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16. Abstract

Every year a large amount of toner is produced for copiers and printers by toner manufacturing companies. Toner, the dry ink used in laser printers and copiers, can be blended in to asphalt to improve strength and temperature resistance properties. Some of the toner does not meet quality specifications for use in copiers or printers and consequently becomes a waste product of the manufacturing process. This manufacturing waste, along with the spent toner from copiers and printers, is dumped into landfills for lack of a better way to utilize the material. A cooperative research project, 7-3933, undertaken by the Texas Department of Transportation and the University of Texas at Austin, investigated the feasibility and potential benefits of utilizing waste toner in hot-mix asphalt concrete. This implementation project transferred the results from project 7-3933, in which the feasibility and potential benefits of utilizing waste toner in hot-mix asphalt concrete were investigated. The results of this study can assist industry and state agencies in their efforts to utilize toner in binder modification.

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The Toner-Modified Asphalt Demonstration Projects

Yetkin Yildirim
Armagan Korkmaz
Jorge Prozzi

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Implementation Project 5-3933-01: *Toner Modified Asphalt*

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Dr. Yetkin Yildirim
P.E. (Texas No. 92787)

Table of Contents

Preface 1

Chapter 1. Introduction 3

BACKGROUND 4

IMPLEMENTATION 7

OBJECTIVES 7

Availability of Waste Toner 7

Findings 8

Chapter 2. Experimental Program 9

BINDER DESIGNS 9

MATERIALS 10

MIXTURE DESIGNS 11

Mixture Design for Houston Project 11

Mixture Design for Pharr Project 12

Mixture Design for Laredo Project 14

Mixture Design for Bryan Project 16

Chapter 3. Binder Designs 19

BINDER DESIGN FOR HOUSTON PROJECT 19

Effective Reaction Conditions 19

Design Toner-Modification Level 20

Mixing and Compaction Temperatures 22

Storage Stability 24

BINDER DESIGN FOR PHARR PROJECT 25

Effective Reaction Conditions 25

Design Toner-Modification Level 26

Mixing and Compaction Temperatures 28

Storage Stability 29

BINDER DESIGN FOR LAREDO PROJECT 30

Effective Reaction Conditions 30

Design Toner-Modification Level 31

Mixing and Compaction Temperatures 33

Storage Stability 34

BINDER DESIGN FOR BRYAN PROJECT 35

Effective Reaction Time 35

Mixing and Compaction Temperatures 36

Storage Stability 37

Design Toner-Modification Level 37

Chapter 4. Construction of the Test Section 39
Chapter 5. Post-Construction Pavement Evaluation Results 43
Visual Pavement Surveys 43
Profiler Data 44
HWTD Tests 46
Chapter 6. Conclusions 57
References 61
Appendix A. Composition of Toners 63
Appendix B. Mixture Design Information 67
Appendix C. Binder Design Information 77
1. Binder Design for Houston Project 79
2. Binder Design for Pharr Project 82
3. Binder Design for Laredo Project 86
4. Binder Design for Bryan Project 90
Appendix D. Post-Construction Pavement Evaluation 95
Appendix E. Profiler Data from the Test Sections 103
Appendix F. Air Void Contents for the Field Cores 107

List of Tables

Table 2.1 Asphalt and Toner Information for the Test Sections ... 10
Table 2.2 Gradation of the Aggregates Used in the Houston Project ... 11
Table 2.3 TxDOT Specifications for Percentage Passing from Each Sieve Size ... 12
Table 2.4 Design Information ... 12
Table 2.5 Gradation of the Aggregates Used in the Pharr Project ... 13
Table 2.6 TxDOT Specifications for Percentage Passing from Each Sieve Size ... 13
Table 2.7 Design Information ... 14
Table 2.8 Gradation of the Aggregates Used in the Laredo Project ... 15
Table 2.9 TxDOT Specifications for Percentage Passing from Each Sieve Size ... 15
Table 2.10 Design Information ... 16
Table 2.11 Gradation of the Aggregates Used in the Bryan Project ... 17
Table 2.12 TxDOT Specifications for Percentage Passing from Each Sieve Size ... 17
Table 2.13 Design Information ... 18
Table 3.1 Superpave Binder Requirements for PG 70-16 ... 20
Table 3.2 Equations for Estimated Relations ... 21
Table 3.3 Estimated Binder Properties at Different Toner-Modification Levels ... 22
Table 3.4 Superpave Binder Requirements for PG 64-22 ... 27
Table 3.5 Equations for Estimated Relations ... 27
Table 3.6 Superpave PG Binder Requirements for PG 76-16 ... 31
Table 3.7 Equations for Estimated Relations ... 31
Table 3.8 Estimated Binder Properties at Different Toner-Modification Levels ... 32
Table 3.9 Superpave Binder Requirements for PG 64-22 ... 38
Table 3.10 Equations for Estimated Relations ... 38
Table 5.1 Profile Rut Depths ... 46
Table 5.2 Experimental Design for HWTD Tests ... 49
Table 5.3 Rut Depths for the Test Sections ... 50
Table 5.4 Slopes of Data Curves ... 50
Table 5.5 Areas under the Best Fit Curves ... 51
Table A.1 Composition for the Toner Provided by Nashua ... 65
Table A.2 Composition for the Toner Provided by Ricoh ... 65
Table A.3 Composition for the Toner Provided by Lexmark ... 65
Table B.1 Summary of Mixture Properties with Different Asphalt Content ... 69
Table B.2 Summary of Mixture Properties with Different Asphalt Content ... 71
Table B.3 Summary of Mixture Properties with different Asphalt Contents ... 73
Table B.4 Summary of Mixture Properties with Different Asphalt Content ... 75
Table D.1 Pharr Visual Survey of Control Test Section ... 99
Table D.2 Pharr Visual Survey of Toner Test Section ... 100
Table D.3 Laredo Visual Survey of Toner Test Section ... 101
Table D.4 Houston Visual Survey of Control Test Section ... 101
Table D.5 Houston Visual Survey of Toner Test Section ... 101
Table E.1 Rut Depth Calculations ... 105

List of Figures

Figure 3.1 Shear modulus as a function of blending time 20
Figure 3.2 Viscosity shear rate relation at 135˚ C and 165˚ C........ 23
Figure 3.3 Viscosity temperature relationship at 12.5 percent toner-modification level........ 24
Figure 3.4 Results of stability test at 12.5 percent toner-modification level 25
Figure 3.5 Shear modulus as a function of blending period 26
Figure 3.6 Viscosity vs. temperature at 7 percent toner-modification level........ 28
Figure 3.7 Results of stability test at 7 percent toner-modification level 29
Figure 3.8 Shear modulus as a function of blending period 30
Figure 3.9 Viscosity vs. Temperature at 14.5 percent toner-modification level........ 33
Figure 3.10 Results of storage stability test at 14.5 percent toner-modification level........ 34
Figure 3.11 Shear Modulus as a Function of Blending Period 35
Figure 3.12 Viscosity vs. Temperature at 7 percent toner-modification level........ 36
Figure 4.1 Placement of Toner into the Mixer........ 39
Figure 4.2 Mixer used in Pharr, Laredo, and Bryan Projects 40
Figure 4.3 Computer Control Unit for the Mixer 41
Figure 5.1 Rut Depth Profile........ 45
Figure 5.2 Hamburg Wheel Tracking Device........ 47
Figure 5.3 An example of Hamburg Wheel Tracking Device output........ 48
Figure 5.4 Bryan Test Section Results........ 52
Figure 5.5 Houston Test Section Results........ 53
Figure 5.6 Laredo Control and Toner Test Section Results........ 54
Figure 5.7 Pharr Toner and Control Test Section Results 55
Figure B.1 Asphalt content vs. density 70
Figure B.2 Asphalt content vs. VMA (percent)........ 70
Figure B.3 Asphalt content vs. density 72
Figure B.4 Asphalt content vs. VMA (percent)........ 72
Figure B.5 Asphalt content vs. density 74
Figure B.6 Asphalt content vs. VMA 74
Figure B.7 Asphalt content vs. density 76
Figure B.8 Asphalt content vs. VMA (percent)........ 76
Figure C.1.i DSR Test results for the original binder at different toner levels........ 79
Figure C.1.ii DSR Test results for the RTFO-aged binder 79
Figure C.1.iii DSR Test results for the PAV-aged binder 80
Figure C.1.iv Creep stiffness values from BBR 80
Figure C.1.v Logarithmic creep rate (m-value) values from BBR 81
Figure C.2.i DSR Test results for the original binder at 64˚C and 70˚C 82
Figure C.2.ii DSR Test results for the RTFO-aged binder at 64˚ and 70˚C 83
Figure C.2.iii DSR Test results for the PAV-aged binder 84
Figure C.2.iv Creep stiffness values from BBR 85
Figure C.2.v Logarithmic creep rate (m-value) values from BBR 85
Figure C.3.i DSR Test results for the original binder modified........ 86
Figure C.3.ii DSR Test results for the RTFO-aged binder 86
Figure C.3.iii DSR Test results for the PAV-aged binder modified........ 87
Figure C.3.iv Creep stiffness values from BBR 87

Figure C.3.v Logarithmic Creep rate (m-value) values from BBR 88
Figure C.3.vi Creep stiffness values from BBR (–12˚C).. 88
Figure C.3.vii Logarithmic creep rate (m-value) values from BBR (–12˚C) 89
Figure C.4.i DSR Test Results for the original binder at 64° C and 70° C 90
Figure C.4.ii DSR Test Results for the RTFO-aged binder at 64° C and 70° C........................... 91
Figure C.4.iii DSR Test Results for the PAV-aged binder 92
Figure C.4.iv Creep Stiffness values from BBR... 93
Figure C.4.v Logarithmic Creep Rate (m-value) values from BBR 93
Figure D.1 Bryan Test Section Overview.. 97
Figure D.2 Pharr Test Section Overview... 97
Figure D.3 Laredo Test Section Overview 98
Figure D.4 Houston Test Section Overview 98
Figure E.1 Rut Depth Profile 105
Figure F.1 Air Void Content of Tested Specimen 109

Preface

This is the final report from the Center for Transportation Research on Project 3933. It presents the mixture designs and toner-modified binder designs for the Houston, Pharr, Laredo, and Bryan projects, observations during the construction of the test sections, and post-construction pavement evaluation results.

Implementation Statement

Every year a large amount of toner is produced for copiers and printers by toner manufacturing companies. Toner, the dry ink used in laser printers and copiers, can be blended with asphalt to improve strength and temperature-resistance properties. Some of the toner does not meet quality specifications for use in copiers or printers and consequently becomes a waste product of the manufacturing process. This manufacturing waste, along with the spent toner from copiers and printers, is dumped into landfills for lack of a better way to utilize the material.

A cooperative research project, 7-3933, undertaken by the Texas Department of Transportation and The University of Texas at Austin investigated the feasibility and potential benefits of utilizing waste toner in hot-mix asphalt concrete. This implementation project transferred the results from project 7-3933, in which the feasibility and potential benefits of utilizing waste toner in hot-mix asphalt concrete was investigated.

The results of this study can assist industry and state agencies in their efforts to utilize toner in binder modification.

Chapter 1. Introduction

Waste toner has the potential to become a serious solid waste disposal problem. If the toner does not meet quality specifications, it becomes a waste product of the manufacturing process. This manufacturing waste, along with the spent toner residue from copiers and printer cartridges, is dumped into landfills since there is not any better way of utilizing the material. The amount of waste toner generated each year in the United States is an estimated 9,000 to 25,000 tons.

There are certain considerations regarding the use of toner or any other waste material in asphalt pavements. Practicality, costs, and benefits associated with the usage of waste materials in asphalt pavements must also be examined. The most important consideration is the effect of incorporating the waste material on pavement performance.

Incorporating a waste product can enhance some or all asphalt material properties and performance, it can have no effect, or it can have a negative effect. When a waste material is proven likely to improve asphalt pavement performance, there must be a sufficient amount of the material available to form a feasible product. There must be component applications for the material that would make its use cost effective. A balance between cost of material and increased pavement performance needs to exist.

A cooperative research project, 7-3933, undertaken by the Texas Department of Transportation and The University of Texas at Austin, investigated the feasibility and potential benefits of utilizing waste toner in hot-mix asphalt concrete. For this research study, a number of different types of waste and spent toners were obtained and blended with asphalt cement at different ratios, and then the binder and mixture properties resulting from the waste toner addition were evaluated. Superpave binder performance tests, including complex shear modulus at high and intermediate temperatures, low-temperature creep stiffness, and rotational viscosity, were used to evaluate binder properties. The modified binders were used in asphalt-aggregate mixtures to evaluate mixture behavior and properties. Hveem stability, resilient modulus, and indirect tensile strength were measured and evaluated. In addition, for three different levels of toner modification, a Superpave mix design was performed. The results of research project 7-3933 are summarized in Research Report 3933-1F, "Use of Waste Toner in Asphaltic Concrete," published by the Center for Transportation Research (CTR).

This implementation project transferred the results from project 7-3933. This report summarizes the mixture designs and toner-modified binder designs for the Houston, Pharr, Laredo, and Bryan projects, observations during the construction of the test sections, and the post-construction pavement evaluation results.

For each of the projects, a binder design was performed, including blending time, PG grading, storage stability, and mixing and compaction temperature calculation. The PG properties of the toner-modified asphalt binders used in each test section varied according to the amount of polymers in the toner. Objectives of the research included determining the toner levels needed to arrive at a given PG grade as well as achieving a better understanding of the effect of toner level on the PG properties of a binder.

Test results indicate that the stiffness of the blend increases with increased toner content at all temperatures and that this stiffening effect is more pronounced at higher levels of toner in a parabolic relationship. Results also show that two hours of blending time is sufficient to achieve a homogeneous toner-asphalt mix, significant storage stability problems are expected regardless of the level of toner in the blend, and the mixing and compaction temperatures stay at reasonable levels. Results from pavement condition surveys show that toner-modified test sections generally have low levels of distress with a high resistance to rutting.

BACKGROUND

Recycled materials used in paving mixtures include materials such as rubber, reclaimed asphalt pavement (RAP), shingles, plastic, and toner. These materials have been considered waste materials from some operations. Waste toner refers to produced toner that does not meet required specifications, whereas spent toner is the residue left in cartridges in copies and printers (1). Spent toner is of a different particle size compared to the original toner and contaminated with dust picked up from paper. The material is not considered an environmental hazard, and it is not combustible or flammable; however, airborne toner may present an explosion hazard due to the small particle size.

As Kent et al. noted, when any nonbituminous component is added to a bituminous paving mixture, a number of important issues need to be considered. These include physical and chemical changes in the properties of the original material components, which could be altered by the resulting addition and the method used to incorporate the desired component (1, 2). The chemical compatibility of the components plays a fundamental role throughout the life of the resulting mixture, which requires special attention as it could affect the expected life-cycle cost of the project. Project feasibility and cost effectiveness are also determined by the availability of sufficient recycled material. Cost, performance, and environmental concerns must be evaluated to determine whether a product adds value. A value-added material reduces costs by saving on materials (aggregate and binder), and its performance is generally demonstrated to be equal to or better than that of mixes consisting solely of virgin material. Kent et al. argue that, unlike value-added recycled materials or by-products used in hot-mix asphalt (HMA), some waste products provide little or no measurable benefit (1).

As stated in Button et al., "after evaluating the toner-modified asphalt in the laboratory in Oklahoma in 1990, Ayers and Tripathi demonstrated that waste toner retrieved from Xerox duplicators could be successfully incorporated into asphalt cement and asphalt concrete" (3, 4). When they blended 2 percent to 10 percent toner by weight with asphalt cement, the temperature susceptibility of the resulting binders was reduced. When blending waste toner with asphalt paving mixtures, they found that increasing toner content successively increased Hveem stability. Dry toner added to asphalt appeared to be the most successful method for field operations. They concluded that Xerox toner could be a beneficial additive to asphalt paving mixtures.

Another experiment is reported by Diamond for a resurfacing project on I-15 in Nevada, where waste toner was added to the aggregate. The researchers were dissatisfied with the product and reported that working with the material was not easy, since there were problems with rolling, flaking, and poor adhesion (5).

As indicated by Solaimanian et al., as the amount of waste toner increases, the stiffness and viscosity of the modified binder increase. Higher stability and strength are also observed in modified mixtures with toner compared with unmodified blends (6). According to this study, good performance is expected where permanent deformation is the major concern, and minor cracking due to low temperature is expected. However, concerns are raised as to the validity of the low-temperature response of toner-modified binder, which may contrast with reported test results of polyethylene, elastomer, and plastomer-modified binders. These binders have presented an improved crack-retarding effect of the mixture even though the stiffness increased (7).

In the Solaimanian study, four different levels of waste toner modification and four different toners were used to study the effect of toner on asphalt properties. A control mixture was employed with two dosage rates to measure the effect of waste toner on asphalt mixture characteristics. The study recommends incorporating the toner powder into the asphalt cement since the use of dispersing oil will result in a softened binder, while water will result in foamed asphalt. Stirring time is emphasized so that a complete reaction takes place and a homogeneous material is obtained. Shear rate during addition is an important factor influencing the properties of the toner-asphalt blend.

Solaimanian et al. recommend a minimum stirring time of two hours above the toner melting point to obtain a homogeneous material; however, in the case of high shear blending, they state that the stirring period can be as short as 20-30 minutes. The test results indicated that each toner-asphalt combination should be tested separately for a proper assessment. The material does not have sufficient storage stability; accordingly, the toner-modified asphalt needs to be agitated before mixing with aggregates.

From the references consulted, it is known that the acceptable range for toner particle size varies among different manufacturers depending on the type of material used and the technology used in the manufacturing. The acceptable average size is about 10 µm. The melting point is in the range of 100˚ C to 150˚ C, and the ignition temperature is in general over 350˚ C.

IMPLEMENTATION

Four test sections were constructed to evaluate the benefits of toner-modified asphalt binders. These test sections were constructed in the Houston, Pharr, Laredo, and Bryan districts. There are two general approaches for incorporating a material such as waste toner into asphalt mixtures. One is by directly adding dry toner to the aggregate; the other is by incorporating the toner into the asphalt cement. This latter approach can be performed either through direct incorporation of the dry toner into the asphalt or through a medium such as oil, a dispersing agent, or water in conjunction with an emulsifying agent. Because dry toner was directly introduced into the asphalt binder with success in this implementation program, this approach is recommended.

OBJECTIVES

This implementation project transferred the results from project 7-3933, in which the feasibility and potential benefits of utilizing waste toner in hot-mix asphalt concrete were investigated. Project 7-3933 included procuring a number of waste and spent toner types, blending them with asphalt cement at different ratios, and evaluating the binder and mixture properties resulting from the toner addition. At the end of this research study, TxDOT received a patent on blending toner with asphalt to improve hot-mix asphalt concrete performance. To execute this patent, TxDOT needs to fully comprehend the performance of different types of toner. In this implementation project, four test sections were constructed and the data from these sections were gathered and analyzed to evaluate the benefits of this patent. The main objective of this study was to identify use of waste toner as an asphalt binder modifier as an alternative to sending the material to the landfill.

Availability of Waste Toner

The toner industry generates between 9,000 to 25,000 tons (20 million lbs to 55 million lbs) of waste toner per year. Moreover, the industry is willing to pay for disposal alternatives to the landfill. If the above-mentioned amount of toner is used, waste toner can modify approximately 3.0 million tons of HMA. This use of waste toner can potentially benefit both highway agencies and the construction industry.

Findings

The results of this study indicated that as the amount of waste toner in the blend increases, the stiffness and viscosity of the binder increases. The increase in stiffness is evident at high, intermediate, and low temperatures. The mixture analysis also indicates higher strength and stability for toner-modified asphalt concrete compared with unmodified mixtures. The increase in binder stiffness at high temperatures is a positive effect since resistance to permanent deformation is increased. However, an increase in stiffness at low temperatures is not favorable because of the increased potential for low-temperature cracking. The toner-modified binder is expected to perform satisfactorily in areas where permanent deformation is of great concern and where an increase in low-temperature stiffness will not cause cracking problems. Results from toner-modified test sections demonstrated that these sections showed no significant distresses and a high resistance to rutting.

Chapter 2. Experimental Program

The demonstration projects are intended to provide firsthand experience with the material for asphalt producers and generate interest in using waste toner as an asphalt modifier. To achieve the research objectives, test sections were constructed in the Houston, Pharr, Laredo, and Bryan districts. In all projects, PG 64-22 base binder from different producers was used as base binder. Three different types of toner were utilized for binder modification purposes.

BINDER DESIGNS

Superpave binder performance tests, including Dynamic Shear Rheometer (DSR) and Rotational Viscometer (RV) for high and intermediate temperatures, and Bending Beam Rheometer (BBR) for low temperatures, were used to evaluate binder properties for different levels of toner modification. Binder design included information on effective binder-toner reaction time, effective stirring time, effect of toner content on performance grade, storage stability, and mixing and compaction temperatures for toner-modified asphalt binders.

The reaction time needed to obtain a homogeneous binder-toner blend was investigated by using a Lightning™ mixer with a three-blade impeller (7.6-cm diameter) at 500 revolutions per minute for different time durations at a constant temperature. Complex modulus versus blending period was then plotted to find the efficient blending time needed to achieve a homogeneous mix. Following the estimation of reaction period, samples were prepared at different toner-modification levels, and full PG binder tests were conducted.

For the Houston and Laredo projects, the percentage of toner required to achieve a specific performance grade was calculated. Trial blends containing different percentages of toner were prepared, and a full performance-grade binder classification was conducted on each trial blend. Relationships between PG binder specification requirements and percentage of toner were then established to find the effective toner-modification levels that reached the desired PG-grade binder. Conversely, for the Pharr and Bryan projects, a previously defined 7 percent toner level was used to study the effects of this toner percentage on the binder properties.

Storage stability at the chosen toner-modification level was measured according to AASHTO PP5-93. Since viscosity of modified binders depends on both shear rate and temperature, mixing and compaction temperatures were investigated by using the Brookfield viscometer at two different temperatures and at 500 1/s shear rate, so that the relationship between viscosity and temperature could be established (8).

MATERIALS

In all projects, PG 64-22 base binder from different producers was used. Superpave binder tests were conducted to verify that the binders met all the PG requirements. In this project, magnetic and nonmagnetic toners were used. Magnetic toners contain metal particles, which are used in desktop printers to help facilitate printing. This type of toner typically has a lower polymer content than a nonmagnetic toner. The primary component of the nonmagnetic Lexmark and magnetic Nashua toner samples is 80–90 percent styrene acrylic copolymer (SAC) and 75–85 percent styrene butadiene copolymer (SBC), respectively. The Nashua toner contains a significant amount of magnetite (15–20 percent). The Ricoh nonmagnetic toner, in contrast, is mainly composed of polyester with up to 15 percent of SAC. All three samples contained up to 9 percent carbon black. Table 2.1 gives information about the toners and binders used in each project. Detailed information about the composition of the toners used in this study is included in Appendix A.

Table 2.1 Asphalt and Toner Information for the Test Sections

Test Section	**Asphalt**	**Toner Type**	**Toner Amount**	**Toner Supplier**
Pharr	PG 64-22	Nonmagnetic	7%	Lexmark
Laredo	PG 64-22	Magnetic	14.5%	Nashua Corp.
Houston	PG 64-22	Nonmagnetic	12.5%	Ricoh
Bryan	PG 64-22	Magnetic	7%	Nashua Corp.

MIXTURE DESIGNS

Mixture Design for Houston Project

For the Houston project, Martin Marietta Materials designed Type D mix with PG 70-22 asphalt binder. The test section was constructed on SH 3 highway in Brazoria County, Galveston. The contractor of the project was Hubco Inc. The mix design was employed using PG 70-22 asphalt binder grade with 0.8 percent HP Plus additive. Four different aggregate sources were used, including D Rock (Meridian Rock), F Rock (Meridian Rock), Sand (Meridian Rock), and River Sand (C.S.B.). The percentage of the aggregates in the blend and the gradation of the aggregates are given in Table 2.2. TxDOT specifications for aggregate gradation and cumulative pass are shown in Table 2.3.

Table 2.2 Gradation of the Aggregates Used in the Houston Project

	Fordyce Grade 4 (35%)	Fordyce Grade 6 (27%)	Fordyce W.C. Screenings (23%)	Fordyce Cyclone Sand (15%)
Sieve Size	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**
12.5mm	100	100	100	100
9.5 mm	93.6	93.8	100	100
4.75 mm	30.5	51.4	99.9	99.3
2.0 mm	3.3	10	92.3	94.7
0.425 mm	2.5	1.3	32.6	70.6
0.180 mm	2.3	0.6	16.1	11.8
0.075mm	1.9	0.2	12.4	3.1

Table 2.3 TxDOT Specifications for Percentage Passing from Each Sieve Size

Sieve Size	TxDOT Specification (Passing percent)	Cumulative Pass (percent)
12.5mm	98-100	100
9.5 mm	85-100	96.1
4.75 mm	50-70	62.5
2.0 mm	32-42	39.3
0.425 mm	11-26	19.4
0.180 mm	4-14	6.5
0.075mm	1-6	4.2

Mixtures with different asphalt contents were prepared to determine the optimum asphalt content. A summary of mixture properties with different asphalt content is shown in Table B.1 in Appendix B. Effective Specific Gravity (Ge), Optimum Asphalt Content at Optimum Density, VMA at Optimum Asphalt Content, Specific Gravity at Optimum Asphalt Content (Ga), Maximum Specific Gravity at Optimum Asphalt Content (Gr), and Theoretical Maximum Specific Gravity at Optimum Asphalt Content (Gt) were determined. Design information is given in Table 2.4.

Table 2.4 Design Information

Effective Specific Gravity (Ge)	2.659
Optimum Asphalt Content at Optimum Density	5.0 %
VMA at Optimum Asphalt Content	15.2%
Specific Gravity at Optimum Asphalt Content (Ga)	2.371
Maximum Specific Gravity at Optimum Asphalt Content (Gr)	2.472
Theoretical Maximum Specific Gravity at Optimum Asphalt Content (Gt)	2.470

Mixture Design for Pharr Project

In the Pharr project, the test section was built on FM 800 in Cameron County. Type D mix design was employed using PG 64-22 asphalt binder grade. The asphalt source is Trygeant Refineries. The mix design included four aggregate types and 1 percent lime as an antistripping agent. The aggregate sources are Fordyce Grade 4, Fordyce Grade 6, Fordyce W.C. Screenings, Fordyce Cyclone Sand, and Aggregate Number 5 Lime. Aggregate gradation is given in Table 2.5. TxDOT specifications for aggregate gradation are shown in Table 2.6.

Table 2.5 Gradation of the Aggregates Used in the Pharr Project

	Fordyce Grade 4 (32%)	**Fordyce Grade 6 (32%)**	**Fordyce W.C. Screenings (20%)**	**Fordyce Cyclone Sand (15%)**
Sieve Size	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**
16 mm	100	100	100	100
12.5mm	98.1	100	100	100
9.5 mm	71.6	100	100	100
4.75 mm	14	74.8	95	100
2.0 mm	4.9	21.3	61.3	99.6
0.425 mm	2.3	3.8	31.2	97.6
0.180 mm	1.2	2.5	8.9	37.4
0.075 mm	0.8	2.0	2.8	8.1

Table 2.6 TxDOT Specifications for Percentage Passing from Each Sieve Size

Sieve Size	**TxDOT Specification (Passing %)**	**Cumulative Pass (%)**
12.5mm	98-100	99.4
9.5 mm	85-100	90.9
4.75 mm	50-70	63.4
2.0 mm	32-42	36.8
0.425 mm	11-26	23.7
0.180 mm	4-14	9.6
0.075mm	1-6	3.7

A linear shrinkage test, Tex-107-E, was performed on the fine aggregates. For this test, the maximum value in the specifications is 3. The test result on the fine aggregate was 1. On combined aggregates, the sand equivalent test was conducted. The minimum value in the specifications for this test is 45. The test result for this test was 50.

Mixtures with different asphalt contents were prepared to determine the optimum asphalt content. A summary of mixture properties with different asphalt content is shown in Table B.2 in

Appendix B. Effective Specific Gravity (Ge), Optimum Asphalt Content at Optimum Density, VMA at Optimum Asphalt Content, Specific Gravity at Optimum Asphalt Content (Ga), Maximum Specific Gravity at Optimum Asphalt Content (Gr), and Theoretical Maximum Specific Gravity at Optimum Asphalt Content (Gt) were determined. Design information for the samples used in this project is given in Table 2.7.

Table 2.7 Design Information

Effective Specific Gravity (Ge)	2.631
Optimum Asphalt Content at Optimum Density	5.5%
VMA at Optimum Asphalt Content	16.3 %
Specific Gravity at Optimum Asphalt Content (Ga)	2.330
Maximum Specific Gravity at Optimum Asphalt Content (Gr)	2.427
Theoretical Maximum Specific Gravity at Optimum Asphalt Content (Gt)	2.426

Mixture Design for Laredo Project

In the Laredo project, Martin Mariatta Materials Southwest, Ltd. produced Type C mixtures with PG 76-22 asphalt binder and 1 percent antistripping agent. The test section was built on SH 97 in LaSalle County. The contractor for this project was E. E. Hood. Type C mix design was employed using Trumbull PG 76-22 asphalt binder grade. The antistripping agent used in this project was Unichem 8162. The mix design includes six aggregate types. A summary of mixture properties with different asphalt contents is shown in Table B.3 in Appendix B. Gradation of the aggregates and TxDOT specifications for aggregate gradation are given in Table 2.8 and Table 2.9, respectively.

Table 2.8 Gradation of the Aggregates Used in the Laredo Project

	Aggr. 1 (3/4-5/8) (%15)	**Aggr. 2 (5/8-1/2) (%13)**	**Aggr. 3 (3/8-1/4) (%14)**	**Aggr. 4 (Gr.10) (%14)**	**Aggr. 5 (Mfg LSFs) (%34)**	**Aggr. 6 (W. Silica) (%10)**
Sieve Size	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**
22.4 mm	100	100	100	100	100	100
16 mm	88	99.9	100	100	100	100
9.5 mm	6	18.6	99.7	100	100	100
4.75 mm	3.2	2.8	17.7	86.5	99.8	100
2.0 mm	2.8	2.0	2.8	6.2	71.1	99.5
0.425 mm	2.1	1.8	2.0	1.8	25.2	66
0.180 mm	2	1.7	1.8	1.7	13.6	14.1
0.075 mm	1.8	1.6	1.7	1.6	8.8	1.5

Table 2.9 TxDOT Specifications for Percentage Passing from Each Sieve Size

Sieve Size	**TxDOT Specification (% Passing)**	**Cumulative Pass (%)**
22.5 mm	98-100	100
16 mm	95-100	98.2
9.5 mm	70-85	75.3
4.75 mm	43-63	59.4
2.0 mm	30-40	36.1
0.425 mm	10-25	16.2
0.180 mm	3-13	7.0
0.075mm	1-6	4.1

The effect of asphalt content on density, unit weight, air content, specific gravities, percentage of voids filled with bitumen, and voids in mineral aggregate (VMA) were observed. It was observed that increasing asphalt content increases the density, compacted unit weight, bulk specific gravity, and percentage of voids filled with bitumen. On the other hand, the percentage of air voids, maximum specific gravity, and VMA decreases with increasing asphalt content. Optimum asphalt content, bulk specific gravity, theoretical specific gravity, unit weight, and VMA at optimum density were determined. Design information is given in Table 2.10.

Table 2.10 Design Information

Optimum Asphalt Content	4.7 %
Bulk Specific Gravity	2.376
Theoretical Specific Gravity	2.476
Voids in Mineral Aggregate	14.8

Mixture Design for Bryan Project

In the Bryan project, the test section was constructed on US 77 in Milam County, Bryan. The contractor for the project was Young Contractors. The mix design utilized for the project was Type CMHB-C using 4.6 percent Fina PG 64-22 asphalt binder. The six different aggregates used in this project include the following: C Rock (Hansen), D Rock (Hansen), F Rock (Hansen), Dry Screening (Hansen), Sand (Young Materials), and Lime (Chemlime). Lime (1.5 percent) was added as an antistripping agent. The percentage of the aggregates in the blend and the gradation of the aggregates are provided in Table 2.11. TxDOT specifications for aggregate gradation and cumulative pass are shown in Table 2.12.

Mixtures with different asphalt content were prepared to determine the optimum asphalt content. A summary of mixture properties with different asphalt contents is shown in Table B.4 in Appendix B. Effective Specific Gravity (Ge), Optimum Asphalt Content at Optimum Density, VMA at Optimum Asphalt Content, Specific Gravity at Optimum Asphalt Content (Ga), Maximum Specific Gravity at Optimum Asphalt Content (Gr), and Theoretical Maximum Specific Gravity at Optimum Asphalt Content (Gt) were determined. Design information is provided in Table 2.13.

Table 2.11 Gradation of the Aggregates Used in the Bryan Project

	Aggr. 1 (C Rock) (%40)	Aggr. 2 (D Rock) (%16)	Aggr. 3 (F Rock) (%18)	Aggr. 4 (Dry Scr.) (%17)	Aggr. 5 (Sand) (%7.5)
Sieve Size	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**
22.4 mm	100	100	100	100	100
16 mm	100	100	100	100	100
9.5 mm	9.3	76.5	100	100	100
4.75 mm	3.7	6.1	67.1	78.5	97.4
2.0 mm	3.6	3.6	6.9	49.3	91.5
0.425 mm	3.3	2.9	3.9	27.3	60.7
0.180 mm	3.1	2.7	3.6	21.7	13
0.075 mm	2.7	2.4	3.4	18.2	5.9

Table 2.12 TxDOT Specifications for Percentage Passing from Each Sieve Size

Sieve Size	TxDOT Specification (% Passing)	Cumulative Pass (%)
22.5 mm	98-100	100
16 mm	98-100	100
9.5 mm	50-70	59.9
4.75 mm	30-45	36.7
2.0 mm	15-25	20
0.425 mm	6-20	13.2
0.180 mm	6-18	8.4
0.075mm	5-8	7.1

Table 2.13 Design Information

Effective Specific Gravity (Ge)	2.587
Optimum Asphalt Content at Optimum Density	4.60%
VMA at Optimum Asphalt Content	14.00%
Specific Gravity at Optimum Asphalt Content (Ga)	2.333
Maximum Specific Gravity at Optimum Asphalt Content (Gr)	2.422
Theoretical Maximum Specific Gravity at Optimum Asphalt Content (Gt)	2.418

Chapter 3. Binder Designs

BINDER DESIGN FOR HOUSTON PROJECT

CTR conducted the binder design for toner-modified binder for the Houston demonstration project (9). The design included information on the effective reaction time between binder and toner, effective stirring time to achieve a homogeneous mix, effective toner content range to achieve the required performance grade, storage stability of toner-modified asphalt binders, and mixing and compaction temperatures for toner-modified asphalt binders. The amount of toner required to achieve PG 70-16 was found to be between 11 - 14 percent.

Originally, PG 76-16 was the intended binder for this project. However, in order to reach PG 76-16, it would have been necessary to add more than 30 percent toner to the base binder. Since adding 30 percent toner might change the characteristics of the binder completely, it was decided to modify the binder to achieve PG 70-16.

Effective Reaction Conditions

The first consideration in developing a binder design was to determine the effective reaction conditions. In order to obtain a homogenous binder, 7 percent toner was blended and reacted using a Lightning™ mixer with the base asphalt. The mixing took place at 500 revolutions per minute at 163° C. At the end of the reaction period, the samples were tested for complex shear modulus at 64° C. The change in complex modulus versus blending time was plotted to find the efficient blending time to achieve a homogeneous mix. Figure 3.1 shows this relation.

The results plotted in Figure 3.1 indicate that as the blending time increases, the complex modulus increases for the first 100 minutes. After that, complex modulus values stay constant. From Figure 3.1, it can be assumed that after 100 minutes of stirring, a homogenous toner asphalt mixture can be achieved. Based on this information, it was decided to use a blending time of two hours.

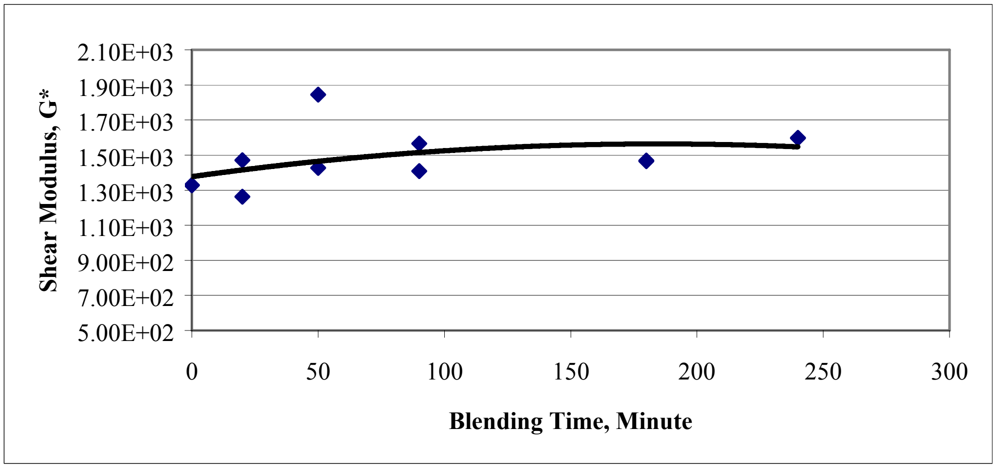


Figure 3.1 Shear modulus as a function of blending time

For this study, mixing was conducted using a Lightning™ mixer (Model L1U08) with a three-blade impeller (7.6-cm diameter) at a rate of 500 revolutions per minute. Different mixing conditions affect the mixing time to achieve a homogenous mixture. During construction of the test sections, the conditions for mixing toner and asphalt might be completely different from those conditions at the CTR laboratory. To solve this problem, viscosity values can be monitored regularly during the mixing process at the plant.

Design Toner-Modification Level

Trial blends containing different percentages of toner were prepared. Full performance-grade binder classification testing was conducted on each trial blend. Trial blends were prepared at 0 percent, 7 percent, 14 percent, 21 percent, and 30 percent toner-modification levels. Table 3.1 shows the requirements for PG 70-16 binders.

Table 3.1 Superpave Binder Requirements for PG 70-16

PG 70-16		Test Temperature, °C	Requirement
Original	G*/sinδ	70	Minimum 1.00 kPa
RTFO	G*/sinδ	70	Minimum 2.20 kPa
PAV	G*sinδ	28	Maximum 5000 kPa
PAV	S	-6	Maximum 300 MPa
PAV	m-value	-6	Minimum 0.300

All tests listed in Table 3.1 were conducted at required temperatures. Tests were conducted at different toner-modification levels to establish the relations between toner-modification level and the requirements listed in Table 3.1. Figures showing the relations for these five requirements are included in Appendix C. Equations and RV values are shown in Table 3.2.

Table 3.2 Equations for Estimated Relations

Percent Toner vs.	Binder	Equation	R^2
G*/sin δ	Original	Y = -0.4469x2 + 45.239x + 544.32	0.9642
G*/sin δ	RTFO	Y = -1.2485x2 + 122.54x + 1306.7	0.9768
G*sin δ	PAV	Y = 9672.7x2 + 11789x + 3E+06	0.9235
S	PAV	Y = 43.284x2 - 310.88x + 53720	0.634
m-value	PAV	Y = -5E-05x2 - 0.0003x + 0.0773	0.8666

Based on the equations listed in Table 3.2, values required in the Superpave binder specification were calculated at different toner-modification levels. Values were calculated between 7 and 19 percent toner modification for the five Superpave requirements listed in Table 3.1. Calculated values are shown in Table 3.3.

As can be seen from Table 3.3, binders under 12 percent toner modification do not meet the requirements for G*/sinδ on original binders. For RTFO-aged binder, the base binder should be modified with a minimum of 8 percent toner to meet the requirements for G*/sinδ. The base binder should be modified less than 14 percent to meet the requirements for G*sinδ. Between 7 and 19 percent modification levels, binders meet the requirements for creep stiffness (S) in all cases, but for logarithmic creep rate (m-value), more than 18 percent toner modification did not meet the requirements.

Table 3.3 Estimated Binder Properties at Different Toner-Modification Levels

	Original	RTFO	PAV	PAV	PAV
Percent Toner	G*/sinδ (Pa)	G*/sinδ (Pa)	G*sinδ (Pa)	S	m-value
7	*839*	*2103*	3556485	95844	0.355
8	*878*	2207	3713365	98000	0.350
9	*915*	2308	3889590	100601	0.346
10	*952*	2407	4085160	103648	0.341
11	*988*	2504	4300076	107140	0.337
12	**1023**	**2597**	**4534337**	**111077**	**0.332**
13	**1057**	**2689**	**4787943**	**115459**	**0.327**
14	1090	2778	*5060895*	120286	0.322
15	1122	2864	*5353193*	125559	0.317
16	1154	2948	*5664835*	131277	0.313
17	1184	3029	*5995823*	137440	0.308
18	1214	3108	*6346157*	144048	0.302
19	1243	3184	*6715836*	151101	0.297

The critical values come from G*/sinδ on original binder and G*sinδ on PAV-aged binder to achieve PG 70-16. As can be seen from Table 3.3, only 12 and 13 percent toner modifications met all the Superpave binder requirements. From this information, it was decided to use 12.5 percent toner modification for this project.

Mixing and Compaction Temperatures

Lab mixing and compaction temperatures were calculated at a 12.5 percent toner-modification level. The method developed by CTR and reported in Research Report 1250-5 for the calculation of mixing and compaction temperatures was used in this project (8). Viscosity of modified binders depends on both shear rate and temperature. Accordingly, in viscosity calculations, the effect of these factors was included. A relation between shear rate and viscosity was established by the Brookfield viscometer to estimate the shear rate dependency of the toner-modified binder. Measurements were conducted at 135° C and 165° C. Figure 3.2 shows the relationship at these temperatures.

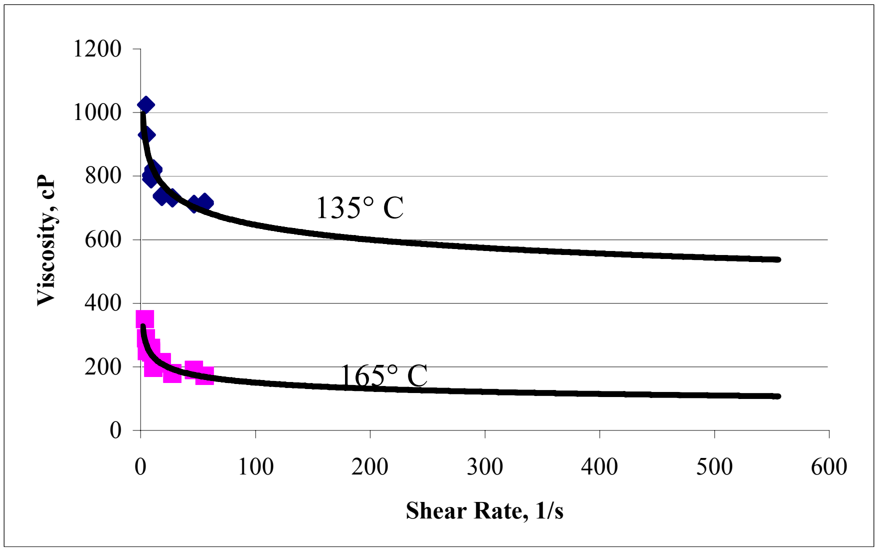


Figure 3.2 Viscosity shear rate relation at 135˚ C and 165˚ C

Based on the relationship shown in Figure 3.2, viscosity values at 500 1/s shear rate were calculated. These viscosity values were used to establish the relation between viscosity and temperature. CTR recommends a viscosity value of 275 cP for the calculation of mixing temperature and 550 cP for the calculation of compaction temperature. These viscosity values were used to estimate the mixing and compaction temperatures. Figure 3.3 shows the relation between viscosity and temperature at 12.5 percent toner-modification level. Based on the relation shown in Figure 3.3, mixing temperature was found to be 147° C and compaction temperature was found to be 136° C.

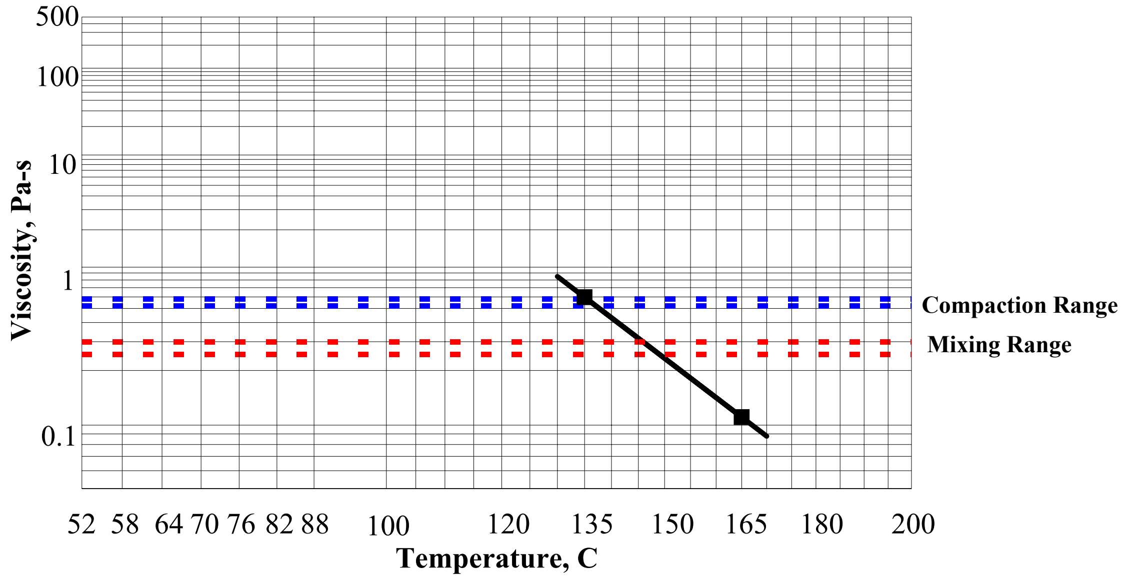


Figure 3.3 Viscosity temperature relationship at 12.5 percent toner-modification level.

Storage Stability

Storage stability was measured using AASHTO PP5-93 at 12.5 percent toner-modification level. A modified asphalt sample was poured into an aluminum tube and held in a vertical position throughout the aging portion of the test. The top of the tube was sealed, and the sample was placed in a 163° C oven for 2 hours. The sample was removed from the oven, and immediately placed in a freezer at –5° C. The tube was taken and cut into three pieces. The top and bottom pieces were each placed in a different container and held at 163° C to remove the aluminum pieces. The resulting specimens were tested for complex shear modulus. The results are shown in Figure 3.4.

The specimens taken from the bottom part of the tube showed 15 percent higher viscosity than the binder taken from the top portion. In this study, the specimen was left in the oven only for 2 hours. However, according to AASHTO PP5-93, the required duration of the specimen in the oven is 48 hours. The difference in viscosity exhibited between the top and bottom in such a short time shows a significant storage stability problem.

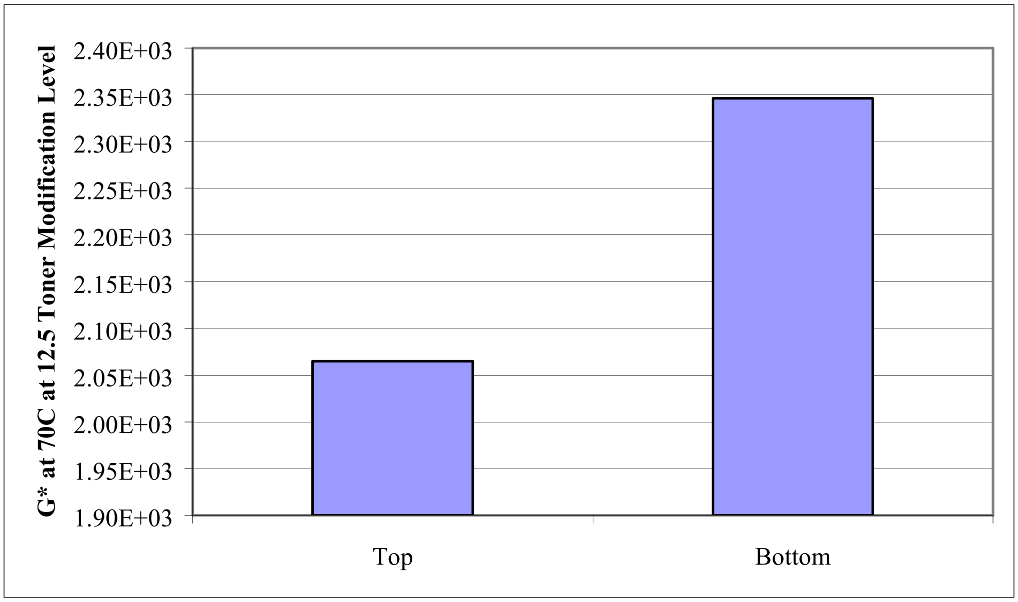


Figure 3.4 Results of stability test at 12.5 percent toner-modification level

BINDER DESIGN FOR PHARR PROJECT

CTR completed the work to evaluate the effect of a 7 percent toner-modification design for a specified nonmagnetic toner-modified binder corresponding to the Pharr demonstration project (10). The objective of the project is to achieve a better understanding of the effect of toner on the relationship between PG specifications and toner level. The project included information on the effective reaction time between binder and toner, the effective stirring time to achieve a homogeneous mix, and the effect of 7 percent toner content on the PG 64-22 base binder. Storage stability, and mixing and compaction temperatures for nonmagnetic toner-modified asphalt binders were also determined.

Effective Reaction Conditions

Using 7 percent toner, blending was carried out at 500 revolutions per minute at 163° C. The samples were taken throughout the blending process and tested for complex shear modulus at 64° C. The change in complex modulus versus blending time was plotted to find the efficient blending time to achieve a homogeneous mix. Figure 3.5 shows this relation. It was concluded that after 60 minutes of mixing, the binder-toner mastic was sufficiently homogenous.

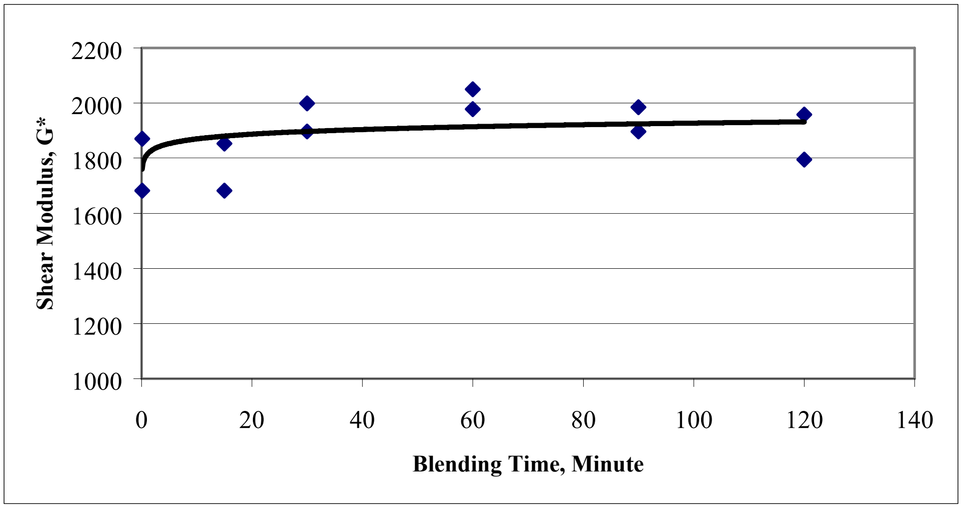


Figure 3.5 Shear modulus as a function of blending period

Design Toner-Modification Level

Full performance-grade binder classification testing was conducted on a blend prepared at a 7 percent toner-modification level. Initially, it was believed that a PG 70-22 binder with 7 percent toner would satisfy specifications; however, the RTFO-aged binder did not comply with the minimum 2.2Kpa requirement, due to a decline on the high-temperature side toward a PG 64-22, as shown in Appendix C. As for the intermediate-temperature properties, the PG 64-22 did not comply with the Pressure Aging Vessel (PAV)-aged binder test at 25° C, which requires a maximum 5000Kpa. Consequently, a 7 percent toner-modified binder finally met all PG grading requirements for a PG 64-16. The testing sequence, corresponding temperatures, and specifications are shown in Table 3.4.

Table 3.4 Superpave Binder Requirements for PG 64-22

Test	Original	RTFO	PAV	PAV	PAV
Parameter	G*/sinδ	G*/sinδ	G*sinδ	S	m-value
PG 70-22 Test Temperatures	70	70	25	-12	-12
PG 64-22 Test Temperatures	64	64	25	-12	-12
PG 64-16 Test Temperatures	64	64	28	-6	-6
Requirement	Min. 1.0Kpa	Min 2.2Kpa	Max. 5000Kpa	Max.300Mpa	Min 0.30

All tests listed in Table 3.4 were conducted at the required temperatures. Although the percentage of toner was fixed, tests were conducted at different toner-modification levels to establish the relationship between toner-modification levels so as to verify compliance with the requirements listed in Table 3.4. Figures showing the relationship between toner-modification level and the binder properties for these five requirements are included in Appendix C. Equations and R^2 values are shown in Table 3.5.

Table 3.5 Equations for Estimated Relations

Percent Toner vs.	Binder	Equation	R^2
G*/sin Delta (64) (70)	Original	Y = 37.776x2 – 223.54x + 1295.4 Y = 29.468x2 - 195.65x + 624.04	0.9375 0.9561
G*/sin Delta	RTFO	Y = 98.599x2 – 664.09x + 3406.2 Y = 53.828x2 –384.61x + 1535.8	0.8779 0.8592
G*sin Delta (25) (28)	PAV	Y = 234850x + 5E+06 Y = 156114x + 3E+06	0.9717 0.9741
S (-6)	PAV	Y = 4088.3x + 86523	0.9516
m-value (-6)	PAV	Y = -0.0033x + 0.4285	0.9415

Mixing and Compaction Temperatures

Lab mixing and compaction temperatures were calculated at a 7 percent toner-modification level. The method developed by CTR and reported in Research Report 1250-5 for calculation of mixing and compaction temperatures was used in this project. Viscosity of modified binders depends on both shear rate and temperature. Therefore, the effect of these factors was included in the viscosity calculations. A relationship between shear rate and viscosity was established by the Brookfield viscometer to estimate the shear rate dependency of the toner-modified binder. Measurements were conducted at 135° C and 165° C.

Based on the relationship between viscosity and shear rate, viscosity values at 500 1/s shear rate were estimated. These viscosity values were used to establish the relationship between viscosity and temperature. CTR recommends a viscosity value of 275 cP for the calculation of mixing temperature and 550 cP for the calculation of compaction temperature. These viscosity values were used to estimate the mixing and compaction temperatures. Figure 3.6 shows the relationship between viscosity and temperature at 7 percent toner-modification level. Based on this relationship, the mixing temperature was found to be 149° C, and the compaction temperature was found to be 135° C.

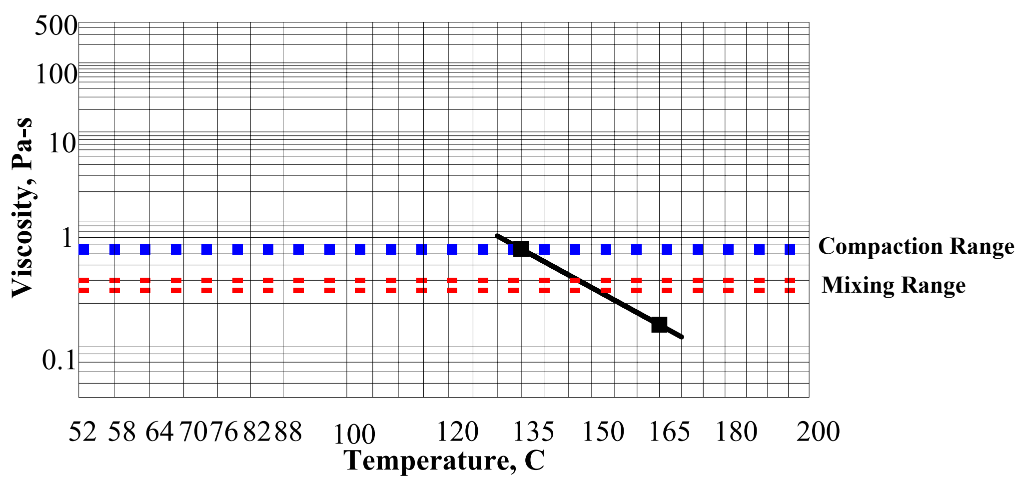


Figure 3.6 Viscosity vs. temperature at 7 percent toner-modification level

Storage Stability

Storage stability was measured using AASHTO PP5-93 at the 7 percent toner-modification level. A modified asphalt sample was poured into an aluminum tube and held in vertical position throughout the aging portion of the test. The top of the tube was sealed and the sample placed in a 163° C oven for 2 hours. The sample was then removed from the oven and immediately placed in a freezer at –5° C. The tube was cut into three pieces, with the top and bottom pieces placed in a different container and held at 163° C to remove the aluminum pieces. The resulting specimens were subsequently tested for complex shear modulus.

The specimens taken from the bottom part of the tube showed up to eight time's higher viscosity than the binder taken from the top portion. In this study, the specimen was left in the oven only for 2 hours instead of 48 hours, as recommended by AASHTO PP5-93. A significant storage stability problem was observed through the high difference in viscosity exhibited between the top and bottom specimens in such a short time. The results of storage stability test are presented in Figure 3.7.

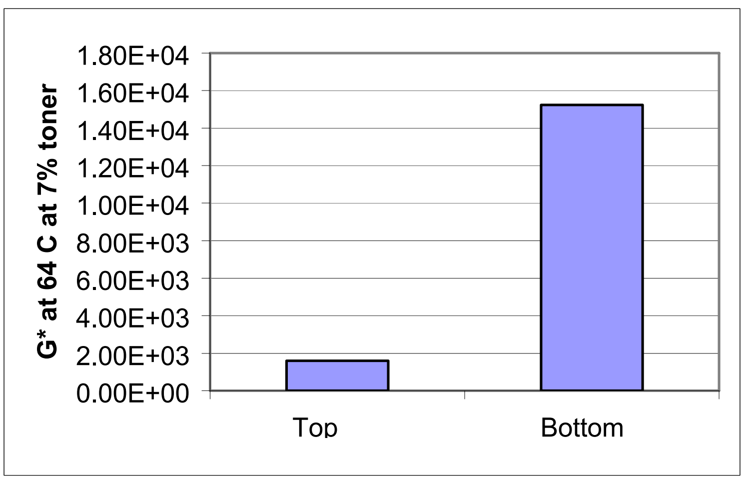


Figure 3.7 Results of stability test at 7 percent toner-modification level

BINDER DESIGN FOR LAREDO PROJECT

The binder design for toner-modified binder for the Laredo demonstration project included information on the effective reaction time between binder and toner, effective stirring time to achieve a homogeneous mix, effective toner content range to achieve the required performance grade, storage stability, and mixing and compaction temperatures. The base binder was a PG 64-22, and the amount of toner required to achieve a PG 76-16 was between 13–14 percent. For this project, 14.5 percent toner is recommended to modify the base binder (11).

Effective Reaction Conditions

The results of the effect of stirring period are presented in Figure 3.8. In order to obtain a homogeneous binder, 5 percent toner was blended using a Lightning™ mixer with the base asphalt. The mixing took place at 500 revolutions per minute at 163° C. At the end of the reaction period, the samples were tested for complex shear modulus at 64° C. The change in complex modulus versus blending time was plotted to find the most efficient blending time to achieve a homogeneous mix.

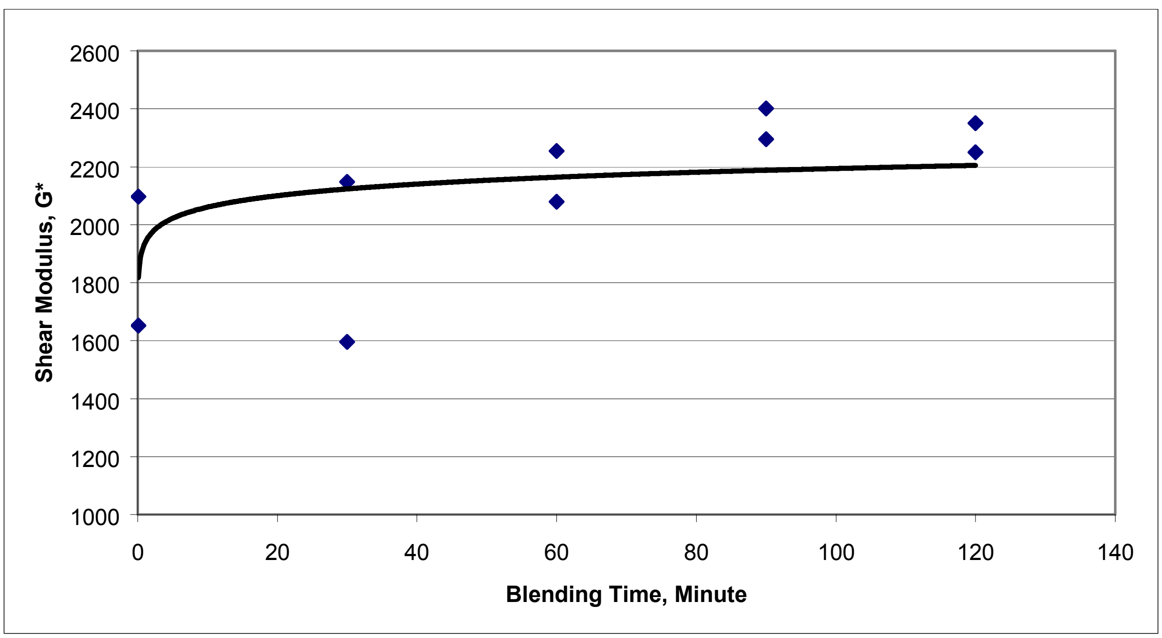


Figure 3.8 Shear modulus as a function of blending period

Design Toner-Modification Level

Trial blends containing different percentages of toner were prepared to calculate the toner-modification level necessary to achieve PG 76-16. The toner-binder blends were prepared at 0 percent, 5 percent, 10 percent, and 15 percent toner-modification levels. Full performance-grade binder classification testing was conducted on each toner-modification level. Superpave binder specifications for PG 76-16 are shown in Table 3.6

Table 3.6 Superpave PG Binder Requirements for PG 76-16

Test	Original	RTFO	PAV	PAV	PAV
Parameter	G*/sinδ	G*/sinδ	G*sinδ	S	m-value
Test Temperature	76	76	28	-6	-6
Requirement	Min. 1.0Kpa	Min 2.2Kpa	Max. 5000Kpa	Max.300Mpa	Min 0.30

All tests listed in Table 3.6 were conducted at the specified temperatures. Tests were conducted at different toner-modification levels to establish the relationship between toner-modification level and the requirements listed in Table 3.6. Figures showing the relationship for these five requirements are included in Appendix C. Equations and RV values are shown in Table 3.7.

Table 3.7 Equations for Estimated Relations

Percent Toner vs.	Binder	Equation	R^2
G*/sin δ	Original	$Y = 0.9819x^2 + 65.982x + 458.5$	0.71
G*/sin δ	RTFO	$Y = 4.751x^2 + 24.197x + 957.68$	0.9948
G*sin δ	PAV	$Y = 2376.9x^2 + 109113x + 2E+06$	0.9334
S	PAV	$Y =62.167x^2 + 1287.8x + 71481$	0.8711
m-value	PAV	$Y = -1E-05x^2 - 0.0025x + 0.3922$	0.8591

Based on the equations listed in Table 3.7, values required in the Superpave binder specification were calculated at different toner levels. These results are presented in Table 3.8 for values between 7–19 percent toner modification for the five Superpave requirements listed in Table 3.6.

As can be seen from Table 3.8, binders below 8 percent toner modification do not meet the requirements for G*/sinδ on original binders. For RTFO-aged binder, the base binder should be modified with a minimum of 14 percent toner to meet the requirements for G*/sinδ. Consequently, the base binder should be modified with more than 14 percent toner to meet the requirements for G*sinδ, since the RTFO-aged specification is barely satisfied. Other than this, creep stiffness (S), and logarithmic creep rate (m-value) meet the specification requirements for toner-modification levels between 7–19 percent.

Table 3.8 Estimated Binder Properties at Different Toner-Modification Levels

	Original	RTFO	PAV	PAV	PAV
Percent Toner	G*/sinδ (Pa)	G*/sinδ (Pa)	G*sinδ (Pa)	S	m-value
7	968.4871	*1359.858*	2880259	83541.78	0.37421
8	1049.198	*1455.32*	3025026	85762.09	0.37156
9	1131.872	*1560.284*	3174546	88106.73	0.36889
10	1216.51	*1674.75*	3328820	90575.7	0.3662
11	1303.112	*1798.718*	3487848	93169.01	0.36349
12	1391.678	*1932.188*	3651630	95886.65	0.36076
13	1482.207	*2075.16*	3820165	98728.62	0.35801
14	1574.700	2227.634	3993454	101694.9	0.35524
15	1669.158	2389.61	4171498	104785.6	0.35245
16	1765.578	2561.088	4354294	108000.6	0.34964
17	1863.963	2742.068	4541845	111339.9	0.34681
18	1964.312	2932.55	4734150	114803.5	0.34396
19	2066.624	3132.534	4931208	118391.5	0.34109

The numbers in italics in each column represent the specification results for the corresponding toner percentage, which do not meet a particular criterion. The critical figure stems from G*/sinδ on RTFO-aged binder to achieve PG 76-16, with a value of 13.9 percent toner modification needed to meet all Superpave binder requirements. Since the above-mentioned parameter is barely met (see Appendix C), to be on the safe side, 14.5 percent toner was used to modify the base binder.

Mixing and Compaction Temperatures

Lab mixing and compaction temperatures were calculated at a 14.5 percent toner-modification level. The method developed by CTR and reported in Research Report 1250-5 for the calculation of mixing and compaction temperatures was used in this project. Since viscosity of modified binders depends on both shear rate and temperature, the effect of these factors was included in the viscosity calculations. A relationship between shear rate and viscosity was established by the Brookfield viscometer to estimate the shear rate dependency of the toner- modified binder. Measurements were conducted at 135° C and 165° C.

Based on the relations between viscosity and shear rate, viscosity values at 500 1/s shear rate were calculated. These viscosity values were used to establish the relationship between viscosity and temperature. CTR recommends a viscosity value of 275 cP for the calculation of mixing temperature and 550 cP for the calculation of compaction temperature. These viscosity values were used to estimate the mixing and compaction temperatures. Figure 3.9 shows the relationship between viscosity and temperature at a 14.5 percent toner-modification level. Based on the relationship shown in Figure 3.9, mixing temperature was found to be 156° C, and compaction temperature was found to be 141° C.

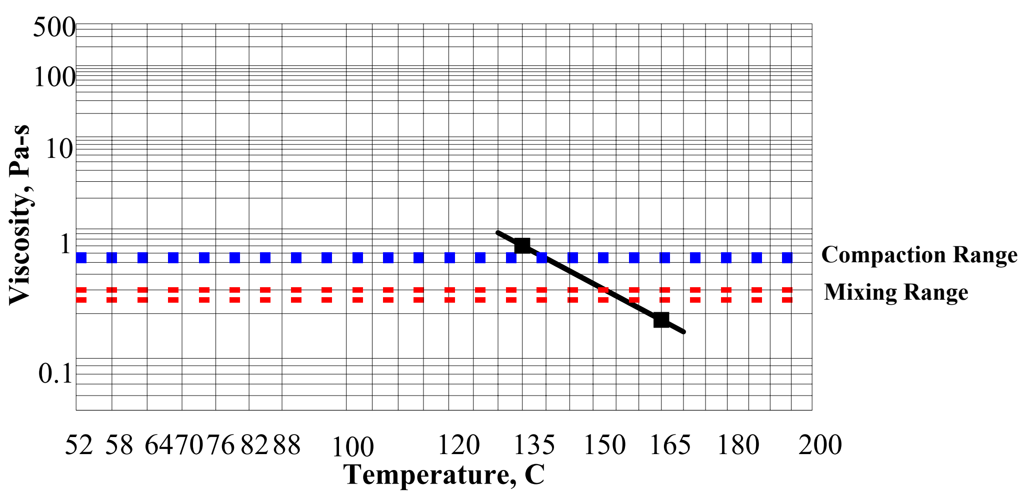


Figure 3.9 Viscosity vs. Temperature at 14.5 percent toner-modification level.

Storage Stability

Storage stability was measured using AASHTO PP5-93 at a 14.5 percent toner-modification level. A modified asphalt sample was poured into an aluminum tube and held in vertical position throughout the aging portion of the test. The top of the tube was sealed and the sample placed in a 163° C oven for 2 hours. The sample was then removed and immediately placed in a freezer at –5° C. The tube was cut into three pieces, with the top and bottom pieces placed in a different container and held at 163° C to remove the aluminum pieces. The resulting specimens were subsequently tested for complex shear modulus.

The specimens taken from the bottom part of the tube showed up to four time's higher viscosity than the binder taken from the top portion. In this study, the specimen was left in the oven for only 2 hours, whereas AASHTO PP5-93 requires the specimen to remain in the oven for 48 hours. However, the difference in viscosity exhibited between the top and bottom in such a short time shows a significant storage stability problem. Figure 3.10 shows the results of the storage stability test.

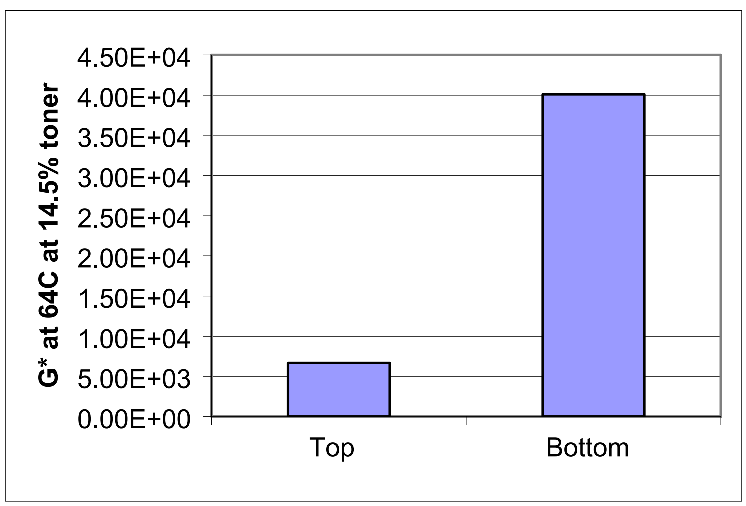


Figure 3.10 Results of storage stability test at 14.5 percent toner-modification level

BINDER DESIGN FOR BRYAN PROJECT

In this binder design, the effect of a 7 percent toner modification on the properties of the binder received from Fina Oil Company was evaluated for the Bryant toner project. The design includes information on effective reaction time between the binder and toner, stirring time to arrive at a homogeneous mixture, and the effect of a 7 percent toner modification on the PG 64-16 base binder. In addition, storage stability and mixing and compaction temperatures for the 7 percent toner-modified asphalt binders were tested. Finally, performance-grade classification tests on 14 and 21 percent toner-modified binders were conducted to better understand the relationship between PG specifications and toner level.

Effective Reaction Time

Seven percent toner was used and blending was carried out at 500 revolutions per minute at 163° C. The samples were taken throughout the blending process and tested for complex shear modulus at 64° C. The change in complex shear modulus versus blending time was monitored to determine an effective blending time to achieve a homogeneous mix. Figure 3.11 shows this relationship. As can be seen from this figure, shear modulus increases rapidly during the first 30 minutes after the blending process started; however, the shear modulus seems to stabilize after this period. Based on this empirical relationship, it was concluded that after 60 minutes of mixing, the binder-toner mastic is sufficiently homogenous.

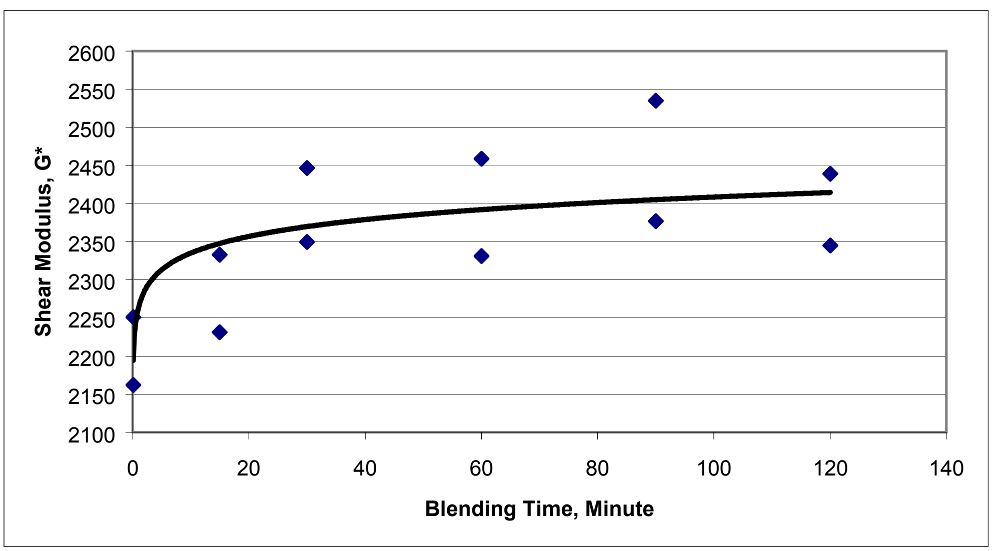


Figure 3.11 Shear Modulus as a Function of Blending Period

Mixing and Compaction Temperatures

Lab mixing and compaction temperatures were calculated at 7 percent toner-modification level. The method developed by the Center for Transportation Research (CTR) and reported in Research Report 1250-5 for the calculation of mixing and compaction temperatures was used in this project.

It is known that the viscosity of modified binders depends on both shear rate and temperature. Accordingly, the effect of these factors was included in the viscosity calculations. A relationship between shear rate and viscosity was established by the Brookfield viscometer to estimate the shear rate dependency of the toner-modified binder. Measurements were conducted at 135° C and 165° C.

Viscosity values at 500 1/s shear rate were estimated based on the relationship between viscosity and shear rate. The viscosity values of 109 cP and 423 cP for 165° C and 135° C, respectively, were used to establish the relationship between viscosity and temperature. CTR recommends a 275 cP viscosity value for calculating mixing temperature and 550 cP viscosity value for calculating compaction temperature. Figure 3.12 shows the relationship between viscosity and temperature at a 7 percent toner-modification level. Based on this relationship, the mixing temperature was found to be 144° C, and the compaction temperature was found to be 130° C.

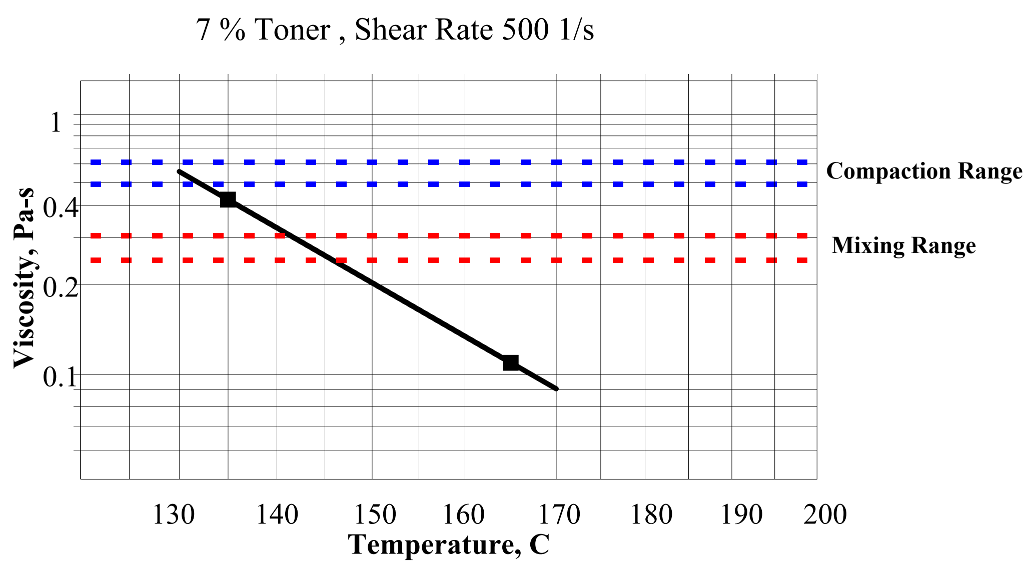


Figure 3.12 Viscosity vs. Temperature at 7 percent toner-modification level

Storage Stability

Storage stability was measured using AASHTO PP5-93 at a 7 percent toner-modification level. A modified asphalt sample was poured into an aluminum tube and held in a vertical position throughout the aging portion of the test. The top of the tube was sealed and the sample was placed in a 163° C oven for 2 hours. The sample was then removed from the oven, and immediately placed in a freezer at –5° C. The tube was cut into three pieces, with the top and bottom portions placed in different containers and heated to 163° C to remove the aluminum pieces. The resulting specimens were subsequently tested for complex shear modulus.

The specimens taken from the bottom part of the tube showed up to 6 times higher G*/Sinδ value than the binder taken from the top portion. In this study, the specimens were left in the oven only for 2 hours instead of 48 hours as recommended by AASHTO PP5-93. A significant storage stability problem was observed through the high difference in viscosity exhibited between the top and bottom in such a short time. This problem should be taken into consideration when storing toner-modified binder. The results of the storage stability test are presented in Figure 3.13.

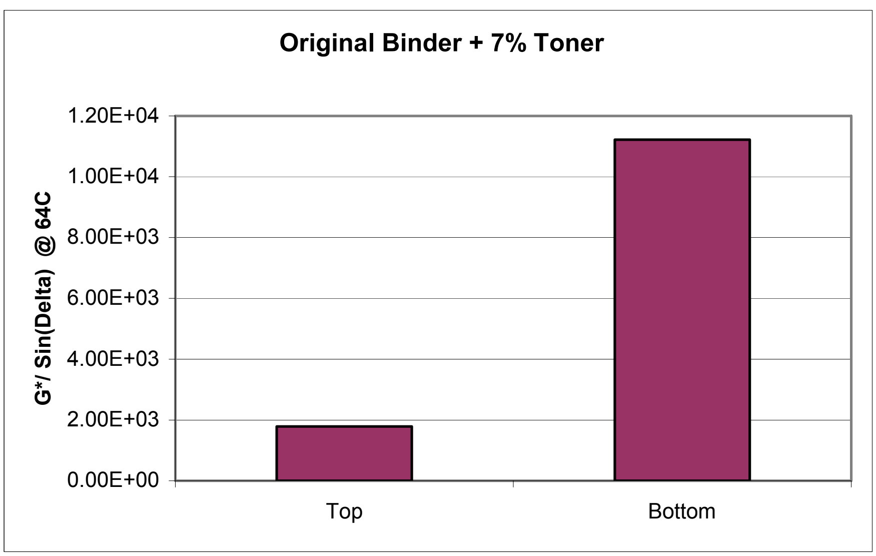


Figure 3.13 Results of Stability Test at 7 percent toner-modification level

Design Toner-Modification Level

Full performance-grade binder classification testing was conducted on a blend prepared at a 7 percent toner-modification level. It was found that 7 percent toner modified binder meets the

DSR requirements for original and RTFO-aged binder at 70° C. In addition, a 7 percent toner modified binder complies just within the DSR requirements on the Pressure Aging Vessel (PAV)-aged binder test at 28° C. Accordingly, a 7 percent toner-modified binder meets all the PG grading requirements for a PG 70-16. The testing sequence and corresponding temperatures and specifications are shown in Table 3.9. All tests listed in Table 3.9 were conducted at the required temperatures.

Although the toner percent amount was fixed at 7 percent, tests were also conducted at different toner-modification levels to establish the relationship between toner-modification levels so as to verify compliance with the requirements listed in Table 3.9. Figures showing the relationship between toner-modification level and the binder properties for these five requirements are included in Appendix C. The corresponding regression equations are included in Table 3.10.

Table 3.9 Superpave Binder Requirements for PG 64-22

Test	Original	RTFO	PAV	PAV	PAV
Parameter	G*/sinδ	G*/sinδ	G*/sinδ	S	m-value
PG 70-16 Test Temperatures	70	70	25	-12	-12
PG 64-16 Test Temperatures	64	64	28	-6	-6
Requirement	Min. 1.0 kPa	Min 2.2 kPa	Max. 5000 kPa	Max.300 MPa	Min 0.30

Table 3.10 Equations for Estimated Relations

Percent Toner vs.	Binder	Equation (t-statistics)	R^2
G*/sin Delta (70)	Original	$Y = 4.82x^2 + 62x + 494$	0.99
G*/sin Delta (70)	RTFO	$Y = 7.46x^2 - 7.07x + 2103$	0.88
G*/sin Delta (28)	PAV	$Y = 11095x^2 - 46699x + 5E+06$	0.99
S (-6)	PAV	$Y = 0.20x^2 - 0.08x + 103$	0.99
m-value (-6)	PAV	Y = -9E-05x2 - 0.0009x + 0.36	0.99

Chapter 4. Construction of the Test Section

Construction of all of the test sections took more than a year. Figures displaying the setup of the test sections were included in Appendix D. First, the test sections in the Houston district were constructed on September 26, 2001, by Hubco Construction Company on SH 3 in Galveston. In this project, 64-22 binder was modified by using 12.5 percent toner. Ricoh provided the toner used in this project in boxes. The mixing process was not a continuous process and mixing was conducted in batches. The mixing was done in equipment that had two 5-ton tanks for mixing and a 15-ton tank used for storage. Five-ton batches were prepared separately. For each batch, the toner was first weighed on an external scale and then poured into the mixer. Figure 4.1 shows the placement of toner into the mixer.

Figure 4.1 Placement of Toner into the Mixer

The percentages of toner to binder were calculated for each batch. The operator was able to control the flow of binder into the tank to obtain 8,759 lbs for each batch. Based on this value, it was calculated that 1,251 lbs of toner was sufficient for the binder modification. Overall, mixing toner in this way was difficult for the operator, especially with controlling the amount of toner in each batch and placing the toner inside the mixer.

The second test section was constructed in the Pharr district on March 14, 2002, by Ballenger Construction on FM 800 in Cameron County. In this project, the toner came in barrels from Lexmark. Seven percent nonmagnetic toner was used to modify PG 64-22 base binder. For the mixing process, a different mixer, which has two different tanks, was employed. One tank was used to store the toner, and the other tank was used to mix the toner and binder. Figure 4.2 shows the mixer used in this project.

Figure 4.2 Mixer used in Pharr, Laredo, and Bryan Projects

The mixing process was monitored in real time by a computer. Figure 4.3 shows the computer used to control the mixing process. In this process, the toner was first placed into the hopper. Then the weight of the toner was measured. After that, the toner was moved into the mixing process. The computer monitored the mixing process by measuring the weight in each tank. The mixing speed was 3000 rpm.

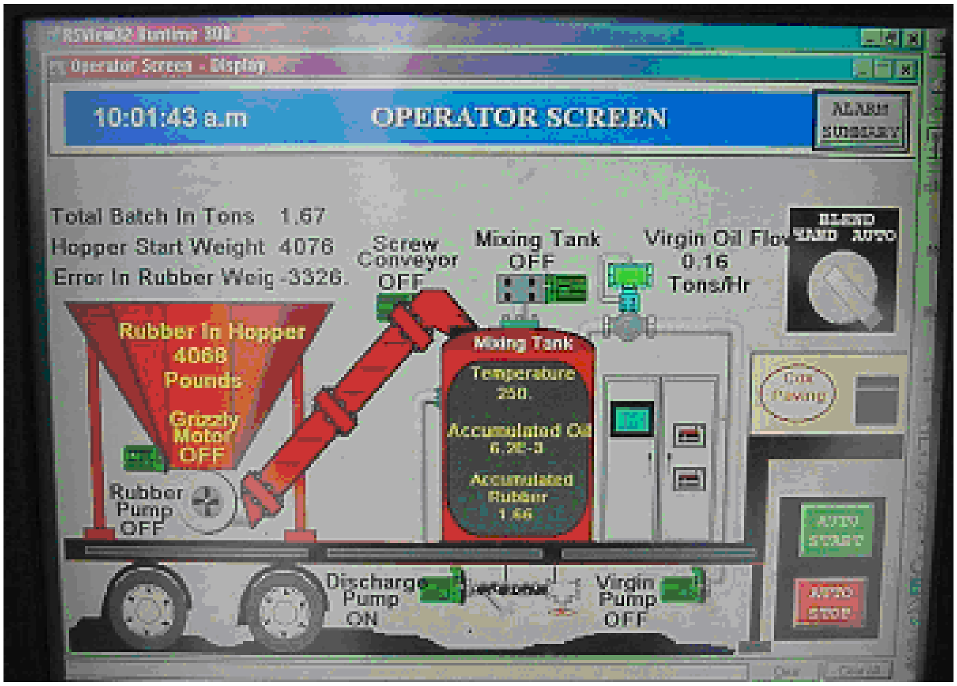


Figure 4.3 Computer Control Unit for the Mixer

The third test section was constructed in the Bryan district on August 19, 2002, on US 77 in Milam County. In this project, PG 64-22 base binder was modified with 7 percent magnetic toner produced by Nashua in barrels. The same mixer used in the Pharr project was used to mix asphalt and toner.

The last test section constructed for this implementation project was constructed in Laredo on October 1, 2002. These test sections were constructed by EE Hood and Sons Construction Company. The mix was prepared at Martin Marietta, and the test section was constructed in Cotulla, La Salle County. Toner for this project was provided by Nashua in barrels. PG 64-22 binder was mixed with 14.5 percent magnetic toner to achieve a PG 76-16. The same mixer used in the Pharr project was used to mix the asphalt and toner.

From the construction of the test section, it is observed that the transportation of the toner in barrels is better than transportation in boxes in terms of ease of handling. Toner is composed of fine particles and the handling of toner throughout the mixing process is difficult. Especially in the Houston project, we observed this problem since the toner was weighed separately in each batch. For an easy mixing process, computerized mixing equipment is helpful.

In every project, after the mixing process, the toner-modified binder looked uniform. In each project, the toner-modified binders were agitated before being used in the preparation of the mixes. Consequently, potential storage problems were prevented. In all cases, mix produced at the plant was uniform and workable. No significant problem was observed throughout the compaction process.

Chapter 5. Post-Construction Pavement Evaluation Results

Post-construction pavement evaluations were conducted on the test sections approximately one year after the completion of the constructions. For these evaluations, visual pavement condition surveys were conducted, profiler data in each test section were collected, and the cores were collected for Hamburg Wheel Tracking Device (HWTD) testing.

Visual Pavement Surveys

For the visual pavement survey, the distress identification manual for long-term pavement performance prepared during the Strategic Highway Research Program (SHRP) was used. This manual was initially developed for use in long-term pavement performance, asphalt characteristics, maintenance cost-effectiveness, and cement and concrete studies being conducted under SHRP. The manual classifies distresses in pavements into five general modes: Cracking, patching and potholes, surface deformations, surface defects, and miscellaneous distresses.

The survey procedure for the study was conducted as follows: First, the 1000-ft length of each section (control/toner) of the road was measured. Second, the notes of length and type of crack were documented for each control/toner section. The two types of cracks observed from the test sections were: longitudinal—cracks running parallel to laydown direction of the pavement; and transverse —cracks that extend across the laydown direction.

For the Bryan sections, there was no visual distress observed for a half mile into both of the test sections. There was a notable color change at the control/toner boundary, and in addition, the wheel path on the control section was visible due to a color difference between the wheel path and the surrounding asphalt. The control section showed some segregation in certain areas. Some small rutting in localized areas (most noticeably around 100 ft and 380 ft away from the control/toner boundary) was observed in the control section. These sections showed very little rutting throughout the observed area. Both the control and toner test sections did not exhibit signs of cracking.

For the Pharr section, both control and toner-modified test sections displayed transverse cracks along the lanes. In addition, longitudinal and transverse cracks were observed along the shoulders of both sections. The spacing between the transverse cracks ranged from 9 – 40 ft in each test section lane. However, no significant rutting was observed on either test section. Approximately the same amount of cracking was observed in each section. All of the cracks observed in these sections were transverse cracks. Tables D.1 and D.2 in Appendix D summarize the distresses observed in this sections.

For the Laredo section, neither the control nor toner-modified test sections exhibited any signs of significant distress along the wheel paths. A little bit more rutting was observed in the control section relative to the toner section. The toner test section had several insignificant hairline cracks. These cracks are in the form of low-level longitudinal and transverse cracks. Table D.3 showing the list of the cracks is included in the Appendix D.

The Houston test section consists of five lanes, with two lanes heading north, two more heading south, and a center lane acting as a turning lane. The control section consists of the two northbound lanes, while the turning and inside southbound lane make up the toner section. The overall performance of the control and toner test sections was similar. The toner section showed better performance in terms of rutting. For cracks extending into the control and toner sections, it was observed that the cracks were mostly hairline in nature. The number of cracks observed in selected 1,000-ft sections was insignificant. The list of the cracks was included in Appendix D.

Visual pavement condition surveys showed that no significant distress was observed in the test sections. All of the distresses observed were at low levels. It is observed that toner sections have higher rutting resistance, but the number of cracks is higher in these sections based on the data collected from the test sections.

Profiler Data

Profile data was collected along the profile of the roads in order to get an estimate of the in-place rutting of the asphalt pavement. The profile was collected one lane length in each measurement. Two rut depths were found for each profile that corresponds to the inside and the outside wheel paths. The final depth of the rutting was found using AASHTO Designation PP38-00, and the equation to find the perpendicular distance from a point to a line made by two points was used to calculate the rut depth. Using AASHTO Designation PP38-00, five points (A, B, C, D, and E) are focused on in analyzing the profiler data. Two points, A and C, that create a line were chosen as the two highest points across the first half of the data for the outside wheel path and the two highest points on the second half of the data, C and E, respectively, for the inside wheel path. Points B and D were the deepest points across A and C, and C and E, respectively, for the profile, and thus provided the depth of the rut for the outside and inside wheel paths. An example of how the rutting depths were found is given in Figure 5.1, and the rut depths that were found are shown in Table 5.1.

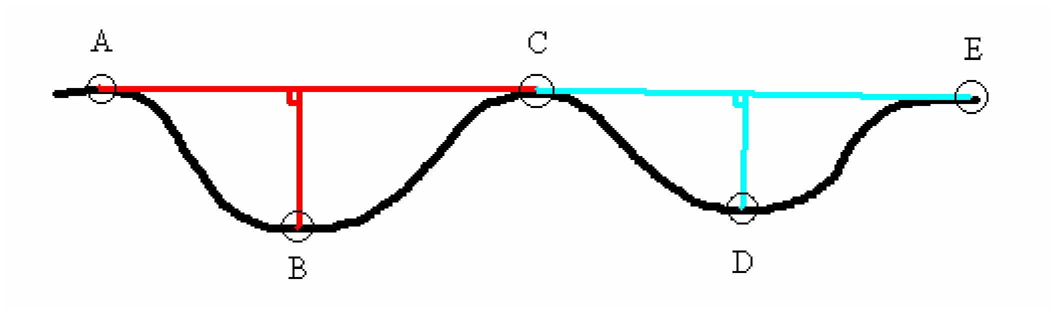


Figure 5.1 Rut Depth Profile

Table 5.1 Profile Rut Depths

Location	Section	Rut	Rut Depth (mm)
Houston	Control	Outside	2.11
		Inside	2.63
	Toner	Outside	1.02
		Inside	2.36
Laredo	Control	Outside	2.40
		Inside	2.04
	Toner	Outside	2.17
		Inside	1.46
Pharr	Control	Outside	1.29
		Inside	2.47
	Toner	Outside	1.16
		Inside	2.03
Bryan	Control	Outside	1.88
		Inside	1.97
	Toner	Outside	1.80
		Inside	1.24

The profile data proved the conclusions of visual pavement condition survey about rutting. The profile rut depths show that up to this point in time, there is very little rutting present in the test sections. In all test sections, the toner sections have shown a slightly higher resistance to rutting according to the results. Detailed data for the calculations for the rut depths were included in Appendix E.

HWTD Tests

The field cores collected from the field visits were tested by using HWTD equipment. For this purpose, 150 mm cores were collected from both control and toner sections in all districts. Permanent deformation is a major concern for asphalt pavements and is one of the areas where the addition of toner might help prevent permanent deformation. The HWTD provides a good indication of the susceptibility of an asphalt pavement to permanent deformation and has the ability to provide data in a relatively quick nature.

HWTD Equipment

The Hamburg Wheel Tracking Device, shown in Figure 5.2, can be used to assess the effect of rutting and moisture damage (basically stripping). Two steel wheels, which operate simultaneously, move back and forth on asphalt specimens. The wheels are 203.6 mm in diameter and 47 mm in width. Each wheel applies 705 ± 22 N of force and makes 50 passes in one minute. Specimens are placed onto a stainless steel tray, which is mounted in a water tank. The water tank, which is used as a temperature conditioner, stabilizes the testing temperature ranging from 25˚–70˚ C. There are also gauges that read the depth of the wheel ruts after a certain amount of wheel passes. Depth measurements can be taken after every 20, 50, 100, and 200 wheel passes. The device includes a linear variable differential transformer, which has an accuracy of 0.01 mm.

Figure 5.2 Hamburg Wheel Tracking Device

An analysis of test results is shown in Figure 5.3. There are five important indices, as can be seen from the figure. Post compaction is the immediate consolidation of the specimen at the beginning of the test. It is considered as densification of the mixture during the first 1,000 wheel passes.

Creep slope is used to correlate with rutting. As seen in Figure 5.3, there is a dramatic change in the slope after around 10,000 passes. This point is called the stripping inflection point, and it is the number of wheel passes and rut depth where the stripping starts to take place. Stripping slope curve is used to represent the effect of moisture. Stripping slope and failure rut depth are also used as a performance parameter.

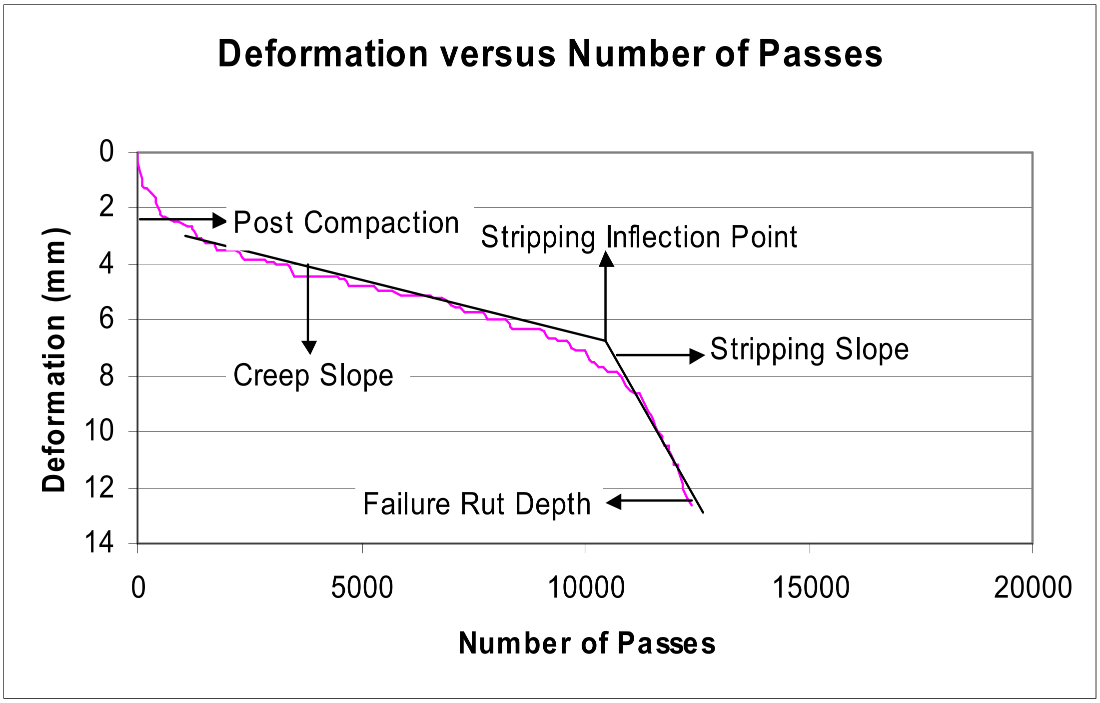


Figure 5.3 An example of Hamburg Wheel Tracking Device output

Testing time depends on the failure point of the specimens. The test terminates when rut depth exceeds a certain value or when a predetermined number of wheel passes is reached, whichever occurs first. In this study, the number of wheel passes was chosen to be 20,000. None of the specimens failed before this point.

Experimental Design

As mentioned in Research Report 3933-1, toner-modified and control test sections were constructed in the Pharr, Laredo, Houston, and Bryan districts in Texas. From these test sections, cores were collected in the pavement of both the toner-modified and control sections. These field cores were tested by using the HWTD at 50˚ C. The data for each test was analyzed. The testing plan is outlined in Table 5.2.

Table 5.2 Experimental Design for HWTD Tests

Location	***Pharr***		***Laredo***		***Houston***		***Bryan***	
Section	Control	Toner-Modified	Control	Toner-Modified	Control	Toner-Modified	Control	Toner-Modified
Number of Specimens	2	2	2	2	2	2	2	2

The air void content is also pertinent information to the performance of the specimens and was calculated using volumetric analysis of the compacted samples. The air void contents of the specimens for the tested samples are included in Appendix F.

The HWTD had two wheels operating at one time, with two samples tested per wheel. For each wheel, two samples from the same test section were tested. The HWTD collects depth readings at 11 different points along the testing path. The value given is specified by a special excel macro which chooses the deepest rut depth over the 11 points as the rut depth value at that pass.

Throughout the testing, there were two modes of stopping the test. The first mode of stopping the test occurred when significant failure appeared in the asphalt pavement, which is signified by the test reaching a maximum rut depth of 12.5 mm. The second mode of stopping the test occurred when the pavement successfully endured 20,000 passes of the HWTD. Consequently, the HWTD stopped when either one of the two modes of stoppage occurred.

Test Results

Test results are presented in tables showing rut depths, slope values at different number of passes, and the area under the rutting curves. Rut depths at various numbers of wheel passes are provided below in Table 5.3 for the test sections.

Table 5.3 Rut Depths for the Test Sections

Location	Section	Rut Depth (mm) Number of Wheel Passes 1000	4000	8000	12000	20000
Pharr	Control	9.84	N/A	N/A	N/A	N/A
	Toner	4.04	10.52	N/A	N/A	N/A
Laredo	Control	4.54	6.85	9.43	10.84	N/A
	Toner	3.03	6.63	12.13	N/A	N/A
Houston	Control	3.31	5.69	8.72	N/A	N/A
	Toner	2.52	3.94	4.79	5.35	14.92
Bryan	Control	4.36	7.26	10.53	13.9	N/A
	Toner	4.09	6.77	8.11	9.62	N/A

In the analysis of the data, the slope of the rutting curve from the HWTD output gives another indication of how well the pavement is performing. The data was put into a curve analysis program where a best fit curve with the highest r value was used to analyze the data. The slopes of the best fit curve at various data points are given in Table 5.4. It can be reasoned that the larger the slope, the faster the asphalt pavement was rutting; consequently, lower slopes are desirable.

Table 5.4 Slopes of Data Curves

Location	Section	Slope Number of Wheel Passes 1000	4000	8000	12000	20000
Pharr	Control	0.00709	N/A	N/A	N/A	N/A
	Toner	0.00308	0.00221	N/A	N/A	N/A
Laredo	Control	0.00134	0.000716	0.000522	0.000434	N/A
	Toner	0.00165	0.00106	0.00135	N/A	N/A
Houston	Control	0.00139	0.000557	0.00139	N/A	N/A
	Toner	0.00062	0.000432	0.000145	0.00021	0.00311
Bryan	Control	0.00137	0.000904	0.000781	0.000884	N/A
	Toner	0.00154	0.000522	0.000265	0.000457	N/A

Another indication of how the asphalt pavements are performing is the area underneath the best fit slope. The larger the area underneath the curve, the larger the deformation or the earlier the deformation occurred in the asphalt pavement. The large area underneath the curve that would be caused by a large deformation would have occurred by having a very large deformation at a given number of wheel passes. A large area underneath the curve could also be caused by a significant deformation that occurred at an early number of wheel passes in the testing of the pavement. Even though there might not be a noticeable increase of rutting, the area would tend to be large. It is important to look at the areas underneath the best fit curves, keeping in mind the slope and shape of the curve up to the specific number of wheel passes. The areas underneath the best fit curves are shown in Table 5.5.

Table 5.5 Areas under the Best Fit Curves

Location	***Section***	**Areas**				
		Number of Wheel Passes				
		1000	**4000**	**8000**	**12000**	**20000**
Pharr	**Control**	5510	N/A	N/A	N/A	N/A
	Toner	2420	25100	N/A	N/A	N/A
Laredo	**Control**	3230	20100	52700	93800	N/A
	Toner	2110	16700	53000	N/A	N/A
Houston	**Control**	2230	15900	43500	N/A	N/A
	Toner	1880	11000	28800	49500	118000
Bryan	**Control**	3300	20700	56600	105000	N/A
	Toner	3120	20100	50400	85500	N/A

Both the Bryan and Houston test sections showed that the toner-modified sections performed better than control sections. For the Bryan test section, the toner-modified core exhibited 3.3 mm less rutting than the control core when the test was stopped at 16,941 passes. The toner-modified core took 3,680 more passes than the control core to demonstrate 14mm of rutting. Throughout the tests, the toner-modified core exhibited less rutting at any given number of passes than the control section. Figure 5.4 displays the resulting HWTD rutting curves for the Bryan test section.

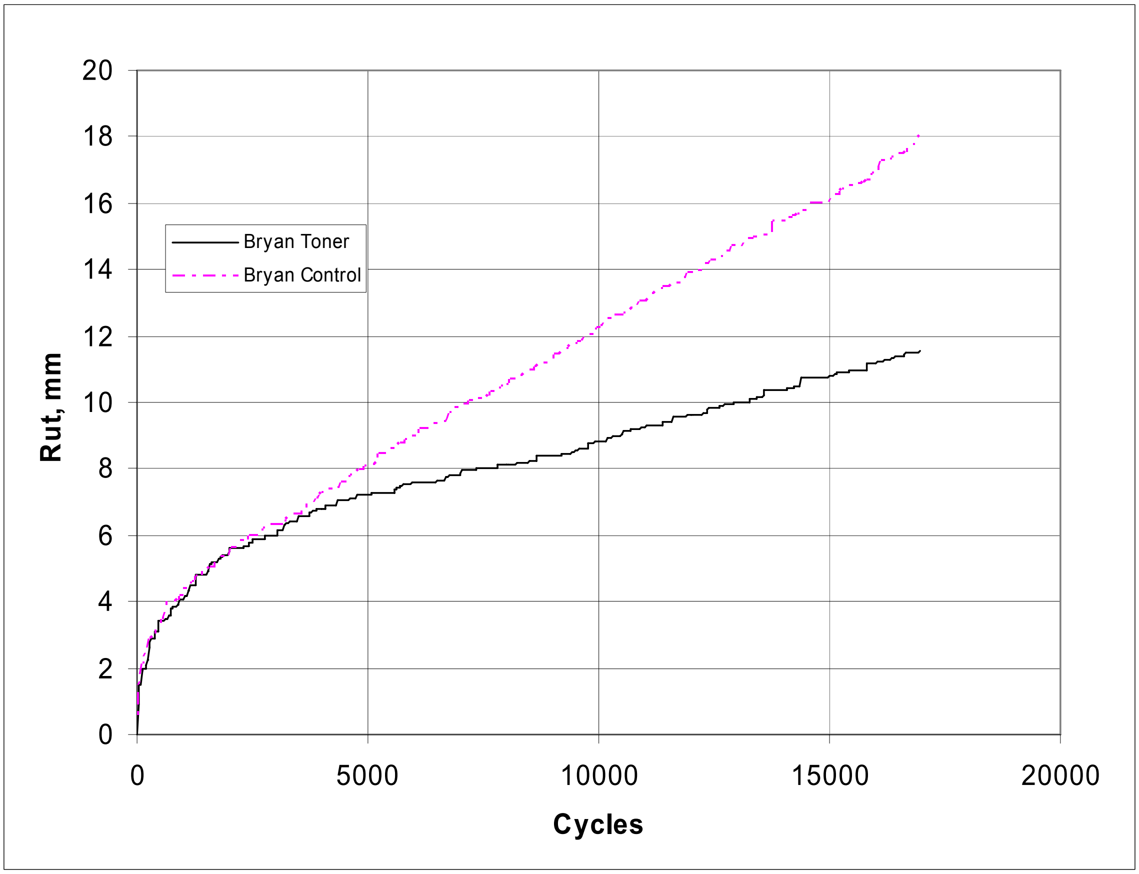


Figure 5.4 Bryan Test Section Results

The toner-modified core from the Houston section also performed better in the HWTD testing than the control core. The control core failed with 13.5 mm of rutting at 10,000 passes, while the toner-modified core showed only 5.3 mm of rutting at 10,000 passes, a difference of 8.3 mm. The toner-modified test core showed 13.5 mm of rutting at 19,201 passes (a 9,201 difference) and ultimately failed with 14.9 mm of rutting at 19,700 passes. Throughout the tests, the toner-modified core exhibited less rutting at any given pass number than the control section. Figure 5.5 shows the HWTD results for the Houston test sections.

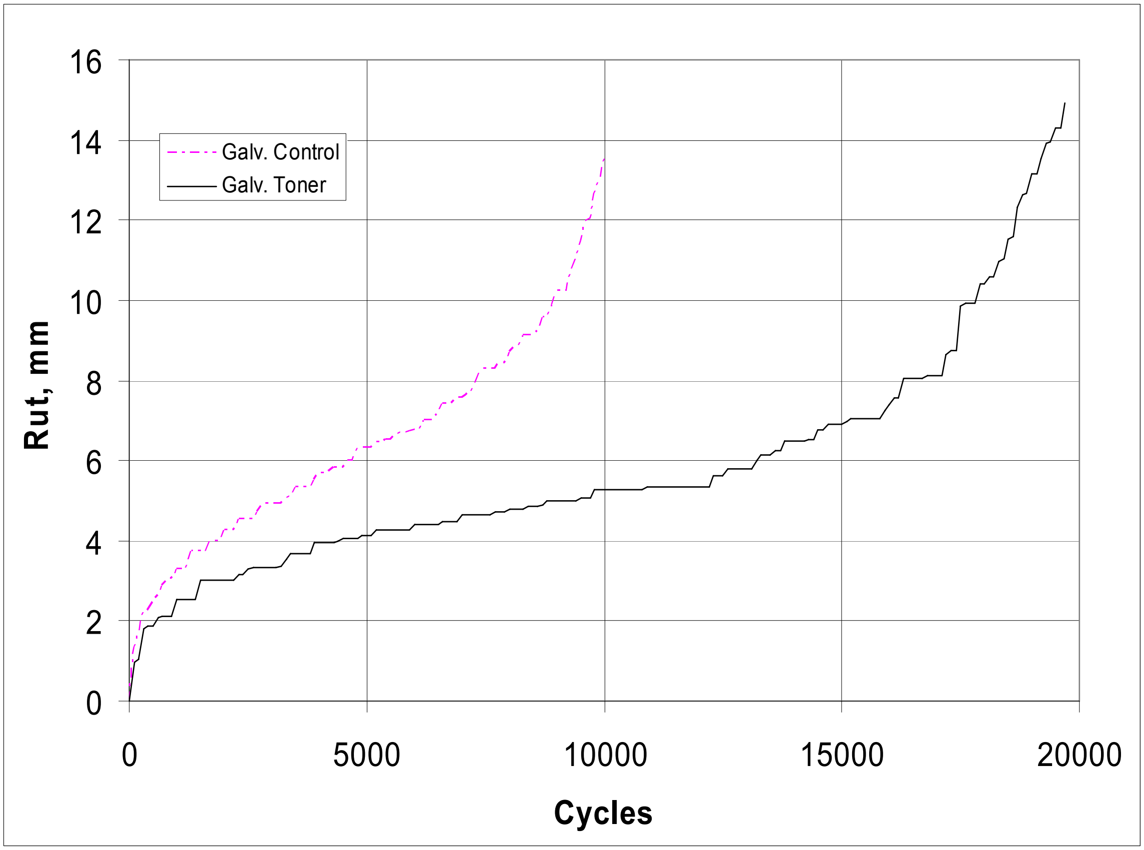


Figure 5.5 Houston Test Section Results

The Laredo control test section performed better than the Laredo toner test section in the HWTD testing. The toner core failed with 13.5 mm of rutting at 9,201 passes, while the control core exhibited only 10.2 mm of rutting at 9,201 passes. It took 7,101 passes for the control core to exhibit 13.5 mm of rutting (a 7,900 pass difference) and ultimately failed at 17,801 passes with 13.9 mm of rutting. Although the toner-modified core performed poorly compared to the control core, the toner core did display less rutting initially (below 4,000 passes) compared to the control core. The cores collected from toner section had approximately 2.4 percent more air voids than the control section. Air void is a very important factor for HWTD test. Most probably, this significant difference between the air voids of the cores collected from the toner and control sections are the main reasons for the difference between the test result. Figure 5.6 displays the HWTD results for the Laredo test section.

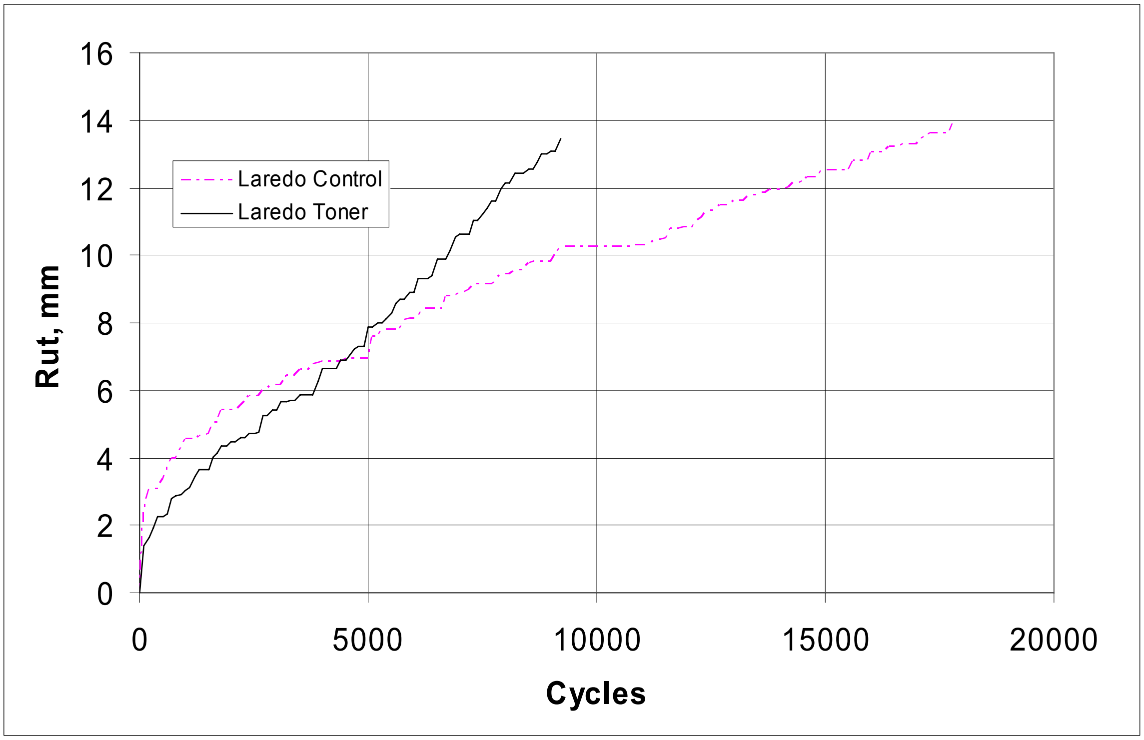


Figure 5.6 Laredo Control and Toner Test Section Results

The Pharr toner and control test sections performed the poorest of the four test sections. The control asphalt pavement failed with 10.3 mm of rutting after 1,801 wheel passes, while the toner-modified section failed at 5,401 wheel passes after 14.9 mm of rutting. At 1,801 wheel passes, the toner-modified section showed 6.6 mm of rutting, and did not display 10.5 mm of rutting until 3,801 wheel passes. Figure 5.7 shows the results from the HWTD for the Pharr toner and control test sections.

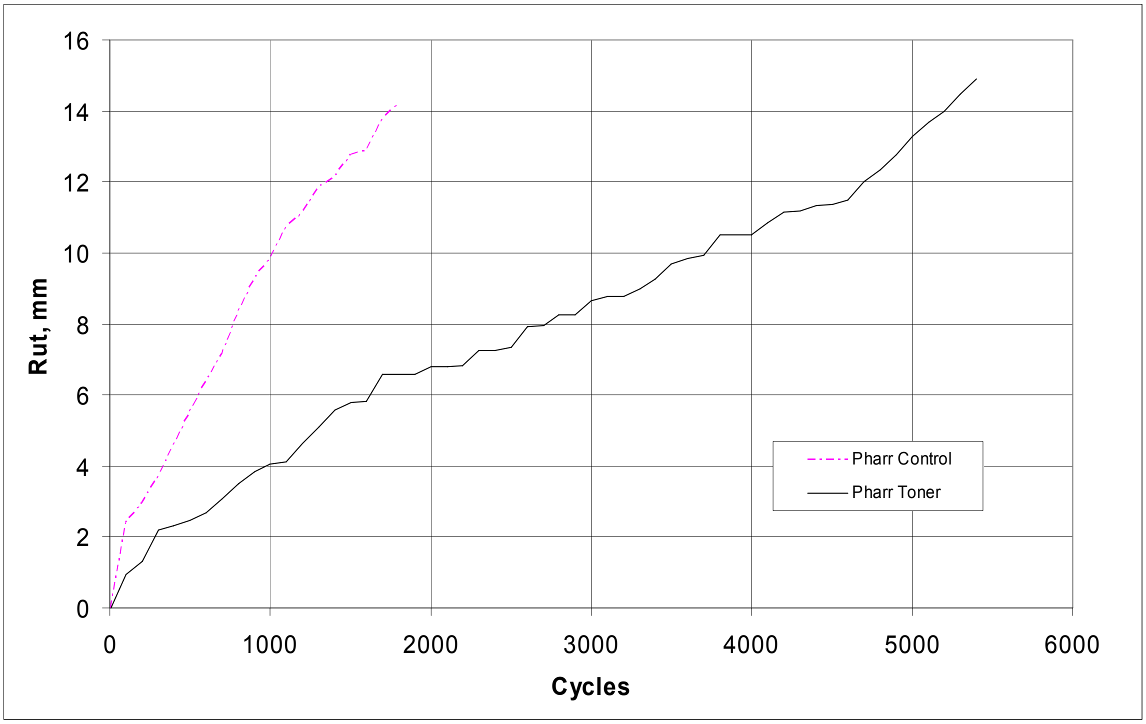


Figure 5.7 Pharr Toner and Control Test Section Results

Overall field cores collected from toner sections showed better performance than the cores collected from control sections. Only in Laredo did the cores collected from toner modified section show lower performance, which is most probably because of the high difference in the air void content between the toner and control sections.

Chapter 6. Conclusions

This report summarizes the mixture designs and the binder designs of demonstration projects in the Houston, Pharr, Laredo, and Bryan districts in Texas where waste toner was used as an asphalt modifier. It also includes post-construction evaluation results from the test sections.

For each of the projects, a binder design was performed, including blending time, PG grading, storage stability, and mixing and compaction temperature calculations. The PG properties of the toner-modified asphalt binders used in each test section varied according to the amount of polymers in the toner. Objectives of the research included determining the toner levels needed to arrive at a given PG grade as well as achieving a better understanding of the effect of toner level on the PG properties of a binder.

The same grade base binder was used for each demonstration project (PG 64-22), and the objectives were basically two-fold. The first objective was to study the effective level of toner needed to achieve a desired PG grade. In accordance with this, Laredo, with a 14.5 percent magnetic-toner level and around 80 percent SAC, had $G^*/\sin\delta$ for the RTFO-aged binder test as the governing PG criteria to achieve a PG 76-16. Houston, with 12.5 percent nonmagnetic toner level and 15 percent SAC, had $G^*/\sin\delta$ on the original binder and $G^*\sin\delta$ on the PAV-aged binder as the governing criteria to achieve a PG 70-16.

The second objective was to study the effect on the binder properties of a PG 64-22 as a result of adding 7 percent nonmagnetic toner. In the Pharr project, the RTFO-aged binder and the PAV-aged binder at an intermediate temperature (25° C) were the governing PG criteria for a 7 percent toner-modified binder to meet all the PG grading requirements of a PG 64-16. In Bryan, it was found that 7 percent magnetic toner-modified binder meets the DSR requirements for original and RTFO-aged binder at 70° C. In addition, 7 percent toner-modified binder complies just within the DSR requirements on the Pressure Aging Vessel (PAV)-aged binder test at 28° C. Accordingly, in the Bryan project, a 7 percent toner-modified binder meets all the PG grading requirements for a PG 70-16.

The testing showed that a stiffening effect occurs as the toner level is increased at all temperatures, which, for the most part, shows a parabolic trend. At higher percentages of toner, the stiffening effect is more significant.

The BBR test also demonstrated a decrease in m-value and an increase in creep stiffness. This change in binder properties makes the modified binder more susceptible to low-temperature cracking. In general, there is a parabolic trend in the stiffening effect of the modified binder as the level of toner increases, at all temperatures. At higher percentages of toner, the stiffening effect is more significant.

It is also concluded that the toner-modified asphalt needs to be agitated before mixing with aggregates, since it does not have sufficient storage stability. A blending time of 60–90 minutes was found to be adequate to achieve a homogeneous asphalt–toner mix.

It took more than a year to construct the test sections, during which time several observations were made. Since toner is composed of fine particles, it was determined that it is easier to handle toner in barrels rather than in boxes. The dusty composition of toner makes its handling throughout the mixing process difficult. The problem associated with handling the toner was especially clear in the Houston project since the toner was weighed separately in each batch. To facilitate mixing, it is useful to employ computerized mixing equipment. In every project, the toner-modified binder looked uniform after the mixing process. Also in each project, in order to prevent potential storage problems, the toner-modified binders were agitated before being mixed with aggregates in the mixing plant. In these cases, uniform and workable mixes were produced at the plant. In addition, no significant problems were observed throughout the compaction process.

About one year after the construction of the test sections was complete, post-construction pavement evaluations were conducted. Evaluations included visual pavement condition surveys, the collection of profiler data in each test section, and the collection of cores in each section for HWTD testing.

Overall, visual pavement condition surveys of the test sections demonstrated all distresses to be at low levels with no observable significant distress present. These conclusions from the visual pavement condition survey about rutting were supported by the profile data collected. The profile rut depths show that up to this point, there is little rutting present in the test sections. Of all the test sections, results have shown that toner sections have a higher resistance to rutting. Although toner modified sections have shown to have higher rutting resistance than control sections, the number of cracks is higher in toner-modified sections based on the data collected.

Finally, HWTD tests showed that the field cores collected from toner sections performed better than the cores collected from control sections. Only the toner-modified cores collected in Laredo showed lower performance, which is most probably owing to the high difference in air void content between the toner and control sections.

The finding of this implementation project supported the findings of the previous research study. Overall, it was concluded in Research Report 3933-1F, that waste toner can be used as an asphalt-binder modifier. The binder, modified with reasonable amounts of waste toner, is workable. The toner-modified binder improves the high-temperature properties as far as resistance to permanent deformation is concerned. The toner increases the low-temperature stiffness to some extent, and in that regard, is not favorable (7).

References

1. Kent, R. H., R. B. McGennis, B. Prowell, and A. Stonex. "Current and Future Use of Nonbituminous Components of Bituminous Paving Mixtures," A2D02: Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures Transportation in the New Millennium, TRB Publications.

2. Kelley, W. "Waste Toner: What to do?" ICRA ReNews International Cartridge Recycling Association, Haines City, Florida, 1993.

3. Button, J., W. D. Williams, and J. A. Sherocman. "Roofing Shingles and Toner in Asphalt Pavements," Research Report 1344-2F, Texas Department of Transportation, 1996.

4. Ayers, M. E., and R. Tripathi. "Incorporation of Xerox Waste Toner Material in Asphalt Cement and Asphalt Concrete," Research Report DHT-36, Texas Department of Transportation, 1994.

5. Diamond A. S. "Toner on the Turnpike." *R&R News Magazine*, May 1996.

6. Solaimanian, M., T. W. Kennedy, and K. Tripathi. "Performance Characteristics of Asphalt Binders and Mixtures Modified by Waste Toner," Transportation Research Record No. 1638, 1998.

7. Solaimanian, M., T. W. Kennedy, and R. B. McGennis. "Use of Waste Toner in Asphaltic Concrete," Research Report 3933-1F, Texas Department of Transportation, 1997.

8. Yildirim, Y., M. Solaimanian, and T. W. Kennedy. "Mixing and Compaction Temperatures for Superpave Mixes," *Journal of the Association of Asphalt Paving Technologists*, 2000.

9. Yildirim, Y., and T. W. Kennedy. "Design of Toner Modification for the Houston Demonstration Project," Center for Transportation Research, September 2001.

10. Yildirim, Y., and T. W. Kennedy. "Design of Toner Modification for The Pharr Demonstration Project," Center for Transportation Research, June 2002.

11. Yildirim, Y., and T. W. Kennedy. "Design of Toner Modification for The Laredo Demonstration Project," Center for Transportation Research, June 2002.

12. Yildirim, Y., Hazlett, D., Davio R., *"Toner Modified Asphalt Demonstration Projects*," Resources, Conservation and Recycling, Elsevier Journals, June 2004.

Appendix A. Composition of Toners

Table A.1 Composition for the Toner Provided by Nashua

Ingredients	Percent (wt.)
Carbon Black	1-5
Styrene Butadiene Copolymer	75-85
Magnetite	15-20
Quaternary Ammonium Compound	<2

Table A.2 Composition for the Toner Provided by Ricoh

Ingredients	Percent (wt.)
Polyester Resin	70
Styrene Acrylic Polymer	15
Carbon Black	9
Wax	4
Dye	2

Table A.3 Composition for the Toner Provided by Lexmark

Ingredients	Percent (wt.)
Styrene Acrylic Polymer	80-90
Carbon Black	3-8
Iron Oxide	5-13

Appendix B. Mixture Design Information

Houston Project

Specimens were prepared with different percentages of asphalt content to determine the effect of asphalt content on density, VMA, and specific gravity of mixtures. Mixtures contained 4.0 percent, 4.5 percent, 5.0 percent, 5.5 percent, and 6.0 percent asphalt. Specific Gravity of Specimen (Ga), Maximum Specific Gravity (Gr), Effective Gravity (Ge), Theoretical Maximum Specific Gravity (Gt), Density (from Gt), and Voids in Mineral Aggregates (VMA) were determined for each mixture. Properties for mixtures are given in Table B.1. Asphalt content versus density and asphalt content versus VMA graphs are shown in the Figure B.1 and Figure B.2, respectively.

Table B.1 Summary of Mixture Properties with Different Asphalt Content

Asphalt Content	**Specific Specimen Gravity**	**Max. Specimen Gravity**	**Effective Gravity**	**Theoretical Max. Specific Gravity**	**Density**	**VMA**
percent	Ga	Gr	Ge	Gt	percent	percent
4.0	2.352	2.495	2.648	2.504	93.9	15.1
4.5	2.363	2.485	2.658	2.486	95.1	15.1
5.0	2.372	2.471	2.662	2.468	96.1	15.2
5.5	2.381	2.450	2.658	2.451	97.1	15.4
6.0	2.395	2.440	2.667	2.433	98.4	15.3

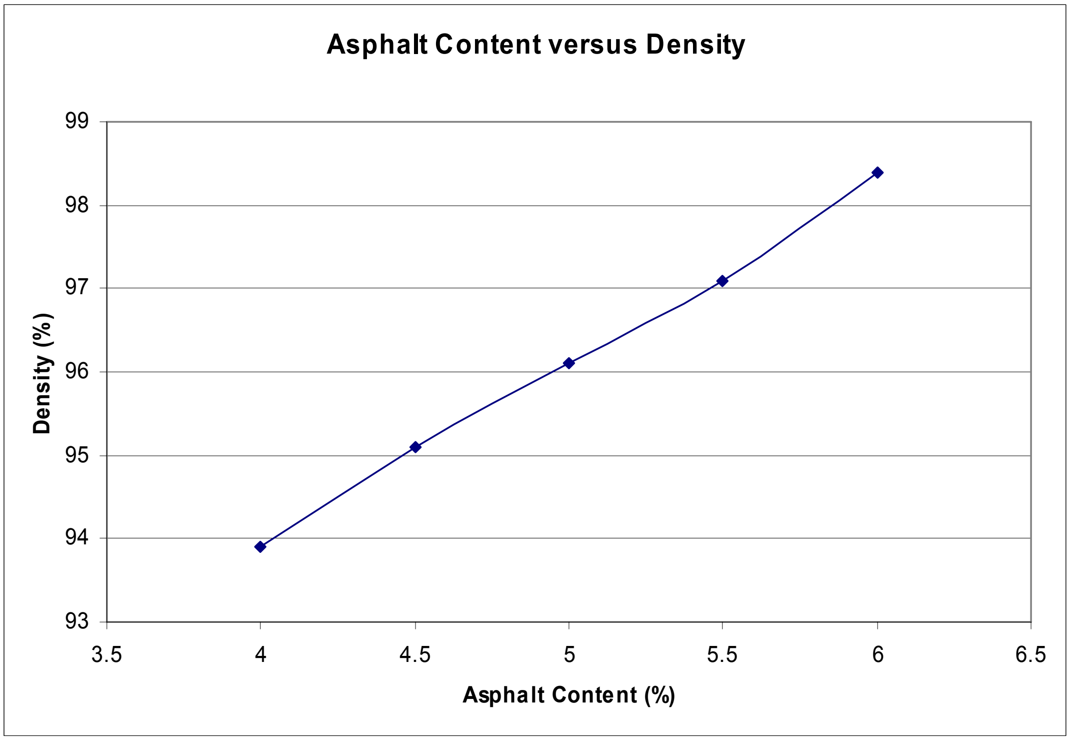


Figure B.1 Asphalt content vs. density

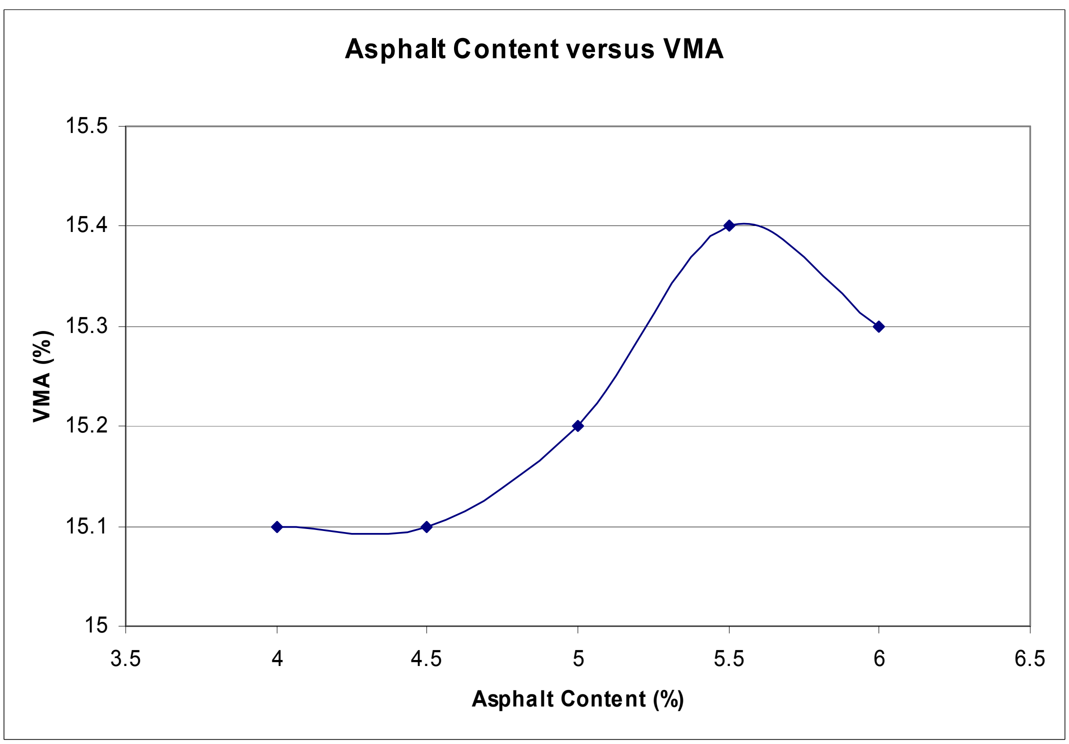


Figure B.2 Asphalt content vs. VMA (percent)

Pharr Project

Type D mixture design was used with different percentages of asphalt to determine the effect of asphalt content on density and VMA properties of a mixture. The mixture contained 3.5 percent, 4.5 percent, 5.5 percent, 6.5 percent, and 7.5 percent asphalt. Specific Gravity of Specimen (Ga), Maximum Specific Gravity (Gr), Effective Gravity (Ge), Theoretical Maximum Specific Gravity (Gt), Density (from Gt), and Voids in Mineral Aggregates (VMA) were determined for each mixture. Properties for mixtures are given in Table B.2. Asphalt content versus density and asphalt content versus VMA graphs are shown in Figure B.3 and Figure B.4, respectively.

Table B.2 Summary of Mixture Properties with Different Asphalt Content

Asphalt Content	**Specific Specimen Gravity**	**Max. Specimen Gravity**	**Effective Gravity**	**Theoretical Max. Specific Gravity**	**Density**	**VMA**
percent	Ga	Gr	Ge	Gt	percent	percent
3.5	2.254	2.494	2.629	2.496	90.3	17.3
4.5	2.292	2.469	2.642	2.460	93.2	16.8
5.5	2.331	2.425	2.631	2.425	96.1	16.3
6.5	2.350	2.385	2.623	2.391	98.3	16.5
7.5	2.336	2.356	2.629	2.358	99.1	17.9

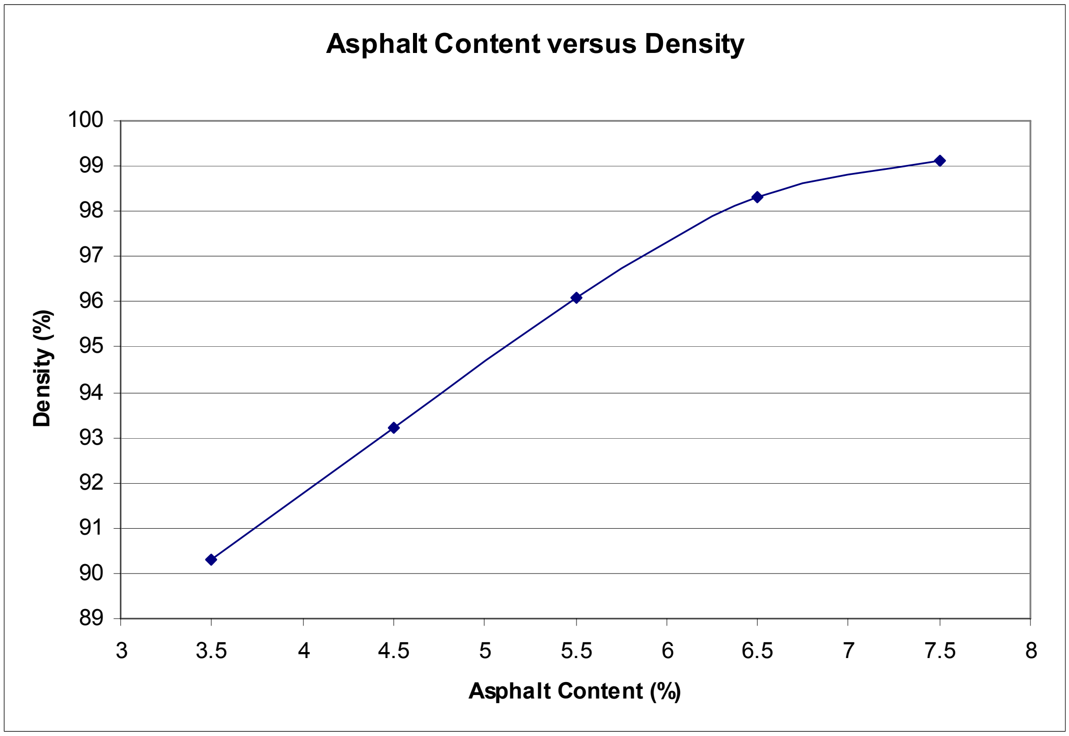


Figure B.3 Asphalt content vs. density

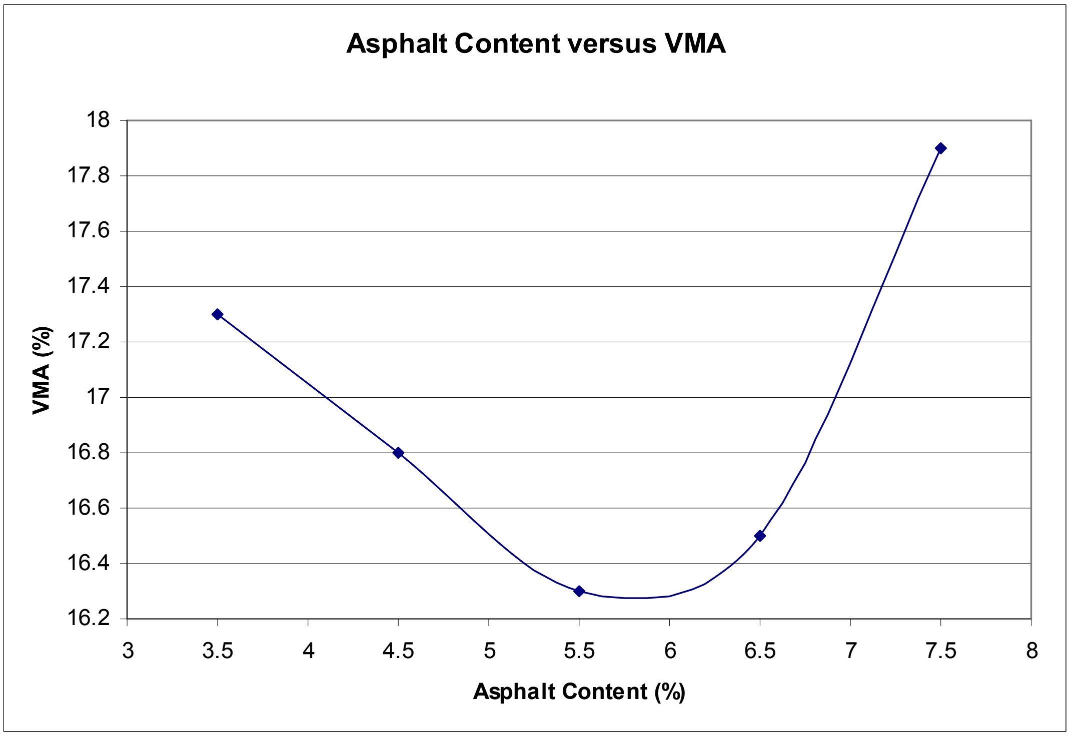


Figure B.4 Asphalt content vs. VMA (percent)

Laredo Project:

Type C mixture design was used with five different percentages of asphalt to determine the effect of asphalt content on other properties such as density, total air voids, specific gravities, and VMA of an HMA mixture. The mixture contained 3.5 percent, 4.0 percent, 4.5 percent, 5.0 percent, and 5.5 percent asphalt. Bulk Specific Gravity, Maximum Specific Gravity, Density, Unit Weight, Percent Air, Voids in Mineral Aggregates (VMA), and Percent Voids Filled were determined for each mixture. Properties for mixtures are given in Table B.3.

Table B.3 Summary of Mixture Properties with different Asphalt Contents

Asphalt Content	Bulk Sp. Gr.	Max. Specimen Gravity	Density	Unit Weight	Percent Air	Percent VMA	Percent Voids Filled
3.5	2.333	2.521	92.5	145.5	7.5	15.3	51.3
4.0	2.339	2.502	93.5	146.0	6.5	15.5	58.1
4.5	2.372	2.484	95.5	148.0	4.5	14.8	69.5
5.0	2.381	2.466	96.6	148.6	3.4	14.9	77.0
5.5	2.393	2.448	97.8	149.3	2.2	14.9	84.9

Graphs showing asphalt content versus density and asphalt content versus VMA were plotted. Optimum asphalt content was determined from optimum density. VMA and percent air at optimum asphalt content were also determined using the graphs. Graphs are shown in Figures B.5 and B.6.

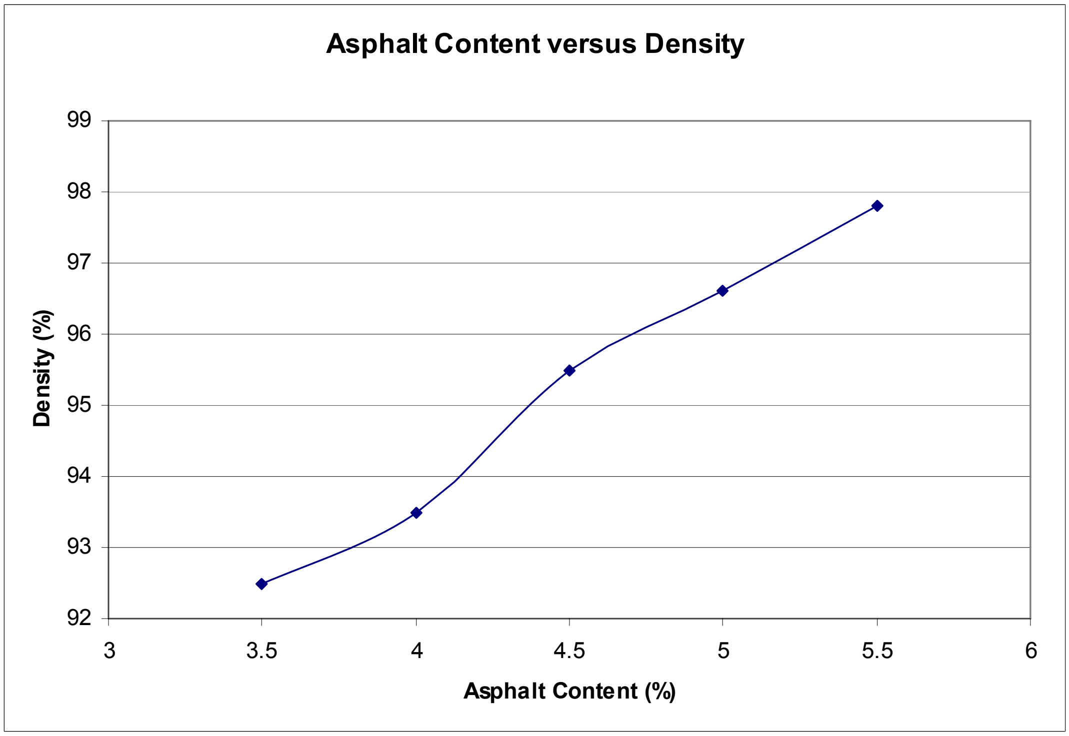


Figure B.5 Asphalt content vs. density

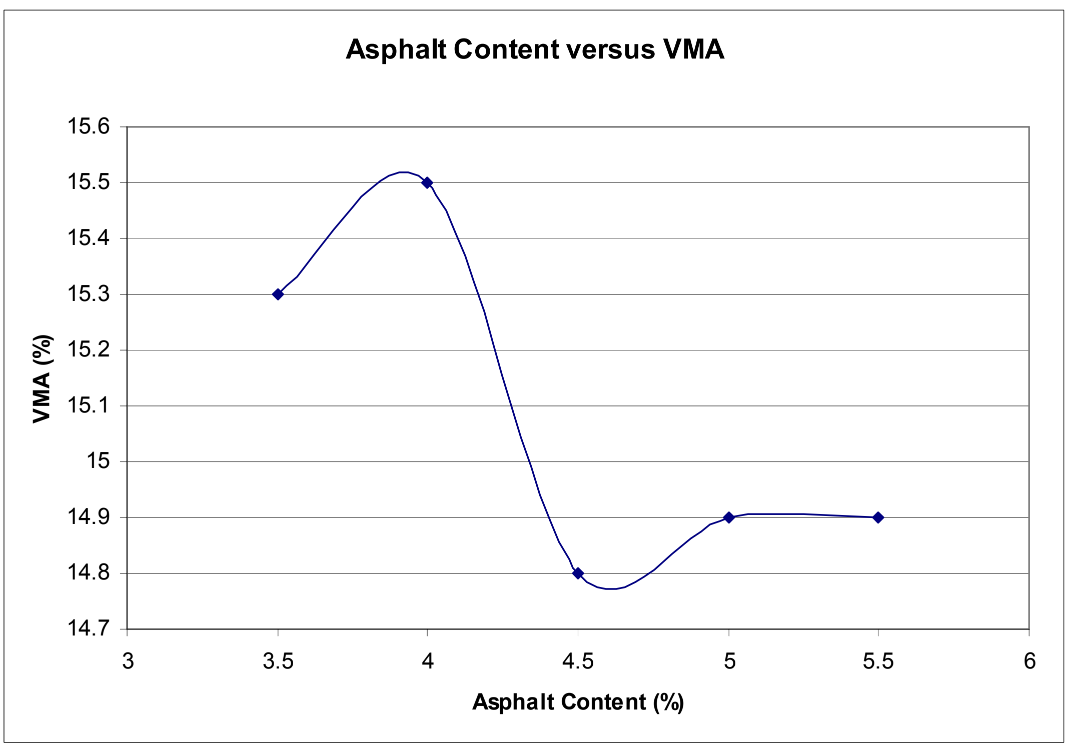


Figure B.6 Asphalt content vs. VMA

Bryan Project:

Specimens were prepared with varying percentages of asphalt content to determine the effect of asphalt content on density, Voids in Mineral Aggregates (VMA), and specific gravity of mixtures. Mixtures contained 3.5 percent, 4.0 percent, 4.5 percent, 5.0 percent, and 5.5 percent asphalt. Specific Gravity (Ga), Maximum Specific Gravity (Gr), Effective Gravity (Ge), Theoretical Maximum Specific Gravity (Gt), Density (from Gt), and Voids in Mineral Aggregates (VMA) were determined for each mixture. Properties for the mixtures are given in Table B.4. Asphalt content versus density and asphalt content versus VMA graphs are shown in Figure B.7 and Figure B.8, respectively.

Table B.4 Summary of Mixture Properties with Different Asphalt Content

Asphalt Content	Specific Specimen Gravity	Max. Specific Gravity	Effective Gravity	Theoretical Max. Specific Gravity	Density	VMA
percent	Ga	Gr	Ge	Gt	percent	Percent
3.50	2.306	2.447	2.577	2.456	93.9	14.0
4.00	2.327	2.431	2.578	2.438	95.4	13.6
4.50	2.333	2.425	2.592	2.421	96.4	13.9
5.00	2.331	2.409	2.593	2.404	97.0	14.4
5.50	2.325	2.393	2.595	2.387	97.4	15.1

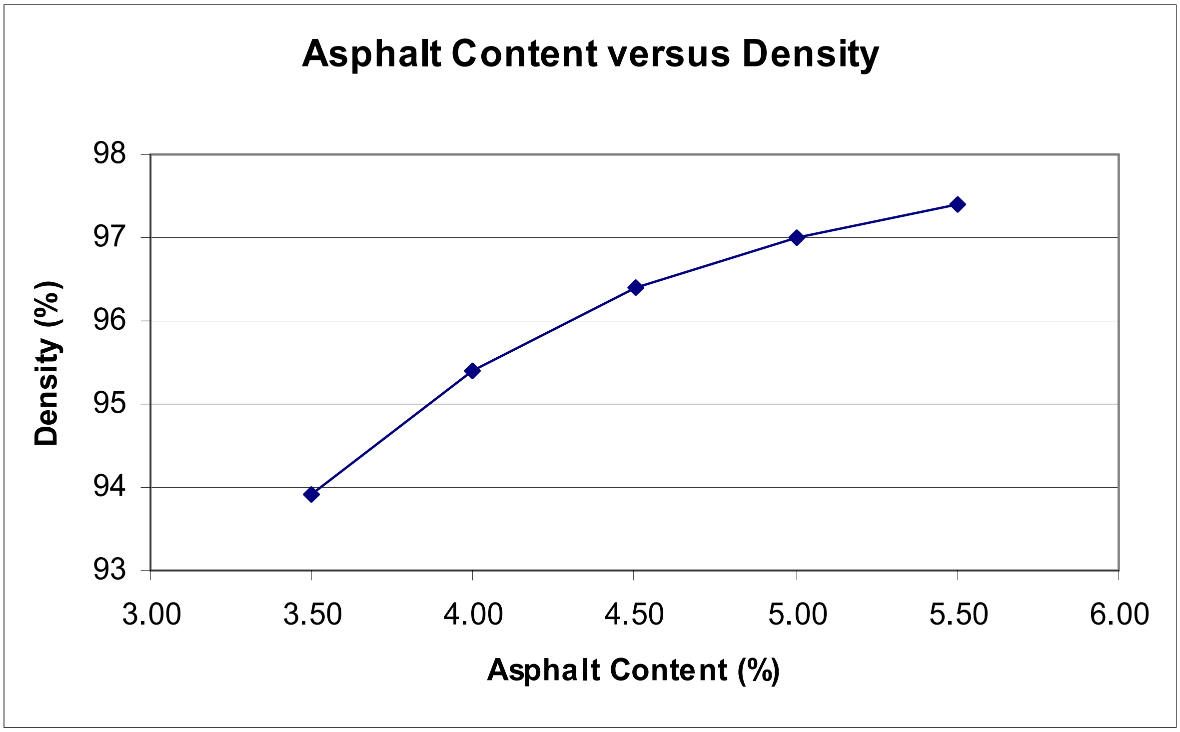


Figure B.7 Asphalt content vs. density

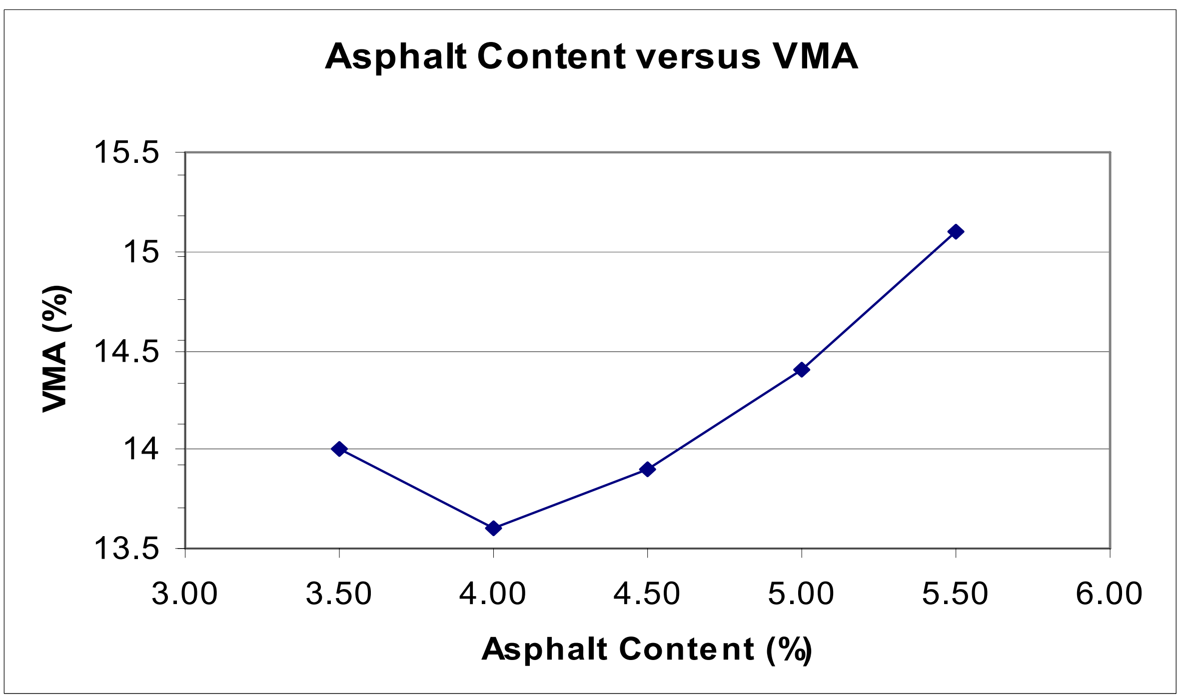


Figure B.8 Asphalt content vs. VMA (percent)

Appendix C. Binder Design Information

1. Binder Design for Houston Project

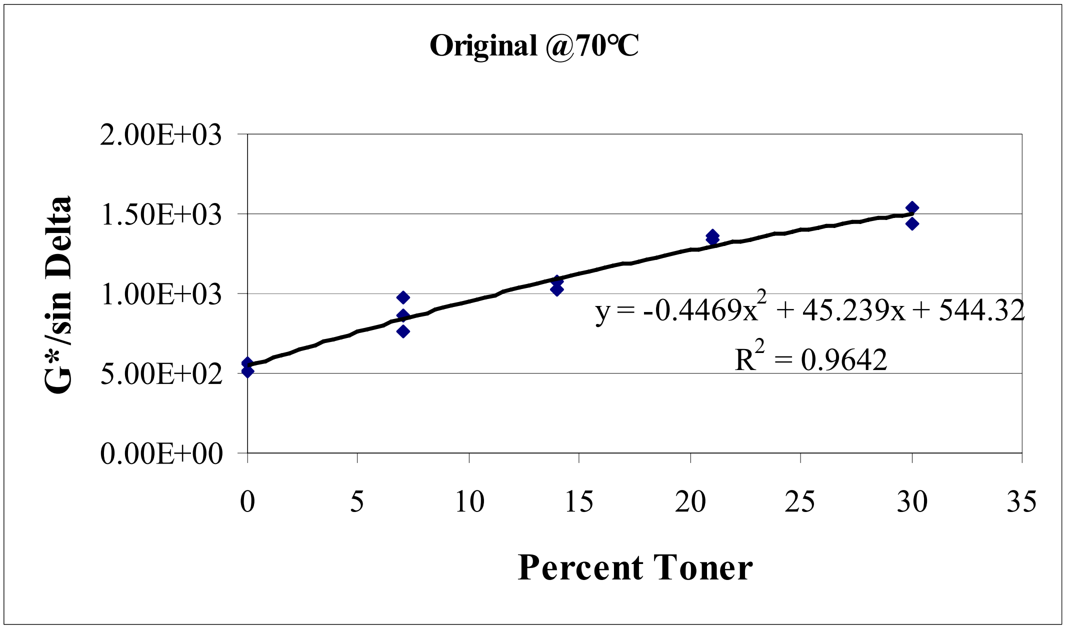


Figure C.1.i DSR Test results for the original binder at different toner levels

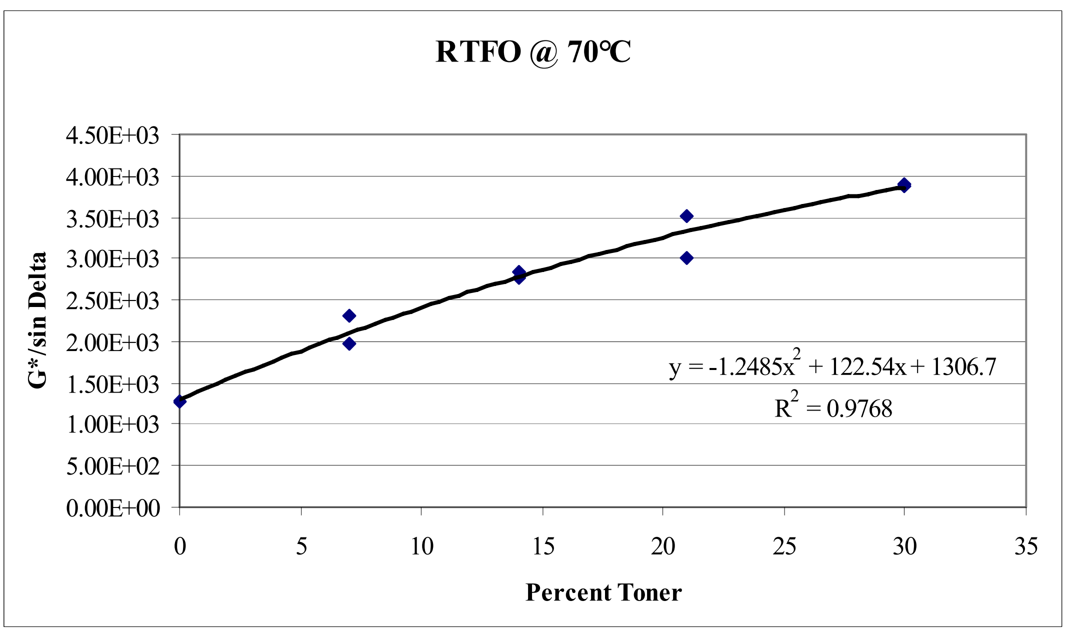


Figure C.1.ii DSR Test results for the RTFO-aged binder

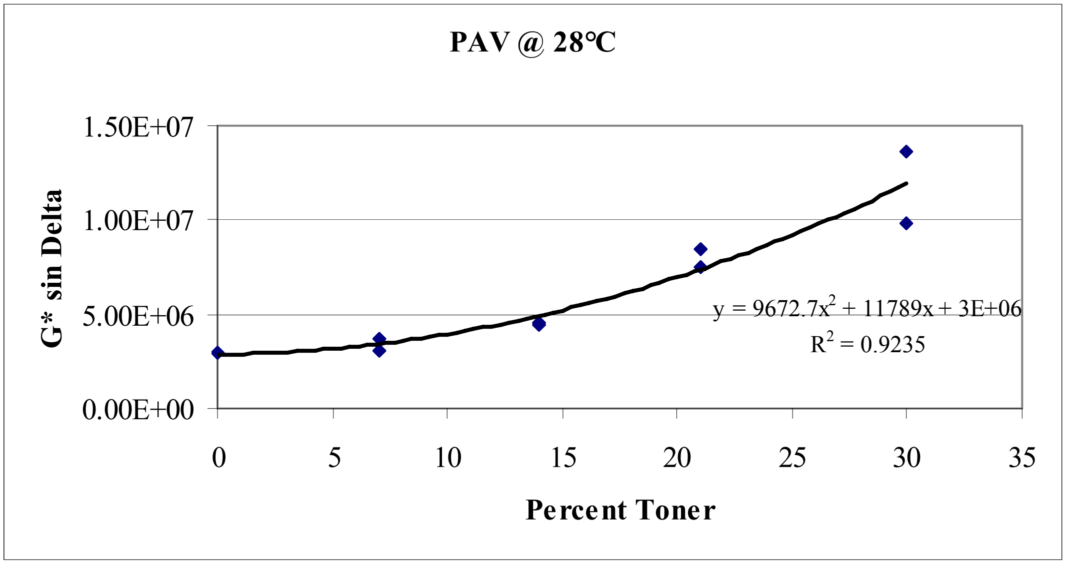


Figure C.1.iii DSR Test results for the PAV-aged binder

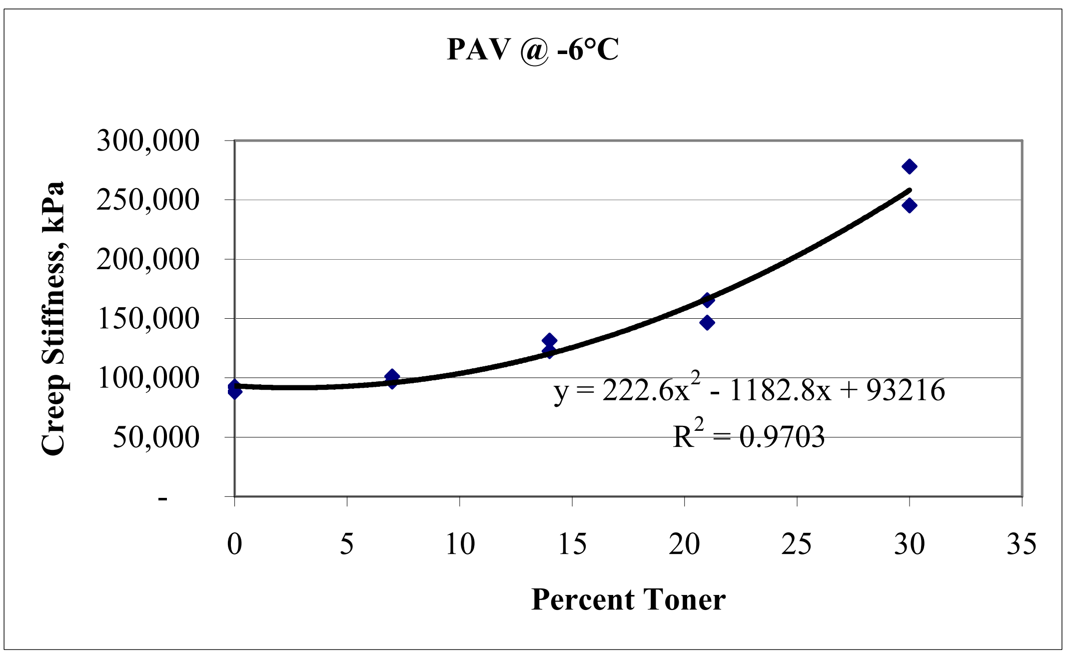


Figure C.1.iv Creep stiffness values from BBR

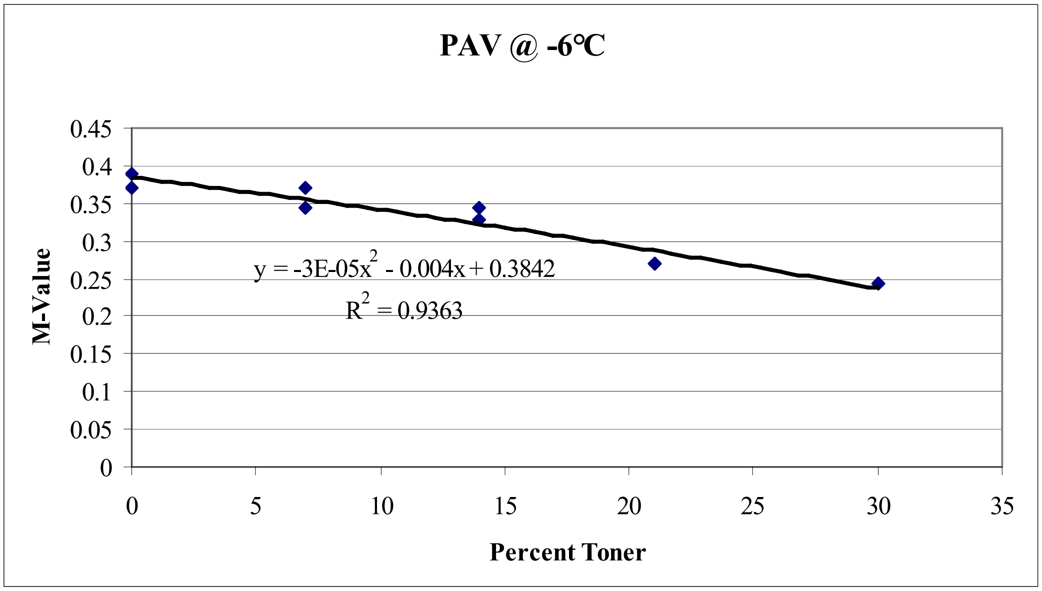
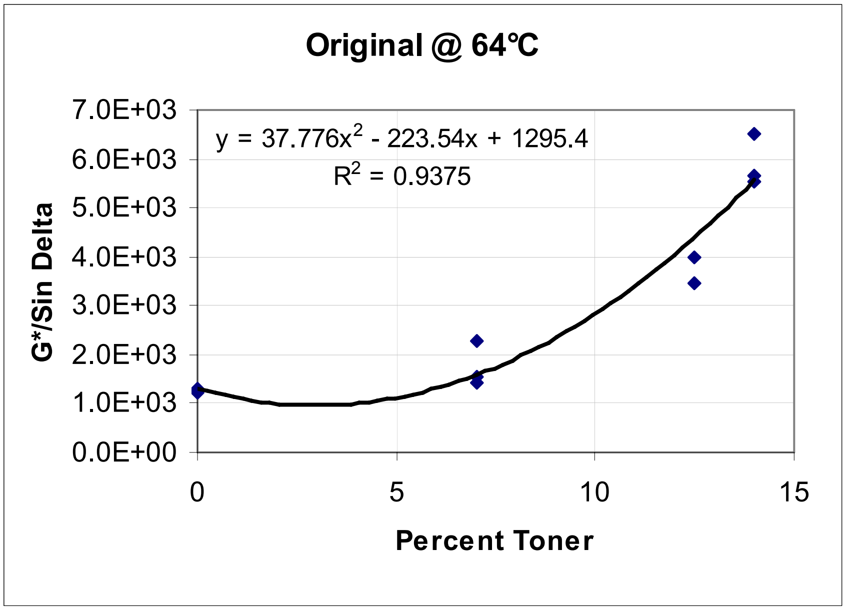


Figure C.1.v Logarithmic creep rate (m-value) values from BBR

2. Binder Design for Pharr Project



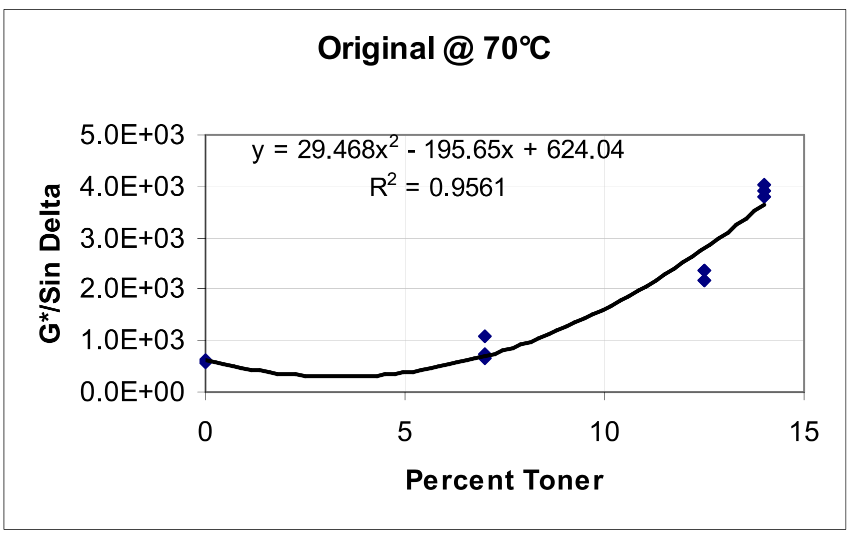
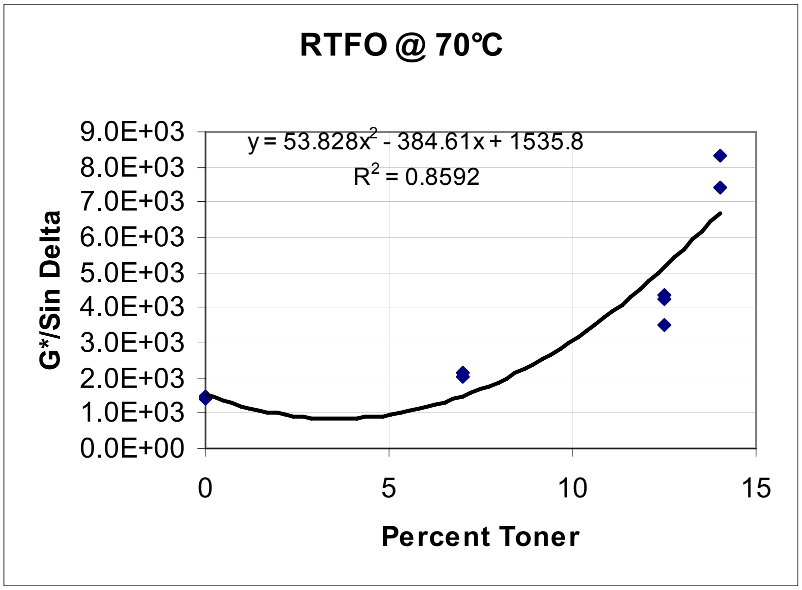


Figure C.2.i DSR Test results for the original binder at 64˚C and 70˚C



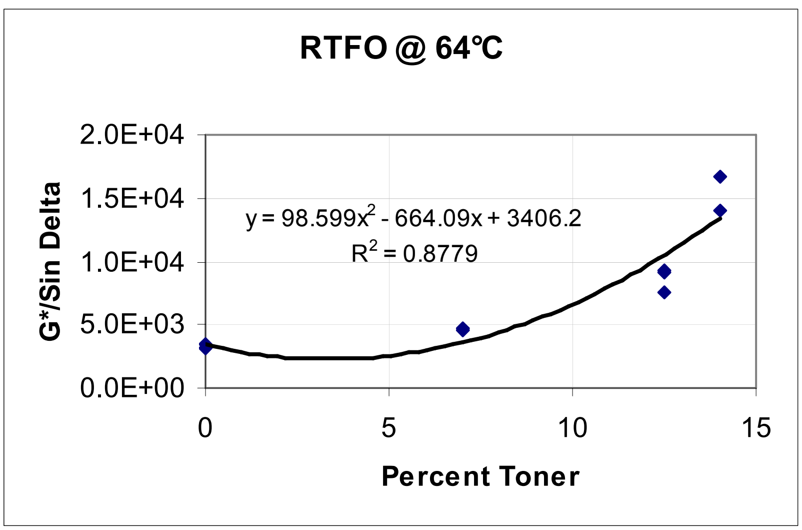
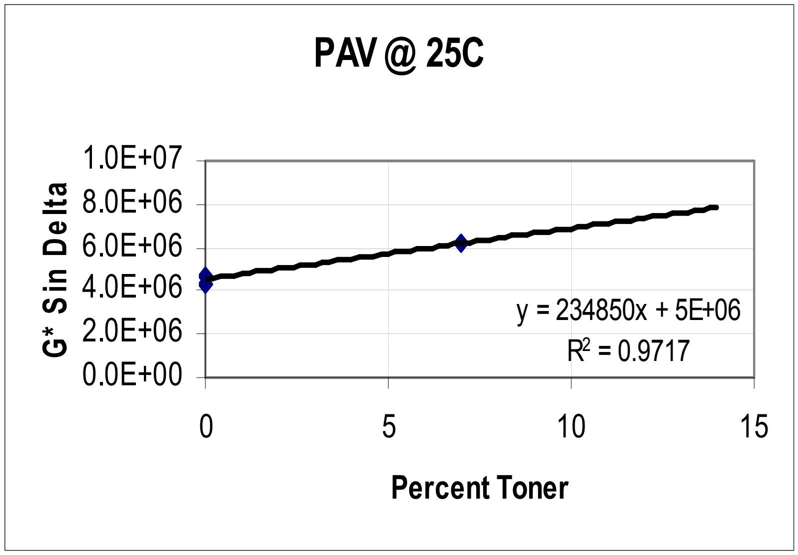


Figure C.2.ii DSR Test results for the RTFO-aged binder at 64° and 70°C



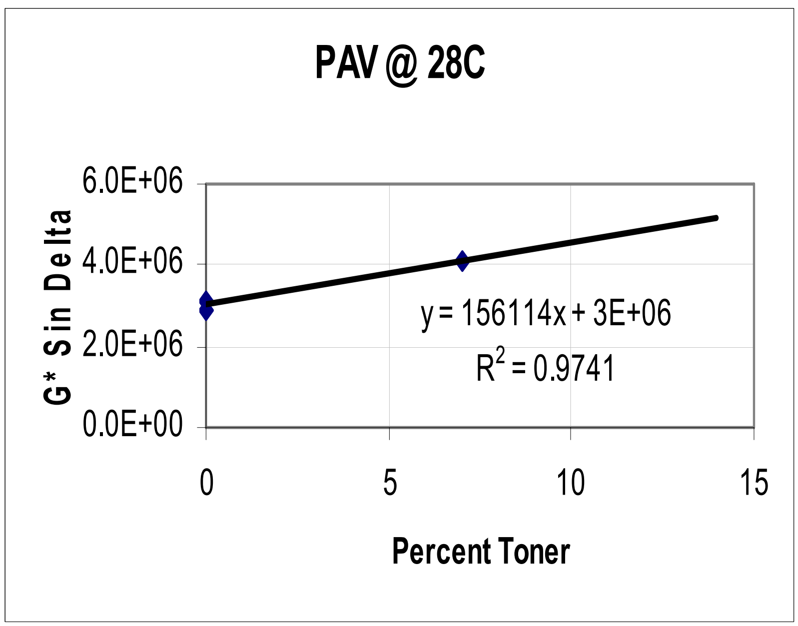


Figure C.2.iii DSR Test results for the PAV-aged binder

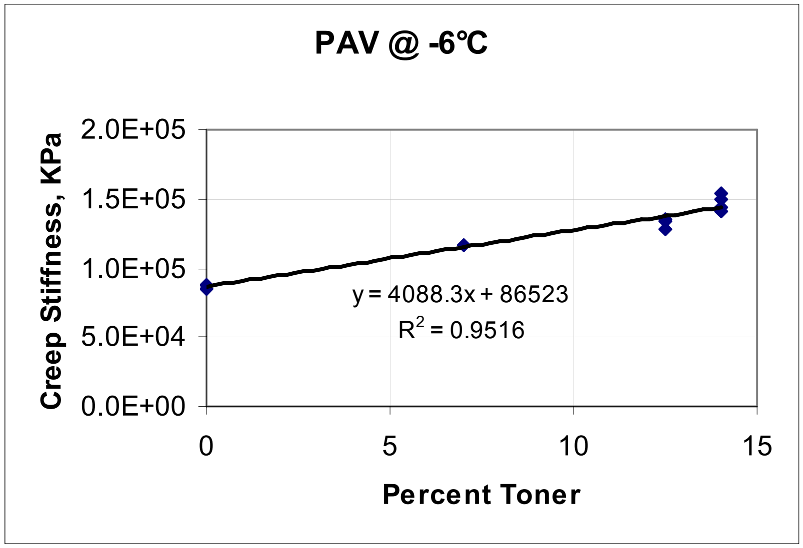


Figure C.2.iv Creep stiffness values from BBR

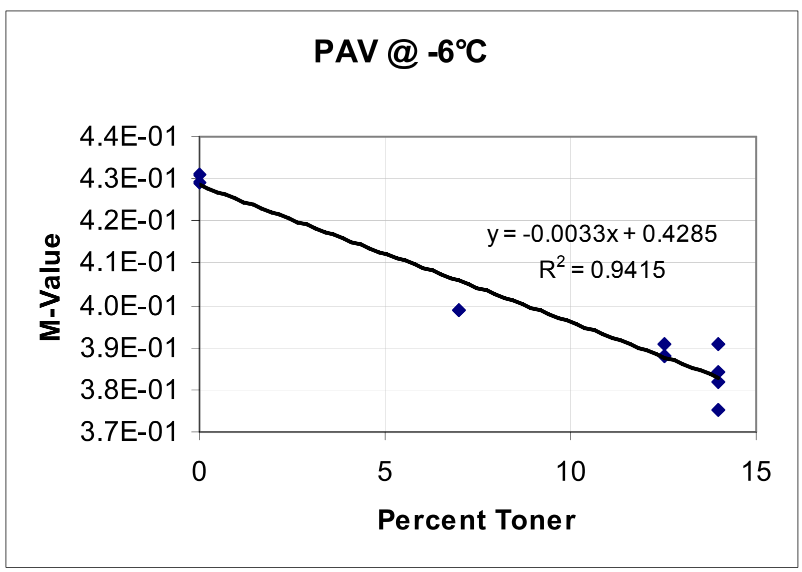


Figure C.2.v Logarithmic creep rate (m-value) values from BBR

3. Binder Design for Laredo Project

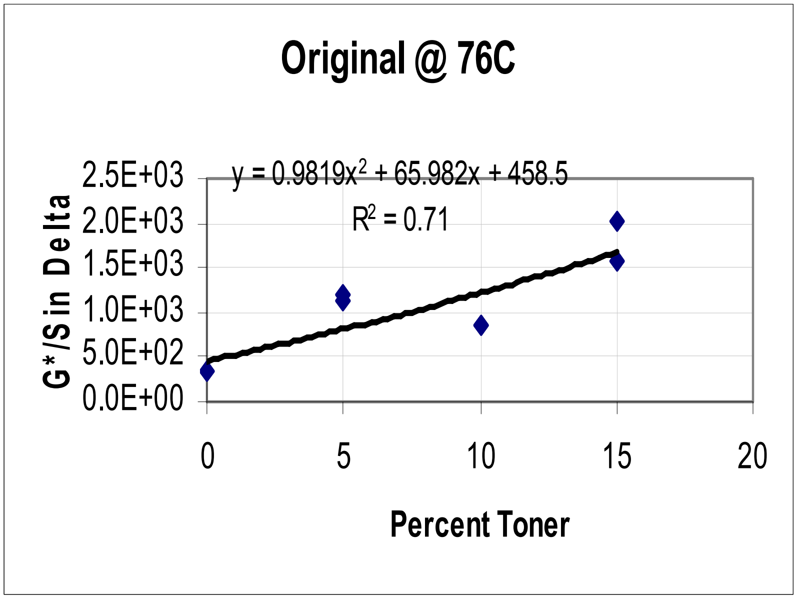


Figure C.3.i DSR Test results for the original binder modified

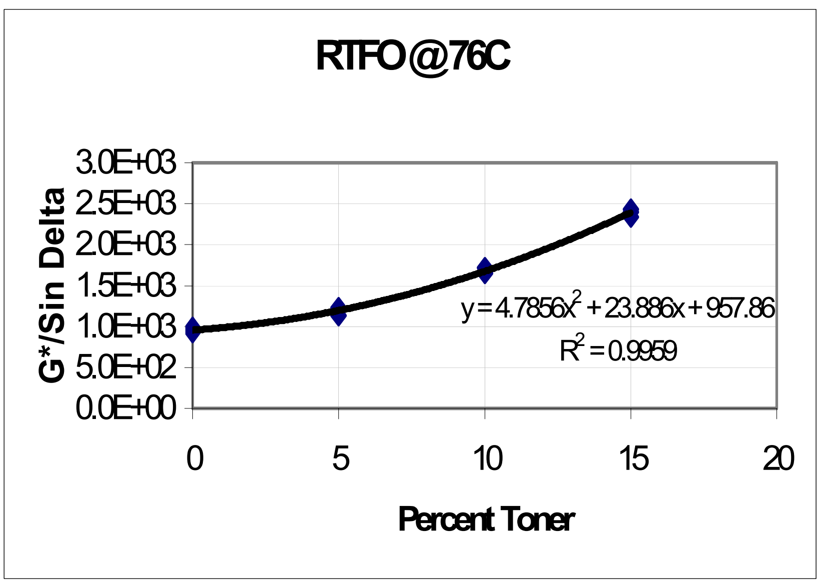


Figure C.3.ii DSR Test results for the RTFO-aged binder

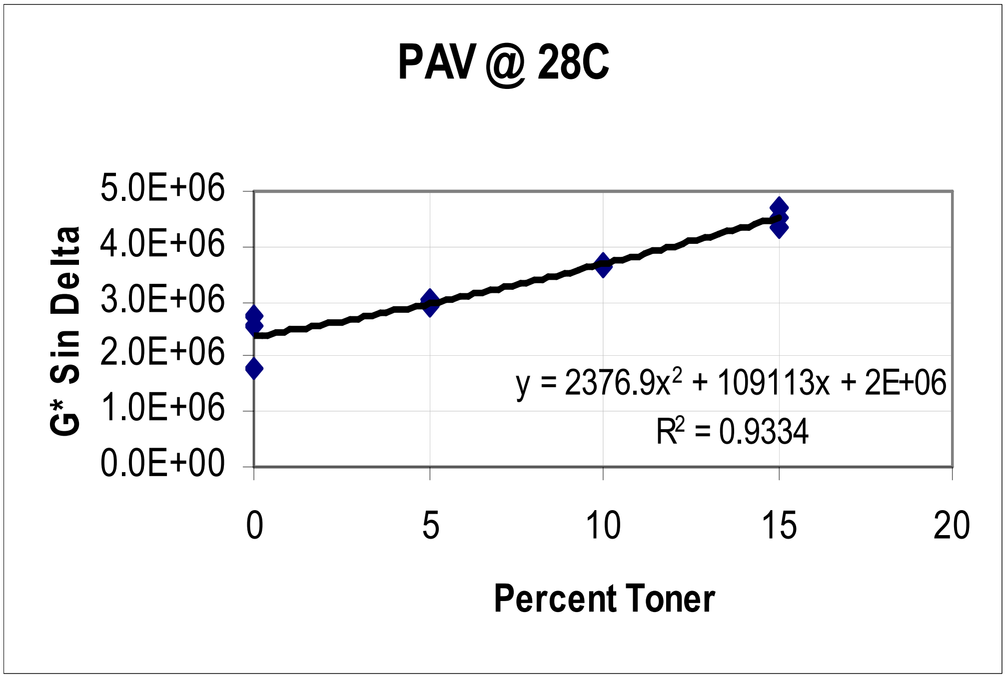


Figure C.3.iii DSR Test results for the PAV-aged binder modified

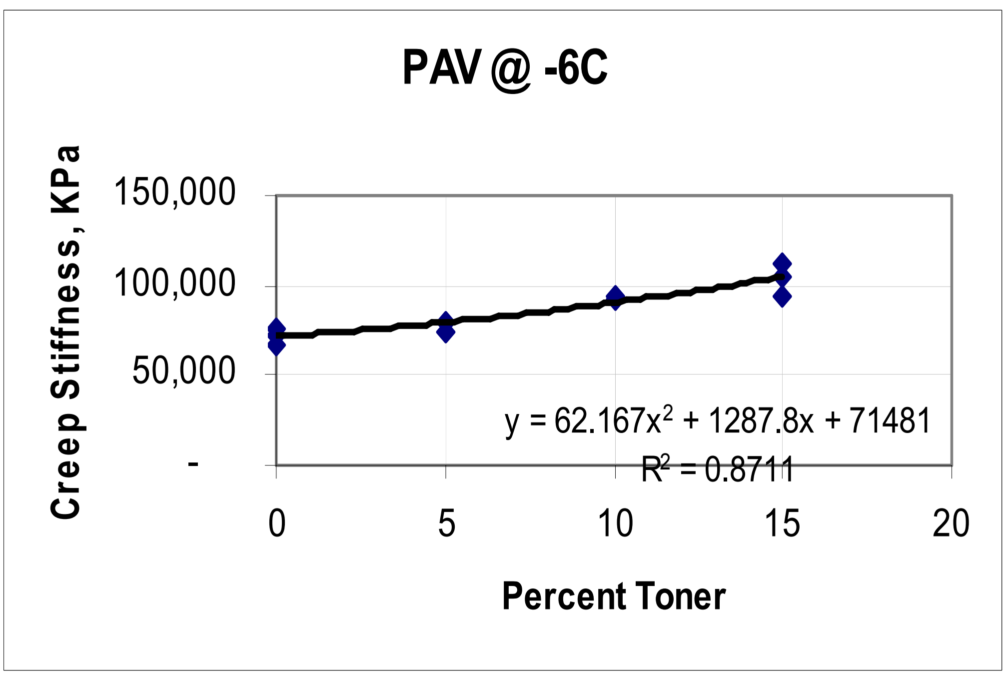


Figure C.3.iv Creep stiffness values from BBR

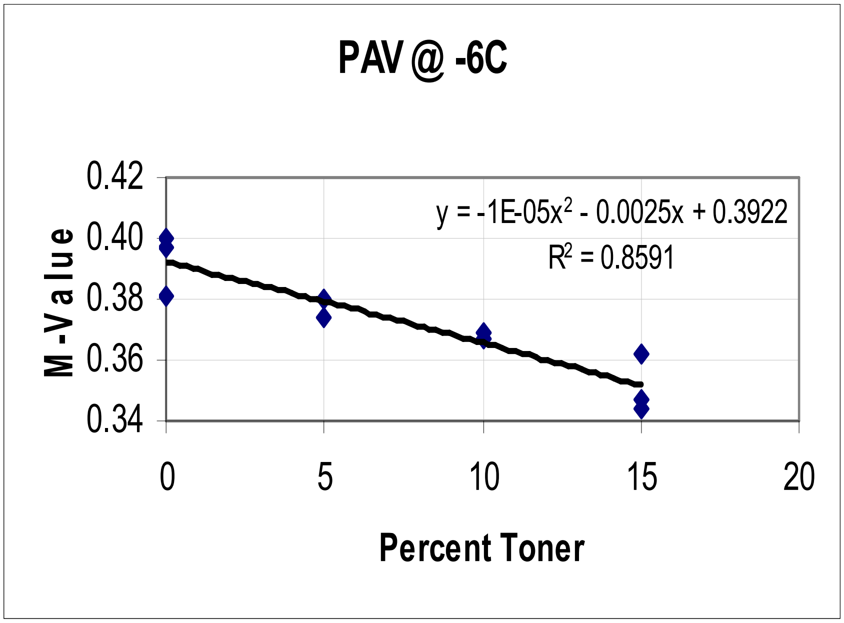


Figure C.3.v Logarithmic Creep rate (m-value) values from BBR

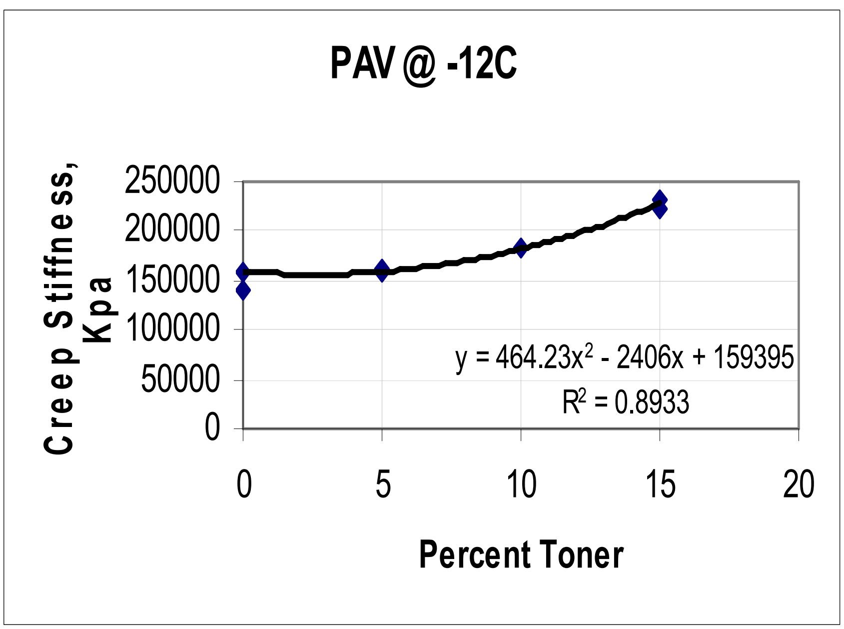


Figure C.3.vi Creep stiffness values from BBR (–12˚C)

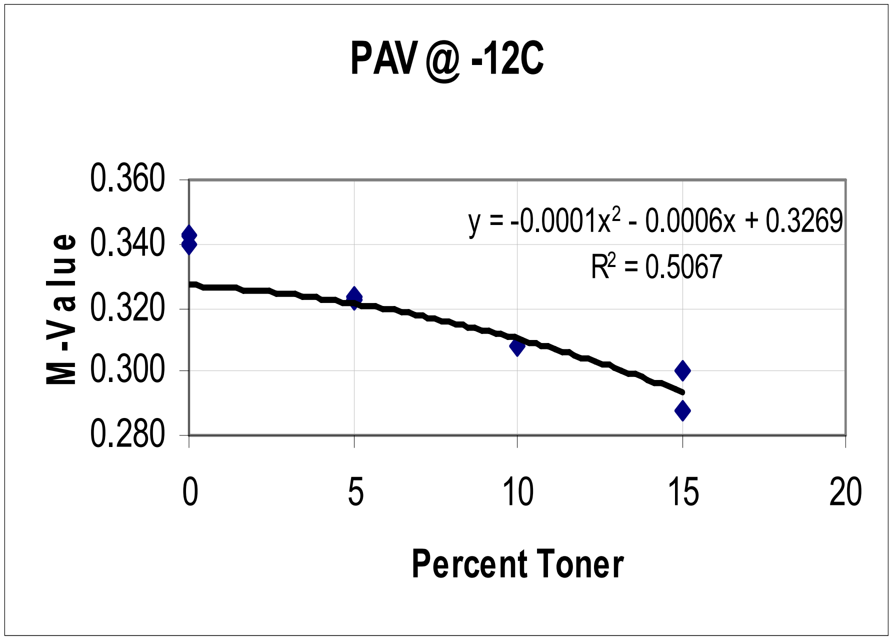
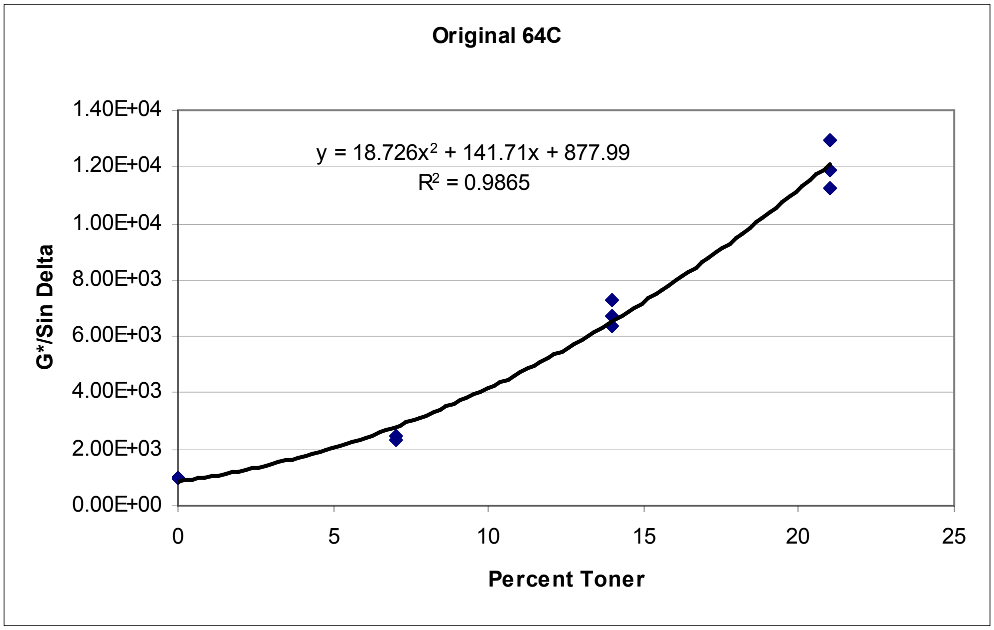


Figure C.3.vii Logarithmic creep rate (m-value) values from BBR (–12˚C)

4. Binder Design for Bryan Project



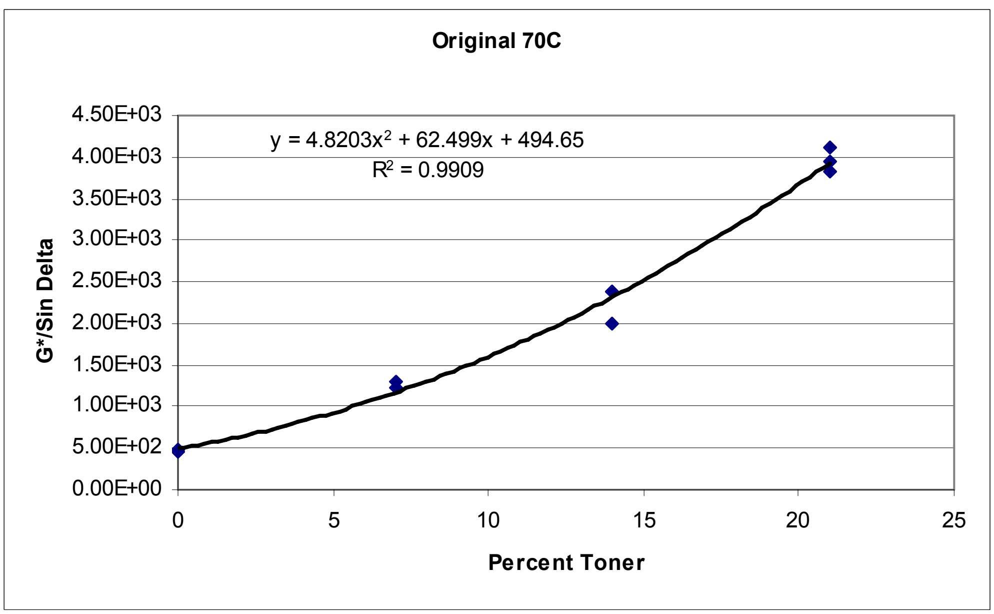


Figure C.4.i DSR Test Results for the original binder at 64° C and 70° C

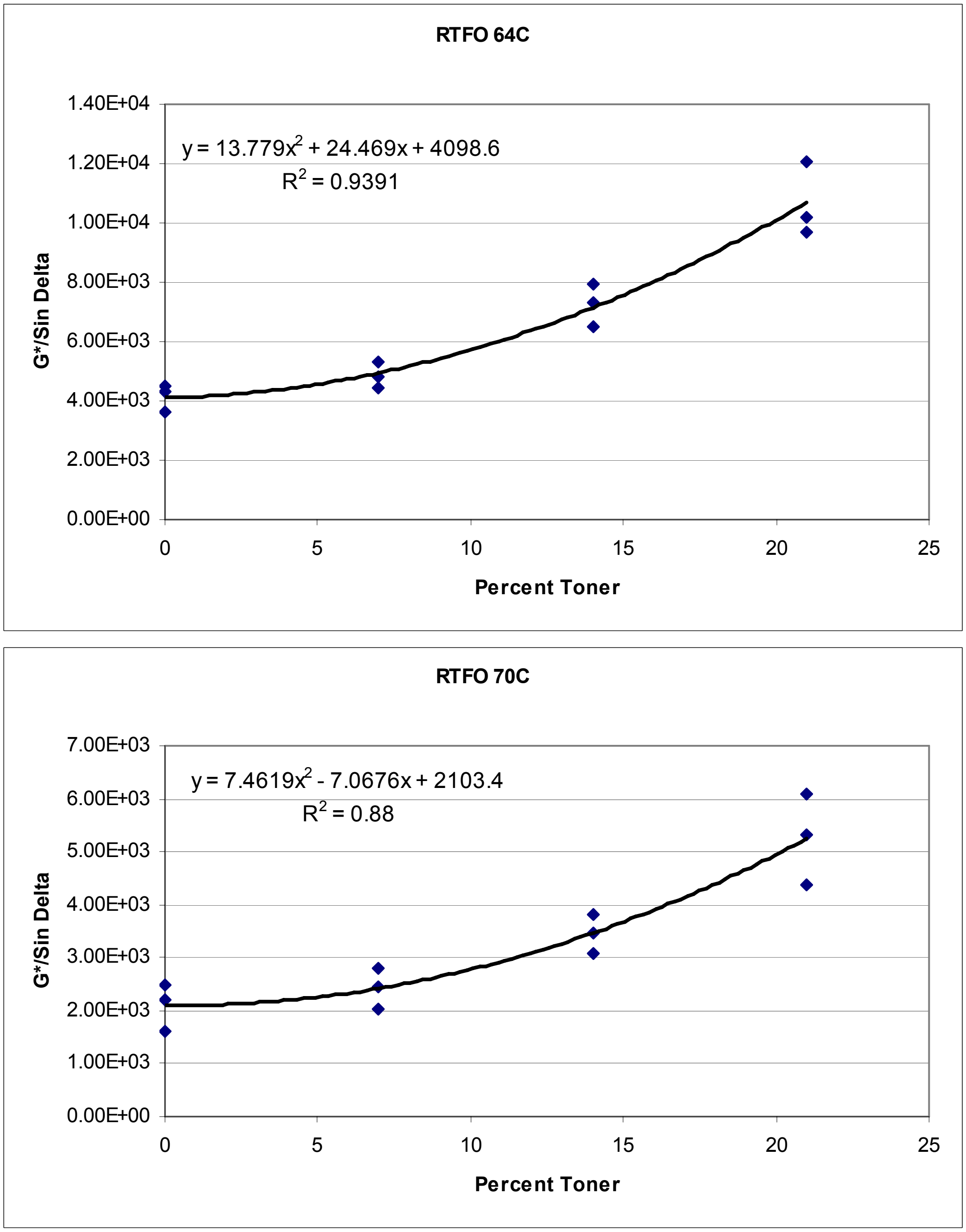
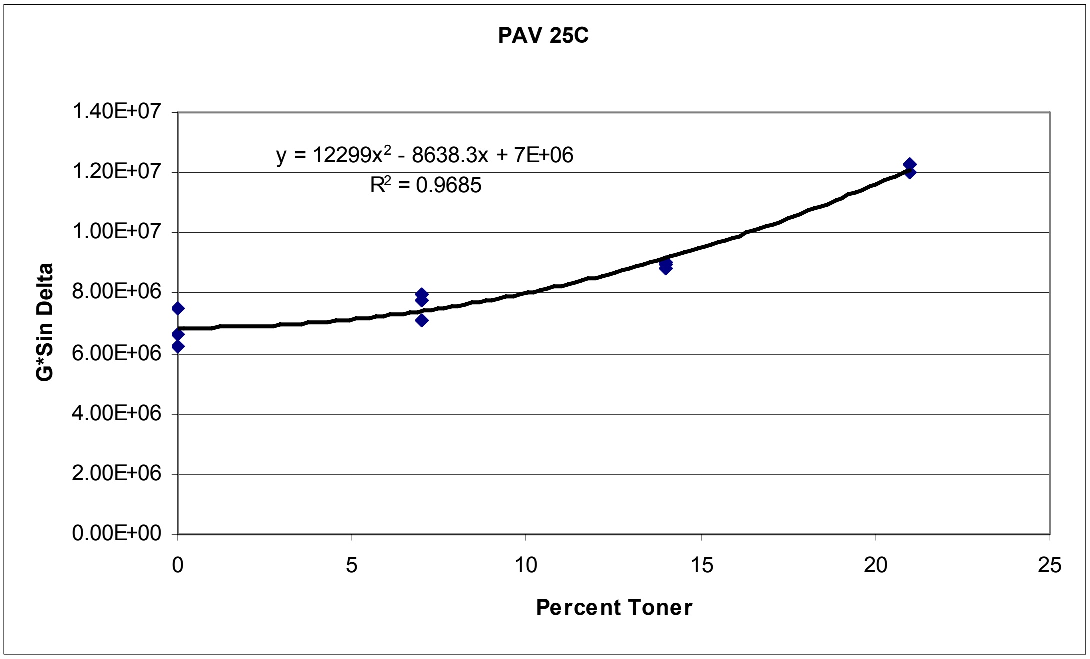


Figure C.4.ii DSR Test Results for the RTFO-aged binder at 64° C and 70° C



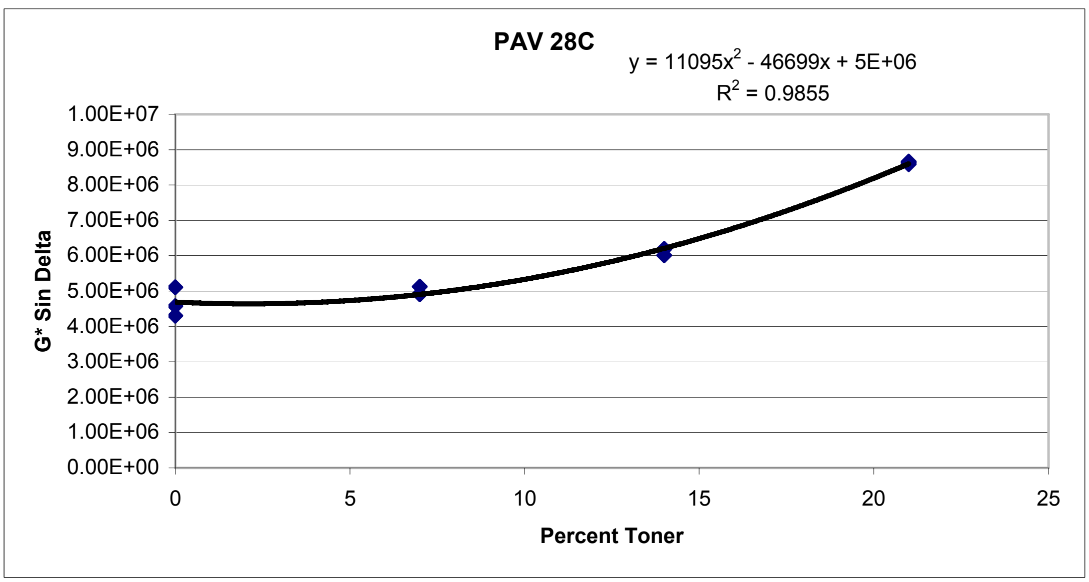


Figure C.4.iii DSR Test Results for the PAV-aged binder

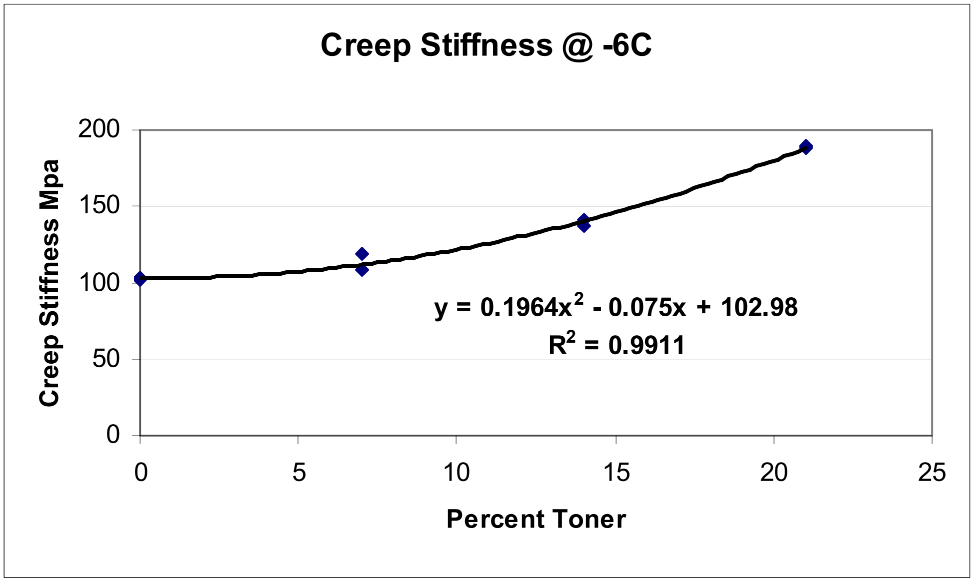


Figure C.4.iv Creep Stiffness values from BBR

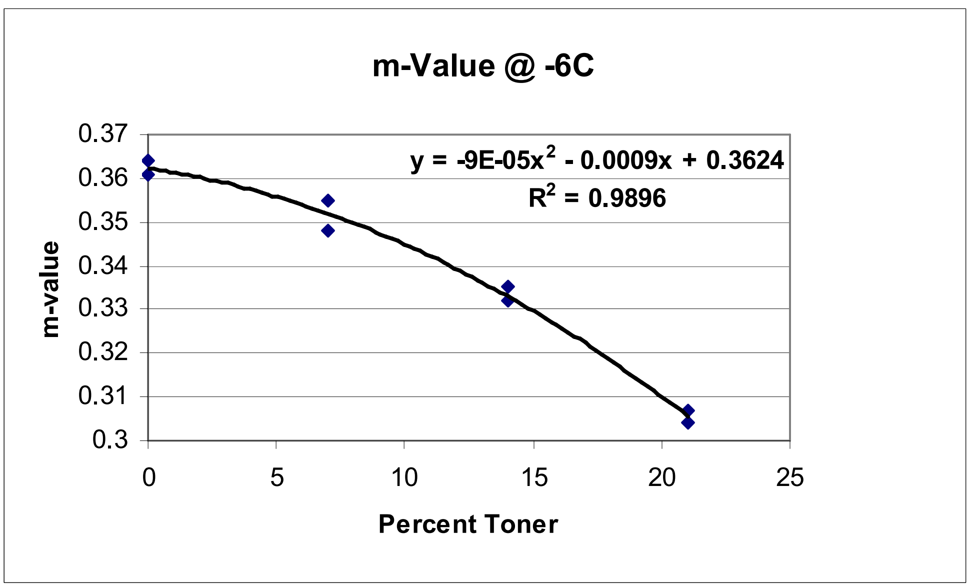


Figure C.4.v Logarithmic Creep Rate (m-value) values from BBR

Appendix D. Post-Construction Pavement Evaluation

Figure D.1 Bryan Test Section Overview

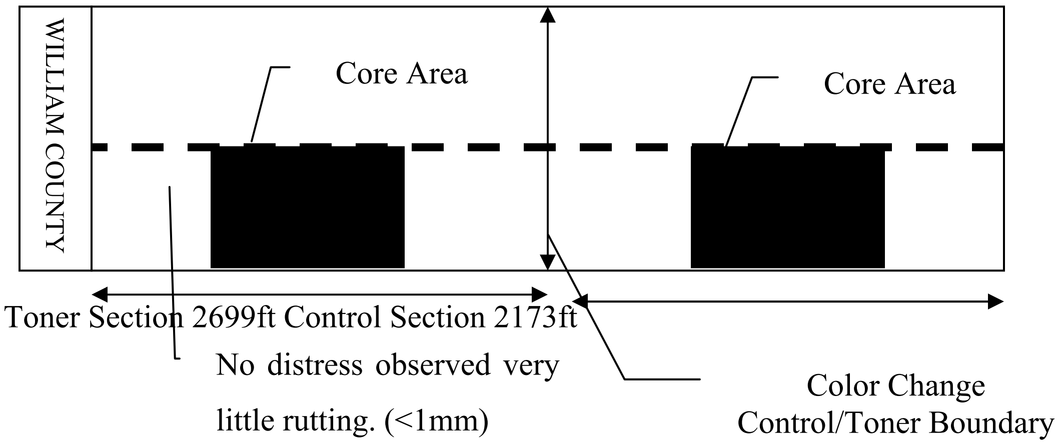


Figure D.2 Pharr Test Section Overview

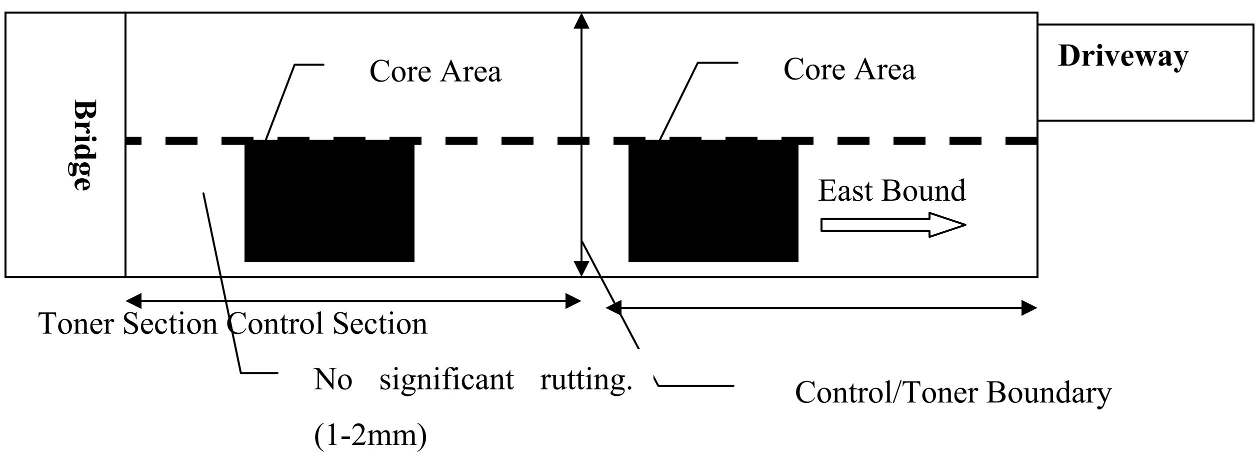


Figure D.3 Laredo Test Section Overview

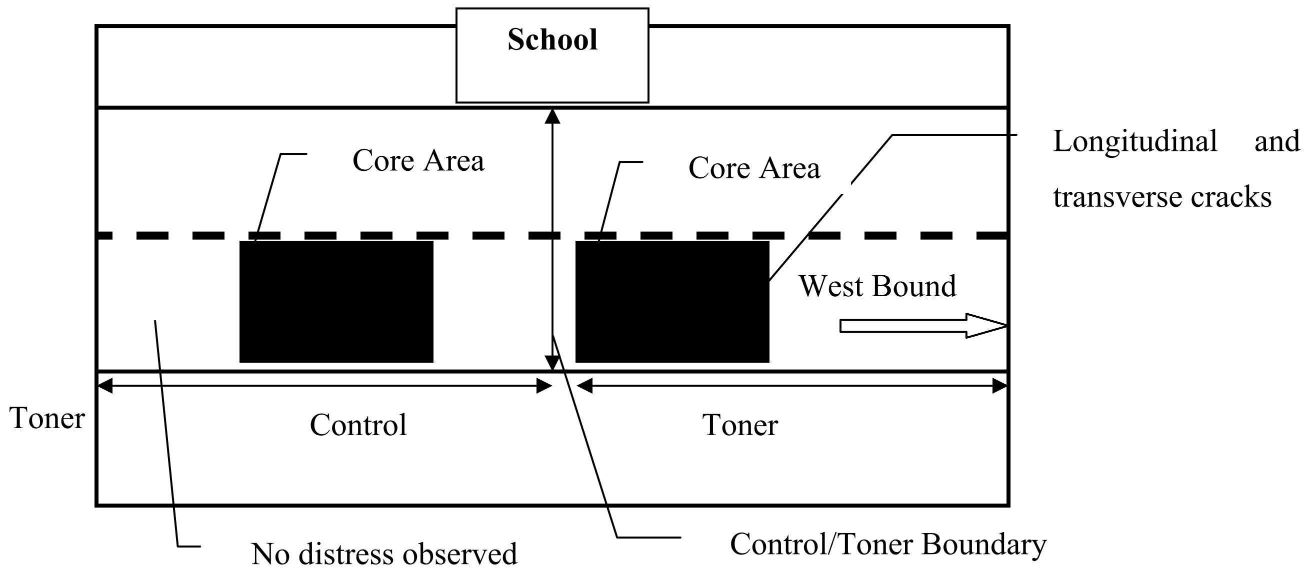


Figure D.4 Houston Test Section Overview

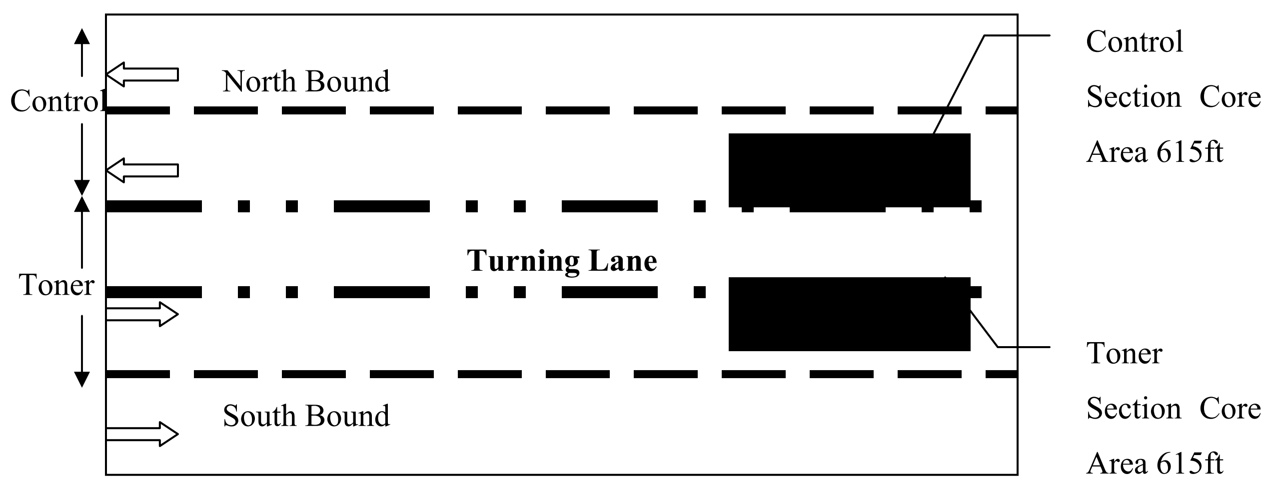


Table D.1 Pharr Visual Survey of Control Test Section

TYPE	SEALED	LENGTH (ft)	SEVERITY LEVEL
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	NO	NA	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	4FT	Low
TRN	YES	LANE WTH	Low
TRN	NO	NA	Low
TRN	NO	NA	Low
TRN	NO	NA	Low
TRN	NO	NA	Low
TRN	NO	NA	Low
TRN	YES	3FT	Low

Table D.2 Pharr Visual Survey of Toner Test Section

TYPE	SEALED	LENGTH (ft)	SEVERITY LEVEL
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	3FT	Low
TRN	YES	3FT	Low
TRN	YES	6FT	Low
TRN	YES	3FT	Low
TRN	YES	10FT	Low
TRN	YES	3FT	Low
TRN	NO	NA	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	8FT	Low
TRN	YES	LANE WTH	Low
TRN	YES	6FT	Low
TRN	YES	LANE WTH	Low
TRN	NO	NA	Low
TRN	YES	6FT	Low
TRN	YES	8FT	Low
TRN	YES	8FT	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	LANE WTH	Low
TRN	YES	8FT	Low

Table D.3 Laredo Visual Survey of Toner Test Section

TYPE	SEALED	LENGTH (ft)	SEVERITY LEVEL
LONG	NO	19	Low
LONG	NO	3	Low
LONG	NO	38	Low
TRN	NO	LANE WTH	Low
LONG	NO	32	Low
TRN	NO	LANE WTH	Low

Table D.4 Houston Visual Survey of Control Test Section

TYPE	SEALED	LENGTH (ft)	SEVERITY LEVEL
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low

Table D.5 Houston Visual Survey of Toner Test Section

TYPE	SEALED	LENGTH (ft)	SEVERITY LEVEL
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low
TRN	NO	LANE WTH	Low

Appendix E. Profiler Data from the Test Sections

Table E.1 Rut Depth Calculations

Location	Section	Rut	A		B (deepest point)		C		Rut Depth
			x	y	x	y	x	y	(mm)
Houston	D.S. 2	Outside	101.5	2	1235.1	21.93	2071	40.3	**2.11**
		Inside	1986.9	38.5	3105	60.4	3217.4	65.5	**2.63**
	D.S. 1	Outside	782.8	16.5	1130.6	22.4	1737.1	35.5	**1.02**
		Inside	1737.1	35.5	2261.1	44.2	3087	64	**2.36**
Laredo	Control	Outside	115.2	1.5	1356.2	12.8	2181.2	24.3	**2.40**
		Inside	2181.2	24.3	2939.5	37.9	3320.8	47.8	**2.04**
	Toner	Outside	256	0.1	824.5	9.2	1491.5	24.6	**2.17**
		Inside	1596.8	26.7	2441	43.2	2828	52.9	**1.46**
Pharr	Control	Outside	1206.9	-0.4	1641.1	-0.6	2000.8	1.6	**1.29**
		Inside	2110.2	1.9	2922.6	2.6	3443.6	7.1	**2.47**
	Toner	Outside	1096.7	6.2	1983.8	7	2501.1	9.3	**1.16**
		Inside	2501.1	9.3	3165.7	10.7	3663.6	15.3	**2.03**
Bryan	Control	Outside	709.2	13.1	1235.4	21.7	2156.2	41.7	**1.88**
		Inside	2335	45.1	2607.6	49.2	3105.3	60.2	**1.97**
	Toner	Outside	784	16.4	1131.8	20.9	1918.2	37.2	**1.80**
		Inside	1918.2	37.2	2417	45.6	2914.1	57.9	**1.24**

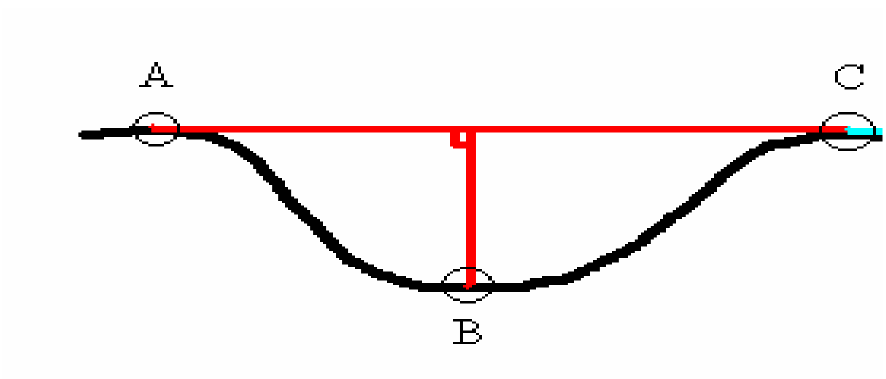


Figure E.1 Rut Depth Profile

Appendix F. Air Void Contents for the Field Cores

Figure F.1 Air Void Content of Tested Specimen

Location	*Section*	*Sample*	**Air Voids (percent)**
Pharr	**Control**	**1st**	8.4
		2nd	9.8
	Toner	**1st**	9.1
		2nd	8.2
Laredo	**Control**	**1st**	7.3
		2nd	8.6
	Toner	**1st**	10.4
		2nd	10.4
Houston	**Control**	**1st**	9.7
		2nd	9.1
	Toner	**1st**	7.2
		2nd	7.3
Bryan	**Control**	**1st**	9.2
		2nd	9.4
	Toner	**1st**	8.6
		2nd	8.9