Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-97/3933-1F		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
USE OF WASTE TONER IN ASPHALTIC CONCRETE	5. Report Date: February 1997 6. Performing Organization Code:
7. Author(s) Mansour Solaimanian, Thomas W. Kennedy, and Robert B. McGennis	8. Performing Organization Report No. Research Report 3933-1F
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, Texas 78705-2650	10. Work Unit No. (TRAIS) 11. Contract or Grant No. Research Study 7-3933
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Final 14. Sponsoring Agency Code

15. Supplementary Notes

Study conducted in cooperation with the Texas Department of Transportation.
Research study title: "Use of Waste Toner in Asphaltic Concrete, Phase II"

16. Abstract

Every year, a tremendous amount of toner is produced for copiers and printers by toner manufacturing companies throughout the United States. Some of this toner does not meet quality specifications and consequently 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 for lack of a better way of utilizing the material.

A cooperative research project 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. The research program included procuring a number of different waste and spent toners, blending them with asphalt cement at different ratios, and evaluating the binder and mixtures properties resulting from the waste toner addition. 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, a Superpave mix design was carried out for three different levels of toner modification (0 percent, 5 percent, and 16 percent, by mass of asphalt binder-toner blend).

The results of this study indicated that as the amount of waste toner in the blend increases, the stiffness and the viscosity of the modified binder increase. The increase in stiffness is evident at high, intermediate, and at 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. However, the toner-modified binder is expected to perform satisfactorily in areas where permanent deformation is of great concern, and where some increase in low-temperature stiffness will not cause cracking problems.

We found that an AC-20 asphalt cement (based on the viscosity grading system), which is graded as PG64-28 in the Superpave performance grading system, will grade as PG70-22 with the addition of 10 percent waste toner. In northern and central Texas, a PG64-22 asphalt cement is expected to perform satisfactorily, based on a 98 percent reliability. Therefore, the AC-20 asphalt cement modified with 10 percent waste toner, as investigated in this research, satisfies the performance criteria for such regions.

17. Key Words	18. Distribution Statement
Waste toner, asphaltic concrete	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	70	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

USE OF WASTE TONER IN ASPHALTIC CONCRETE

by

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Research Report 3933-1F

Research Project 7-3933
Use of Waste Toner in Asphaltic Concrete

conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

by the

CENTER FOR TRANSPORTATION RESEARCH
Bureau of Engineering Research
THE UNIVERSITY OF TEXAS AT AUSTIN

February 1997

IMPLEMENTATION RECOMMENDATION

The results of this research study indicate that waste toner has the potential to be used as an asphalt modifier. A test section is expected to be built based on the findings of this research program to evaluate the mixture behavior under realistic field conditions. If satisfactory field performance is also observed, both the pavement industry and toner manufacturers will benefit from using waste toner in asphalt concrete. In addition, valuable space will be saved in landfills which are constantly being filled with different waste materials. It is anticipated that special specification items, dealing with hot mix asphalt concrete, will be affected if waste toner is accepted by TxDOT to be used in asphalt concrete.

Prepared in cooperation with the Texas Department of Transportation

PREFACE

This is the first and final report for research projects 7-2916 and 7-3933, "Use of Waste Toner in Asphaltic Concrete, Phases I and II." This study was established and sponsored by TxDOT to investigate the feasibility and benefits of utilizing waste toner in asphalt concrete. The project was carried out during a 6-month period. An extensive amount of laboratory testing was performed during this period to provide sufficient information for the subject project. This report presents the test results, findings, conclusions, and recommendations based on the conducted work.

The success of this project was made possible only through the cooperation and assistance of a number of dedicated people. Special thanks are extended to Mr. Rakesh Tripathi, the director of the research project, and Mr. Kirby Pickett, District Engineer of Waco, who provided the research team with valuable guidance through the course of the program. The valuable comments of Ms. Rebecca Davio and Ms. Lisa Lukefahr of TxDOT are truly appreciated. The authors also gratefully acknowledge the efforts of Mr. Eugene Betts and Mr. Weng Tam, who were highly involved in carrying out the required laboratory tests. The support of the Center for Transportation Research is also greatly appreciated.

We are also very grateful to Mr. Housam El Jurdy of Ricoh Electronics Inc., Mr. Daniel Wilburn of SHARP Manufacturing Corporation of America, and Mr. Paul Rossi of Canon Virginia Incorporated for providing the research team with the required waste toner. Special thanks are also extended to Mr. Arthur Diamond of Diamond Research Corporation for providing the research team with valuable information.

DISCLAIMERS

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SUMMARY

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CHAPTER 1. INTRODUCTION

1.1 UTILIZING WASTE TONER IN ASPHALT

State agencies are constantly seeking ways of enhancing performance of hot mix asphalt pavements through improved designs, workmanship, and materials (and at a reasonable cost). In this regard, one approach pursued is to modify conventional asphalt binders and mixtures with different kinds of materials, including recycled and waste materials. Obviously, both the environment and the paving industry benefit from the use of waste material in asphalt if improved pavement performance is gained. One reason for the benefit to the environment is due to the fact that landfills can hardly accommodate demand and are quickly reaching capacity. Investigating the potential use of waste materials in asphalt is a large and growing area of research. At this time, there is considerable emphasis on the use of recycled materials for highway construction. Many states have initiated legislation to direct their highway agencies to investigate the possibility of recycling different waste byproducts into highway pavements.

In brief, societal and environmental concerns, diminishing landfills, and potential for cost-effective and improved pavement performance through recycled materials provide a strong incentive for agencies such as the Texas Department of Transportation (TxDOT) to consider landfilling waste in asphalt pavements. The term "linear landfill" was coined by *Asphalt Contractor Magazine* (1) to describe this trend.

The use of any waste material in asphalt pavements challenges the industries involved. There are three main questions to be addressed in regard to the use of waste materials in asphalt pavements:

- What are the environmental effects of the use of the waste material in asphalt pavements (environmental analysis)?
- What are the costs and benefits associated with such an action (economic analysis)?
- How practical is it to use the waste in the asphalt pavement and how is the pavement performance influenced by incorporating the waste material (engineering analysis)?

In regard to the environmental issue, one needs to determine if there are any hazards as a result of exposure to the waste product to be used (rather than landfilled). An economic analysis is crucial to determine how the costs (landfilling versus use in the pavement) are influenced. Finally, the issue of pavement performance and feasibility of utilizing the waste material in asphalt needs to be addressed. It is also important to know if incorporation of the waste requires special equipment and techniques.

With respect to the resulting asphalt material properties and pavement performance, incorporating a waste product can

- enhance some or all of the properties,
- have no effect, or
- have a detrimental effect

Agency strategy regarding the last two instances is fairly straightforward. It is assumed that if there is a detrimental effect, an agency such as TxDOT would not consider the use of the waste product, since the investment would not be cost effective. In the case where there is no effect, an agency has to decide whether the slightly (or possibly greatly) increased cost of handling the material is worth doing society the favor of disposing of the material. Traditionally, agencies have elected not to incorporate such products, though that situation may change in the future as landfilling and tipping fees increase.

By far the scenario requiring the most attention occurs when the waste product shows potential for improving one or more properties of asphalt materials. Inevitably, the product must translate from being a waste product to being a viable construction material (considering the economies of such materials). Examples of products that have made this transition include scrap tires, waste polyethylene, waste cellulose, and fly ash. This last material, used in portland cement concrete, is an excellent example of a material that was formerly considered waste but, through research and experience, was demonstrated to offer considerable advantages to the construction industry.

When a waste product is shown to have the potential to improve asphalt pavement performance, numerous questions must be answered prior to its widespread use. For example, is there enough of the material available to form a feasible product? Are there competent applications for the material that would affect the cost effectiveness of the material? Does the use of this material increase the cost, and, if so, is the increased cost of the material worthwhile in terms of the increased pavement performance? What engineering properties are enhanced? What engineering properties are sacrificed? How can the material be incorporated? How can the material be specified by a public agency?

1.2. WASTE TONER AS A MODIFIER

1.2.1. Description of Toner

Toner is the dry ink utilized in copiers, laser printers, and fax machines. It exists as an extremely fine solid powder, black in color, and with a slightly plastic odor. The acceptable range for the "powder grain size" varies for different manufacturers, depending on the type of material used and on the technology used in manufacturing. However, the average acceptable size is about 10 microns.

The dry powder in contact with the "developer" (micro-carrier) builds up an electric charge so that the ink "sticks" to the paper in the copy machine when it comes in contact with the paper. Typically, the toner is either a single-component type in which the main resin is a polyester-type material, or a double component type in which the main resin is styrene acrylate copolymer. The mono-component type is typically used in laser printers, while the double-component type is used in copiers. The common type of toner, as formed during the manufacturing process, comes from extrusion. In other words, the chemical components are mixed, heated, melted, and extruded to result in the specified toner.

The specific gravity of the toner grain particles varies between 1.0 and 1.7, depending on the type. The melting point is in the range of 100 and 150°C, and the ignition temperature is expected to exceed 350°C.

1.2.2 Handling and Safety

Toner is considered a non-toxic, non-hazardous dust. However, because of the extremely fine size of its dust particles, toner may cause respiratory tract irritation in those individuals exposed to large quantities and for long periods of time, as is the case with any fine non-toxic dust. In general, the material is not considered to cause any adverse environmental effects.

It is always good practice to be aware of and follow the guidelines outlined in the material safety data sheet of the product when handling the material or working with it. Good industrial hygiene practice should be followed, which includes preventing eye contact, minimizing skin contact, and avoiding inhalation. Dust generation and accumulation should be minimized. The toner container should be kept closed and adequate ventilation should be provided when using the material.

It is important that the waste toner be thoroughly examined for possible effects of static electric charges before attempts are made to blend this material with asphalt in large quantities. Such examination is important with respect to safety and handling. The waste toner is a resistive powder in regard to generation of electric charges. Transporting the material between different containers is not expected to impose any problems as long as transport pipes are properly grounded. The material is not combustible and is non-flammable. However, it should not be exposed to open flames, owing to the possibility of explosions. In this regard, it is like most other organic materials in powder form that are capable of creating a dust explosion.

1.2.3. Description of Waste Toner

The toner considered to be "waste" may come from two sources:

1. from the manufacturing process,
2. from copier machines and laser printer cartridges

Some distinguish between the two by using the term "waste toner" for the waste from manufacturing and "excess or spent toner" for the residue left in cartridges in copiers and printers. During the manufacturing process, toner that does not pass the specified grain size distribution range (finer or coarser than specification limits) is considered waste. Some of the waste is recycled back into manufacturing, and some (that which cannot be processed again) will be discarded. Spent toner is of a different particle size (compared with the original toner) and is contaminated with paper dust. In addition, spent toner is not capable of sticking to the paper owing to improper or insufficient charge.

1.2.4. Disposing of Waste Toner

The waste toner that cannot be recycled into the manufacturing process must be discarded. According to the manufacturers, most of the waste toner is placed in landfills. The same happens to the spent toner, either along with the cartridge, or by itself after rechargers have emptied the cartridge for reuse. Some remanufacturing companies have collection systems that guide the spent toner out of the cartridges into barrels. These barrels are eventually carried to the landfill. It is expected that considerable cost is associated with collection, transportation, and landfilling this waste material.

Another approach for disposing of the waste toner has been the incineration process (oxidation process). DeMulle (2) describes a catalytic incinerator developed at Spectrum Research Laboratory (SRL). The device operates at a temperature exceeding 2200°C, and incinerates about 400 kilograms of toner per day. The heat generated during the incineration is close to 2100 Megajoules. The generated heat can be recovered and converted into energy.

The toner industry has reported on the use of waste toner in different industries. For example, low percentages of this material have been used as pigment for plastic auto-parts. The hydrocarbons from the toner have also been extracted and used by some as fuel to a limited extent (3). According to one manufacturer, waste toner has been researched for use in rubber products, bumper guards, plastic furniture, and boiler gaskets (3). Waste toner has also been sought for use in compounding shoes (3). However, despite these uses, the major quantity of waste toner is landfilled.

1.2.5. Quantity of Waste Toner

It is not precisely known how much waste toner is produced and landfilled. According to some estimates, the total resulting both from manufacturing and from spent cartridges exceeds 9,000 metric tons per year (4). Obviously, not all manufacturers produce the same amount of waste. The amount depends on the technology and on the quantity of the toner produced in each plant. One manufacturer reports production of over 600 tons of waste toner per year based on a toner production level of about 7,700 tons per year (about 9 percent waste).

Clearly, businesses worldwide can produce thousands of spent cartridges daily. While some are discarded at dumpsites, most are sent to rechargers and cartridge manufacturers who empty the cartridges of the spent toner, and refill them with new toner. The quantities vary depending on how large the recharging facility is. Two recharging companies report receiving about 6,000 and 8,000 laser printer cartridges per month, respectively (3). Considering the number of such companies, and the amount of spent toner collected in each, it is estimated that the total quantity of waste toner is in the range of thousands of tons per year.

From these volume estimates, there appears to be a sufficient amount of the material to be used in pavements. The important matter is to investigate the effect of the material on pavement performance.

1.3. PAST EXPERIENCE WITH WASTE TONER IN PAVEMENTS

There have been reports of two cases where waste toner has been used in asphalt pavements on an experimental basis. The first comes from the work of Ayers and Tripathi (5), who report of a test section placed in Oklahoma in 1990, after a period of evaluating the toner-modified asphalt in the laboratory. Apparently, the test section is still in good condition. The waste toner was directly added to the aggregate before blending it with asphalt cement.

The second experiment is reported by Diamond (4) for a resurfacing job on I-15 in Nevada. The waste toner was simply added to the aggregate as in the Oklahoma project. Overall dissatisfaction was expressed and it was reported that working with the material was difficult (e.g., black dust created from the fine powder was a nuisance). There is no evidence regarding how much of the toner was really used in this project, and for what length of roadway. Problems with rolling and poor adhesion were also reported.

1.4. RESEARCH APPROACH

This research program was carried out in three phases: (1) a feasibility study, (2) a study of engineering properties, and (3) an investigation of the most viable methods of incorporation. The feasibility study ascertained whether sufficient waste toner existed to offer a viable asphalt material modifier. During the second phase, engineering properties were measured both on binders and mixtures modified with waste toner. In the final phase, the most viable methods of incorporating waste material into asphalt binder and/or mixtures were investigated.

Chapter 2 describes the experimental program and the tests performed. Chapter 3 includes a detailed discussion and analysis of the results of the research program. Finally, the conclusions and recommendations are presented in Chapter 4.

CHAPTER 2. EXPERIMENTAL PROGRAM

This research program was carried out in three phases: (1) a feasibility study, (2) an engineering study, and (3) an analysis of methods of incorporation. This chapter describes the three phases of the experimental program.

2.1. FEASIBILITY STUDY

This phase of the program included the following: (1) identifying different types of toners and their components, (2) investigating the commercially available quantities of waste toner, and (3) identifying alternative uses of waste toner.

This phase was accomplished by contacting manufacturers. Different manufacturers and their locations were determined. The material safety data sheets on different toner products were collected. The quantities produced were investigated. Some manufacturers were not willing to disclose information regarding quantities of toner, the waste, or their chemical compositions.

Competing uses for the waste toner were investigated. This investigation was necessary since, if it was found that a competing use placed a relatively high value on waste toner, it would make it uneconomical for use in paving applications. As mentioned in Chapter 1, however, at this point the use of waste toner in other industries is very limited, and no competition was identified. The feasibility study was explained in Chapter 1.

2.2. ENGINEERING STUDY

The portion of the program was focused on determining the changes occurring in the engineering properties of both the binder and the mixture with the addition of the waste toner. The following describes this phase of the experimental program.

2.2.1. Asphalt Binder Modification

2.2.1.1. Tests performed and properties measured: Two different asphalt cements and four different levels of waste toner modification were used to determine the effect of toner on the asphalt properties, as indicated in Table 2.1. In addition, an experiment was developed to compare the differences between different toners and an inert filler (Table 2.2).

An experimental problem regarding waste toner as an asphalt binder modifier is that of reaction time. It is required to know how long stirring of the modifier (waste toner) in the asphalt cement needs to be continued in order to obtain a homogenous binder. In fact, all particulate modifiers exhibit a trend toward reaction time dependent properties. For example, a study of fine crumb rubber modifier (CRM, 6) showed that an optimum reaction time of 1 hour was suitable for blends of fine CRM and asphalt. In another study (7) it was found that a reaction period of 24 hours was necessary to achieve mechanical equilibrium for a blend of asphalt and fine ground phenolic resin. Of course, such time is dependent on the type and intensity of agitation and stirring, as well as on the temperature at which blending takes place. However, as part of the binder study, the first step in this experiment was to make a brief check on the reaction time dependency of waste toner modified binders, as well as on the required mixing time. To accomplish this step, 10 percent waste toner was blended using a "Lightnin" mixer with an AC-20 and reacted for 30, 60, 90, and 120 minutes at a constant temperature of 163°C and at a stirring rate of 500 revolutions per minute. At the end of the reaction period, a sample of the binder was equilibrated to 64°C and tested for complex shear modulus G* and phase angle δ. Table 2.3 indicates the experiment carried out for this purpose.

Table 2.1. Testing Matrix for Binder Modification Evaluation

Binder (1)	Waste Toner (2) %	Unaged Binder				RTFO(3)	PAV (4)	
		Storage Stability	Vis. at 135°C	Vis at 165°C	G* (5) & δ (6)	G* & δ	G* & δ	S (7) & m (8)
AC-5	0	√	√	√	√	√	√	√
	5	√	√	√	√	√	√	√
	10	√	√	√	√	√	√	√
	16	√	√	√	√	√	√	√
AC-20	0	√	√	√	√	√	√	√
	5	√	√	√	√	√	√	√
	10	√	√	√	√	√	√	√
	16	√	√	√	√	√	√	√
AC-45P	0				√	√	√	√

1. Binder was from coastal refineries
2. Percent by mass of asphalt binder-toner blend
3. Rolling thin film oven
4. Pressure aging vessel
5. Complex shear modulus
6. Phase angle
7. Creep stiffness
8. Logarithmic creep rate

Table 2.2. Testing Matrix to Compare Different Waste Toners

Binder	Modifier Type	Waste Toner %	Unaged Binder				RTFO	PAV
			Vis. at 135°C	Vis at 165°C	G*& δ	G* & δ	G* & δ	S & m
AC-20	Toner 1 (1): WT1	10	√	√	√	√	√	√
	Toner 2 (2): WT2	10	√	√	√	√	√	√
	Toner 3 (3): WT3	10	√	√	√	√	√	√
	Cartridge (4): WT4	10	√	√	√	√	√	√
	Inert Filler (5)	10	√	√	√	√	√	√

1. From the first toner manufacturer (with designation WT1)
2. From the second toner manufacturer (with designation WT2)
3. From the third toner manufacturer (with designation WT3)
4. From spent cartridge out of a copier machine (with designation WT4)
5. Ground silica powder (inert filler)

Table 2.3. Testing Matrix to Determine the Required Stirring Time

Binder	Modifier Type	Waste Toner %	Stirring Period, minutes	Unaged Binder	
				Vis. at 135°C	G*& δ
AC-20	Cartridge Spent Toner	10	30	√	√
		10	60	√	√
		10	90	√	√
		10	120	√	√

2.2.1.2. Description of Tests: TxDOT has expressed its intent to adopt the Superpave binder specification within the next several years. Consequently, most of the measurements in the above matrices are aimed at determining binder characteristics in terms of Superpave performance-based binder tests. In fact, these tests are ideally suited to measuring the performance enhancing effect of modified binders. This protocol has been successfully used to characterize particulate-filled binders, including binders containing fine crumb rubber (6). A brief description of these tests follows.

Measurement of binder viscosity was accomplished at 135°C and 165°C using a rotational viscometer (ASTM D4402). Viscosity at 135°C was measured to determine the effect of waste toner on handling and pumping properties. Measurements of viscosity also took place at 165°C so that viscosity-temperature relationships could be developed for determination of temperatures required for mixing with aggregate and compaction.

Storage stability was measured using AASHTO PP5-93, which is a measure of long-term stability of a modified binder. The test requires the following steps:

- The modified binder is strained through a 300-μ sieve.
- Fifty grams of the filtered sample is poured into an aluminum tube and held in a vertical position at all times.
- The top of the tube is sealed and the sample is placed in a 163°C oven for 48 hours.
- The sample is removed from the oven, and immediately placed and left in a freezer at -5°C.
- The tube is cut into three pieces. The top, middle, and bottom pieces are each placed in a different container and held at 163°C to remove the aluminum pieces.
- The resulting specimens are tested for complex shear modulus using the dynamic shear rheometer.

Complex shear modulus (G*) and phase angle (δ) are measures of the overall shear stiffness and viscous behavior of an asphalt binder. In this experiment, they were measured using a Bohlin Instruments' dynamic shear rheometer (DSR) at The University of Texas at

Austin's Transportation Materials Laboratory, in accordance with AASHTO TP5. In a dynamic shear rheometer, the shear strain response of an asphalt binder to a dynamic shear stress is measured (Figure 2.1). Shear stress is applied in a dynamic oscillatory shear mode at 10 radians per second. G* is computed as the ratio of the maximum shear stress (τ_{max}) to the maximum shear strain (γ_{max}). Because of the viscoelastic properties of asphalt binders, the shear strain response is out of phase with the applied shear stress. The time lag between applied stress and resulting strain is converted to a phase angle (δ).

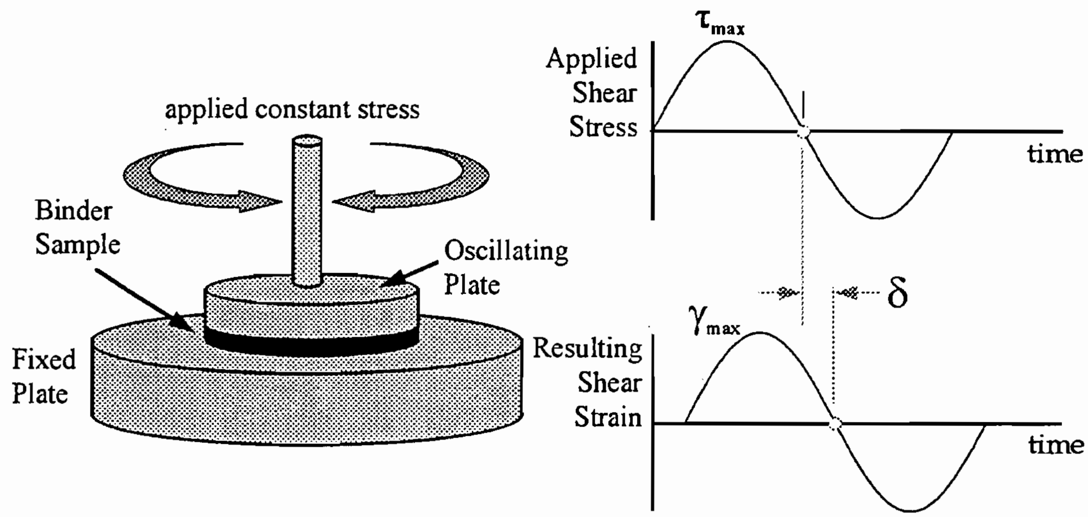


Figure 2.1. Principles of a Dynamic Shear Rheometer

G* and δ were measured on unaged binder, on binder short-term aged in a rolling thin-film oven (RTFO), and on binder long-term aged in a pressure-aging vessel (PAV). The RTFO test, conducted according to AASHTO TP240, simulates binder aging in a hot mixing facility. Thus, measuring G* and δ on RTFO residue should estimate whether tender mix behavior or rutting resistance is affected by the addition of waste toner.

The PAV creates a long-term aged binder with properties similar to those associated with an eight-year pavement. In PAV, the binder is aged under a pressure of 2070 kPa and at 100°C for 20 hours. Measuring G* and δ on PAV residue will estimate whether the waste toner modified binders are too stiff at intermediate temperatures (which would create a mix susceptible to fatigue cracking). These parameters were measured at intermediate temperatures of 19°C and 25°C. PAV tests were conducted according to AASHTO PP1.

Finally, creep stiffness (S) and logarithmic creep rate (m) were measured on binders at -12°C and -18°C according to AASHTO TP3. S and m are measured on PAV residue. These properties were measured using a Cannon bending beam rheometer (BBR) at The University of Texas at Austin's Transportation Materials Laboratory. The bending beam rheometer is used to measure the low temperature creep response of asphalt binder. The principles of BBR are illustrated in Figure 2.2. A one-Newton load is applied to a small prismatic asphalt beam specimen for 240 seconds. A deflection transducer is used in BBR to measure deflection as a function of time ($\Delta(t)$). S is computed at 8, 15, 30, 60, 120, and 240 seconds by using simple engineering beam principles. The slope of the logarithm of creep stiffness versus logarithm of loading time curve at 60 seconds is the m-value. A higher m-value means that a binder is more effective at shedding stresses that build up in asphalt when the pavement temperature drops. Measuring S and m on PAV residue will estimate whether waste toner modified binders are too stiff at low temperatures and whether such modification creates a mix susceptible to low temperature cracking.

In general, the strategy behind modifying binders is to depend on the base asphalt to provide suitable low temperature properties while depending on the modifier to provide suitable high temperature properties. Regions with periodic cold weather might use a modified AC-5. Regions susceptible to prolonged hot weather would likely use modified AC-10 or AC-20. For this experiment, AC-5 and AC-20 were selected to efficiently cover this range of materials. For comparison purposes, results from an additional control asphalt, AC-45P, were used. This binder is used in Texas for a variety of hot weather applications.

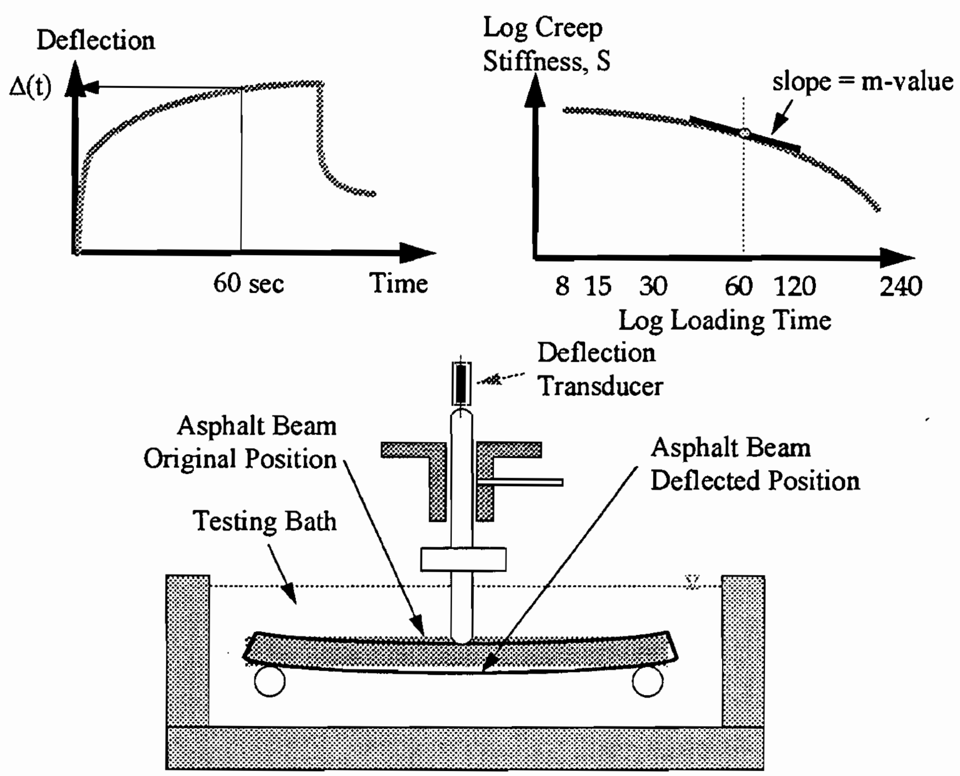


Figure 2.2. Principles of the Bending Beam Rheometer

2.2.1.3. Dosage Rate of Waste Toner: The dosage rates of waste toner proposed for use in this experiment are 5, 10, and 16 percent by mass of asphalt-toner blend. Five to 10 percent represents a dosage range commonly used for particulate binder modifiers. Based on experience with similar particulate materials, dosage rates higher than 10 percent may cause handling difficulties if waste toner is to be used as a binder modifier. The only proven way to achieve higher dosage rates with particulate systems is to use expensive stabilizers that effectively transform the binder into a colloidal system. While that may be possible for waste toner, it is beyond the proposed resources of this project. However, a dosage rate of 16 percent was adopted in order to frame the results in terms of the work of Ayers and Tripathi (5), who used 16 percent as the highest rate.

2.2.2. Asphalt Mixture Modification

In this task, a control asphalt mixture was employed with two dosage rates to measure the effect of waste toner on asphalt mixture characteristics. The testing matrix shown in Table 2.4 was used. The mixture dosage rates shown represent the range used in the binder analysis phase.

The control mix (i.e., 0 percent waste toner) was a Superpave-design-based mix for an Austin District project. The design was developed at The University of Texas at Austin's Transportation Materials Laboratory. It roughly corresponds to a TxDOT Type C mix and is composed of a blend of 30 percent crushed limestone C-Rock (non-polishing source), 20 percent crushed limestone D-Rock, 25 percent crushed limestone F-Rock, 15 percent crushed limestone washed screenings, and 10 percent unwashed screenings.

Table 2.4. Testing Matrix for Asphalt Mixture Analysis

% Waste Toner[1]	Binder Content[2] %	Hveem Stability	VMA[3]	VFA[4]	Compaction Slope[5]	Resilient Modulus	Indirect Tensile Strength	Indirect Tensile Strain
0	√	√	√	√	√	√	√	√
5	√	√	√	√	√	√	√	√
16	√	√	√	√	√	√	√	√

[1] Percentage is by mass of binder-toner mix
[2] Binder content at 4% air voids in Superpave gyratory compactor
[3] Voids in the mineral aggregate
[4] Voids filled with asphalt
[5] Compaction slope k in Superpave gyratory compactor

For each trial blend of aggregates, Texas Test Method Tex-204-F was used to arrive at a binder content at 4 percent air voids. At that binder content, mixture volumetric properties such as voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA) were determined. In addition, Hveem stability, which is TxDOT's primary mixture design strength test, was measured using Tex-207-F.

The compaction slope was measured using the Superpave gyratory compactor (SGC). A schematic of the SGC is shown in Figure 2.3. The SGC applies a constant compaction pressure of 600 kPa at a compaction angle of 1.25.° During compaction, specimen height is recorded, which allows density to be estimated at any point throughout the compaction process.

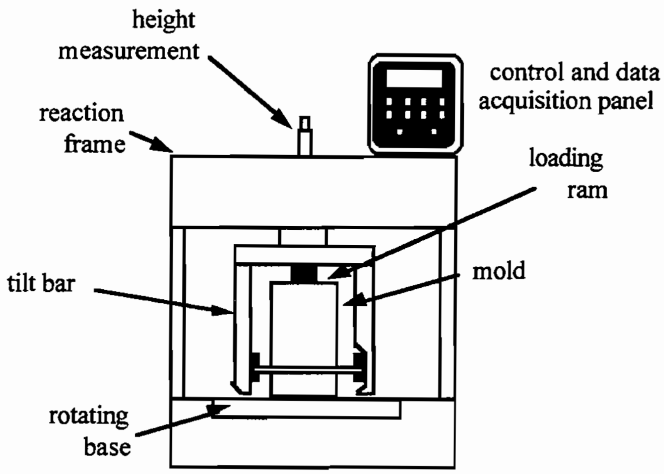


Figure 2.3. Features of the Superpave Gyratory Compactor

As a result, densification relationships such as that shown in Figure 2.4 are developed. The slope of the relationship between relative density and logarithm of the number of gyrations is an indication of aggregate structure for the same binder content. The purpose of determining compaction slope in this experiment was to measure the effect of waste toner on aggregate structure. When plotted in the manner shown in Figure 2.4, steeper compaction slopes are an indication of a tougher stone skeletons

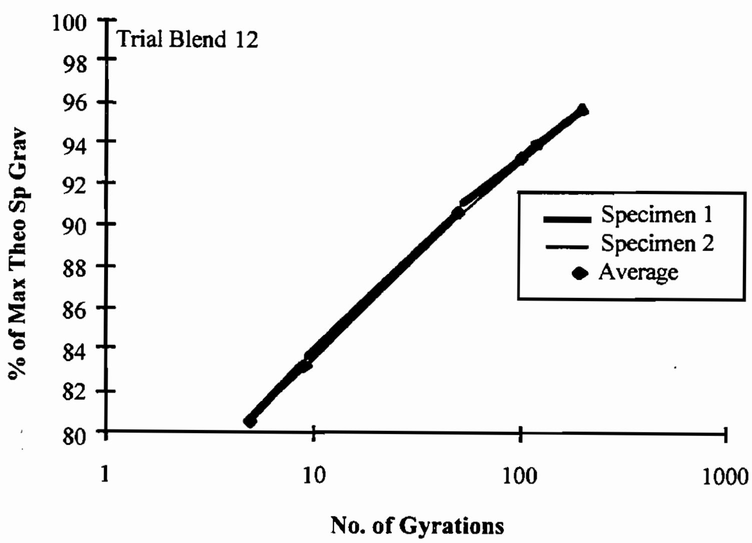


Figure 2.4. An Example of Densification Plot for a Superpave Mix Using SGC

Resilient modulus of the mixes was determined in accordance with ASTM D4123. This step illustrates the effect of waste toner on stiffness characteristics of the mixes. This is necessary to estimate the structural contribution of waste-toner-modified mixes. The indirect tensile strength and tensile strain at failure were also measured in accordance with ASTM D4123.

2.2.3. Methods of Incorporation

The purpose of this task was to identify potential ways of incorporating waste toner into asphalt binders and/or mixtures. Because of the nature of this project, it was assumed that TxDOT does not intend for new methods to be developed. Instead, it was assumed that the research would proceed by a literature search to identify existing fine particle incorporation methods that exhibit potential for waste toner. Because the final phase of this project might involve full-scale production of a waste toner modified mix, the research was aimed at identifying and determining the best incorporation method in case waste toner would gain wide acceptance. It was also directed toward a practical method that could be used by a contractor in the Waco District for the test project.

2.2.3.1. Binder Methods: Numerous methods exist to incorporate particulates into asphalt binders. Many of these methods involve the use of a carrier oil or dispersant. As Ayers and Tripathi (3) point out, however, these dispersants often have adverse effects on binder properties and overwhelm the effect of the modifier. In 1989, the American Gilsonite Company developed a method for blending finely ground gilsonite into asphalt binders. This approach was successfully field tested on a project in the San Antonio District. Other systems, such as those developed by the Rouse Rubber Company and Novophalt Corporation, might also be used.

2.2.3.2. Mixture Methods: Utilizing waste toner as a mixture modifier presents a special challenge. Volumetric proportioning might be necessary to accurately meter waste toner. This would involve use of a rotating vane type of feed system, which is sometimes used for mixture modifiers like hydrated lime.

In recent years, mass metering of mixture modifiers has been developed to a greater extent. Augering systems have been used, with varying degrees of success, to incorporate mineral fillers, baghouse fines, and other fine aggregate systems. Pneumatic feed systems also have been used for these materials, though these systems have not exhibited consistent accuracy. It may be that the best approach is to use existing systems developed for incorporating baghouse fines, but modified to handle low specific gravity materials like waste toner. Recently, on projects in Texas and elsewhere, cellulose fibers have been incorporated into stone matrix asphalt (SMA) to function as a stabilizer to retard draindown. It is possible that the systems used for incorporating cellulose may prove to be the best method for waste toner, since cellulose is also a relatively low specific gravity material.

CHAPTER 3. ANALYSIS AND DISCUSSION OF RESULTS

Laboratory testing and analysis of the binders and mixtures were carried out according to the experimental program outlined and discussed in Chapter 2. The results of this testing and analysis are presented in this chapter. The analysis of results will be presented in two sections: (1) the binders modified with waste toner, and (2) the mixtures prepared with toner-modified binders.

3.1. THE BINDERS MODIFIED WITH WASTE TONER

The binder results are presented in the following categories:

a. storage stability
b. reaction time and stirring period
c. effects of amount of waste toner in asphalt cement
d. effects of waste toners from different manufacturers
e. effects of waste toner on binder properties compared with that of inert filler
f. effects of waste toner on binder properties compared with that of polymers

3.1.1. Storage Stability

The results of storage stability for one of the waste toners are shown in Figure 3.1 (figures for this chapter begin on page 23; see also Table A.2 in the appendix for numerical values). The figure indicates the results for complex shear modulus for samples taken at the top, middle, and bottom of the test tube. It can be observed that the material is not sufficiently stable at storage. The bottom sample indicates about 10 percent higher modulus than the top sample. This result is for the 10 percent waste toner level. Table A.2. also indicates the results for the rotational viscosity. The bottom portion of the tube indicates about 18 percent higher viscosity than that for the top portion of the tube. It is expected that the difference in results from top and bottom portions will be higher if higher levels of waste toner are utilized. Therefore, it is necessary to agitate the binder-toner blend before it is utilized in the mixture.

3.1.2. Reaction Time and Stirring Period

The results of the effect of stirring period are presented in Figure 3.2 (see also Table A.3 in the appendix for the numerical values). Ten percent waste toner was used and blending was carried out at 500 revolutions per minute at 163°C. Samples were taken at intervals of 30, 60, 120, and 240 minute blending periods. The results plotted in Figure 3.2 indicate that as the blending period increases, the complex modulus from DSR increases. However, as stirring takes place for a longer period, the rate of change in stiffness is reduced. It can be reasonably assumed that after two hours of agitation, the binder-toner mastic is sufficiently homogenous. Visual observation of the modified binder indicated a fairly homogeneous material with no visible lumps after two hours of stirring.

It is important to keep in mind that the type and rate of shear blending can influence the properties of the toner-asphalt blend. For this project, mixing was conducted with the aid of a Lighnin™ mixer (Model L1U08) with a three-blade impeller (7.6-cm, or 3-inch, diameter) at a rate of 500 revolutions per minute (RPM). Different mixing and pumping actions can affect the quality of the blend and the final product. If blending is performed at a significantly higher speed (very high rate shear blending) with a impeller capable of a very high pumping action, a homogenous blend may be obtained more quickly.

3.1.3. Comparing the Effects of Utilizing Different Amounts of Waste Toner in Asphalt

The results of utilizing different amounts of waste toner in asphalt are shown in Figures 3.3 through 3.7 (see also Figures A.1 through A.10 as well as Tables A.1 of the appendix for numerical values). The results are for three different levels of toner used with two binders (Coastal AC-5 and Coastal AC-20), and for the following properties: complex shear modulus and phase angle from dynamic shear rheometer at high and intermediate temperatures, creep stiffness and logarithmic creep rate from bending beam rheometer at low temperature, percent mass loss from rolling thin-film oven test, and rotational viscosity.

A stiffening effect is obviously observed as the amount of toner is increased in the toner-binder mastic at all temperatures. The increase in complex modulus (Figures 3.3 and 3.4) follows a parabolic trend in the sense that at higher concentrations of the toner, the stiffening effect is increasingly significant. For example, for both the AC-20 and AC-5 binders, adding 16 percent waste toner has increased the $G^*/\sin\delta$ 3 to 4 times when compared with the corresponding neat asphalts. In general, as the amount of toner increases, the phase angle decreases (both at intermediate and high temperatures) implying that the ratio of loss modulus (viscous component) to storage modulus (elastic component) becomes smaller (Figure 3.4). This change is considered a favorable effect. However, it can be observed that the change in phase angle owing to increasing the amount of toner is more significant for AC-5 than for AC-20. For example, the phase angle at 64°C is reduced only about 6 percent when 16 percent toner is added to AC-20, while over 13 percent reduction in phase angle is observed when this amount of toner is added to AC-5.

The increase in stiffness can also be observed at low temperatures as the results from the bending beam rheometer indicate (Figures 3.5 and 3.6 and Table A.1). However, the change in stiffness resulting from the use of the waste toner is more significant for the softer asphalt (i.e., for the AC-5 which exhibits 80 percent increase in stiffness as a result of adding 16 percent waste toner compared with AC-20 which exhibits about 60 percent increase at this toner level). It can also be noticed that the logarithmic creep rate (m) decreases as more toner is used. This decrease in m value implies that the rate of change of stiffness with time is reduced with more toner. Excessively low m value is not desirable, since it indicates that the binder does not relax rapidly enough under stress and, consequently, the chances for thermal cracking increase. The classification of binders in the Superpave PG grading system is shown in Table 3.1.

Table 3.1. Classification of Binders (Performance Grading)

AC Gr.	% Waste Toner	High Temp. °C	Low Temp °C	Interm. Temp. °C	Grade	AC Gr.	% Waste Toner	High Temp. °C	Low Temp. °C	Interm. Temp. °C	Grade
20	0	64	-28	22	64-28	5	0	52	-34	19	52-34
20	5	70	-22	28	70-22	5	5	58	-34	13	58-34
20	10	70	-22	28	70-22	5	10	64	-22	25	64-22
20	16	76	-16	34	76-16	5	16	70	-22	28	70-22

It can be seen that, for example, the neat AC-20 Coastal binder classifies as a PG 64-28. The binder-toner mastic with 10 percent waste toner classifies as a PG 70-22. Therefore, both high and low temperature properties are highly affected as a result of this modification. In general, it appears that the toner improves the high-temperature properties of the binder, while it adversely affects the low temperature properties. However, this impact on low-temperature stiffness may not pose problems in the regions where excessive low-temperatures are not common and hot summer temperatures are of concern. For example, for the Waco District, a PG64-22 binder is required at a 98 percent reliability level. Therefore, the AC-20 modified with 10 percent waste toner meets the performance criteria for the Waco District.

3.1.4. Comparing the Effect of Different Waste Toners

The results of this section of the study are presented in Figures 3.8 through 10 (as well as in Table A.4 in the appendix). Three waste toners from three different manufacturers, including the spent toner from a copier machine (designated by symbol WT4 in this report), were used for comparison. The amount of waste toner blended into asphalt in all cases was 10 percent by weight of the asphalt-toner mastic, with the initial assumption that all of them have approximately the same specific gravity. Consequently, the percent volume in the blend for all of them would be the same. However, it was later discovered that there were differences in specific gravities, so that percent volume of waste toner is not the same for all the them. The following table indicates the volumes of the waste toners used as a percent of the volume of the asphalt-toner:

Modifier	WT1	WT2	WT3	WT4	Filler
Sp. Gr.	1.08	1.1	1.4	1.1	2.65
% Weight(1)	10	10	10	10	21
% Volume(2)	9.4	9.3	7.0	9.3	9.3

(1) As a percent of the total mass of the asphalt-additive mastic
(2) As a percent of the total volume of the asphalt-additive mastic

Figure 3.8 indicates that there are differences in behavior of unaged binders modified with different waste toners. While WT3 has been used with the lowest volume in the blend compared with the other waste toners, it has resulted in the highest complex shear modulus for the unaged binder. For the RTFO and PAV-aged binders, WT3 results are comparable with those from other waste toners. However, results should be interpreted with caution since WT3 has been used at 7 percent volume level and others have been used at around 9 to 10 percent volume level.

The results for rotational viscosity and stiffness after long-term aging are shown in Figure 3.9. The results indicate that viscosity values are within a close range for different waste toners.

The creep stiffness at -18°C varies between 300 to 400 MPa for binders modified with different types of waste toners. They all yield higher stiffness values compared with the neat AC-20, which has a creep stiffness of about 279 MPa at -18°C. It can be seen that WT2 yields the highest creep stiffness (S) and lowest logarithmic creep rate (m) compared to all the others. The reason for this behavior is not clear, considering the similarity of this waste toner to WT1 and WT4. One difference between WT2 and waste toners WT1 and WT4 is that WT2 has more than 90 percent styrene acrylate copolymer, while the other two have between 80 to 90 percent of this copolymer. WT3, which exhibited the highest shear modulus for unaged and short-term aged binders (Figure 3.8), has 45 to 55 percent styrene acrylate copolymer.

3.1.5. Comparing the Effect of Waste Toner on Binder Properties with that of Inert Filler Materials

As defined in this study, the filler is considered the material passing the 0.075-mm sieve. In general, a filler material is used in hot mix asphalt because it provides more stability and strength. The main action of a filler is considered to be filling the voids between the coarse aggregates in the mixture. However, research has indicated that the function of the mineral filler is more than just void filling, and some physico-chemical interaction occurs between the asphalt and the filler (8 and 9). The effect of the filler on the binder depends on the geometric irregularities, such as shape, angularity, and surface texture. This last item affects the surface activity: capacity of the filler surface to absorb binder. Another very important factor is the size distribution of the filler material. The larger particles of a filler material probably serve to fill the voids between the coarse aggregates. However, very fine particles of filler may become suspended in the asphalt forming a mastic (8). Fine baghouse dust, primarily 0.02 millimeters and finer, tends to combine with the asphalt and act as an asphalt extender. Asphalt components are adsorbed by the suspended filler particles, resulting in an increase in viscosity.

We decided to compare the effect of the waste toner and the effect of an inert filler on binder properties. The reason for such comparison was to determine if the observed behavior of the binder-toner blend was simply a mechanical phenomenon. For this study, a ground crystalline silica sand powder was used as the filler material. This filler is manufactured primarily as a filler material for paints, coatings, adhesives, sealants, and ceramics. It is bright, white, angular or sub-angular, well-graded, low in moisture, inert, and at least 99.2 percent SiO_2. Ninety-eight percent of this material is finer than 40 μm. The mean particle diameter for this material is about 8 μm, which is comparable to that of toner particles. This silica powder has a specific gravity of 2.65, which is about 2.4 times the specific gravity of toners used in this research study. The volume of this material used in the binder-filler mastic was the same volume as that of the reference toner used in the binder. This means that more filler material by weight was used compared to the toner, so that the same volume could be obtained (because of the higher specific gravity of the silica filler compared to that of the toner).

The results are shown in Figures 3.8 through 3.10. Numerical values are presented in Table A.4 of the appendix. Figure 3.8 indicates that the silica powder filler results in $G^*/\sin\delta$ for both unaged and short-term aged binders, considerably less than that of waste toners. The complex modulus at intermediate temperatures and creep stiffness at low temperatures are within the same range as that for the toner-modified binders. The rotational viscosity of the filler-binder mastic is also less than that of toner-modified binders. In general, it can be concluded that the waste toners have a larger effect in increasing the binder stiffness at high temperatures, compared with the inert filler used in this study. In other words, the effect of the waste toner is more than a simple mechanical stiffening effect. However, at low temperatures, the effect of this filler cannot be easily distinguished from that of the waste toners.

3.1.6. Comparing the Effect of Waste Toner on Binder Properties with that of Polymers

The main constituent of the waste toners studied in the course of this research program is styrene-acrylate copolymer. Styrene and acrylic are both plastomeric in behavior, and both are in the group of thermoplastic materials. Three of the four waste toners used in this study have at least 80 percent of this copolymer, while one consists of about 50 percent styrene-acrylate and 50 percent iron oxide (WT3). Therefore, we decided to include a number of polymer-modified binders, including AC-45P for comparison.

For this research, the properties of toner-modified binders are compared with three polymer-modified binders: AC-30P (Gulf States Asphalt), AC-45P (Gulf States Asphalt), and AC-45P (Koch). AC-30P and AC-45P are modified binders with a minimum viscosity of 300 Pa.S (3000 poise), and 450 Pa.S (4500 poise) at 60°C, respectively, and with a minimum of 3 percent styrene-butadiene-styrene copolymer. Figure 3.8 indicates that the Koch AC-45P, while unaged, has a complex modulus comparable to that of the binders modified with waste toners. However, from the same figure it can be seen that the effect of long-term aging on this AC-45P binder is not so significant as it is on the toner-modified binders.

Unaged, short-term aged, and long-term aged binders modified with the waste toner have considerably higher modulus than the AC-30P, as can be seen from Figure 3.8. However, at very low temperatures (as shown for -18°C in Figure 3.9), the creep stiffness values and logarithmic creep rate values for waste toner binders and AC-30P are similar (other than WT2).

The results from bending beam rheometer testing at low temperatures indicate that waste-toner modified binders, to an extent, have a higher stiffness and lower creep rate than the neat AC-20 (Figure 3.9). However, this may not necessarily result in adverse behavior. In general, research indicates that when a thermoplastic material such as polyethylene is added to an asphalt binder, the stiffness of the binder will increase with the polymer content (10). This is true at even very low temperatures. Therefore, it will not be surprising to observe a higher stiffness for polyethylene-modified binders compared with unmodified binders when the bending beam rheometer is used. However, based on previous research, the crack blunting effect of the mixture improves even though stiffness increases by the addition of the polyethylene (10). In addition, some direct tension tests carried out by Brule and Maze (11) indicate that there is not a large difference in low-temperature behavior between bitumens modified with elastomers (SBS or SBR) and those modified with plastomers (EVA). Such findings were the results of low-temperature tension tests under an extension speed of 1 mm/min. It is not, however, clear to what extent these findings are applicable to asphalt binders modified with the waste toner.

3.2. THE MIXTURES PREPARED WITH TONER-MODIFIED BINDERS

The results of this part of study are presented and discussed for the following items:

a. Effect of Waste Toner on Superpave Mix Design and Optimum Binder Content
b. Effect of Waste Toner on Resilient Modulus and Indirect Tensile Strength
c. Effect of Waste Toner on the Hveem Stability

3.2.1. Effect of Waste Toner on Superpave Mix Design and Optimum Binder Content

As mentioned before, three levels of toner (0 percent, 5 percent, and 16 percent by weight) with the coastal AC-20 asphalt were used for this study. The AC-5 asphalt was excluded from this part of the project. The combined gradation of aggregates is shown in Figure 3.11. Preparation of mixtures was carried out according to procedures explained in Chapter 2. Compaction took place using the Superpave gyratory compactor (SGC). Figure 3.12 indicates air voids as a function of the binder content at design number of gyrations. In this graph, three lines, representing 0 percent, 5 percent, and 16 percent toner levels, are shown. It can be observed that there is a slight difference in optimum asphalt content selected at 4 percent air voids. If no toner is used, the optimum binder content is between 5.2 and 5.3 percent, while 5 percent and 16 percent toner levels in the binder yield an optimum asphalt content of about 5.5 percent. It is interesting to note that the amount of toner does not affect the optimum asphalt content significantly. The graphs for voids in the mineral aggregate (VMA), percent voids filled with asphalt (VFA), and the slope of the compaction curve are also presented in Figure 3.13. For all levels of toner content, the minimum required VMA is satisfied even though higher VMA's are obtained for toner-modified binders. Percent voids filled with asphalt is the same for all three levels. The compaction slopes are different even for the same binder content. However, there is no trend in the relationship between this slope and toner content.

As shown in Figure 3.12, mixing and compaction for no-toner binder were carried out at 135° C and 121°C, respectively, which are common mixing and compaction temperatures used in Texas for unmodified asphalt binders. Mixing and compaction for toner-modified binders were performed at equiviscous temperatures, as shown in the figure.

When the specimens for resilient modulus testing were to be prepared at a 7 percent air void level, we decided to use equiviscous temperature for all binders, with or without toner. When the results of this second-phase compaction were used to determine the optimum asphalt content at 4 percent air void level, an optimum binder content of approximately 5.1 percent was obtained for all three cases (0 percent , 5 percent, and 16 percent waste toner). However, the results of this case in determination of the optimum binder content are not as accurate as the typical case followed (as discussed above). This is primarily because the compaction for resilient modulus specimens was not continued to the maximum number of gyrations. Compaction was rather carried out to an extent that 7 percent void level was obtained in the specimen. Therefore, extrapolation was utilized to determine the air void level at design number of gyrations for resilient modulus specimens.

However, based on these results, it can be concluded that adding the waste toner, in the range of 5 percent to 16 percent as examined during the course of this research program, does not significantly change the optimum binder content.

3.2.2. Effect of Waste Toner on Resilient Modulus and Indirect Tensile Strength

For this part of the study, a total of nine specimens (three replicates for three different levels of waste toner content) were compacted using the Superpave gyratory compactor. Attempts were made to compact all the specimens to approximately 7 percent air voids by adjusting the height to which the specimens were to be compacted. This goal was successfully accomplished, since the range of air voids for the nine compacted specimens was between 6.5 and 7.3 percent. The specimens were mixed and compacted at 5.2 percent binder content and at equiviscous temperatures. The binder content was selected at 5.2 percent because this was the design binder content for the case where no waste toner was used. The same binder content was used for all specimens so that the results would not be affected by changes in this parameter. Resilient modulus and indirect tensile strength of the specimens were determined according to ASTM D4123. Tensile strain at failure was also obtained for the specimens. The results are illustrated in Figure 3.14 and Table 3.3. As expected, with an increase in the amount of waste toner, the modulus and tensile strength increase, while the tensile strain at failure decreases, indicating a more brittle behavior. Table 3.3 indicates that the addition of 16 percent waste toner causes a significantly higher change in the measured properties compared with the addition of 5 percent waste toner.

Table 3.3. Results of Indirect Tensile Test

% Toner	Resilient Modulus		Indirect Tensile Strength		Tensile Strain at Failure	
	KPa	% Increase(1)	KPa	% Increase(1)		% Decrease(1)
0	1,558,951	00.0	760	00.0	0.005445	00.0
5	1,608,750	3.2	951	25.1	0.004170	23.4
16	1,997,041	28.1	1395	83.6	0.001999	63.3

(1) Increase or decrease is measured with respect to the binder with no waste toner

3.2.3. Effect of Waste Toner on the Hveem Stability

A series of nine specimens were prepared at three levels of toner content (0 percent, 5 percent, and 16 percent by weight). Three specimens were prepared at each level. All specimens were prepared at the same binder content (5.2 percent). Compaction of specimens was conducted according to test method Tex-206-F. The resulting air voids for all specimens were similar, as can be seen in Table 3.4. The specimens were tested for Hveem stability according to Texas Test Method Tex-208-F. The results are shown in Figure 3.15. It can be observed that the stability increases as the amount of toner increases. It can also be seen that there is a significant increase in stability once the waste toner level is increased from 5 percent to 16 percent.

3.3. METHODS OF INCORPORATION

As was discussed in Chapter 2, 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.

Blending dry toner into the aggregate is not recommended as an effective and appropriate method because it poses a series of problems: the dry toner is extremely fine in size and difficult to handle without creating considerable black dust, which might also impose health hazards. In addition, the waste toner added directly to the aggregate may just act as a filler rather than exhibiting its polymeric properties. Such properties can be accessed if the toner is properly blended and melted inside the asphalt cement. However, use of oil as a medium to disperse toner into the asphalt will result in a softened binder, while use of water will result in a foamed asphalt. Neither of these two approaches is recommended.

Because dry toner was directly introduced into the asphalt binder with success in this research program, this approach is recommended. However, care should be taken to carry out such blending at a temperature sufficiently higher than the melting point of the toner. In addition, stirring should be allowed to take place for a sufficient amount of time so that a complete reaction takes place and a homogeneous material is obtained.

The quality of the final product and the time required to obtain a homogenous blend depends on the type, intensity, and the temperature at which stirring occurs.

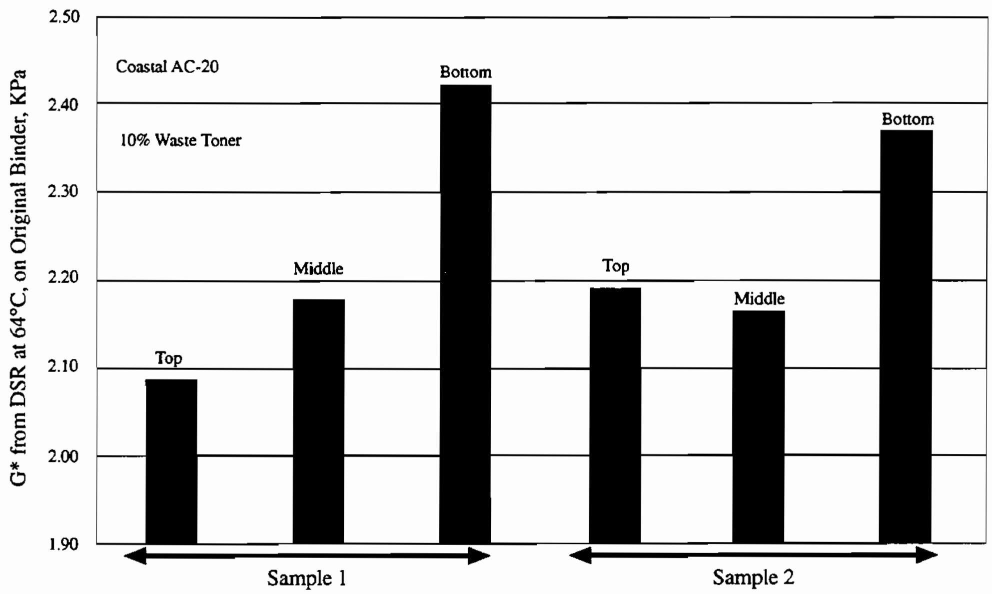


Figure 3.1. Bar Chart Indicating the Results of Stability Test for Samples from Two Different Tubes

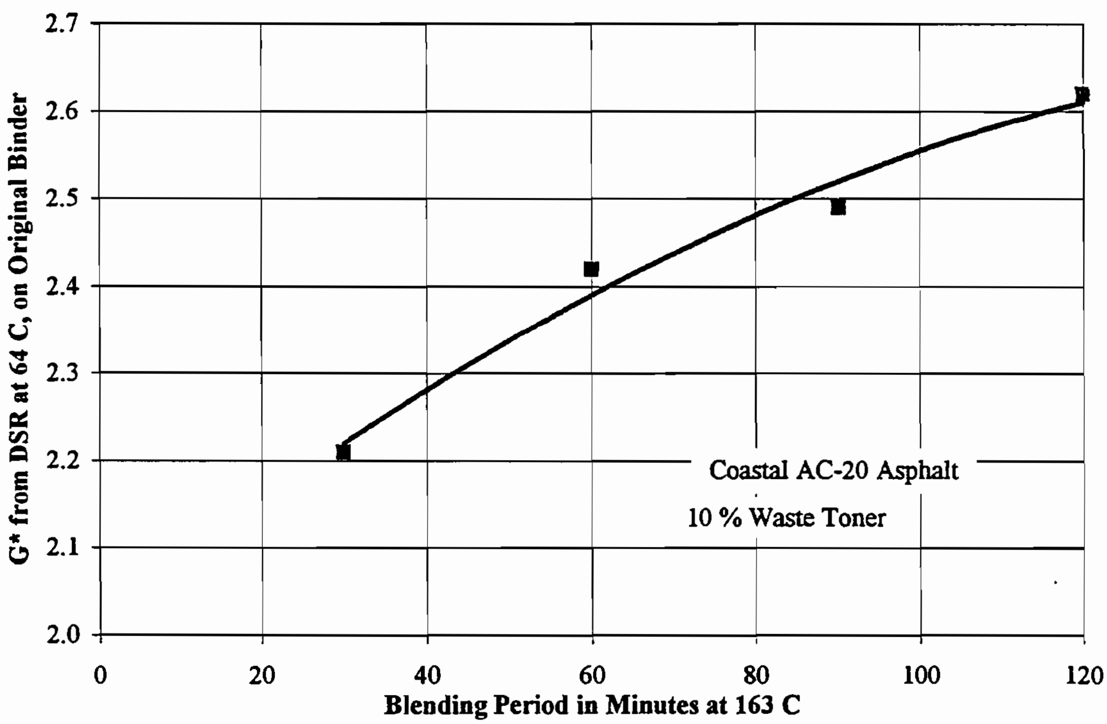


Figure 3.2. Complex Moduls as a Function of Blending Period

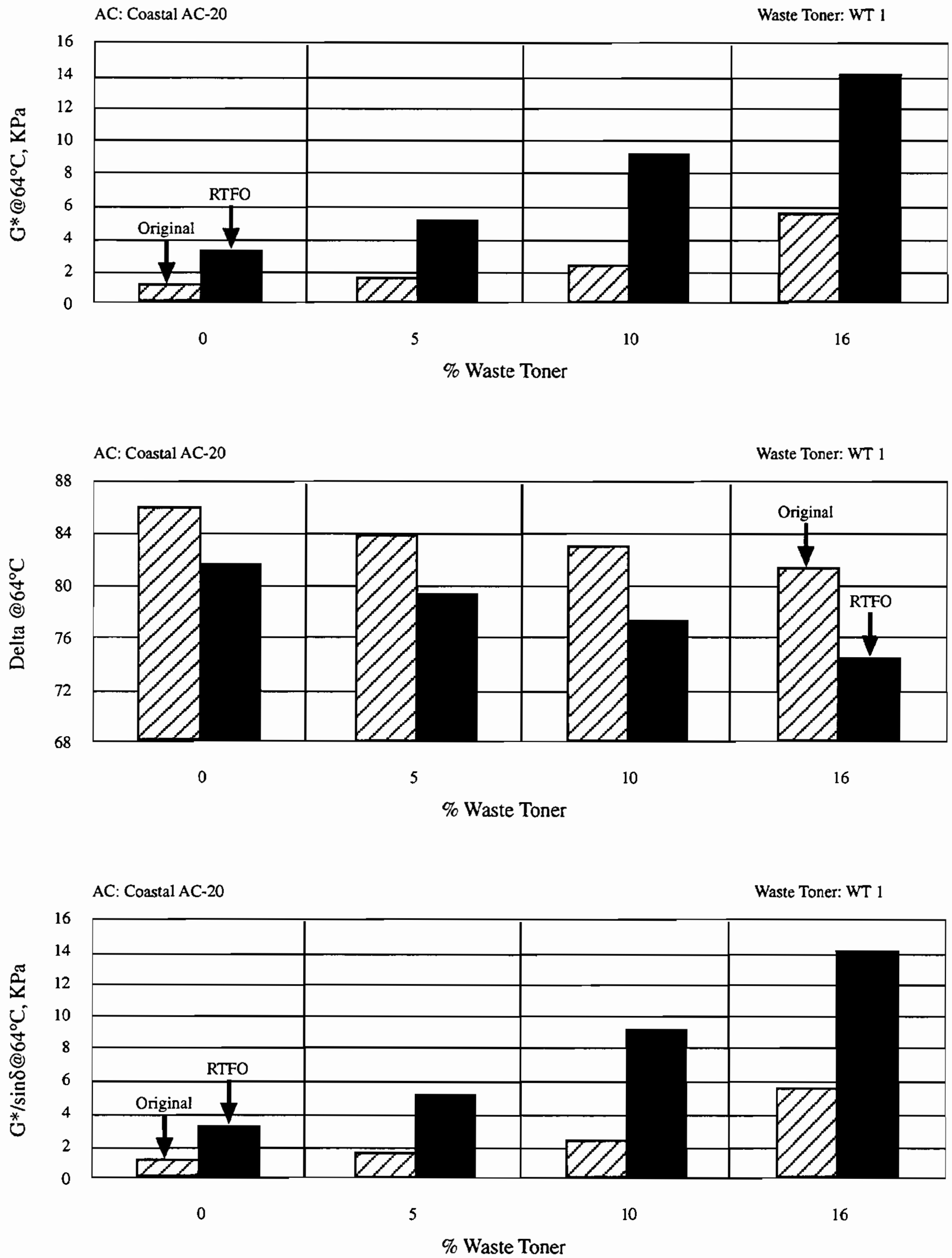


Figure 3.3. Results of Dynamic Shear Rheometer Testing for AC-20 Asphalt with Different Amounts of Toner

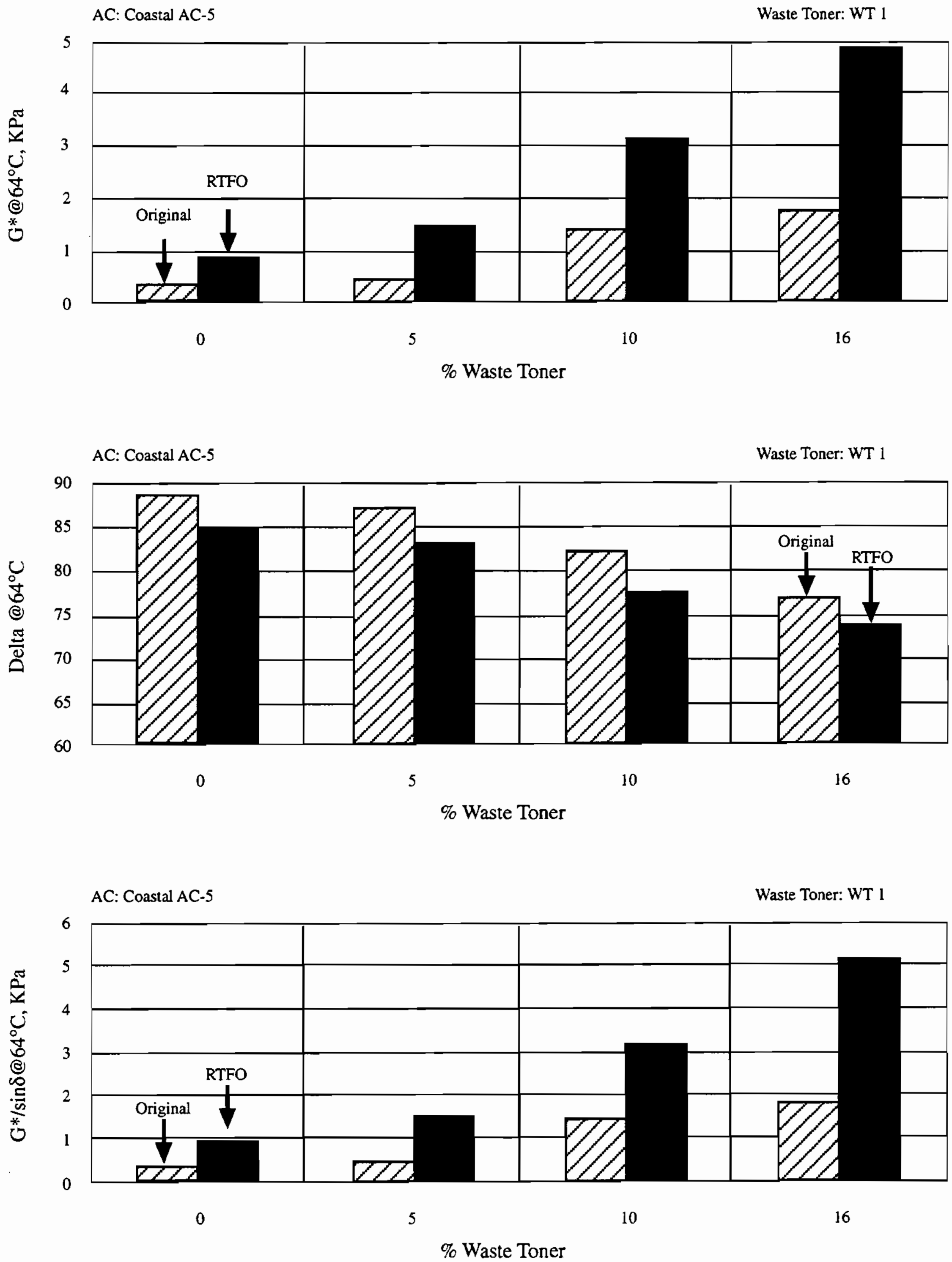


Figure 3.4. Results of Dynamic Shear Rheometer Testing for AC-5 Asphalt with Different Amounts of Toner

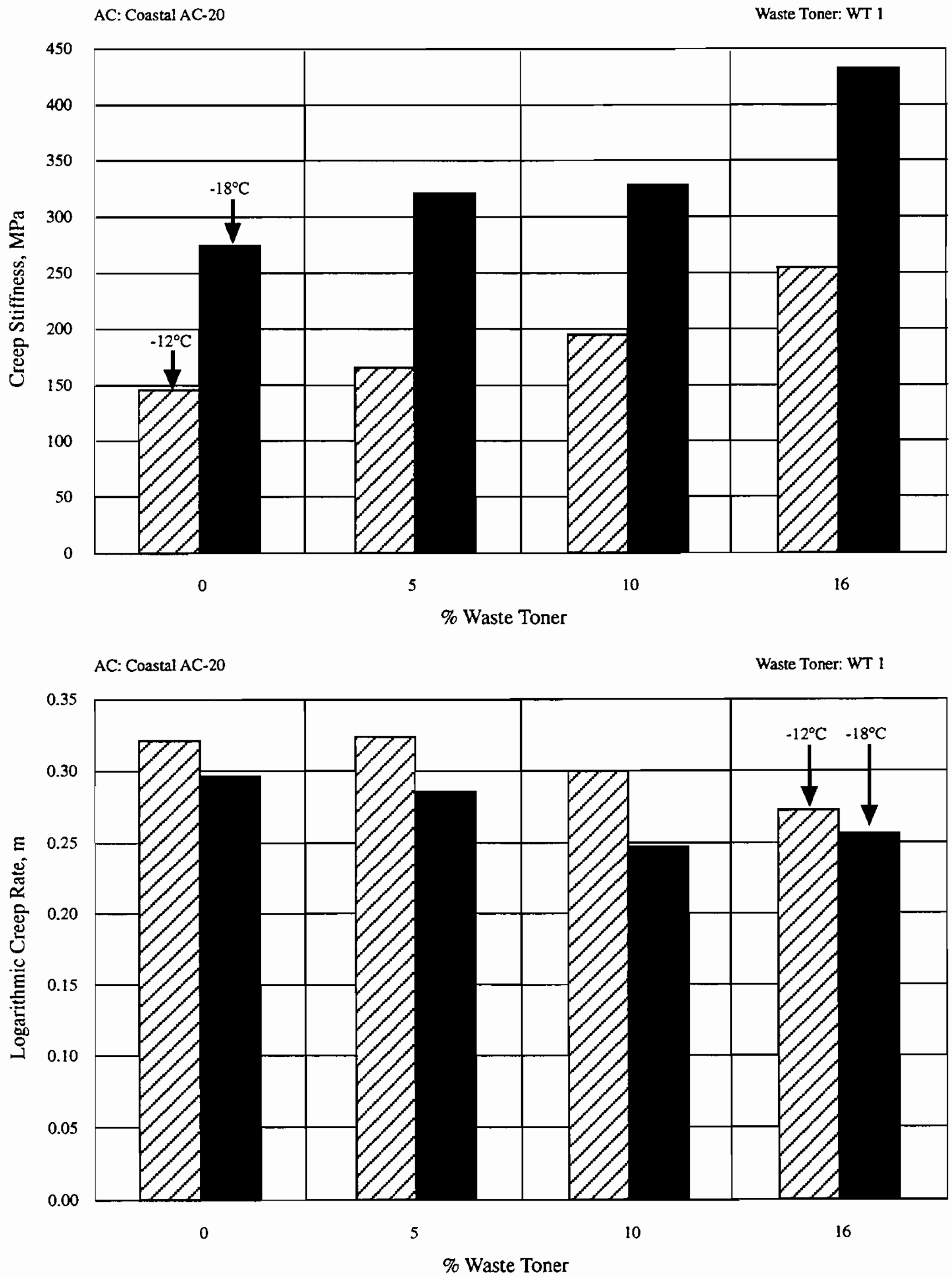
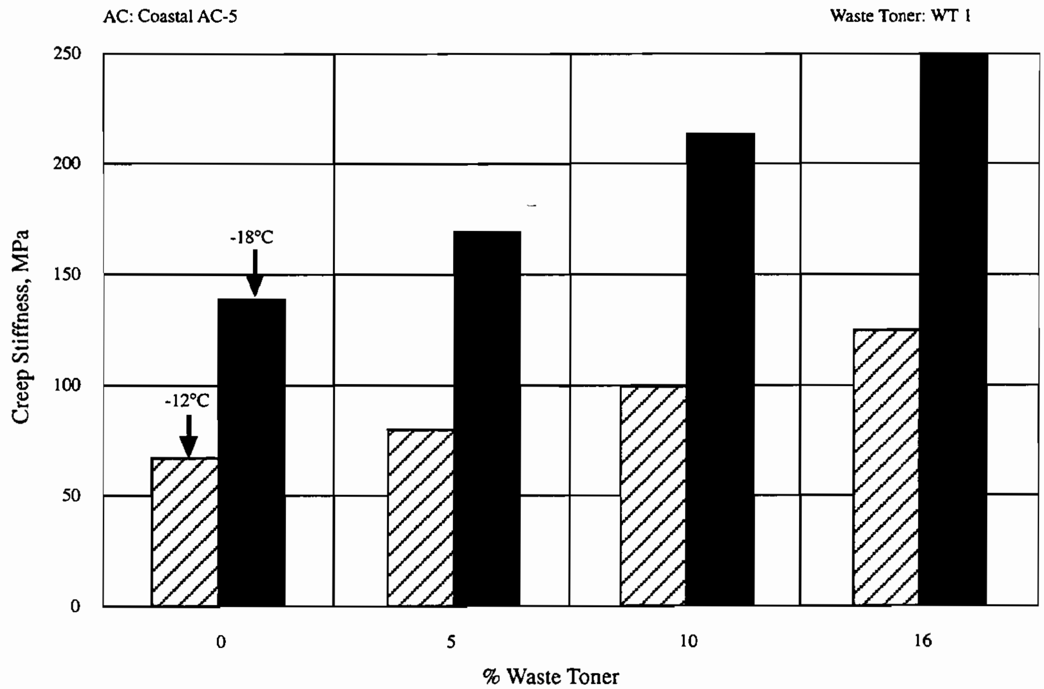


Figure 3.5. Results of Bending Beam Rheometer Testing for AC-20 Asphalt with Different Amounts of Toner



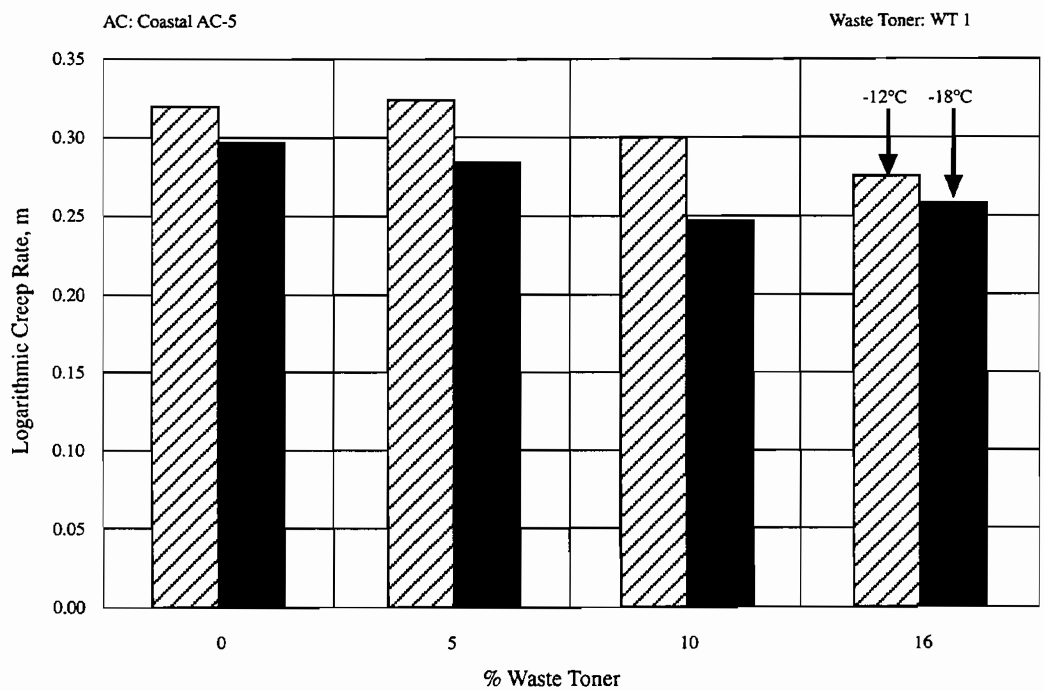


Figure 3.6. Results of Bending Beam Rheometer Testing for AC-5 Asphalt with Different Amounts of Toner

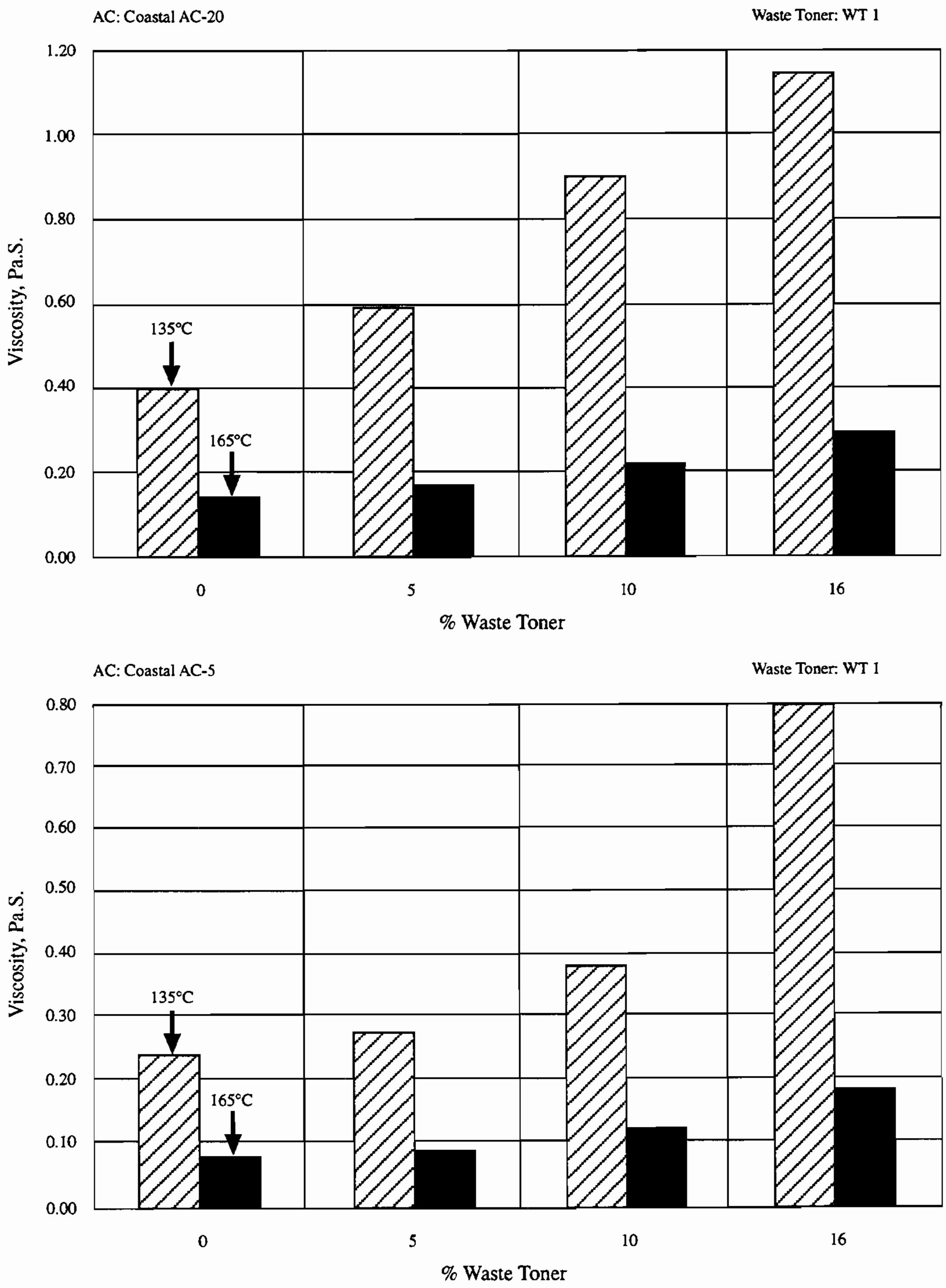


Figure 3.7. Results of Testing with the Rotational Viscometer for Asphalts Modified with Different Amounts of Toner

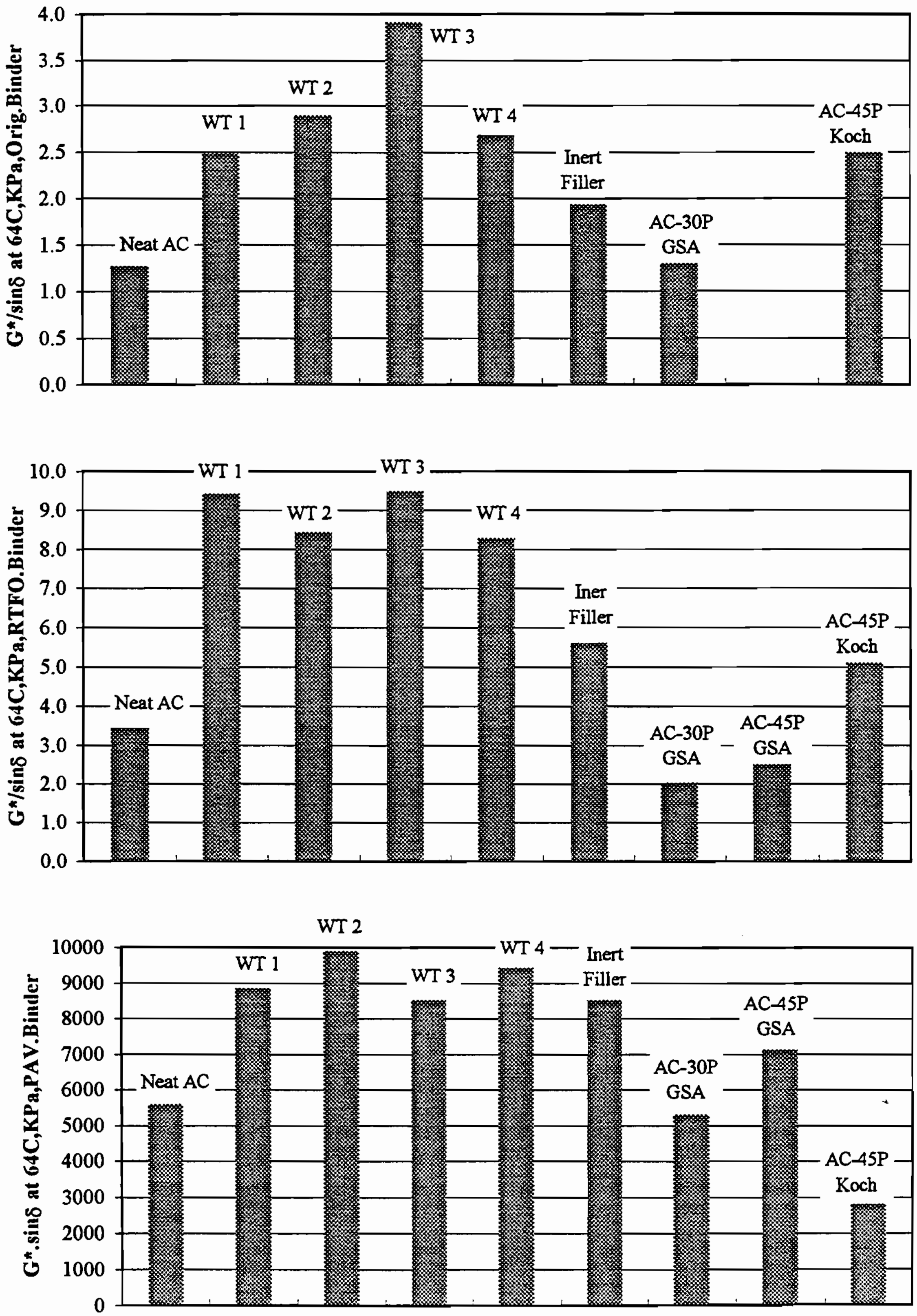


Figure 3.8. Results of Dynamic Shear Rheometer Testing for Asphalts with Different Modifiers

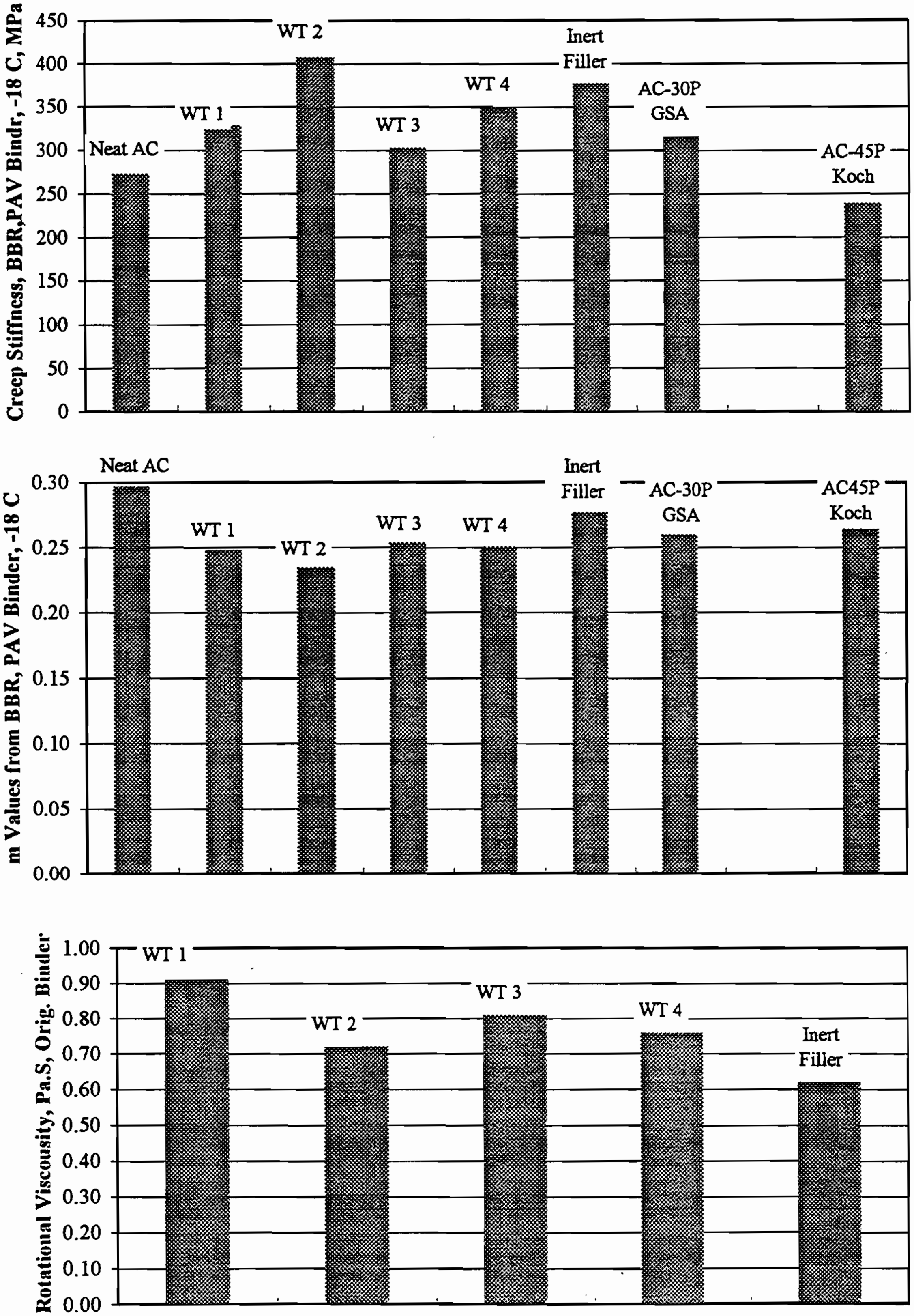


Figure 3.9. Results from Bending Beam Rheometer at -18°C and Rotational Viscosity Testing for Asphalts with Different Modifiers

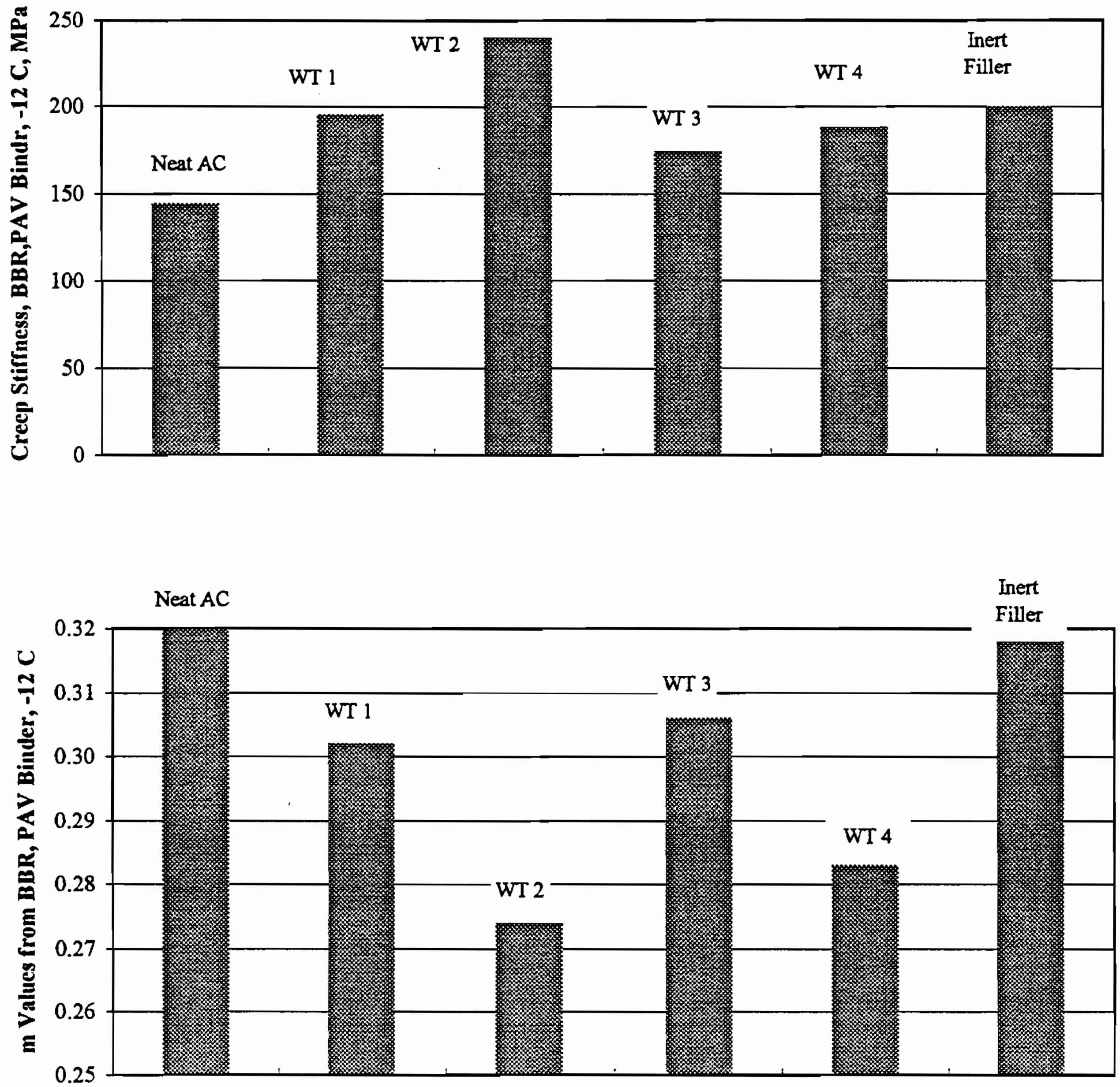


Figure 3.10. Results from Bending Beam Rheometer at -12°C and Rotational Viscosity Testing for Asphalts with Different Modifiers

Table 3.2. Gradation Table for the Material Selected for Mix Design and Analysis

Sieves	Materials (% Passing)					%Pass
SI,mm	Aggregates					
Units	C	D	F	W.S	D.S.	Comb.
25.00	100.0	100.0	100.0	100.0	100.0	100.0
19.00	98.0	100.0	100.0	100.0	100.0	99.4
12.50	47.0	90.5	100.0	100.0	100.0	82.2
9.50	4.7	82.0	100.0	100.0	100.0	67.8
4.75	0.3	16.8	93.9	99.4	99.9	51.8
2.36	0.2	6.5	26.5	79.3	93.0	29.2
1.18	0.1	4.2	9.0	44.6	73.0	17.1
0.60	0.1	3.8	4.5	21.0	59.0	11.0
0.30	0.1	3.5	2.0	11.0	48.0	7.7
0.15	0.1	3.0	1.5	4.5	30.7	4.8
0.08	0.1	2.4	1.3	2.6	22.9	3.5
0.00	0.0	0.0	0.0	0.0	0.0	0.0

Agg.	Source
C	Delta Materials, Marble Falls, C-Rock
D	Alamo Crushed Stone, D-Rock
F	Alamo Crushed Stone, F-Rock
W.S.	Washed Screen., Alamo Crushed Stone
D.S.	Dry Screen., Texas Crushed Stone

% Blend	30	20	25	15	10

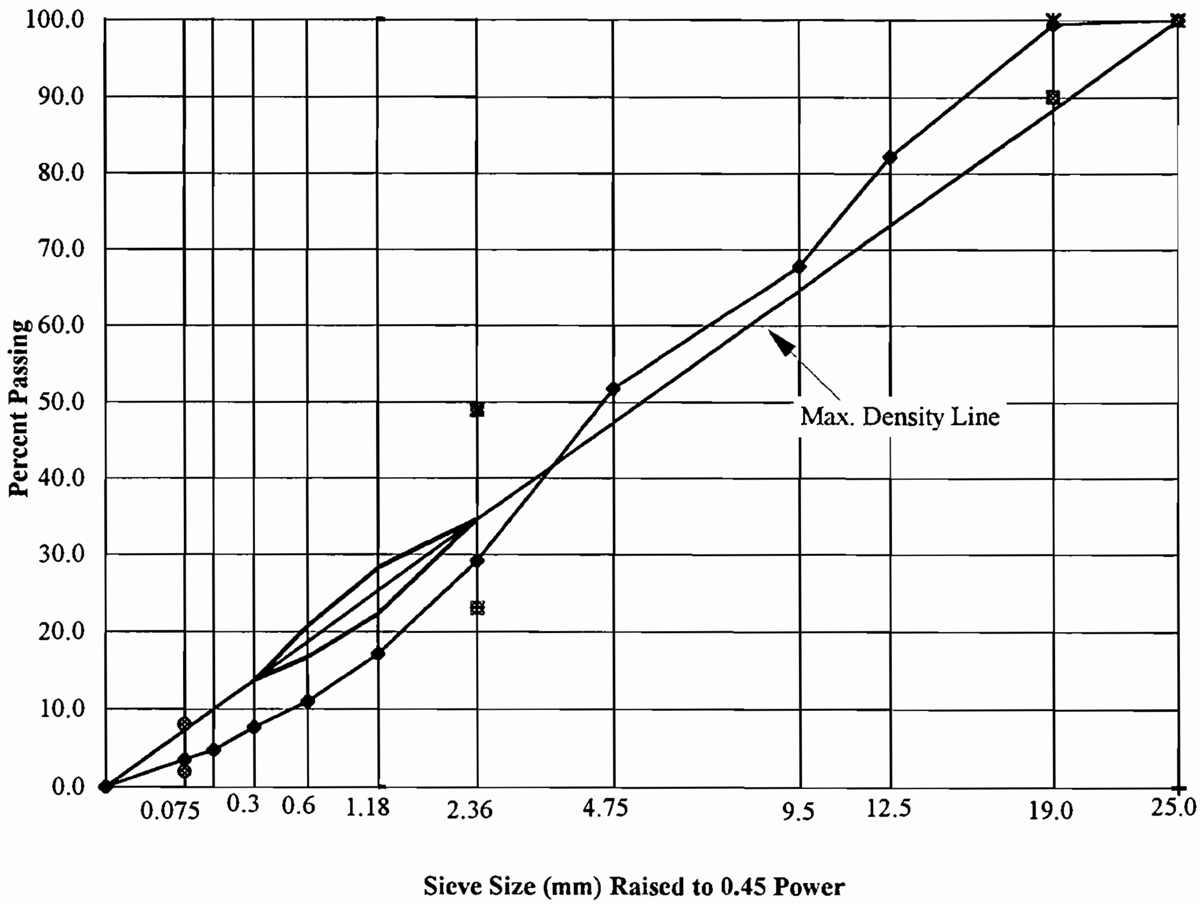


Figure 3.11. Gradation Chart (19-mm Maximum Nominal Size) Selected for Mixture Analysis

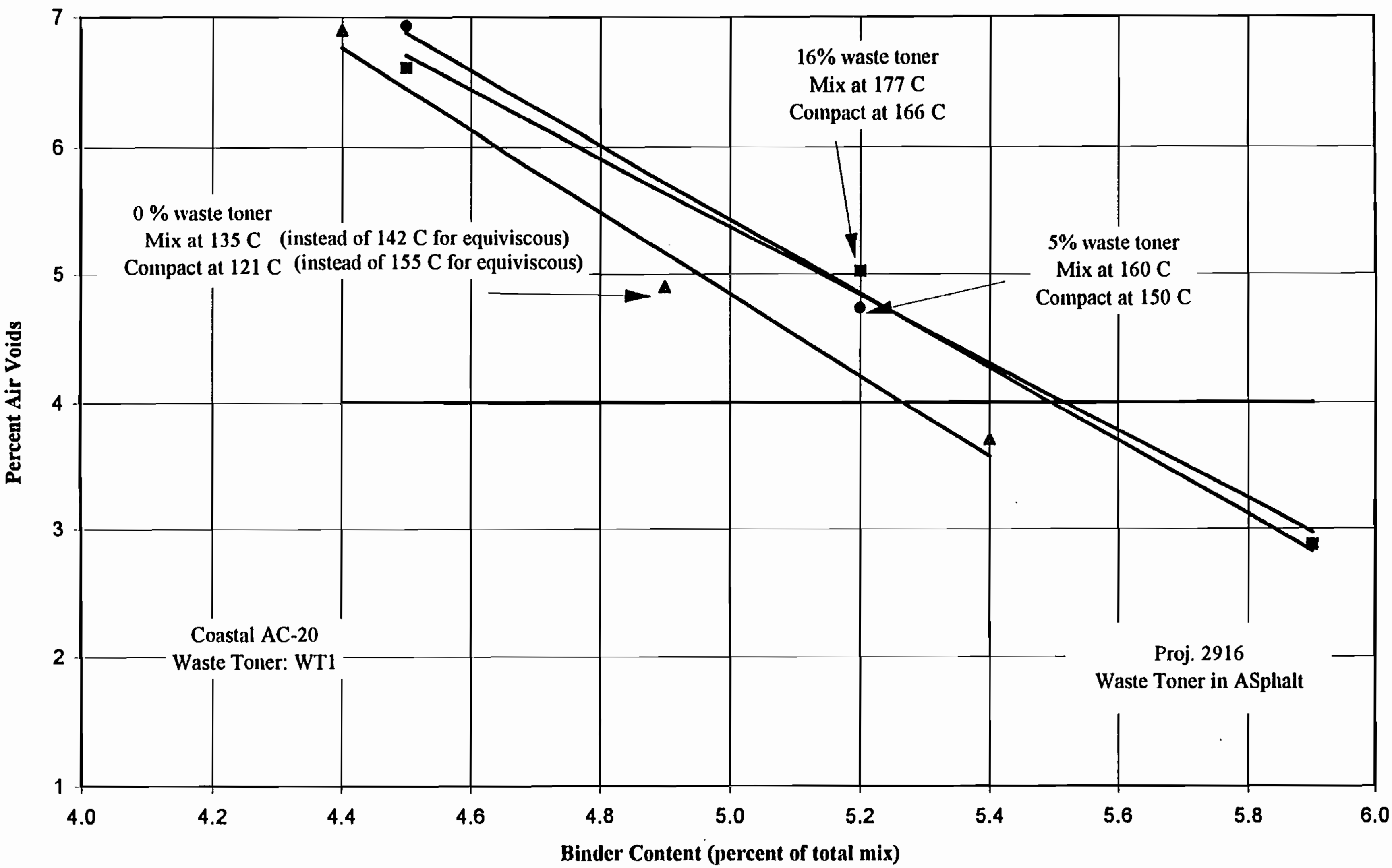


Figure 3.12. Percent Air Voids for Gyratory Compacted Specimens as a Function of Binder Content at Design Number of Gyrations

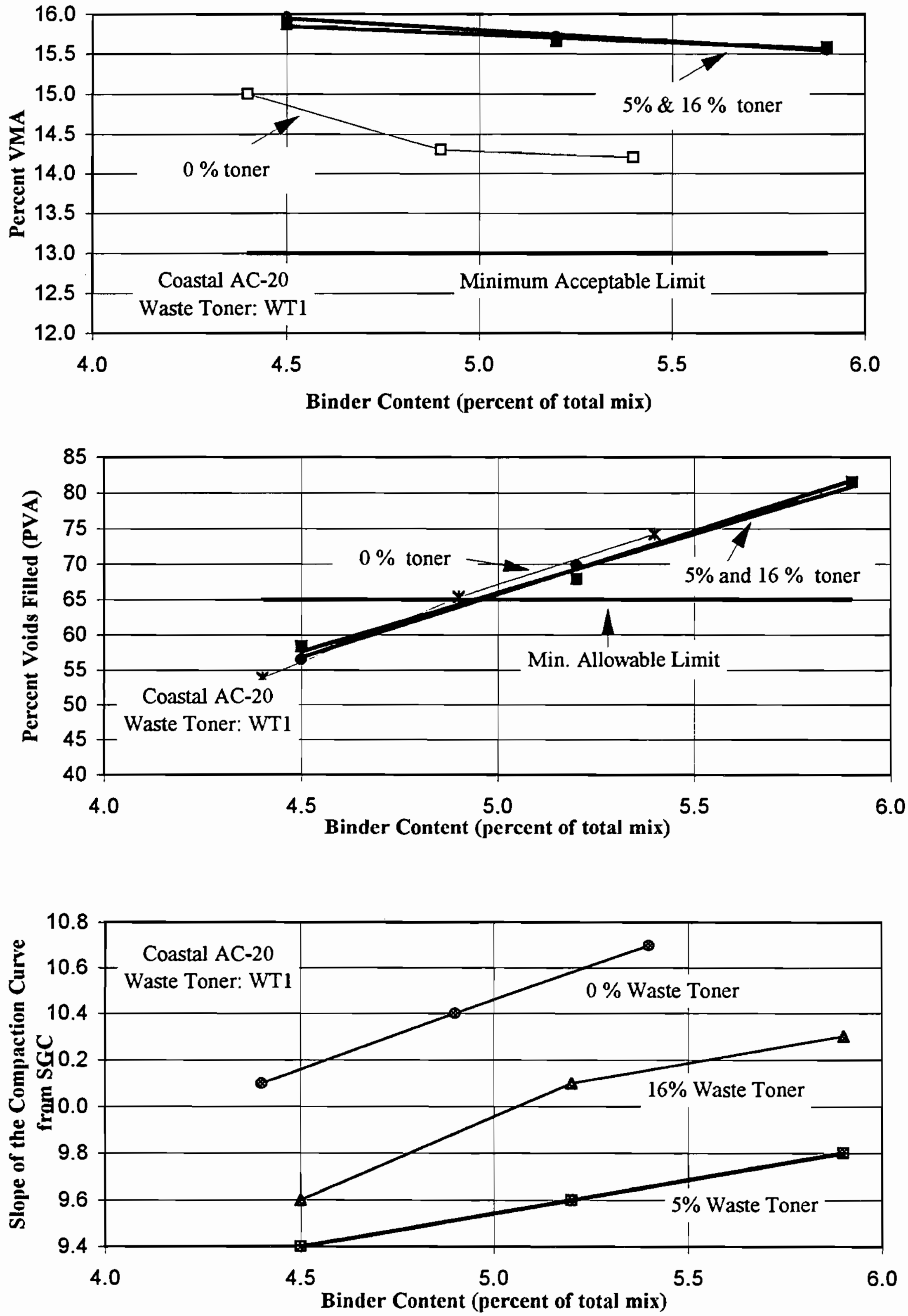


Figure 3.13. Some of the Mixture Properties at Different Binder Contents

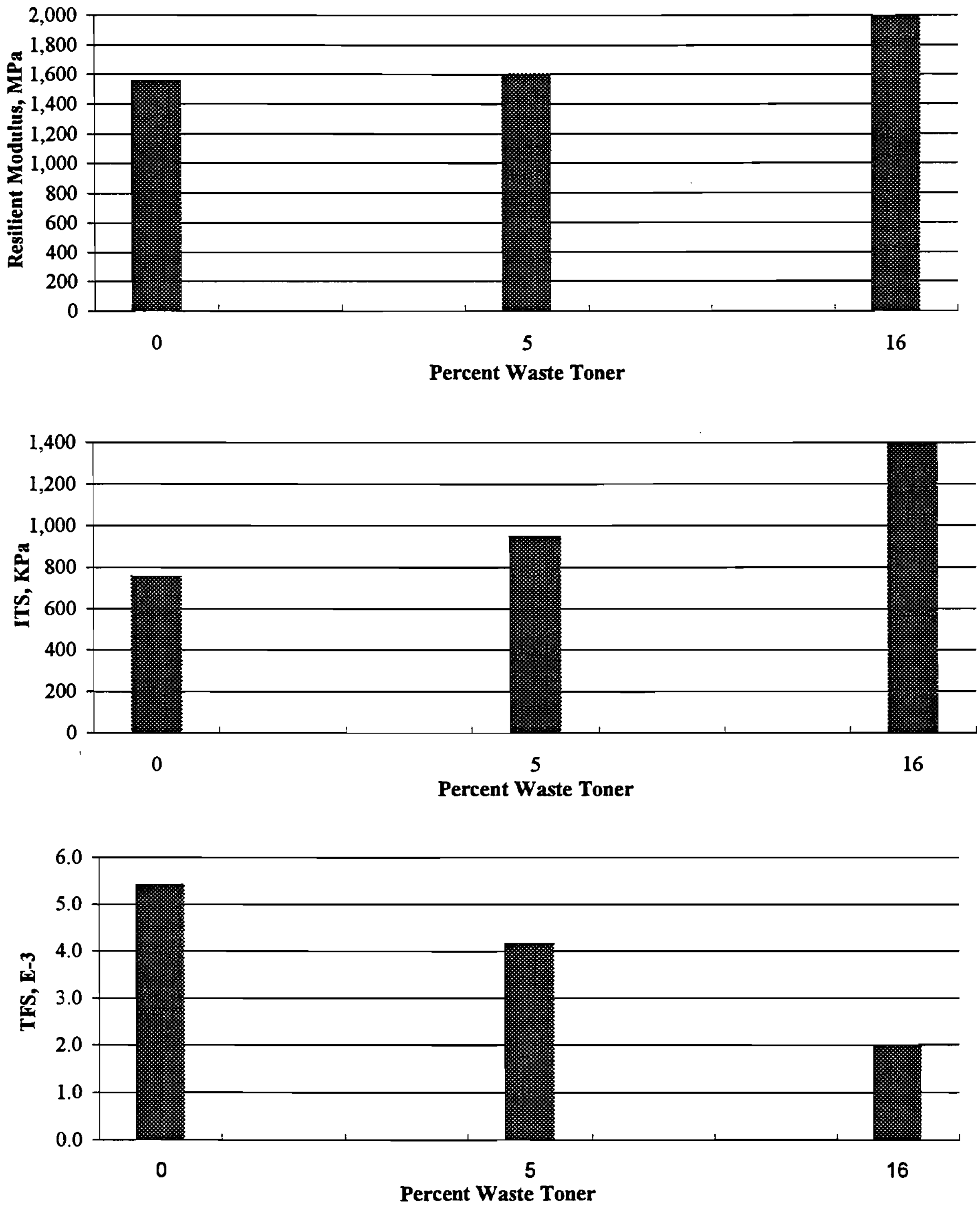


Figure 3.14. Resilient Modulus, Indirect Tensile Strength (ITS), and Tensile Strain at Failure (TSF) of SGC Compacted Specimens as a Function of Percent Waste Toner in Binder

Table 3.3. Results of Hveem Stability Testing

Spec. Ident.	% Waste Toner	Binder Contnt %	Air Voids %	Hveem Stability	Air Voids Avg., %	Hveem Stability Avg.
D4-1	0	5.2	4.2	50		
D4-2			3.7	55		
D4-3			3.6	51	3.9	52
D5-1	5	5.2	3.9	58		
D5-2			3.8	56		
D5-3			3.9	51	3.9	55
D6-1	16	5.2	4.3	61		
D6-2			4.1	62		
D6-3			4.5	66	4.3	63

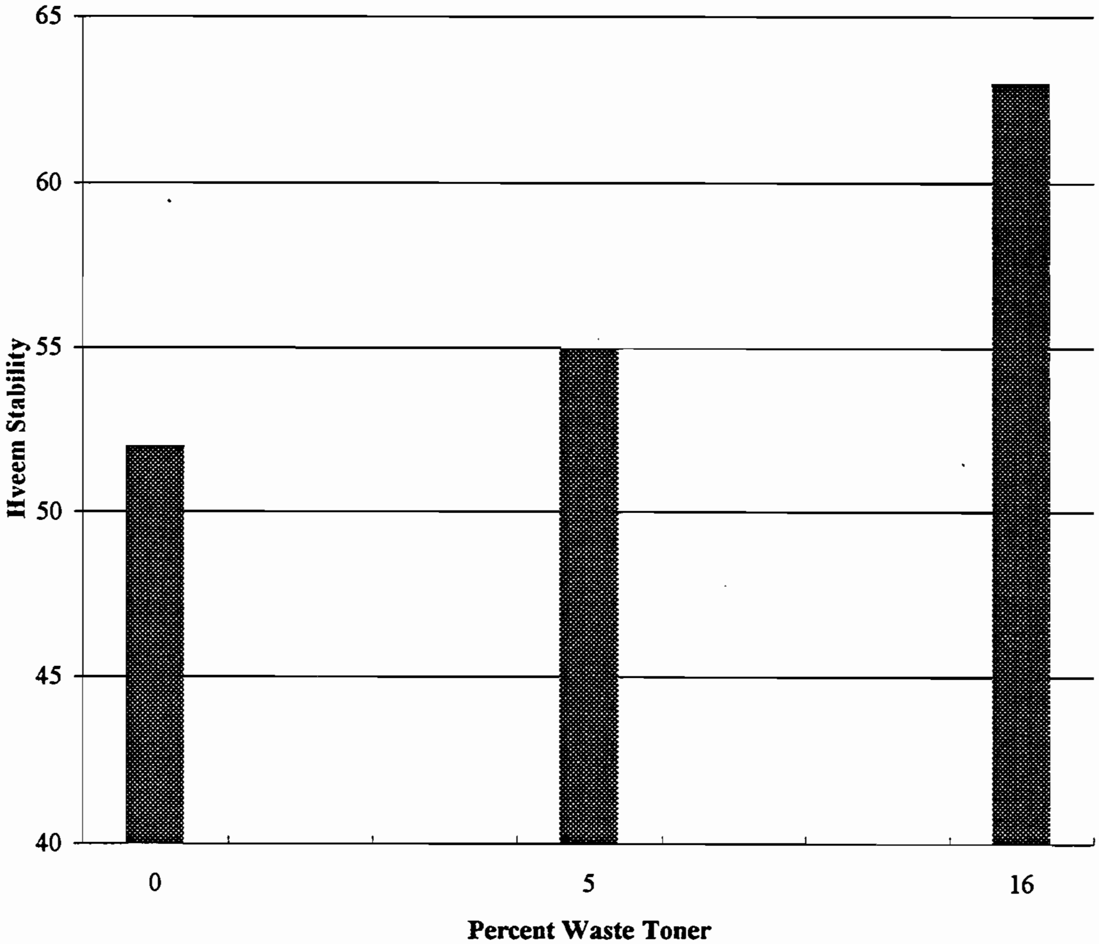


Figure 3.15. Hveem Stability as a Function of Percent Waste Toner in Binder

CHAPTER 4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations are based on the findings of this research project.

4.1. CONCLUSIONS

Overall, it can be concluded 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. Specific conclusions regarding the contents of the research program can be summarized as follows:

- At least two hours of stirring of the waste toner in asphalt, at temperatures above the melting point of the waste toner, is required to obtain a homogeneous material. Such a period is required if typical mixing equipment and rotation speed, such as the ones used for this research, are used. In the case of very high shear blending, the stirring period can be as short as 20 to 30 minutes.
- The material does not have sufficient storage stability. The toner-modified asphalt needs to be agitated before being mixed with aggregate.
- The viscosity of the binder increases as the amount of toner is increased.
- The complex modulus of the binder (G*) at high and intermediate temperatures is increased with the increase in the amount of waste toner.
- The binder stiffness (S) at low temperatures is increased with an increase in the amount of waste toner.
- The logarithmic creep rate of the binder (m) decreases with an increase in the amount of waste toner.
- There are differences between the effects of different waste toners on asphalt properties. Each toner in combination with a specific asphalt should be tested and investigated separately to assess how the binder properties are influenced.
- There is a positive effect on binder properties at high temperatures; at low-temperatures there is an adverse effect.

4.2. RECOMMENDATIONS

It is recommended that a test section be built using the reference waste toner (WT1) studied in this research project. It is suggested that at least two lanes (a passing lane and a driving lane) for a length of approximately 1000 meters be constructed. The toner content should be between 6 and 8 percent, based on the asphalt and aggregate selected for the project. In addition to the results of this research study, a field study can assist TxDOT in deciding whether the material should be introduced into asphalt material. The testing matrix in Table 4.1 is proposed for the full-scale field project.

Table 4.1. Testing Matrix for Full-Scale Study (Field Project)

Mix	Plant Produced Property			
	Asphalt Content	Air Voids	VMA	Hveem Stability
Control	√	√	√	√
Control with Waste Toner	√	√	√	√

These properties are proposed to be measured to determine whether the presence of waste toner affects routine TxDOT quality assurance parameters.

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APPENDIX A:

BINDER ANALYSIS AND TEST RESULTS FROM
Dynamic Shear Rheometer
Bending Beam Rheometer
Rotational Viscometer

MIXTURE ANALYSIS AND TEST RESULTS FROM
Superpave Gyratory Compaction
Indirect Tensile Tests
Resilient Modulus Tests
Vheem Stability

Table A.1. Results of Superpave Binder Tests on Asphalts Modified with Different Amounts of Waste Toner.

% WT	Waste Toner Source	AC Gr.	AC Source	DSR @ 64 C						DSR, PAV						BBR, PAV				Rotational Vis.		Mass Loss %
				ORIG. G*,KPa	RTFO G*,KPa	ORIG. δ, deg	RTFO δ, deg	ORIG. G*/sinδ	RTFO G*/sinδ	@ 19 C G*,KPa	@ 25 C G*,KPa	@19 C δ, deg	@25 C δ, deg	@19 C G*.sinδ	@25 C G*.sinδ	@ -12 C S,MPa	@ -12 C m	@ -18 C S,MPa	@ -18 C m	@135 C Pa.S	165 Pa.S	
0		20	Coastal	1.27	3.40	86.10	81.50	1.27	3.44	8763	4440	39.70	44.30	5597	3101	144.4	0.320	273.0	0.297	0.40	0.14	0.21
5	Cartridg	20	Coastal	1.95	N/A	85.60	N/A	1.96	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10		20	Coastal	2.67	8.07	83.80	76.80	2.69	8.29	15928	8475	36.30	41.40	9430	5605	188.0	0.283	350.8	0.251	0.76	N/A	0.15
0		20	Coastal	1.27	3.40	86.10	81.50	1.27	3.44	8763	4440	39.70	44.30	5597	3101	144.4	0.320	273.0	0.297	0.40	0.14	0.21
5	WT 1	20	Coastal	1.90	5.14	84.20	79.30	1.91	5.23	11013	5640	38.60	43.30	6871	3868	167.5	0.324	318.6	0.285	0.59	0.17	0.11
10		20	Coastal	2.46	9.18	83.00	77.20	2.48	9.41	15310	6678	35.30	41.05	8847	4386	195.2	0.302	328.3	0.248	0.91	0.22	N/A
16		20	Coastal	5.65	14.14	81.10	74.30	5.72	14.69	18125	9090	34.90	41.40	10370	6011	254.9	0.275	434.1	0.258	1.16	0.29	0.14
0		5	Coastal	0.40	0.93	88.80	85.10	0.40	0.93	4488	1719	43.60	48.10	3095	1279	68.3	0.367	138.2	0.332	0.24	0.08	0.36
5	WT 1	5	Coastal	0.49	1.48	87.30	83.20	0.49	1.49	4703	2184	42.60	46.80	3183	1592	80.1	0.369	168.8	0.322	0.28	0.08	0.28
10		5	Coastal	1.43	3.13	82.20	77.20	1.44	3.21	8613	3214	39.20	44.10	5444	2237	100.7	0.342	213.9	0.289	0.38	0.12	0.33
16		5	Coastal	1.77	4.96	76.70	73.60	1.82	5.17	8764	4543	40.10	44.50	5645	3184	124.5	0.325	249.9	0.270	0.80	0.18	0.38

Table A.2. Results of Stability Test for Waste Toner Modified Asphalt

Homogeneity Test	
Waste Toner	10%
Source	Cartridge
AC GRADE	20
AC SOURCE: COASTAL	

Position in Tube	Sampl No.	DSR @ 64 ORIG. G* KPa	DSR @ 64 ORIG. %change from Top	DSR @ 64 ORIG. δ deg	Rotat. Visc Pa.s @ 135	%chge from Top
Top	1	2.09	0.0	83.6	0.59	0.0
Mid.	1	2.18	4.3	84.0		
Bot.	1	2.42	15.8	83.7	0.70	18.6
Top	2	2.19	0.0	83.7	0.56	0.0
Mid.	2	2.16	-1.4	83.5		
Bot.	2	2.37	8.2	83.5	0.66	17.9

Table A.3. Complex Modulus Results for Different Blending Periods(*)

Blend Time minutes	G*,KPa	δ, deg	G*/sinδ
30	2.21	84.5	2.22
60	2.42	84.1	2.43
90	2.49	83.8	2.50
120	2.62	83.8	2.64

(*) DSR results on original binder at 64 C

Table A.4. Results of Superpave Binder Tests on Asphalts Modified with an Inert Filler Material, Several Polymer, and Different Waste Toners

% Modif	Modif Source	AC Gr.	AC Source	DSR @ 64 C ORIG. G*,KPa	DSR @ 64 C RTFO G*,KPa	DSR @ 64 C ORIG. δ, deg	DSR @ 64 C RTFO δ, deg	DSR @ 64 C ORIG. G*/sinδ	DSR @ 64 C RTFO G*/sinδ	DSR, PAV @ 19 C G*,KPa	DSR, PAV @ 25 C G*,KPa	DSR, PAV @19 C δ, deg	DSR, PAV @25 C δ, deg	DSR, PAV @19 C G*.sinδ	DSR, PAV @25 C G*.sinδ
0	None	20	Coastal	1.27	3.40	86.10	81.50	1.27	3.44	8763	4440	39.70	44.30	5597	3101
10	WT 1	20	Coastal	2.46	9.18	83.00	77.20	2.48	9.41	15310	6678	35.30	41.05	8847	4386
10	WT 2	20	Coastal	2.88	8.22	84.10	77.20	2.90	8.43	16969	8262	35.70	41.30	9902	5453
10	WT 3	20	Coastal	3.85	9.17	79.60	74.80	3.91	9.50	14928	6794	34.80	39.90	8520	4358
10	WT4	20	Coastal	2.67	8.07	83.80	76.80	2.69	8.29	15928	8475	36.30	41.40	9430	5605
10	Filler	20	Coastal	1.93	5.01	85.60	63.40	1.94	5.60	13809	6709	38.10	43.30	8521	4601
>3	SBS	30P	GSA					1.42	2.03					5316	
>3	SBS	45P	GSA						2.51					7118	
>3	SBS	45P	Koch					2.71	5.36					2799	

% Mod.	Modif Source	AC Gr.	AC Source	BBR, PAV @ -12 C S,MPa	BBR, PAV @ -12 C m	BBR, PAV @ -18 C S,MPa	BBR, PAV @ -18 C m	Rotational Vis. 135 Pa.S	Rotational Vis. 165 Pa.S	Mass Loss %
0	None	20	Coastal	144.4	0.320	273.0	0.297			0.17
10	WT 1	20	Coastal	195.2	0.302	328.3	0.248	0.91	0.22	N/A
10	WT 2	20	Coastal	240.4	0.274	408.0	0.235	0.72		0.20
10	WT 3	20	Coastal	174.2	0.306	302.5	0.254	0.81		0.23
10	WT4	20	Coastal	188.0	0.283	350.8	0.251	0.76		0.15
10	Filler	20	Coastal	200.0	0.318	377.5	0.277	0.62		0.10
>3	SBS	30P	GSA			315.7	0.260			
>3	SBS	45P	GSA							
>3	SBS	45P	Koch			238.7	0.280			

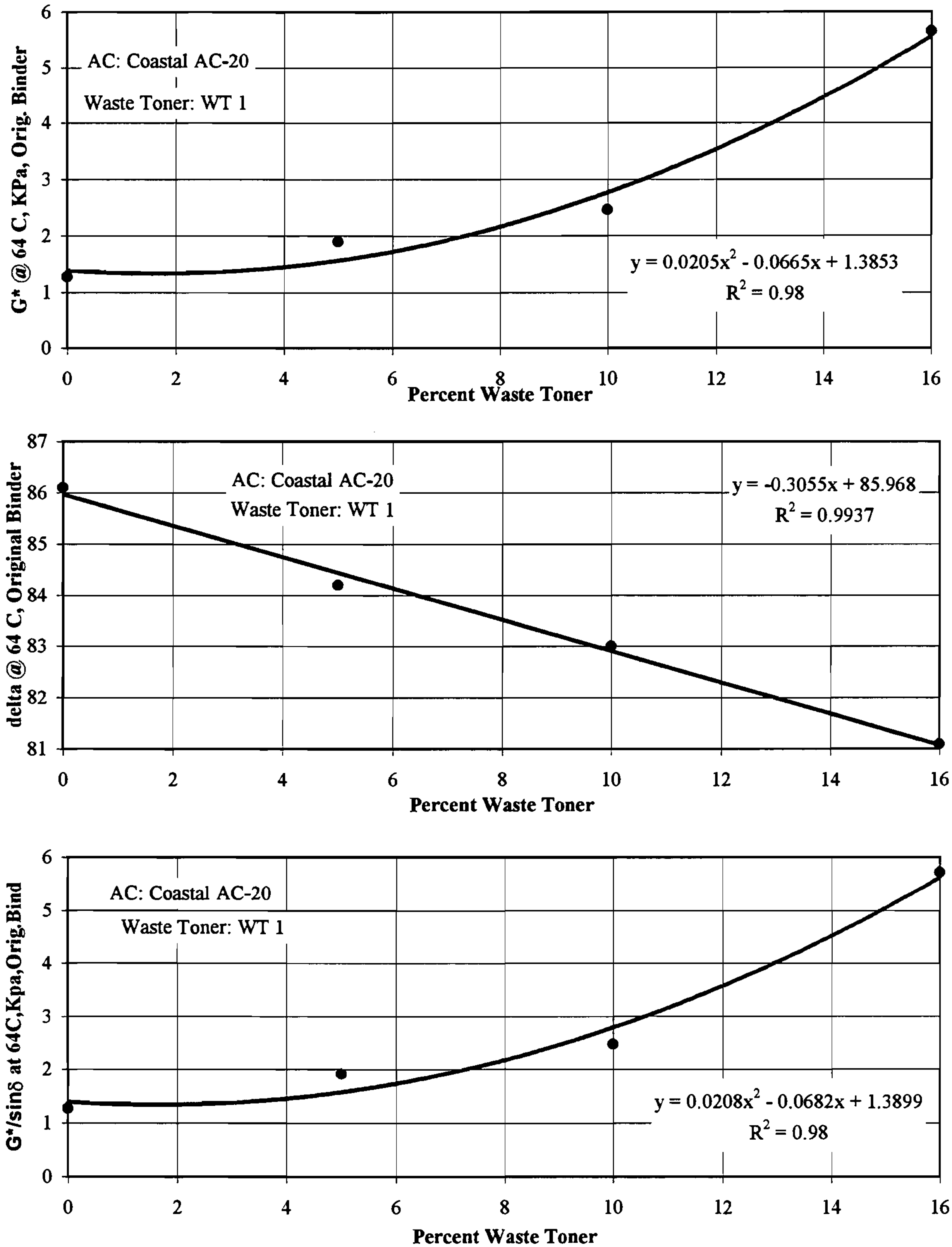


Figure A.1. Test Results from Dynamic Shear Rheometer Testing for the Unaged Binder (AC-20) for Different Toner Amounts.

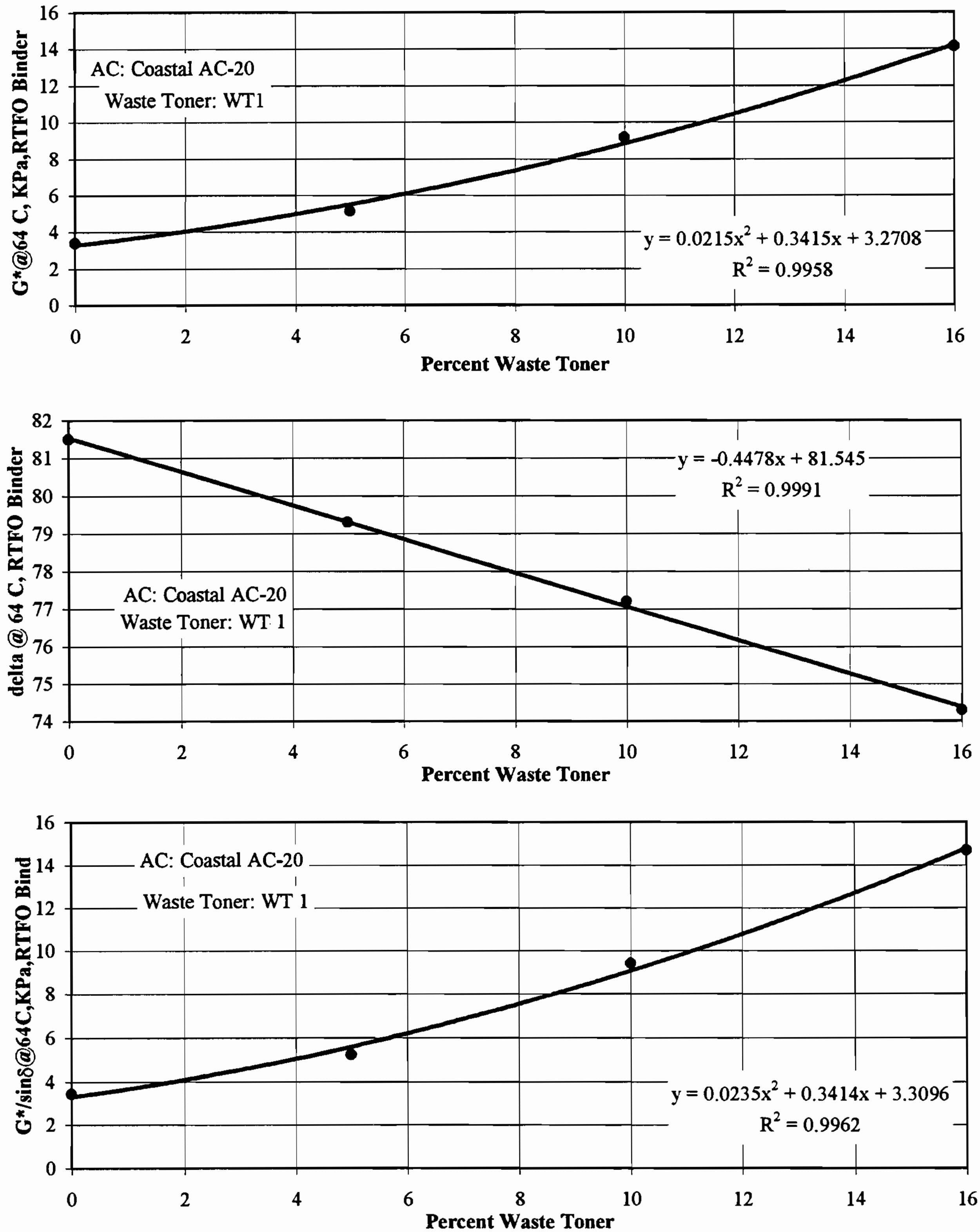


Figure A.2. Test Results from Dynamic Shear Rheometer Testing for the RTFO-Aged Binder (AC-20) Modified with Different Toner Amounts.

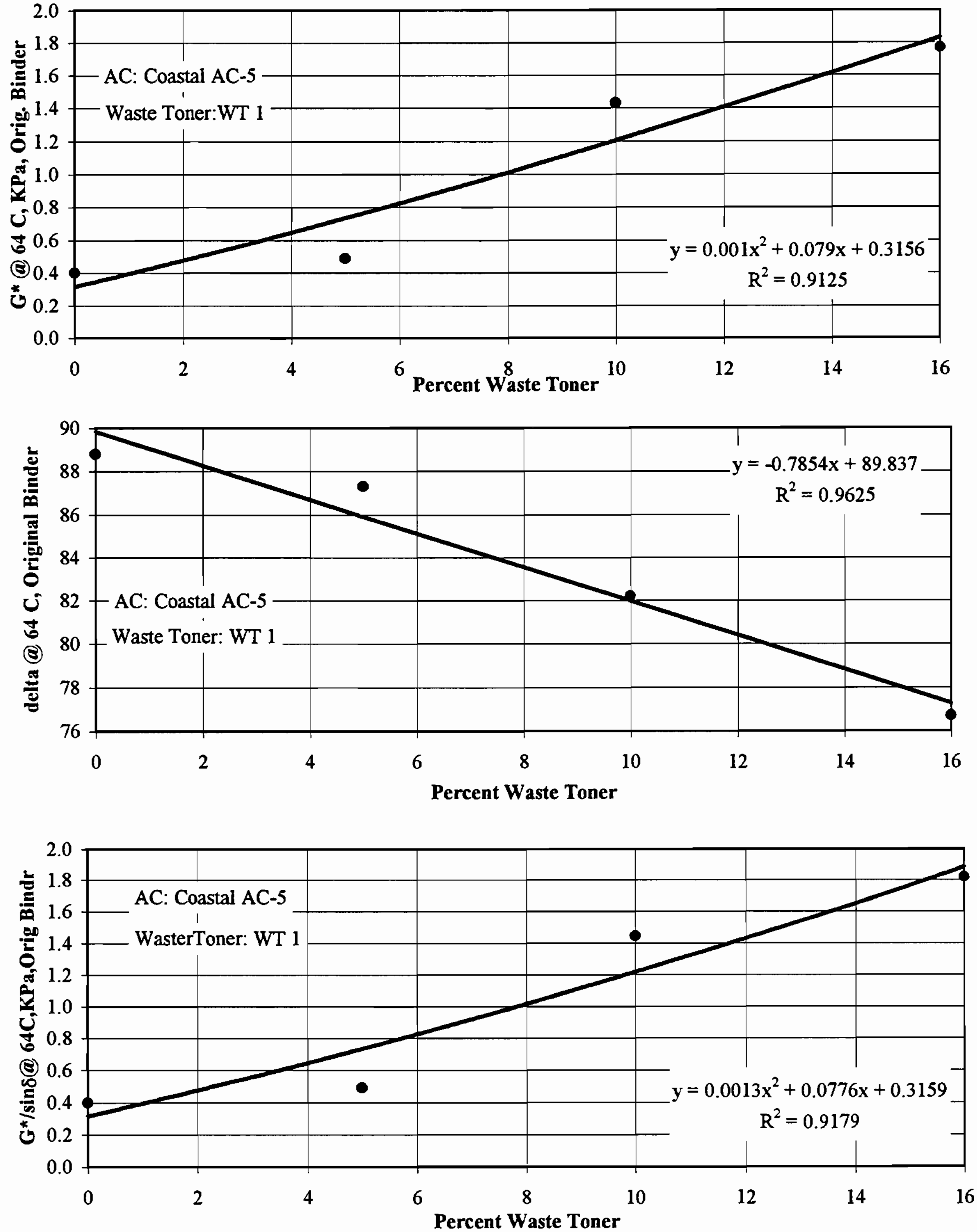


Figure A.3. Test Results from DSR for the Unaged Binder (AC-5) Modified with Different Toner Amounts.

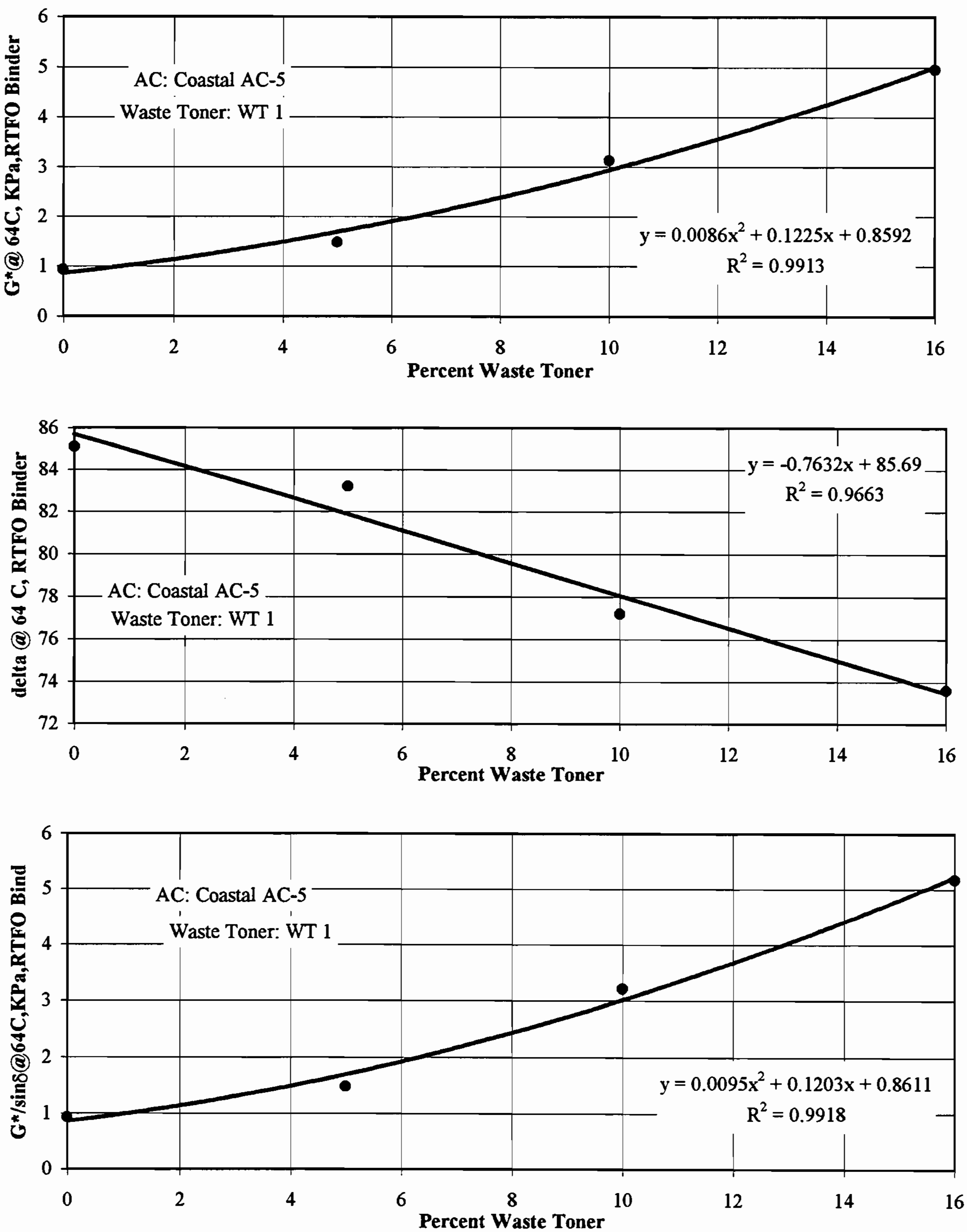
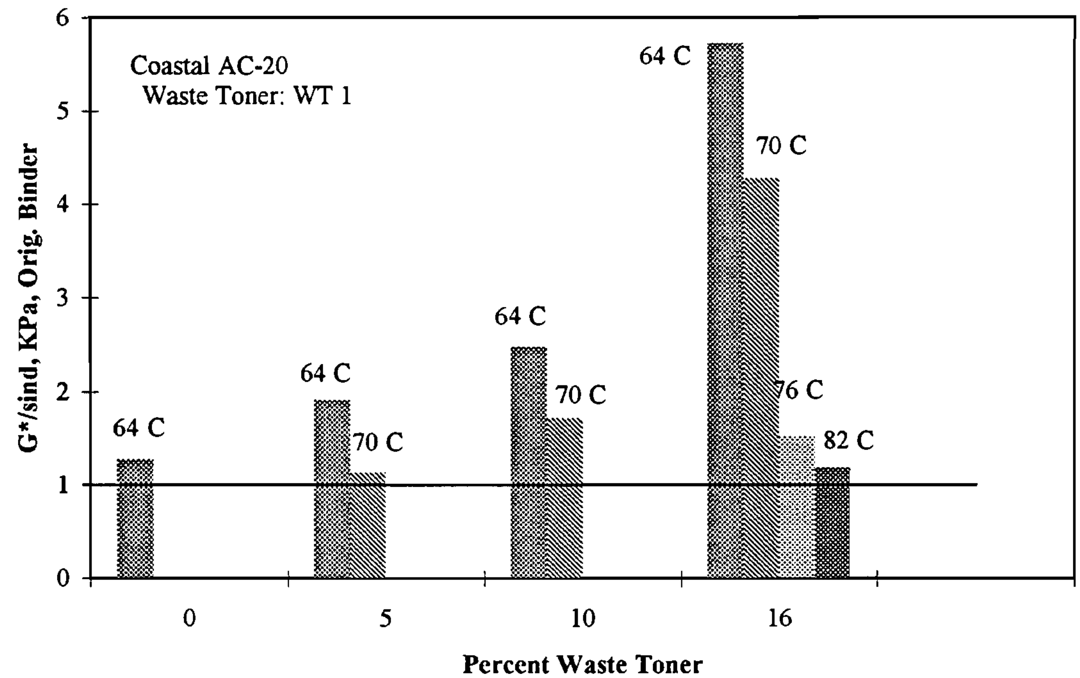


Figure A.4. Test Results from DSR for the RTFO-Aged Binder (AC-5) for Different Toner Amounts.



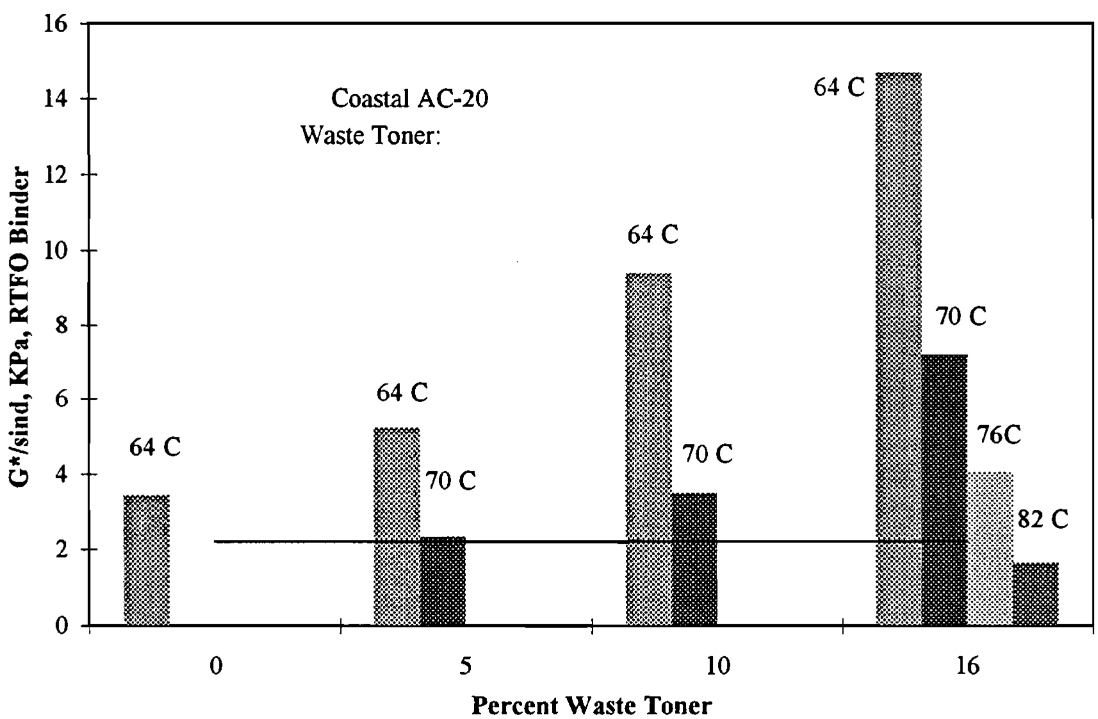
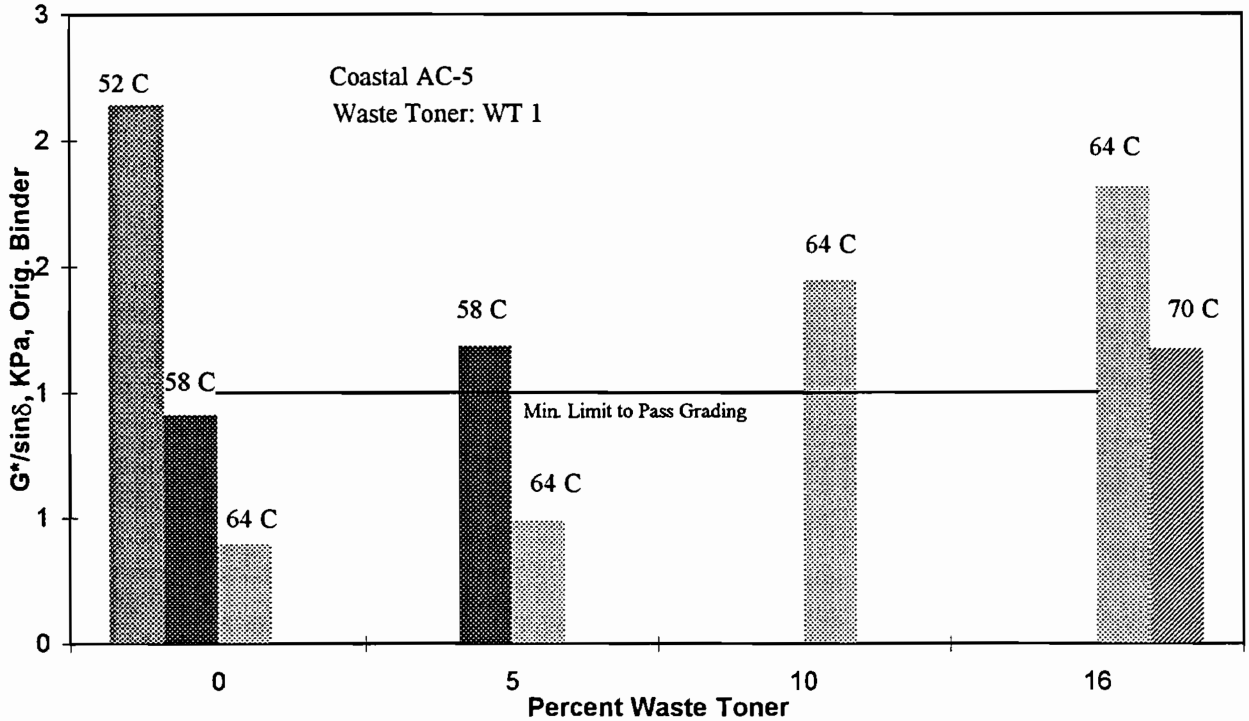


Figure A.5. Results from Dynamic Shear Rheometer Testing at Different Temperatures for AC-20 Asphalt Modified with Different Toner Amounts.



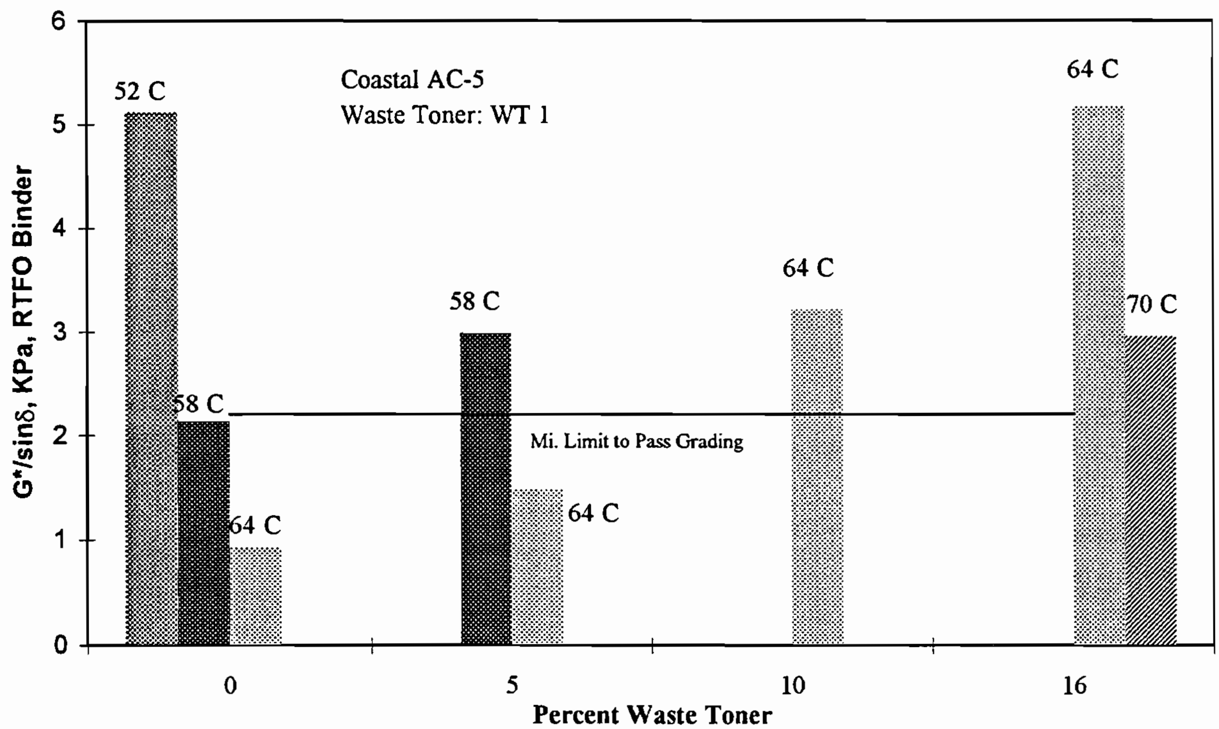


Figure A.6. Results from Dynamic Shear Rheometer Testing at Different Temperatures for AC-5 Asphalt. Modified with Different Toner Amounts.

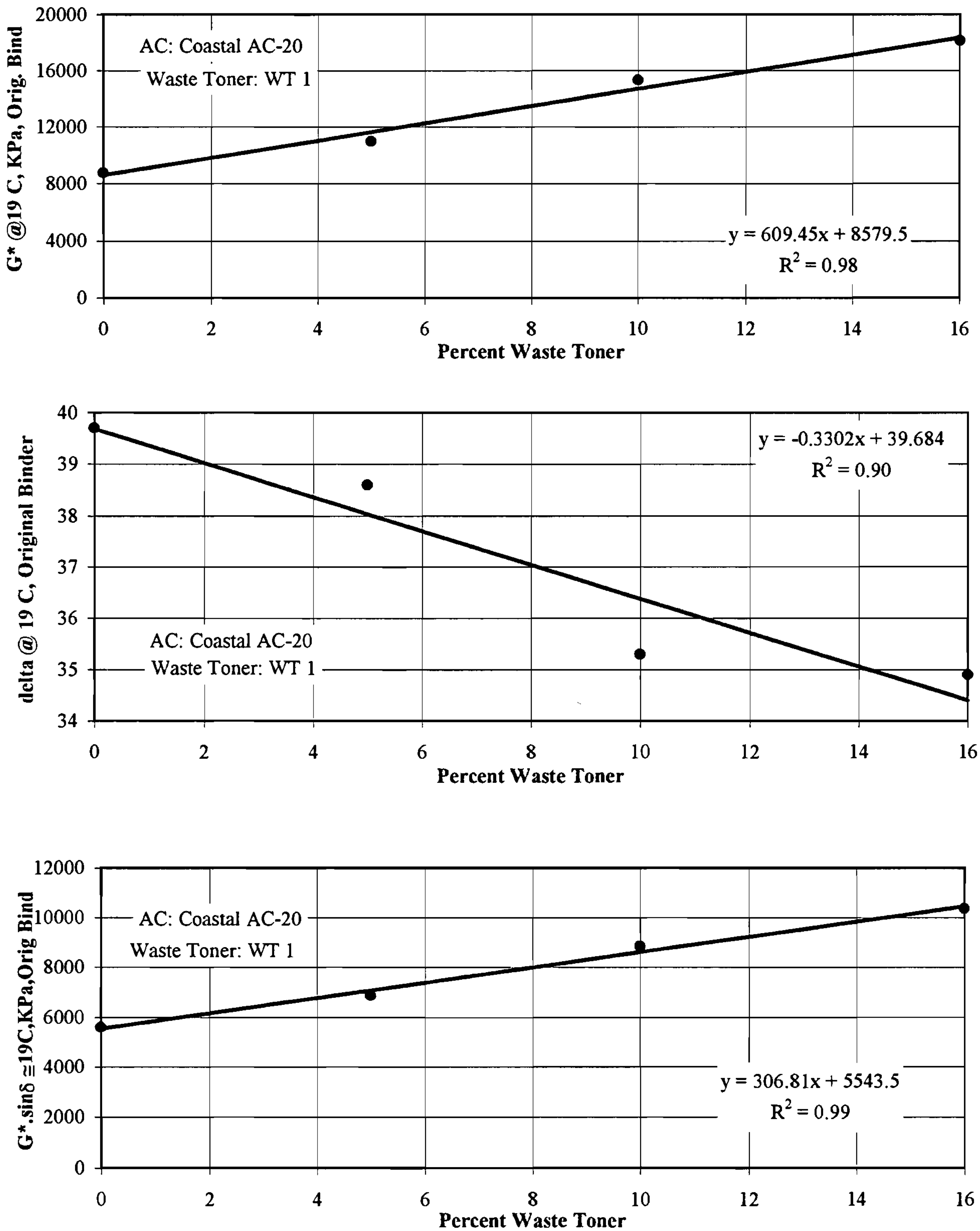
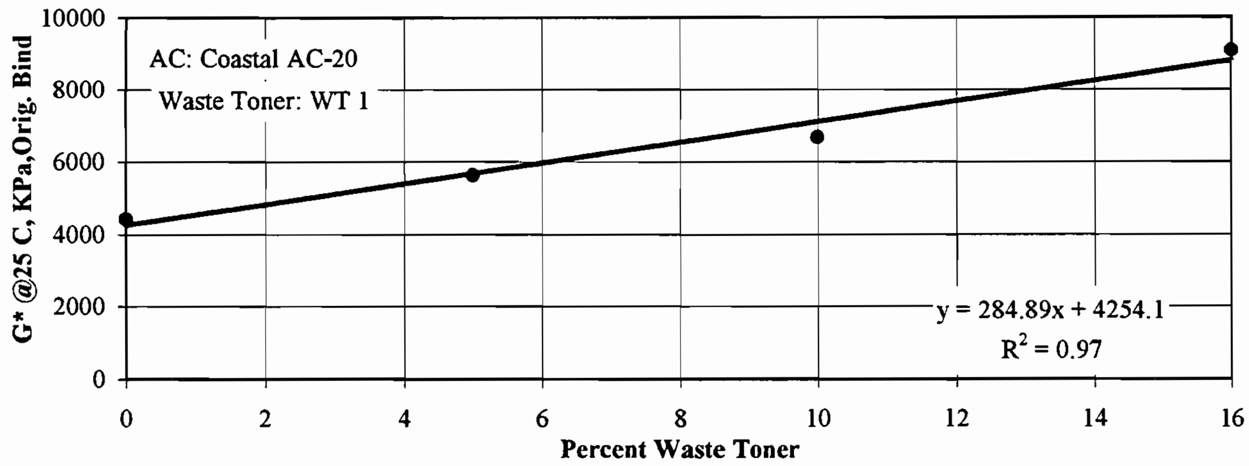
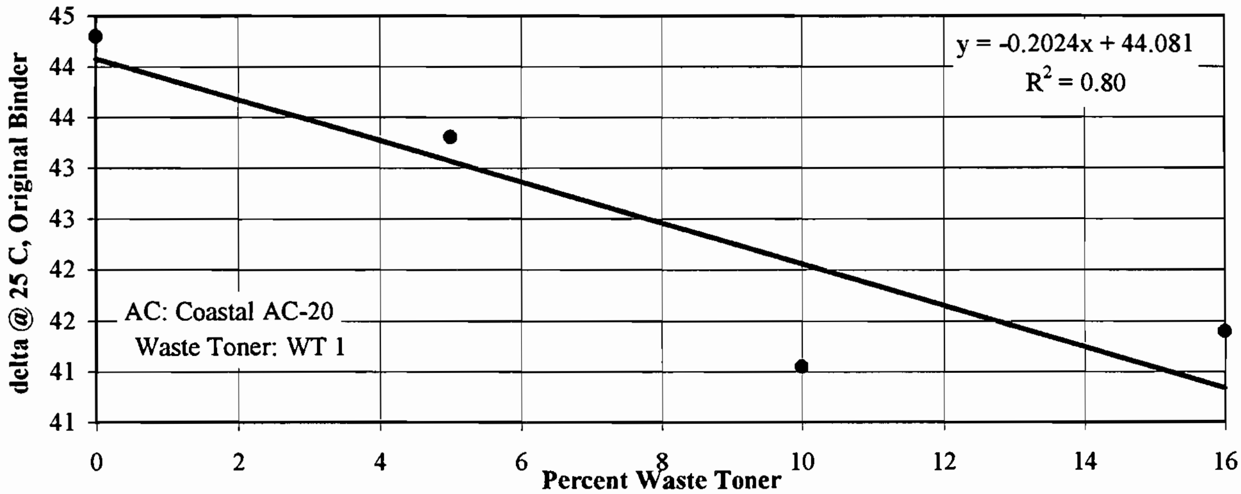


Figure A.7. Test Results from DSR for the PAV-Aged Binder (AC-20) Modified with Different Amounts of Toner.





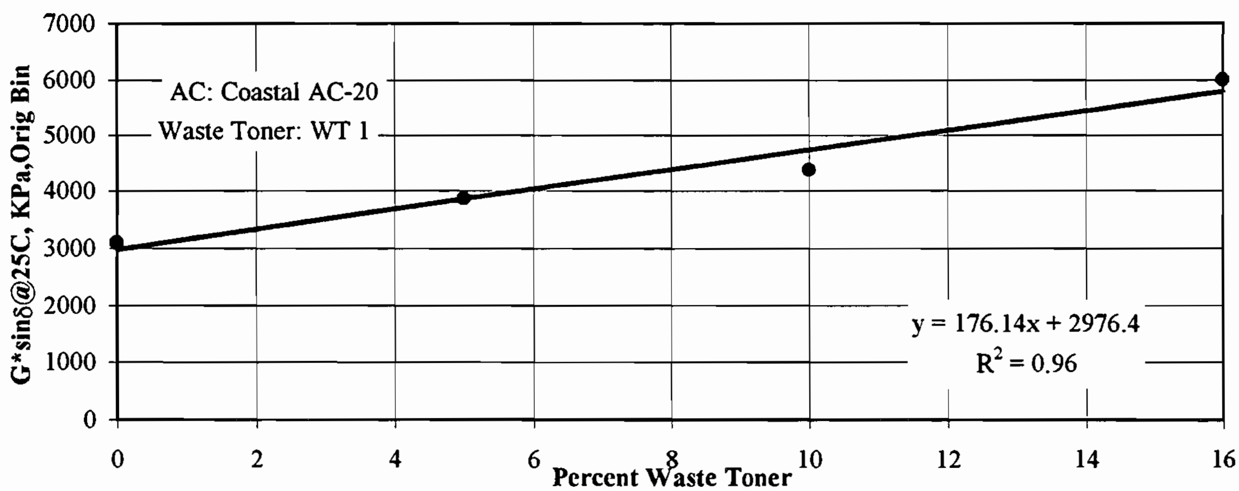


Figure A.8. Test Results from DSR for the PAV-Aged Binder (AC-20) Modified with Different Toner Amounts.

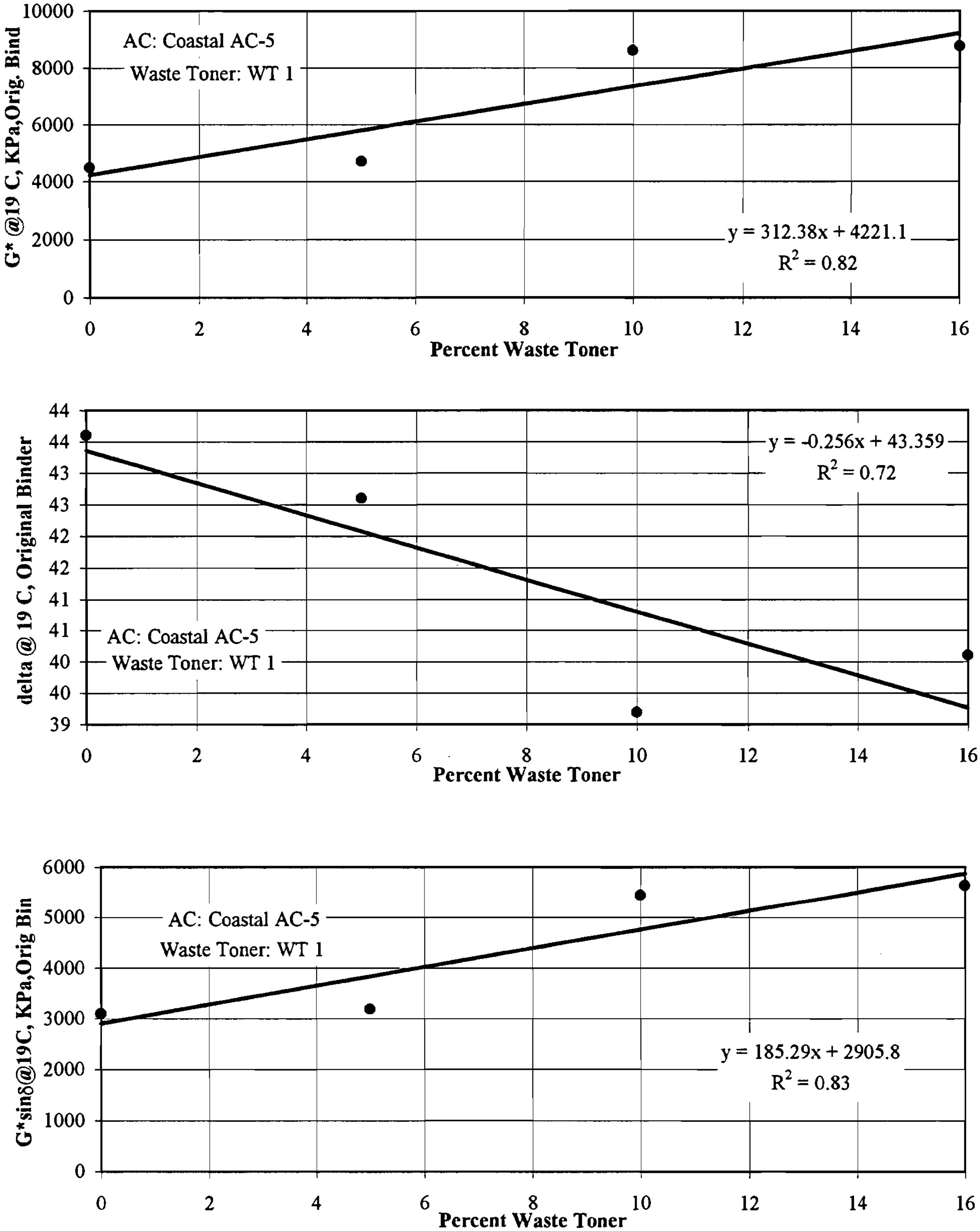


Figure A.9. Test Results from DSR for the PAV-Aged Binder (AC-5) Modified with Different Toner Amounts.

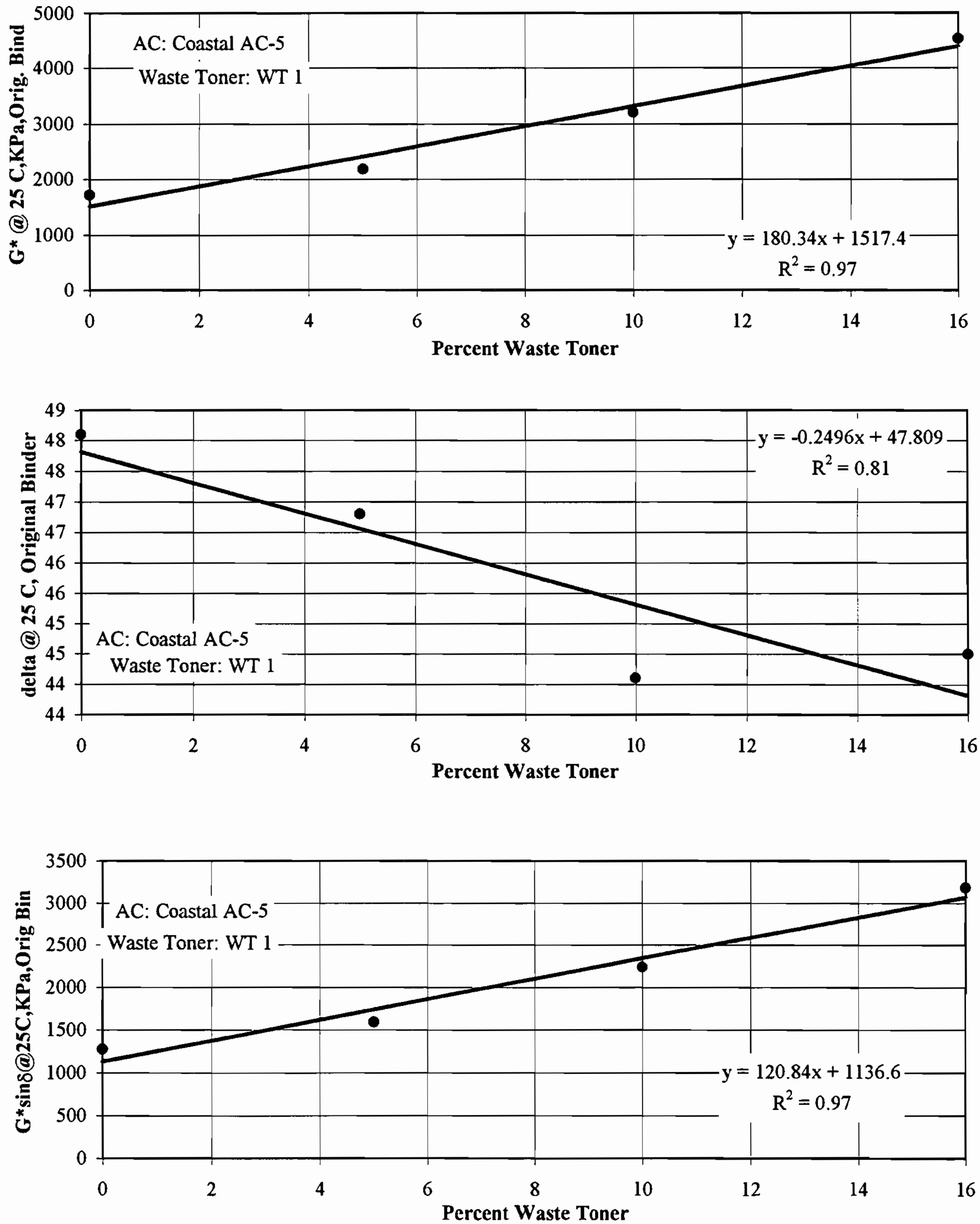


Figure A.10. Test Results from DSR for the PAV-Aged Binder (AC-5) Modified with Different Toner Amounts.

Table A.5. Results of Specimen Compaction Using Superpave Gyratory Compactor.

Gmm (meas)	2.466				%Binder		4.5	
Mold Area	17671.3 sq. mm.				% Waste Toner		5	
Spec. No.	A1-1				A1-2			
Dry Wght(gr)	4687.4				4697.7			
Gyrations	Ht,mm	Gmb estm.	Gmb corr.	%Gmm	Ht,mm	Gmb estm.	Gmb corr.	%Gmm
2	143.9	1.843	1.901	77.1	143.4	1.854	1.915	77.7
5	138.5	1.915	1.975	80.1	137.6	1.932	1.996	80.9
8	135.4	1.959	2.021	81.9	134.3	1.979	2.045	82.9
20	129.2	2.053	2.118	85.9	128.0	2.077	2.146	87.0
50	123.4	2.150	2.217	89.9	122.2	2.175	2.248	91.1
96	119.8	2.214	2.284	92.6	118.7	2.240	2.314	93.8
130	118.3	2.242	2.313	93.8	117.3	2.266	2.341	94.9
152	117.6	2.256	2.326	94.3	116.7	2.278	2.353	95.4
Gmb(meas)		2.326				2.353		
Corr. Factor		1.031				1.033		

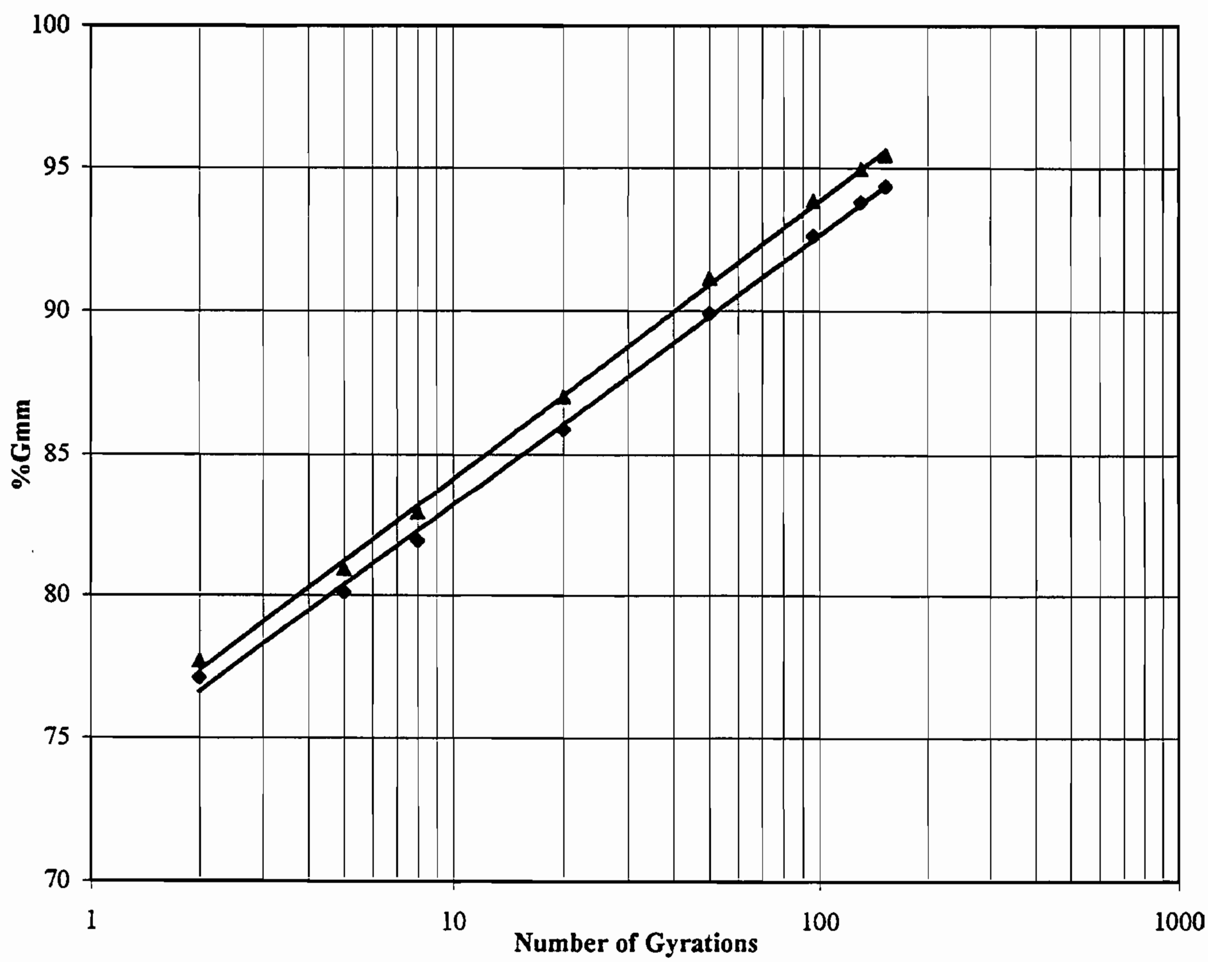


Figure A.11. Specimen Density as a Percent of Maximum Theoretical Density as a Function of No. of Gyrations.

Table A.6. Results of Specimen Compaction Using Superpave Gyratory Compactor.

Gmm (meas)	2.434				%Binder		5.2	
Mold Area	17671.3 sq. mm.				% Waste Toner		5	
Spec. No.		A2-1				A2-2		
Dry Wght(gr)		4725.1				4727.3		
Gyrations	Ht,mm	Gmb estm.	Gmb corr.	%Gmm	Ht,mm	Gmb estm.	Gmb corr.	%Gmm
2	142.1	1.867	1.926	79.1	144.8	1.836	1.905	78.3
5	136.3	1.946	2.008	82.5	138.9	1.914	1.986	81.6
8	133.1	1.993	2.056	84.5	135.6	1.960	2.034	83.6
20	126.7	2.094	2.160	88.7	128.9	2.062	2.140	87.9
50	121.0	2.192	2.262	92.9	122.8	2.165	2.247	92.3
96	117.4	2.259	2.331	95.8	119.1	2.232	2.316	95.2
130	116.1	2.285	2.357	96.8	117.7	2.259	2.344	96.3
152	115.4	2.299	2.372	97.4	117.0	2.272	2.358	96.9
Gmb(meas)		2.372				2.358		
Corr. Factor		1.032				1.038		

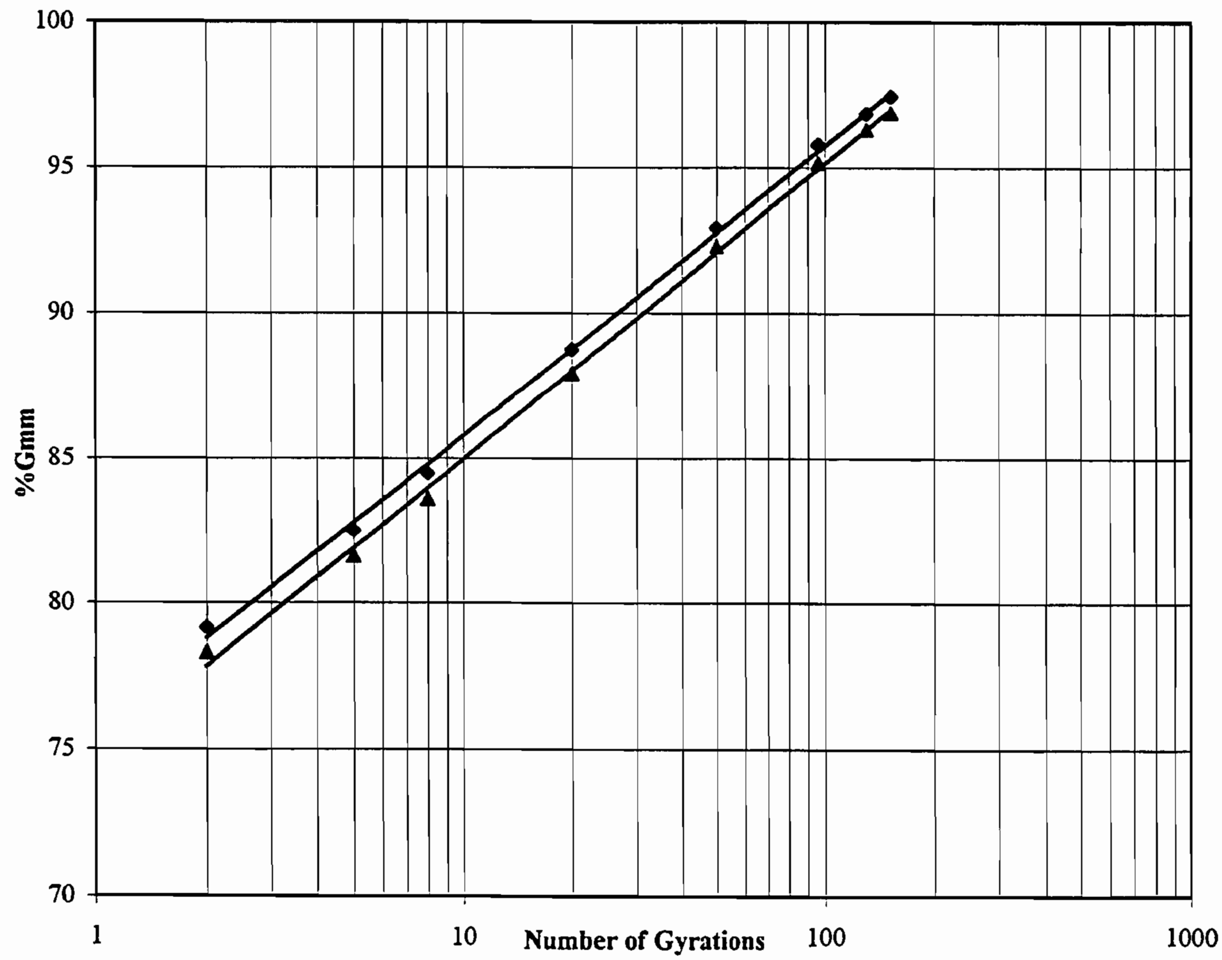


Figure A.12. Specimen Density as a Percent of Maximum Theoretical Density as a Function of No. of Gyrations.

Table A.7. Results of Specimen Compaction Using Superpave Gyratory Compactor.

Gmm (meas)	2.410				%Binder		5.9	
Mold Area	17671.3 sq. mm.				% Waste Toner		5	
Spec. No.	A3-1				A3-2			
Dry Wght(gr)	4752.5				4760.9			
Gyrations	Ht,mm	Gmb estm.	Gmb corr.	%Gmm	Ht,mm	Gmb estm.	Gmb corr.	%Gmm
2	142.2	1.865	1.939	80.5	144.8	1.836	1.930	80.1
5	136.5	1.943	2.020	83.8	138.9	1.914	2.012	83.5
8	133.2	1.991	2.070	85.9	135.6	1.960	2.061	85.5
20	126.8	2.092	2.175	90.2	128.9	2.062	2.168	90.0
50	121.0	2.192	2.279	94.6	122.8	2.165	2.276	94.4
96	117.6	2.256	2.345	97.3	119.1	2.232	2.346	97.4
130	116.3	2.281	2.371	98.4	117.7	2.259	2.374	98.5
152	115.7	2.293	2.383	98.9	117.0	2.272	2.388	99.1
Gmb(meas)		2.383				2.388		
Corr. Factor		1.039				1.051		

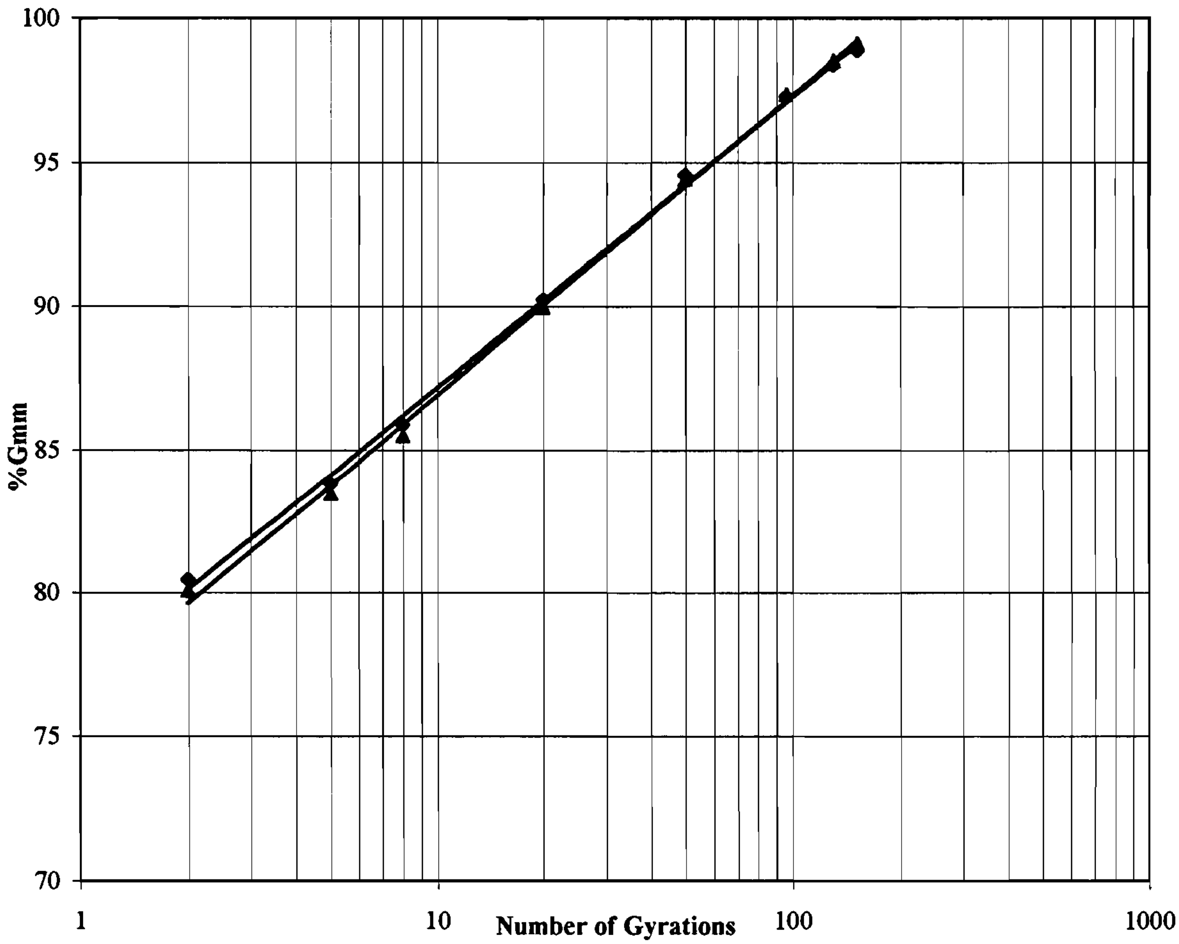


Figure A.13. Specimen Density as a Percent of Maximum Theoretical Density as a Function of No. of Gyrations.

Table A.8. Results of Specimen Compaction Using Superpave Gyratory Compactor.

Gmm (meas)	2.460				%Binder		4.5	
Mold Area	17671.3 sq. mm.				% Waste Toner		16	
Spec. No.		A4-1				A4-2		
Dry Wght(gr)		4687.6				4700.1		
Gyrations	Ht,mm	Gmb estm.	Gmb corr.	%Gmm	Ht,mm	Gmb estm.	Gmb corr.	%Gmm
2	144.0	1.842	1.910	77.7	143.5	1.853	1.919	78.0
5	138.2	1.919	1.991	80.9	137.9	1.929	1.997	81.2
8	134.8	1.968	2.041	83.0	134.8	1.973	2.043	83.0
20	128.5	2.064	2.141	87.0	128.7	2.067	2.139	87.0
50	122.8	2.160	2.240	91.1	123.2	2.159	2.235	90.8
96	119.5	2.220	2.302	93.6	119.7	2.222	2.300	93.5
130	118.2	2.244	2.327	94.6	118.3	2.248	2.327	94.6
152	117.6	2.256	2.339	95.1	117.7	2.260	2.339	95.1
Gmb(meas)		2.3393				2.339		
Corr. Factor		1.037				1.035		

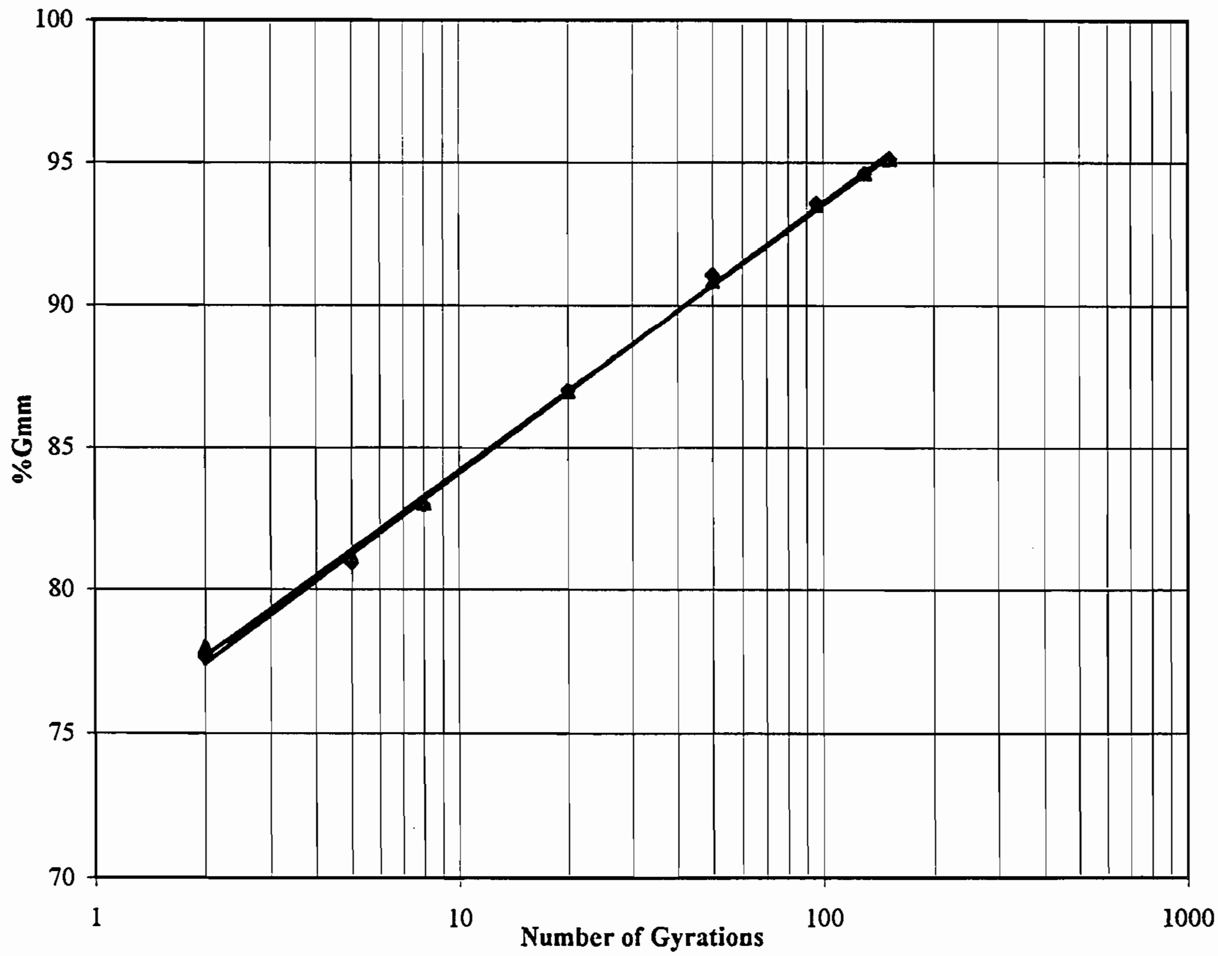


Figure A.14. Specimen Density as a Percent of Maximum Theoretical Density as a Function of No. of Gyrations.

Table A.9. Results of Specimen Compaction Using Superpave Gyratory Compactor.

Gmm (meas)	2.443				%Binder		5.2	
Mold Area	17671.3 sq. mm.				% Waste Toner		16	
Spec. No.		A5-1				A5-2		
Dry Wght(gr)		4721.2				4738.7		
Gyrations	Ht,mm	Gmb estm.	Gmb corr.	%Gmm	Ht,mm	Gmb estm.	Gmb corr.	%Gmm
2	142.0	1.868	1.936	79.2	143.2	1.857	1.927	78.9
5	136.4	1.945	2.015	82.5	137.3	1.937	2.010	82.3
8	133.3	1.990	2.062	84.4	133.9	1.986	2.061	84.4
20	127.2	2.085	2.161	88.5	127.6	2.084	2.162	88.5
50	121.7	2.180	2.259	92.5	122.0	2.180	2.262	92.6
96	118.3	2.242	2.324	95.1	118.7	2.241	2.325	95.2
130	117.0	2.267	2.350	96.2	117.4	2.266	2.350	96.2
152	116.4	2.279	2.362	96.7	116.8	2.277	2.362	96.7
Gmb(meas)		2.362				2.362		
Corr. Factor		1.036				1.037		

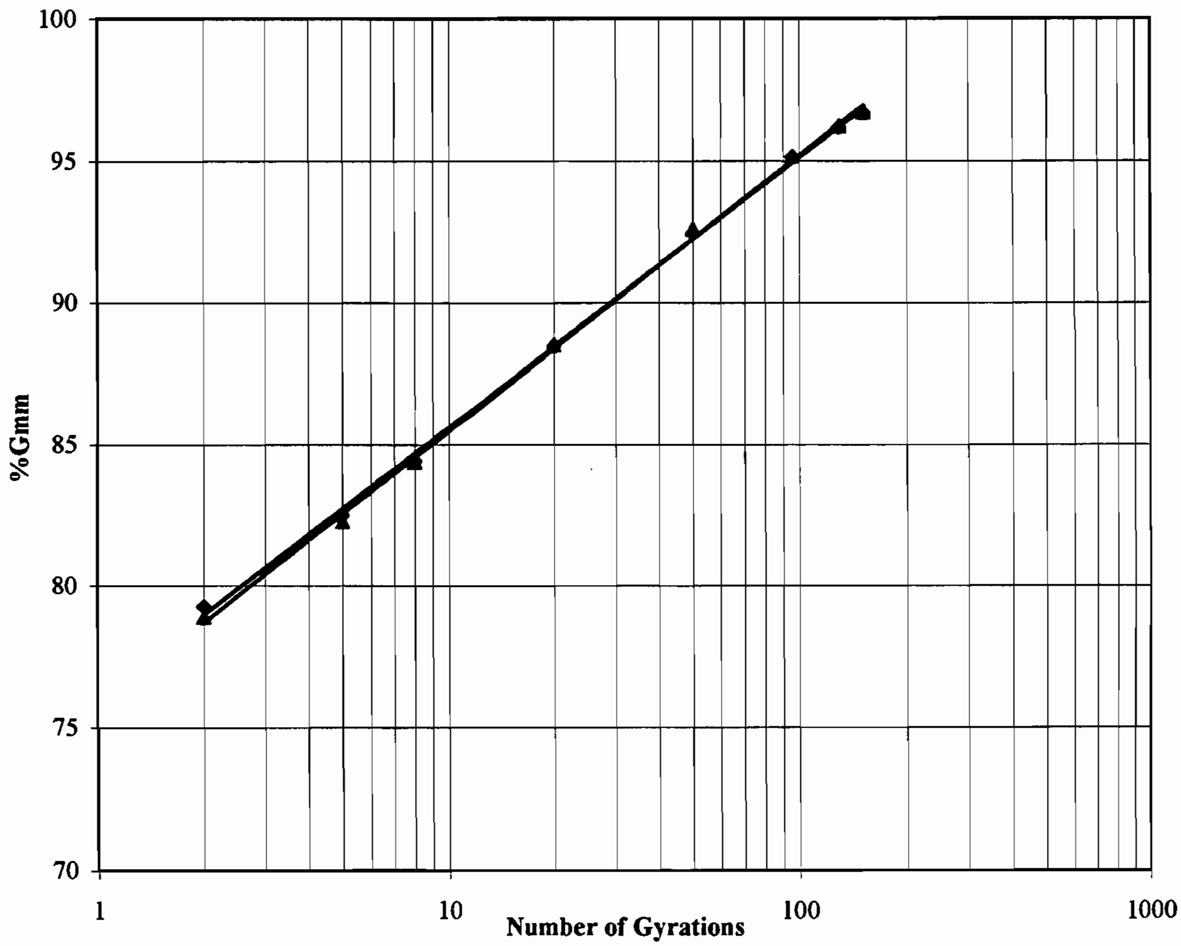


Figure A.15. Specimen Density as a Percent of Maximum Theoretical Density as a Function of No. of Gyrations.

Table A.10. Results of Specimen Compaction Using Superpave Gyratory Compactor.

Gmm (meas)	2.410			%Binder		5.9		
Mold Area	17671.3 sq. mm.			% Waste Toner		16		
Spec. No.		A6-1				A6-2		
Dry Wght(gr)		4752.5				4760.9		
Gyrations	Ht,mm	Gmb estm.	Gmb corr.	%Gmm	Ht,mm	Gmb estm.	Gmb corr.	%Gmm
2	142.3	1.864	1.943	80.6	141.7	1.877	1.952	81.0
5	136.5	1.943	2.026	84.1	135.9	1.957	2.036	84.5
8	133.2	1.991	2.076	86.2	132.6	2.006	2.086	86.6
20	126.9	2.090	2.179	90.4	126.4	2.104	2.189	90.8
50	121.2	2.189	2.282	94.7	120.8	2.202	2.290	95.0
96	118.0	2.248	2.344	97.2	117.7	2.260	2.350	97.5
130	116.9	2.269	2.366	98.2	116.7	2.279	2.371	98.4
152	116.5	2.277	2.374	98.5	116.2	2.289	2.381	98.8
Gmb(meas)		2.374				2.381		
Corr. Factor		1.043				1.040		

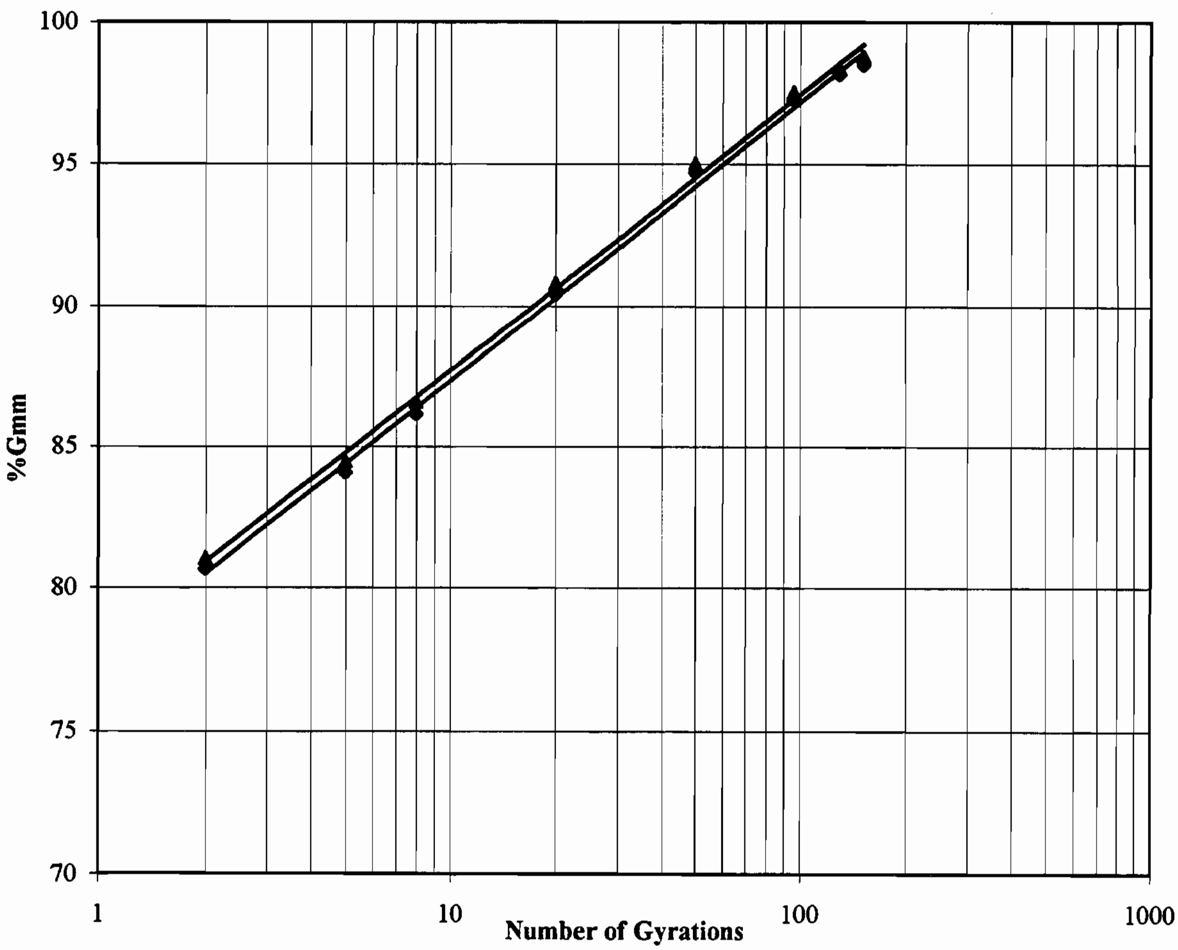


Figure A.16. Specimen Density as a Percent of Maximum Theoretical Density as a Function of No. of Gyrations.