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16. Abstract

The Texas Department of Transportation (TxDOT) spends over $250 million per year to maintain almost 200,000 miles of roadway with more than 450 million vehicle miles per day. Seal coats are very important for the Department's preventive maintenance program. Seal coats are one of the most important elements of pavement maintenance because they slow down pavement deterioration. It is less expensive to seal coat roads with low traffic volumes every few years than it is to overlay or completely replace the road. Seal coats also beautify and seal the road from water. In addition, seal coats are instrumental in maintaining and recovering skid resistance, which is a major safety requirement in pavement maintenance.

The purpose of this research project is to develop an objective technique to accurately evaluate pavement distresses including raveling (loss of aggregate) and excess binder (flushing or bleeding). Current methods available to evaluate seal coat distresses are very subjective and they include visual inspection by different people. This method is subject to different interpretation by the different inspectors with different levels of knowledge and experience on pavement distresses. Currently, there is no method based on equipment measurements to scientifically evaluate the performance of seal coats and reduce the subjective ness of seal coat performance evaluations. A methodology based on texture could be an option to measure seal coat performance as affected by flushing and raveling.

Two portable tools are available for measuring pavement texture and need to be evaluated for measuring texture of seal coats, the Circular Track Meter (CTM) (ASTM E 2157 – 01) and the Outflow Meter (OFM) (ASTM E 2380 – 05). The CTM and the OFM provide measurements of pavement texture that has been shown to correlate with skid resistance. The CTM would be the most feasible and practical for a TxDOT inspector to carry in his or her truck. The Outflow Meter is also simple to use and it only requires water to operate. On the other hand, the CTM is several times more expensive than the OFM; it requires the use of a laptop computer, and preferably two people to operate. The correlation between the OFM and the CTM will be presented later in this report. In addition, preliminary performance curves for seal coats based on texture degradation are also reported.

A factorial table of seal coat test sections based on age and traffic was defined by this research project and pavement texture data was collected using the CTM and OFM. These data were summarized to develop CTM and OFM correlations. In addition, the research developed seal coat failure criteria based on texture and makes recommendations on how to establish a systematic procedure to evaluate seal coats.

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Seal Coat, pavement texture, safety

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EVALUATION OF SEAL COAT PERFORMANCE USING MACRO-TEXTURE MEASUREMENTS

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José Weissmann

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"Evaluation of a System for Measuring Seal Coat Quality"

Performed in cooperation with the

TEXAS DEPARTMENT OF TRANSPORTATION

and the

FEDERAL HIGHWAY ADMINISTRATION

By the

THE UNIVERSITY OF TEXAS AT SAN ANTONIO

Department of Civil and Environmental Engineering

January 2008

ABSTRACT

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CHAPTER 1

Introduction

A seal coat, also known as chip seal, consists of the application of asphalt material called binder and aggregate sprayed in a thin layer to existing pavements in order to seal the road surface and extend their service life. By sealing the surface, water is kept from infiltrating the asphalt pavement, protecting it and slowing the rate at which it deteriorates. Seal coats are fairly inexpensive and highly successful if applied correctly. Seal coats present an economic benefit over resurfacing or reconstruction of the roadway and are strongly supported by life-cycle cost analysis of pavement maintenance and rehabilitation alternatives for low-volume roads. Seal coats are not intended as a permanent wearing surface and may last about eight years on average. Some seal coats have performed very well for over ten years. The life of a seal coat may vary depending on traffic weight, volume and weather conditions. Even though seal coats can provide strength to the roadway surface against traffic loads, they are not intended to increase the structural capacity of the pavement. By preventing the penetration of water, seal coats allow the original strength of the pavement and subgrade to be conserved. A seal coat is only a temporary solution for pavements with cracks due to heavy traffic loads. Pavements with these types of cracks, usually wider than ¼ inch, may need base repair before seal coat. A thick overlay or reconstruction of the affected area is usually required to fix these types of cracks. Seal coats are also not intended to improve ride quality. Overlays or reconstruction are usually required to improve pavement ride quality. However, seal coats are very effective in extending pavement life through crack sealing and recovering skid resistance (Texas Department of Transportation, 2006).

One of the main purposes to seal coat a road is to improve surface friction, also known as skid resistance, and provide a wearing surface for all-weather conditions. A reduced friction factor between the roadway surface and the vehicles tires is the primary cause of crashes, especially when friction is compromised due to weather conditions such as rain. Due to the type of aggregate rock used in some parts of the country, improving friction may sometimes be a challenging task for the engineers (Fakhri, Mansour, and Amoosoltani, Ershad, 2005).

Beautification is another benefit of a fresh seal coat. A new seal coat gives the road a darker color, which makes it look like new, resulting in higher driver satisfaction.

Pavements that show signs of bleeding or flushing are difficult to fix with seal coats. The type of binder used at these locations would have to be changed. A larger size aggregate is recommended for seal coats on flushed pavements.

Seal coats are very successful on both low and medium traffic roads, but tend to perform even better on low volume roads, with low truck traffic. Roads with an average daily traffic in excess of 10,000 vehicles per day are considered as high traffic by the Texas Department of Transportation in their Seal Coat and Surface Treatment Manual. Problems that may occur in high-traffic roads include loss of aggregate, vehicle damage from the loss of aggregate, flushing, and tire noise. The liability due to vehicle damage from the lose aggregate is one of the main reasons for not using seal coats on heavy traveled roads. Damage may occur to windshields, headlights, and paint of the vehicle (Texas Department of Transportation, 2004).

The performance of seal coats depends on several factors including construction practices, properties of the asphalt binder and aggregate, amounts of both binder and aggregate used, amount and type of traffic, and weather conditions among others (Texas Department of Transportation, 2004).

Among the most serious defects in seal coats are flushing or bleeding (excess binder), raveling (loss of aggregate), and streaking.

Flushing occurs when too much binder is used during construction. It is one of the most common defects. The excess binder travels upward to the pavement surface. The pavement looks black and shiny. This defect tends to lead to loss of friction between the vehicle tires and the pavement resulting in loss of skid resistance (Texas Department of Transportation, 2004). Figure 1.1 is an example of a road showing extreme flushing.

Figure 1.1. Seal coat pavement showing signs of flushing

On the other hand, not enough binder leads to raveling, also known as loss of aggregate. Sometimes the surface where the seal coat is applied is very porous or has open cracks resulting in the binder soaking into it. When this occurs, not enough binder remains on top of the road to hold the aggregate in place. Raveling occurs less often than flushing.

Streaking results when longitudinal strips of seal coat contain different amounts of binder due to lack of uniform application of binder by the sprayer. Dark streaks occur when there is not enough binder to hold the aggregate in place. These dark streaks are weak points in which the seal coat will deteriorate first. Streaking can also result in loss of skid resistance and also cause vehicle steering problems resulting in unsafe driving. The more common causes of streaking are mechanical faults and improper adjustments of the binder distributors. Applying the binder at temperatures too low would also result in streaking. Mechanical faults include the use of spray nozzles that are partially or completely clogged, using spray nozzles of different sizes and different discharge rates, nozzles not been set properly at the correct angle, using damaged nozzles, and nozzles not spaced evenly (Texas Department of Transportation, 2004).

Seal coats are used extensively throughout the State of Texas as a preventive maintenance practice. The Texas Department of Transportation (TxDOT) has a long history of highway pavement preservation dating back to the early 1900s. It was then when TxDOT began using seal coats as a wearing surface for low volume roads. The Texas Department of Transportation finally established a formal preventive maintenance program in 1987. In 2006, the program was funded by $250 million. Typical projects eligible for the preventive maintenance program include seal coats, microsurfacing, crack sealing, and thin asphalt pavement overlays. More than half of the problems that develop with asphalt pavements are due to oxidation of the solids in the asphalt binder and water infiltration. Water infiltration can be almost eliminated with a preventive maintenance program using selected treatments depending on the condition of the road. Preventive maintenance helps to preserve a pavement and extend its service life. Depending on available funds, it is common practice to place seal coats every six to eight years in Texas (Texas Department of Transportation, 2006).

Since seal coats do not provide any additional structural strength to an existing pavement, seal coats are not recommended for structurally deficient roads. Pavements with extensive signs of distress are not good candidates for a preventive maintenance treatment such as seal coat. Seal coats may increase the service life of the pavement for a few more years until funds become available for reconstruction.

Some of the factors that may influence the decision to seal coat a road as a maintenance treatment may include the overall condition of the pavement, traffic volume, percent of heavy vehicles, any repairs done prior to seal coat, and cost of the seal coat compared to other alternatives.

As defined by the Federal Highway Administration (FHWA), pavement preservation involves an organized approach to protecting the investment in existing roadways by improving pavement performance and increasing the service life in a feasible way (Texas Department of Transportation, 2006).

1.1 Texas Department of Transportation’s Seal Coat Program

The Texas Department of Transportation definition of pavement preservation, as mentioned in the Texas Pavement Preservation Program Manual (Texas Department of Transportation, 2006), involves extending the life of good pavements by applying timely preventive maintenance treatments, performed at the optimal time to preserve pavement condition throughout its service life or to extend the life of the pavement, and to reduce the amount of water infiltrating the pavement structure, protecting the pavement system, slowing the rate of deterioration, and correcting surface deficiencies. In 2005, TxDOT seal coated over 19,000 lane miles throughout the State of Texas (Texas Department of Transportation, 2006). Figure 1.2 shows the amount of money spent on seal coats from 2000 to 2005.

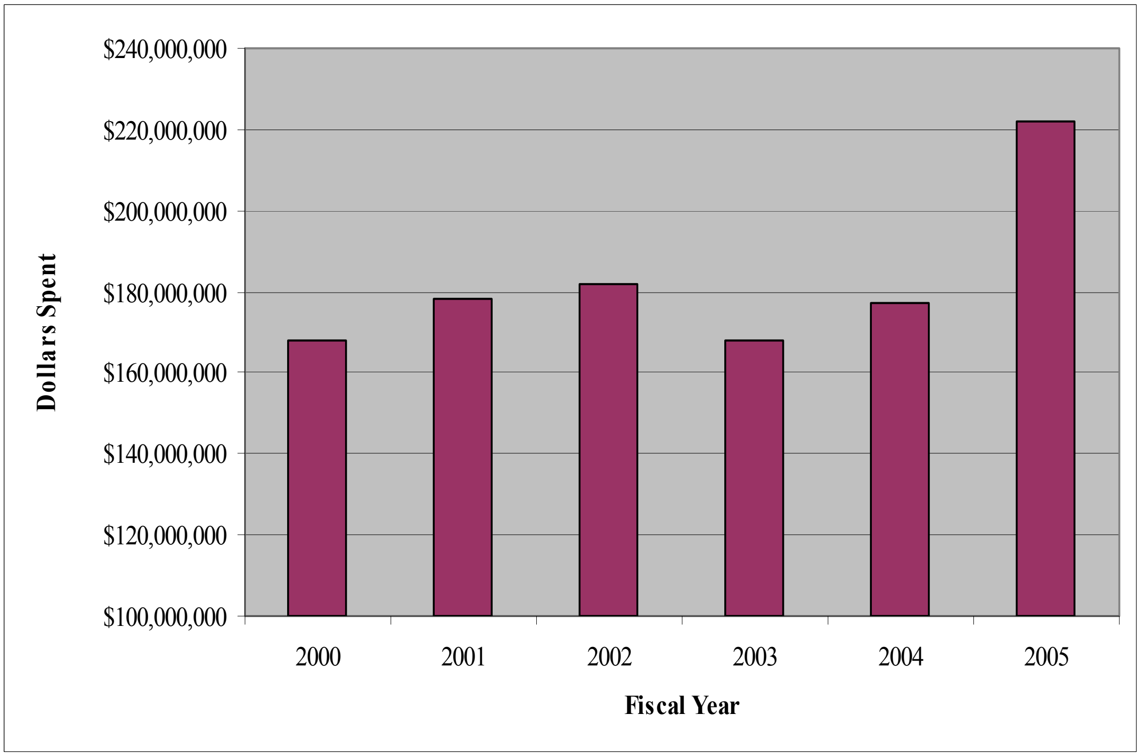

Figure 1.2. Seal Coat Dollars Spent

(Texas Department of transportation, 2006)

The current process the Texas Department of Transportation uses for selecting pavements to receive seal coats starts with maintenance section supervisors inspecting the roads visually. The maintenance supervisors are usually the most familiar with the roads and their maintenance history. A list of possible roads to be seal coated is prepared and submitted to the District Office for review and approval. A designated person from the District Office then travels the roads to ensure that they are good candidates for seal coat by visually inspecting the candidate sections.

In some districts roads are selected for seal coat treatment based on time of the last seal coat, in such a way that roads are sealed every 6 to 10 years based on traffic.

No non-subjective procedures are used to select the candidates for seal coat and a scientific measurement of seal coat performance would help the TxDOT District Office in prioritizing and selecting pavement sections for the seal coat program. The following chapters in this report will summarize the research findings on using texture measurements of seal coats as a non-subjective measurement to identify priorities for seal coating and measure seal coat performance.

CHAPTER 2

Skid Resistance

Friction between the pavement and the vehicle's tires during undesirable weather conditions, especially during wet weather when friction is compromised, is a major safety concern. Pavement friction is affected by macrotexture and microtexture. Wet friction pavement performance depends on the hardness of the aggregate for microtexture preservation and initial microtexture of the aggregate. Successful design of pavements that last for several years requires specific guidelines and procedures for the right selection of aggregates to be used in the pavement mixture.

Skid resistance could be defined as the force produced between a locked tire and the pavement as it slides along the surface to come to a complete stop. Macrotexture and microtexture are two properties of the road surface that contribute to skid resistance (Cairney, 1997).

Drivers may not be aware that the pavement is losing skid resistance until many crashes start occurring at a particular location. It could be used in a court of law if it is proven that a crash was caused due to a pavement with very poor skid resistance. The friction between the pavement surface and the vehicle's tires plays a very important role in keeping the vehicle safely on the road. Friction is what allows a vehicle to start from a complete stop without spinning its tires; safely come to a complete stop without skidding; and go around curves without spinning out of control and running off the road (Kuennen, 2003).

Acceptable skid resistance can be recovered without major reconstruction of the road. Asphalt overlays and seal coats can help increase skid resistance. Pavement milling by specialized machinery can also improve friction and ride quality in both rigid and flexible pavements. The friction or skid resistance of a pavement is not the same as its smoothness. Some engineers have gone further to say that friction and skid resistance are not the same thing. Some say that friction refers to the actual forces that are developed between a specific tire and a specific road at a specific time under specific conditions. They define skid resistance as the contribution that the road makes to create friction. Skid resistance is then referred to as a measurement of friction under specific conditions in which various parameters are controlled (Kuennen, 2003).

The definitions and discussion included in this chapter will serve as a basis for the analysis of the field data collected by this research project and reported in Chapters 5 and 6, where performance of seal coats and failure criteria based on macrotexture are discussed.

2.1 Macrotexture

Macrotexture is the texture provided by the aggregate itself and it provides drainage for water removal between the tire and the pavement surface, which allows for better tire contact with the pavement, improves friction, and also helps prevent hydroplaning at high speeds. Macrotexture is defined by wavelengths of 0.02 to 2 inches (0.5 to50 mm) and vertical amplitudes of 0.004 to 0.8 inches (0.1 to 20 mm). Macrotexture is also obtained through grooves or channels placed intentionally in the road to allow for water to escape from under a vehicle’s tires. Shallow textures may not produce good results. Deeper grooves and channels have proven to be more effective in providing better surface drainage and improved friction, especially in wet weather conditions reducing the number of crashes. Macrotexture is related to pavement noise due to dense graded mixtures (Kuennen, 2003).

2.2 Microtexture

Microtexture is the texture of the aggregate itself and it provides a gritty surface for thin water films to penetrate resulting in improved friction. Good microtexture is defined by wavelengths of 0.0004 to 0.02 inches (0.01 to 5 mm) and vertical amplitudes of 0.008 inches (0.2 mm). Microtexture is the most critical element of surface friction. Microtexture provides the vehicle with stopping power on rigid or flexible pavement, in dry or wet weather, at low speeds. There is currently no system capable of measuring pavement microtexture at highway speeds (Kuennen, 2003).

Skid resistance begins with microtexture. As the pavement wears down due to traffic, some of its microtexture can be lost. Losing microtexture is not of great concern since a good pavement macrotexture is what increases friction and the ability for a vehicle to stop effectively. Having the right type of aggregate is very important because softer aggregates can polish under tire wear and contribute to a vehicle skidding on the pavement and possibly resulting in a crash. Polished aggregate has a shiny look when looking down the road and it almost looks like the pavement is wet. One way to improve skid resistance is by using good quality aggregates. In seal coats, the coarse aggregate is exposed at the surface. The microtexture of the aggregate exposed will influence friction when the pavement is wet. The grading of the aggregates exposed at the surface influence macrotexture and will help prevent hydroplaning. Some states use ASTM D 3319 “Standard Practice for the Accelerated Polishing of Aggregates Using the British Wheel” to ensure good friction. This ASTM Standard simulates the polishing action of vehicles on coarse aggregates used in asphalt pavements (Kuennen, 2003).

Figure 2.1 shows the difference between macrotexture and microtexture.

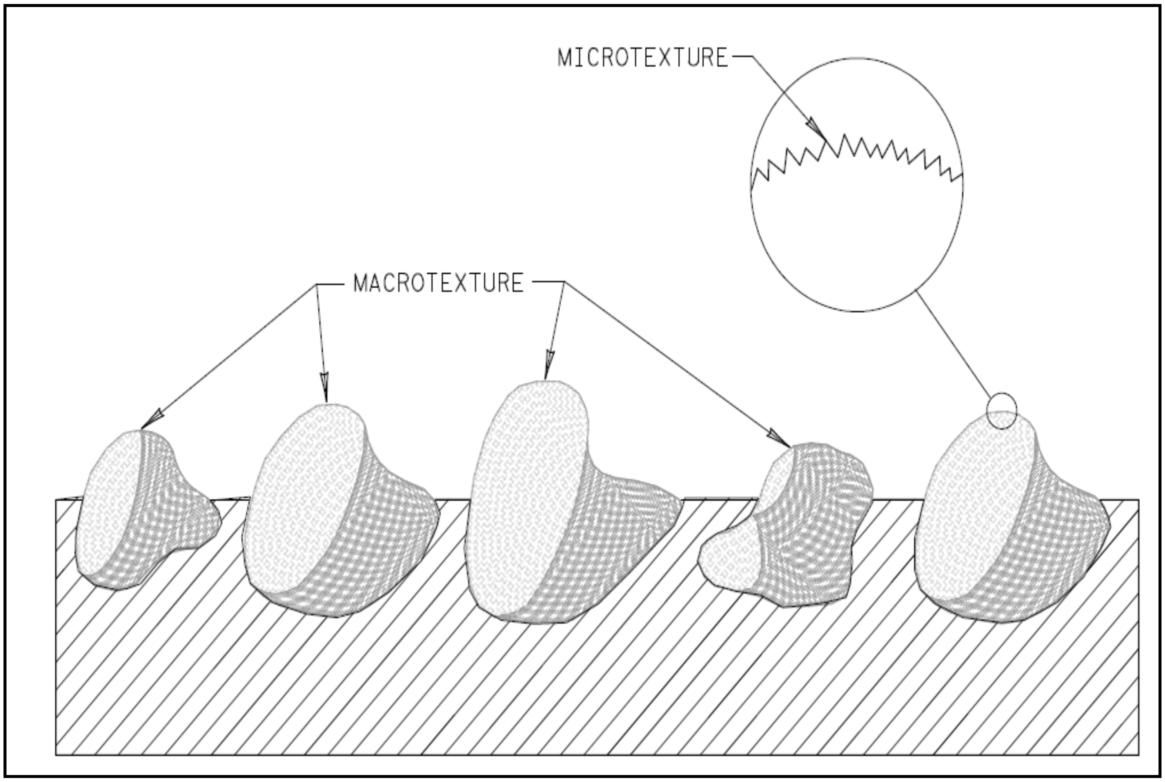

Figure 2.1. Macrotexture and microtexture representation

(Oliver, John W. H., and Halligan, Steve, 2006)

2.3 Methods to Measure Skid Resistance

A number of different techniques have been developed for measuring the skid resistance of a pavement. These techniques are based on different principles and as discussed before, the results are affected by the pavement macrotexture and microtexture.

Specialized equipments are available to pavement managers to measure skid resistance. These include the skid trailer (also known as locked wheel method), the pendulum method and the sideways force method.

2.3.1 Skid Trailer

The skid trailer and is used by many agencies, including the Texas Department of Transportation (TxDOT), to measure skid resistance. The skid trailer tests the pavement by using a trailer pulled by a truck at 64 km/hr (40 mph). This test is standardized by ASTM E 274 – 06 (ASTM International, 2007). One of the trailer wheels is locked for a few seconds while water is being applied just in front of it. The drag force produced by the test wheel is measured electronically by a force transducer attached to the trailer tow bar. The measurement is taken after a short interval in order to allow the tire temperature to stabilize. Then the friction is calculated by dividing the drag force of the wheel by its weight. Skid numbers are very important in a decision support system such as a pavement management system (Cairney, 1997).

Even though skid trailers are built according to the same principles and use a standard specified tire, there are different types of skid trailers built to different design specifications. The results obtained by one type of skid trailer are not directly comparable to the results obtained by a different type of trailer. Therefore the results cannot be used for comparison purposes, unless the same skid trailer is used. Skid trailers are capable of collecting extensive measurements at highway speed. Skid trailer have been widely used in the United States and Europe (Cairney, 1997).

Figure 2.2 shows a skid trailer used by the North Carolina Department of Transportation.

Figure 2.2 Skid Trailer (North Carolina Department of Transportation)

2.3.2 Pendulum Method

Another technique used for measuring skid resistance is the British Pendulum Tester (BPT) which is described in ASTM E 303 – 93 (ASTM International, 2007). It works by releasing a pendulum fitted with a rubber shoe which makes contact with the road surface. This device works by measuring the extent to which the pendulum is retarded when it comes in contact with the surface. The speed at which the pendulum contacts the surface is relatively low (approximately 10 km/hr). This device is mainly used for measuring microtexture and skid resistance at low speeds. This is important to determine the quality of aggregates used. In contrast to the skid trailer, this device is easy to carry and more affordable. The British Pendulum Tester is not capable of taking continuous measurements at highway speeds, making labor intensive if large amounts of data are required. It has been used to investigate the relationships between skid resistance and crashes (Cairney, 1997).

Figure 2.3 shows all of the different parts of the British Pendulum.

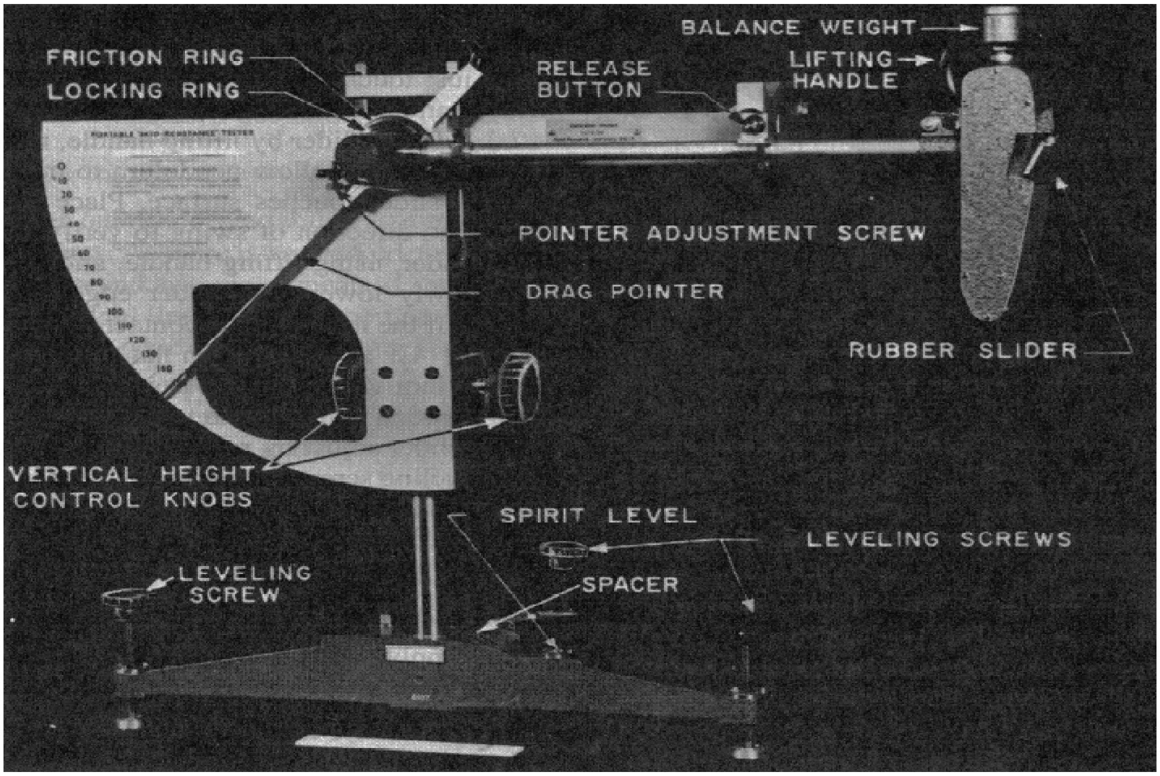

Figure 2.3. British Pendulum (ASTM International, 2007)

2.3.3 Sideways Force Method

In the sideways force method, an extra wheel is mounted to the vehicle at a twenty degree angle to the direction of traffic. In some machines, a wheel for each wheel path is mounted. Usually the test consists of a truck carrying a water tank and one or two test wheels placed over the wheel path. The force generated by the wheel as the vehicle travels is measured. The sideway force coefficient, a measure of the resistance being offered by the pavement, is calculated by taking the ratio of the force created at right angles to the wheel to the vertical force on the wheel. Similar to the skid trailer method, water is sprayed in front of the test wheel. A smooth tire is used to avoid the results being affected by the different tire wear. Using this method, measurements can be taking at highway speed. There is also no need for braking as it is the case with the skid trailer (Cairney, 1997).

CHAPTER 3

Methods for Measuring Pavement Texture

Measuring pavement macrotexture has been a standard for many years in other countries. Recognizing the importance of pavement macrotexture in proving adequate skid resistance has been increasing in the past few years in the United States. As a result many new pavement texture testers are being developed and currently being used. Measuring pavement macrotexture has been made easier in the recent years thanks to developments in laser technology which allows data to be collected at highway speeds of up to 70 mph (Abe, H., Henry, J.J., Tamai, A., and Wambold, J.,2000).

In the past, pavement macrotexture has been measured using a volumetric technique like the Sand Patch Test which consists of spreading a known volume of material, in this case sand, on the pavement and measuring the area covered by the sand (ASTM E 965, ASTM International, 2007).

The Outflow Method is another way of measuring pavement macrotexture. An Outflow Meter (OFM) is used for this method (ASTM E 2380, ASTM International, 2007). The Outflow Meter consists of a vertical cylinder with a rubber gasket at the bottom. The pavement macrotexture is measured indirectly by measuring the amount of time it takes for a known volume of water to flow out of a cylinder that is filled with water and placed over the pavement to be evaluated.

A new device introduced in 1998 for measuring pavement texture is the Circular Track Meter. The Circular Track Meter is portable and it could be used in the laboratory as well as in the field. It utilizes a laser to measure the profile of a circle 284 mm in diameter (ASTM E 2157, ASTM International, 2007).

The following paragraphs include a description, as found in the most current ASTM Standards and Specifications Book (ASTM International, 2007), of the most common methods used for measuring pavement macrotexture including the Circular Track Meter (CTM), Outflow Meter, and Sand Patch Test. For the purposes of this research, the Circular Track Meter and Outflow Meter were used and the results were compared.

3.1 Sand Patch Test

As described in ASTM E 965 (ASTM international, 2007), this method is used to determine the average depth of pavement macrotexture by applying a known volume of material, in most cases sand, on the pavement surface and measuring the total area covered. Knowing the pavement macrotexture depth is important in order to evaluate the pavement surface texture. The pavement macrotexture values obtained using this method, also in combination with the other tests mentioned earlier, may be used to determine the pavement skid resistance capability and the suitability of different paving materials such as different aggregate types and sizes. This technique only provides a value of the pavement macrotexture and it is not sensitive enough to measure microtexture. The results from this procedure do not necessarily correlate directly with results obtained by other methods, just as the outflow meter or the CTM.

The materials needed to perform this test include a known quantity of sand, a container of known volume, a screen, a brush for cleaning the pavement surface of any loose debris, a flat tool for spreading the sand on the pavement, and a ruler for measuring the area covered by the sand. Figure 3.1 shows the various tools used for the Sand Patch Method.

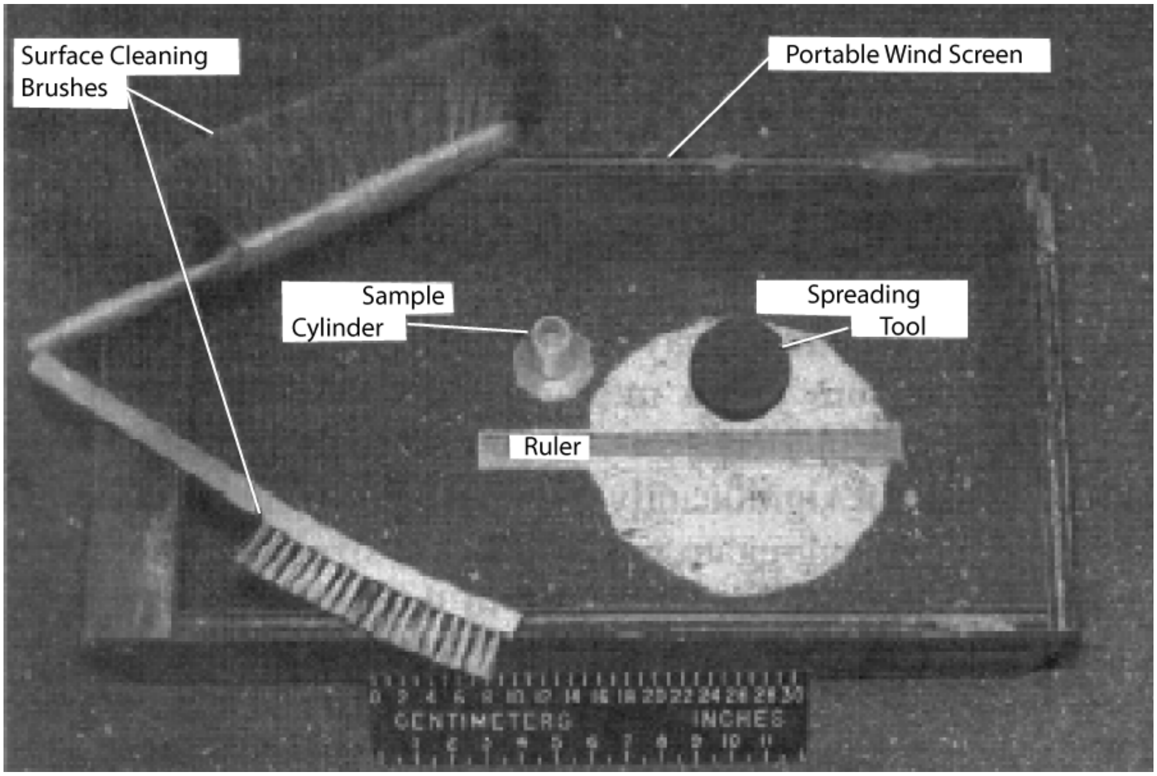

Figure 3.1 Tools used for performing the sand patch test

(ASTM International, 2007)

The test involves spreading a known volume of sand on a dry and clean section of pavement. The section of pavement chosen to be measured should not have any localized characteristics such as crack and joints. The selected area is cleaned of any loose aggregate or debris using the brush. The screen is placed around the section being measured. The container of known volume is filled with sand and gently tapped at the bottom several times on a hard surface. This helps the sand to settle. More sand is added to the container until is full to the top and leveled using a straightedge. The measured volume of sand is poured on the cleaned surface with the area protected by the screen. The sand is spread into a circular patch with the disk tool filling the pavement voids flush with the aggregate tops. The diameter of the circular area covered by the sand is then measured at a minimum of four equally spaced locations around the sample circumference. Finally, the average diameter for all four readings the computed and recorded.

The average depth can now be calculated between the bottom of the pavement voids and the top of the aggregate by using the following equation:

$$MTD = 4V \div \Pi D^2 \tag{3-1}$$

where,

MTD is the Mean Texture Depth of pavement macrotexture,

V is the sample volume, and

D is the average diameter of the area covered by the material.

(ASTM International, 2007)

3.2 Circular Track Meter

The Circular Track Meter (CTM) is a laser based device in which a Laser Displacement Sensor is used to measure the road surface macrotexture at a static location. The CTM provides the user with the Mean Profile Depth (MPD) and the Root Mean Square (RMS) (ASTM International, 2007). The International Friction Index (IFI) can also be obtained by using the CTM in combination with the Dynamic Friction Tester (DFT).

It has been demonstrated that by analyzing the profile data given by the CTM, a very reliable prediction of the volumetric Mean Texture Depth (MTD) and of the Outflow Time can be obtained. A study with data from three years of testing was used to evaluate the correlation of the CTM calculated Mean Profile Depth (MPD) to the volumetric Texture Depth obtained by the

San Patch Method and the Outflow Time. In all cases the correlation coefficients showed to be very high (Abe, H., Henry, J.J., Tamai, A., and Wambold, J.,2000).

The CTM is described in ASTM E 2157 (ASTM International, 2007). The Circular Track Meter uses a laser-displacement sensor mounted on an arm to profile a circle 284 mm in diameter. The arm rotates 80 mm above the surface and it is powered by DC motor at a tangential velocity of 6 m/min in a counterclockwise direction. The CTM is controlled by a laptop computer which saves and processes the data. The profile measured by the Circular Track Meter is divided into eight equal segments of 111.5 mm each. Computer software then computes the MPD in accordance to ASTM Practice E 1845 (ASTM International, 2007) and the RMS or both for each of the eight segments. The given MPD and RMS is the average of all segment depths.

The volumetric MTD was found to be linked to the speed constant of the International Friction Index. The MPD obtained by the CTM is also linked to the MTD and can replace the volumetric measurement obtained using the Sand Patch Method described in ASTM E 965 (ASTM International, 2007) for determination of the MTD.

Figure 3.2 shows the Circular Track Meter.

Figure 3.2 Circular Track Meter

3.2.1 Mean Profile Depth (MPD)

A standard practice for calculating pavement macrotexture mean profile depth is found in ASTM E 1845 (ASTM International, 2007). It covers the calculation of mean profile depth from a profile of pavement macrotexture. The mean profile depth has been used successfully in determining the speed constant of wet pavement friction.

Mean profile depth is the average of all the mean segment depths of all the segments of the measured profile. A linear transformation of the mean profile depth can provide an estimate of the mean texture depth (MTD) measured by the sand patch method described in ASTM E 965 (ASTM International, 2007).

The measured profile is divided for analysis purposes into segments each having a baselength of 100 mm or 3.9 inches. The segment is further divided in half and the height of the highest peak in each half of the segments is determined. The difference between that height and the average level of the segment is calculated. The MPD is the average value of these differences for all segments of the measured profile.

Figure 3.3 illustrates the calculation procedure for the MPD.

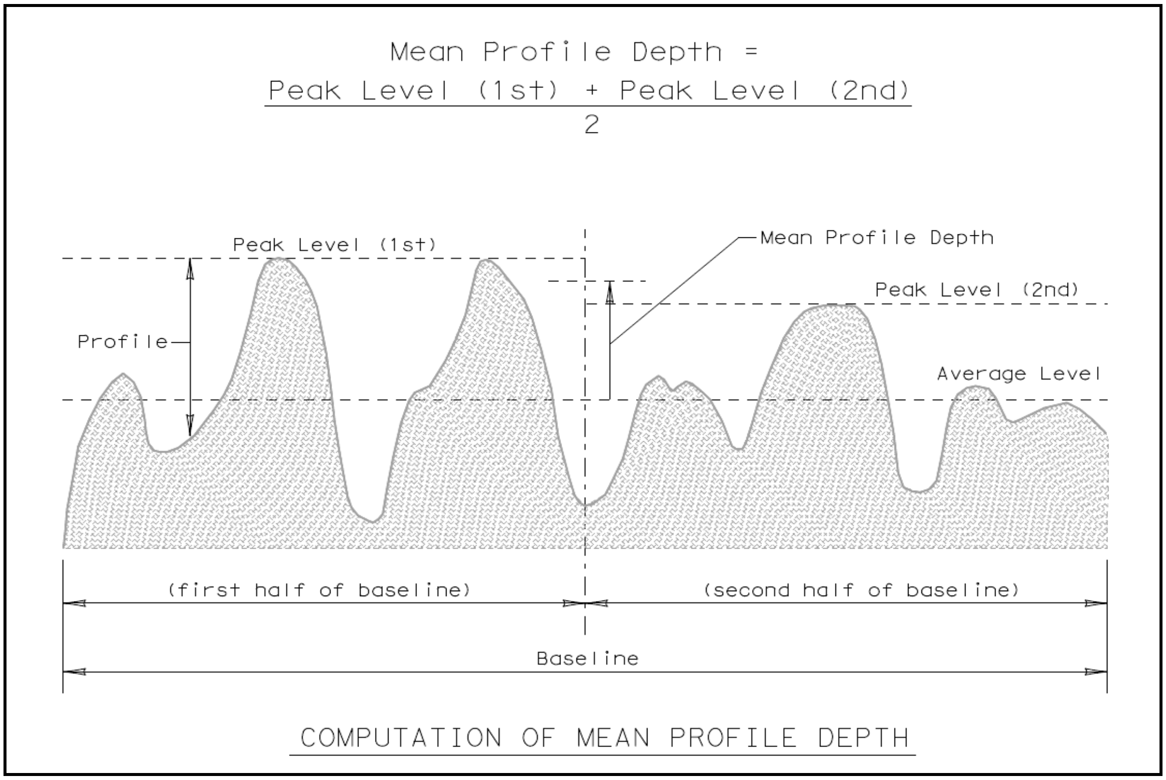

Figure 3.3 Procedure for Computing Mean Profile Depth (MPD)

(ASTM International, 2007)

3.3 Outflow Meter

This procedure, which is described in ASTM E 2380 (ASTM International, 2007), relates the texture of the pavement to its drainage capability through its surface voids. The outflow meter measures how long it takes for a known amount of water to escape through the voids in the pavement. This test provides an indication of the ability of the pavement to relieve water pressure from the vehicle tires. This would provide the engineer a clear indication of hydroplaning potential under wet weather conditions. The faster the water escapes from the outflow meter, the least amount of water that may be present between the tire and the pavement therefore improving the amount of friction between the tire and the pavement. In other words, the faster the water escapes the outflow meter, the more texture the pavement has, which finally would improve friction. The higher coefficient of friction would reduce a vehicle's stopping distance. This would then translate to fewer crashes, especially in adverse weather conditions when friction is compromised. Figure 3.4 shows the OFM.

Figure 3.4 Outflow Meter

The outflow meter consists of a vertical cylinder for holding the water. It is opened on the top and bottom with a rubber gasket around the bottom opening in order to create a seal against the surface being measured. Water is discharged through the bottom opening and it is controlled by a spring plunger. Two float switches are located inside the cylinder and wired to an electronic timer located on top of the outflow meter. With the plunger closing the bottom or discharge opening, the outflow meter is placed on the desired surface to be measured. The outflow meter device is placed on the pavement making sure that it is stable and that the rubber seal uniformly makes contact with the pavement surface. The cylinder is then filled with enough water to activate the top float switch. The timer is reset and the plunger is released allowing the water to be discharged through the bottom opening. As water escapes the outflow meter, it triggers the first float switch, which causes the timer to start counting. As the water goes down, it triggers the bottom float switch causing the timer to stop. The time that it took for the water to drain from the top switch to the bottom switch is shown on the timer. This is known as the outflow time.

The precision of the outflow meter that reads whole seconds only is 0.187 seconds. The outflow meter that reads to 0.001 seconds has a standard deviation of 0.143 seconds.

Figure 3.5 shows a diagram of the Outflow Meter with its different parts.

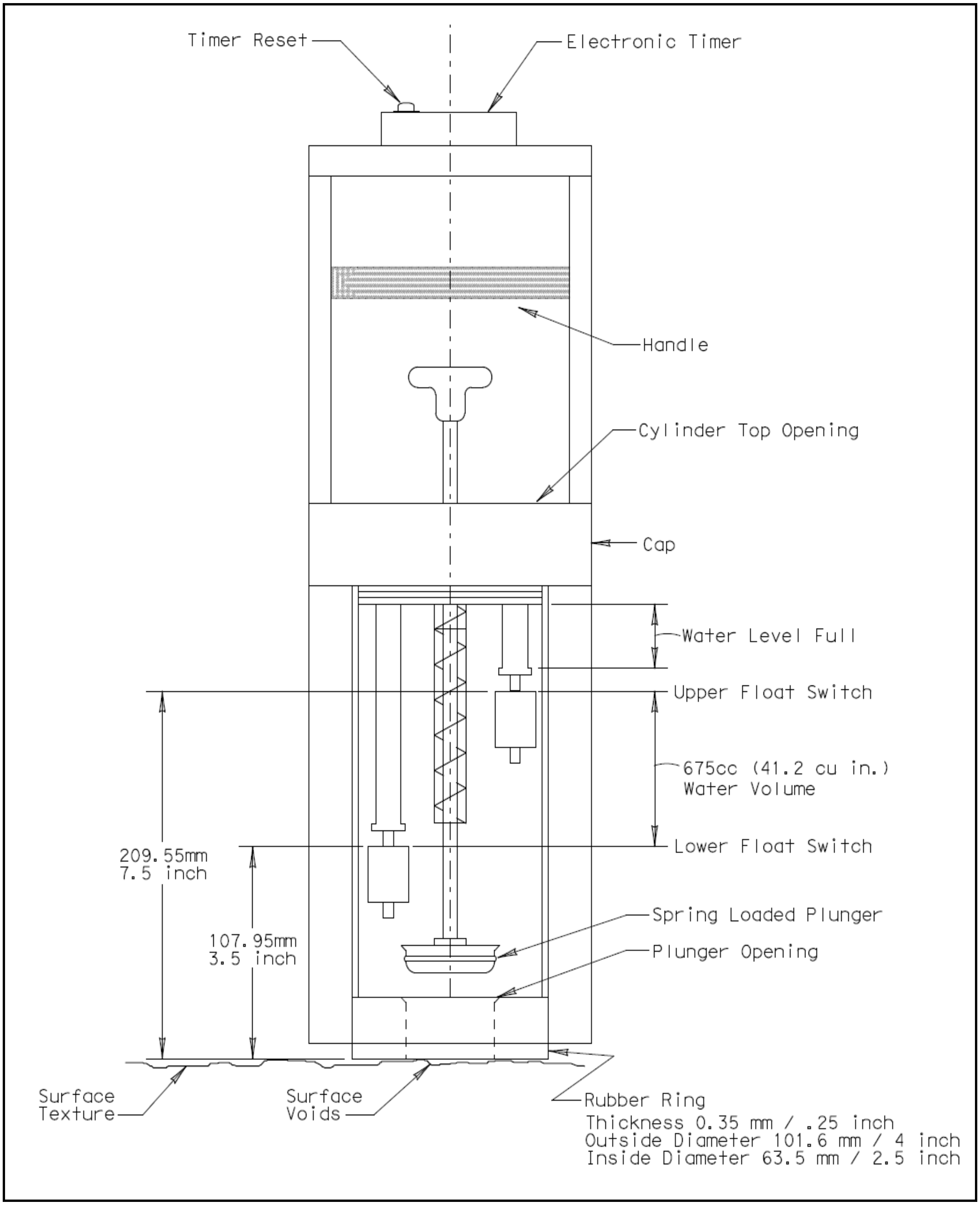

Figure 3.5 Outflow Meter Diagram (ASTM International, 2007)

3.4 Dynamic Friction Tester

As described in ASTM E 1911 (ASTM International, 2007), this test procedure is used to measure paved surface frictional properties as a function of speed. The Dynamic Friction Tester (DFT) can be used in the laboratory and in the field. The Dynamic Friction tester consists of a horizontal spinning disk fitted with three spring loaded rubber sliders which touch the surface as the disk rotational speed decreases due to the friction between the sliders and the surface being tested. The disk is brought to the desired rotational speed. The Dynamic Friction Tester is capable of providing a maximum tangential velocity of 90 km/h. A water supply unit delivers water in front of the sliders and the disk is lowered to contact the test surface. The sliders generate torque during the spin down which is measured and then used to calculate the friction as a function of speed. The torque is monitored continuously as the disk rotational speed reduces due to the friction between the sliders and the test surface. The torque signal is reduced to a measurement of friction by converting the torque to the force on the sliders and dividing the weight of the disk and the motor. The friction at 20, 40, 60, and 80 km/h is recorded and the friction-speed relationship is plotted.

This test provides a measure of surface friction as a function of sliding speed. The test is useful in determining the relative effects of various polishing agents such as vehicle tire on different type of materials.

Data was collected using the Dynamic Friction Tester on two seal coat sections of different age, ADT, and overall condition. The first site was located on FM 1283 in Bandera County. The second section tested was on RM 1376 located in Kendall County. The latter location was recently seal coated. Data was also collected at each one of the sites using the outflow and the circular track meter for comparison purposes.

Tables 3.1 and 3.2 summarize the data collected at each one of the sites mentioned above using all three measuring devices (CTM, OFM, and DFT). From the tables, “f” represents the friction value measured (FRS) by the Dynamic Friction Tester at a given slip speed (S) of 60 km/h. The information obtained from the CTM and the DFT can be used to calculate the International Friction Index (IFI) as discussed later in the chapter. Refer to the appendix for pictures of FM 1283 and RM 1376.

Table 3.1 Data Collected for FM 1283

Wheel Path	f at 60 kph	MPD (mm)	OFT (sec)	Age	ADT
Left	0.37	0.95	6	7	3750
Right	0.30	0.85	7		

Table 3.2 Data Collected for RM 1376

Wheel Path	f at 60 kph	MPD (mm)	OFT (sec)	Age	ADT
Left	0.70	3.04	0	New	710
Right	0.75	3.06	0		

Figure 3.6 shows the Dynamic Friction being used on RM 1376 in Kendall County. This section is representative of a new seal coat.

Figure 3.6 Dynamic Friction Tester

3.4.1 International Friction Index (IFI)

This practice, as described in ASTM E 1960 (ASTM International, 2007), is used for calculating the International Friction Index (IFI) of the pavement. The IFI has been used by the pavement management community to harmonize friction measurement equipment. This practice uses measured data of the pavement surface on macrotexture and the friction measured by the equipment at some slip speed (FRS) on wet pavement. The practice accommodates these data measured with different equipment at any measuring speed. Measurement of the pavement macrotexture is used to estimate the speed constant (S_p). The measured friction (FRS) at some slip speed (S) is used with the speed constant of the pavement (S_p) to calculate the friction at 60 km/h and a linear regression is used on FR60 to find the calibrated friction value at 60 km/h (F60). F60 and S_p are then reported as IFI (F60, S_p). F60 and S_p have proven to be able to predict the speed dependence of wet pavement-related measurements of the various types of friction-measuring equipment. F60 and S_p have also been found to be reliable predictors of the dependence of wet pavement friction on tire slip and vehicle speed. A significant characteristic of the IFI Model is that the measurement of friction with a device does not have to be at one of the speeds run in the experiment. FRS can be measured at some speed S and adjusted to FR60. If a device cannot maintain its normal operating speed and must run at some speed higher or lower because of traffic, the model still works well. In that case S is determined by the vehicle speed (V) which can be converted S.

The speed constant (S_p) in km/h is determined from the Mean Profile Depth (MPD) as follows:

$$S_p = 14.2 + 89.7MPD \tag{3-2}$$

where,

S_p is the speed constant in km/h, and

MPD is the mean profile depth in mm.

The next equation uses the FRS at a given S to adjust the friction to a common slip speed of 60 km/h. This is accomplished using the speed number predicted by the texture measurement in the previous equation and using the following relationship:

$$FR60 = FRS \times EXP[(S - 60) \div S_p] \tag{3-3}$$

where:

FR60 is the adjusted value of friction from a slip speed S to 60 km/h,

FRS is the friction measured by the equipment at slip speed S, and

S is the slip speed of the equipment, and

S_p is the speed constant.

The final step in the harmonization is the calibration of the equipment, by regression of the adjusted measurement FR60, with the calibrated Friction Number F60:

$$F60 = A + B \times FR60 \tag{3-4}$$

where,

F60 is the calibrated Friction Number,

A and B are calibration constants depending on the method used,

FR60 is the adjusted value of friction from a slip speed S to 60 km/h.

Combining the results, F60 can be expressed in terms of the friction and texture measurement (FRS and TX):

$$F60 = A + B \times FRS \times EXP[-(60 - S) \div S_p] + CTX \tag{3-5}$$

where,

A, B, and C are calibration constants depending on the method used, FRS is the friction measured by the equipment at slip speed S,

S is the slip speed of the equipment, and

TX is the pavement texture measurement (mm).

F60 is the prediction of the calibrated Friction Number and S_p is the prediction of the calibrated Speed Number. The values of F60 and S_p are reported as the International Friction Index.

Friction at some other slip speed S may be calculated with the following expression:

$$FS = F60 \times EXP[(60 - S) \div S_p] \tag{3-6}$$

CHAPTER 4

Data Collection

4.1 Factorial Design

For the data collection, it was decided to create a factorial table with two factors as an effective way to examine the interaction effects on different seal coat roads. The two factors selected for the factorial table are age and average daily traffic (ADT). Another factor that influences seal coat wear is the percentage of heavy vehicles. Unfortunately, this information was not available at the time of this research. A factorial design offers the researcher several benefits including the ability to perform the analysis of the influence of several factors on a given response.

4.2 Procedure

The seal coat sections were divided into four groups according to age, of fifteen to twenty roads each. The four age groups are as follows:

- 1 year old,
- 2 years old,
- 4 years old,
- and 7 to 10 years old.

Figure 4.1 shows a distribution according to age of all the seal coat sections for which data was collected using the Outflow Meter (OFM) and the Circular Track Meter (CTM).

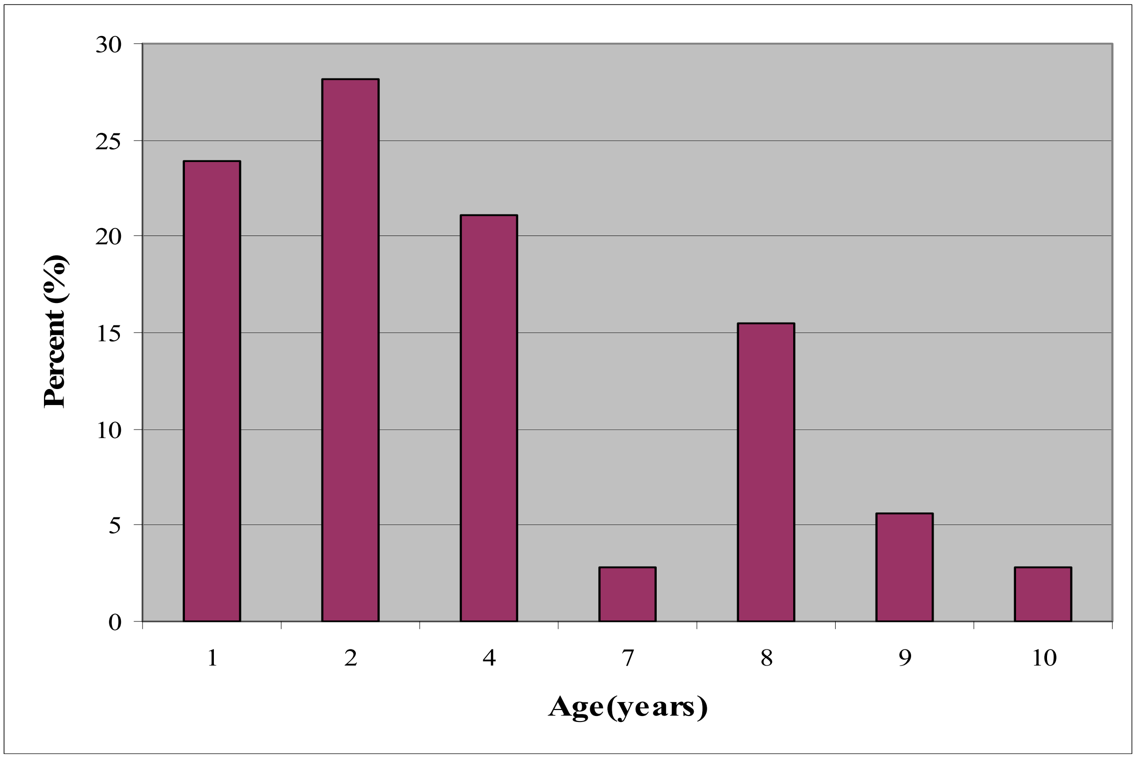

Figure 4.1 Seal coat sections distribution by age

Each one of the seal coat groups was subdivided according to average daily traffic (ADT). The ADT ranged from less than five hundred vehicles per day in rural areas to over twenty thousand vehicles per day in some state highways. It is not common to see seal coat roads for the higher end of the ADT spectrum. Seal coats are intended for low to medium volume roads.

Figure 4.2 shows the distribution according to ADT of all seventy one seal coat sections surveyed.

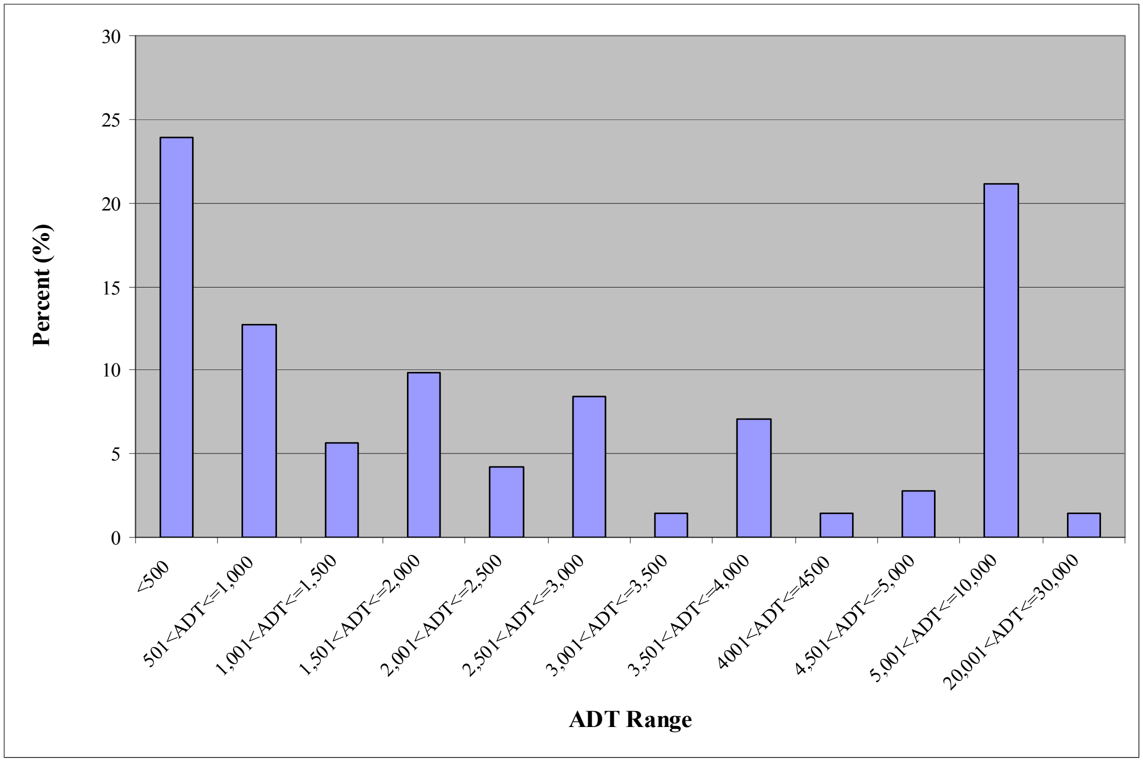

Figure 4.2 Seal coat sections distribution by age

For each road section selected, several readings were taken using the outflow meter and the circular track meter. Each one of the spots selected on the road was measured using both devices. This allowed the establishment of a correlation between the outflow and the circular track meter. The readings were taken on the right wheel path for some of the sections and on both wheel paths for some of the pavement sections.

All of the pavement sections were identified from the Texas Department of Transportation, San Antonio District records, using their inventory system for as-built plans. The as-built plans are kept in the District Office and they are accessible to the general public. Most of the as-built plans for the most recent construction projects can also be downloaded from the Texas Department of Transportation website. The pavement sections are grouped together according to their letting date. The plans can be easily found using a system similar to most libraries. Information about the different sections such as type of aggregate used, type of binder used, asphalt spray rate, and material quantities can be obtained from the plans. The plans also include a detail map of the location for each road. Most of the recent plans also include the ADT information for each road. When the ADT was not available from the as-built plans, it was obtained from Traffic Maps also kept at San Antonio the District Office. These maps contain current ADT for most major roads in the San Antonio District. The San Antonio District consists of Bexar County and eleven other surrounding counties including Atascosa, Bandera, Comal, Frio, Guadalupe, Kendall, Kerr, McMullen, Medina, Uvalde and Wilson. The ADT is one of the factors selected for the factorial table. The ADT plays and important role in the seal coat performance over the years. A low ADT seal coat road will not perform the same as a high ADT seal coat road. Vehicles wear down the wearing surface of the road, in this case the seal coat, as they travel over it. The more vehicles travel over a road, the faster the road is expected to deteriorate and reach the end of its service life. As the seal coat surface deteriorates due to traffic volume, the aggregate gets reoriented and pushed into the binder. If too much binder is applied during construction, this will lead to a pavement distress condition refers to as flushing or bleeding. On the other hand, if too little binder was used, it will lead to loss of aggregate or raveling.

The sections identified by the procedure described above are included in the following table. It may be observed in Table 4.1 that roads of high traffic and age greater than 7 years are difficult to locate. As mentioned earlier, seal coats are not intended for roads with high ADT. Overlays are preferred over seal coat for roads with high volumes of vehicles. Seal coats lasts about eight years on average, making older seal coat pavement sections difficult to find. Data for seventy one seal coat sections were collected using the OFM and the CTM.

Table 4.1 Completed Factorial Table

ADT/Age (yrs)	1	2	4	7	8	9	10
<500	FM 2200, RM 1051, FM 2690	FM 472, FM 1341, RM 1077	SH 85,FM 1332, RM 337, FM 472, FM 2748		FM 2200, FM 1403, SH 39, FM 462	FM 2730	FM 30
501-1000	SH 16, SH 127	FM 1273,RM 187	SH 16, RM 2828, RM 1050			RM 1376	SH 127
1001-1500			FM 474		FM 117, RM 187	RM 473	
1501-2000	FM 2537, FM 311, FM 471	FM 2369, IH 35 FR	FM 1101		FM 1574		
2001-2500		FM 481			FM 2252, SH 173		
2501-3000	FM 1516, FM 3009	SH 27, FM 1044			FM 463		
3001-3500				SH 16, FM 1283			
3501-4000	SH 173, RM 783	FM 1102	FM 306				
4001-4500	FM 2790						
4501-5000		SH 46, FM 1435, SH 16					
5001-10000	FM 1346, FM 3159, SH 39, SH 16	SH 46, SH 27, RM 783, SH 16	FM 306, SH 16, US 87, SH 123		SH 132	RM 2722	
10001-20000		US 90					
20001-30000		FM 725					

Table 4.1 shows the completed factorial table with all the roads for which outflow time and mean profile depth were collected. A total of seventy one seal coat sections were tested using the two devices. The table shows a wide range of roads of different age and different average daily traffic.

Standard procedure for each section was to establish traffic control and take readings with the OFM and the CTM at representative spots in the test section. Each spot on the road has two readings and for some of the sections a location is also available in terms of GPS coordinates.

Figure 4.3 shows the data collection using the CTM.

Figure 4.3 Data collection using the CTM

The data collection was started with the seven to ten year old road sections, since these were scheduled to be seal coated again soon during TxDOT's 2007 Seal Coat Program. For this group, only two measurements were taken using the outflow meter and the circular track meter for each road. The two measurements were only taken on the right wheel path. There are a number of reasons for taking the measurements on the right wheel path only. One of the reasons was safety since the traffic control provided was very limited. It was also pre-determined and later confirmed in the filed, that the right wheel path would have more wear than the left wheel path. There are several reasons for this, but the main one is that on a crowned road, water tends to accumulate closer to the right wheel path. As mentioned earlier, water is the primary enemy of pavements. Another reason is that the roadway has less structural support towards the edge.

The section of road selected would have to meet some criteria. It would have to be a long stretch of road with plenty of sight distance for safety reasons in establishing traffic control and executing the readings. It would also have to be representative of the overall condition of the road. Spots on the road with isolated shows of any type of distress were not measured. Intersections and driveway entrances where a number of vehicles would accelerate or slow down were avoided. Sections were traffic would be able to travel at the posted speed limit were preferred for measuring.

It was later decided to increase the number of measurement to five spots to better represent the section of road and also measure the left wheel path. The other three groups of roads were measured this way. Each one of these groups consisted of road sections that had seal coats one, two, and four years old respectively.

Figure 4.4 shows the data collection on the right wheel path using the outflow meter.

Figure 4.4 Data collection using the OFM

Each road section measured was tied to a reference marker. Coordinates were also recorded using a global positioning system (GPS). At each one of the sites the condition of the road was recorded. A small description of the road condition was noted and pictures were taken using a digital camera. The images taken help show the overall condition of the roadway. Some of the pictures taken can be found in the appendix. An electronic database contains all of the information for the entire seventy one seal coat sections tested including measurements, photos, and locations. This database is available in a companion CD.

Figure 4.5 shows the exact location of one of the sections tested using Google Earth and the GPS coordinates obtained in the field.

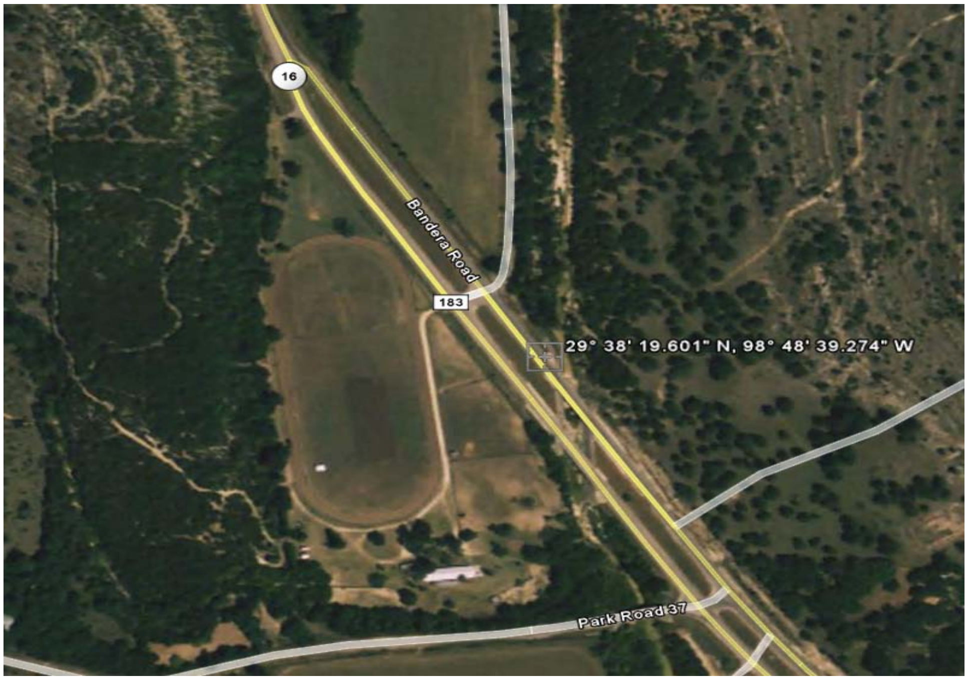

Figure 4.5 Site location using Google Earth

Table 4.2 shows an example of the type of information that is available in the electronic database compiled by this project and available in a companion CD. It contains Road, Age, ADT, OFM and CTM measurements, GPS coordinates, and a link to the digital photos. The raw data from the OFT and the CTM measurements can be found in the appendix. The complete electronic database can be obtained upon request.

Table 4.2 Database example

Right Wheel Track												
Road	**Age**	**ADT**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**
RM 1051	1	190	0	3.56	0	3.85	0	3.53	0	3.97	0	3.39

Latitude	**Longitude**	**Pictures**
29° 33' 39.587" N	99° 50' 39.309" W	C:\Seal Coat\Pictures\1 yr old seal coats\RM 1051
29° 08' 41.726" N	98° 55' 19.530" W	C:\Seal Coat\Pictures\1 yr old seal coats\FM 2200

CHAPTER 5

Data Analysis

5.1 Descriptive Statistics

Table 5.1 shows the distribution of measurements taken using the outflow meter and the circular track meter texture measuring devices per ADT and age categories. There are a total of twelve ADT categories ranging from less than 500 ADT to 30,000 ADT. There are also a total of seven age categories ranging from 1 year to 10 years old. A total of 558 readings were taken using the two devices for all categories of ADT and age. There can be more than one seal coat section under one category of ADT or age. For most seal coat sections, ten measurements, five on each wheel path, were taken using the OFT and the CTM. For the older seal coats between seven to ten years old, only two measurements were taken on the right wheel path using the two devices. As explained earlier in Chapter IV, only two measurements were taken on the right wheel path only with both devices. It was later decided to take five measurements on both wheel paths. It can be seen from the graph in figure 5.2 that there are many more readings for seal coat sections between 1 and 4 years old than there are for the older seal coats between 7 and 10 years old. It can also be seen from the distribution in figure 5.1 that there are significantly more readings for roads with an ADT of 10,000 or less than there are for roads with an ADT of more than 20,000. As mentioned in a previous chapter, seal coats last an average of eight years, therefore older seal coats are more difficult to find. Seal coats are also not intended for high traffic roads. Seal coats perform better on low to medium traffic volume roads with low volumes of heavy vehicles. Overlays are preferred for roads with a high ADT.

Table 5.1 Seal Coat readings Distribution by Age and ADT

ADT/Age	**1**	**2**	**4**	**7**	**8**	**9**	**10**	**Total**
<=500	30	30	50	0	8	2	2	**122**
501<ADT<=1,000	20	20	30	0	0	2	2	**74**
1,001< ADT <=1,500	0	0	10	0	4	2	0	**16**
1,501< ADT <=2,000	30	20	10	0	2	0	0	**62**
2,001< ADT <=2,500	0	10	0	0	4	0	0	**14**
2,501< ADT <=3,000	20	30	0	0	2	0	0	**52**
3,001< ADT <=3,500	0	0	10	0	0	0	0	**10**
3,501< ADT <=4,000	20	10	0	4	0	0	0	**34**
4001< ADT <=4500	10	0	0	0	0	0	0	**10**
4,501< ADT <=5,000	0	20	0	0	0	0	0	**20**
5,001< ADT <=10,000	40	50	40	0	2	2	0	**134**
20,001< ADT <=30,000	0	10	0	0	0	0	0	**10**
Total	**170**	**200**	**150**	**4**	**22**	**8**	**4**	**558**

Figure 5.1 shows the frequency distribution of seal coat sections per ADT class in percentage form. A total of seventy one sites were tested. All seventy one sections tested are part of TxDOT's San Antonio District. The San Antonio District carries out a seal coat program every year during the summer months. The seal coat plans are prepared in-house by TxDOT's engineers and technicians.

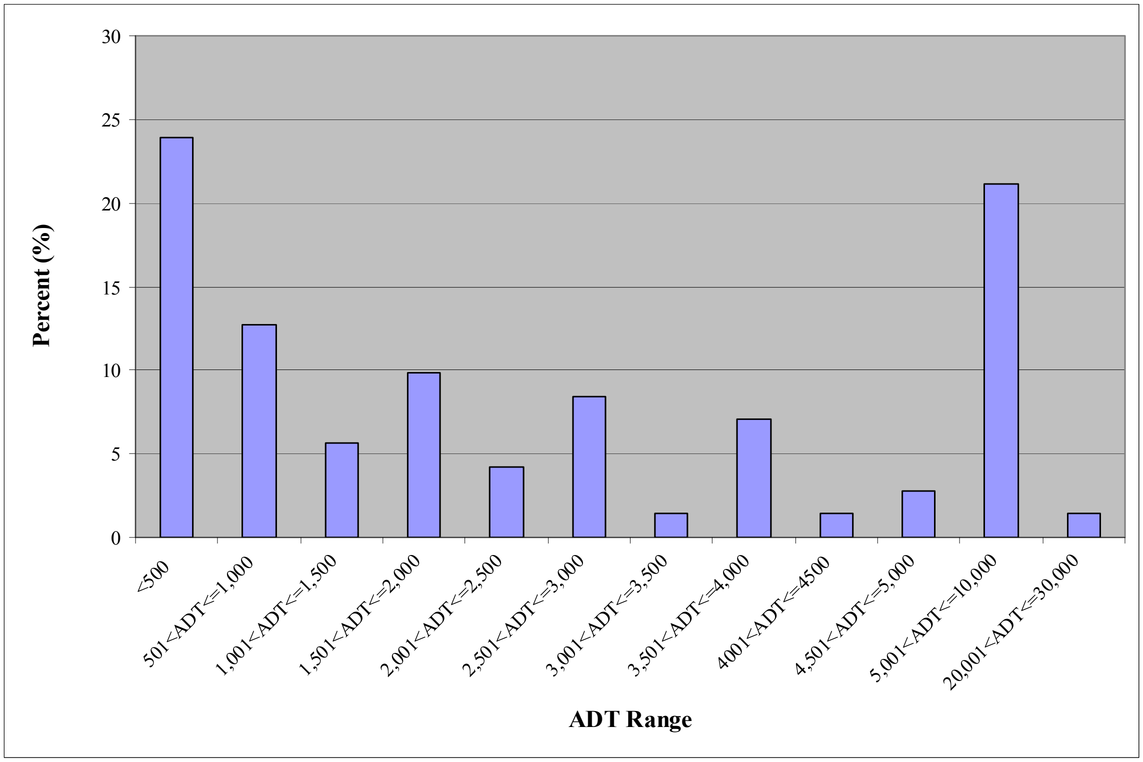

Figure 5.1 Seal coat sections distribution by ADT

Figure 5.2 shows the frequency distribution of all seventy one seal coat sections according to age. As mentioned before, seal coats lasts and average of eight years, therefore older seal coat sections are more difficult to find.

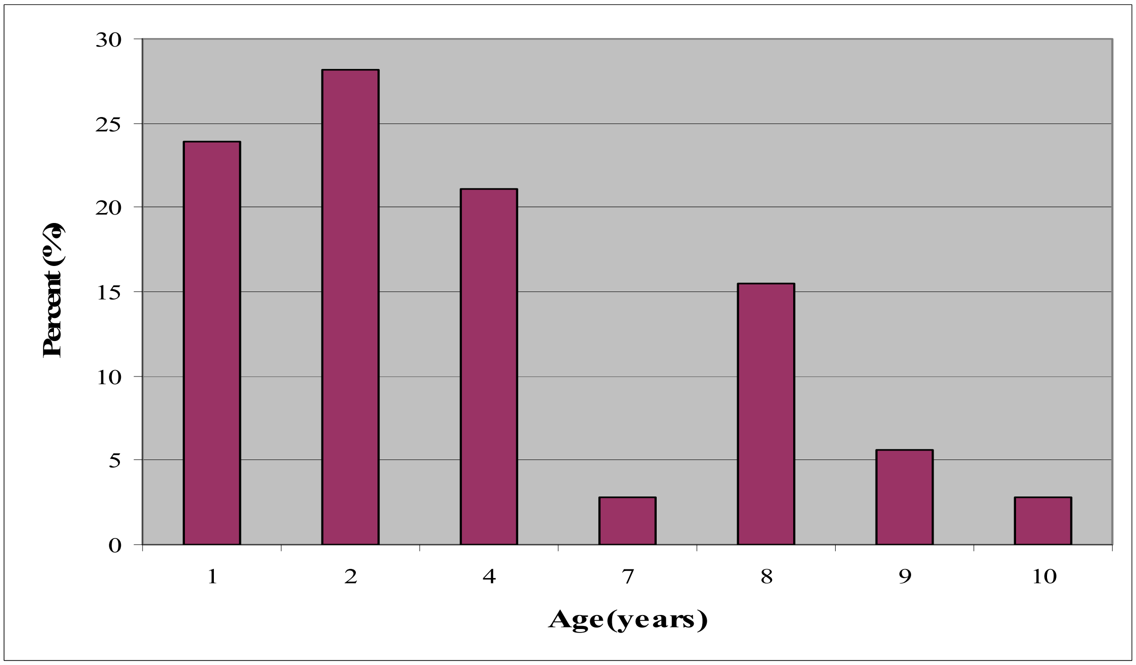

Figure 5.2 Seal coat sections distribution by age

Figure 5.3 shows the cumulative frequency for Outflow Time for the seventy one test sections. The reading for the 50th percentile is about 3 seconds.

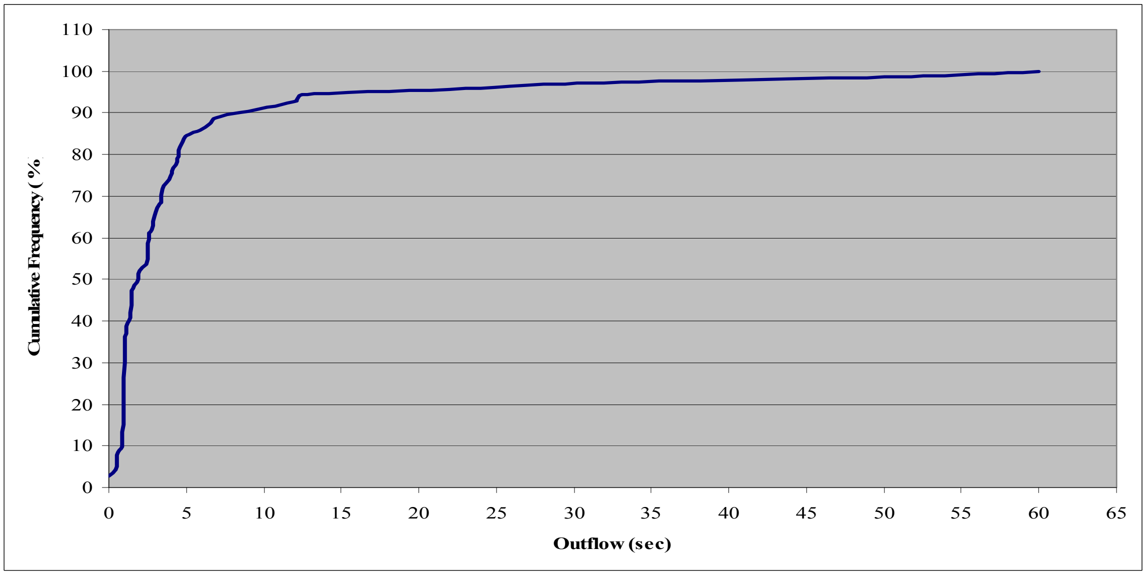

Figure 5.3 Outflow Time Cumulative Frequency

Figure 5.4 shows the cumulative frequency for MPD for the seventy one test sections. The MPD for the 50th percentile is about 1.6 mm.

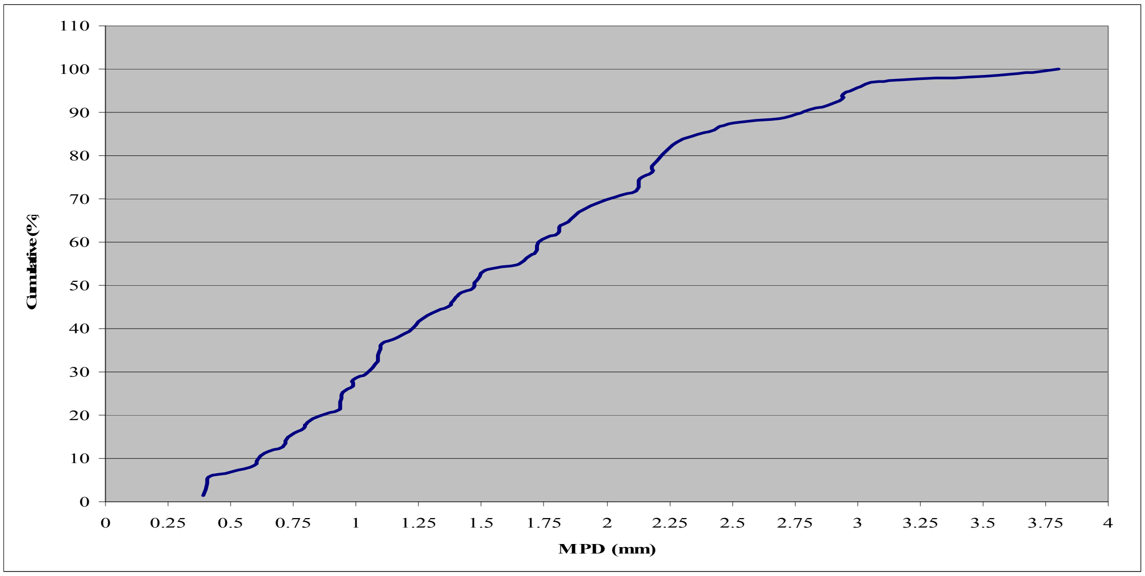

Figure 5.4 MPD Cumulative Frequency

Table 5.2 shows the average MPD readings as taken by the CTM for all seal coat sections tested. The table is cross tabulation of ADT, Road, and Age and it summarizes the average values for MPD for the seventy one test pavement sections surveyed.

Table 5.2 Average MPD Readings (mm)

		Age						
ADT	**Road**	**1**	**2**	**4**	**7**	**8**	**9**	**10**
<500	FM 30	.	.	.	.	.	.	1.37
	RM 1051	3.56	.	.	.	.	.	.
	FM 1332	.	.	1.47	.	.	.	.
	FM 2730	.	.	.	.	.	1.39	.

Table 5.2– Average MPD Readings (mm) Continued

		Age						
ADT	**Road**	**1**	**2**	**4**	**7**	**8**	**9**	**10**
	RM 337	.	.	2.18	.	.	.	.
	FM 462	.	.	.	.	1.1	.	.
	FM 2200age1	2.94	.	.	.	.	.	.
	FM 2200age8	.	.	.	.	0.51	.	.
	FM 2690	3.8	.	.	.	.	.	.
	SH 39age8	.	.	.	.	1.24	.	.
	FM 1341	.	2.34	.	.	.	.	.
	FM 472age1	.	1.81	.	.	.	.	.
	FM 2748	.	.	2.13	.	.	.	.
	FM 472	.	.	2.25	.	.	.	.
	SH 85	.	.	0.81	.	.	.	.
	FM 1403	.	.	.	.	1.04	.	.
	RM 1077	.	2.2	.	.	.	.	.
501<ADT<=1,000	FM 1273	.	2.14	.	.	.	.	.
	SH 127age10	.	.	.	.	.	.	1.07
	RM 1376	.	.	.	.	.	2.12	.
	RM 187age2	.	2.18	.	.	.	.	.
	SH 127age1	2.43	.	.	.	.	.	.
	RM 1050	.	.	1.72	.	.	.	.
	FM 2828	.	.	2.94	.	.	.	.
	SH 16low	.	.	1.26	.	.	.	.
	SH 16lowag1	2.88	.	.	.	.	.	.
1,001<ADT<=1,500	FM 474	.	.	1.21	.	.	.	.
	FM 473	.	.	.	.	.	0.41	.
	RM 187age8	.	.	.	.	1.65	.	.
	FM 117	.	.	.	.	1.68	.	.
1,501<ADT<=2,000	FM 311	3	.	.	.	.	.	.
	FM471	3.08	.	.	.	.	.	.
	FM 2369	.	1.74	.	.	.	.	.
	FM 1574	.	.	.	.	0.94	.	.
	FM 2537	1.72	.	.	.	.	.	.

Table 5.2 – Average MPD Readings (mm) Continued

		Age						
ADT	**Road**	**1**	**2**	**4**	**7**	**8**	**9**	**10**
	FM 1101	.	.	1.3	.	.	.	.
	IH35 FR	.	2.03	.	.	.	.	.
2,001<ADT<=2,500	SH 173	.	.	.	.	0.39	.	.
	FM 481	.	0.71	.	.	.	.	.
	FM 2252	.	.	.	.	0.64	.	.
2,501<ADT<=3,000	FM 3009	1.81	.	.	.	.	.	.
	SH 463	.	.	.	.	1.09	.	.
	SH 27 Kerr	.	0.93	.	.	.	.	.
	FM 1435	.	0.99	.	.	.	.	.
	FM 1044	.	1.91	.	.	.	.	.
	FM 1516	1.49	.	.	.	.	.	.
3,001<ADT<=3,500	FM 306 adt3k	.	.	0.95	.	.	.	.
3,501<ADT<=4,000	FM 1102	.	1.85	.	.	.	.	.
	SH 16age7	.	.	.	0.7	.	.	.
	FM 1283	.	.	.	0.4	.	.	.
	FM 783age1	2.22	.	.	.	.	.	.
	SH173	2.79	.	.	.	.	.	.
4001<ADT<=4500	FM 2790	2.49	.	.	.	.	.	.
4,501<ADT<=5,000	SH 46 Comal	.	0.61	.	.	.	.	.
	SH16ADT5K	.	1.87	.	.	.	.	.
5,001<ADT<=10,000	SH 16age1	2.71	.	.	.	.	.	.
	SH 123 adt5k	.	.	0.59	.	.	.	.
	SH 16 high	.	.	0.95	.	.	.	.
	FM 3159	1.96	.	.	.	.	.	.
	FM 306 adt7k	.	.	1.51	.	.	.	.
	SH 39age1	1.47	.	.	.	.	.	.
	FM 783	.	0.99	.	.	.	.	.
	SH 46 Kendall	.	0.79	.	.	.	.	.
	SH 27 Kendall	.	2.28	.	.	.	.	.
	US 90 ML	.	0.85	.	.	.	.	.
	SH 16ADT8K	.	1.09	.	.	.	.	.

Table 5.2 – Average MPD Readings (mm) Continued

		Age						
ADT	**Road**	**1**	**2**	**4**	**7**	**8**	**9**	**10**
	US 87	.	.	0.4	.	.	.	.
	SH 132	.	.	.	.	0.75	.	.
	FM 1346	1.41	.	.	.	.	.	.
	FM 2722	.	.	.	.	.	1.11	.
20,001<ADT<=30,000	FM 725	.	1.17	.	.	.	.	.

Table 5.3 reports the average outflow readings as taken by the outflow meter for all seal coat sections tested. As before, for the MPD readings, the table presents the cross-tabulation of ADT, Road, and Age.

Table 5.3 Average Outflow Readings (sec)

		Age						
ADT	**Road**	**1**	**2**	**4**	**7**	**8**	**9**	**10**
<500	FM 30	.	.	.	.	.	.	3
	RM 1051	0	.	.	.	.	.	.
	FM 1332	.	.	3	.	.	.	.
	FM 2730	.	.	.	.	.	3	.
	RM 337	.	.	1	.	.	.	.
	FM 462	.	.	.	.	4.5	.	.
	FM 2200age1	1	.	.	.	.	.	.
	FM 2200age8	.	.	.	.	13	.	.
	FM 2690	0	.	.	.	.	.	.
	SH 39age8	.	.	.	.	1.5	.	.
	FM 1341	.	0.9	.	.	.	.	.
	FM 472age1	.	1.5	.	.	.	.	.
	FM 2748	.	.	1.6	.	.	.	.

Table 5.3 – Average Outflow Readings (sec) Continued

		Age						
ADT	**Road**	**1**	**2**	**4**	**7**	**8**	**9**	**10**
	FM 472	.	.	1	.	.	.	.
	SH 85	.	.	3.4	.	.	.	.
	FM 1403	.	.	.	.	2.5	.	.
	RM 1077	.	1.1	.	.	.	.	.
501<ADT<=1,000	FM 1273	.	1.2	.	.	.	.	.
	SH 127age10	.	.	.	.	.	.	4
	RM 1376	.	.	.	.	.	1	.
	RM 187age2	.	1.5	.	.	.	.	.
	SH 127age1	1	.	.	.	.	.	.
	RM 1050	.	.	1.8	.	.	.	.
	FM 2828	.	.	1	.	.	.	.
	SH 16low	.	.	2.8	.	.	.	.
	SH 16lowag1	0	.	.	.	.	.	.
1,001<ADT<=1,500	FM 474	.	.	2.4	.	.	.	.
	FM 473	.	.	.	.	.	51	.
	RM 187age8	.	.	.	.	2	.	.
	FM 117	.	.	.	.	1	.	.
1,501<ADT<=2,000	FM 311	1	.	.	.	.	.	.
	FM471	1	.	.	.	.	.	.
	FM 2369	.	1	.	.	.	.	.
	FM 1574	.	.	.	.	3.5	.	.
	FM 2537	1	.	.	.	.	.	.
	FM 1101	.	.	2.6	.	.	.	.
	IH35 FR	.	1	.	.	.	.	.
2,001<ADT<=2,500	SH 173	.	.	.	.	31	.	.
	FM 481	.	6.9	.	.	.	.	.
	FM 2252	.	.	.	.	8.5	.	.
2,501<ADT<=3,000	FM 3009	1	.	.	.	.	.	.
	SH 463	.	.	.	.	4.5	.	.
	SH 27 Kerr	.	4	.	.	.	.	.
	FM 1435	.	4.6	.	.	.	.	.

Table 5.3 – Average Outflow Readings (sec) Continued

		Age						
ADT	**Road**	**1**	**2**	**4**	**7**	**8**	**9**	**10**
	FM 1044	.	1.9	.	.	.	.	.
	FM 1516	1	.	.	.	.	.	.
3,001<ADT<=3,500	FM 306 adt3k	.	.	4.3	.	.	.	.
3,501<ADT<=4,000	FM 1102	.	1	.	.	.	.	.
	SH 16age7	.	.	.	2	.	.	.
	FM 1283	.	.	.	22	.	.	.
	FM 783age1	1	.	.	.	.	.	.
	SH173	1	.	.	.	.	.	.
4001<ADT<=4500	FM 2790	1	.	.	.	.	.	.
4,501<ADT<=5,000	SH 46 Comal	.	12	.	.	.	.	.
	SH16ADT5K	.	1	.	.	.	.	.
5,001<ADT<=10,000	SH 16age1	1	.	.	.	.	.	.
	SH 123 adt5k	.	.	11	.	.	.	.
	SH 16 high	.	.	4.8	.	.	.	.
	FM 3159	1	.	.	.	.	.	.
	FM 306 adt7k	.	.	2.5	.	.	.	.
	SH 39age1	1	.	.	.	.	.	.
	FM 783	.	3.2	.	.	.	.	.
	SH 46 Kendall	.	5.9	.	.	.	.	.
	SH 27 Kendall	.	1	.	.	.	.	.
	US 90 ML	.	4.1	.	.	.	.	.
	SH 16ADT8K	.	2.6	.	.	.	.	.
	US 87	.	.	30	.	.	.	.
	SH 132	.	.	.	.	6.5	.	.
	FM 1346	3	.	.	.	.	.	.
	FM 2722	.	.	.	.	.	5	.
20,001<ADT<=30,000	FM 725	.	3.5	.	.	.	.	.

5.2 Analysis of Variance

An Analysis of Variance, ANOVA, was performed using the SAS System (SAS/STAT User's Guide, 1999).

5.2.1 Wheel Path Influence on Outflow Time

The analysis shows no statistical influence of wheel path on outflow times. As seen in Table 5.4, the R square is insignificant and the F statistics show that we cannot reject the null hypothesis that the means for the outflow readings are the same for the left and right wheel paths.

Table 5.4 Wheel Path Influence on Outflow Time

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	1	130.120	130.120	1.54	0.215
Error	556	47003.178	84.538		
Corrected Total	557	47133.299			

R-Square	**Coeff Var**	**Root MSE**	**Outflow Mean**
0.002761	242.348	9.194	3.793

5.2.2 Wheel Path Influence on MPD

The following table shows no statistical influence of wheel path on outflow times. As seen in the Table 5.5, the R square is insignificant and the F statistics show that we cannot reject the null hypothesis that the means for the MPD readings are the same for the left and the right wheel paths.

Table 5.5 Wheel Path Influence on MPD

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	1.728	1.728	2.48	0.115
Error	556	387.390	0.696		
Corrected Total	557	389.118			
R-Square	**Coeff Var**	**Root MSE**	**MPD Mean**		
0.004442	47.615	0.834	1.753		

5.2.3 ADT and Age Influence on Outflow Time

Table 5.6 shows that outflow time as a function of ADT and age is very significant. The means are significantly different for the ADT and Age outflow measurements and there is very significant interaction between ADT and Age as indicated by the F values.

Table 5.6 Outflow Time Statistics

Class Level Information					
Class	**Levels**	**Values**			
ADT	60	60 190 200 230 250 260 300 325 340 350 400 490 500 680 700 710 750 780 830 880 940 960 1050 1100 1200 1500 1550 1700 1780 1800 1850 2000 2200 2400 2500 2600 2650 2700 2900 3300 3700 3750 4500 4700 5000 5400 5600 6400 6500 6900 6925 7200 7300 7750 7950 8400 9200 9400 9800 21000			
Age	7	1 2 4 7 8 9 10			
Number of observations		558			
Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	66	42420.149	642.729	66.96	<.0001
Error	491	4713.150	9.599		
Corrected Total	557	47133.299			
R-Square	**Coeff Var**	**Root MSE**	**Outflow Mean**		
0.900004	81.663	3.098	3.793		

5.2.4 ADT and Age Influence on MPD

Table 5.7 shows that MPD as a function of ADT and age is very significant. The means are significantly different for the ADT and Age MPD measurements and there is very significant interaction between ADT and Age as indicated by the F values reported in Table 5.7.

Table 5.7 MPD Statistics

<table>
<tr><th colspan="7">Class Level Information</th></tr>
<tr><td>Class</td><td>Levels</td><td colspan="5">Values</td></tr>
<tr><td>ADT</td><td>60</td><td colspan="5">60 190 200 230 250 260 300 325 340 350 400 490 500 680 700 710 750 780 830 880 940 960 1050 1100 1200 1500 1550 1700 1780 1800 1850 2000 2200 2400 2500 2600 2650 2700 2900 3300 3700 3750 4500 4700 5000 5400 5600 6400 6500 6900 6925 7200 7300 7750 7950 8400 9200 9400 9800 21000</td></tr>
<tr><td>Age</td><td>7</td><td colspan="5">1 2 4 7 8 9 10</td></tr>
<tr><td colspan="2">Number of observations</td><td colspan="5">558</td></tr>
<tr><td colspan="2">Source</td><td>DF</td><td>Sum of Squares</td><td>Mean Square</td><td>F Value</td><td>Pr > F</td></tr>
<tr><td colspan="2">Model</td><td>66</td><td>342.393</td><td>5.188</td><td>54.51</td><td><.0001</td></tr>
<tr><td colspan="2">Error</td><td>491</td><td>46.725</td><td>0.095</td><td></td><td></td></tr>
<tr><td colspan="2">Corrected Total</td><td>557</td><td>389.119</td><td></td><td></td><td></td></tr>
<tr><td colspan="2">R-Square</td><td colspan="2">Coeff Var</td><td>Root MSE</td><td colspan="2">MPD Mean</td></tr>
<tr><td colspan="2">0.880</td><td colspan="2">17.597</td><td>0.308</td><td colspan="2">1.753</td></tr>
</table>

5.3 Relationship between MPD and Outflow Readings

The Outflow Meter (OFM) provides its user with results measured in seconds, which decrease as pavement texture increases, and vice versa. The Circular Track Meter (CTM) provides the user with mean profile depth in millimeters. The outflow meter used for this research has a resolution of one second. It is important to note that the outflow meter and the circular track meter do not measure the exact same area. The diameter of the area measured by the circular track meter is almost three times bigger than the diameter of the area measured by the outflow meter. The data collected by the circular track meter is divided into eight arcs of one hundred and twenty eight samples each. The circular meter then takes an average of all the data points. Because the outflow meter truncates, the unit that measures whole seconds has a bias of 0.6 seconds as compared to the other more precise outflow meters with a resolution of 0.001 seconds. The range of outflow time from which this relationship was developed is from one second to thirty seconds. After an outflow time reading of thirty seconds, the test would be manually stopped. It was pre-determined that an outflow time of thirty seconds was considered failure. A reading of thirty seconds would occur when the pavement texture is so smooth that water leaks out of the outflow meter very slowly. Because the resolution for the outflow meter used for this research is limited to one second, it is difficult to obtain accurate results when the outflow time is less than 3 seconds. Due to this rather coarse resolution, the correlation between the outflow time and the mean profile depth obtained from the circular track meter is also affected.

Figure 5.5 shows the relationship between MPD and outflow time for all of the seal coat sections for which data was collected. A total of seventy one sections were measured and 558 readings were taken using both texture measuring devices. It can be seen from the graph how outflow time increases as MPD decreases. There is a good correlation between MPD and outflow time. The R square is 0.75 as reported in Table 5.8. Equation 5-1 presents this correlation.

$$MPD = 2.05817 - 1.3865 \times Log(Outflow) \tag{5-1}$$

MPD in mm

Outflow time in seconds

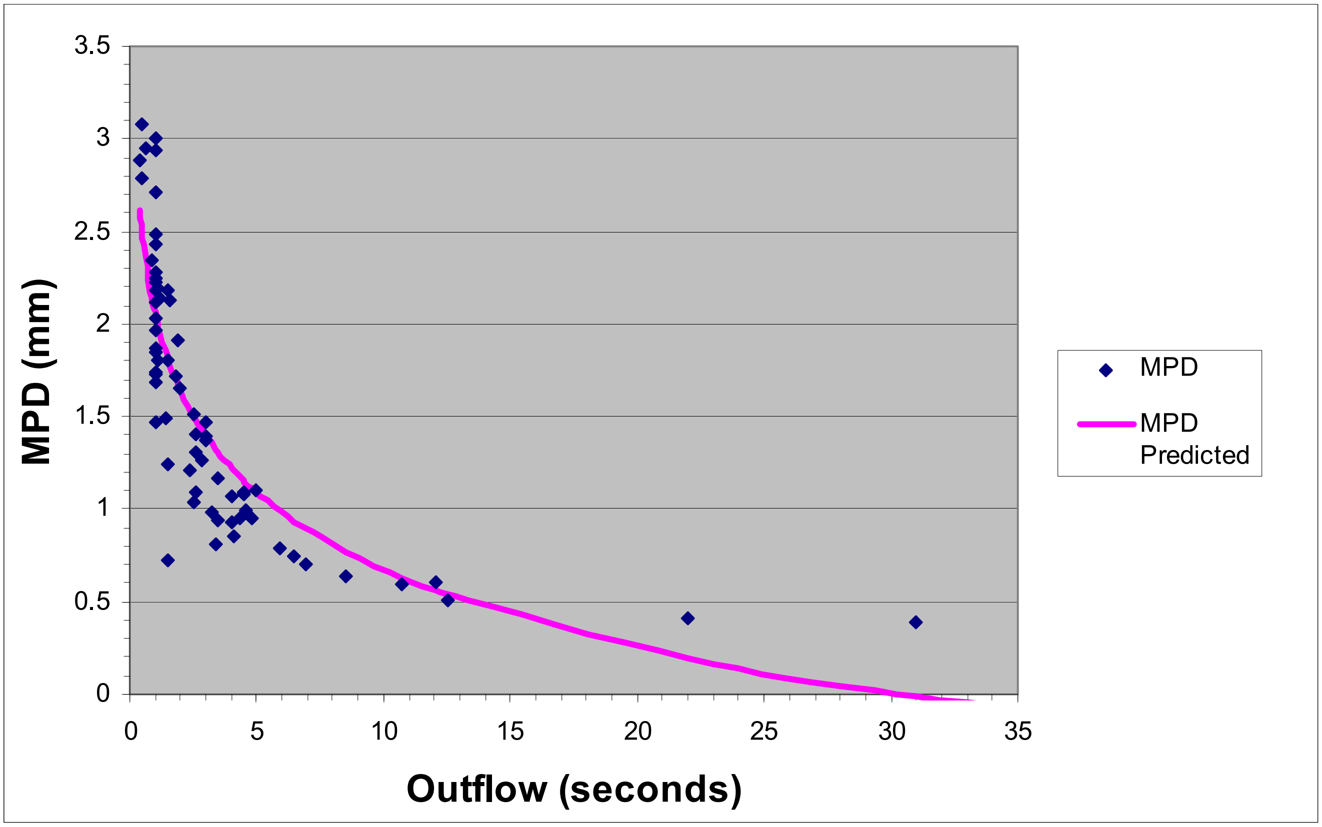

Figure 5.5 MPD vs. OFT

Table 5.8 MPD vs. OFT Statistics

<table>
<tr><th colspan="7">Analysis of Variance</th></tr>
<tr><th colspan="2">Source</th><th>DF</th><th>Sum of Squares</th><th>Mean Square</th><th>F Value</th><th>Pr > F</th></tr>
<tr><td colspan="2">Model</td><td>1</td><td>27.311</td><td>27.311</td><td>197.28</td><td><.0001</td></tr>
<tr><td colspan="2">Error</td><td>67</td><td>9.275</td><td>0.138</td><td></td><td></td></tr>
<tr><td colspan="2">Corrected Total</td><td>68</td><td>36.586</td><td></td><td></td><td></td></tr>
<tr><th colspan="7">Parameter Estimates</th></tr>
<tr><th>Variable</th><th>Label</th><th>DF</th><th>Parameter</th><th>Standard</th><th>t Value</th><th>Pr > |t|</th></tr>
<tr><td>Intercept</td><td>Intercept</td><td>1</td><td>2.058</td><td>0.058</td><td>35.41</td><td><.0001</td></tr>
<tr><td>logoutflow</td><td></td><td>1</td><td>-1.386</td><td>0.098</td><td>-14.05</td><td><.0001</td></tr>
<tr><td colspan="2">Root MSE</td><td colspan="2">0.372</td><td colspan="2">R-Square</td><td>0.746</td></tr>
<tr><td colspan="2">Dependent Mean</td><td colspan="2">1.537</td><td colspan="2">Adj R-Sq</td><td>0.743</td></tr>
<tr><td colspan="2">Coeff Var</td><td colspan="2">24.1929</td><td colspan="2"></td><td></td></tr>
</table>

Tables 5.8 shows a good statistical correlation between MPD and OFT, with excellent F and t statistics for the model and coefficients respectively.

5.4 Performance Curve in Terms of MPD

There is limited information on traffic available from the traffic maps at TxDOT. The traffic information for each one of the seventy one road test sections is the two way ADT. For the development of improved performance relationships additional data on load spectra will be needed. A preliminary performance curve based on MPD readings was developed using the concept of Cumulative Vehicles. For each of the seventy one test sections the cumulative traffic was calculated by the following formula. Shortcomings on this approach are related to the assumption of a constant mix (heavy and passenger vehicles) that does not change in time.

$$CumulativeTraffic = Age \times (ADT \div 2) \times 365 \tag{5-2}$$

Table 5.9 illustrates the calculations for a few ADT, Age combinations from test sections in the database. Equation 5-2 shows how the calculation is performed.

Table 5.9 Cumulative Traffic

Road	ADT	Age	Cumulative Traffic
FM 2252	2,500	8	3,650,000
FM 2369	1,780	2	649,700
FM 2537	1,800	1	328,500
FM 2690	300	1	54,750
FM 2722	9,800	9	16,096,500
FM 2730	230	9	377,775
FM 2748	400	4	292,000
FM 2790	4,500	1	821,250

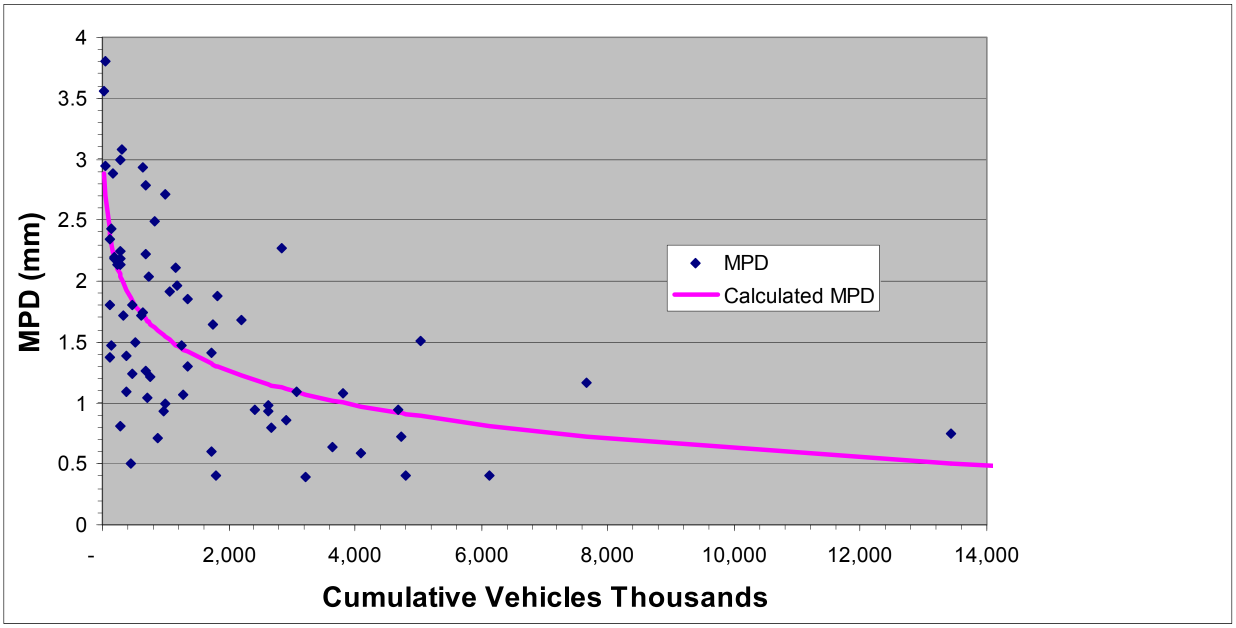

Figure 5.6 Seal Coat Performance Curve in Terms of MPD

Figure 5.6 shows how MPD decreases as the number of cumulative vehicles increases. A new seal coat will deteriorate quickly at first because the aggregate gets reoriented and pushed into the binder by the vehicles going over it. The deterioration will then slow down until it becomes asymptotic towards the right of the graph. Using this figure and the Cumulative Traffic Equation (5-2), the age at which a road will reach a certain MPD can be calculated. This method can be used to predict the service life of a seal coat. The failure and remaining life issue will be discussed in more detail in the next chapter. Equation 5-3 represents the correlation between MPD and Cumulative Vehicles.

$$MPD = 4.30948 - 0.9235 \times Log\left(CumulativeTraffic \times 10^{3}\right) \qquad (5\text{-}3)$$

CHAPTER 6

Development of Failure Criteria

6.1 Introduction

The need for maintaining good quality road surfacing is important in order to ensure vehicle safety. As defined earlier, macrotexture is the texture provided by the aggregate size and shape providing improved friction between the vehicle's tires and the pavement at high speeds. Recent studies have shown an increase in vehicle crashes once macrotexture, as measured by the MPD, falls below a certain threshold (Cairney, 2006). Based on this strong correlation between macrotexture and crashes, MPD becomes a good candidate for establishing failure criteria for seal coats. Thus, seal coat failure will be focused on the relationship between macrotexture and the number of crashes with a literature search being performed and summarized by this chapter with the objective of establishing thresholds for seal coat failure.

6.2 Earlier Research

Roe (1991) studied the relationship between macrotexture and the number of vehicle crashes. Macrotexture was measured using a laser device. The measurement of macrotexture used was Sensor Measured Texture Depth (SMTD), which is simply the average depth of the pavement surface macrotexture. MTD varies slightly from MPD. The relationship between MTD and MPD is defined later in the chapter. The study compared macrotexture at crash sites with macrotexture for the whole road. The study concluded that SMTD was a significant factor, with sites that presented a SMTD less than 0.8 showing a significant increase in crash incidence. This indicates a higher probability of crashing associated with low macrotexture. The study also shows that the number of crashes almost double when SMTD is less than 0.4 mm when comparing with the rest of the population of crash sites studied. Two further aspects of this study are very important. First, all crashes were classified into skidding crashes with a wet pavement, skidding crashes with a dry pavement, non-skidding crashes with a wet pavement, and non-skidding crashes with a dry pavement. The relationship of all these categories of crash to macrotexture was similar. This suggests that the wet pavement aspect of macrotexture is of little relevance. Second, there was a concern that the relationship that was observed might be the result of crashes occurring where macrotexture was already low. In order to account for this possibility, crashes where divided between those that occurred near intersections and those that occurred elsewhere. The four macrotexture relationships to crashes were found to be very similar. These findings reinforced the relationship between low macrotexture and crashes already identified in the initial research (Cairney, 2006).

In a similar research, Gothie (1993) reports a study involving wet-road crashes and macrotexture. The study covered 215 km of national roads in the Alpes region of France with an average daily traffic of approximately 10,000 vehicles. The study included 201 wet-road crashes over a period of almost five years. The relationship between crashes and macrotexture can be seen in figure 6.1. The top line represents the maximum wet road crash rates, the middle line the mean and the bottom line the lowest wet road crash rate. It can be seen that crash rate increases considerably when macrotexture drops below 0.5 mm. The x-axis represents macrotexture and the y-axis the wet road crash rate per 10^8 vehicles/km/year (Cairney, 2006).

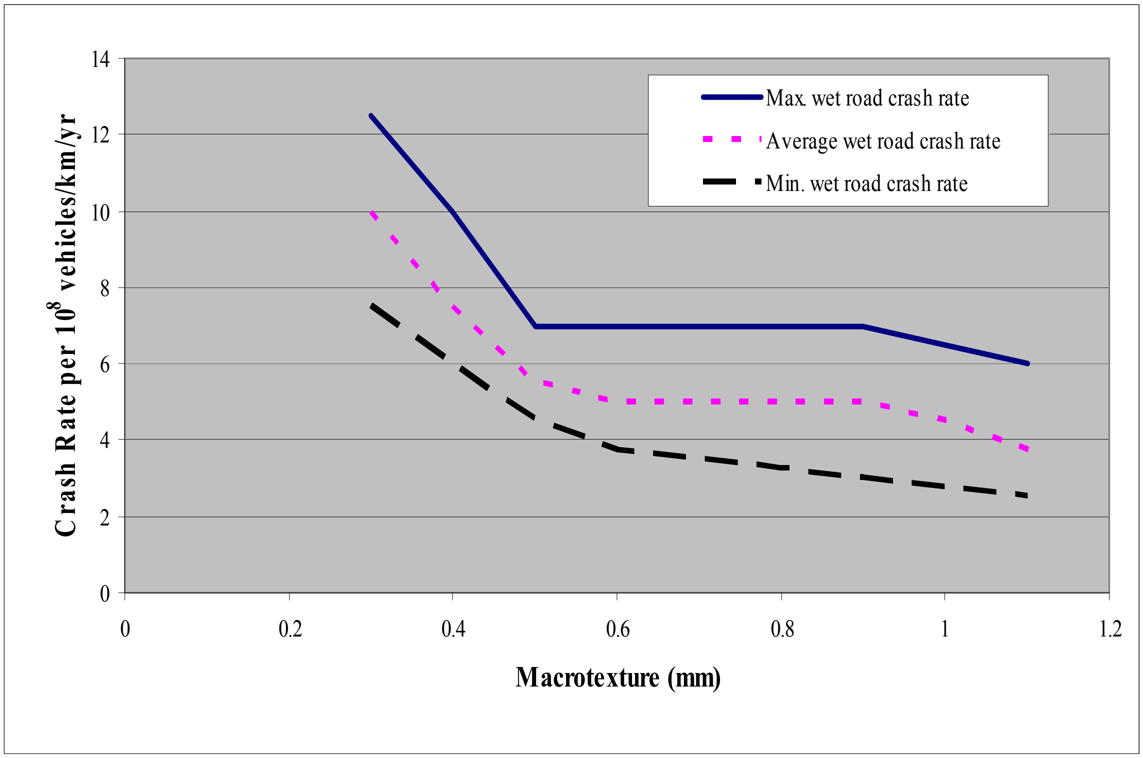

Figure 6.1 Relationship between macrotexture and wet road crash rate (Cairney, 2006)

The two studies mentioned above agree that there is an increased risk of crashes linked to low pavement macrotexture. The only difference between the two studies seems to be in the threshold value at which the frequency of crashes increases. The numerical difference could be due to the type of road or traffic systems in the two countries. It could also be due to a calibration of macrotexture measuring equipment or data handling. The important conclusion of these studies, is that a clear connection can be established between crash rates and pavement macrotexture.

In addition, the two findings reported by Roe (1991) reinforce the possibility of macrotexture as an indicator of safety performance. The finding that wet and dry pavement crashes have the same relationship to macrotexture is a clear indicator of the risk which applies to all crashes when macrotexture deteriorates beyond a certain point. The other finding, showing that the relationship between crashes and macrotexture was not the result of crashes being associated with intersections, answers any questions associated with the fact that the relationship may be affected by the higher levels of conflicting traffic occurrences (Cairney, 2006).

6.3 Recent Research

Two separate studies have been completed recently to study the relationship between crash rate and macrotexture (Cairney, 2006). The road selected for both studies was Princes Highway West, between Geelong and Portland. The road is almost 281 kilometers long, of which over 244 kilometers are rural with a speed limit of over 80 km/h and over 36 kilometers were urban with a speed limit of 80 km/h or less. The macrotexture surveys were obtained using a multi-laser texture profilometer while traveling at highway speeds. All records were GPS-referenced. The macrotexture data was available in one direction of travel only and it was analyzed in 20 meter sections. A macrotexture survey was completed for each of the studies. The first survey was done in 2000 for the first study in which it was matched with crash data for the years 1998-2002. The second survey was done in 2002 for the second study and matched with crash data from 2001 to 2003 (Cairney, 2006).

6.3.1 Study 1

Figure 6.2 shows the percentage of rural crash sites for each macrotexture category and the percentage of all sites that fell into the same category. A higher percentage of crash sites than all sites indicate that the crash rate is greater than average for that category, and vice versa. It can be observed that the crash risk is significantly above average for sites with macrotexture of 0.3

mm. It can also be noticed that the crash rate decreases for all sites as macrotexture increases. Similar results were obtained for urban sites.

Two significant observations were made for this study. First, there was no increase in the percentage of low macrotexture sites for wet weather crashes. Second, there was a significant increase in the percentage of crashes for low macrotexture sites at intersections. This shows that there is no relationship between macrotexture and crashes occurring in wet weather. However, these data show that crashes are more likely to occur at intersections where unexpected braking is more likely (Cairney, 2006).

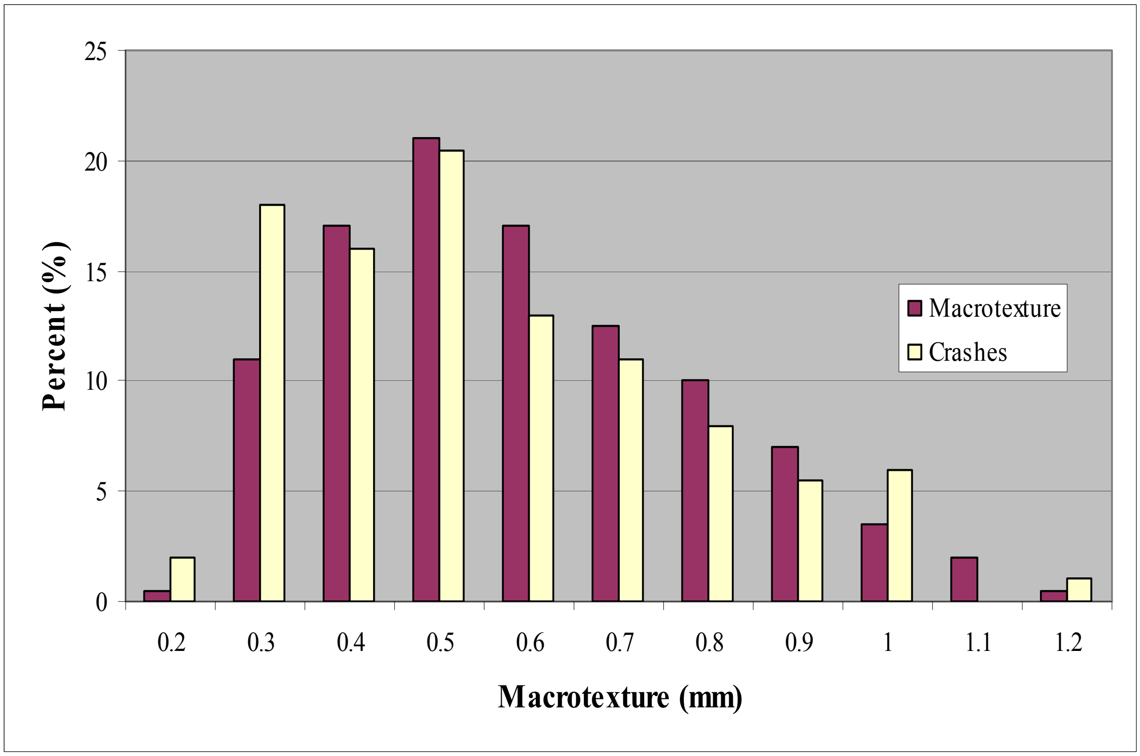

Figure 6.2 Relationship between macrotexture on all sites and at crash sites for Princes Highway West, rural (Cairney, 2006)

6.3.2 Study 2

The second study completed recently to show the relationship between crash rate and macrotexture was part of a larger study to examine relationships between rutting, macrotexture and roughness, and their relationship to crashes (Cairney, 2006).

The relationship between macrotexture and crash sites can be seen in figure 6.3. For sites with a SMTD of 0.4 mm or less, there is a greater percentage of crash sites than for all sites. The opposite is true for sites with an SMTD of 0.5 mm or greater, except for sites in the upper SMTD range of 0.90 and 1.00 mm, but the number is small. The results may have been affected by not having enough data available.

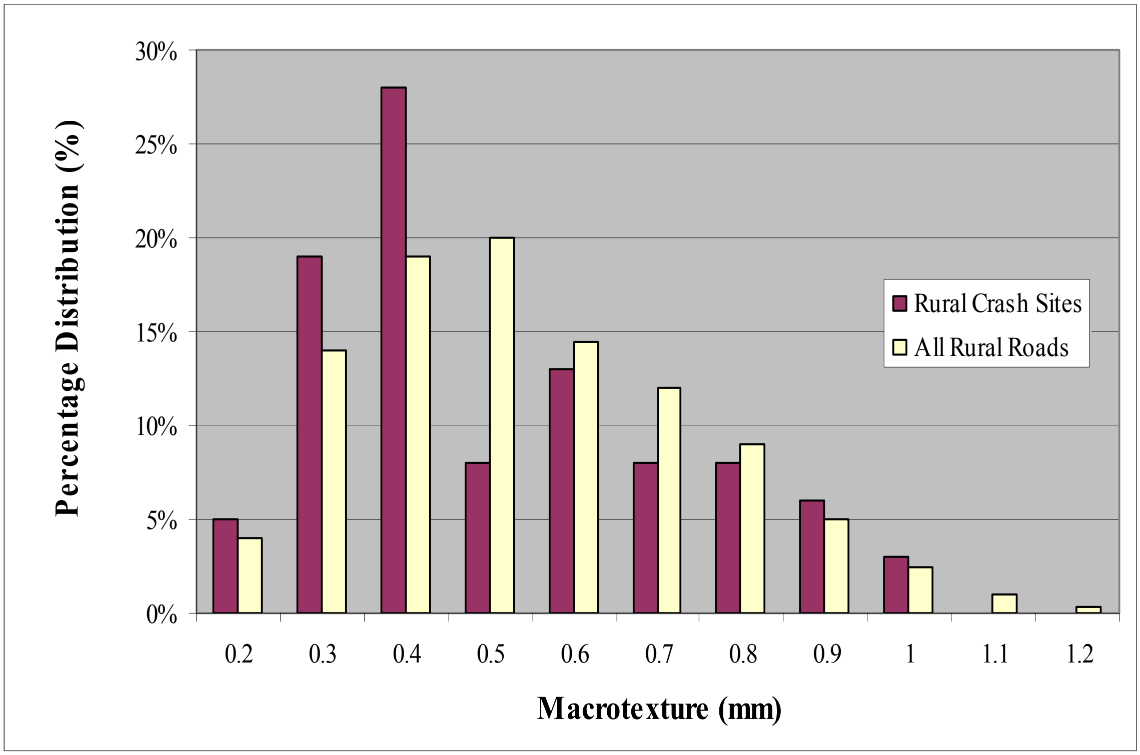

Figure 6.3 Relationship between macrotexture on all sites and at crash sites (Cairney, 2006)

Table 6.1 Macrotexture at crash sites and other sites (Cairney, 2006)

Macrotexture (SMTD)	Crash Sites	Other Sites
0.4 or less	98 (52.7%)	15,540 (36.85%)
0.5 or more	88 (47.3%)	26,630 (63.2%)
Total	186 (100%)	42,389 (100%)

Table 6.1 shows the percentage of crash sites significantly exceeds the proportion of other sites for a SMTD of less than 0.4 mm. Sites with an SMTD of less than 0.4 mm accounted for 36.6 percent of other sites and 52.7 percent of crash sites. The likelihood of crashing at a site with SMTD of 0.4 or less is 43 percent higher (Cairney, 2006).

Table 6.2 shows little difference between the percentage of low macrotexture sites for wet weather and dry weather crashes. However, the number of crashes in wet weather is small.

Table 6.2 Road conditions at crash sites (Cairney, 2006)

Macrotexture (SMTD)	Wet	Dry
0.4 or less	5 (19.2%)	36 (23.7%)
0.5 or more	21 (80.8%)	116 (76.3%)
All sites	26 (100%)	152 (100%)

For the second study, it was possible to obtain traffic flow estimates. Table 6.3 shows that the crash rate is about 80 percent higher when SMTD falls below 0.4 mm.

Table 6.3 Crash rate per million vehicle/km (Cairney, 2006)

Macrotexture (SMTD)	**10^6 vehicle/km 1999-2003**	**No of crashes**	**Crashes/million Vehicle/km**
0.4 or less	251	46	0.1833
more than 0.4	838	84	0.1002

These two studies showed a significant difference in crash rate between sites with low macrotexture and sites with higher macrotexture. Crash rate was double for sites with low macrotexture. In view of these findings, and the simplicity and low cost of conducting macrotexture surveys, it is important to consider that macrotexture could be used as an indicator of pavement condition for safety management purposes (Cairney, 2006).

6.4 Threshold

The studies above show a clear relationship between crash rate and macrotexture. Out of all the studies mentioned above, the study by Gothie (1993) shows a significant increase in crash rate at low levels of macrotexture. From the graph in figure 6.1, it can be seen that the steep increase occurs when SMTD falls below 0.5 mm. Since the SMTD value of 0.5 mm is the most conservative from all of the studies, it is then recommended to use it as the threshold for failure for seal coats.

The following ASTM equation, equation 6-1, shows the relationship between Mean Texture Depth (MTD) and Mean Profile Depth (MPD). All of the data collected in this research was using the outflow meter and the circular track meter. The circular track meter reports results in MPD while the results from the outflow meter are in seconds. The correlation between the two devices used is shown in chapter 5.

$$MTD = 0.947 \times MPD + 0.069 \qquad (6\text{-}1)$$

where,

MTD = Mean Texture Depth (mm)

MPD = Mean Profile Depth (mm)

or,

$$MTD = 0.947 \times MPD + 0.0027 \qquad (6\text{-}2)$$

where,

MTD = Mean Texture Depth (inches)

MPD = Mean Profile Depth (inches)

Using the appropriate equation above, a SMTD value of 0.5 mm is equivalent to a MPD value of 0.46 mm.

6.5 Failure and Factorial Collected Data

By using all of the data collected by the outflow meter and the circular track meter and comparing all of the results, a MPD value of 0.46 mm corresponds to an outflow time of about 14.5 seconds. This value was obtained by using the correlation presented in Figure 5.5 and summarized by equation 5-1 which was developed using the data collected by this research project.

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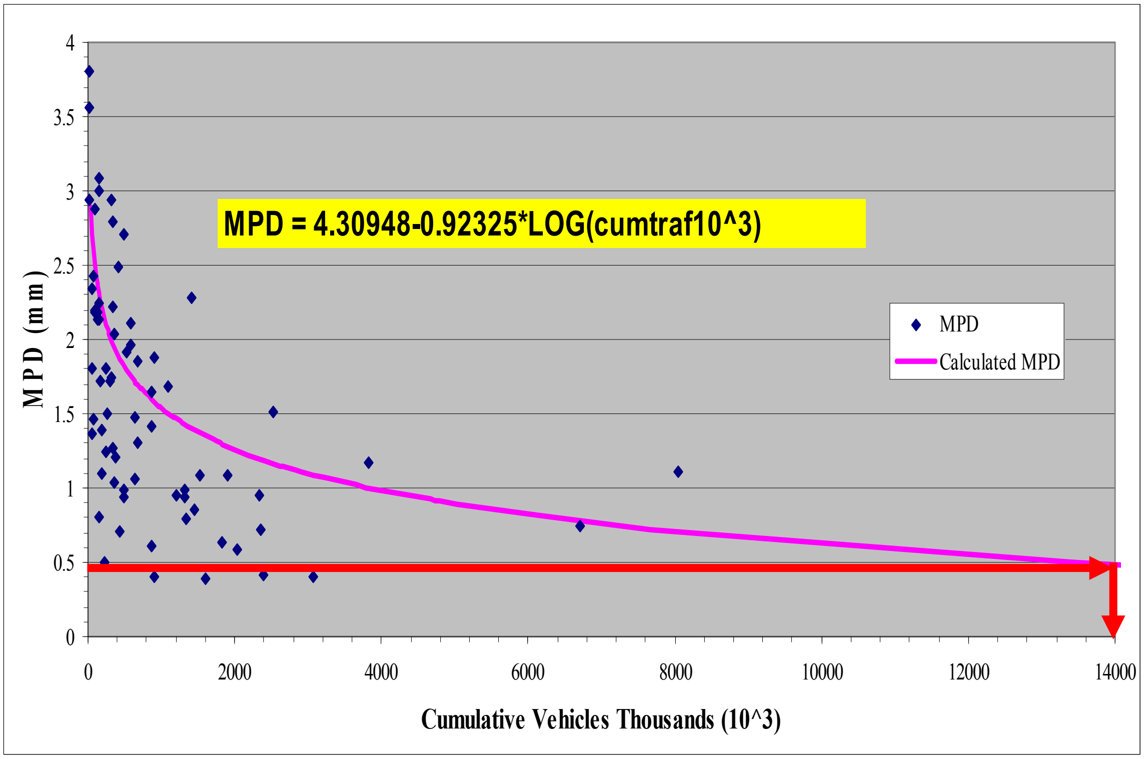

Figure 6.4 Seal Coat Failure Criteria in Terms of MPD and Cumulative Traffic

Figure 6.4 shows that failure occurs on average at a cumulative traffic of $14X10^6$ vehicles, which corresponds to an age of 8 years for a bi-directional ADT of 9,500 vehicles per day. This may be shown by substituting the 9,500 bidirectional ADT in Equation 5-2 and calculation for age.

$$0.46 = 4.30948 - 0.92325 \times LOG(cumtraf\,10^3) \qquad (6\text{-}3)$$

The threshold for failure can be defined as any seal coat road with a mean profile depth of 0.46 mm or less and an outflow time of 14.5 seconds or greater.

Figure 6.5 shows failure for a seal coat road with an MPD of 0.46 mm or less and a corresponding outflow time of 14.5 seconds or greater using the correlation between MPD and outflow time developed by this research project and summarized in Equation 6-4.

$$0.46 = 2.05817 - 1.3865 \times LOG(Outflow) \tag{6-4}$$

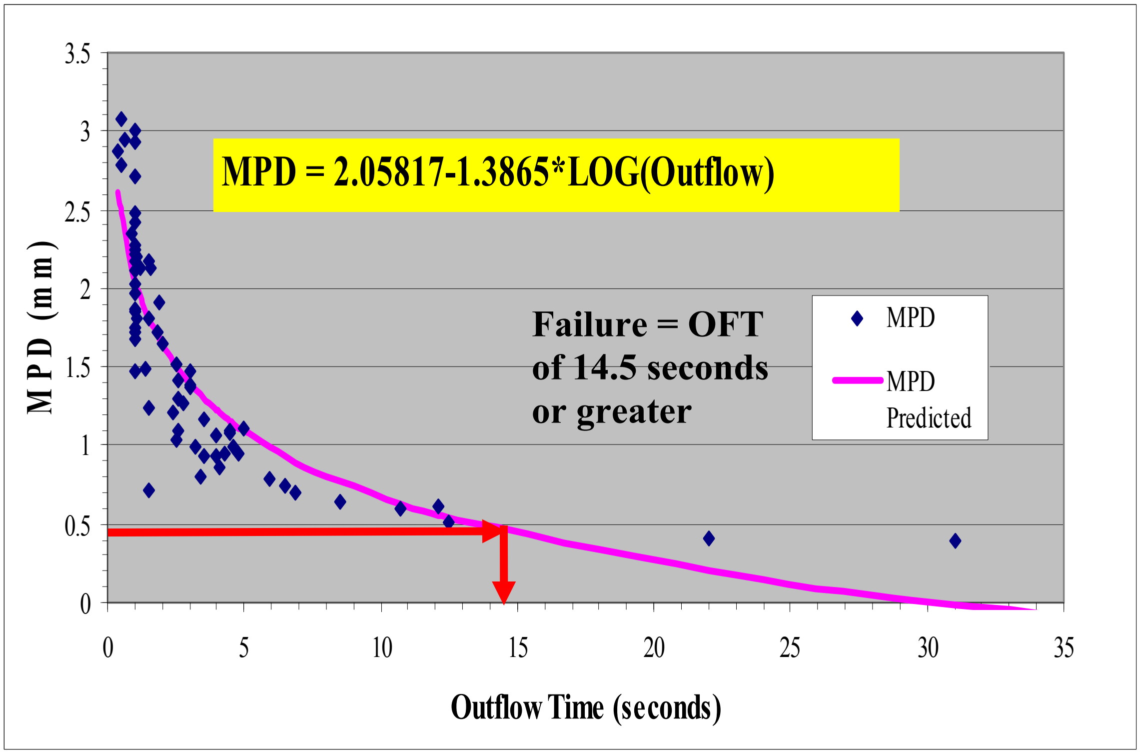

Figure 6.5 Outflow Time Failure Criteria

CHAPTER 7

Conclusions and Recommendations for Future Research

7.1 Conclusions

The literature survey showed that seal coats applied early in the summer seemed to perform better than those applied at the end of the summer (Gransberg, D., and James, D., 2005). This is because seal coats applied early in the summer are given more time to cure before being subject to the low temperatures of the winter season. It is then recommended that seal coating is done early in the summer season. This could be achieved by awarding seal coat contracts accordingly (Gransberg, D., and James, D., 2005).

Other road work like patching, crack sealing, and stripping should also be completed as far in advance of the seal coat as possible in order to allow maximum curing time for those other types of work. It is recommended that this type of work is performed the year before seal coating. Studies have shown that patches and crack sealing are common causes of bleeding due to localized increase of asphalt over the sealed cracks and patches. As mentioned before, patching and crack sealing should be done far enough in advance, a minimum of six months is recommended, in order to allow for the patches to cure. Agencies should enforce the contract's seasonal limitations in case where the contractor has fallen behind schedule (Gransberg, D., and James, D., 2005).

In other countries, seal coat contracts are moving in the direction of performance driven contracts. In these contracts, all of the liability is assumed by the contractor. The state agency is only responsibly for specifying the desired outcome to the contractor. In New Zealand, the seal coat texture is measured by using the sand patch method, as described previously in another chapter, after the new seal coat road has been in service for one year. The payment to the contractor is then adjusted depending if the road's macrotexture has performed as desired. A similar type of contract could be implemented in The United States by State Agencies like the Texas Department of Transportation in order to ensure seal coat quality after the work is completed and the new seal coat has been in service for a period of time. This will require that the contractor provide a written warranty of their seal coat work. Implementing warranties may help TxDOT save money by providing a mechanism that requires the contractor to repair failures that are a consequence of poor materials or labor. Warranties will also encourage contractors to provide a better finished product. The use of warranties are the main difference between seal coat contracts in the United States and that of other countries like Canada and New Zealand, which have already implemented warranties in their seal coat programs (Gransberg, D., and James, D., 2005).

Research has shown that there has not been any significant increase in bid prices to reflect the use of warranties in seal coat contracts. Research also shows that seal coat lasts twice as long in countries that implemented warranties in their seal coat contracts (Gransberg, D., and James, D., 2005).

Because other countries like New Zealand have been extremely successful using warranties, it is recommended that the Texas Department of Transportation also implements the use of warranties. This has created in New Zealand a strong financial incentive for seal coat contractors to both design and install the best possible seal coat (Gransberg, D., and James, D., 2005). A preliminary performance curve was developed by this research project and it is included in Chapter 5 (Figure 22). This could provide initial guidance on expected performance in terms of macrotexture as measured by MPD.

Studies show an inability to determine the exact rate of binder and aggregate appplied at a failed seal coat section. It is recommended that a study of seal coat construction record keeping and performance monitoring is implemented (Gransberg, D., and James, D., 2005). Performance could then be measured using the MPD criteria.

Another research showed that the importance of the roller in achieving aggregate embedment is not well understood. It is recommended that a study of seal coat rolling practice is conducted. Optimum size and weight of the roller should be investigated (Gransberg, D., and James, D., 2005).

The research showed that MPD is an effective indicator to measure seal coat quality. It also showed a good correlation between the outflow meter and the circular track meter. This indicates that the outflow meter could be used by a Texas Department of Transportation inspector as a portable and inexpensive device to measure seal coat quality. The outflow meter could be used to determine if the seal coat has failed using the recommended thresholds determined by this research and documented in Chapter 6 of this report.

A threshold for seal coat failure was obtained from this research. A failed seal coat cold be defined as one with a MPD of 0.46 mm or less or an equivalent outflow time of 14.5 seconds or greater. A seal coat also reaches failure at a cumulative traffic of $14X10^6$ vehicles.

7.2 Recommendations for future research

Unfortunately, the traffic data available for this study did not include growth rates, traffic classification, and axle loads. It is strongly recommended that the preliminary curve in terms of texture developed by this research be updated using a carefully designed factorial that would include detailed traffic characterization and the influence of traffic on seal coat performance as measured by macrotexture.

APPENDIX A. Seal Coat Pictures

Figure A.1 New seal coat

Figure A.2 New seal coat close up

Figure A.3 Seal coat with excessive flushing

Figure A.4 Close up of seal coat with excessive flushing

Figure A.5 Seal coat with moderate flushing

Figure A.6 Close up of seal coat with moderate flushing

Figure A.7 Seal coat showing little distress

Figure A.8. Close up of seal coat showing little distress

APPENDIX B. FM 1283 and RM 1376 Pictures.

Figure B.1 FM 1283

Figure B.2 Close up of FM 1283

Figure B.3 RM 1376

Figure B.4 Close up of RM 1376

APPENDIX C. Raw Data

Table C.1 1 year old seal coats – Left wheel path

Road	Age	ADT	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)
RM 1051	1	190	0	3.47	0	3.90	0	3.38	0	3.22	0	3.34
FM 2200	1	300	0	3.07	0	2.86	1	3.22	0	2.79	0	3.06
FM 2690	1	300	0	4.32	0	3.95	0	4.07	0	3.91	0	4.09
SH 127	1	780	1	2.00	1	2.32	1	2.79	1	2.14	1	2.55
SH 16	1	960	1	2.65	1	2.96	0	3.10	0	3.05	0	2.92
FM 311	1	1550	1	3.06	1	2.98	1	3.07	1	3.10	1	2.92
FM471	1	1700	0	2.97	0	3.26	0	3.24	0	4.03	0	3.39
FM 2537	1	1800	1	1.98	1	1.64	1	1.44	1	1.41	1	1.14
FM 3009	1	2600	2	1.86	1	1.80	1	1.82	1	2.45	1	2.03
FM 1516	1	2900	1	1.55	1	1.56	1	2.05	1	1.65	1	1.72
FM 783	1	3750	1	1.94	1	2.36	1	2.12	1	2.35	1	1.91
SH173	1	3750	0	2.97	0	2.47	0	2.76	0	2.87	0	2.98
FM 2790	1	4500	1	2.55	1	2.56	1	2.26	1	2.33	1	2.43
SH 16	1	5400	1	2.35	1	2.84	1	2.70	1	2.76	1	2.80
FM 3159	1	6500	1	1.71	1	2.10	1	2.20	1	2.05	1	1.96
SH 39	1	6925	1	1.25	1	1.54	1	1.42	1	1.32	1	1.26
FM 1346	1	9400	3	1.61	3	1.41	3	1.92	3	1.24	3	1.28

Table C.2 1 year old seal coats – Right wheel path

Road	**Age**	**ADT**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**
RM 1051	1	190	0	3.56	0	3.85	0	3.53	0	3.97	0	3.39
FM 2200	1	300	1	2.82	1	3.53	1	2.81	1	2.60	1	2.68
FM 2690	1	300	0	4.02	0	3.37	0	3.28	0	3.74	0	3.28
SH 127	1	780	1	2.53	1	2.22	1	2.74	1	2.46	1	2.53
SH 16	1	960	1	2.41	1	2.83	0	2.61	0	3.04	0	3.23
FM 311	1	1550	1	3.02	1	2.90	1	2.75	1	3.00	1	3.19
FM471	1	1700	1	2.21	1	3.07	1	3.10	1	2.89	1	2.66
FM 2537	1	1800	1	2.09	1	1.68	1	1.50	1	2.26	1	2.09
FM 3009	1	2600	1	1.89	1	1.56	1	1.71	1	1.41	1	1.52
FM 1516	1	2900	2	1.16	1	1.13	2	1.46	2	1.41	2	1.25
FM 783	1	3750	1	2.36	1	2.80	1	2.24	1	2.00	1	2.15
SH 173	1	3750	1	2.80	1	2.91	1	2.86	1	2.53	1	2.72
FM 2790	1	4500	1	2.33	1	2.37	1	2.81	1	2.54	1	2.68
SH 16	1	5400	1	2.92	1	2.86	1	2.85	1	2.23	1	2.68
FM 3159	1	6500	1	1.35	1	2.30	1	1.91	1	2.01	1	2.10
SH 39	1	6925	1	1.56	1	1.54	1	1.56	1	1.86	1	1.43
FM 1346	1	9400	3	1.41	2	1.48	2	1.32	2	0.99	2	1.43

Table C.3 2 year old seal coats – Left wheel path

Road	Age	ADT	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)
FM 1341	2	340	0	2.31	1	2.74	1	2.05	1	2.43	1	2.01
FM 472	2	350	1	2.12	1	2.07	1	2.04	1	2.14	1	1.87
RM 1077	2	500	1	2.62	0	2.49	1	2.70	1	2.15	1	2.13
FM 1273	2	680	2	2.14	2	2.19	1	2.44	1	2.06	1	2.11
RM 187	2	750	3	1.01	2	1.12	2	1.60	2	2.27	2	1.90
FM 2369	2	1780	1	1.79	1	1.46	1	1.97	1	1.56	1	1.70
IH 35 FR	2	2000	1	1.82	1	2.01	1	2.22	1	2.59	1	2.27
FM 481	2	2400	4	0.76	11	0.67	3	0.66	2	0.60	8	0.56
SH 27	2	2650	5	0.91	4	0.87	6	0.99	4	0.92	4	0.95
FM 1435	2	2700	3	1.15	6	0.88	6	1.06	6	0.79	3	1.07
FM 1044	2	2900	2	1.93	1	1.98	1	1.90	1	1.72	1	1.83
FM 1102	2	3700	1	2.11	1	1.74	1	1.82	1	1.89	1	1.86
SH 46	2	4700	9	0.55	9	0.51	8	0.73	8	0.66	15	0.63
SH 16	2	5000	1	1.55	1	1.86	1	2.18	1	2.07	1	1.81
FM 783	2	7200	1	1.16	4	1.06	4	0.88	4	0.92	4	0.82
SH 46	2	7300	8	0.85	4	1.18	3	0.88	4	0.84	4	0.75
SH 27	2	7750	1	2.46	1	2.33	1	2.11	1	2.39	1	2.79
US 90 ML	2	7950	6	0.88	4	0.82	2	0.89	3	0.77	3	0.90
SH 16	2	8400	2	0.86	3	1.06	4	1.07	3	1.32	2	1.20
FM 725	2	21000	4	1.10	2	1.10	3	1.55	4	1.22	3	1.37

Table C.4 2 year old seal coats – Right wheel path

Road	**Age**	**ADT**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**	**OF (sec)**	**MPD (mm)**
FM 1341	2	340	1	1.98	1	2.42	1	2.32	1	2.62	1	2.54
FM 472	2	350	2	1.58	2	1.46	2	1.69	2	1.47	2	1.64
RM 1077	2	500	1	1.87	2	2.09	1	2.15	2	1.97	1	1.81
FM 1273	2	680	1	1.84	1	2.20	1	2.07	1	2.11	1	2.19
RM 187	2	750	1	2.19	2	2.98	0	3.03	0	2.92	1	2.77
FM 2369	2	1780	1	1.99	1	1.72	1	1.62	1	1.83	1	1.80
IH 35 FR	2	2000	1	1.67	1	1.92	1	1.94	1	2.13	1	1.76
FM 481	2	2400	9	0.88	11	0.86	8	0.73	7	0.70	6	0.64
SH 27	2	2650	4	0.93	3	0.97	4	0.87	3	0.93	3	0.99
FM 1435	2	2700	1	0.91	6	0.94	5	1.04	2	0.90	8	1.15
FM 1044	2	2900	2	1.86	3	2.03	2	2.37	3	1.81	3	1.68
FM 1102	2	3700	1	1.90	1	1.90	1	1.83	1	1.84	1	1.60
SH 46	2	4700	9	0.66	8	0.72	9	0.74	9	0.50	30	0.36
SH 16	2	5000	1	1.83	1	2.28	1	1.90	1	1.54	1	1.71
FM 783	2	7200	3	1.27	3	1.02	2	1.19	3	0.79	4	0.75
SH 46	2	7300	10	0.78	14	0.66	3	0.70	3	0.71	6	0.58
SH 27	2	7750	1	1.93	1	2.36	1	2.08	1	2.26	1	2.05
US 90 ML	2	7950	3	0.85	5	0.92	7	0.71	4	0.78	4	1.02
SH 16	2	8400	2	1.01	3	0.98	3	1.22	2	0.92	2	1.24
FM 725	2	21000	7	0.84	3	1.11	2	1.02	4	1.16	3	1.20

Table C.5 4 year old seal coats – Left wheel path

Road	Age	ADT	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)
FM 1332	4	200	3	1.59	3	1.82	3	1.36	3	1.37	3	1.78
RM 337	4	250	1	2.24	1	2.45	1	2.02	1	1.81	1	1.99
FM 472	4	400	1	1.90	1	2.07	1	2.52	1	2.13	1	2.22
SH 85	4	400	3	0.96	5	0.86	2	0.78	4	0.57	2	0.78
FM 2748	4	400	1	1.90	2	2.00	1	2.27	2	2.11	1	2.47
RM 1050	4	830	1	1.58	2	1.66	3	1.38	2	2.05	2	1.89
FM 2828	4	880	1	3.10	1	2.91	1	2.79	1	2.58	1	2.93
SH 16	4	940	3	1.26	1	1.22	3	1.31	2	1.11	1	0.98
FM 474	4	1050	2	1.04	3	1.20	3	1.04	3	0.93	3	0.99
FM 1101	4	1850	2	1.32	2	1.16	2	1.44	2	1.45	2	1.14
FM 306	4	3300	4	0.84	5	0.90	4	0.87	7	0.67	5	0.67
SH 123	4	5600	8	0.45	30	0.63	4	0.45	7	0.45	7	0.44
SH 16	4	6400	4	1.36	4	1.11	4	1.13	4	0.84	4	0.80
FM 306	4	6900	2	1.33	1	1.64	3	1.40	2	1.59	3	1.68
US 87	4	8400	30	0.46	30	0.43	30	0.33	30	0.43	30	0.38

Table C.6 4 year old seal coats – Right wheel path

Road	Age	ADT	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)
FM 1332	4	200	3	1.31	3	1.14	3	1.04	3	1.62	3	1.66
RM 337	4	250	1	2.26	1	2.21	1	2.45	1	2.19	1	2.18
FM 472	4	400	1	2.13	1	2.35	1	2.52	1	2.22	1	2.39
SH 85	4	400	2	1.07	3	0.67	3	0.58	3	0.81	7	1.00
FM 2748	4	400	2	2.11	2	2.30	2	2.25	1	2.03	2	1.86
RM 1050	4	830	2	1.98	1	1.56	1	1.57	2	1.82	2	1.66
FM 2828	4	880	1	3.68	1	2.75	1	3.01	1	2.77	1	2.85
SH 16	4	940	3	1.09	6	1.39	4	1.43	2	1.47	3	1.37
FM 474	4	1050	2	1.40	2	1.32	2	1.46	2	1.46	2	1.29
FM 1101	4	1850	5	1.34	1	1.20	3	1.16	2	1.30	5	1.53
FM 306	4	3300	3	1.38	4	1.07	3	1.05	4	1.10	4	0.92
SH 123	4	5600	7	0.76	17	0.57	10	0.66	8	0.81	9	0.69
SH 16	4	6400	6	0.86	8	0.88	3	0.78	7	0.83	4	0.88
FM 306	4	6900	4	1.22	3	1.36	3	1.60	2	1.61	2	1.69
US 87	4	8400	30	0.45	30	0.25	30	0.52	30	0.39	30	0.39

Table C.7 7 – 10 year old seal coats – Right wheel path

Road	Age	ADT	OF (sec)	MPD (mm)	OF (sec)	MPD (mm)
FM 30	10	60	3	1.27	3	1.47
FM 2730	9	230	2	1.46	4	1.32
FM 462	8	260	3	1.21	6	0.98
FM 2200	8	300	13	0.58	12	0.43
SH 39	8	325	1	1.12	2	1.36
FM 1403	8	490	3	0.98	2	1.10
SH 127	10	700	4	0.90	4	1.23
RM 1376	9	710	1	2.19	1	2.04
FM 473	9	1100	30	0.42	19	0.39
RM 187	8	1200	2	1.65	2	1.60
FM 117	8	1500	1	1.35	1	1.60
FM 1574	8	1800	3	0.86	4	1.01
SH 173	8	2200	30	0.39	12	0.39
FM 2252	8	2500	8	0.64	9	0.63
SH 463	8	2600	6	1.19	3	0.98
SH 16	7	3700	5	0.71	7	0.73
FM 1283	7	3750	13	0.42	30	0.40
SH 132	8	9200	3	0.74	10	0.75
FM 2722	9	9800	5	1.22	5	0.99

REFERENCES

Abe, H., Henry, J.J., Tamai, A., and Wambold, J. 2000. Measurement of Pavement Macrotexture using a CTMeter. Paper No. 01-3519, Transportation Research Board, Washington, DC.

ASTM International 2007. Annual Book of ASTM Standards. American Society for Testing and Materials, Section 4, Volume 04.03, Baltimore, MD.

Cairney, Peter. 1997. Skid Resistance and Crashes – a Review of the Literature. Research Report ARR 311, ARRB Transportation Research Ltd, Australia.

Cairney, Peter. 2006. Macrotexture and Crash Risk – Some Recent Findings from Australia and their Implications. Research into Practice: 22nd ARRB Conference Proceedings, ARRB Group Ltd, Australia.

Fakhri, Mansour, and Amoosoltani, Ershad. 2005. Skid Resistance Assessment of Chip Seal Mixture. School of Civil Engineering, K.N. Toosi University of Technology, Techran, Iran.

Gransberg, D., and James, D. 2005. Chip Seal Best Practices. NCHRP Synthesis 342, Transportation Research Board, Washington, DC.

Hanson, Douglas I., and Prowell, Brian D. 2004. Evaluation of Circular Texture Meter for Measuring Surface Texture of Pavements. National Center for Asphalt Technology, NCAT Report 04-05, Auburn University, Auburn, AL.

Kuennen, Tom. 2003. Creating Friction Where Rubber Meets the Road. Better Roads Magazine, October.

Oliver, John W. H., and Halligan, Steve. 2006. A Targeted Approach to the Measurement of Skid Resistance. Research into Practice: 22nd ARRB Conference Proceedings, ARRB Group Ltd, Australia.

Papagiannakis, A.T., and Masad, E.A. 2008. Pavement Design and Materials. United States: John Wiley and Sons, Inc.

SAS/STAT User's Guide. 1999. Cary, NC: SAS Institute.

Texas Department of Transportation 2004. Seal Coat and Surface Treatment Manual. Texas Department of Transportation, July 2004.

Texas Department of Transportation 2006. Texas Pavement Preservation Program. Texas Department of Transportation, 2006.