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16. Abstract

Every year a big 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 utilizing 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 will transfer 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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Binder Designs for the Toner-Modified Asphalt Demonstration Projects

Yetkin Yildirim
Thomas W. Kennedy

Research Report 3933-01-IMP-1

Implementation Project 5-3933
Toner-Modified Asphalt

Conducted for the
Texas Department of Transportation
in cooperation with
U.S. Department of Transportation
Federal Highway Administration
by the
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Bureau of Engineering Research
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Preface

This is the first report from the Center for Transportation Research on Project 3933. It presents the toner-modified binder designs for Houston, Laredo, and Pharr projects and observations during the construction of the test sections for the first year of a 3-year study.

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 into 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 will transfer 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.

Disclaimers

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Table of Contents

Chapter 1. Introduction 1
BACKGROUND 2
IMPLEMENTATION 5
OBJECTIVES 5
Availability of Waste Toner 6
Findings 6
Chapter 2. Experimental Program 7
BINDER DESIGNS 7
MATERIALS 8
MIXTURE DESIGNS 9
Mixture Design for Houston Project 9
Mixture Design for Pharr Project 11
Mixture Design for Laredo Project 13
Chapter 3. Binder Designs 15
BINDER DESIGN FOR HOUSTON PROJECT 15
Effective Reaction Conditions 15
Design Toner-Modification Level 16
Mixing and Compaction Temperatures 18
Storage Stability 20
BINDER DESIGN FOR PHARR PROJECT 21
Effective Reaction Conditions 21
Design Toner Modification Level 22
Mixing and Compaction Temperatures 24
Storage Stability 25
BINDER DESIGN FOR LAREDO PROJECT 25
Effective Reaction Conditions 26
Design Toner-Modification Level 27
Mixing and Compaction Temperatures 29
Storage Stability 30
Chapter 4. The Hamburg Wheel Tracking Device Results 33
Chapter 5. Conclusions 39
References 41
Appendix A. Mixture Design Information 43
Appendix B. Binder Design Information 55
1. BINDER DESIGN FOR HOUSTON PROJECT 57
2. BINDER DESIGN FOR PHARR PROJECT 60
3. BINDER DESIGN FOR LAREDO 64

List of Tables

Table 2.1 Asphalt and Toner Information for the Test Sections....8
Table 2.2 Gradation of the Aggregates Used in the Houston Project....9
Table 2.3 TxDOT Specifications for Percentage Passing from Each Sieve Size....10
Table 2.4 Aggregate Material Properties....10
Table 2.5 Design Information....11
Table 2.6 Gradation of the Aggregates Used in The Pharr Project....11
Table 2.7 TxDOT Specifications for Percentage Passing from Each Sieve Size....12
Table 2.8 Design Information....13
Table 2.9 Gradation of the Aggregates Used in the Laredo Project....13
Table 2.10 TxDOT Specifications for Percentage Passing from Each Sieve Size....14
Table 2.11 Design Information....14
Table 3.1 Superpave Binder Requirements for PG 70-16....16
Table 3.2 Equations for Estimated Relations....17
Table 3.3 Estimated Values of Superpave Requirements at Different Toner Modification Levels....18
Table 3.4 Superpave Binder Requirements for PG 64-22....23
Table 3.5 Equations for Estimated Relations....23
Table 3.6 Superpave PG Binder Requirements for PG 76-16....27
Table 3.7 Equations for Estimated Relations....27
Table 3.8 Estimated Values of Superpave Requirements at Different Toner Modification Levels.....28
Table 4.1 Rut Depths at Various Wheel Passes for Control Mixture and 12.5% Toner-Modified Mixes....37
Table 4.2 HWTD Indices for Control Mixture and 12.5% Toner-Modified Asphalt Mixture....37
Table A.1 Summary of Mixture Properties with Different Asphalt Content....45
Table A.2 Summary of Mixture Properties with Different Asphalt Content....47
Table A.3 Summary of Mixture Properties with different Asphalt Contents....49
Table A.4 Indirect Tensile Strength Test Results for Dry Conditioning Samples....52
Table A.5 Indirect Tensile Strength Test Results for 55-80% Saturation Samples....52
Table A.6 Indirect Tensile Strength Test Results for 30-Min. Saturation Samples....53

List of Figures

Figure 3.1 Shear modulus as a function of blending time 16
Figure 3.2 Viscosity shear rate relation at 135°C and 165°C 19
Figure 3.3 Viscosity temperature relation at 12.5 toner modification level 20
Figure 3.4 Results of stability test at 12.5 toner modification level 21
Figure 3.5 Shear modulus as a function of blending period 22
Figure 3.6 Viscosity vs. temperature at 7% toner modification level 24
Figure 3.7 Results of stability test at 7% toner-modification level 25
Figure 3.8 Shear modulus as a function of blending period 26
Figure 3.9 Viscosity vs. Temperature at 14.5% Toner Modification Level. 30
Figure 3.10 Results of storage stability test at 14.5% toner modification level 31
Figure 4.1 Hamburg Wheel Tracking Device 34
Figure 4.2 An example of Hamburg Wheel Tracking Device output: permanent deformation vs. number of wheel passes 35
Figure 4.3 The HWTD Test Results for Control Mixture and 12.5% Toner Modified Asphalt Mixture at 50°C 36
Figure A.1 Asphalt content vs. density 46
Figure A.2 Asphalt content vs. VMA(%) 46
Figure A.3 Asphalt content vs. density 48
Figure A.4 Asphalt content vs. VMA(%) 48
Figure A.5 Asphalt content vs. density 50
Figure A.6 Asphalt content vs. VMA 51
Figure A.7 Asphalt content vs. percentage of air 51
Figure B.1.i Test results from DSR for the original binder modified with different toner amounts 57
Figure B.1.ii Test results from DSR for the RTFO-aged binder modified with different toner amounts 57
Figure B.1.iii Test results from DSR for the PAV-aged binder modified with different toner amounts 58
Figure B.1.iv Creep stiffness values from BBR 58
Figure B.1.v Logarithmic creep rate (m-value) values from BBR 59
Figure B.2.i Test results from DSR for the original binder modified with different toner amounts and for 64˚ and 70˚C 60
Figure B.2.ii Test results from DSR for the RTFO-aged binder modified with different toner amounts and for 64˚ and 70˚C 61
Figure B.2.iii Test results from DSR for the PAV-aged binder modified with different toner amounts 62
Figure B.2.iv Creep stiffness values from BBR 63
Figure B.2.v Logarithmic creep rate (m-value) values from BBR 63
Figure B.3.i Test results from DSR for the original binder modified with different toner amounts 64
Figure B.3.ii Test results from DSR for the RTFO-aged binder modified with different toner amounts 64
Figure B.3.iii Test results from DSR for the PAV-aged binder modified with different toner amounts 65

Figure B.3.iv Creep stiffness values from BBR 65
Figure B.3.v Logarithmic Creep rate (m-value) values from BBR 66
Figure B.3.vi Creep stiffness values from BBR (–12˚C)..66
Figure B.3.vii Logarithmic creep rate (m-value) values from BBR (–12˚C) 67

Chapter 1. Introduction

Every year, a tremendous amount of toner is produced for copiers and printers by toner manufacturing companies throughout the United States. 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 materials in asphalt pavements. The use of the waste material in asphalt pavements may have adverse environmental effects. Practicality, costs, and benefits associated with the usage of waste materials in the asphalt pavements must also to be examined. The most important consideration is the effect of incorporating the waste material on the pavement performance.

Incorporating a waste product can enhance some or all asphalt material properties and performance, or it can have no effect, or it can have a negative effect. When a waste material is proven to be 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 7-3933 are summarized in "Use of Waste Toner in Asphaltic Concrete." Research Report 3933-1F published by Center for Transportation Research.

This implementation project will transfer the results from project 7-3933, in which the feasibility and potential benefits of utilizing waste toner in hot-mix asphalt concrete were investigated. This report summarizes mixture designs and the binder designs of three demonstration projects in the Laredo, Houston, and Pharr districts in Texas where waste toner was used as an asphalt modifier. It also includes Hamburg Wheel Tracking Device (HWTD) test results for the Houston project.

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 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 toner in the blend; and the mixing and compaction temperatures stay at reasonable levels.

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 is a special attention because it could affect the expected life-cycle cost of the project. Project feasibility and cost effectiveness are also determined by 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 generally shows 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 very high shear blending, they state that the stirring period can be as short as 20 to 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; therefore, 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, while the ignition temperature is expected to exceed 350˚C.

IMPLEMENTATION

It was decided to construct four test sections to evaluate the benefits of toner-modified asphalt binders. These test sections are being constructed in the Laredo, Pharr, Bryan, and Houston districts. A final report documenting performance of the test sections will be prepared in order to achieve full-scale implementation.

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 research program, this approach is recommended.

OBJECTIVES

This implementation project will expand on 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 will be constructed to gather and analyze data 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 industry generates between 9,000 to 25,000 tons (20 million pounds and 55 million pounds) 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 to 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 temperature is a positive effect since resistance to permanent deformation is increased. However, 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 increase in low-temperature stiffness will not cause cracking problems.

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, in the first year, three test sections were constructed in the Houston, Laredo, and Pharr districts.

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 30, 60, 90, and 120 minutes 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 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 project, 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 three 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 non-magnetic Lexmark and magnetic Nashua toner samples is 75-90 percent styrene acrylic copolymers (SAC). The Nashua toner contains a significant amount of magnetite (15-20 percent). The Ricoh nonmagnetic toner, in contrast, is composed of mainly 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.

Table 2.1 Asphalt and Toner Information for the Test Sections

Test Section	**Asphalt**	**Toner Type**	**Toner Amount**	**SAC Content**	**Toner Supplier**
Pharr	PG 64-22	Nonmagnetic	7%	50-80%	Lexmark
Laredo	PG 64-22	Magnetic	14.5%	82%	Nashua Corp.
Houston	PG 64-22	Nonmagnetic	12.5%	15%	Ricoh

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. 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: 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 %)	Cumulative Pass (%)
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

Aggregate properties were tested for compliance with the TxDOT specifications. TxDOT test numbers, specifications, and test results for D Rock Meridian Rock and F Rock Meridian Rock are given in Table 2.4.

Table 2.4 Aggregate Material Properties

Test Name	TxDOT Test Number	TxDOT Specification	D Rock Meridian Rock	F Rock Meridian Rock
Decantation	Tex-217-F	1.5 Max	0.3	0.3
Deleterious Materials	Tex-217-F	1.5 Max	0	0
Magnesium Sulfate Soundness	Tex-411-A	30 Max	2	1.13
Los Angeles Abrasion	Tex-410-A	40 Max	26	29
Crushed Face Count	Tex-460-A	85 Min	100	100

Mixtures with different asphalt content were prepared to determine the optimum asphalt content. A summary of mixture properties with different asphalt content is shown in Table A.1 in Appendix A. 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 2.5.

Table 2.5 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 F.M. 800 in Cameron County. A Type D mix design was used with PG 64-22 from Trigeant Refining. 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 the Table 2.6. TxDOT specifications for aggregate gradation are shown in Table 2.7.

Table 2.6 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%)**	**Aggr. # 5 Lime (1%)**
Sieve Size	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**	**Percent Passing (%)**
16 mm	100	100	100	100	100
12.5mm	98.1	100	100	100	100
9.5 mm	71.6	100	100	100	100
4.75 mm	14	74.8	95	100	100
2.0 mm	4.9	21.3	61.3	99.6	100
0.425 mm	2.3	3.8	31.2	97.6	100
0.180 mm	1.2	2.5	8.9	37.4	100
0.075 mm	0.8	2.0	2.8	8.1	100

Table 2.7 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 content were prepared to determine the optimum asphalt content. A summary of mixture properties with different asphalt content is shown in Table A.2. 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 2.8.

Table 2.8 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 Marietta 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 is 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. Mix design includes six aggregate types. Gradation of the aggregates and TxDOT specifications for aggregate gradation are given in Table 2.9 and Table 2.10, respectively.

Table 2.9 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 2.10 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

Indirect tensile strength tests were performed in accordance with the test method Tex-531-C. Tests were performed for three different conditions: Samples tested in a dry condition (Group A), samples with saturation levels from 55 percent up to 80 percent (Group B), and samples that were saturated for 30 minutes (Group C). Test results are given in Table A.4, Table A.5, and Table A.6 in Appendix A.

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 2.11.

Table 2.11 Design Information

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

Chapter 3. Binder Designs

BINDER DESIGN FOR HOUSTON PROJECT

CTR completed 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 and 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 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.

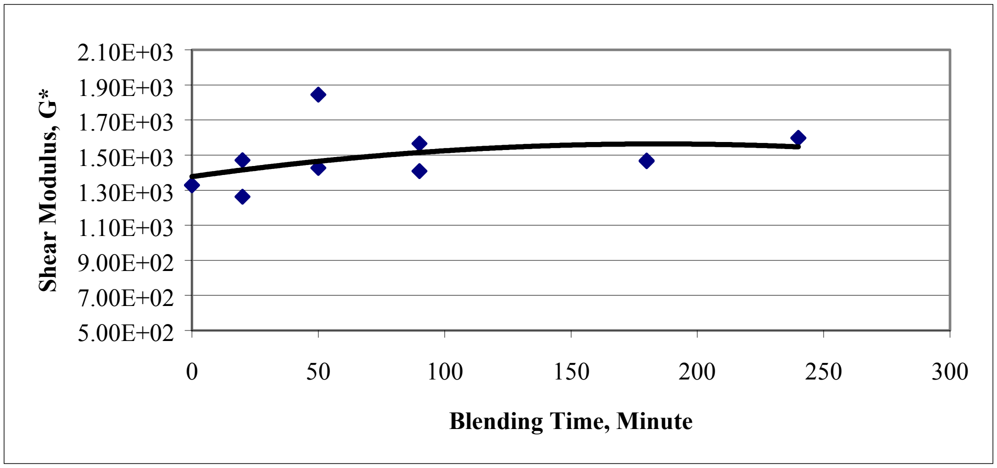

Figure 3.1 Shear modulus as a function of blending time

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 will 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%, 7%, 14%, 21%, and 30% 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 B. Equations and R^2 values are shown in Table 3.2.

Table 3.2 Equations for Estimated Relations

Percent Toner v.s.	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 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 level, in all cases binders meet the requirements for creep stiffness (S), but for logarithmic creep rate (m-value) more than 18 percent toner modification did not meet the requirements.

Table 3.3 Estimated Values of Superpave Requirements 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 modification 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 12.5 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 (8). Viscosity of modified binders depends on both shear rate and temperature. Therefore, 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 relations at these temperatures.

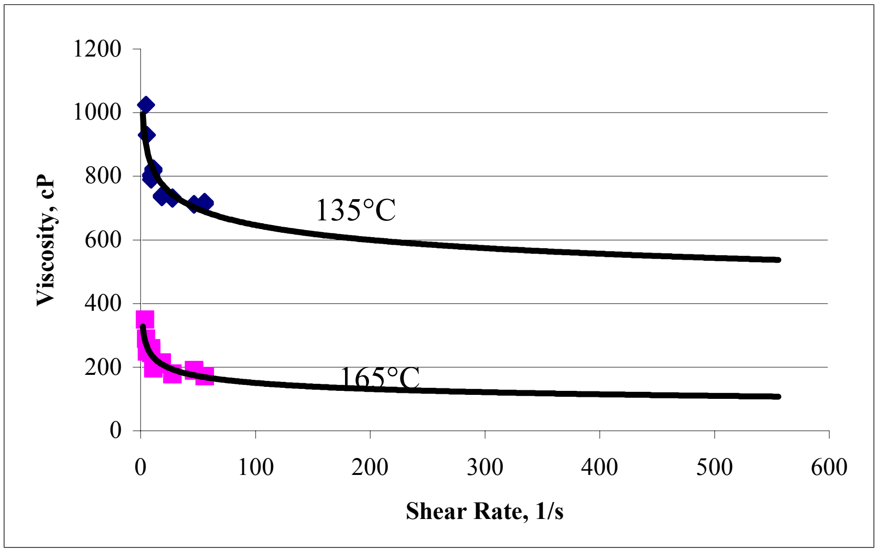

Figure 3.2 Viscosity shear rate relation at 135°C and 165°C

Based on the relations 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 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.

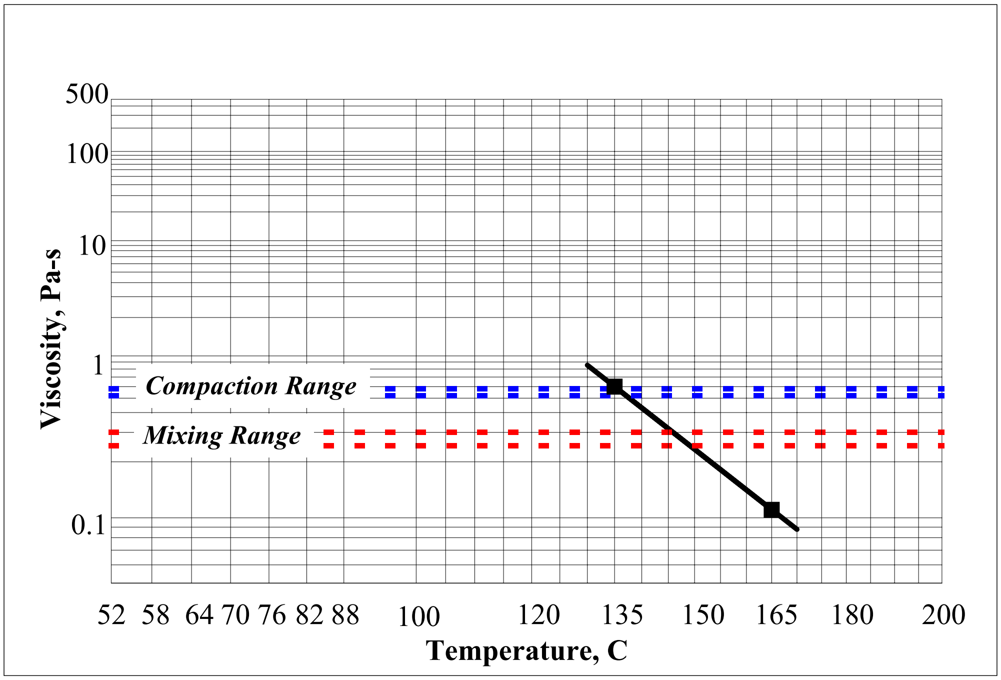

Figure 3.3 Viscosity temperature relation at 12.5 toner modification level

Storage Stability

Storage stability was measured using AASHTO PP5-93 at 12.5 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 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 sample was then removed from the freezer and the tube was 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 modulus 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 modulus exhibited between the top and bottom in such a short time shows a significant storage stability problem.

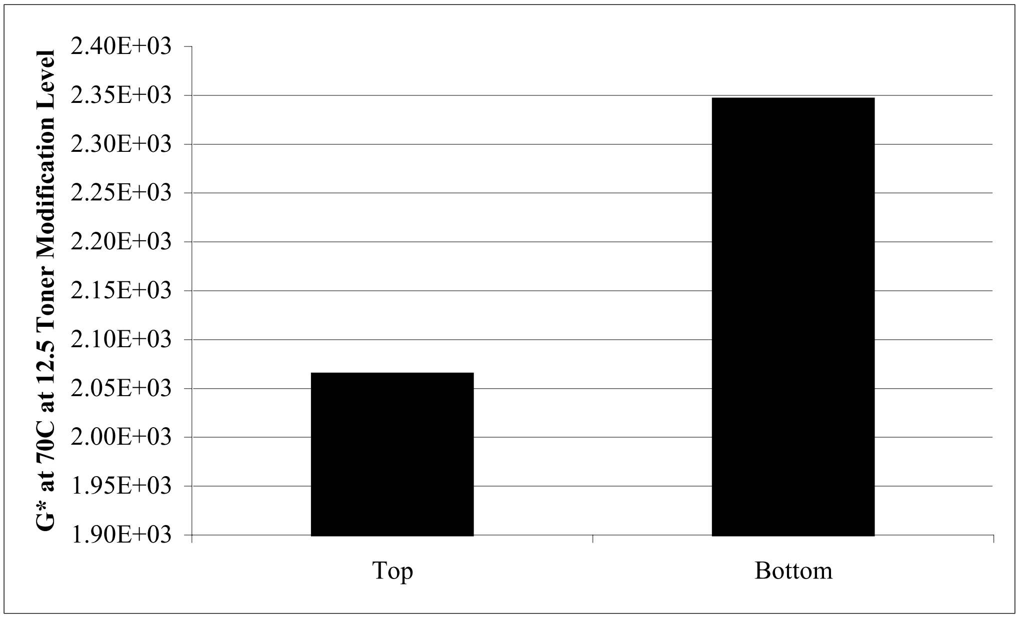

Figure 3.4 Results of stability test at 12.5 toner modification level

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 this 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, 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.

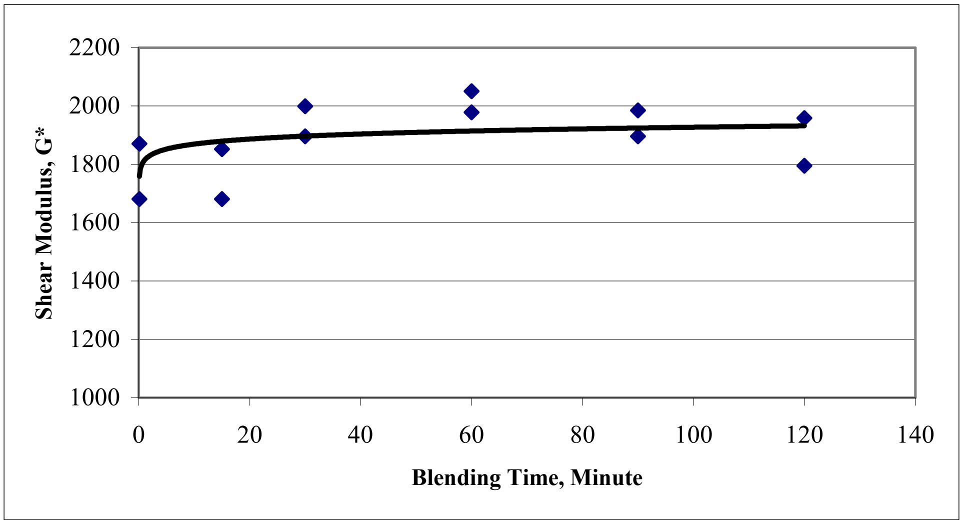

Figure 3.5 Shear modulus as a function of blending period

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 64-22 binder with 7 percent toner would satisfy specifications for PG 70-22; however, the RTFO aged binder did not comply with the minimum 2.2Kpa requirement, as shown in Appendix B. As for the intermediate-temperature properties, the binder-toner blend did not comply with the PG 64-22 requirements for Pressure Aging Vessel (PAV) aged binder tested at 25°C, which requires a maximum 5000Kpa. Therefore, 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 relations 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 B. Equations and R^2 values are shown in Table 3.5.

Table 3.5 Equations for Estimated Relations

Percent Toner v.s.	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 relations 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 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, mixing temperature was found to be 149°C, and compaction temperature was found to be 135°C.

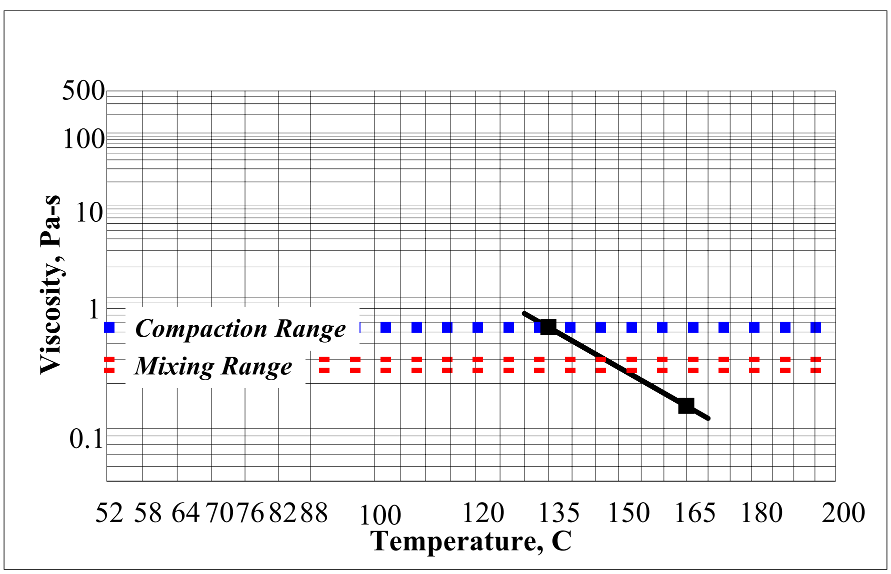

Figure 3.6 Viscosity vs. temperature at 7% toner modification level

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 times higher modulus 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 modulus exhibited between the top and bottom specimens in such a short time. The results of storage stability test are presented in Figure 3.7.

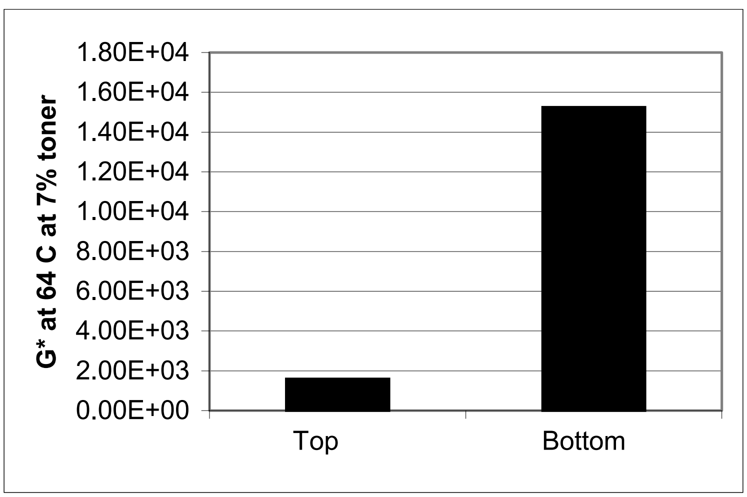

Figure 3.7 Results of stability test at 7% toner-modification level

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 and 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 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 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.

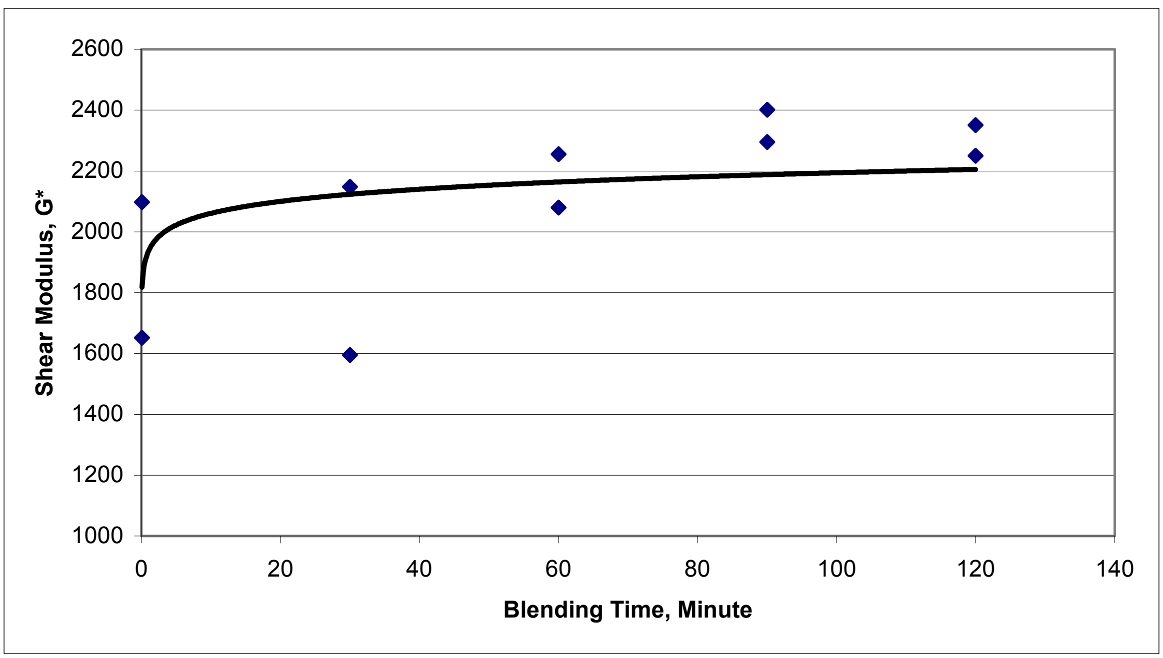

Figure 3.8 Shear modulus as a function of blending period

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 relations between toner-modification level and the requirements listed in Table 3.6. Figures showing the relations for these five requirements are included in Appendix A. Equations and R^2 values are shown in Table 3.7.

Table 3.7 Equations for Estimated Relations

Percent Toner v.s.	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 and 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. Therefore, 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 just barely satisfied. Other than this, creep stiffness (S) and logarithmic creep rate (m-value) meet the specification requirements for toner-modification levels between 7 and 19 percent.

Table 3.8 Estimated Values of Superpave Requirements 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 abovementioned parameter is barely met (see Appendix B), it was decided that, to be on the safe side, 14.5% toner would be used to modify the base binder.

Mixing and Compaction Temperatures

Lab mixing and compaction temperatures were calculated at 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 calculation of mixing temperature and 550 cP for 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 14.5 percent toner-modification level. Based on the relationship shown in Figure 2, mixing temperature was found to be 156°C, and compaction temperature was found to be 141°C.

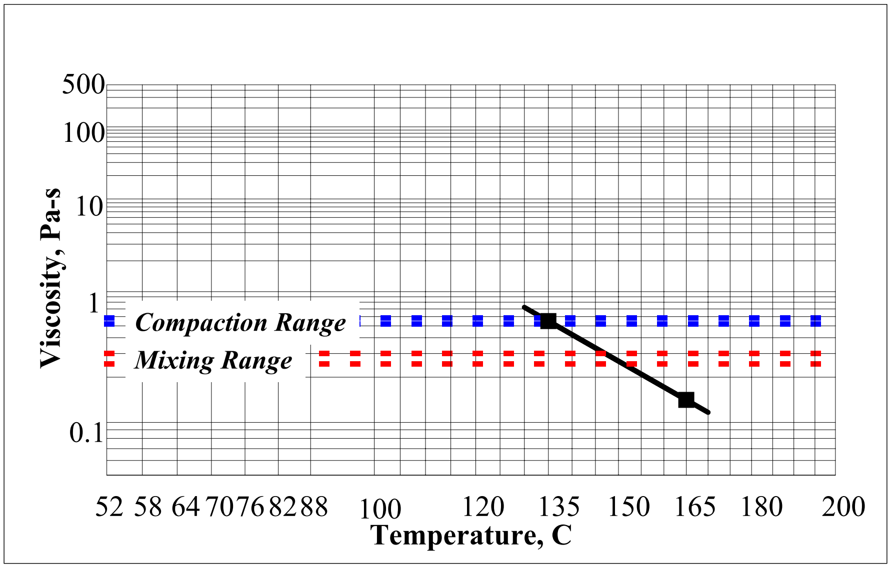

Figure 3.9 Viscosity vs. Temperature at 14.5% Toner Modification Level.

Storage Stability

Storage stability was measured using AASHTO PP5-93 at 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 times higher modulus than the binder taken from the top portion. In this study, the specimen was left in the oven only for 2 hours, whereas AASHTO PP5-93 requires the specimen to remain in the oven for 48 hours. However, the difference in modulus 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.

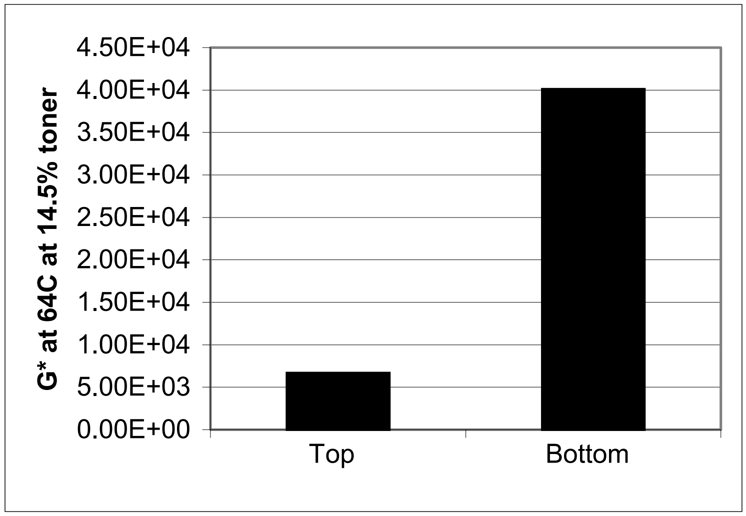

Figure 3.10 Results of storage stability test at 14.5% toner modification level

Chapter 4. The Hamburg Wheel Tracking Device Results

In the Houston project, PG 64-22 binder modified with 12.5 percent toner was used. Modification changed the binder grade from PG 64-22 to PG 70-16. On the control section the same mix design with PG 70-22 binder was employed. The performance of the mixtures was evaluated using the Hamburg Wheel Tracking Device at 50˚C.

The Hamburg Wheel Tracking Device, shown in Figure 4.1, 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˚ to 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 transducer, which has an accuracy of 0.01 mm.

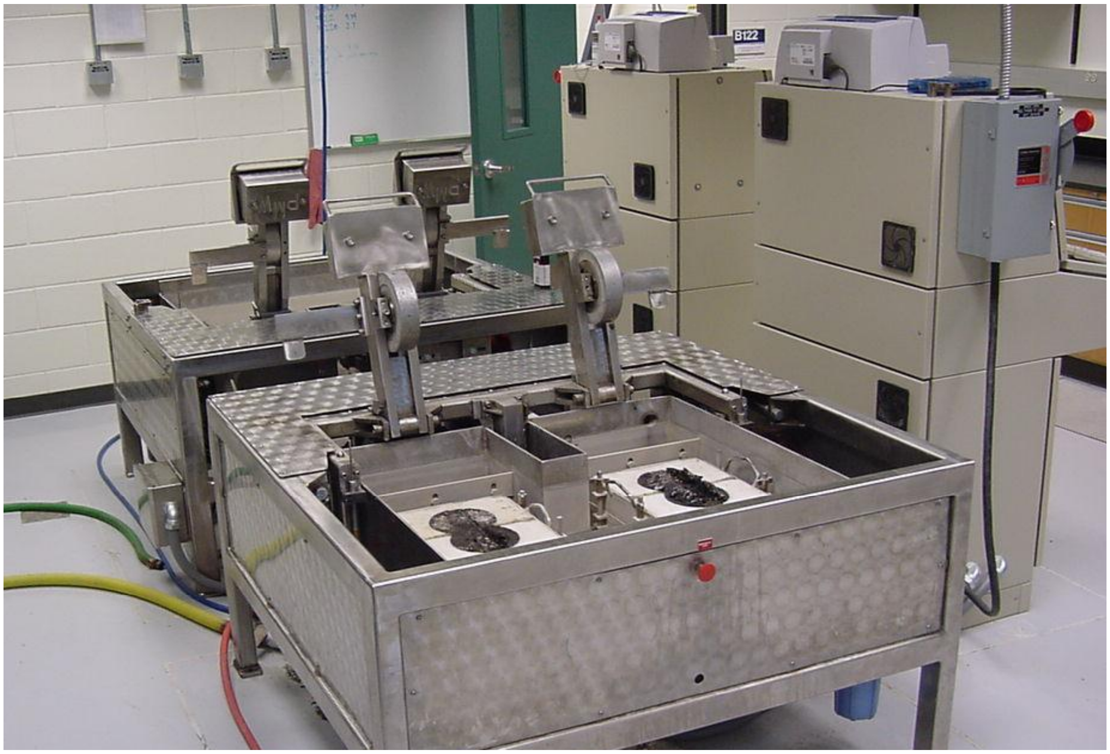

Figure 4.1 Hamburg Wheel Tracking Device

An analysis of test results is shown in Figure 4.2. 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. Slope is shown in passes per mm, which is the inverse of the slope of the curve shown. As seen in Figure 4.2, 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. As in creep slope, number of wheel passes per mm (inverse slope) is used in stripping slope. Stripping slope and failure rut depth are also used as a performance parameter.

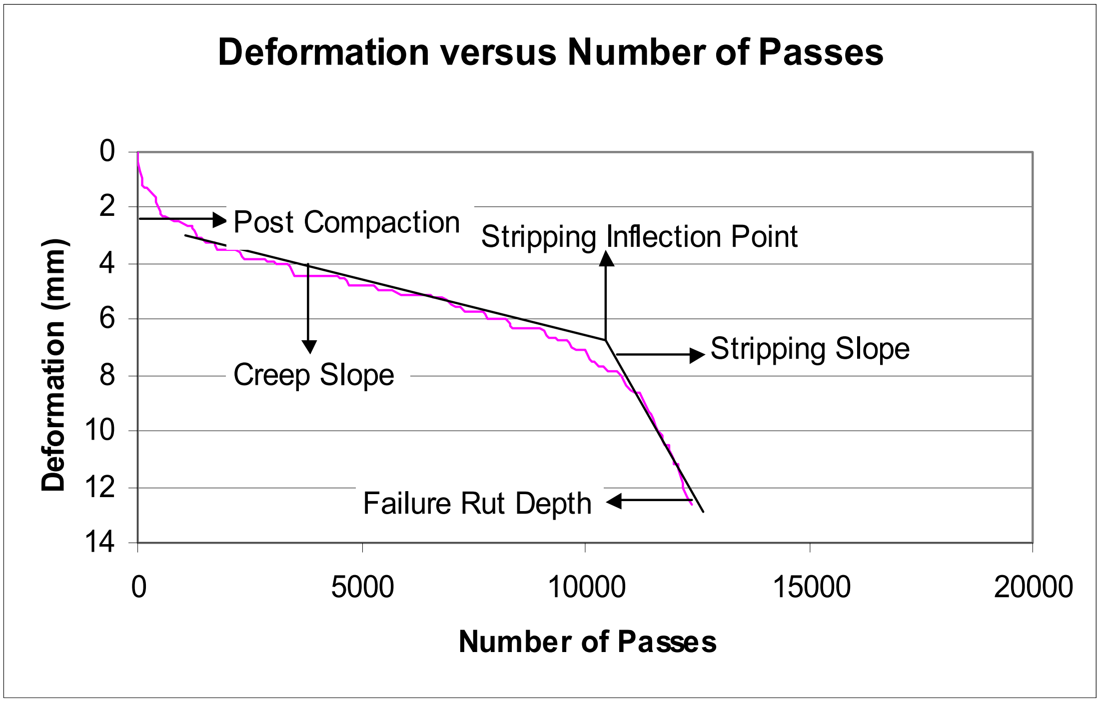

Figure 4.2 An example of Hamburg Wheel Tracking Device output: permanent deformation vs. number of wheel passes

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.

Hamburg Wheel Tracking Device tests were performed on the mixtures used in the control section and 12.5 percent toner-modified asphalt binder specimens. The addition of 12.5 percent toner changed the grade of asphalt from PG 64-22 to PG 70-16. Toner-modified binder specimen showed higher resistance to rutting deformation than the mixture used in the control section did, as can be seen from Figure 4.3. Specimens did not show any stripping slope.

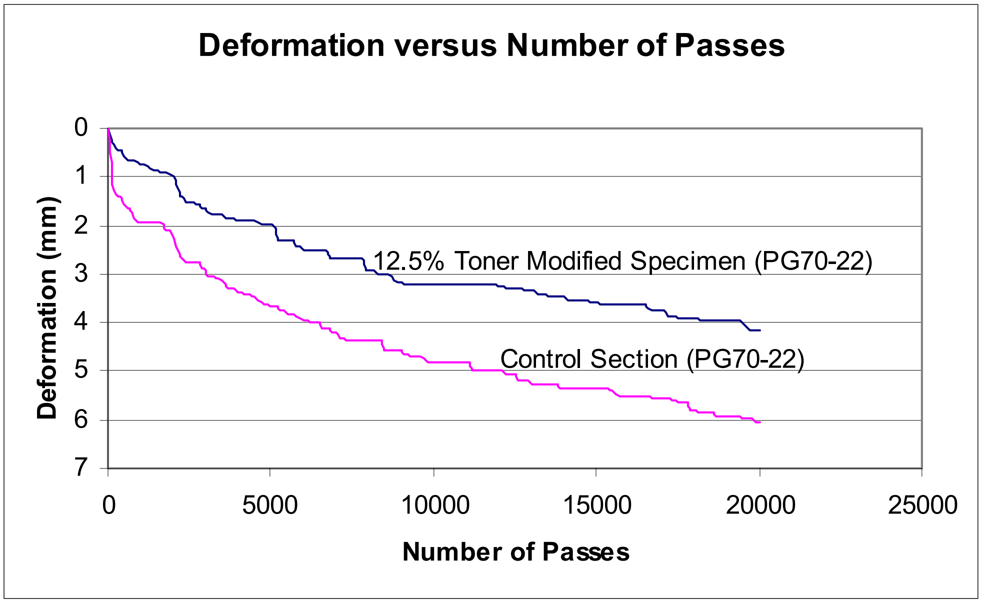

Figure 4.3 The HWTD Test Results for Control Mixture and 12.5% Toner Modified Asphalt Mixture at 50°C

The 12.5 percent toner-modified binder specimen always had lower rut depths and better indices throughout the test. Rut depths at various wheel passes are summarized in Table 4.1. The HWTD indices are shown in Table 4.2.

Table 4.1 Rut Depths at Various Wheel Passes for Control Mixture and 12.5% Toner-Modified Mixes

Mix ID	Binder Type	Rut Depth (mm)				
		Number of Wheel Passes				
		1,000	5,000	10,000	15,000	20,000
Original Binder	PG 70-22	1.95	3.68	4.83	5.36	6.05
12.5% Toner Modified	PG 70-16	0.75	1.99	3.21	3.6	4.15

Table 4.2 HWTD Indices for Control Mixture and 12.5% Toner-Modified Asphalt Mixture

INDICES	SPECIMENS	
	Original Binder	Toner Modified
Post Compaction Point (mm)	1.95	0.75
Creep Slope (Passes/mm)	4785	6024
Stripping Inflection Point	N/A	N/A
Stripping Slope (Passes/mm)	N/A	N/A
Failure Rut Depth (mm)	6.05	4.15

Chapter 5. Conclusions

This report summarizes mixture designs and the binder designs of three demonstration projects in the Laredo, Houston, and Pharr districts in Texas where waste toner was used as an asphalt modifier. It also includes Hamburg Wheel Tracking Device (HWTD) test results for the Houston project.

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.

The same grade base binder was used for each demonstration project (PG 64-22), and the objectives were fundamentally two:

1) 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.

2) 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 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.

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. Thus, overall at higher percentages of toner, the stiffening effect is more significant.

The BBR test also demonstrated a decrease in m-value and 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. Furthermore, a blending time of 60 to 90 minutes was found to be adequate to achieve homogeneous asphalt–toner mix.

In this report, test results of the mixtures for the Houston project were included. Hamburg Wheel Tracking Device tests were performed on the specimens prepared from the mixtures used in the control section and on the specimens with 12.5 percent toner-modified asphalt binder. The addition of 12.5 percent toner changed the grade of asphalt from PG 64-22 to PG 70-16. Toner -modified binder specimen showed higher resistance to rutting deformation than the mixture used in the control section did.

References

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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.

Appendix A. Mixture Design Information

Houston Project

Specimens were prepared with different percentage of asphalt contents 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 A.1. Asphalt content versus density and asphalt content versus VMA graphs are shown in the Figure A.1 and Figure A.2 respectively.

Table A.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
%	Ga	Gr	Ge	Gt	%	%
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

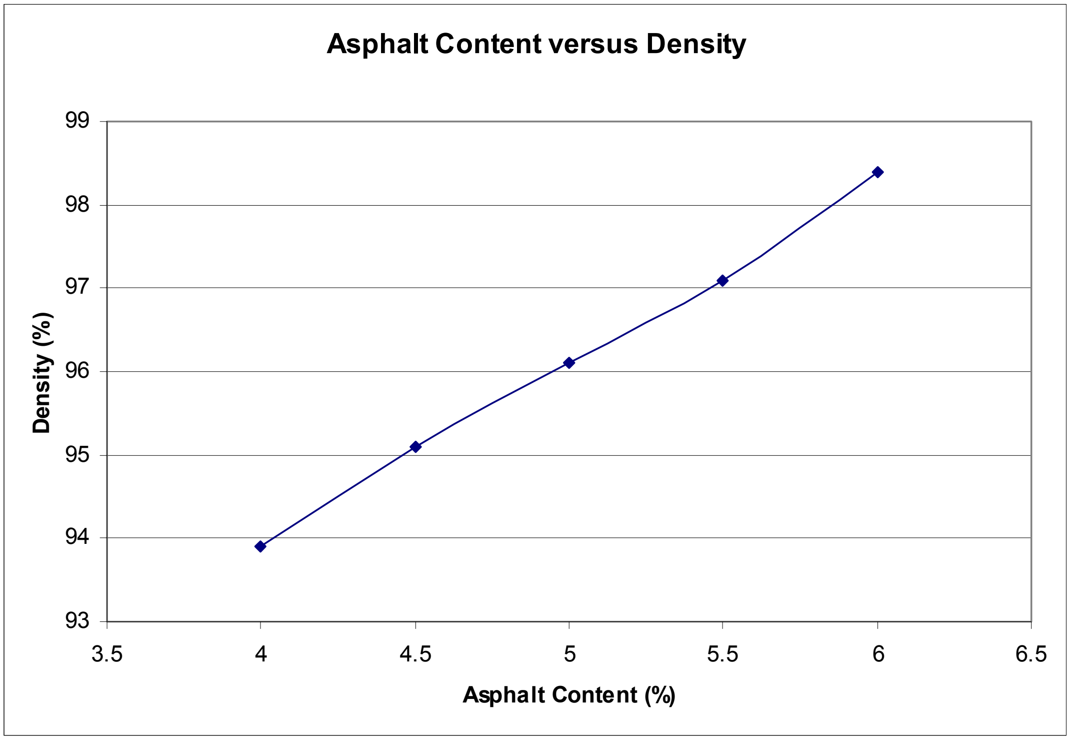


Figure A.1 Asphalt content vs. density

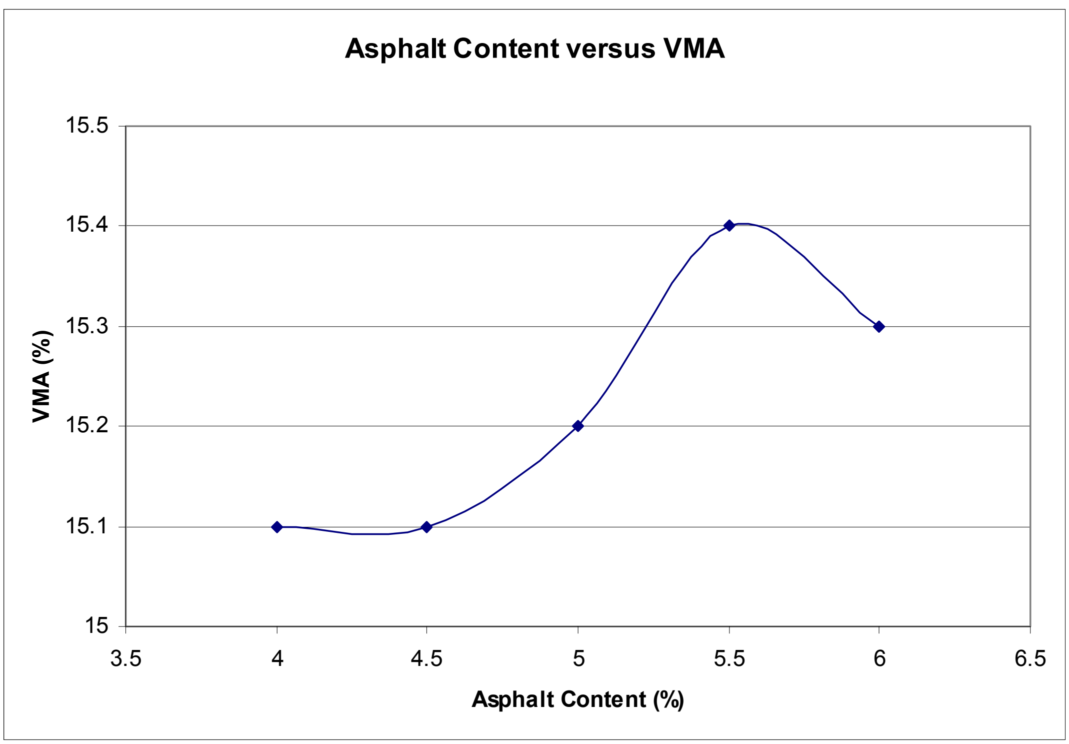


Figure A.2 Asphalt content vs. VMA(%)

Pharr Project

Type D mixture design was used with different percentage of asphalt to determine the effect of asphalt content on density and VMA properties of a mixture. 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 A.2. Asphalt content versus density and asphalt content versus VMA graphs are shown in Figure A.3 and Figure A.4 respectively.

Table A.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
%	Ga	Gr	Ge	Gt	%	%
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

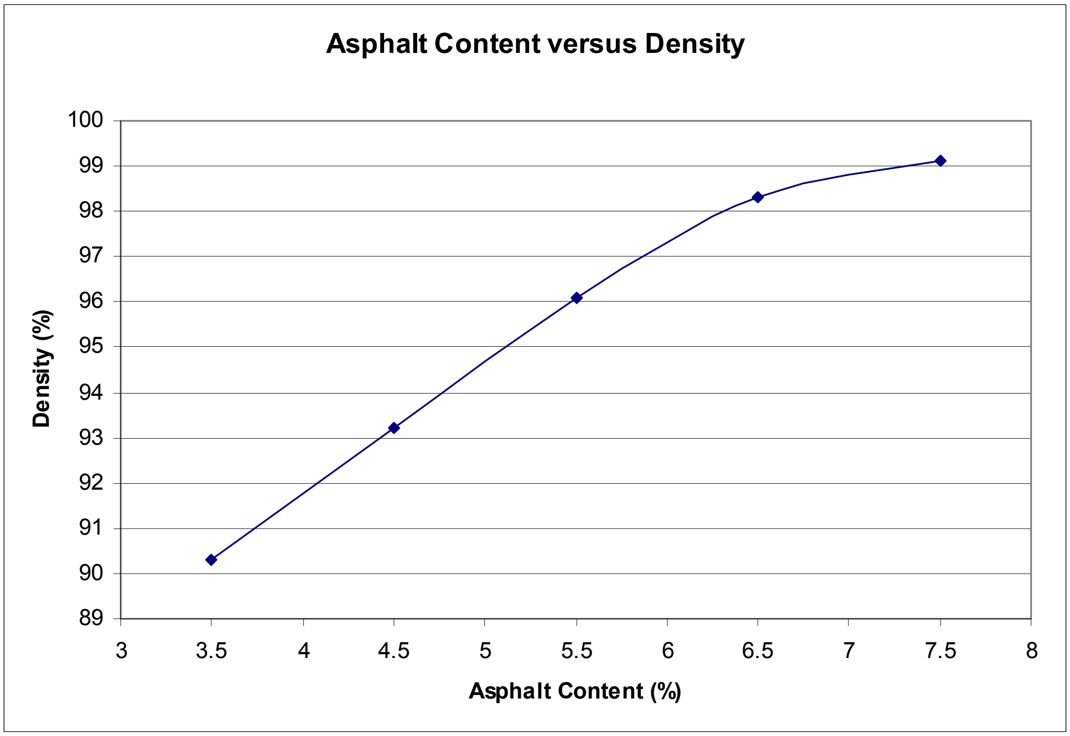


Figure A.3 Asphalt content vs. density

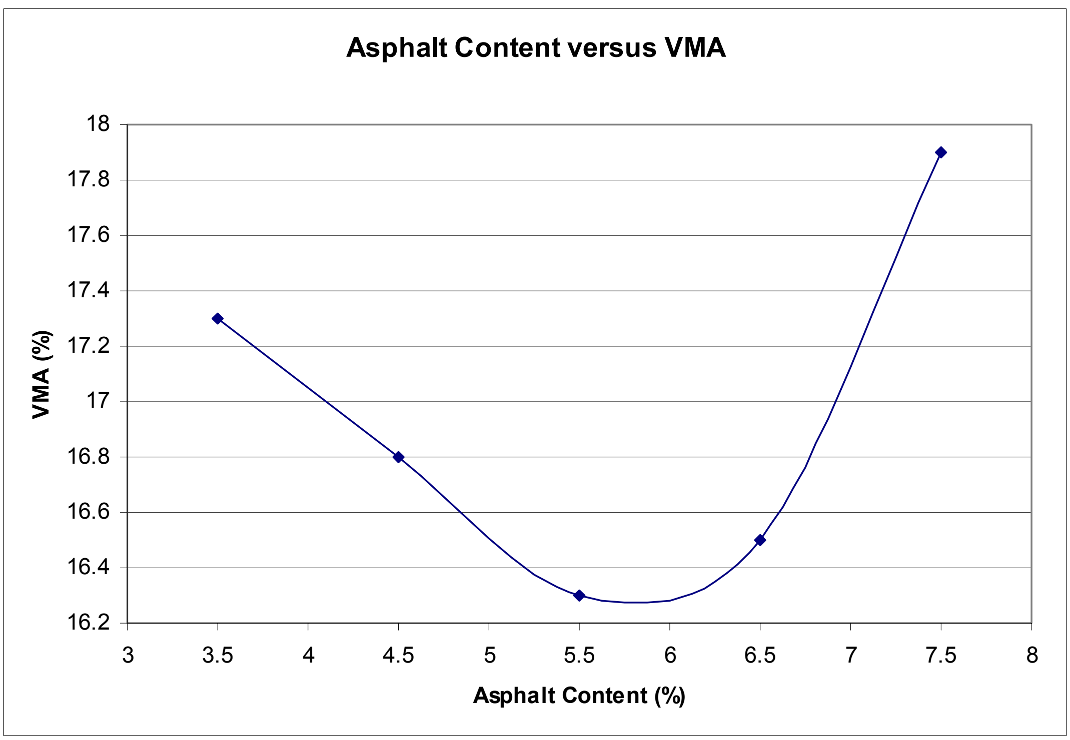


Figure A.4 Asphalt content vs. VMA(%)

Laredo Project:

Type C mixture design was used with five different percentage of asphalt to determine the effect of asphalt content on the other properties such as density, total air voids, specific gravities, and VMA of an HMA mixture. Mixture contained used were 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 A.6.

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

Asphalt Content	Bulk Sp. Gr.	Max. Sp. Gr.	Density	Unit Weight	% Air	% VMA	% 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, asphalt content versus VMA, and asphalt content versus percentage of air 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 Figure A.5, Figure A.6, and Figure A.7.

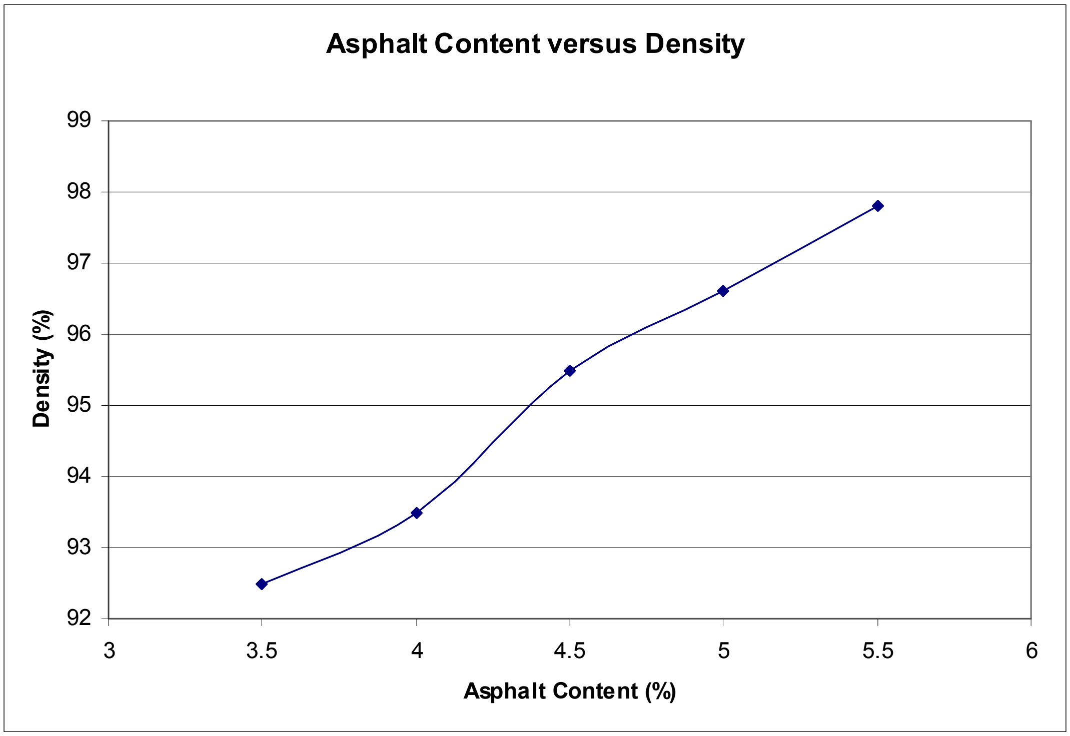


Figure A.5 Asphalt content vs. density

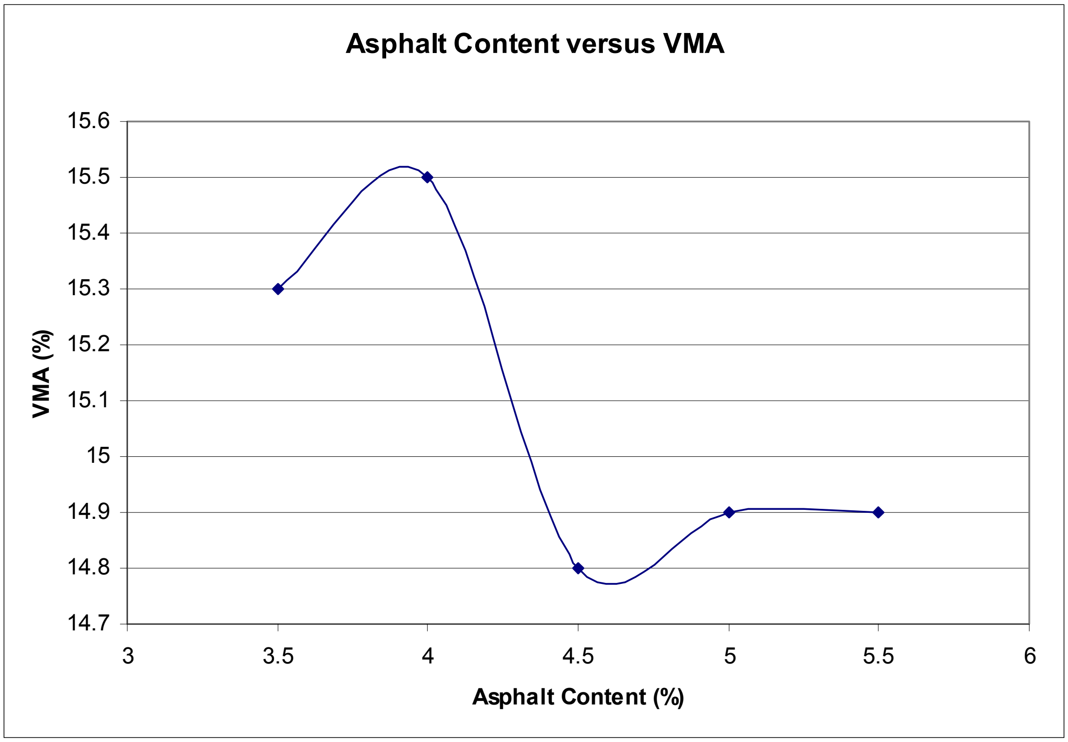


Figure A.6 Asphalt content vs. VMA

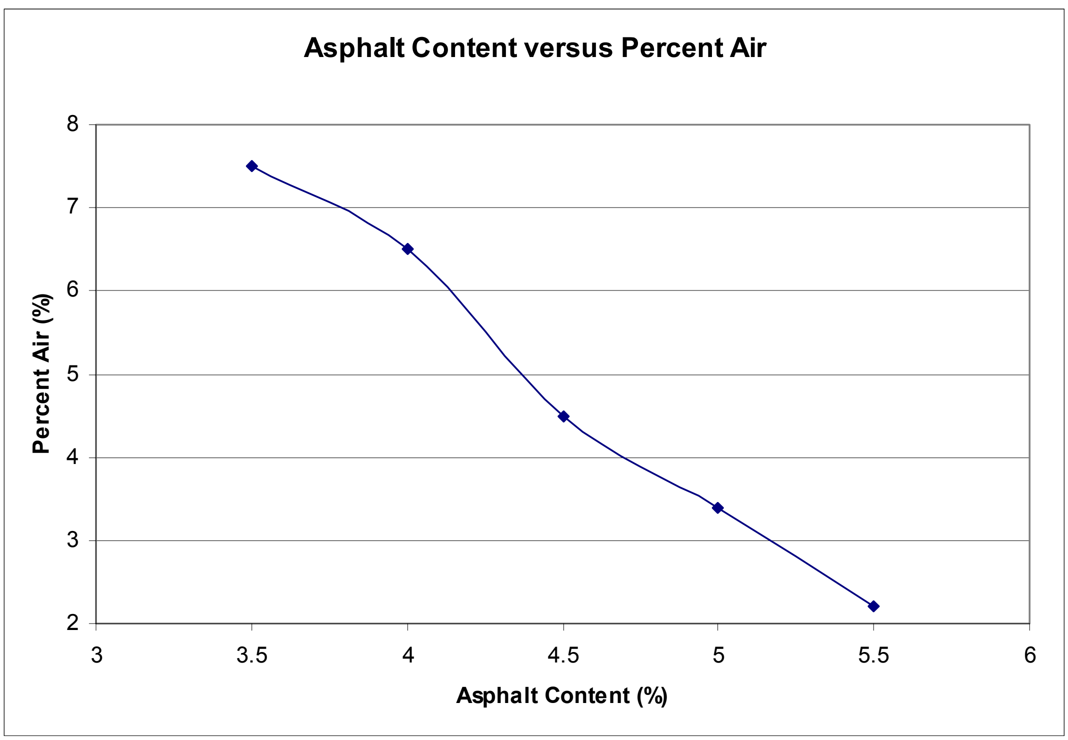


Figure A.7 Asphalt content vs. percentage of air

Table A.4 Indirect Tensile Strength Test Results for Dry Conditioning Samples

Specimen Number	1	2	3	4
Air Weight	940.1	939.3	941.2	938.9
SSD Weight	941.3	940.4	943.5	940.5
Weight in Water	537.5	536.4	534.2	537.3
Spec. Volume	403.8	404.0	409.3	403.0
Grav. of Spec.	2.328	2.325	2.300	2.330
Dry Density	94.1	94.0	93.0	94.2
Adsorption by Vol.	**0.30**	**0.27**	**0.56**	**0.35**
Indirect Tensile Strength Test				
Mold Height	1.98	1.98	2.01	1.98
Dial Reading	158	188	145	160
Load at Failure	1548	1881	1455	1603
TSR	124.8	148.2	112.9	126.3

Table A.5 Indirect Tensile Strength Test Results for 55-80% Saturation Samples

Grouping ID	Dry Conditioning			
Specimen Number	1	2	3	4
Air Weight	941.1	939.8	940.6	936.0
SSD Weight	942.0	940.5	942.2	937.1
Weight in Water	537.4	536.3	535.9	537.1
Spec. Volume	404.6	404.2	406.3	406.0
Grav. of Spec.	2.326	2.325	2.315	2.305
Dry Density	94.1	94.0	93.6	93.2
Adsorption by Vol.	0.22	0.17	0.39	0.27
Saturated SSD Wt.	954.5	952.4	956.9	951.1
Sat Water Wt	550.2	548.7	550.9	546.1
Sat Volume	390.9	391.1	389.7	389.9
Sat Gravity	2.408	2.403	2.414	2.401
Sat Density	97.4	97.2	97.6	97.1
% Voids Filled w/Water	55.5	52.7	62.3	56.8
Adsorption by Vol.	3.31	3.12	4.00	3.72
Indirect tensile Strength				
Mold Height	1.99	1.99	2.00	2.00
Dial Reading	140	136	126	127
Load at Failure	1405	1365	1266	1276
TSR	110.1	107.0	98.7	99.5

Table A.6 Indirect Tensile Strength Test Results for 30-Min. Saturation Samples

Grouping ID	**Dry Conditioning**			
Specimen Number	**1**	**2**	**3**	**4**
Air Weight	940.3	936.7	940.3	940.8
SSD Weight	941.2	937.9	941.4	942.3
Weight in Water	536.9	534.3	536.0	536.3
Spec. Volume	404.3	403.6	405.4	406.0
Grav. of Spec.	2.326	2.321	2.319	2.317
Dry Density	94.0	93.8	93.8	93.7
Adsorption by Vol1	0.22	0.30	0.27	0.37
Saturated SSD Wt.	958.7	954.9	958.9	960.9
Sat Water Wt	554.8	552.6	554.5	556.0
Sat Volume	385.5	384.1	385.8	384.8
Sat Gravity	2.439	2.439	2.437	2.445
Sat Density	98.6	98.6	98.6	98.9
% Voids Filled w/Water	77.0	77.4	76.7	82.0
Adsorption by Vol1	4.55	4.51	4.59	4.95
Indirect tensile Strength				
Mold Height	1.98	2.00	1.99	2.00
Dial Reading	137	138	133	128
Load at Failure	1375	1385	1336	1286
TSR	108.3	108.0	104.7	100.3

Appendix B. Binder Design Information

1. BINDER DESIGN FOR HOUSTON PROJECT

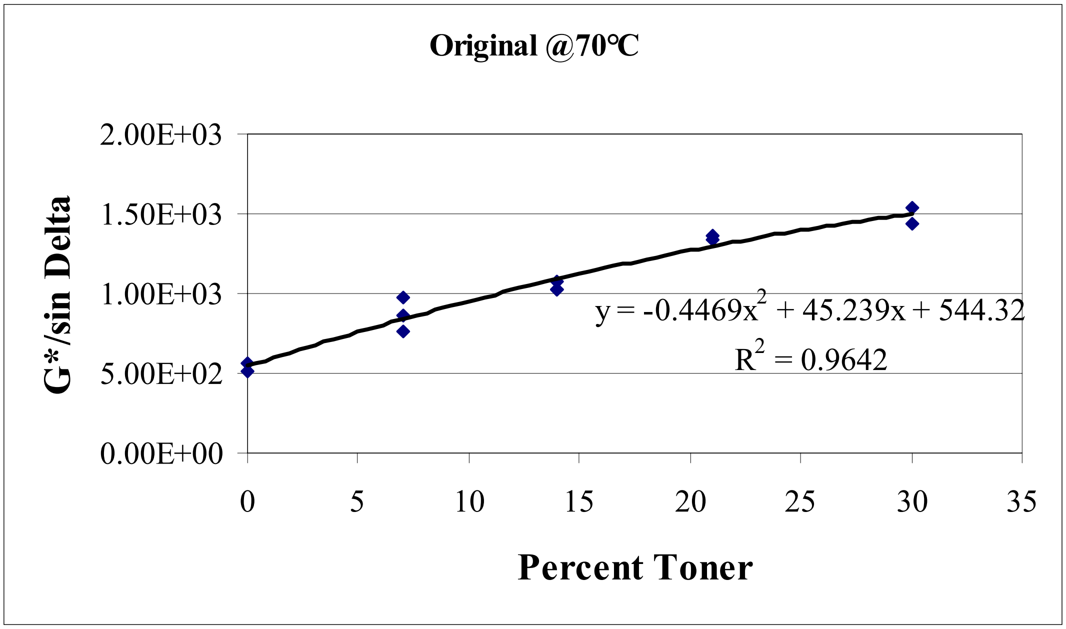


Figure B.1.i Test results from DSR for the original binder modified with different toner amounts

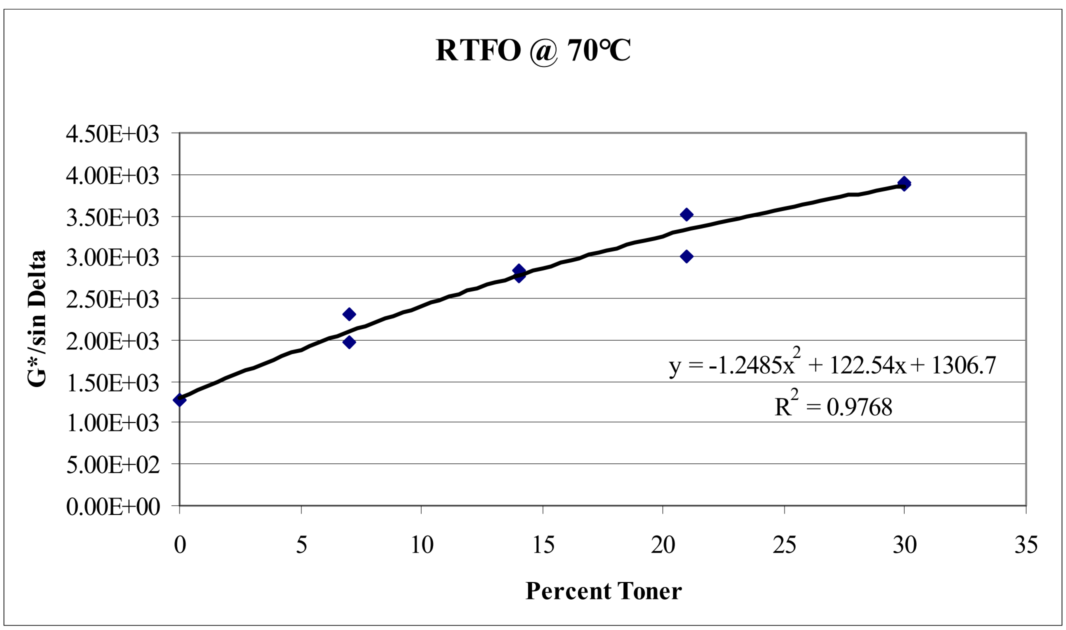


Figure B.1.ii Test results from DSR for the RTFO-aged binder modified with different toner amounts

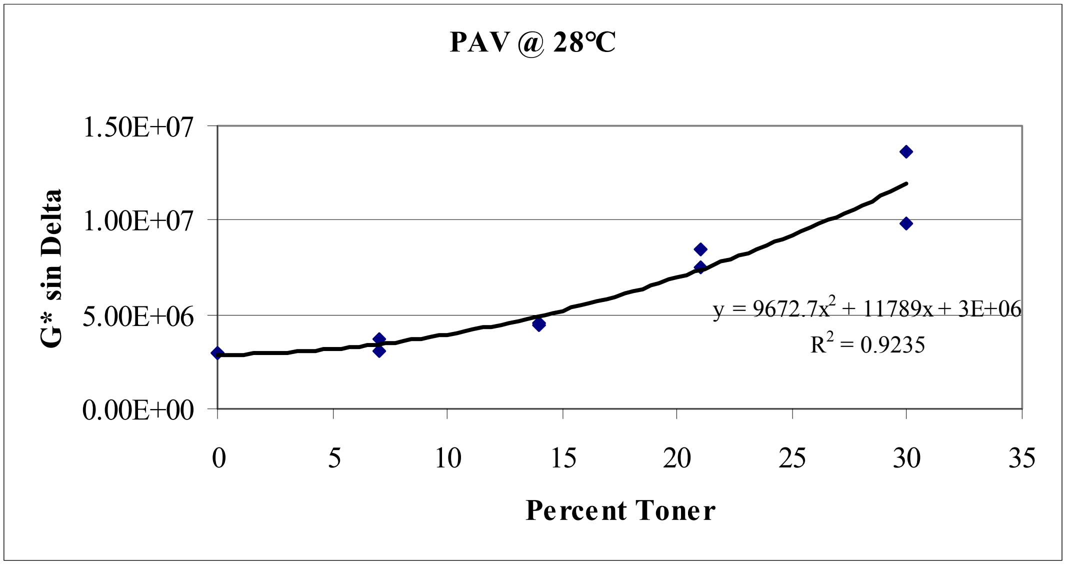


Figure B.1.iii Test results from DSR for the PAV-aged binder modified with different toner amounts

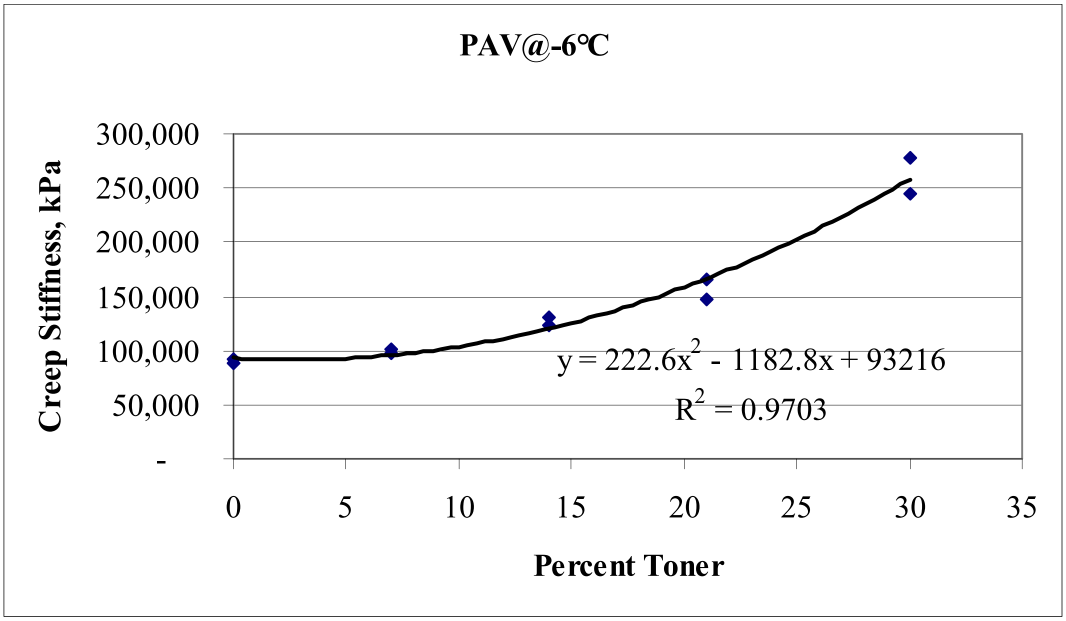


Figure B.1.iv Creep stiffness values from BBR

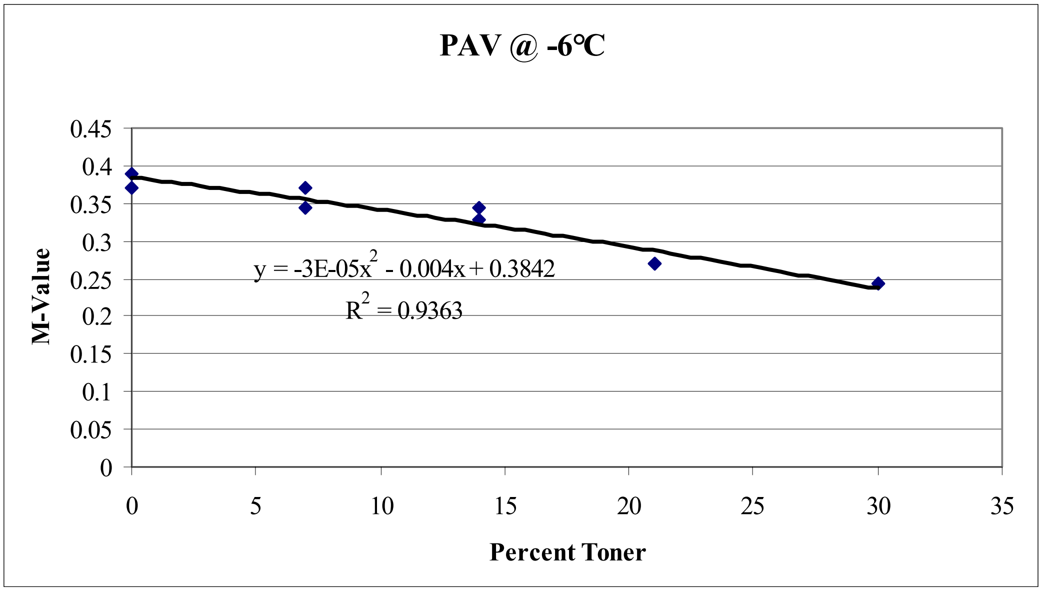
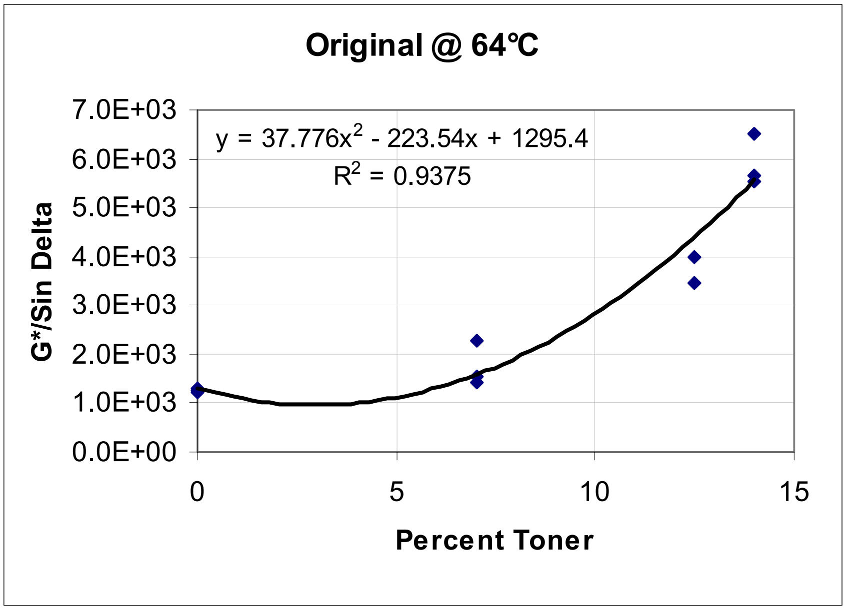


Figure B.1.v Logarithmic creep rate (m-value) values from BBR

2. BINDER DESIGN FOR PHARR PROJECT



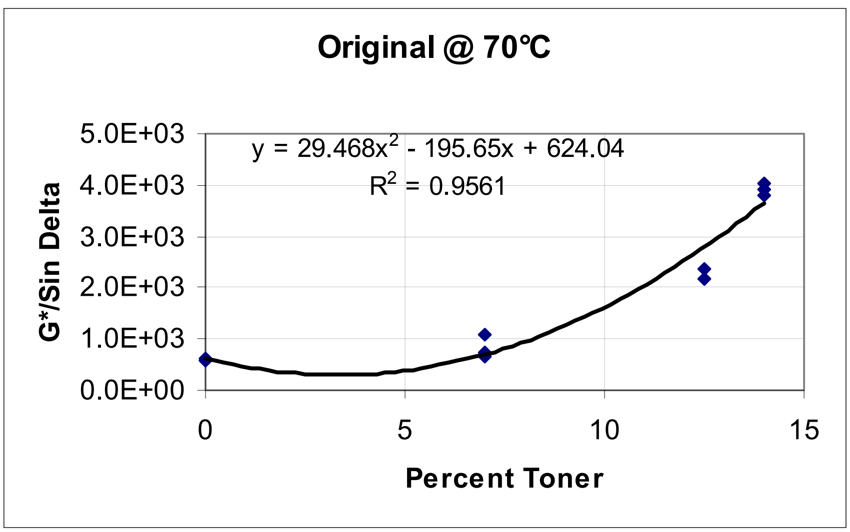
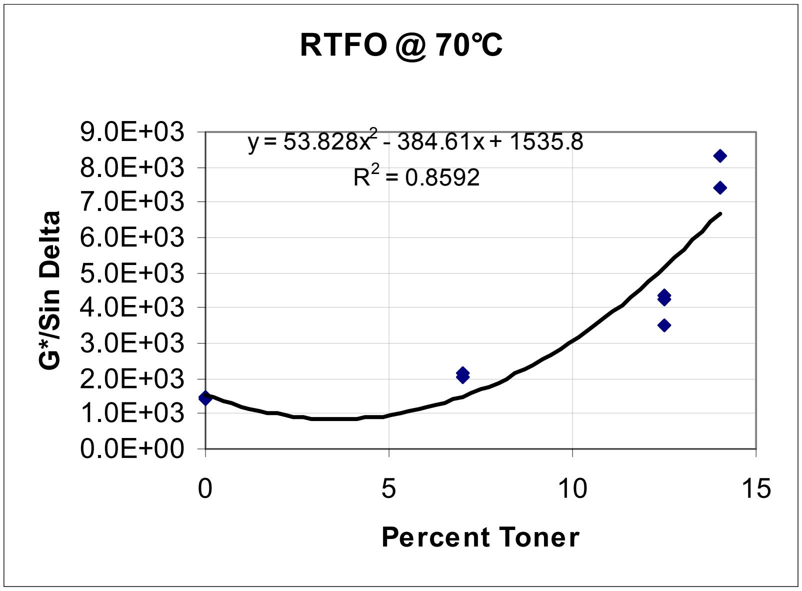


Figure B.2.i Test results from DSR for the original binder modified with different toner amounts and for 64˚ and 70˚C



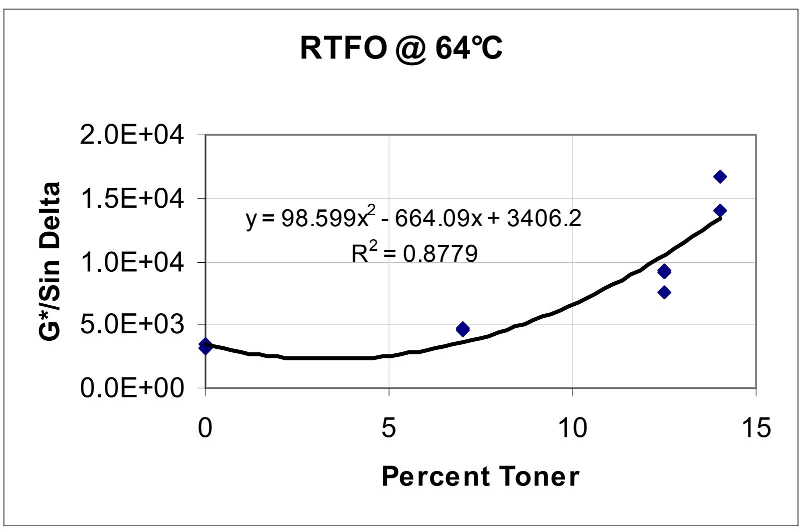
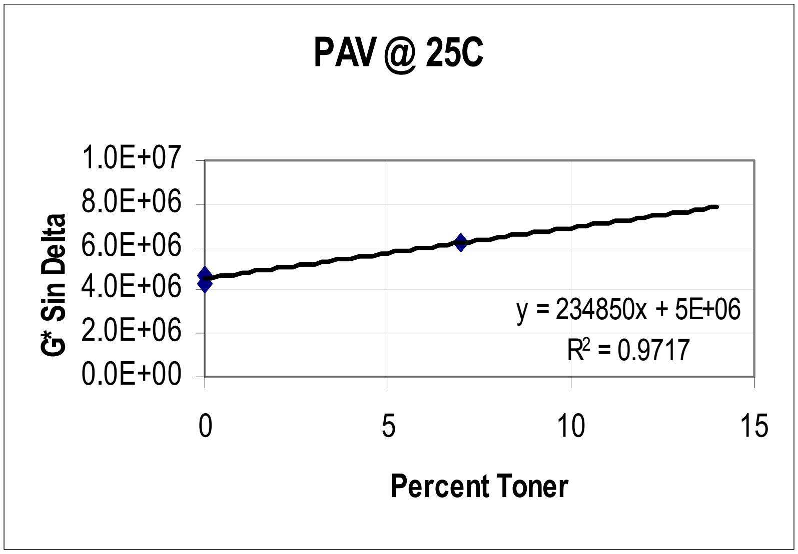


Figure B.2.ii Test results from DSR for the RTFO-aged binder modified with different toner amounts and for 64° and 70°C



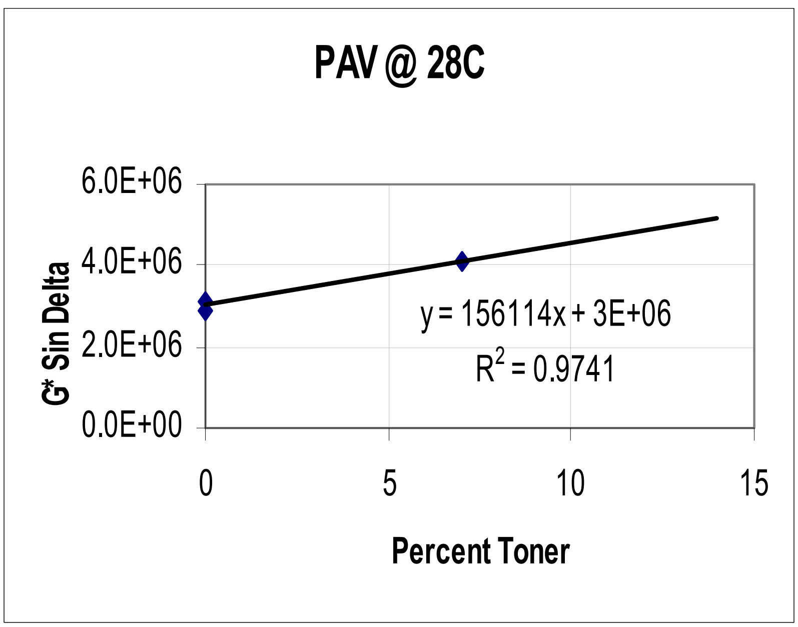


Figure B.2.iii Test results from DSR for the PAV-aged binder modified with different toner amounts

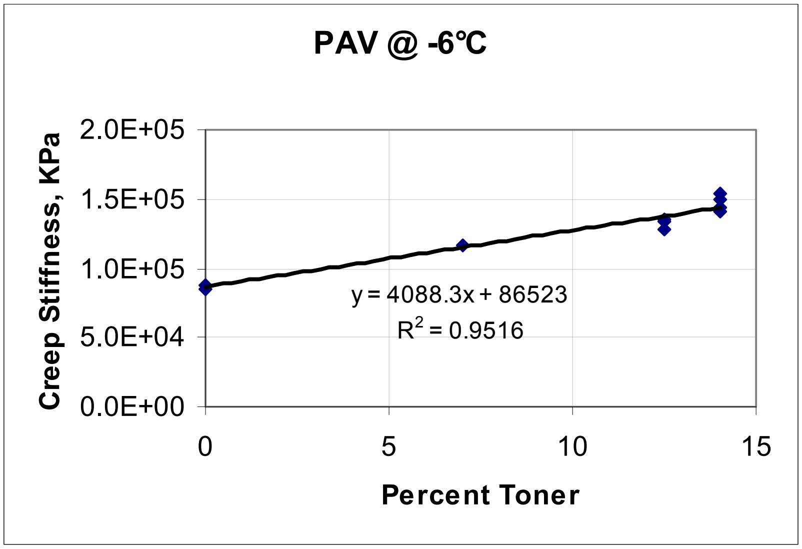


Figure B.2.iv Creep stiffness values from BBR

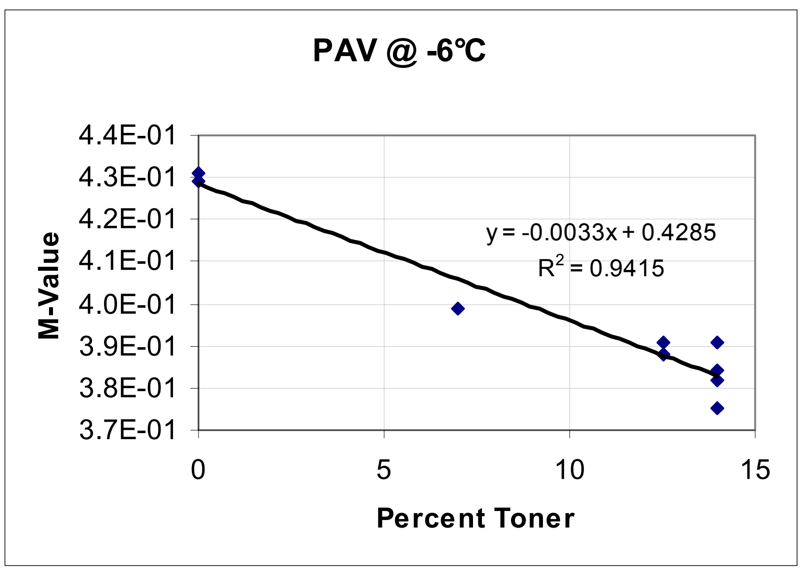


Figure B.2.v Logarithmic creep rate (m-value) values from BBR

3. BINDER DESIGN FOR LAREDO

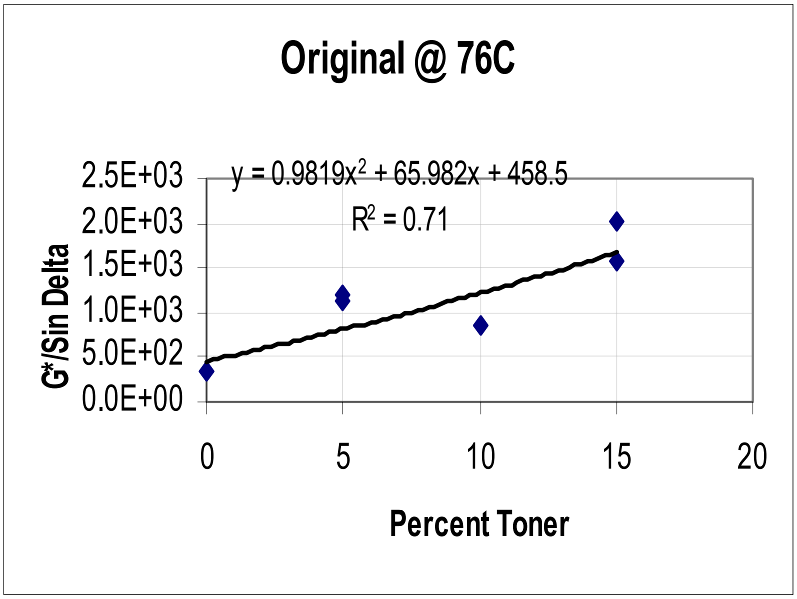


Figure B.3.i Test results from DSR for the original binder modified with different toner amounts

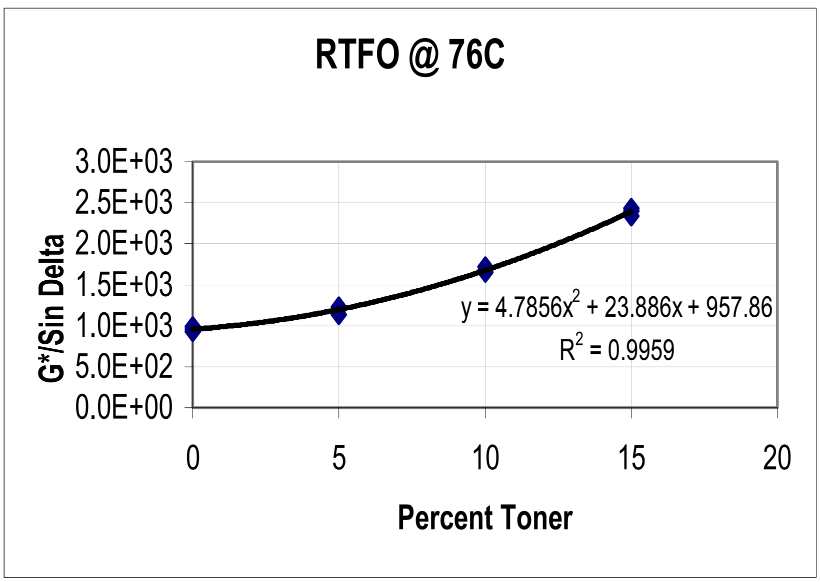


Figure B.3.ii Test results from DSR for the RTFO-aged binder modified with different toner amounts

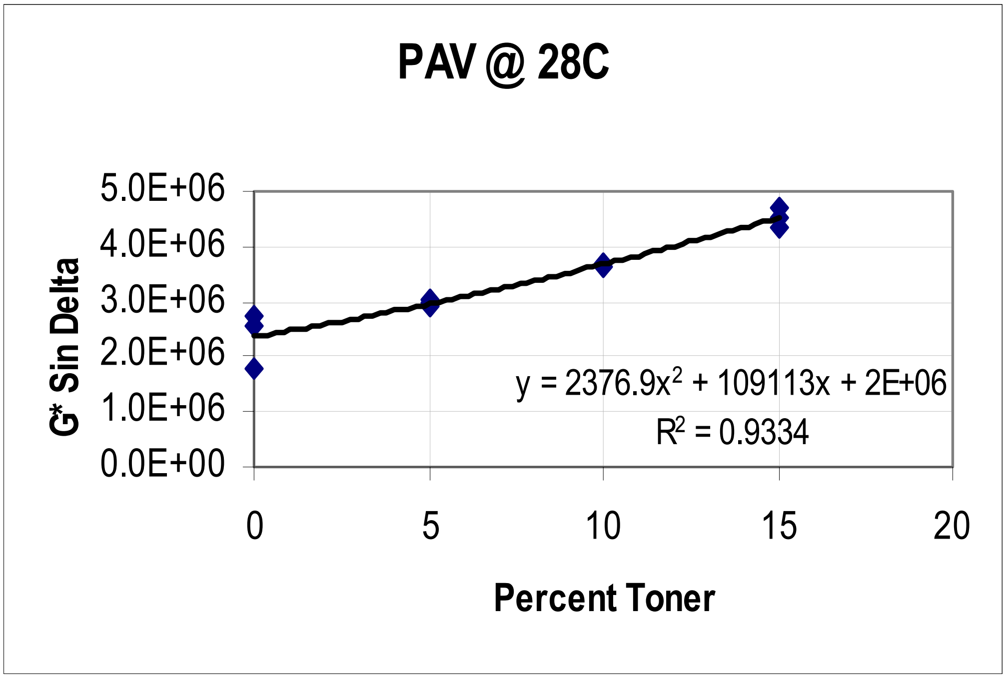


Figure B.3.iii Test results from DSR for the PAV-aged binder modified with different toner amounts

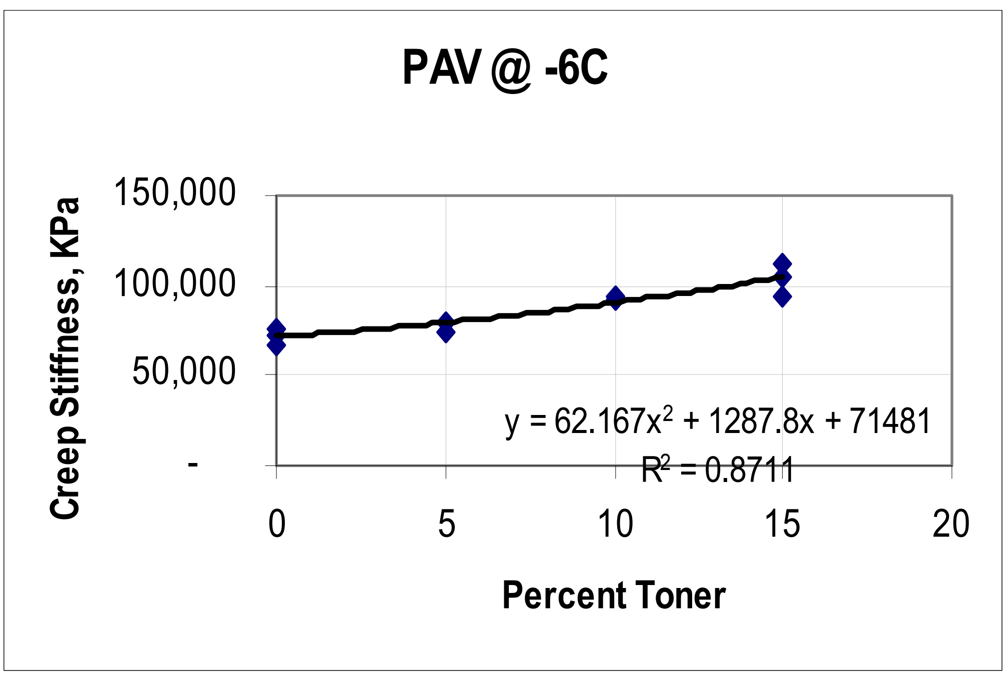


Figure B.3.iv Creep stiffness values from BBR

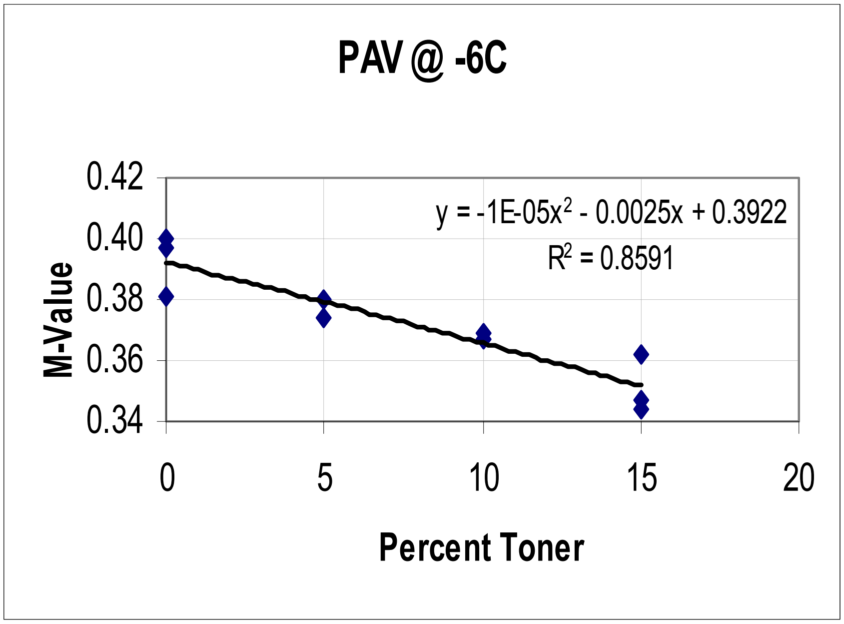


Figure B.3.v Logarithmic Creep rate (m-value) values from BBR

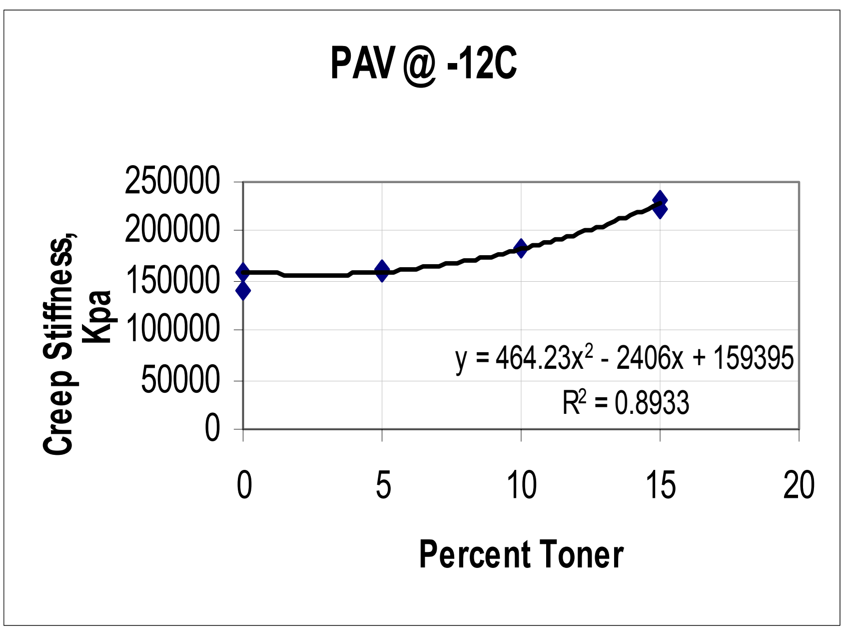


Figure B.3.vi Creep stiffness values from BBR (–12˚C)

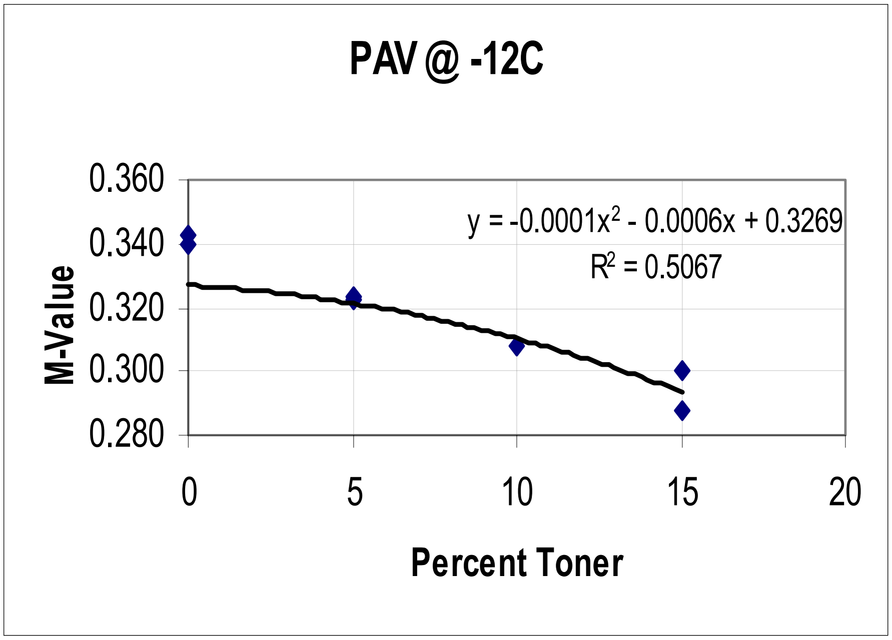


Figure B.3.vii Logarithmic creep rate (m-value) values from BBR (–12˚C)