for As-Constructed properties inside a range for a payment factor of 1.0 or greater. After the analysis of all available test result for HMA properties, and the observation of their distribution, the percentage defective and the percentage within limits, it is suggested the use of production payment factors on asphalt content and on percentage retained on

#30 sieve, percentage retained on #50 sieve and percentage passing #200 sieve.

The payment factors should be extended to percentage retained on #8 sieve to homogenize all the gradation parameter involved. In conclusion, the Asphalt Content and Gradation should be affected by the application of payment factors, since they are properties that influence the asphalt performance.

- Voids in the Mineral Aggregate (VMA) values, depend on gradation and asphalt content, as expected. Additionally, they depend on the laboratory molded-density, which provides information for compaction level of the mix. The model estimated from the regression analysis indicates a strong relationship between VMA and asphalt content, density and gradation. VMA increases when asphalt content increases. The VMA decreases when laboratory-molded density increases. And VMA depends on Gradation parameters.
- No relation was found between the Rut Depth obtained for Hamburg Wheel Test and HMA properties. This can be justified because some variables, such as percentage of rounded sand, were not included in the analysis due to a lack of information. Also, the regression analysis did not find a relation possibly because, for the studied mixes, the rutting values and the other HMA properties were in most cases within tolerance limits.

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BIOGRAPHICAL INFORMATION

Rosario Tripiana Martinez received her Bachelor of Science in Civil Engineering from The Universidad of Granada from Spain in the February of 2007. She started working as an engineer in February, 2007 in a major highway construction project in Spain. She moved to Greece in November, 2009 with the same company to participate in the Ionia Odos Project, an important highway construction along the Greek coast. She moved to USA in May 2011 and she has been working in NTE (IH 820-SH183) till November 2014 and presently at NTI (IH 35W), in all projects as a part of the construction technical office. She was admitted to the graduate program in Transportation at the University of Texas at Arlington in Fall 2012. She completed her Master of Science in Civil Engineering in the Fall of 2014.