Polymer modification of Arab Asphalt to Suit Gulf Countries' performance requirements

Ibrahim Ahmed Suliman Al-Dubabe

Civil Engineering

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Abstract

Asphalt binders are thermo-visco-elastic materials where temperature and rate of load application have a great influence on their behavior. They are classified as a rheological materials since their stress-strain response is both time and temperature dependent. Asphalt binder consistency and hence ability to sustain and hold its fundamental cementing mechanism changes depending on temperature. The neat asphalt binders lack the proper viscous-elastic balance that usually occur due to an effective elastic network created by molecular association. It is hypothesized that proper visco-elastic balance can be formed by creating molecular entanglement in an asphalt through the use of high molecular weight polymeric additives.

In this research, the physical and rheological properties of the locally produced Arab asphalt binders and the performance requirements of the Gulf countries environmenal conditions were determined. Moreover, a procedure for modifying asphalt binders was developed together with a criteria to evaluate the effectiveness of the polymer modification process. The developed procedure and criteria were implemented to modify Arab asphalt binders to satisfy the preformance requirements of the Gulf countries considering rutting, fatigue and low temperature cracking.

The designed experiments and the collected data clearly indicated that the locally produced asphalt binders can be used without modification in areas where the maximum pavement temperature does not exceed 64^{0}C. Temperature zoning indicated that more than 50% of the Gulf countries experience a maximum pavement temperature of 76^{0}C. Therefore, asphalt binder modification is required to meet Gulf countries' performance requirements. It is evident that polymer modification is capable and effective in improving the neat Arab asphalt binders reheological properties to meet and satisfy the performance requirements of the Gulf countries. Further, life cycle cost analysis of various polymer modified mixtures indicates that the polymer modification is feasible and is economically justified. Preliminary evaluation of hot mix asphalt concrete containing polymer modified asphalt binders were performed. These experiments indicated that the performance of a mix containing polyethylene was superior to other mixtures.

Polymer Modification of Arab Asphalt to Suit Gulf Countries' Performance Requirements

BY

Ibrahim Ahmed Suliman Al-Dubabe

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UMI
300 North Zeeb Road
Ann Arbor, MI 48103

King Fahd University of Petroleum and Minerals
Dhahran 31261, Saudi Arabia

COLLEGE of GRADUATE STUDIES

This dissertation, written by **IBRAHIM AHMED SULIMAN AL-DUBABE** under the direction of his Dissertation Advisor and approved by his Dissertation Committee, has been presented to and accepted by the Dean of the College of Graduate Studies, in partial fulfillment of the requirements of the degree of **DOCTOR OF PHILOSOPHY in CIVIL ENGINEERING.**

Dissertation Committee

Dr. Hamad I. Al-Abdul Wahhab
Dissertation Committee Chairman

Dr. Mohammed F. Ali
Co-Chairman

Dr. Gokmen Ergun
Member

Dr. Abdulaziz Bubshait
Member

Dr. Khalid Al-Fosail
Member

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6/1/97

Dr. Sahel N. Abduljauwad
Department Chairman

Dr. Aballah M. Al-Shehri
Dean, College of Graduate Studies

7-1-97
Date

بسم الله الرحمن الرحيم

﴾In the Name of Allah the Most Beneficent, the Most Merciful﴿

إهداء

إلى والدتي الحنونة ....

إلى أولادي و زوجتي العزيزة ....

أهدي جهدي المتواضع سائلا المولى التوفيق و السداد ....

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All Gratitude Is To Allah

Praise and Glory be to the Almighty ALLAH for bestowing me with the health, spirit, power and patience to complete this work.

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NAME : IBRAHIM AHMED SULIMAN AL-DUBABE

TITLE OF STUDY : POLYMER MODIFICATION OF ARAB ASPHALT TO SUIT GULF COUNTRIES' PERFORMANCE REQUIREMENTS

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DOCTOR OF PHILOSOPHY DEGREE
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خلاصة الرسالة

اسم الطالب الكامل : إبراهيم أحمد سليمان الضبيب

عنوان الدراسة : تحسين الاسفلت العربي بإضافة اللدائن ليناسب متطلبات الأداء في دول الخليج العربي.

التخصص : هندسة مدنية .

تاريخ الشهادة : يونيو ١٩٩٦م .

تعتبر مواد الربط الاسفلتية من المواد اللزجة-المرنة-الحرارية حيث تؤثر الحرارة و معدل التحميل على سلوكها، و تصنف هذه المواد ضمن المواد الانسيابية لاعتماد استجابتها للاجهادات و الانفعالات على كلٍ من الحرارة و الزمن، كما يختلف قوام الاسفلت و قدرته على الربط باختلاف الحرارة . و من ناحيةٍ أخرى، فان الاسفلت الحر لا يتوفر فيه الاتزان المناسب بين اللزوجة و المرونة و التي غالباً ما تتوفر في المادة بوجود شبكة مرنةٍ فعالةٍ مهيأةٍ بسبب التلاحم الجزيئي بها . و على هذا ، فانه يفترض إمكانية تشكيل إتزانٍ بين اللزوجة و المرونة بواسطة إيجاد تكتلات جزيئيه في الاسفلت بإضافة مواد لدائنيه ذات أوزان جزيئيه عالية.

تم في هذا البحث تحديد الخصائص الفيزيائية و الانسيابية للاسفلت المنتج محلياً كما تم تحديد متطلبات الأداء في الظروف البيئية في دول الخليج العربي. بالإضافة إلى ذلك، تم تطوير طريقة لتعديل الاسفلت و معيار لتقويم فعالية هذه الطريقة. و بعد ذلك، تم استخدام طريقة التعديل و معيار التقويم التي تم تطويرها في تعديل الاسفلت العربي ليناسب متطلبات الأداء في دول الخليج العربي آخذين في الاعتبار اجهادات التخددات و تشققات الكلل و الحرارة المتدنية.

و قد دلت التجارب و المعلومات التي تم تجميعها على إمكانية استخدام الاسفلت المحلي في مناطق لا تتجاوز درجات الحرارة في طبقات الرصف فيها عن ٦٤°م، و من جهةٍ أخرى، فقد دلت تقسيمات دول الخليج العربي إلى مناطق ذات حدود حرارية متشابهة من حيث درجات الحرارة العليا و الدنيا في طبقات الرصف على أن اكثر من ٥٠٪ من دول الخليج تتعرض لدرجات حرارة تصل إلى ٧٦°م، و من هذا يتضح ضرورة تعديل الاسفلت المنتج محلياً ليناسب الظروف البيئية لدول الخليج العربي. كما دلت التجارب أيضاً على إمكانية تعديل الاسفلت الحر باستخدام مواد اللدائن بفعاليةٍ عاليةٍ، و أن عملية التعديل ذات جدوى اقتصادية بناءً على التحليلات الاقتصادية لدورة الحياة للرصفيات، كما تم أيضاً إجراء تجارب مبدئية على خلطات اسفلتية تحتوي اسفلتاً معدلاً و آخر حر. و دلت هذه التجارب على تفوق الخلطات المحتوية على البولي ايثيلين على نظيراتها المحتوية على الاسفلت الحر.

درجة الدكتوراه في الفلسفة

جامعة الملك فهد للبترول و المعادن

الظهران ، المملكة العربية السعودية

يونيو ١٩٩٦م

NOMENCLATURE

Abbreviation	Description
ANOVA	Analysis of variance
BBR	Bending beam rheometer
BH	PABCO refinery located in Bahrain
CRT	Crumb rubber from tires
δ	Phase angle
DMA	Dynamic mechanical analysis
DSR	Dynamic shear rheometer
ELSYM5	Elastic layer system analysis
EPS	Expandable polystyrene
EUAC	Equivalent uniform annual cost
G^*	Complex shear modulus
GC	Gulf countries (Kingdom of Saudi Arabia, Kuwait, Oman, Bahrain, Qatar and UAE)
GPS	General purpose polystyrene
H_1	Alternate hypothesis
HDPE	High density polyethylene
HIPS	High impact polystyrene
H_o	Null hypothesis
KW	Al-Ahmadi refinery located in /Kuwait

LCCOST	Life cycle cost analysis
LLDPE	Linear low density polyethylene
LSD	Least significant difference
m-value	The slope of the creep stiffness-time curve
NAAB	Neat Arab asphalt binder
OC	Operating characteristics curves
PAV	Pressure aging vessel
PB	Polybelt polymer manufactured by Exxon chemicals
PG	Performance grade
PI	Penetration index
PMAB	Polymer modified asphalt binder
PP	Polypropylene
PR	Penetration ratio
PS	Polystyrene
PVN	Penetration viscosity number
rpm	Revolutions per minutes
RT	Ras Tanura refinery located in Saudi Arabia
RTFOT	Rolling thin film oven test
RV	Rotational viscometer
RY	Riyadh refinery located in Saudi Arabia
S	Creep stiffness
SABIC	Saudi basic industrial corporation

SBR	Styrene-Butadiene-Rubber
SBS	Styrene-Butadiene-Styrene polymer
SHRP	Strategic highway research program
TFOT	Thin film oven test
VTS	Viscosity temperature susceptibility
.	The Transport and road research laboratories wheel tracking machine

Chapter 1

INTRODUCTION

Roadway construction and maintenance are major responsibilities of government agencies. When constructing roadways, engineers must consider the primary user requirements of safety, economy, and convenience. It is, therefore, essential to construct roadways that remain at acceptable service levels for the maximum possible time. In order to achieve this, roadway construction specifications must take into account environmental factors, traffic loads, and traffic volumes in the construction area. Consequently, the selection of building materials is a crucial factor. If an appropriate choice is made, the service life of the pavement is maximized, and maintenance costs are minimized.

1.1 BACKGROUND

The roadway networks of the Gulf Countries (GC) (i.e. Kingdom of Saudi Arabia, Kuwait, Bahrain, Qatar, United Arab Emirates, and Oman) have developed more rapidly than in many other industrialized countries. Due to the availability of relatively low cost asphalt binders, these roadway networks are being built with flexible pavements. The high cementing ability of asphalt binders is utilized to bind aggregate particles together to form a solid, stable, and durable asphalt concrete, which is used to construct road surfaces and bases.

Hot mix asphalt concrete is conventionally composed of two materials: aggregate and asphalt binder. About 94 to 96 percentage by weight of the mix consists of the aggregate, and the remaining 4 to 6 percentage by weight of the mix consists of the asphalt binder. Although the percentage of the asphalt binder is relatively small, the asphalt binder influences pavement performance more than the aggregate because environmental factors such as heat and sun radiation affect the asphalt binder more than they do the aggregate.

The quality of the asphalt binder also play significant roles in the performance of the entire pavement structure. Specifications set forth by road agencies require asphalt binders to have a minimum character by specifying and controlling some of their important physical properties. This was done to minimize inferior performance of pavement structures in the field and explains why researchers and engineers are focusing their attention on improving asphalt binder characteristics by using additives, modifiers, and modification processes.

1.2 PROBLEM STATEMENT

Nowadays, two of the most serious distresses associated with flexible pavements are cracking, which occurs at intermediate and low temperatures, and permanent deformation, which occurs at high temperatures. These distresses reduce the service life of the pavement and increase maintenance costs.

Cracking is categorized in two phenomenological categories: load associated and non-load associated. The principal class of load associated cracking is the fatigue crack, and the principal class of non-load associated cracking is the shrinkage and low

temperature crack. Cracking of flexible pavements usually occurs when vehicular loads and/or low winter temperatures induce tensile forces within asphalt concrete that exceed its tensile strength. The magnitude of these stresses depends on the rate of load application, rate of temperature drop, and on the visco-elastic properties of the asphalt binder at intermediate and low temperatures. Asphalt binders are required to have low stiffness at intermediate and low temperatures so as to sustain severe thermal stresses and hence resist thermal and fatigue cracking.

Permanent deformation is also categorized in two phenomenological categories: densification and lateral displacement. The principle class of permanent deformation is rutting. Rutting of flexible pavements usually occurs when vehicular loads induce shear stresses that exceed the shear strength of the materials contained in the pavement structure. This depends on vehicular loads and the visco-elastic properties of the asphalt binder. Asphalt binders are required to have high stiffness at high temperature to resist rutting.

The hot weather of the Gulf countries has promoted an inferior performance of asphalt concrete mixes in the field. Permanent deformation is considered a serious problem in the road systems of the Gulf countries. Some highways have developed rutting within only a few months after opening. The widespread occurrence of rutting in the roadway networks of the Kingdom of Saudi Arabia, for example, necessitated a national research project to investigate the problem. One of the major findings of this research was the identification of asphalt binders as major contributors to rutting. Moreover, this study recommended that asphalt binder modification is necessary (Fatani et al , 1992).

Asphalt binders are thermo-visco-elastic materials. Temperature and rate of load application have a great influence on their behavior. Asphalt binder consistency, and hence ability to sustain and hold its fundamental cementing mechanism, changes as temperature changes. Goodrich (1988) reported that some neat asphalt binders lack the proper balance of visco-elastic properties. Typically, these properties occur because of an effective elastic network created by natural molecular combination. It is hypothesized that the proper balance of visco-elastic properties can be formed by creating molecular association in an asphalt binder through polymer modification.

In this research, a procedure for modifying asphalt binders was developed together with the criteria to evaluate their effectiveness. The procedure was then implemented to modify Arab asphalt binders to satisfy the performance requirements of the Gulf countries' environmental conditions. Finally, an evaluation using the developed criteria was conducted on the modified Arab asphalt binders.

1.3 OBJECTIVES

The overall goal of this research was to identify an appropriate polymer(s) to modify Arab asphalt binders to satisfy the performance requirements of the Gulf countries. The specific objectives were as follows:

1. To determine the physical properties and visco-elastic behavior of pure and polymer modified Arab asphalt binders by answering the following questions:
   a. What are the physical properties of Arab asphalt binders (specific gravity, penetration, viscosity, ductility, softening point...etc.)?

b. What are the temperature susceptibility and age hardening characteristics of Arab asphalt binders?

c. What are the dynamic visco-elastic parameters of Arab asphalt binders?

d. What are the performance temperature ranges which Arab asphalt binders will be subjected to in the Gulf countries?

2. To develop a procedure to modify Arab asphalt binders to satisfy the Gulf countries' performance requirements and to develop criteria to evaluate the effectiveness of the polymer. In this regard, experiments were designed to answer the following questions:

a. What blending procedure must be used to produce a homogenous asphalt-polymer blend?

b. What is the asphalt binder-polymer blending temperature?

c. How long should the polymer be mixed with the asphalt binder to obtain a homogeneous blend?

d. What are the criteria that signify homogeneity of the mixture?

e. How can the effectiveness of the modification be evaluated?

f. What type of polymer(s) improves the properties of Arab asphalt binders to satisfy the Gulf countries' performance requirements?

g. What polymer concentration should be used?

h. Are there any precautions that should be considered?

Chapter 2

LITERATURE REVIEW

Flexible pavements are defined as asphalt bound layers built over a granular base that rests on compacted natural road bed soil (Hass and Hudson, 1978, 1994; Yoder and Witczak, 1975). The top layers are made of a mixture of mineral aggregate and asphalt binder. The cementing ability of the asphalt is utilized to bind the aggregate particles together to form the asphalt concrete mixture.

In response to load and temperature, the behavior of the asphalt concrete mixture in the field depends on the behavior of its individual ingredients and the combined interaction between them. However, the asphalt binder's content, physical properties, and rheological properties have the most marked effect on the mixture's stability, tensile strain, fatigue life, and permanent deformation characteristics (Valkering and Van Gooswilligen, 1989; Pell and Cooper, 1975; Shook et al., 1982; Monismith et al., 1984; Brown, 1987).

In a study conducted by Fatani and his coworkers (1992) on the permanent deformation (i.e. rutting) of flexible pavements in the Kingdom of Saudi Arabia, a wide range of roadways were selected based on predetermined criteria such as traffic, structural design, construction specifications, and performance. More than twenty road sections,

rutted and non-rutted, were selected. These sections were subjected to comprehensive laboratory and field tests to identify the causes of the rutting. The properties of the asphalt binder, the aggregate, and the asphalt concrete mixture of rutted and non-rutted sections were statistically compared. The rutted and non-rutted sections were taken from the same road, while all other variables such as traffic, environment, etc. were kept constant. Based on the results of these comparisons, the asphalt binder was found to be a contributing factor in the kingdom's pavement rutting problem. This conclusion was reached because the asphalt concrete mixtures in rutted and non-rutted sections showed a significant difference in the physical properties of their asphalt binders as shown in Table 2.1. The study also concluded that a thorough investigation of the physical and rheological properties of local asphalt is needed.

The literature review is divided into three sections. The first section briefly describes the asphalt binder's properties, testing, and rheology. The second section focuses on polymers, and the third section summarizes national and international efforts in the field of polymer modification of asphalt binders.

2.1 ASPHALT BINDERS

An asphalt binder, as defined by the American Society for Testing and Materials (ASTM, 1985), is a dark brown to black cementitious material in which the predominate constituents are composed principally of high molecular weight hydrocarbons. Asphalt possesses strongly adhesive and water resistance characteristics. Asphalt binders are thermo-visco-elastic materials. They behave as elastic solids at either low temperatures or during rapid rates of load application and behave as viscous liquids at either high

Table 2.1: Physical Properties of Asphalt Binders from Rutted and Non-Rutted Sections in the Kingdom of Saudi Arabia (Fatani et al, 1992).

Road Name	Study Section	Absolute Viscosity @ 60 °C Poises	Kinematic Viscosity @ 135 °C cSt	Softening Point °C
Abuhdriah Expressway-Section A	Non-Rutted	64795	1843	66.2
Abuhdriah Expressway-Section A	Rutted	20765	1258	62.1
Abuhdriah Expressway-Section B	Non-Rutted	48228	1559	67.6
Abuhdriah Expressway-Section B	Rutted	42365	1646	64.1
Riyadh-Qassim Expressway-Section 2	Non-Rutted	66252	1264	65.3
Riyadh-Qassim Expressway-Section 2	Rutted	20601	930	60.5
Riyadh-Qassim Expressway-Section 3	Non-Rutted	206568	2344	74.2
Riyadh-Qassim Expressway-Section 3	Rutted	33826	1352	63.2
Jammom-Zima Road	Non-Rutted	93732	2128	70
Jammom-Zima Road	Rutted	65862	1920	68.6
Jeddah-Makkah Expressway	Non-Rutted	174691	2278	72.2
Jeddah-Makkah Expressway	Rutted	43668	1420	64.6
Makkah-Taif Expressway	Non-Rutted	11351	893	58.8
Makkah-Taif Expressway	Rutted	7552	769	54.1

Statistical Analysis of the Asphalt Properties

Variable	Mean		P-Value	Significant @ 0.1
	None-Rutted	Rutted		
Absolute Viscosity	88861.88	33519.86	0.056	Yes
Kinematic Viscosity	1782.75	1327.86	0.078	Yes
Softening Point	67.9	62.46	0.04	Yes

temperatures or during slow rates of load application. Asphalt binders are required to have a very low sensitivity to thermal changes and rate of load application and should have high resistance to permanent deformation, tensile stresses, and fatigue stresses (Brule, 1988).

Some asphalt binders will have suitable structural balance to provide the required behavior while others will be less capable of doing so. On the other hand, some service conditions, such as that of the Gulf countries, may be so severe that no asphalt binders will be able to withstand them without modification (Goodrich, 1989; Focus, 1991; Fatani et al, 1992). Daily and seasonal temperature variations, increased truck traffic volume, loading and tire pressure, high temperature permanent deformation, and low temperature thermal cracking have led to an increasing need for asphalt binder modification (Anderson, 1991).

Asphalt binders are obtained by various refining processes. They can be the residue from vacuum distillation, or they can be the material precipitated by liquid propane-liquid butane mixtures during the deasphalting stage of petroleum refining. Most asphalts are straight distillation residue. The behavior and properties of asphalts are dependent on their constituents. The commercial types of asphalt can broadly be classified into two categories (Roberts et al, 1991):

1. ***Natural asphalts:*** These are naturally found deposits of soft and hard friable black materials such as the Trinidad Lake deposits on the island of Trinidad in the West Indies.

2. ***Petroleum Asphalts:*** These are colloidally dispersed hydrocarbons obtained by refining crude oils. These are commonly used in the construction of flexible pavements worldwide as well as in the Gulf countries.

A survey of the existing refineries in the Gulf countries indicated that the following four refineries produce asphalt binders:

1. Ras Tanura Refinery, Saudi Arabia (RT).
2. Riyadh Refinery, Saudi Arabia (RY).
3. Al-Ahmadi Refinery, Kuwait (KW).
4. BAPCO, Refinery, Bahrain (BH).

2.1.1 Physical Properties

The physical properties of asphalt binders are important for various engineering applications such as quality control during production and construction, storage requirements, and safety precautions, to name just a few. The most important physical properties are specific gravity, consistency, thermal coefficients, surface tension, solubility in solvents, and flash point.

Specific gravity is useful in making temperature-volume corrections and in determining the proper weight of the asphalt binder during construction. The specific gravity of asphalt refined from petroleum at ordinary temperature varies from 0.95 to 1.05. The specific gravity of an asphalt binder is measured using the pycnometer method (Monismith, 1985; Roberts, 1991).

Consistency describes the degree of fluidity or plasticity of an asphalt binder at various temperatures. The importance of investigating this physical property of an

asphalt binder is realized due to the thermoelastic nature of asphalt binders. Asphalt possesses varying consistency and fluidity levels at different temperatures. Realizing the variation in consistency with temperature of an asphalt binder is important since asphalt mixes go through various stages of heating during production and construction. Asphalt binder consistency is measured at various physical states such as the semi-solid range using a penetration test, beginning of fluidity using a softening point (R&B) test, fluidity range using viscosity tests, and elongation using a ductility test (Roberts, 1991; Asphalt Institute, 1983; Heukelom, 1973).

Thermal coefficients such as coefficients of cubical expansion, linear expansion, specific heat, and thermal conductivity are important when calculating asphalt shrinkage for sealing and joint filling, when calculating storage capacity, and when predicting low temperature cracking. The cubical and linear coefficients of expansion range from about 33×10^{-6} to 42×10^{-6} per ^{o}C and from 6×10^{-4} to 2×10^{-4} per ^{o}C respectively. Thermal conductivity and specific heat range from 0.12 to 0.15 kg-cal/m/^{o}C hr and 0.413 to 0.447 cal/gm/^{o}C respectively (Barth, 1984; Finn, 1967; Saal, 1958).

Surface and interfacial tension of asphalt binders controls their ability to spread onto and resist stripping off of aggregate surfaces. The performance of asphalt binders in the presence of water is dictated by their surface and interfacial tension characteristics. Surface tension for asphalt binders ranges from 21 to 39 dynes/cm^2 with typical values being 25 to 30 dynes/cm^2. Interfacial tension is the energy or work required to enlarge the surface of separation between the asphalt binder and the aggregate. It becomes vital in studies of emulsification of asphalt, asphalt soil stabilization, and detection of salts and

impurities in asphalt binders. Interfacial tension between an asphalt binder and water ranges between 15 to 30 dynes/cm^2 with typical values being 15 to 20 dynes/cm^2. Interfacial tension can be determined through microscopic methods. This is done by measuring the dimensions of drops of asphalt binder on a flat plate (Monismith, 1985; Saal, 1958).

By definition, an asphalt binder is totally soluble in carbon solvents. The presence of insoluble matters such as wax, fillers, inert materials, clays, silts, or metallic oxides in an asphalt binder affects its purity and reduces its cementing ability. Solubility of an asphalt binder in trichloroethylene, for example, should be at least 99.0%. Asphalt binder purity is determined by the solubility test (Roberts, 1991; Ministry of Communications, 1972; Barth, 1984).

Flash and fire characteristics of an asphalt binder are conventionally measured as a safety precaution, since asphalt binders are heated to high temperatures during production and during construction of asphalt concrete mixtures. Asphalt binders will produce enough vapor to flash if heated to high temperatures. The presence of volatile low boiling oil fractions in an asphalt binder increase the amount of vapors and hence reduce the temperature at which flashing will occur. The flash point of an asphalt binder is measured using the Cleveland open cup method (Barth, 1984; Roberts, 1991).

2.1.2 Rheology

The term rheology refers to the science of studying the deformation and flow properties of substances. In studying the rheology of an asphalt binder, the variations or changes in the physical properties of an asphalt under heating, cooling, flow,

solidification, distortion, and stress are quantified. More precisely, studies of asphalt rheology concentrate on determining the stress-strain relationship as a function of load time and temperature. Asphalt rheology is concerned with (1) What kind of colloidal system is to be measured in engineering units, and (2) What is the physical or mechanical stability of this colloidal system under varying conditions of temperature, time, and stress (Thenoux, 1987; Barth, 1984; Sisko and Brunstrum, 1969; Finn, 1967).

Asphalt must meet two rheological requirements: It must deform without rupture, and it must recover from these deformations. The patterns to be considered in asphalt rheology studies include the following:

1. Elastic response after a series of deformations,
2. Stress or strain relaxation after deformation,
3. Strain relaxation with time,
4. Creep recovery, and
5. Change of strain with time under a constant stress (creep).

Temperature greatly affects the flow, brittleness, and consistency of asphalt binders. Because asphalt is made up of a large number of hydrocarbons, increasing temperature will gradually change the physical state of the asphalt from semi-solid to fluid. (Brule et al., 1988).

Asphalt binders are neither perfectly elastic, obeying Hook's law of elasticity, nor perfectly viscous, obeying Newton's law of viscosity. Asphalts behave, within a normal temperature range of −10°C to 60°C, as either visco-elastic or as a non-Newtonian

material, where a delayed elastic response governs its behavior. At either low temperatures (below –10°C) or at high rates of loading, they may behave as elastic material; however, at high temperatures (above 60°C) or at low rates of loading, they may behave as viscous material (Thenoux, 1987; Barth, 1984).

The lack of correlation between the rheological properties and asphalt binder physical properties currently used to grade asphalt is strongly evidenced by the fact that asphalt meeting the same physical criteria (penetration and/or viscosity) did not perform similarly in the field. This is due to the fact that these tests do not recognize the non-Newtonian characteristics of asphalt. For example, asphalt from different sources having the same penetration will exhibit a wide range of variation in the viscosity as shown in Table 2.2 (Lenoble, 1994; Thenoux, 1987; Rogue, 1985; Webster, 1987; Huber and Heiman, 1987; Barth, 1984).

Asphalt binders can be classified into three rheological classes: sol (viscous or Newtonian), sol-gel (visco-elastic), and gel (elastic or non-Newtonian) (Saal and Labout, 1954; Monismith, 1985).

Sol Asphalts (Viscous or Newtonian)

In these asphalts, the asphaltenes are well dissolved in the oil-resin phase. They manifest a purely viscous flow. Shearing stress and rate of shear exhibit a linear relationship with a constant slope representing the viscosity, and they are highly temperature susceptible. At high temperature they become fluids of high viscosity, while at low temperatures they become brittle. They are typically made from refinery

Table 2.2: Variation of Saybolt-Furol Viscosity @ 135°C for 95/100 Penetration Grade Asphalt (Barth, 1984)

Origin	Viscosity (Sec.)
Kern River, California	81
Smackover, Arkansas	160
Mara, Venezuela	163
Lagunillas, Venezuela	181
Kirkuk, Iraq	187
Kuwait	189
Irma, Arkansas	210
Baxterville, Mississippi	245
Panuco, Mexico	290

lubricating-oil extracts.

Sol-Jel Asphalts (Visco-Elastic)

Sol-Jel asphalts are typically made from steam and/or vacuum refined petroleum asphalts. Elastic deformability exists in them. At constant shear stress, the rate of deformation decreases at the beginning of the test and recovers after stress removal. In general, these types of asphalts exhibit both definite elastic effects and some permanent deformation. They also exhibit intermediate temperature susceptibility and are termed as normal asphalts.

Jel Asphalts (Elastic or Non-Newtonian)

In jel-type asphalts, the asphaltenes are poorly dissolved in the oil-resin phase. They exhibit a considerable amount of retarded deformation, showing some properties of true gels such as complex flow, various forms of resilience, and thixotropy. Their temperature susceptibility is low.

Rheological evaluations of asphalt binders include the following properties:

1. Viscosity
2. Temperature susceptibility
3. Age hardening
4. Stiffness modulus
5. Shear susceptibility

2.1.2.1 Viscosity

Viscosity is defined simply as the flow resistance of a liquid. It is regarded as the broad general term for consistency. Consequently, the higher the viscosity value of a liquid the more nearly it approaches a semi-solid state (Wallace and Martin, 1967). Viscosity is considered as a fundamental measurement of asphalt binder consistency since it is not affected by changes in the configuration of test instrumentation or the geometry of the sample (Puzinauskas, 1980). Viscosity is not only a numerical value, it refers to the rheological state, whether a Newtonian or non-Newtonian fluid, of the asphalt binder (Barth, 1984).

For asphalt binders, two types of viscosity are commonly measured: the absolute viscosity at 60°C and kinematic viscosity at 135°C. These measurements are commonly performed using viscosity tubes. Rotational viscosity at 135°C is gaining more attention and is measured using a Brookfiled viscometer. Another device used to measure viscosity is the sliding plate viscometer, which allows measurement of viscosity at low temperatures such as 25°C (NATC, 1993; Finjin and Krooshof, 1970).

2.1.2.2 Temperature Susceptibility

The rate at which asphalt changes from a certain consistency state to another, as measured by either penetration or viscosity, is defined as the temperature susceptibility. For example, the higher the rate of change or the greater the slope of the temperature viscosity relationship, the higher the temperature susceptibility of the asphalt binder (Mcleod ,1989, 1972; Button et al, 1983).

Many indexes were developed to evaluate the temperature susceptibility of asphalt binders. These include the penetration index (PI), the penetration-viscosity number (PVN) index, and the viscosity-temperature susceptibility (VTS) index.

As derived from the penetration test, temperature susceptibility is defined as the penetration index, PI, and can be calculated from the following equation:

$$PI = \frac{20-500A}{1+50A} \tag{2.1}$$

where,

$$A = \frac{\text{log pen at } T_1 - \text{log pen at } T_2}{T_1 - T_2} \tag{2.2}$$

pen = penetration at 100 gm and 5 sec

T_i = temperature, °C

PI ranges from minus three (–3) for highly temperature susceptible asphalt binders to plus seven (+7) for the least temperature susceptible asphalt binders. Normal asphalt binders are defined as those having a penetration index between zero (0) and minus one (–1). The penetration index values of various asphalts are shown in Table 2.3 (Roberts, 1991; Monismith, 1985; Pfeiffer and Van Doormal, 1950).

The penetration viscosity number, PVN, is based on the penetration of the asphalt binder at 25°C and viscosity at either 60°C or 135°C. Lower PVN indicates greater temperature susceptibility. Typical values range between 0.0 to –1.5 (McLeod, 1972 and 1989). The following formula is used to calculate the PVN (Roberts, 1991; Heukeolm, 1973; Monismith, 1985):

Table 2.3: Penetration Index of 85-100 Penetration Grade Asphalt Binder from Various Sources (Barth, 1984).

Asphalt Source	Penetration Index
1. Steam and/or vacuum refined type	
Boscan (Venezuelan)	-0.3
California (USA)	-1.8
Poza Rica (Mexico)	-0.7
Ragusa (Italy)	-0.3
Kuwait	-1.7 to -0.3
Kirkuk (Iraq)	-.08
Aramco (Saudi Arabia)	-0.7
2. Oxidized Type	
Kuwait	-1.0 to over 1.0
California, Ragus, Trinidad	over 1.0
3. Coal tar pitch (2 penetration)	- 4

$$\text{PVN} = \frac{(4.258 - 0.7967 \log P) - \log X}{(0.7951 - 0.1858 \log P)} (-1.5) \tag{2.3}$$

where

X = viscosity at 135°C, cSt

P = penetration at 25°C, dmm

The viscosity temperature susceptibility index, VTS, is based on the viscosity at two temperatures. The higher the VTS number, the higher the temperature susceptibility of the asphalt binder. VTS typically ranges between 3.36 to 3.98 and can be calculated using the following formula (Roberts, 1991; Terrel, 1988; Puzinauskas, 1980; Thenoux, 1987):

$$\text{VTS} = \frac{\log \log \eta \text{ at } T_2 - \log \log \eta \text{ at } T_1}{\log T_1 - \log T_2} \tag{2.4}$$

where

η = the viscosity at T_1 or T_2, cSt

T_i = temperature, °C

2.1.2.3 Age Hardening

Two modes of asphalt aging is evident, the first is the rapid aging due to the high temperature of the asphalt mixture production and the second is the slow aging at the low temperature in the road. The properties of the aged asphalt is more important than the properties of the fresh asphalt since the asphalt binder will exhibit some aging once incorporated into the hot mixture. Aging of asphalt binder is an undesirable action since it increases the cracking potential of the asphalt concrete mixture (Roberts, 1991).

Asphalt binder age hardening in service has been attributed to six factors as follows (Roberts, 1991 and Monismith, 1985):

(1) ***Oxidation***: reaction of the asphalt binder with oxygen,

(2) ***Volatilization***: evaporation of light constituents of the asphalt binder,

(3) ***Polymerization:*** combining of like molecules to form larger ones,

(4) ***Thixotropy:*** steric hardening due to formation of a structure with time,

(5) ***Syneresis:*** exudation reaction of thin oily liquids to the surface and

(6) ***Separation:*** removal of the oily constituents, resins or asphaltenes due to selective absorption of some aggregate.

Many researchers tried to develop test methods to predict the in service aging of the asphalt mixture such as Thin Film Oven Test, Rolling Thin Film Oven Test, Tilted Thin Film Oven Test, Microfilm Durability Test, Rolling Microfilm Circulating Test and the Pressure Aging Vessel (Valerga et al, 1970; Griffin et al, 1959; Schmidet and Santucci, 1973 ; Kemp, 1984 ; Lang and Thomas, 1939 ; Hveem et al., 1959 ; Welborn, 1984, ; Button, 1983, NATC 1993).

To evaluate the effect of aging on asphalt, consistency tests are usually performed on fresh samples. Those samples are then aged using the TFO or RTFO, and the consistency tests are repeated on the aged samples. The following indices are usually used to quantify the amount of heat hardening:

- Retained penetration @ 25°C,

$$RP25 = \frac{\text{Pen @ } 25^\circ\text{C of aged samples}}{\text{Pen @ } 25^\circ\text{C of fresh samples}} \tag{2.5}$$

Larger RP25 indicates lower heat hardening.

- Retained penetration @ 4°C,

$$RP4 = \frac{\text{Pen @ } 4°\text{C of aged samples}}{\text{Pen @ } 4°\text{C of fresh samples}} \tag{2.6}$$

Larger RP4 indicates lower heat hardening.

- Viscosity ratio @ 60°C,

$$VR60 = \frac{\text{Absolute viscosity @ } 60°\text{C of aged samples}}{\text{Absolute viscosity @ } 60°\text{C of fresh samples}} \tag{2.7}$$

Larger VR60 indicates larger heat hardening.

- Viscosity ratio @ 135°C,

$$VR135 = \frac{\text{Kinematic viscosity @ } 135°\text{C of aged samples}}{\text{Kinematic viscosity @ } 135°\text{C of fresh samples}} \tag{2.8}$$

Larger VR135 indicates larger heat hardening.

2.1.2.4 Stiffness Modulus

The Stiffness Modulus is the ratio of applied stress to resulted strain. Due to the rheological nature of asphalt binders and the dependency of their behavior on temperature and time rate of loading, the asphalt binder stiffness modulus is determined and specified

as a function of temperature and time. Van Der Poel (1954) suggested to use a single stress and the resulted strain to determine the asphalt binder stiffness modulus. The following formula represents this idea:

$$S\,(t,T) = \sigma/\varepsilon \tag{2.9}$$

where

S = stiffness in psi or kg/cm^2,

σ = applied axial stress,

ε = resulted axial strain,

t = time of loading, and

T = temperature of testing.

The asphalt binder stiffness modulus can be determined by direct or indirect methods. Direct methods determine the asphalt binder stiffness by conducting creep, relaxation, and constant-rate-of strain in either compression, tension, dynamic or flexural testing. The Shell sliding plate rheometer is used to measure asphalt binder stiffness at low temperatures and was used to verify the accuracy of different indirect methods used to predict asphalt binder stiffness (Fenjin and Krooshof, 1970; Roberts, 1991; Anani and Al-Abdullwahhab, 1982).

Indirect methods provide an estimate of asphalt binder stiffness through the use of nomographs that utilize routine laboratory testing such as softening point and penetration (Van Der Poel, 1954; Finn, 1967; Monismith, 1985).

2.1.2.5 Shear Susceptibility

Asphalt binders that obey Newton's law of viscosity (at high temperature or slow rate of loading) can be characterized by a single constant property, namely, the coefficient of viscosity, η, relating the shear stress to the rate of shear. In this case, the viscosity does not change with the rate of shear. The shear stress vs. shear rate relationship is a straight line with the slope representing the viscosity.

On the other hand, non-Newtonian asphalts (at low temperatures or fast rate of loading) are those that exhibit a change in viscosity with a change in the rate of shear. In other words, the viscosity depends on the rate of shear and increases as the rate of shear increases.

The shear index is the rate of change of viscosity with the rate of shear. It can be determined by conducting viscosity measurements at various shear rates and then plotting the shear rate vs. viscosity on a log-log graph. The slope of this plot is the shear index (Roberts, 1991; Barth, 1984; Puzinauskas, 1980; Bahia and Davies, 1994; Traxler, 1963).

2.1.3 Asphalt Binder Characterization

Many researchers have found that conventional evaluations of asphalt binders, those based on penetration and viscosity, are lacking.

1. They do not directly correlate with the actual service behavior of the pavement.
2. They do not address any mode of pavement failure.
3. They do not control variations in viscosity at temperatures other than testing temperatures.

4. They do not reflect the effect of the aging process as shown in Figure 2.1.

Physical properties currently in use are not sufficient to predict asphalt performance (Dickinson, 1981; Epps, 1983; Puzinauskas, 1967; Garrick et al., 1988; Brule et al., 1986).

Performance-based evaluations of asphalt binders would specify and require those properties and quality levels that, if achieved during production and construction, will ensure acceptable service over a given period of time. Performance-based evaluations specify meaningful and precise test methods whose parameters can be related to performance of the material in service. This type of evaluation is needed mainly for two reasons: (1) to preserve the huge investment in the roadway network by minimizing maintenance and rehabilitation costs and maximizing the service life of the pavement structure and (2) to prevent premature failures (rutting, fatigue, and low temperature cracking) that are being experienced (Epps, 1983).

Bahia and Anderson (1994) presented an excellent compilation and summary of the problems and deficiencies in conventional asphalt binder characterization methodologies. The following paragraphs further summarize their findings.

Asphalt binder rheological characterization has long been recognized by researchers and engineers dealing with flexible pavements. However, this was never an easy task due to the nature of the asphalt binder and the complexity and high costs of the required testing equipment. This has led researchers to adapt simplified asphalt binder properties that randomly were correlated with various indicators of pavement

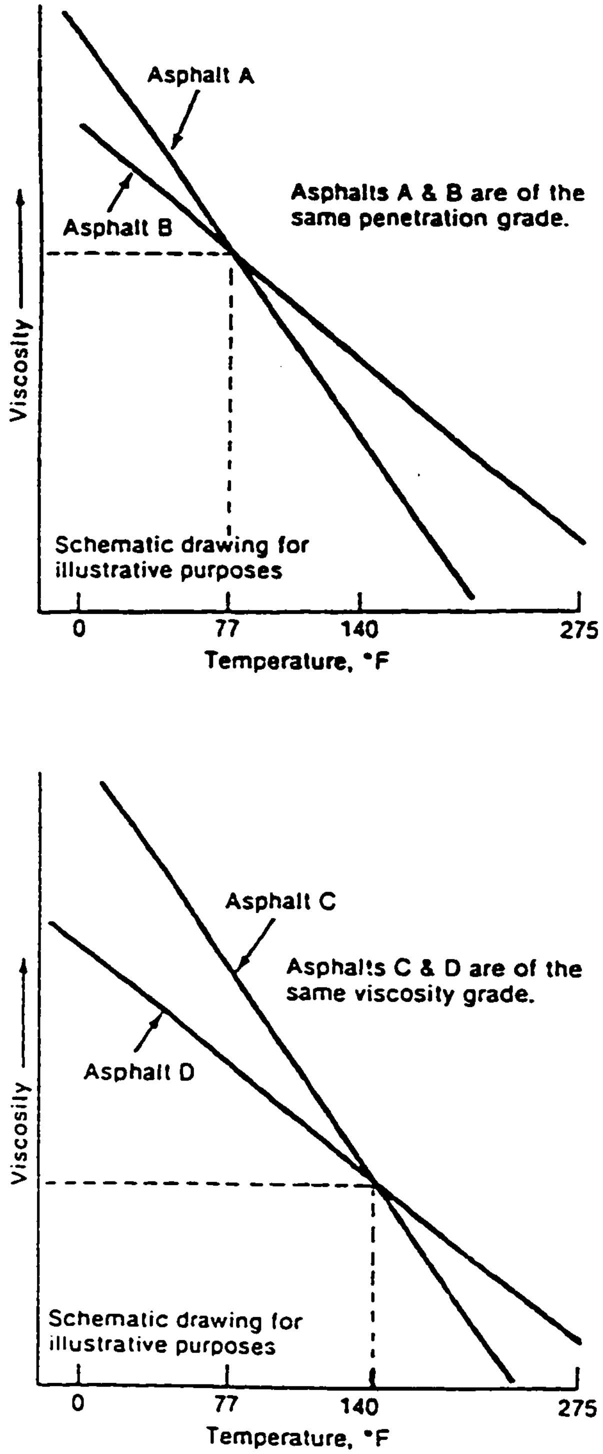


Figure 2.1: Variation in Viscosity of Two Penetration Graded Asphalts at Different Temperatures (Epps, 1983)

performance. These properties can be divided into three main groups: (1) empirical single point measurements, (2) viscosity measurements, and (3) susceptibility parameters.

2.1.3.1 Empirical Single Point Measurements

Penetration, softening point, and ductility are the most common empirical measures used to characterize asphalt binders and hence, determine the role of the asphalt binder in pavement performance. This is done by correlating those empirical measures with pavement performance indicators such as rutting, fatigue, and thermal cracking.

The fact that these measures are empirical has not allowed them to be expressed in engineering units nor allowed them to be directly related to the required rheological properties of the asphalt binders. Moreover, they do not consider the dependency of the asphalt binder behavior on rate of loading and do not indicate whether the asphalt at the test temperature is more elastic or more viscous. These measures are independent because they are conducted at different temperatures, different loading modes, and different loading rates.

Many studies have tried to correlate these measures with fundamental rheological properties. Several formulas were proposed to calculate the coefficient of viscosity from penetration (Saal, 1958; Heukelom, 1973; Van Der Pole, 1954). Ductility could not be correlated with any fundamental property. Current correlations related to these measures are specific to the type of asphalt binders studied, suffer from exceptions and size of sample and, therefore, lack statistical significance.

2.1.3.2 Viscosity Measurements

Absolute viscosity is a fundamental measure of Newtonian fluids. Asphalt exhibits this type of flow only at high temperatures or at slow rates of loading. In practice, temperature levels and traffic loading do not fall in this range; therefore, the asphalt will respond in a non-Newtonian fashion and cannot be characterized by the absolute viscosity.

The apparent viscosity measured at a certain shear rate, strain, or stress is a fundamental property that represents asphalt binder behavior only at the selected shear rate, strain, or stress. The question imposed is, "Where should the apparent viscosity be measured within the time, stress, and temperature domains?"

2.1.3.3 Susceptibility Parameters

The problems mentioned earlier regarding single point measurements have led many researchers to develop parameters that describe a wider range of asphalt binder properties within the time-temperature domain.

Temperature susceptibility methods, discussed in section 2.1.2.2, were developed to assess changes in asphalt binder consistency with changes in temperature. These methods have inherited the deficiencies associated with the empiricism and the rheological problems discussed earlier for the measures used to compute them. Figure. 2.2 shows three asphalt binders with the same stiffness at 77°C, yet they have completely different temperature susceptibility levels. These methods neglect the fact that asphalt

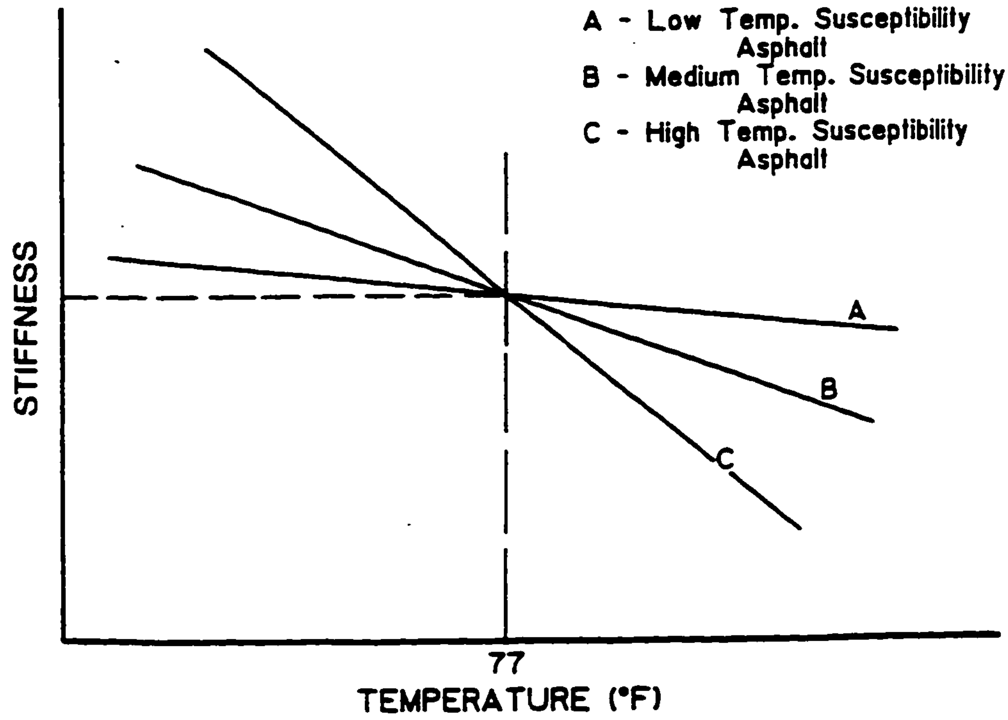


Figure 2.2: Temperature Susceptibility of Asphalt Binders (Roberts, 1991)

binder rheological properties are time dependent; furthermore, they do not represent a constant material property since the time-temperature dependency is non-linear.

Shear susceptibility parameters such as the shear index and the degree of complex flow were used to represent the shear susceptibility of asphalt binders. Both parameters are determined assuming a linear relationship between shear stress and rate of shear, which in fact is not always true. The relationship between shear stress and shear rate is linear only at very small stress levels and is non-linear elsewhere. The load history also affects both parameters. Moreover, the problems associated with the apparent viscosity discussed earlier influence the shear susceptibility parameters.

These important findings related to the conventional measures have paved the way for the Strategic Highway Research Program (SHRP) to suggest new fundamentally sound rheological parameters to represent asphalt rheological behavior.

2.1.3.4 Rheological-Performance Based Evaluation System

The SHRP proposed new measures and properties were selected carefully based on the following criteria:

1. identifying critical pavement failures,
2. understanding the identified failure mechanisms,
3. defining the asphalt binder role in resisting the identified failures, and
4. selecting the required measures that best reflect the binder's role.

The critical pavement failures identified were (1) Rutting, (2) Fatigue Cracking, and (3) Low Temperature Cracking. These failures were thoroughly evaluated, and the role of the asphalt binder was identified. The properties of asphalt binder that control the

occurrence of these failures was determined. These properties were then used to evaluate asphalt binder concerning its performance in actual service.

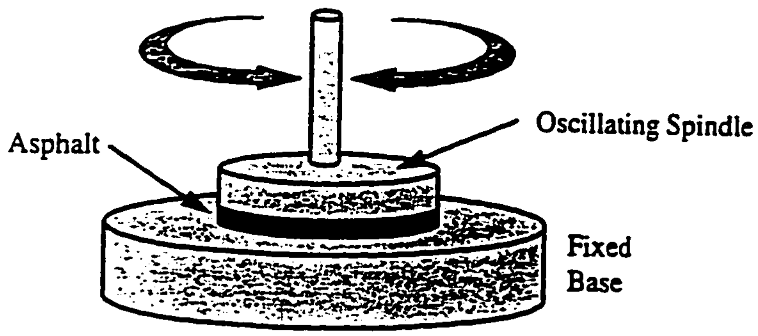
The suitability of a given asphalt binder to a certain area is determined by the extreme temperatures (average seven day maximum pavement design temperature and the minimum pavement design temperature) and the anticipated traffic usage level for the facility under consideration. The asphalt binder rheological properties related to the above mentioned distresses were specified and are required to satisfy a certain threshold value at the temperature regime in which the binder is expected to serve. The selected tests in the proposed asphalt binder evaluation as well as their threshold values are briefly described in the following sections.

2.1.3.4.1 The Rotational Viscometer

High temperature workability of the asphalt binder during pumping and mixing is characterized by the rotational viscosity. This viscosity is measured using the Brookfield apparatus which is a rotational coaxial cylinder viscometer. SHRP has specified a maximum value of 3000 cP for the rotational viscosity measured at 135 °C so that the asphalt binder has an adequate workability and pumpability.

2.1.3.4.2 The Dynamic Shear Rheometer

The viscous and elastic behavior of asphalt binder are characterized by the dynamic shear rheometer (DSR). This characterization is accomplished by measuring the shear modulus , G^*, and the phase angle, δ, of the asphalt binder as shown in Figure 2.3.



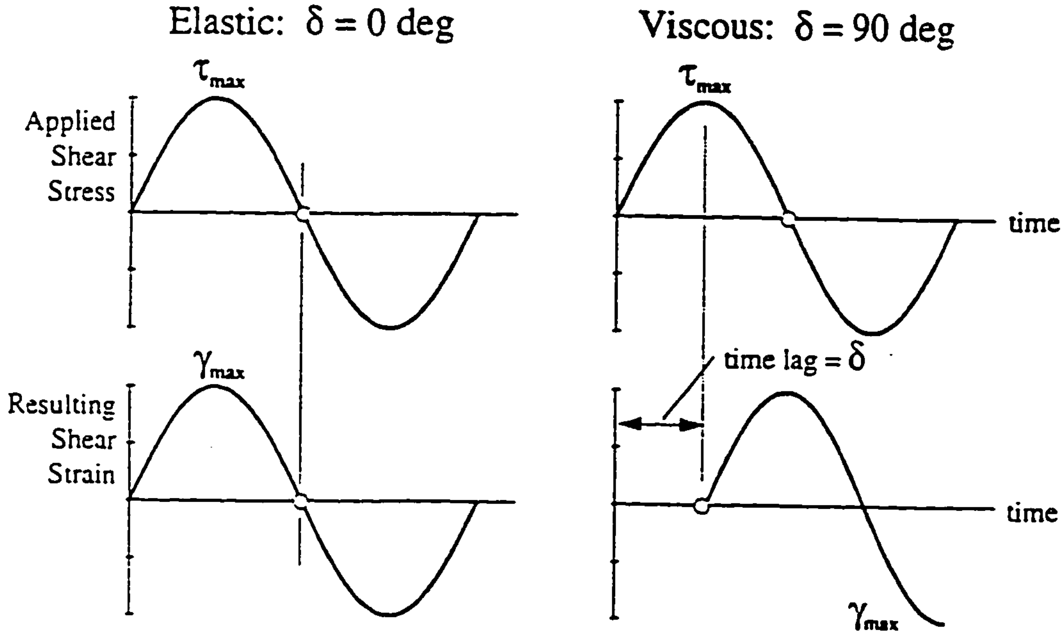


Figure 2.3: Dynamic Shear Rheometer Geometry and Typical Stress-Strain Output for a Constant Stress Rheometer (SHRP 1993).

G^* is a measure of the total resistance of the asphalt binder to deformation and is calculated by the following formula:

$$G^* = \tau_{max}/\gamma_{max} \qquad (2.10)$$

where,

τ_{max} = the maximum shear stress, and

γ_{max} = the maximum shear strain.

The phase angle, δ, is a measure of the distribution of the relative amounts of recoverable and non-recoverable deformation as shown in Figure 2.4. The phase angle is computed as the time lag between the applied strain and the resulting stress.

SHRP evaluation system provides two parameters these are:

1. $G^*/\sin\delta$ at the average 7-day maximum pavement design temperature for the control of rutting.
2. $G^*\sin\delta$ at moderate pavement temperature for the control of fatigue cracking.

A minimum threshold value for the parameter "$G^*/\sin(\delta)$" measured at the maximum pavement design temperature and an oscillation frequency of 10 radians/second (1.59 Hz) are specified; (1) for the fresh (unaged) sample "$G^*/\sin(\delta)$" must be more than 1.0 kPa at a strain amplitude of 12.5 % and (2) for the rolling thin film oven residue (RTFOT) sample "$G^*/\sin(\delta)$" must be more than 2.2 kPa at a strain amplitude of 10 %. For the control of fatigue cracking, the parameter $G^*\sin\delta$ at a frequency of 10 radians/second (1.59 Hz) and a strain amplitude of 1.0 % must be less

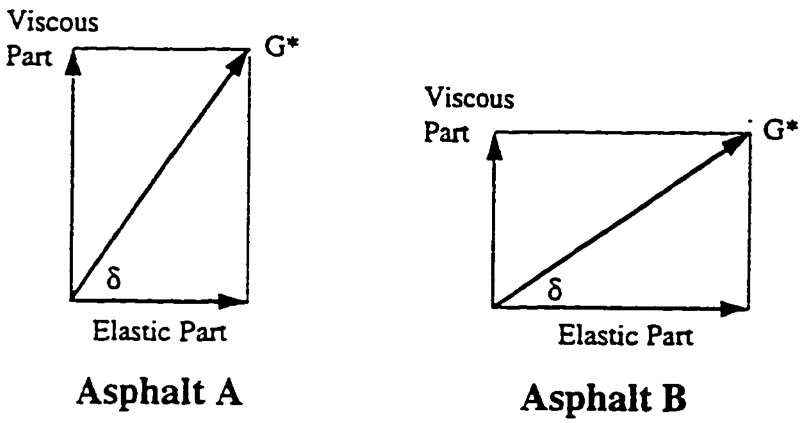


Figure 2.4: Distribution of Shear Modulus to Elastic and Viscous Components Using δ (SHRP, 1993)

than 5000 kPa measured at the moderate pavement temperature for the pressure aging vessel residue sample (NATC, 1993; Goodrich, 1988 and 1989; Dickinson, 1981).

2.1.3.4.3 The Bending Beam Rheometer

The low temperature parameters are measured by the bending beam rheometer (BBR). The BBR measures at the minimum pavement design temperature, on a beam sample of the asphalt binder, the constant loading resistance and the changes in the stiffness with changes in the time of loading and compute the *creep stiffness* and the *m-value* which is the slope of the log creep stiffness vs. log loading time curve at 60 seconds. For an adequate low temperature cracking resistance, the creep stiffness must be less than 300 MPa and the m-value must be greater than 0.3.

Creep stiffness is a measure of the asphalt's resistance to deformation due to constant loading, and it is calculated by measuring the deflection of the beam after 60 seconds of loading and substituting its value in the following equation:

$$S(t) = P\,L^3 / b\,h^3\,\delta(t) \qquad (2.11)$$

where,

$S(t)$ = creep stiffness at time, $t = 60$ seconds;

P = applied constant load, 100 g;

L = distance between beam supports, 102 mm;

b = beam width, 12.5 mm;

h = beam thickness, 6.25 mm; and

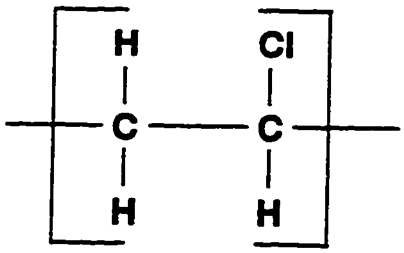
$\delta(t)$ = deflection at time, $t = 60$ seconds.

Creep stiffness is desired at the minimum pavement design temperature after 2 hours of load. However, the SHRP team utilized the temperature-time superposition by raising the test temperature 10°C. An equal stiffness is obtained after a 60 second loading (Asphalt Institute, 1993). If the creep stiffness is too high, the asphalt will behave in a brittle manner, and cracking will be more likely to occur. SHRP recommends a maximum value of creep stiffness. The m-value is the rate of change of binder stiffness with load. It is the slope of the log stiffness versus log time curve at any time t. A higher m-value is desirable because it means when there is a change of temperature, the thermal stresses will accumulate but the stiffness will change fast. This leads to the stresses being absorbed and prevents stresses from building up. SHRP recommends a minimum value for m (Asphalt Institute, 1993). This test is a way to measure the resistance of the AC to thermal cracking.

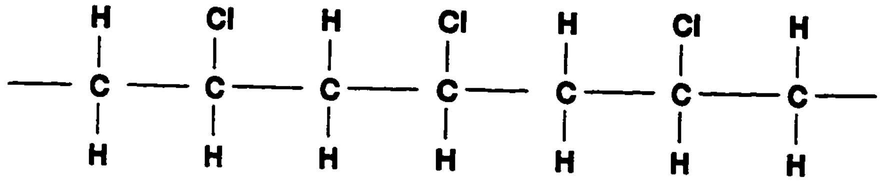
2.2 POLYMERS

The word polymer is a combination of two Greek words "polys" and "meros". "Polys" means numerous, and "meros" means part; therefore polymer is a compound of numerous parts. Actually, a polymer is a large molecule which consists of one or more repeating units linked together by covalent bonds.

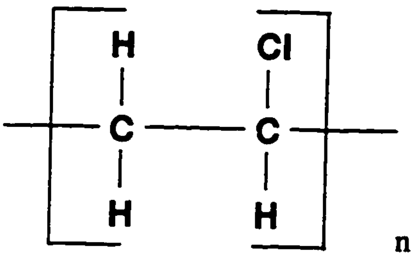
A repeating unit is simply a group of atoms linked together covalently in a particular arrangement. For example, polyvinyl chloride (PVC) has the following repeating units:



A molecule of PVC is a series of these units covalently bonded together as follows:



To indicate the molecular weight, it is usually convenient to use the following shorthand molecular notation:



where the subscript (n) indicates the number of repeating units within the polymer and is termed as the degree of polymerization (d.p.)

The length of a polymer molecule is directly related to (n), and polymers are often regarded as molecules with n >>> 100. For example, a typical molecular weight for a

PVC molecule is 50,000 g/mol. This means that 6.02×10^{23} of these molecules weigh 50,000 grams.

Another term related to polymers is monomer. The monomer is the chemical compound that is used to produce the polymer. For example, ethane is the monomer, or the base chemical compound, in a gaseous form that when subjected to a polymerization process produces a polyethylene polymer (Young, 1981; Brandrup et. al., 1975; Bilmeyer, 1971).

Following are the four generic groups of polymers leading the polymer modification systems that show improved performance in asphalt binders:

1. Thermoplastics (SBS, SIS),
2. Rubbers,
3. Thermoset, and
4. Thermoplastic block copolymer.

Polymeric waste materials are typically used to improve asphalt binder properties for three reasons (Khedaywi and Abu-Orabi, 1989):

1. Availability and relative low cost
2. Improvement of asphalt properties
3. Reduced environmental pollution

Different agencies classify asphalt binder modifiers in different ways. One classification system is to classify the modifiers according to the generic type of material such as rubber, plastics, fibers, fillers, extenders, oxidants, antioxidants, hydrocarbons, and antistriping agents. Rubber and plastic materials are those of concern in this research. Table 2.4 shows this classification as related to rubber and plastic. For each

Table 2.4: Examples of Asphalt Binder Modifiers (Petersen, 1993)

Modifier Type	Producer	Trade Name	Dosage (total mix)	Mixing Temperature	Attributes
SBS	Goodyear	Ultra-Pave70 Ultra-Pave65K	2-5%	Not Avalialble	Less temp. susceptibility, rutting, helps prevent cracking and aging
Ethylene Copolymer	Exxon Chemical	Polybelt	2-6%	320-350 °F	Improves resistance to rutting, no significant changes in production, placement, and compaction of mixture is required.
LDPE	Ergon	Sealo-Flex	3-7%	325-400 °F	Improves durability and water damage resistance of mix, reduces deformation, no significant changes in production, placement, and compaction of mixture is required
EVA	Dupont	Elvax	2-6%	300-350 °F	Improves temperature properties of the asphalt.
Ethylene Based Copolymer (EBC)	ARE Inc.	Straflex	0.4-1% by weight of aggregate	320-350 °F	Increases asphalt-aggregate bond and rutting resistance.

type, the table includes the producer, trade name, suggested dosage, mixing time and temperature, packaging, the attributes of the modifier to the asphalt mixture, and the usual effect of each type on the consistency of the asphalt binder during construction (Petersen, 1993).

2.2.1 Rubber

Rubber is used as an asphalt modifier to increase the stiffness of asphalt at high temperatures and reduce asphalt stiffness at low temperatures. Rubber has been used in different forms. Many researchers studied the effect of reclaimed rubber from tires on the behavior of asphalt binders and asphalt mixtures. Rubber is a thermoplastic material. When stretched at room temperature, it will snap back to its original shape and size (Hicks et al., 1987; Lundy et al., 1987; Reese, 1994; Defoe, 1983; Schuler et al., 1987; Button et al., 1987; Salter and Rafati-Afshar., 1987; Anderton, 1991; Collins and Mikols, 1985; Nadkarnl et al, 1985; Haas, 1983; Al-Abdul Wahhab and Al-Amri, 1991; Bahia and Davies, 1994; Reese, 1994).

The rubber additives used to modify and improve asphalt binder properties are as follows (Terrel and Walter, 1986):

1. Natural latex (NR),
2. Synthetic latex (Styrene-butadiene-rubber or SBR),
3. Block copolymer (Styrene-butadiene-Styrene or SBS), and
4. Reclaimed rubber (Recycled tires).

The attractive rubber properties were flexibility, elasticity, and temperature susceptibility. Rubber particles used in modifying asphalt binders range from passing

AASHTO sieve # 16 to retained sieve # 30 at up to 40 % by weight of the asphalt rubber mixture. The optimum rubber content was about 24% by weight of total mixture (Al-Abdul Wahhab and Al-Amri, 1991; Bahia and Davis, 1994; Huffman, 1980).

During the reaction, rubber particles swell to 2 to 3 times their original volume. This causes a large increase in the mass viscosity of the blend. It is hypothesized that asphalt and rubber have exchange components (Huffman, 1980).

2.2.2 Plastic

Usually plastic refers to the material which can be made to flow under stress. It is also used to refer to the finished product including fillers, stabilizers, etc. Plastics are usually thermoset or thermoplastic materials. Thermoset can be heated and will flow under stress, but once cooled, they cannot be re-softened by heat; unlike thermoplastic materials, which can be softened repeatedly by heat (Karter et al., 1988; Carpenter and Van Dam., 1987; Anderton, 1991; Collins and Mikols, 1985; Fatani et al., 1992; Al-Dhalaan et al., 1992).

The most commonly investigated plastics that are used to modify asphalt binders include low and high density polyethylene (LDPE and HDPE), polypropylene (PE), ethyl-vinyl-acetate (EVA), and polyvinyl chloride (PVC) (Terrel and Epps, 1989)

2.2.3 Combinations

Plastics and rubbers are usually referred to as polymers. Many polymer combinations are used to obtain improved asphalt binder properties. Most single modifiers cannot perform all the required modifications to the asphalt binder. So, a

combination of two or more polymers can be used to achieve all the requirements. The most important factor to consider when using a combination of polymers is to avoid incompatibility and adverse reactions (Goodrich, 1988; Button et al., 1987; Salter and Rafati-Afshar, 1987; Collins and Mikols, 1985).

To be their most effective as asphalt modifiers, polymers must fulfill certain structural requirements. They must contain at least two polystyrene blocks per molecule arranged in linear or branched fashion. An example of a linear arrangement is the styrene-butadiene-styrene (SBS). The polymer should be rich in butadiene which contains typically 30 to 40 % styrene. The molecular weight of the polystyrene block should be larger than 10,000 (Kraus, 1982).

2.3 POLYMER MODIFIED ASPHALT BINDERS

Asphalt binder is a thermoelastic material which behaves as an elastic solid at low service temperatures or during rapid loading and behaves as a viscous liquid at high temperatures or slow loading. This double behavior creates a need to improve the performance of an asphalt binder to minimize stress cracking, which occurs at low temperatures, and permanent deformation, which occurs at high temperatures. Daily and seasonal temperature variations plus the growth in truck traffic volume and loading have increased stresses on asphalt binders. This has lead to an increased demand to modify asphalt binders.

2.3.1 Need for Modification

The concept of modifying asphalt binders and mixtures is not new. Many authors have studied the effects of mineral fillers on the behavior of asphalt (Richardson, 1914; Tunnicliff, 1962; Puzinauskas and Kallas, 1962; Anani and Al-Abdul Wahhab, 1982). The main reasons for using these fillers and some other types of modifiers is that they are industrial waste products and they give extra stiffness to asphalt. Another early method of asphalt modification consisted of mixing two or more asphalt binders of different paving grades or sources. This technique has continued through the years and often delivers a satisfactory end product. One major problem with this technique is that sometimes asphalts are not chemically compatible. Compatibility cannot be predicted effectively and leads to premature pavement distresses (Anderton, 1991).

Anderton (1991) has listed the following factors which have led to increasing interest in asphalt modification:

1. The growing amount of traffic related distresses resulting from escalating traffic demands on all types of asphalt pavements. Higher volumes of traffic, heavier loads, and increasing tire pressures are characteristics of these traffic-related distresses.
2. The increase in the cost of asphalt binders and the trend in refineries of producing lighter fuels on the account of asphalt production.
3. Growing economic pressures that lead to thinner pavements and differed maintenance.
4. Excess supplies of industrial by-products and waste materials. This promotes the idea of converting them into asphalt modifiers.

5. Continued low-temperature thermal cracking and high-temperature deformation distresses.

Although the original idea of using asphalt binder modifiers was to get rid of waste materials, the trend is to produce high-tech modifiers to obtain specific improvements in asphalt pavements.

Modifiers have been used in asphalt mixes to design against or to repair pavements from the following distresses:

1. Surface defects
   - Raveling
   - Stripping
2. Surface deformation
   - Rutting
   - Shoving
   - Distortion
3. Cracking
   - Fatigue cracking (load associated)
   - Thermal cracking (non-load associated)

Terrel and Epps (1989) have graphically represented the typical binder viscosity (stiffness) temperature relationship for both conventional and ideal modified asphalt-aggregate mixtures and for both mixing and in-service temperature ranges as shown in Figure. 2.5. The ideal modified asphalt-aggregate mixture should achieve the following requirements:

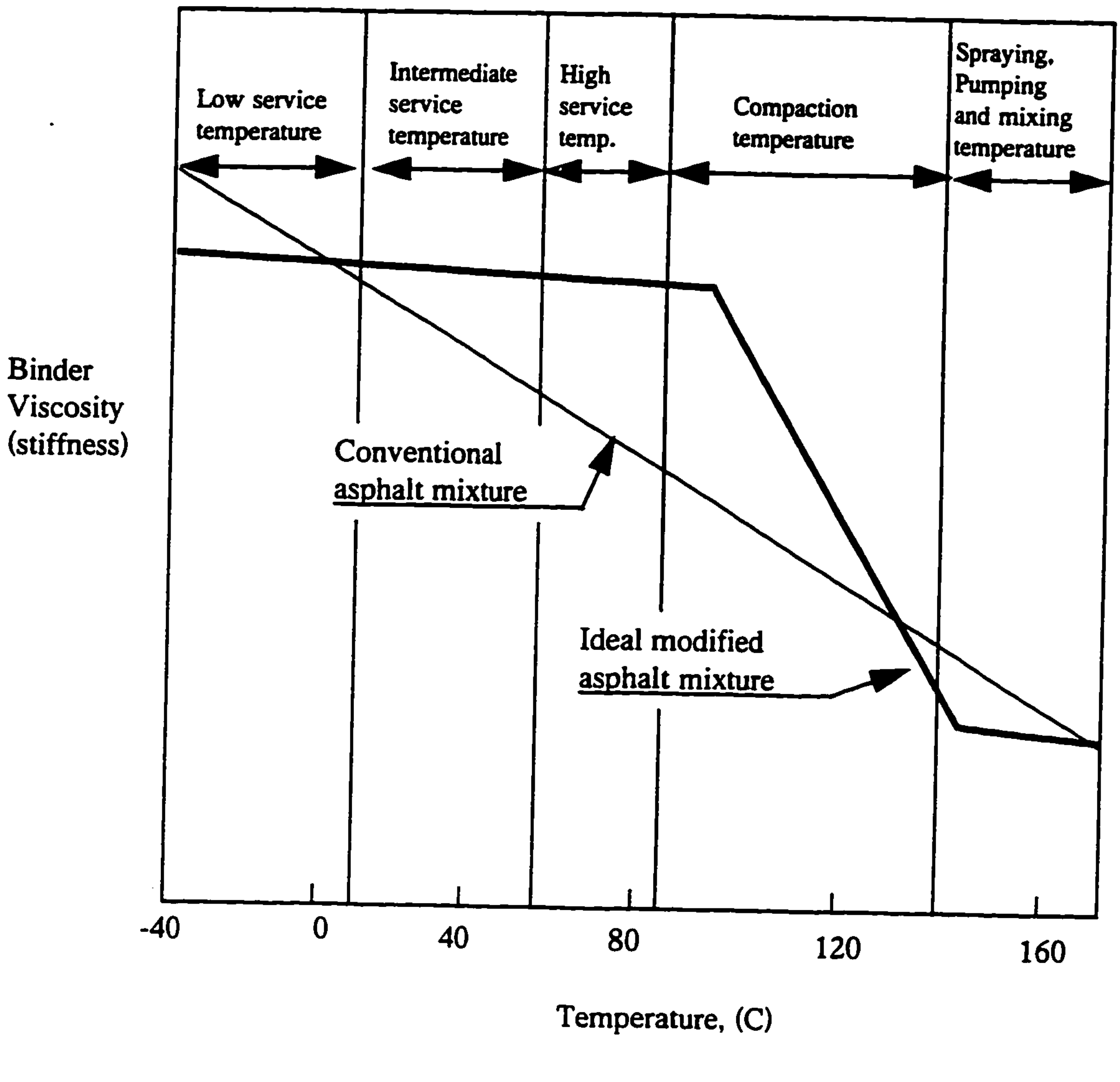


Figure 2.5: Conceptual Representation of Changes in Mixture Stiffness that Can be Obtained with an Ideal Modifier (Terrel and Epps, 1989)

1. Higher stiffness at high temperature to resist rutting and shoving and to improve fatigue life.
2. Lower stiffness in low temperature conditions to reduce thermal cracking.
3. Lower stiffness at very high temperatures (mixing and compaction temperatures) to expedite pumping of the asphalt binder and mixing and compaction of the asphalt mixture.
4. Increase adhesion between the binder and the aggregate to resist stripping.

In addition to the above requirements, Anderton et al. (1991) have identified the following reasons for modifying asphalt binders and asphalt mixtures:

1. Increase strength and stability of mixtures.
2. Improve abrasion resistance of mixtures and reduce raveling.
3. Accelerate early stiffening of tender mixtures.
4. Upgrade marginal asphalt cements.
5. Rejuvenate aged asphalt binders.
6. Reinforce asphalt binders and mixtures.
7. Permit the use of marginal aggregates.
8. Provide improved crack sealing.
9. Provide improved resistance to fuel spillage.
10. Improve resistance to aging or oxidation.
11. Reduce the structural thickness of pavement layers.

Most modified asphalt binders are currently used in seal coats, dense graded asphalt mixtures, and open-graded friction courses. Synthetic latex is usually used in chip seals, and natural latex is also used in slurry seals.

2.3.2 Polymer Blending

Modifiers are usually supplied in one of the following forms:

1. Powder or dust such as fillers or antistripping agents.
2. Pellets or granules such as some types of polymers (LDPE, HDPE, PP) and sulfur.
3. Fibers such as chopped polypropylene, which are usually formed into small bundles that disperse during the mixing operation.
4. Liquids such as recycling and rejuvenating agents, which are usually supplied at high concentrations in drums or tankers.

Each modifier has its own way of mixing and handling. It depends on the modifier type and the purpose of usage. For each modifier, the method of mixing and handling is known either from experience or from supplier recommendations (Terrel and Epps, 1989).

Collins and Boldin (1991) blended the polymer with asphalt by blending the highest polymer concentration with the asphalt binder. This way they developed a master batch; then lower concentrations were obtained by diluting part of the master batch with neat asphalt under low shear mixing for 1½ to 2 hours at 180°C. Stirring speed was adjusted, between 600 to 2,500 rpm, during blending to provide good, consistent agitation without undue entrapment of air. A three blade 5.0 cm diameter boat probe mixer was used for blending the polymer with the asphalt binder. The blending time varied, from ½ hour to 4 hours, depending on the base asphalt binder. The blending end point to produce a homogenous polymer-asphalt blend was determined visually and continued for an additional 15 minutes to insure homogeneity of the blend. In order to avoid any aging effects, samples were tested within 5 to 7 days after blending. To verify this in testing,

the test started at the highest temperature and was reduced accordingly. After the final measurement, the sample was brought back to the highest temperature. If the same measurement was obtained, the cycle was considered; otherwise, the test cycle was repeated.

Huffman (1980) reported that for a homogenous blend, mixing temperature should range from 150°C to 230°C, with a typical range of 175°C to 200°C, for a period between 30 minutes to 4 hours. The temperature at which the blend becomes a homogenous solution is directly proportional to the polymer concentration and asphaltene content of the asphalt binder.

On the other hand, blending polyethylene with non-paraffinic asphalt binders failed because of polyethylene insolubility in asphalts of this type. This necessitated the use of a catalytic reaction. About 1% to 2% by weight kfc-g catalyst was used to homogenize the blend of asphalt and polyethylene. Samples with 0.5% and 1% catalyst were tested for comparison (Milkowski, 1985).

2.3.3 Evaluation of the Modifier Effect

Laboratory and field trials are usually used to evaluate the effectiveness of any modifier and to determine the best dosage.

In a laboratory evaluation, a set of samples is prepared using different percentages of each modifier and different sources and grades of asphalt. Also, a set of samples with no modifiers is prepared to be used as a reference from which to judge the effectiveness of the modification. The usual laboratory tests include the following:

1. Study of the morphology of the asphalt-modifier blend using any magnification procedure. Brule et al. (1988) have suggested that optical microscopy is sufficient. Bouldin et. al. (1991) used scanning transmission electron microscopy (STEM) and fluorescence microscopy. McBee et al. (1981) used the scanning electron microscopy (SEM).
2. Study of the molecular distribution of the mixture using high pressure gel permeation chromatography (Price and Burati, 1990).
3. Dynamic mechanical analysis (Goodrich, 1988; Focus 1991 and 1992; King, et al 1993; Reese, 1994; Bahia and Davis, 1994).
4. Measure of the amount of oxidation by infrared analysis and neutron activation (Goodrich, 1988).

Blends of polymeric materials with asphalt binders are complex and characteristically unique paving material systems. For any specific asphalt binder, the physical properties of the asphalt-polymer blend are affected by the amount of polymeric material added, its composition, and its molecular weight; however, the most important factor may be the compatibility of the asphalt binder with the admix polymer. The ability to enhance compatibility is critical to commercial applications of reinforced asphalt binders (Pearson, 1985). Asphalt-polymer compatibility depends primarily on the asphalt chemical composition, the equilibrium of the asphalt colloidal structure, and the nature and characteristics of the polymer. Asphalt must contain enough aromaticity to dissolve the polymer at mixing temperature (Milkowski, 1985).

Brule et. al. (1988) indicated that block polymers of butadiene and styrene are the most effective materials for converting asphalt binder into a rubber-like material. At ambient temperature, a blend of asphalt binder with a 10 to 14 percentage by weight butadiene-styrene block copolymer exhibits a multi-phase morphology. The first is a polymer swelled with some of the lower molecular weight constituents of the asphalt (oils and resins), and the second is an asphalt phase enriched in asphaltenes. Within the polymer rich phase, there are two phases. This is due to increasing the polymer concentration. The first is swollen polybutadiene, and the second is pure polystyrene domains. If the polymer-rich micro-phase dominates, then the system will act like rubber and show rubber-like elasticity and almost complete recovery of deformation. However, at low polymer concentrations, the polymer rich phase will result in disunited particles, and the system will behave like an asphalt with enhanced consistency and elastic properties.

Collins and Bouldin (1991) reported that no significant changes in the mean molecular weight of SBS polymers were observed during the blending process. However, temperature must be controlled to avoid excessive viscous dissipation during high shear mixing. Hot storage could lead to polymer degradation, especially with unsaturated polymers. The storage temperature should be kept well below 130°C to maximize polymer stability. To verify storage stability, two samples containing 4% SBS were blended and exposed to air with gentle agitation. The first sample was stored at 120 °C, and the second sample was stored at 180°C. Polymer stability at 120 °C was significantly improved relative to the stability of the one stored at 180°C. This could have been improved if a nitrogen blanket had been used.

High density polyethylene deserves special attention. The concentration of the polymer should not exceed 15%; otherwise, the unreacted polyethylene will be precipitated from the blend after cooling down. Mixing time depends on the mixer type but ranges from 2-3 hours. Mixing temperature should be between 170°C and 200°C. Polyethylene is a useful asphalt modifier for increasing the low temperature fracture toughness of asphalt. It may also confer additional pavement stability at elevated temperatures, which would minimize rutting and distortion due to creep (Change et al., 1988; Aubin and Prudhomme, 1984; Khedaywi and Abu-Orabi, 1989).

The use of dynamic mechanical analysis (DMA) to characterize and evaluate neat and polymer modified asphalt binders has gained more attention over the last five years. This is mainly due to the introduction of the asphalt binder grading system and specifications developed by the Strategic Highway Research Program (SHRP). These new specifications rely heavily on determining the complex shear modulus of fresh and laboratory-aged asphalt samples and the flexural creep stiffness at the highest and the lowest temperatures of the site where the asphalt will be used. Workability and safety of the asphalt binder against flashing is also evaluated.

Since SHRP binder specifications are considered new, little research, if any, has been performed using them to evaluate the effectiveness of modifiers.

Bahia and Davies (1994) studied the effect of using crumb rubber (CRM) as a modifier on the performance-related properties of asphalt binders. Three types of CRM and four asphalts with different compositional properties were included in the study. In their evaluation of the effectiveness of CRM on asphalt properties, they measured rheological properties across a wide range of temperatures covered in the Performance

Grade (PG) Specification introduced by SHRP. Their testing program was divided into four main parts:

1. Rotational viscosity was measured using a Brookfield viscometer at different test temperatures to evaluate both the change in consistency and the storage stability after 24 hours of mixing for the different modified binders. This was done to measure response at pumping, storage, and construction temperatures.
2. The Dynamic shear rheometer was used to evaluate the two SHRP recommended parameters namely "$G^*/\sin(\delta)$" and "$G^* \times \sin(\delta)$" within the range of maximum and intermediate pavement temperatures. Two tests were performed in a range of temperatures (5 to 75°C) to cover the temperature range used in SHRP binder specifications.
3. Flexural creep and failure properties at low temperatures were evaluated using the bending beam rheometer and the direct-tension tester.
4. Both the thin film oven test (TFOT) and the pressure aging vessel (PAV) were used to investigate the aging behavior of asphalt rubbers and to compare it with the behavior of the base asphalts. The dynamic shear rheometer, the bending beam rheometer, and the direct tension test were used to measure properties after aging. TFOT was used to simulate aging during the mixing-construction stage, and PAV was used to simulate long-term field aging that takes place during the service life of the pavement.

As recommended by SHRP, to evaluate the contribution of the asphalt binder to rutting, $G^*/ \sin(\delta)$ is evaluated. To evaluate the contribution of the asphalt binder to fatigue cracking performance, $G^* \times \sin(\delta)$ is evaluated. For low-temperature cracking, three parameters are evaluated: creep stiffness, S(t), logarithmic creep rate, m(t), and strain at failure. One of their major conclusions was that SHRP testing procedures can be used to characterize asphalt rubber (Bahia and Davies, 1994; King et al., 1994).

Reese (1994) has indicated that the complex shear modulus (G*) generally increases with increasing rubber content for low concentrations (i.e less than 10%); however, at higher concentrations (more than 10%), the neat asphalt binder is stiffer than the modified.

In the Gulf countries, limited research work has been done on the characterization of polymer modified asphalt cements. Crumb rubber, a local waste from recycled tires, was investigated and found to improve the temperature susceptibility, and stability, and stiffness of asphalt concrete mixes (Al-Abdul Wahhab and Al-Amri, 1991). Novophalt®, a polyethylene-based polymer modification system, and Styrelf, a styrene-butadiene-based polymer modification system, were used in a number of field trials, but no significant differences were noticed in the rut depth, roughness, and deflection between polymer modified and non-modified sections (Al-Dhalaan et. al., 1992). Polybilt®, a styrene-butadiene-styrene-based modifier, and Novophalt® were studied and evaluated for their potential for improving the rut resistance of asphalt mixes by Fatani et al. (1992); about 5% by weight of Polybilt® was found to improve the rut resistance of the asphalt concrete mixes.

In the field evaluation, different road sections were constructed using different types of modifiers at different percentages. Control sections were constructed without the use of modifiers for comparison purposes under the same traffic and support conditions. The performance of all the sections was evaluated at different time periods to determine the effectiveness of the used modifiers. The evaluation included a visual inspection, field testing, and testing of extracted cores (Al-Dhalaan et. al., 1992).

Coplantz et al. (1993) have prepared a comprehensive literature review on asphalt modifiers entitled "Review of Relationships between Modified Asphalt Properties and Pavement Performance". The scope of the review was to collect and summarize information on the technical literature relating modified asphalt properties to field pavement performance. A major conclusion of that review was that asphalt modifiers do influence binder and mixture properties.

2.3.4 Polymer Modification Cost Effectiveness

Another important factor that needs to be investigated and evaluated in modifying asphalt binders with polymeric materials is the economics. Many laboratory trials have justified the use of polymers to improve the properties of asphalt binders, but practical implementation has always been faced with the increased cost of doing so (Denning and Carswell, 1981).

A life cycle cost analysis of pavements constructed using various polymer-modified asphalt binders in comparison to those constructed using neat asphalt binders needs to be performed. However, the significant increase in resistance to traffic of the asphalt binder due to the polymer modification (on the order of four times that of the neat

binder) outweighs the increase in cost due to polymer modification (Lenoble and Nahas, 1994; Dunning et al., 1993).

It is evident from the above discussion and description of the previous efforts in the field of asphalt binder polymer modification that little work has been done within the Gulf countries to investigate the utilization of polymers. Moreover, asphalt binders have not been designed for specific use in pavement construction even though they have many interesting properties. Asphalt temperature susceptibility and variable rheological performance, too soft at high temperature and too brittle at low temperature, lead to increasing interest in modifying asphalt binders for specific locations and environments. This research will thoroughly evaluate compatibility and effectiveness of ***locally*** available polymers in modifying ***locally*** produced asphalt binders for the prevailing environmental conditions of the Gulf countries.

Chapter 3

RESEARCH METHODOLOGY

3.1 RESEARCH STEPS

In order to achieve the stated objectives, this part of the research included asphalt binder samples from all asphalt producing refineries in the Gulf countries. At the time of this research, four refineries were producing paving-grade asphalt binders. The work was carried out in three phases as outlined below and schematically presented in Figure. 3.1.

3.1.1 Temperature Zoning and Characterization of Neat Arab Asphalt Binders

This phase consisted of four tasks as detailed below and shown in Figure. 3.2.

3.1.1.1 Literature Review

A thorough and detailed review of the published national and international literature was conducted. This task provided valuable information about the polymer types and concentrations used in modifying asphalt binders. The results of the detailed literature review were presented in Chapter 2.

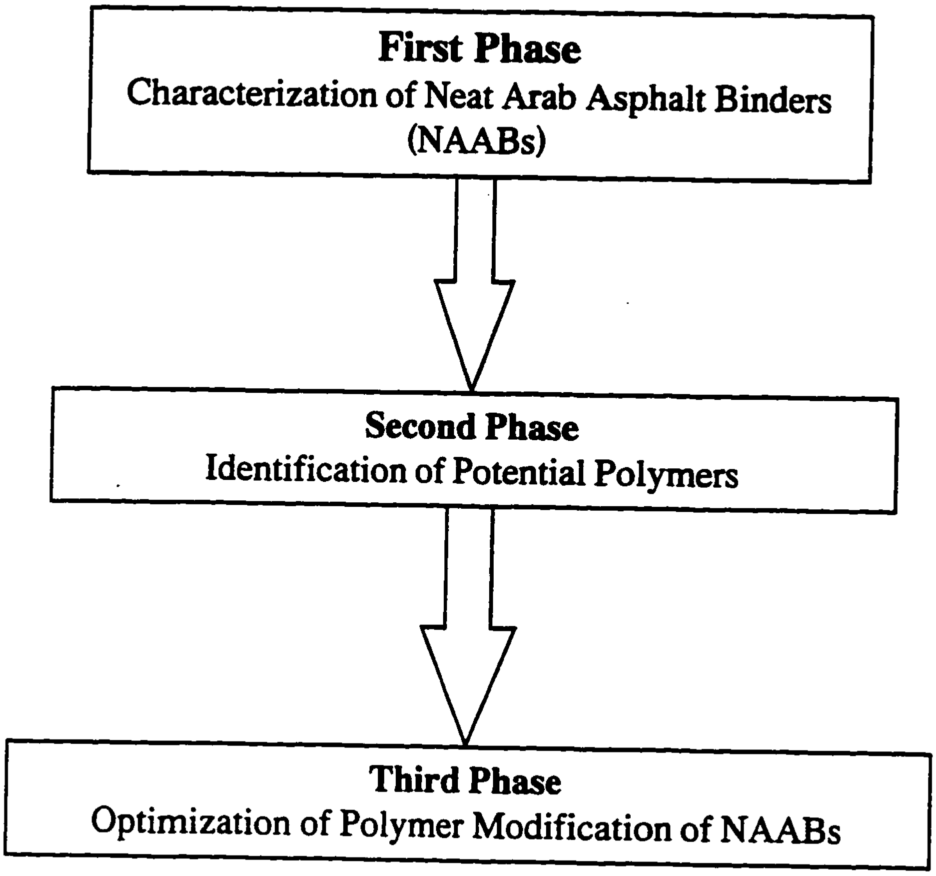


Figure 3.1: Schematic presentation of the work phases

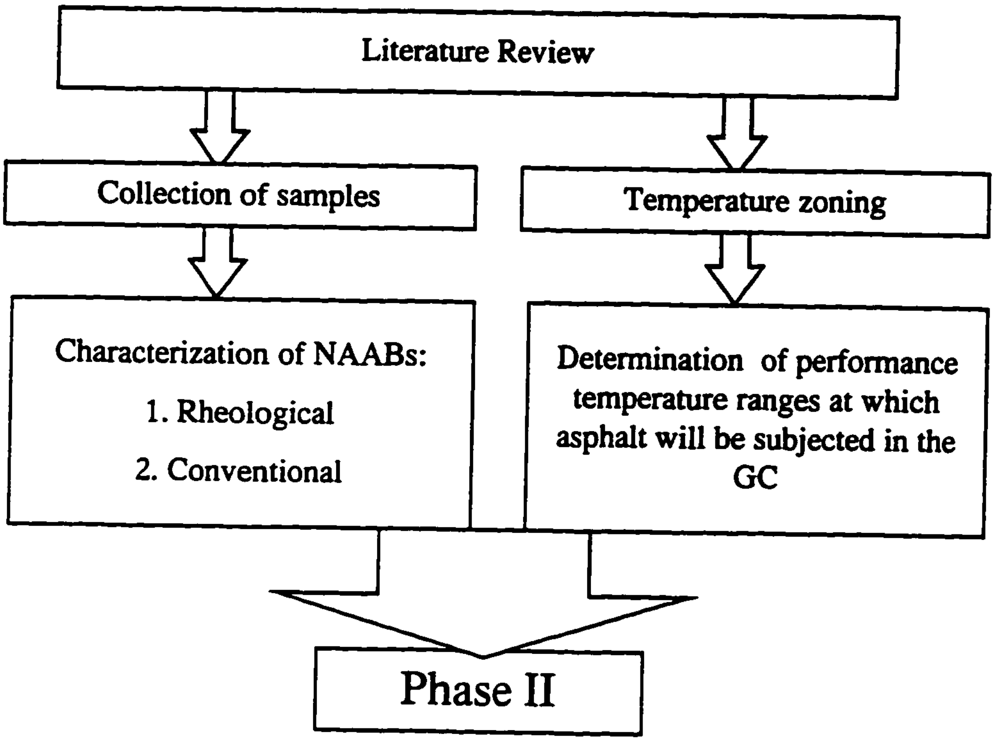


Figure 3.2: Schematic Presentation of the Research Methodology - Temperature Zoning and Characterization of Neat Arab Asphalt Binders

3.1.1.2 Temperature Zoning and Identification of Performance Requirements of Gulf Countries

This comprises determining the temperature ranges at which the asphalt binder will perform satisfactorily in the Gulf countries, taking into consideration rutting, fatigue, and low temperature cracking. Section 4.1.2 provides a detailed discussion concerning the performance requirements of the Gulf countries.

3.1.1.3 Collection of Asphalt Samples

Samples of NAABs in the order of 40 liters were collected from asphalt producing refineries in the Gulf countries. Once samples were received, they were heated once and distributed into smaller containers of about 500 gms each. This eliminated repeated sample heating, which could change the physio-chemical characteristics of the asphalt binders.

3.1.1.4 Characterization of Neat Arab Asphalt Binders (NAABs)

This involved determining the consistency and rheological/performance- related properties of the NAABs. Testing included both fresh and aged samples. Sample aging was accomplished using the rolling thin film oven test (RTFOT) and the pressure aging vessel (PAV). Appendix A provides brief descriptions of the test methods used in this research.

Consistency properties included specific gravity, absolute viscosity at 60 °C, kinematic viscosity at 135°C, low temperature viscosity at 25°C, penetration at 25°C,

penetration at 4°C, ductility at 25°C, softening point, and flash point tests. Fresh and laboratory aged asphalt binders using the rolling thin film oven were tested. The test results were used to describe the temperature susceptibility and age hardening characteristics of the NAABs. This assessment provided a feeling for the relative effect of temperature and aging on the physical properties of the NAABs.

Rheological and performance-related properties of the NAABs were determined using the Dynamic Shear Rheometer (DSR), Rotational Viscometer (RV), and Bending Beam Rheometer (BBR). DSR, RV, and BBR provided valuable information about the visco-elastic behaviors of the NAABs at high, intermediate, and low temperatures. The measured proprieties included the complex shear modulus (G*), the phase angle at which strain lags the stress, rotational viscosity, flexural creep stiffness, and the rate of creep. These tests were done at various temperatures for fresh and laboratory-aged samples.

As a prerequisite for the dynamic mechanical analysis (DMA) testing, the elastic range of NAABs at various age conditions and temperatures was determined. This was accomplished by conducting DMA testing with a strain sweep on a sample of the asphalt binder. The results of the strain sweep provided the strain at which the asphalt behaves as elastic material.

Test results and the assessment of the temperature susceptibility and age hardening are presented and discussed in Chapter 4.

3.1.2 Identification of Potential Polymers

The second phase consisted of four tasks as detailed below and shown in Figure 3.3.

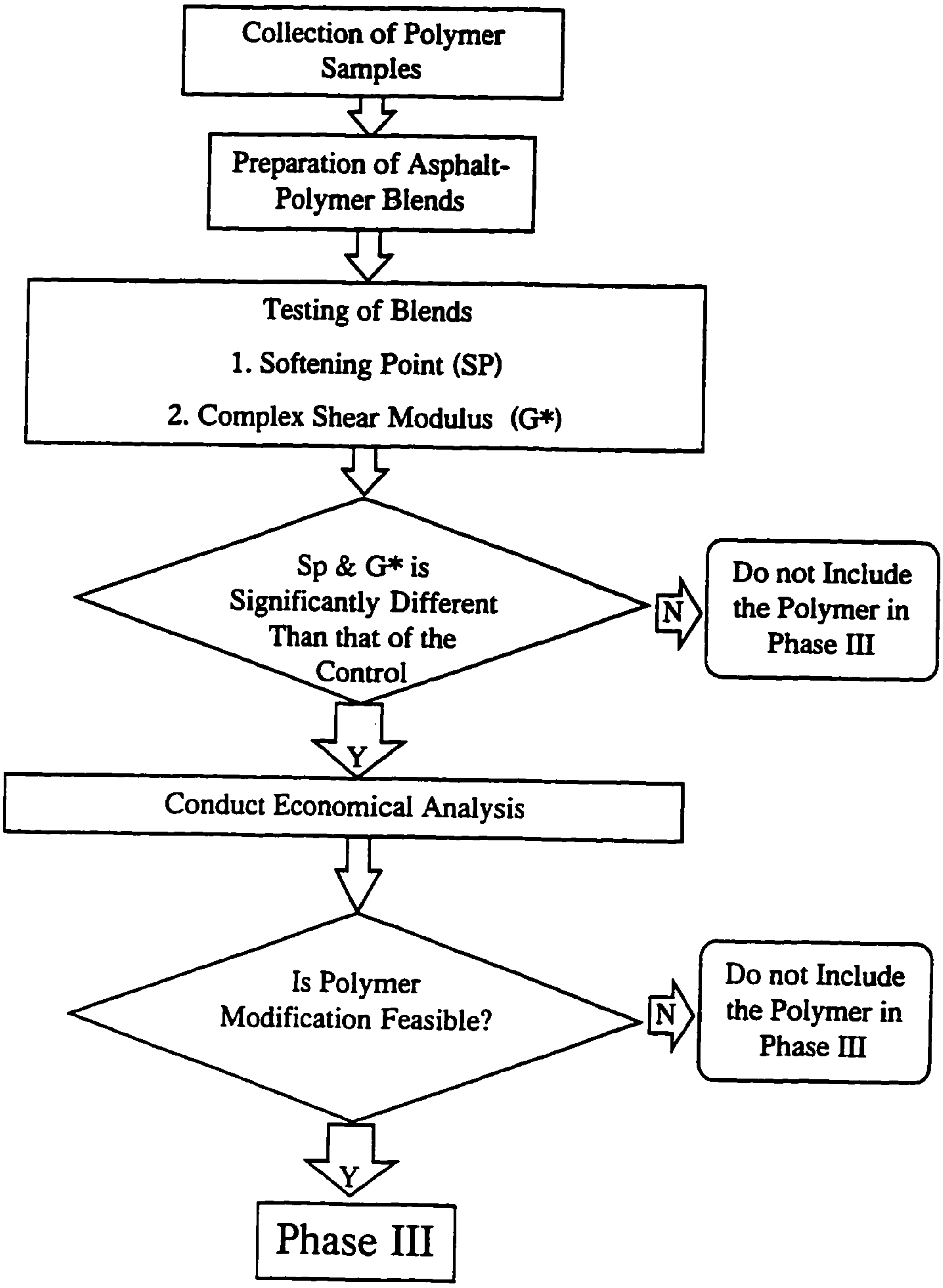


Figure 3.3: Schematic Presentation of the Research Methodology - Identification of Potential Polymers

3.1.2.1 Collection of Polymer Samples

Samples of locally available waste polymers in the form of waste polystyrene cups and crumb rubber from used tires were collected. In addition, polymer samples from the Saudi Arabian Basic Industrial Corporation (SABIC), Shell Chemicals, and Exxon Chemicals were collected.

3.1.2.2 Preparation of Polymer-Asphalt Blend

The collected polymer samples were blended individually with the asphalt binder. An asphalt binder from the Riyadh refinery was used in this phase. The Riyadh refinery was selected because it is the main source of asphalt binder in the Gulf countries. For those newly introduced polymers, three different polymer concentrations were investigated. For other polymers, the manufacturer's recommendations were used. For each polymer type, the identified concentration was used to produce 500 gms of the Polymer Modified Blend (PMB).

3.1.2.3 Testing of Blends

Softening point, shear modulus, and phase angle at 70°C were determined. Five replicates from each blend were tested.

3.1.2.4 Analysis of Results

The collected data for each blend were subjected to extensive analysis and evaluation covering the following aspects:

1. improvement in rheological properties,
2. storage stability, and
3. cost effectiveness.

Statistical comparisons for the differences between neat and modified asphalt binders using the t-test were conducted. Those polymers that displayed a significant increase in the softening point and shear modulus of the asphalt binder were considered for inclusion in the third phase.

Once a polymer was technically qualified, economical analysis was performed to further justify and qualify the polymer to be included in phase three.

Chapter 4 contains a comprehensive discussion of the test results, statistical analysis, cost effectiveness, and the polymers selected for optimization.

3.1.3 Optimization of Polymer Modification of NAABs

This phase consisted of five tasks as detailed below and shown in Figure. 3.4.

3.1.3.1 Development of Polymer Modification Procedure

The suggested procedure to modify asphalt binders using polymer additives is based on the literature review, collected data, and on observations from the second phase. Section 4.4.1 contains detailed descriptions of the suggested polymer modification procedure. The procedure determines the following parameters:

1. the optimum blending time and temperature,
2. blend homogeneity verification method,

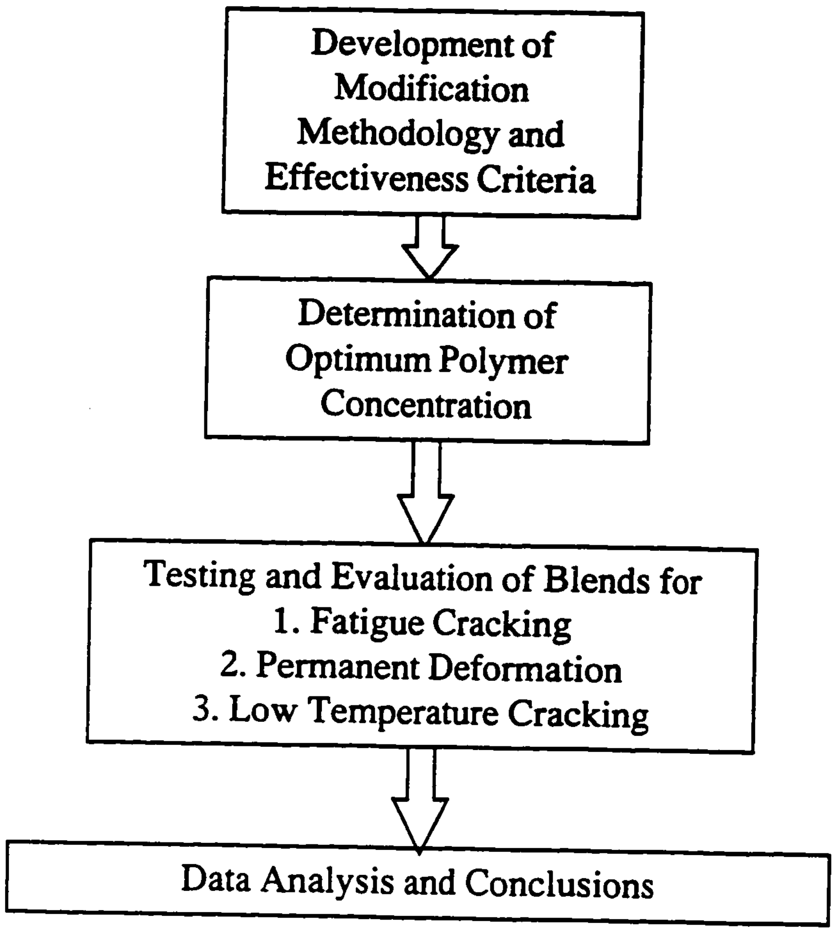


Figure 3.4: Schematic Presentation of the Research Methodology - Optimization of Polymer Modification of NAABs

3. the blend stability and storing conditions, and
4. precautions.

3.1.3.2 Determination of Polymer Concentrations

The four leading polymers that were selected in the second phase were thoroughly studied and evaluated. The cited literature, expert opinions, and manufacturer recommendations were used to define the most appropriate polymer concentration range. Within this range, three concentration levels were investigated representing the high, middle, and low sides of the recommended range.

3.1.3.3 Preparation of Polymer-Asphalt Blends

A total of 64 treatment combinations, including the neat asphalt binder, were blended and prepared. These treatment combinations represent four asphalt sources, four polymer types, and four polymer concentrations as shown in Table 3.1. Randomization, a prerequisite for a valid utilization of the model, was achieved as described in section 3.2.3. The developed modification methodology was followed in blend preparation.

3.1.3.4 Blend Characterization and Evaluation

Once a certain polymer-asphalt blend was prepared, it was subjected to an extensive evaluation that considered the performance requirements of the Gulf countries. The evaluation covered the determination of fatigue, low temperature cracking potential, and rutting susceptibility. Safety requirements were also evaluated.

Table 3.1: Experimental Design Matrix - Phase III

		Asphalt Source			
Polymer Type	**Polymer Concentration**	**Ras Tanura Refinery Saudi Arabia**	**Riyadh Refinery Saudi Arabia**	**BAPCO Refinery Bahrain**	**Al-Ahmadi Refinery Kuwait**
Type 1	Zero	x	x	x	x
	Low	x	x	x	x
	Medium	x	x	x	x
	High	x	x	x	x
Type 2	Zero	x	x	x	x
	Low	x	x	x	x
	Medium	x	x	x	x
	High	x	x	x	x
Type 3	Zero	x	x	x	x
	Low	x	x	x	x
	Medium	x	x	x	x
	High	x	x	x	x
Type 4	Zero	x	x	x	x
	Low	x	x	x	x
	Medium	x	x	x	x
	High	x	x	x	x

(x) represents results of three tests.

3.1.3.5 Data Analysis

All the collected and measured properties were summarized and analyzed using the analysis of variance technique. Influence of the polymer type and concentration were traced and identified using various graphical presentations. The data were analyzed to judge the ability of the polymer additives in improving the visco-elastic properties of NAABs. Chapter 4 provides a detailed discussion and analysis of the test results.

3.2 EXPERIMENTAL DESIGN

This research part of the was divided into three phases. ***The first phase*** defined the physical, rheological, and performance-related properties of the NAABs, the temperature ranges at which Arab asphalt binders will be subjected to in the Gulf countries, and provided the information required to assess the need for polymer modification.

In ***the second phase***, candidate polymer additives were tested and evaluated for their potential to improve the visco-elastic and performance-related properties of NAABs. This phase was considered as a screening phase where polymers that yielded significant improvement in the properties of the NAABs were to be further tested, evaluated, and optimized in ***the third phase***.

3.2.1 Characterization of NAABs

This phase was aimed to characterize the NAABs and identify their physical, rheological, and performance-related properties. Sample size varied depending on the test type.

3.2.2 Identification of Potential Polymers

This phase was designed as a fixed effect one way analysis of variance. All variables were kept constant except one, the polymer type. The hypothesis was that polymer addition and blending with the asphalt binder will improve the asphalt's physical and rheological properties. The response variables that were measured were the softening point, the overall shear modulus, and the phase angle at 70°C. One asphalt binder with three polymer concentrations for new polymers and one concentration for standard polymers were used.

The measured response variables were compared with those of the control asphalt binder (neat). Significance was determined at a confidence level of 95%. The following hypothesis was tested:

$$H_o: \mu_1 = \mu_2$$

$$H_1: \mu_1 \neq \mu_2$$

where

μ_1 = the mean of the response variable (softening point, shear modulus, or phase angle) of the polymer modified asphalt binder

μ_2 = the mean of the response variable (softening point, shear modulus, or phase angle) of the neat asphalt binder

The equality or inequality of the sample variance was tested using the F-test; depending on the F-test results, if equality of variance was granted, the exact t-test was

used; otherwise, the approximated t^*-test was used to test the above mentioned hypothesis (Montgomery, 1984).

Sample size was based on the anticipated variability and the critical difference we wanted to detect in the means of the response variables of the modified and unmodified asphalts. The probability of wrongly failing to reject H_o depends on the true difference between the means (d). The relationship between (d) and the probability of accepting H_o for a particular sample size is called the operating characteristic curve (O.C. curves). A set of O.C. curves for various sample sizes are shown in Figure. 3.5. The parameter on the horizontal axis in Figure. 3.5 is given by the following equation:

$$d = \frac{\mu_1 - \mu_2}{2\sigma} \tag{3.1}$$

Moreover, the sample size used to construct these O.C. curves is given by the following formula (Montgomery 1984):

$$n^* = 2n - 1 \tag{3.2}$$

These curves were used to back-calculate the sample size for a specified difference in the means and a specified standard deviation. Using the softening point as the basis for determining the sample size, since the overall shear modulus and phase angles are expected to have less variability, and assuming the critical difference to be about 6.0°C with a standard deviation of about 1.0°C, the required sample size was then calculated as follows:

$$d = \frac{\mu_1 - \mu_2}{2\sigma} = 6/2 = 3.0$$

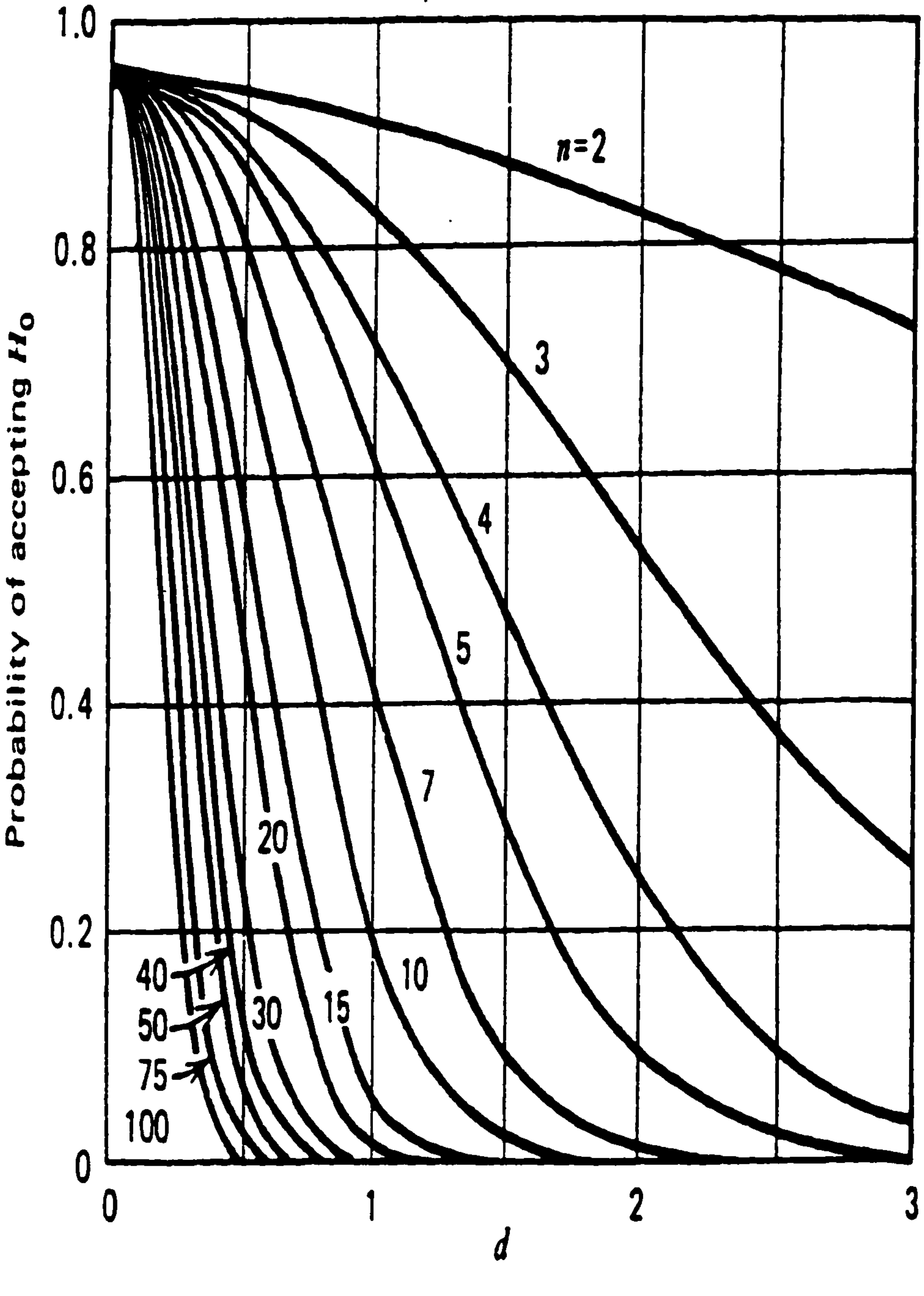


Figure 3.5: Operating Characterisitcs (OC) Curves for the Two-Sided t-test with $\alpha = 0.05$ (Montgomery, 1984)

Using the operating characteristics curves for the two-sided t-test with $\alpha = 0.05$ as shown in Figure. 3.5, n* is approximately 4.0. Therefore, since n* = 2n–1, the required sample size becomes = (n*+1) /2 = (4+1) / 2 = 2.5 or 3 samples.

However, to protect against unforeseen variability and to provide more confidence in the data, the sample size that was used in the second phase was 5 samples.

3.2.3 Optimization of Polymer Modification

This is the main phase of this part of the research. It was designed as a randomized three factor fixed factorial model with three replicates per cell. The levels of the three factors are as follows:

1. **Asphalt source (A)** at four levels, Ras Tanura refinery, Saudi Arabia (RT), Riyadh refinery, Saudi Arabia (RY), Al-Ahmadi refinery, Kuwait (KW), and BAPCO refinery, Bahrain (BH).
2. **Polymer Type (P)** at three levels P_1, P_2, and P_3 as determined from the second phase. A fourth polymer, P_4, was added to this phase increasing the total levels of this factor to four. The reasons behind adding the fourth polymer are discussed in Chapter 4.
3. **Polymer concentration (C)** at four levels zero, low, medium, and high.

The experimental matrix of the third phase was presented in Table 3.1. Testing was totally randomized for all of the three independent variables A, P, and C. In order to achieve randomization, cards were prepared for each treatment combination, totaling 64 combinations (i.e. cards). A card was randomly selected, and the combination from the

:

card, specifying asphalt source (A), polymer type (P), and polymer concentration (C), was blended and tested. After all testing was performed for the selected card, another card was randomly selected, blended, and tested. The fixed effect model is as follows:

$$y_{ijkn} = \mu + A_i + P_j + C_k + AP_{ij} + AC_{ik} + PC_{jk} + APC_{ijk} + \varepsilon_{ijkn} \qquad (3.3)$$

where

y_{ijkn}	=	the response variable for each treatment combination;
μ	=	the overall mean;
A_i	=	the effect of the ith asphalt binder source (i = 1,2,3, or 4);
P_j	=	the effect of the jth polymer type (j = 1, 2, 3 or 4);
C_k	=	the effect of the kth polymer concentration (k= 1,2, 3 or 4);
AP_{ij}	=	second order interaction effect of the ith source and the jth polymer type;
AC_{ik}	=	second order interaction effect of the ith source and the kth polymer concentration;
PC_{jk}	=	second order interaction effect of the jth polymer type and the kth concentration;
APC_{ijk}	=	third order interaction effect of the ith source, jth polymer type, and kth polymer concentration; and
ε_{ijkn}	=	the experimental error of the ith source, jth polymer type, kth polymer concentration, and n replicate (n = 1, 2, or 3).

The analysis of variance technique, as shown in Table 3.2, was used to identify the significance of all of the independent variables and their interactions on the dependent variable.

Table 3.2: The Analysis of Variance Table - Phase III

Source of Variation	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	F_0
Asphalt Source (A)	SS_A	3	$MS_A = SS_A/3$	MS_A/ MS_E
Polymer type (P)	SS_P	3	$MS_P = SS_P/3$	MS_P/ MS_E
Polymer Concentration (C)	SS_C	3	$MS_C = SS_C/3$	MS_C/ MS_E
A x P	SS_{AP}	3 x 3 = 9	$MS_{AP} = SS_{AP}/9$	MS_{AP}/MS_E
A x C	SS_{AC}	3 x 3 = 9	$MS_{AC} = SS_{AC}/9$	MS_{AC}/MS_E
P x C	SS_{PC}	3 x 2 = 9	$MS_{PC} = SS_{PC}/9$	MS_{PC}/MS_E
A x P x C	SS_{APC}	3x 3x 3 = 27	$MS_{APC} = SS_{APC}/27$	MS_{APC}/MS_E
Error	SS_E	191 - 63 = 128	$MS_E = SS_E/128$	
Total	SS_T	(64x3)-1= 191		

Chapter 4

RESULTS AND ANALYSIS

This chapter provides detailed presentations, analysis, and discussion of the test results performed in this research. Also, it contains a thorough discussion about the performance requirements and temperature zoning of the Gulf countries. Appendix A includes a brief description of the test methods used in this research.

4.1 GULF COUNTRIES TEMPERATURE ZONING

As stated in Chapter 1, two of the most serious distresses associated with flexible pavements are cracking and permanent deformation. It was further stated that the main class of permanent deformation is rutting, while cracking is classified into two classes, load associated or fatigue and non-load associated or low temperature cracking. This simply means that for a pavement structure to perform satisfactorily in actual service, it must show high resistance to these distresses.

The question of "Does the pavement have adequate resistance to fatigue, low temperature cracking, and rutting?" has puzzled researchers and engineers working in the field of pavement engineering for a long time.

Extensive research on temperature distribution in asphalt pavements has been carried out in many different climatic areas of the world, such as the US, Australia, South Africa, Kuwait and Saudi Arabia (Kallas, 1966; Witt, 1981; Williamson, 1972; Bissada,

; Potocki, 1973; Fatani et al., 1992; Al-Abdul Wahhab and Balghunaim, 1994).

Several researchers have developed mathematical models to simulate pavement temperature with reasonable accuracy (Dempsy and Thompson, 1970; Venkataraman and Venkatasubramanian, 1977; Dickinson, 1978; Fatani et al., 1992).

Anticipated maximum and minimum pavement temperatures are calculated from air temperature using a set of algorithms. The temperature at various depths can also be estimated from the following equation (Lytton et al., 1993):

$$T_d = (T_s + 17.78)(1 - 2.48d + 10.85d^2 - 24.41d^3) - 17.78 \qquad (4.1)$$

where

T_s = surface temperature in (°C)

T_d = temperature at depth δ in (°C)

d = depth in meters.

The SUPERPAVE® software, which was developed by SHRP, can be used to calculate pavement temperatures at any depth for any given location in North America if the true temperature value is not known. These temperatures were combined to develop temperature zones in the United States.

The asphalt binder specification AASHTO MP1 uses the designation:

PG X-Y

where

PG = stands for performance graded

X = designates the high pavement design temperature, and

Y = designates the low pavement design temperature.

The SHRP design temperatures and corresponding grades are:

High Temperature, °C (X)	PG Grade Designation	Low Temperature, °C (Y)	PG Grade Designation
< 52	52-	> −10	−10
< 58	58-	> −16	−16
< 64	64-	> −22	−22
< 70	70-	> −28	−28
< 76	76-	> −34	−34
< 82	82-	> −40	−40
-	-	> −46	−46

Therefore, asphalt binder PG 70-16 grade is designed to be used in an environment to offer a protection for an average seven (consecutive) day maximum pavement temperature of < 70°C (but greater than 64°C) and a minimum pavement design temperature of > −16°C (but less than −10°C) with 95% confidence.

The issues of concern at this point are (1) the seven day maximum pavement design temperature and (2) the minimum pavement design temperature prevailing in the Gulf countries, so an appropriate asphalt binder can be selected or designed by polymer modification to meet the required performance-related rheological parameters.

4.1.1 Temperature Studies in the Gulf Countries

In the Gulf region, Al-Abdul Wahhab and Balghunaim (1994), Fatani et al. (1992), Potocki (1973) and Bissada (1972) have carried out different research projects to quantify temperature regions in local pavements.

Fatani et al. (1992) in a national project entitled "Evaluation of Permanent Deformation of Asphalt Concrete Pavement in the Kingdom of Saudi Arabia (KSA)," have instrumented different pavement sections for temperature measurement in eastern, central, and western Saudi Arabia. Temperature was measured round-the-clock at the surface and at depths of 2 cm, 4 cm, 8 cm, 16 cm, and at the bottom of asphalt layers. They studied the effect on pavement temperature of factors such as cloud cover, air temperature, and solar radiation. The single most important factor that affects pavement temperature was found to be air temperature, which is directly affected by cloud cover and solar radiation. A database containing two years worth of pavement temperatures was developed. It was observed that the maximum recorded pavement temperature occurs at a depth of 2 cm from pavement surface, while the minimum pavement temperature is always recorded on the surface. A model has been developed and calibrated based on their study to predict maximum pavement temperature at a depth of 2 cm and minimum pavement temperature. The model takes into account air temperature and solar radiation with a high degree of accuracy

Al-Abdul Wahhab and Balghunaim (1994) indicated that extreme pavement temperatures in the arid Saudi environment range between 3°C and 72°C for coastal areas and 4°C and 65°C for inland areas.

Bissada (1972) presented the results of a study on asphalt pavement temperatures relating to the Kuwait climate. He concluded that the asphalt surface course experienced substantial extremes in temperature. Within 9 hours on a summer day, the surface pavement temperatures fluctuate between 32 and 74°C. During the year, asphalt surface

temperatures fluctuate between an average minimum of 5°C and an average maximum of 74°C.

Potocki (1973) carried out a more comprehensive study of pavement temperatures for different pavement cross-sections in Abu Dhabi and Al-Ain in the United Arab Emirates.

4.1.2 Temperature Zoning

In all of the above studies, it was observed that the minimum pavement temperature is always recorded on the surface of the pavement, which matches the lowest air temperature. The average maximum pavement design temperature over seven consecutive days is measured at a depth of 20 mm in pavement as recommended by the FHWA LTPP study (1994). Figure 4.1 shows the relation between air temperature and recorded temperature at a depth of 20 mm in pavement for Saudi Arabia, Kuwait, and the UAE, as reported by the above studies. This relation has been utilized to predict the average seven day maximum pavement design temperature from the calculated average seven day maximum air temperature. The regression formula developed for Kuwait was used for Kuwait; the KSA formula was used for Saudi Arabia and Qatar; and the UAE formula was used for UAE and Oman.

In this research, an extensive study of the temperature regimes within the Gulf countries has been executed. Twenty eight weather stations across the Kingdom and meteorological departments in the Gulf countries were contacted to collect available meteorological data. A huge amount of weather data (covering 26 years) was received

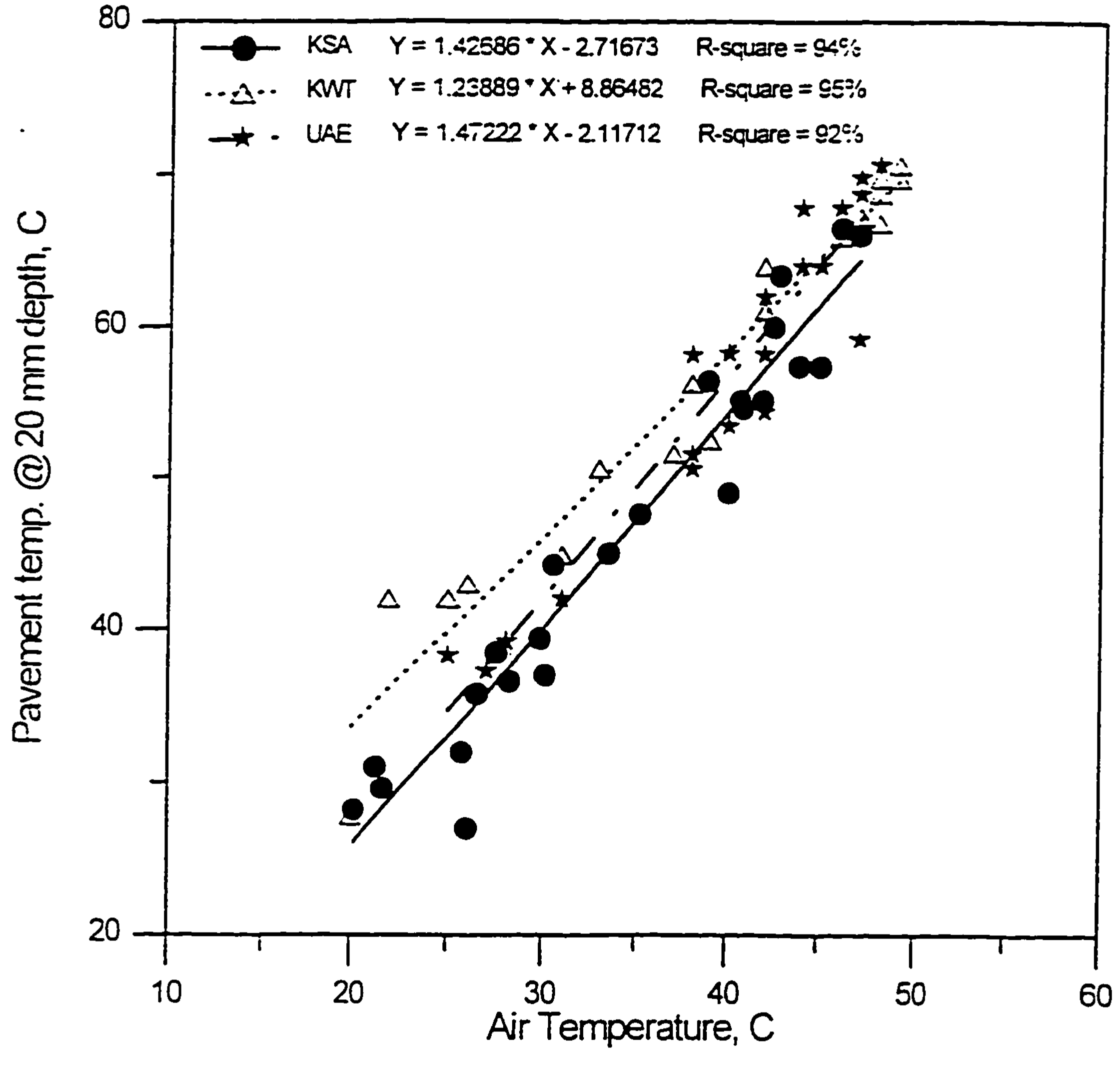


Figure 4.1: Relation Between Air Temperature and Pavement Temperature at a Depth of 20 mm (Fatani et al 1992; Bissada, 1972; Potocki, 1973).

and analyzed to calculate the average seven day maximum air temperature and minimum air temperature. These temperatures are plotted on 1°C interval contour maps for the Gulf countries as shown in Figures 4.2 and 4.3. The minimum pavement temperature contour in the Gulf is shown Figure 4.2. This figure shows that the temperature has never gone below −10 °C. Therefore, it is believed that −10 °C can be considered a conservative minimum design temperature in the Gulf region.

Figure 4.3 shows the average seven day maximum pavement design temperature contour. After thorough evaluation and discussion with the project consultants, it was decided to select performance grades for slow transient loads and a low pavement design temperature of > −10°C. The actual temperature zoning for the asphalt binder specification for the Gulf region is shown in Figure 4.4. Four asphalt binder performance grades that satisfy the high and low temperature requirements are recommended: PG 76-10, PG 70-10, PG 64-10, and PG 58-10.

However, further analysis of the actual temperature zones for the Gulf countries were performed to identify a more practical zones taking into considerations administrative area boarder lines and light traffic loading in certain areas. The analysis have yielded a modified temperature zones for the Gulf countries as shown in Figure 4.5.

4.2 CHARACTERIZATION OF NEAT ARAB ASPHALT BINDERS (NAABs)

This part provides a detailed description of the testing performed to characterize NAABs with respect to their physical, consistency, and rheological properties. A thorough discussion of age hardening and temperature susceptibility is also given.

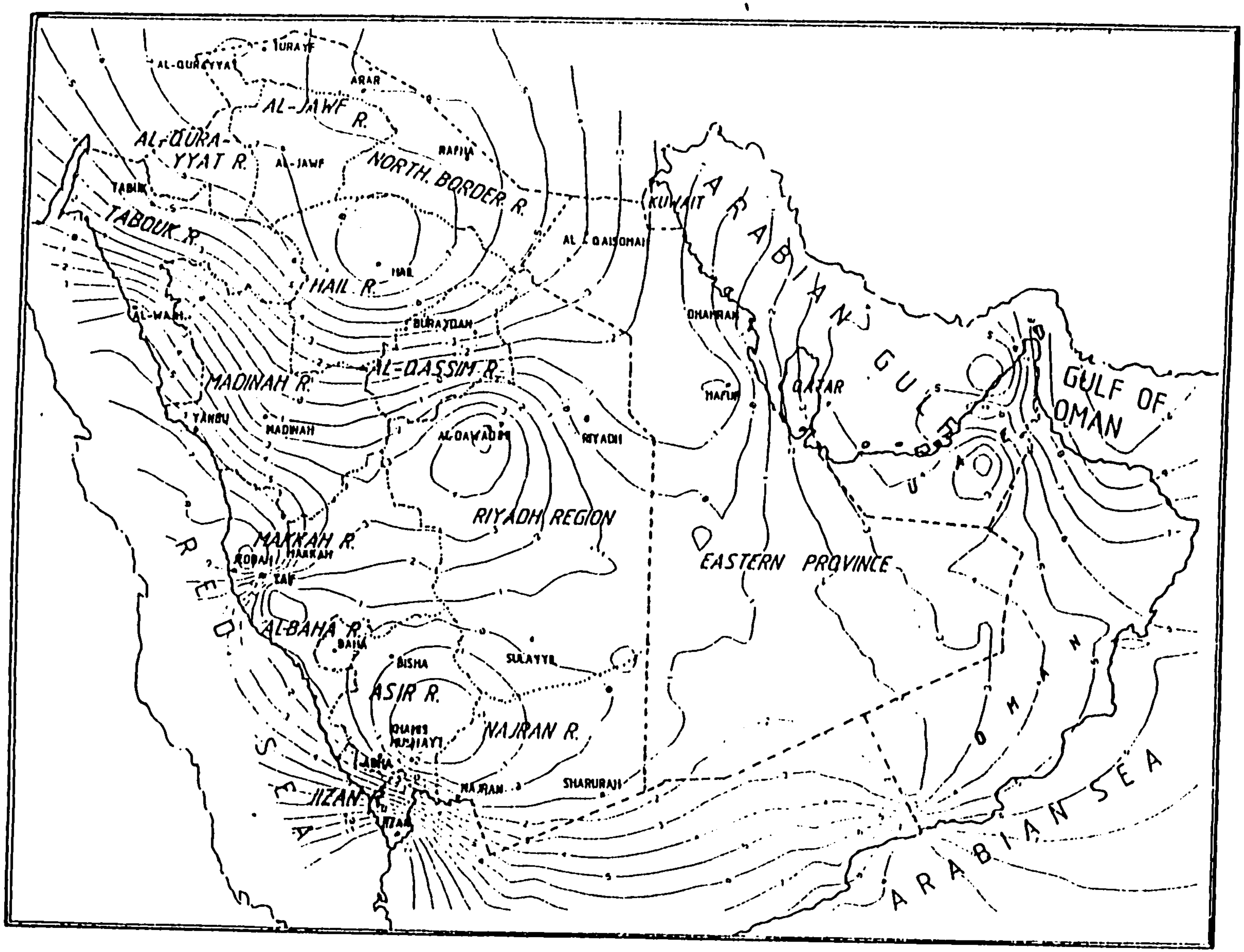


Figure 4.2: Minimum pavement temperature contour in the Gulf countries (Al-Abdul Wahhab et. al, 1995)

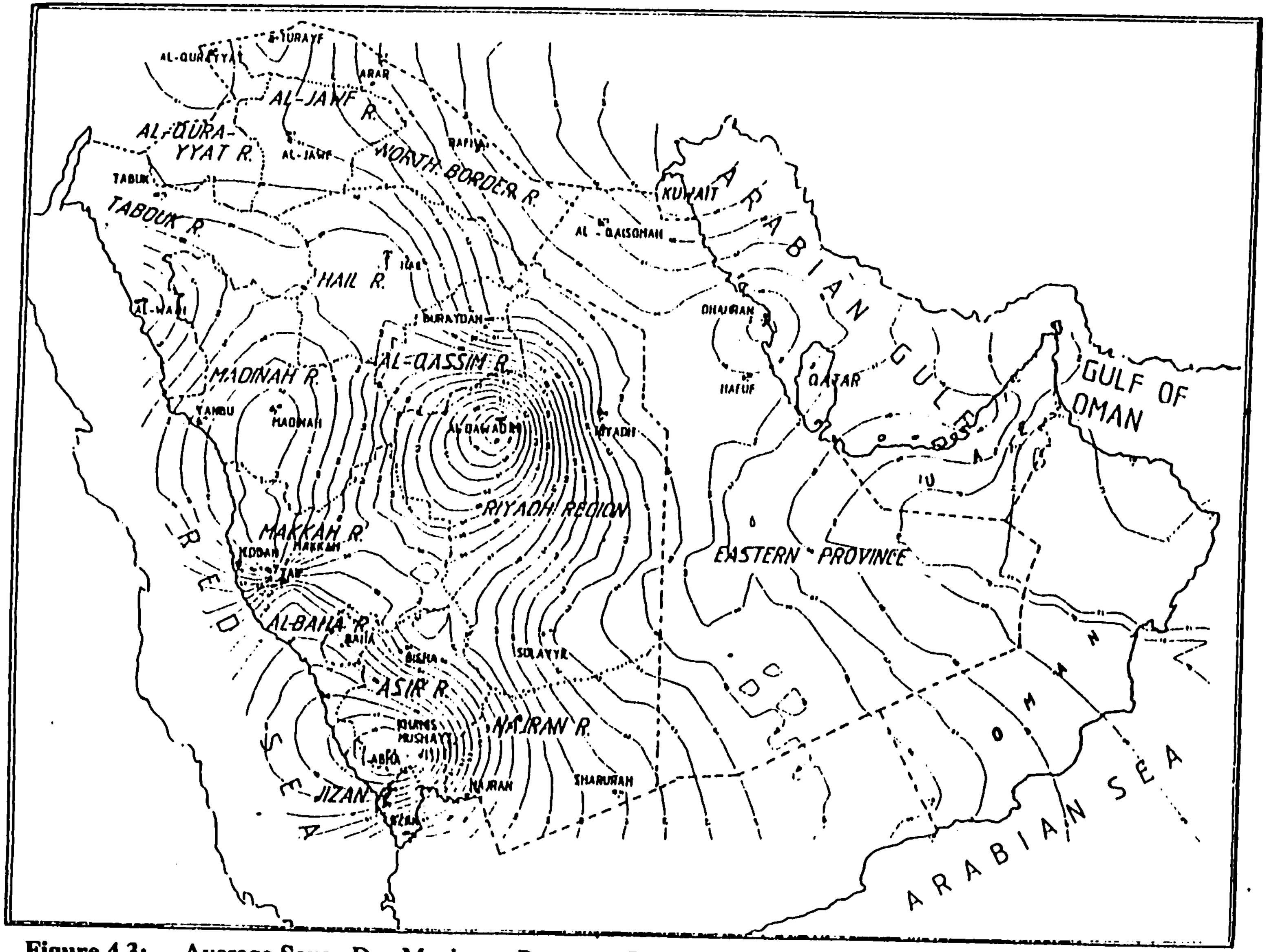


Figure 4.3: Average Seven Day Maximum Pavement Design Temperature Contour for the Gulf Countries (Al-Abdul Wahhab et. al, 1995)

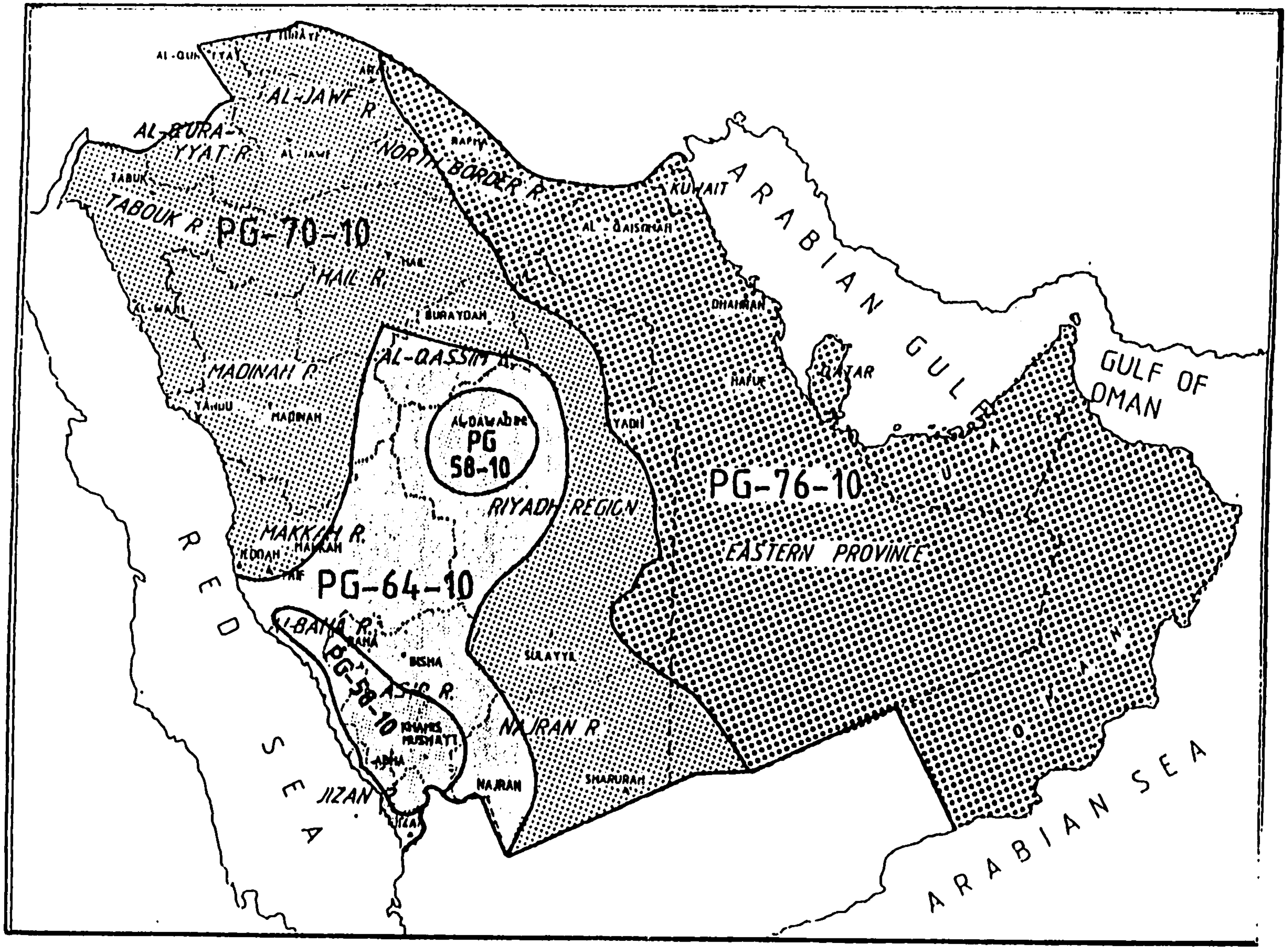


Figure 4.4: Actual Temperature Zoning for the Asphalt Binder Specifications for the Gulf Countries (Al-Abdul Wahhab et al, 1995)

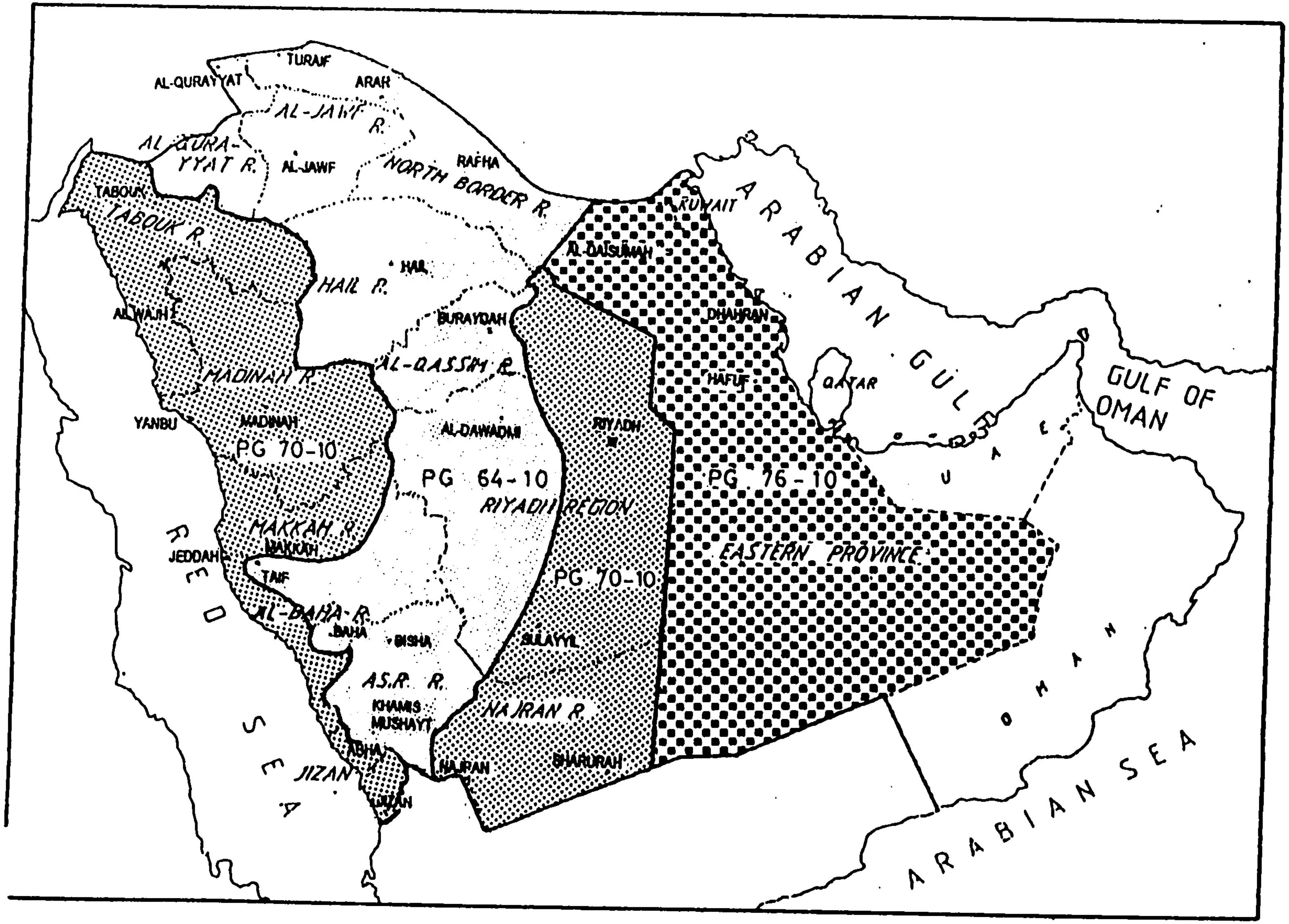


Figure 4.5: Recommended Temperature Zoning for the Asphalt Binder Specifications for the Gulf Countries (Al-Abdul Wahhab et al, 1995)

4.2.1 Physical and Consistency Testing and Age Hardening Characteristics

Collected asphalt samples were subjected to comprehensive testing to determine their physical and consistency properties:

1. Specific Gravity
2. Viscosity at 25°C
3. Absolute Viscosity at 60°C
4. Kinematic Viscosity at 135° C
5. Rotational Viscosity at 135°C
6. Penetration at 25°C and 4° C
7. Softening Point
8. Ductility at 25°C
9. Rolling Thin Film Oven Test at 163°C

The designated specifications were followed strictly for sample preparation and testing. The measured physical properties were utilized to determine AASHTO and WASHO asphalt grading.

Test results are summarized in Table 4.1 and presented in Appendix B. The following are observations that can be stated for asphalt produced in the Gulf countries:

1. Specific gravity of asphalt ranged from 1.019 to 1.037. KW asphalt binder is the heaviest since it has the highest mean (1.035) followed by RY (1.028), BH (1.026), then RT (1.020).

2. Two samples of RT met the 60/70 penetration grade; BH met the 40/50 penetration grade, while the rest of the samples did not meet any penetration

Table 4.1: Summary of Consistency Test Results of NAABs - RT and RY

Test	Ras Tanura Refinery, Saudi Arabia							Riyadh Refinery, Saudi Arabia						
	1	2	3	4	5	Average	Standard Deviation	1	2	3	4	5	Average	Standard Deviation
Specific Gravity	1.024	1.019	1.019	1.019	1.019	1.02	0.002	1.033	1.024	1.028	1.03	1.024	1.03	0.004
Penetration @ 25C, 0.1 mm	60	63	56	51	56	57.20	4.550	54	57	50	54	51	53.20	2.77
Penetration @ 25C of RTFOT residue, 0.1 mm	54	54	50	46	52	51.20	3.347	42	39	39	42	36	39.60	2.51
Penetration @ 4C, 0.1 mm	29	29	31	32	32	30.60	1.517	21	23	21	23	21	21.80	1.10
Penetration @ 4C of RTFOT residue, 0.1 mm	26	27	25	26	29	26.60	1.517	19	19	16	18	19	18.20	1.30
Softening Point, C	50.25	50.75	50	50.75	50.75	50.50	0.354	49.25	49.75	49.75	50	51.25	50.00	0.75
Flash Point, C	310	308	308	309	306	308.20	1.483	332	324	322	320	326	324.80	4.60
Ductility@ 25C, cm	133.33	126.33	150+	119	104.67	-	-	150+	150+	150+	150+	150+	-	-
Low temp. viscosity (sliding plate) @ 25C, Pa.s	136410	74249.5	70500	76401.5	82898.5	88091.90	27383.219	95492.5	91012.0	113760.5	69610.5	98844.5	93744.00	15965.76
Low temp. viscosity @ 25C of RTFOT, Pa.s	270124	150674.5	112377	219781	125485.0	175688.30	67113.057	152994.0	201111.5	163191	160731.5	153671.5	166339.90	19931.35
Absolute Viscosity @ 60C, Poise	3163.51	3204.52	3350.49	3557.79	2986.08	3252.48	214.479	2622.43	2692.74	3096.74	2631.45	2935.45	2795.76	210.81
Absolute Viscosity @ 60C of RTFOT residue, Poise	5110.53	5665.96	5931	8960.09	7033.29	6540.17	1523.022	4565.08	5910.00	6545.91	5096.66	5737.97	5571.12	763.24
Rotational Viscosity @ 135C, cP.s	468	460	460	480	445	462.60	12.798	530	490	490	460	500	494.00	25.10
Kinematic Viscosity @ 135C, cSt	408.12	492.35	491.55	489.32	440.60	464.39	38.318	411.85	438.80	468.2	522.95	556.02	479.56	59.38
Kinematic Viscosity @ 135C of RTFOT, cSt	553.87	587.38	567.54	675.1	568.06	590.39	48.835	543.20	550.90	584.85	547	573.95	559.98	18.35
Asphalt grade (AASHTO viscosity grading)	AC-40	AC-40	AC-40	AC-40	AC-40	-	-	AC-20	AC-40	AC-40	AC-20	AC-40	-	-
Asphalt grade (WASHO viscosity grading)	AR-4000	AR-8000	AR-8000	AR-8000	AR-8000	-	-	AR-4000	AR-4000	AR-8000	AR-4000	AR-8000	-	-

Table 4.1: Summary of Consistency Test Results of NAABs - BH and KW

Test	BAPCO Refinery, Bahrain							Al-Ahmadi Refinery, Kuwait						
	1	2	3	4	5	Average	Standard Deviation	1	2	3	4	5	Average	Standard Deviation
Specific Gravity	1.029	1.025	1.021	1.031	1.025	1.03	0.004	1.037	1.032	1.04	1.033	1.014	1.03	0.01
Penetration @ 25C, 0.1 mm	45	47	48	50	48	47.60	1.82	53	51	54	56	38	50.40	7.16
Penetration @ 25C of RTFOT residue, 0.1 mm	35	35	38	40	38	37.20	2.17	39	32	35	36	31	34.60	3.21
Penetration @ 4C, 0.1 mm	17	17	22	21	23	20.00	2.83	24	23	25	25	23	24.00	1.00
Penetration @ 4C of RTFOT residue, 0.1 mm	16	16	18	17	17	16.80	0.84	16	19	18	19	17	17.80	1.30
Softening Point, C	50.00	49.50	49	49.75	50.00	49.65	0.42	50.25	51	51.5	50	45.75	49.70	2.29
Flash Point, C	338	336	334	336	335	335.80	1.48	294	298	290	284	326	298.40	16.27
Ductility@ 25C, cm	150+	150+	150+	150+	150+	-	-	150+	150+	150+	150+	150+	-	-
Low temp. viscosity (sliding plate) @ 25C, Pa.s	89911.0	103737.5	118866.5	113794	92638.5	103789.50	12692.18	60264.5	83078	79673	98579	211164.5	106551.80	60048.70
Low temp. viscosity @ 25C of RTFOT, Pa.s	205453.5	213037.5	144266.5	209704.5	115218.0	177536.00	44902.53	131770	171112	198399	150627.5	355225.0	201426.70	89463.23
Absolute Viscosity @ 60C, Poise	3398.90	3042.71	2851.91	2978.3	2932.68	3040.90	211.85	3186.53	3452.83	3865	3303.59	6172.06	3996.00	1243.19
Absolute Viscosity @ 60C of RTFOT residue, Poise	5581.27	6136.00	5025.44	5201.67	4992.79	5387.43	479.38	6500.32	6001.61	6992	7630.88	10750.35	7575.03	1874.59
Rotational Viscosity @ 135C, cP.s	465	485	460	455	450	463.00	13.51	500	565	575	590	620	570.00	44.30
Kinematic Viscosity @ 135C, cSt	481.94	485.48	451.34	451.8	447.38	463.59	18.49	530	584.19	530.38	532.56	525.59	540.54	24.53
Kinematic Viscosity @ 135C of RTFOT, cSt	609.36	618.85	628.78	598.27	572.94	605.64	21.49	736.16	686.5	760.38	790.83	593.96	713.57	76.99
Asphalt grade (AASHTO viscosity grading)	AC-40	AC-40	AC-40	AC-40	AC-40	-	-	AC-40	AC-40	AC-40	AC-40	AC-40	-	-
Asphalt grade (WASHO viscosity grading)	AR-4000	AR-8000	AR-4000	AR-4000	AR-4000	-	-	AR-8000	AR-8000	AR-8000	AR-8000	AR-8000	-	-

grades. RT asphalt binder is the softest since it has the highest mean penetration (57.2), followed by KW (53.8), RY (53.2), then the hardest BH (47.6).

3. Penetration at 4°C followed the same trend as that of the penetration at 25°C with RT being the softest since it has the highest mean (30.6), followed by KW (24.0), RY (21.8); BH is the hardest (20.0).

4. Softening point ranged from 50.00°C to 50.75 for RT, from 49.25 to 51.25 for RY, from 49.00 to 50.00 for BH and from 50.00 to 51.50 for the KW samples. RT has the highest mean softening point (50.75), followed by KW (50.65), RY (50.00), then BH (49.65).

5. The flash point of all samples ranged from 298 to 338. KW has the lowest mean (291), followed by RT (308), RY (324.8), then BH (336). All of the samples exhibited flash points which were above the usual minimum limit of 220°C; this provides an adequate safety cushion.

6. All samples showed high ductility value at 25°C except RT with a value of 105 cm, which is still higher than the minimum limit of 100 cm.

7. Absolute viscosity at 135 °C ranged from 2622 Poise to 3865 Poise. RY is the softest since it has the lowest mean (2796) followed by BH (3041), RT (3252), then KW (3474).

8. Rotational viscosity at 135 °C of all samples ranged from 462.6 cP to 559 cP; KW (559) is the hardest followed by RY (494), BH (463), then RT (463).

9. Kinematic viscosity at 135 °C of all samples ranged from 463 cSt to 550 cSt; KW (550) is the hardest followed by RY (480), RT (464), then BH (464).

10. All samples from RT, BH, and KW, and three RY samples are graded as AC-40 according to the AASHTO asphalt grading method, except two RY samples, which had a grade of AC-20.

11. Four RT samples, two RY samples, one BH sample, and all KW samples are graded as AR-8000 according to the WASHO method. The rest are graded as AR-4000.

Statistical analysis was performed to compare various properties of the fresh samples with those of the RTFOT-aged samples. The results are summarized as follows:

1. For penetration at 25°C, 100 gm, 5 sec., the fresh asphalt samples have shown larger mean penetrations (52.95) than the aged samples (40.55). RT has the largest mean penetration, followed by RY, BH, then KW. The fresh samples were less variable (2.765) than the aged (2.964).

2. For penetration at 4°C, 200 gm, 60 sec., the fresh asphalt samples have shown larger mean penetrations (24.15) than the aged samples (19.90). Fresh samples had similar variability for RT (1.517) but were less variable than the aged samples for KW (0.840, 1.220) and RY (1.100, 1.300) and more variable than the aged samples for BH (2.830, 0.840). RT (26.60) has the largest mean penetration, followed by KW (18.00), RY (18.00), then BH (16.80).

3. For viscosity tests (absolute, kinematic, and sliding plate), fresh asphalt samples have smaller mean viscosity in comparison to aged samples and are less variable for all samples except KW in the absolute and sliding plate viscosity but more variable in the kinematic viscosity except BH.

4. For softening point tests, fresh samples have smaller means than aged ones and are more variable except BH and KW.

5. For the ductility test, RT is different; all others are the same.

4.2.1.1 Implications

It is interesting to note that various consistency tests showed some differences in ranking the samples from hardest to softest as summarized below:

Test	Ranking (from hardest to softest)
Penetration at 25°C	BH , RY, KW, RT
Penetration at 4°C	BH, RY, KW, RT
Softening point	RT, KW, RY, BH
Absolute viscosity	KW, RT, BH, RY
Rotational viscosity	KW, RY, BH & RT
Kinematic viscosity	KW, RY, RT & BH

The penetration at 25°C and at 4°C provided identical ranking. Rotational viscosity and Kinematic viscosity provided a similar ranking since the difference between RT and BH is not significant. The softening point and the absolute viscosity provided different rankings from others. The following are some explanations of the noted behavior:

1. The fact that some of these measures are empirical has not allowed them to be expressed in engineering units.

2. These tests do not consider the dependency of the asphalt binder behavior on rate of loading.
3. These measures are conducted at different temperatures, different loading modes, and different loading rates, making them independent measures.
4. The shear rate is variable during the test since it depends on the consistency of the asphalt binder.

Further, the above discussion shows that in general there are differences in consistency between all refineries. Test results show that asphalt binder produced by the same refinery is variable. Refineries need to improve asphalt binder production quality control in order to eliminate the observed variability.

4.2.2 Temperature Susceptibility

The measured physical and consistency properties were used to calculate relevant temperature susceptibility indices such as:

1. Retained penetration at 25°C
2. Retained penetration at 4°C
3. Viscosity Ratio at 25°C
4. Viscosity Ratio at 60°C
5. Viscosity Ratio at 135°C
6. Penetration Index (PI)
7. Penetration temperature susceptibility (PTS)
8. Penetration Ratio (PR)

9. Penetration viscosity number (PVN) and (PVN')

10. Viscosity temperature susceptibility (VTS)

Table 4.2 summarizes the computed indices. The following observations are made:

1. RT has the lowest heat hardening affect measured by the retained penetration at 25°C (RP) (0.90) followed by BH (0.78), RY (0.75), then KW (0.61). Large RP indicates low heat hardening.

2. RT has the lowest heat hardening affect measure by the retained penetration at 4°C (0.87) followed by BH (0.84), RT (0.84), then KW (0.77). Large RP indicates low heat hardening.

3. BH samples showed the lowest heat hardening based on the viscosity at 25°C (1.73) followed by RY (1.82), RT (2.00), then KW (2.16). Large viscosity ratio indicates high heat hardening.

4. BH samples showed the lowest heat hardening based on the absolute viscosity at 60°C (1.77) followed by KW (1.85), RY (1.99), then RT (2.01). Large viscosity ratio indicates high heat hardening.

5. RY samples showed the lowest heat hardening based on the kinematic viscosity at 135°C (1.18). followed by RT(1.27), BH (1.30), then KW (1.31). Large viscosity ratio indicates high heat hardening.

6. The penetration index (PI) ranged from –0.76 to –1.38. RT has the lowest temperature susceptibility (–0.76) followed by KW (–0.86), RY (–1.07), then BH

Table 4.2: Summary of Temperature Susceptibility Indices of NAABs - RT and RY

Test	Ras Tanura Refinery, Saudi Arabia							Riyadh Refinery, Saudi Arabia						
	1	2	3	4	5	Average	Standard Deviation	1	2	3	4	5	Average	Standard Deviation
Retained penetration @ 25C (Heat Hardening) Large RP indicates low HH	0.9	0.86	0.89	0.91	0.92	0.90	0.02	0.78	0.69	0.79	0.78	0.70	0.75	0.05
Retained penetration @ 4C (Heat Hardening) Large RP indicates low HH	0.89	0.91	0.83	0.82	0.92	0.87	0.05	0.88	0.83	0.77	0.8	0.93	0.84	0.06
Viscosity ratio @ 25C (Heat Hardening) Large VR indicates high HH	1.98	2.03	1.59	2.88	1.51	2.00	0.54	1.60	2.21	1.43	2.31	1.55	1.82	0.41
Viscosity ratio @ 60C (Heat Hardening) Large VR indicates high HH	1.62	1.77	1.77	2.52	2.36	2.01	0.40	1.78	2.19	2.11	1.94	1.95	1.99	0.16
Viscosity ratio @ 135C (Heat Hardening) Large VR indicates high HH	1.36	1.19	1.15	1.38	1.29	1.27	0.10	1.30	1.26	1.25	1.05	1.03	1.18	0.13
Penetration Index (PI), Large -ve indicates high Temperature Susceptibility	-0.72	-0.44	-0.95	-0.98	-0.73	-0.76	0.22	-1.2	-0.98	-1.28	-1.01	-0.86	-1.07	0.17
Penetration Temperature Susceptibility	0.02	0.02	0.03	0.03	0.02	0.02	0.01	0.03	0.03	0.03	0.03	0.03	0.03	0.00
Penetration ratio (PR) - low PR indicates large TS	48.81	46.21	54.86	63.21	56.74	53.97	6.72	39.17	39.82	42.32	41.87	40.38	40.71	1.34
Penetration viscosity number (PVN), low PVN indicates large TS	-0.75	-0.42	-0.56	-0.66	-0.70	-0.62	0.13	-0.83	-0.70	-0.74	-0.5	-0.48	-0.65	0.15
Penetration viscosity number (PVN'), low PVN' indicates large TS	-0.37	-0.27	-0.43	-0.51	-0.52	-0.42	0.10	-0.71	-0.62	-0.67	-0.7	-0.69	-0.68	0.04
Viscosity temperature susceptibility (VTS), large VTS indicates large TS	3.65	3.50	3.52	3.55	3.56	3.56	0.06	3.56	3.53	3.53	3.37	3.37	3.47	0.09

Table 4.2: Summary of Temperature Susceptibility Indices of NAABs - BH and KW

Test	BAPCO Refinery, Bahrain							Al-Ahmadi Refinery, Kuwait						
	1	2	3	4	5	Average	Standard Deviation	1	2	3	4	5	Average	Standard Deviation
Retained penetration @ 25C (Heat Hardening) Large RP indicates low HH	0.78	0.75	0.79	0.8	0.78	0.78	0.02	0.63	0.63	0.64	0.64	0.52	0.61	0.05
Retained penetration @ 4C (Heat Hardening) Large RP indicates low HH	0.94	0.94	0.79	0.78	0.74	0.84	0.10	0.84	0.83	0.71	0.76	0.73	0.77	0.06
Viscosity ratio @ 25C (Heat Hardening) Large VR indicates high HH	2.29	2.05	1.21	1.84	1.24	1.73	0.48	2.06	2.06	2.49	1.53	2.64	2.16	0.43
Viscosity ratio @ 60C (Heat Hardening) Large VR indicates high HH	1.64	2.02	1.76	1.75	1.70	1.77	0.15	1.74	1.74	1.81	2.31	1.64	1.85	0.27
Viscosity ratio @ 135C (Heat Hardening) Large VR indicates high HH	1.26	1.27	1.39	1.32	1.28	1.30	0.05	1.18	1.18	1.43	1.48	1.27	1.31	0.14
Penetration Index (PI), Large -ve indicates high Temperature Susceptibility	-1.41	-1.45	-1.53	-1.25	-1.27	-1.38	0.12	-0.93	-0.93	-0.63	-0.93	-0.86	-0.86	0.13
Penetration Temperature Susceptibility	0.03	0.03	0.03	0.03	0.03	0.03	0.00	0.03	0.03	0.02	0.03	0.03	0.03	0.00
Penetration ratio (PR) - low PR indicates large TS	36.79	35.21	46.34	42.08	47.38	41.56	5.48	45.54	45.54	46.21	44.54	44.45	45.26	0.75
Penetration viscosity number (PVN), low PVN indicates large TS	-0.79	-0.74	-0.82	-0.78	-0.83	-0.79	0.04	-0.42	-0.42	-0.48	-0.44	-0.36	-0.42	0.04
Penetration viscosity number (PVN'), low PVN' indicates large TS	-0.72	-0.77	-0.8	-0.7	-0.77	-0.75	0.04	-0.54	0.54	-0.32	-0.43	-0.39	-0.23	0.44
Viscosity temperature susceptibility (VTS), large VTS indicates large TS	3.54	3.49	3.53	3.54	3.54	3.53	0.02	3.39	3.39	3.5	3.45	3.42	3.43	0.05

with the highest temperature susceptibility (–1.38). Large PI negative values indicate large temperature susceptibility.

7. The penetration ratio (PR) of all samples ranged from 40.71 to 53.97. The temperature susceptibility measured by the PR of all samples agrees with that indicated by the PI. Low PR indicates large temperature susceptibility.

8. The penetration viscosity number (PVN and PVN') of all samples ranged from 0.23 to –0.79. KW has the lowest temperature susceptibility measured by the PVN or the PVN' (–0.42, –0.23) followed by RT (–0.62, –0.42), RY (–0.65, –0.68), then BH with the highest temperature susceptibility (–0.79, –0.75). Low PVN indicates large temperature susceptibility.

9. The viscosity temperature susceptibility (VTS) ranged from 3.43 to 3.56. KW has the lowest temperature susceptibility as measured by the VTS (3.43) followed by RY (3.47), BH (3.53), then RT (3.56). Large VTS indicates large temperature susceptibility.

4.2.3 Rheological Testing

Rheological testing comprises the determination of the visco-elastic parameters of the NAABs at various temperatures and aging conditions. Rheological testing included the following tests:

1. Complex shear modulus (G*)
2. Phase angle (δ)
3. Flexural creep stiffness (S)

4. Flexural creep slope (m-value)

5. Short-term aging (RTFOT)

6. Long-term aging (PAV)

The rheological performance-based properties of NAAB samples were determined using the Dynamic Shear Rheometer (DSR) to measure the complex shear modulus and phase angle, the Bending Beam Rheometer (BBR) to measure the flexural creep stiffness and creeping slope, the rolling thin-film-oven test (RTFOT) to simulate short-term aging, and the pressure aging vessel (PAV) to simulate long-term aging. A brief description of these tests is presented in Appendix A. The methods recommended by SHRP, included in the SHRP-A-379 report entitled "The SUPERPAVE Mix Design System Manual of Specifications, Test Methods, and Practices", were strictly followed in sample preparation, asphalt binder aging using the RTFOT and the PAV, and in DSR and BBR testing. Typical printouts of the dynamic shear rheometer and the bending beam rheometer are shown in Figures 4.6 and 4.7.

This evaluation process starts by determining the temperature at which the viscous component of overall binder stiffness, $G^*/\sin\delta$, is more than 1.00 kPa, where G^* and δ are the overall shear modulus and the phase angle of the asphalt binder respectively using the DSR. The conformation of the high temperature evaluation is performed by testing RTFOT-aged samples (RTFOT residue) of the asphalt binder using the DSR. The $G^*/\sin\delta$ of the RTFOT-aged asphalt binder sample must be greater than 2.20 kPa.

DSR Project - SHRP Binder Test - Strain Controlled
(Created by Version 2.05)

Parameters:

Measurement Type: High Temperature Range
Target Temperature: 64.0 °C
Strain Amplitude: 10.00 percent
Plate Diameter: 25.0 mm
Plate Gap: 1.0 mm
Equilibration Time: 0.5 minutes

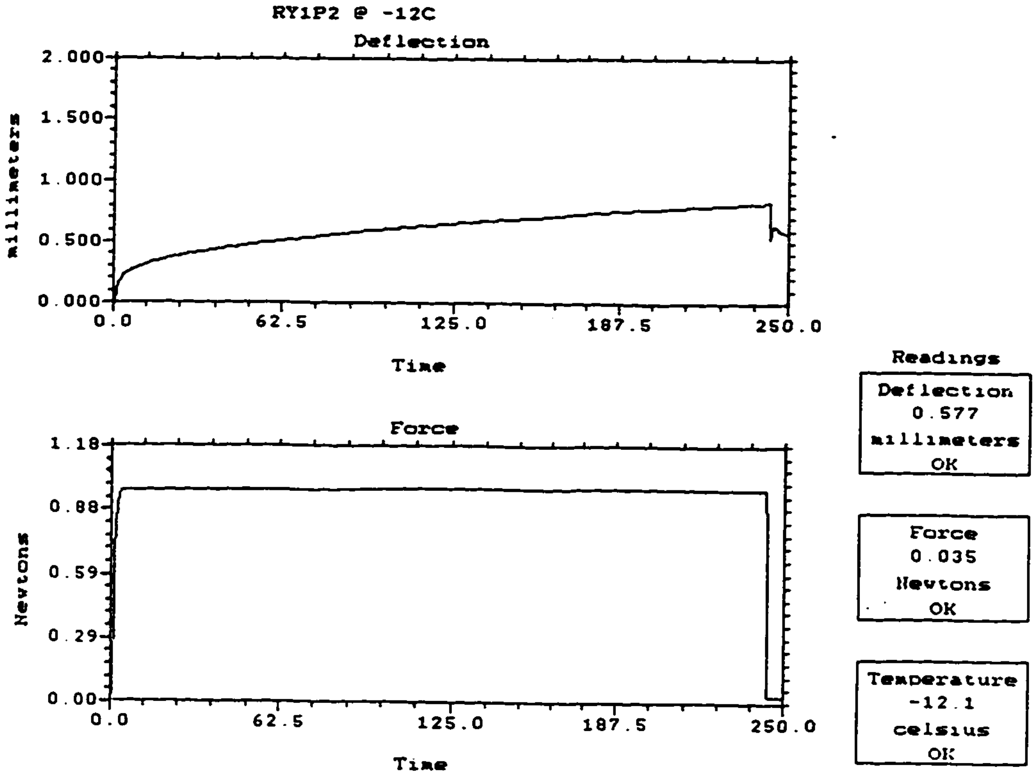
Ancillary Info:

Operator ID: Operator 001
Sample ID: SampleQC01
Sample Type: Rolling Thin Film Oven Test Residue
Test Number: 0001

Measurement Results:

Completed: 11/7/94 10:24:07 AM
Modulus (G*): 3.7726E3 Pascal
Phase Angle (delta): 79.2 degrees
G*/sin(delta): 3.8403E3 Pascal
Strain Amplitude: 4.85 percent
Final Temperature: 64.0 °C
Osc. Frequency: 10.08 radians/second
Test Status: PASSED

Figure 4.6: Typical Printout of the Dynamic Shear Rheometer (DSR).



TEST INFORMATION

Project : Adaptation of SHRP
Operator: DUBABE
Specimen: RY1P2 @ -12C
Time : 18:14:26
Date : 12/13/94
File : RY1P212.DAT

Target Temp: -12.0 C
Actual Temp: -12.1 C
Soak time : 60.0 min
Beam Width : 12.70 mm
Thickness : 6.35 mm

Conf. Test: 2.05144e+00
Date: 12/13/94
Load Const: 0.243902
Defl Const: 0.002424
Date: 11/21/94

RESULTS

t Time (sec)	P Force (N)	d Defl (mm)	Measured Stiffness (kPa)	Estimated Stiffness (kPa)	Difference (%)	m-value
8	.9687	.2703	289000.0	287600.0	-.4935	.285
15	.9690	.3291	237400.0	239300.0	.8119	.299
30	.9714	.4056	193100.0	193400.0	.1492	.315
60	.9744	.5056	155400.0	154500.0	-.5552	.332
120	.9763	.6436	122300.0	122100.0	-.1405	.348
240	.9765	.8268	95230.0	95450.0	.2347	.364

Regression Coefficients
a = 5.694 b = -.2369 c = -.02661 R^2 = 0.999848

- CANNON BENDING BEAM RHEOMETER - V3.1 P to print - ESC to continue

Figure 4.7: Typical Printout of the Bending Beam Rheometer (BBR).

Then the intermediate temperature evaluation was performed. This involved testing an asphalt sample of the PAV-aged asphalt binder (PAV residue) using the DSR to determine the temperature at which the parameter $G^* \times \sin\delta$ is more than 5000 kPa.

The low temperature evaluation was accomplished by testing an aged asphalt binder sample (PAV residue) using the BBR. It involved determining the temperature at which the creep stiffness, S, that describes whether the binder will behave more like an elastic solid or a viscous liquid, is less than 300 MPa and the m-value, which is the rate at which the binder stiffness changes with creep load, is greater than 0.300.

The dynamic mechanical testing using the DSR must be performed at a specific shear strain amplitude that is within the linear visco-elastic limits of the asphalt binder. Within this range, the complex shear modulus is relatively independent of the shear strain. SHRP has recommended strain amplitudes for various aging conditions as shown in Table 4.3.

Table 4.3: Strain amplitudes as recommended by SHRP

Sample Condition	Strain, %
Original Binder	12.5
RTFOT Residue	10.0
PAV Residue	1.0

Therefore, the linear visco-elastic limit for each asphalt source (Ras Tanura refinery (RT), Riyadh refinery (RY), BAPCO refinery (BH), and Al-Ahmadi refinery (KW), for various age conditions (fresh, RTFOT residue, and PAV residue) and for

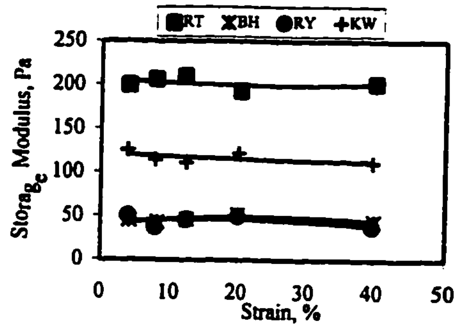
various testing temperatures needs to be identified. In order to identify this limit, a strain sweep test was performed. The strain sweep test involves testing an asphalt sample at various strain amplitudes and measuring the complex shear modulus at each point. A plot of the storage modulus, G'', which represents the in-phase component of the overall complex shear modulus, G^*, vs. the corresponding strain amplitude, was generated and used to identify the linear visco-elastic limits.

NAABs from all sources were tested to identify their linear visco-elastic limits as shown in Table 4.4 and Figure 4.8, which shows plots between the storage modulus and the strain amplitude for various ages and temperatures of all NAABs. Examining these plots clearly indicates that the strain amplitudes that are recommended by SHRP (Table 4.3) to measure the complex shear modulus and the phase angle of the asphalt binder for the three age conditions are within the linear visco-elastic limits for all asphalt samples that were collected from the asphalt producing refineries in the Gulf countries. Therefore, strain amplitudes shown in Table 4.3 were used in dynamic mechanical testing during the evaluation process.

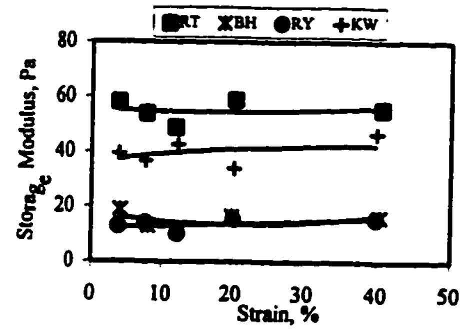
The test results and the computed parameters (i.e $G^*/\sin\delta$ and $G^* x \sin\delta$) of all NAABs are summarized in Table 4.5. Variation of the $G*$ and phase angle with temperature and aging condition (fresh and RTFOT) for various samples (1, 2, 3, 4, and 5) from various sources (RT, RY, BH, and KW) are presented in Appendix B. The following are observations that can be stated for asphalt produced in the Gulf countries.

Table 4.4: Strain Sweep Test to Define the Linear Visco-Elastic Limits of all NA

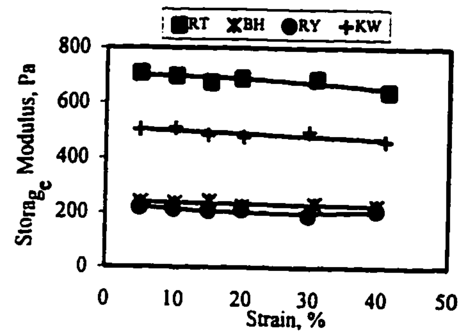
		Asphalt Source							
		Ras Tanura Refinery		Riyadh Refinery		BAPCO Refinery		Al-Ahmadi Refinery	
	Temperature	Measured Strain, %	Storage Modulus Pa	Measured Strain, %	Storage Modulus Pa	Measured Strain, %	Storage Modulus Pa	Measured Strain, %	Storage Modulus Pa
Fresh Binder	64 °C	3.91	199.4	3.98	49.9	4.12	45	3.82	125.2
		7.9	206.3	7.91	36.9	8.22	42.6	7.86	114.4
		12.1	209.4	12.51	45.6	12.54	45.7	12.4	111.3
		20.4	192.4	20.12	49.5	20.07	51	20.14	121.5
		40.3	201.5	39.88	38.1	40.12	43.7	39.88	111.2
	70 °C	3.81	57.99	3.91	12.7	4.11	18.7	3.91	39.2
		7.77	53.8	7.68	13.9	8.13	12.9	7.68	36.6
		11.93	48.8	12.3	10.1	12.21	11.1	12.3	42.5
		20.39	58.8	20.25	15.3	20.01	16.4	20.25	33.9
		40.63	55.5	39.91	15.5	40.38	16.3	39.91	46.6
RTFOT Residue	64 °C	4.85	706.9	5.02	219.1	5.03	236.3	4.91	503.1
		10.11	697.7	9.85	213.2	10.06	234.3	10.06	508.7
		15.17	675.1	14.95	205.6	15.11	240.8	14.83	484.1
		19.75	690	19.94	209	19.98	223.6	20.11	476.7
		30.89	687.6	29.86	189.3	30.74	231.4	29.85	496.1
		41.46	641.7	39.9	208.6	39.9	224.2	41.04	462.1
	70 °C	4.84	245.9	4.79	57.4	4.82	67.4	5.06	167.3
		9.68	248.4	10.12	65.5	9.79	73.2	10.11	162.6
		15.03	251.2	14.89	65.6	14.89	69.2	14.94	164.7
		20.03	231.9	20.11	64.2	19.73	73.9	20.05	166.1
		30.14	248.2	29.98	56.6	28.68	68.2	29.99	172.8
		40.64	232.1	40	58.6	39.91	71.5	40.01	159.4
PAV Residue x 10^6	22 °C	0.1602	5.06	0.2383	6.35	0.1502	10.7	0.2604	5.58
		0.3002	5.09	0.2847	6.36	0.1795	10.6	0.314	5.52
		0.4472	5.03	0.3421	6.32	0.2135	10.7	0.3754	5.52
		0.591	5.03	0.408	6.33	0.2548	10.8	0.4481	5.53
		0.7382	5.01	0.4883	6.32	0.3051	10.6	0.5353	5.5
		0.8865	4.97	0.5774	6.35	0.3667	10.6	0.6364	5.51
		1.041	4.91	0.692	6.33	0.4345	10.6	0.7611	5.51
		1.193	4.87	0.8314	6.28	0.5198	10.6	0.9079	5.5
		1.351	4.83	0.9951	6.24	0.847	10.6	1.081	5.5
		1.514	4.77	1.19	6.22	1.21	10.5	1.288	5.49
	25 °C	0.2176	3.62	0.3535	4.09	0.219	6.99	0.388	3.61
		0.4165	3.58	0.4177	4.12	0.2611	6.98	0.4624	3.61
		0.6118	3.59	0.5011	4.1	0.3126	6.97	0.5538	3.57
		0.8166	3.55	0.5973	4.11	0.3741	6.98	0.6592	3.59
		1.027	3.49	0.7149	4.09	0.4452	6.99	0.7835	3.6
		1.241	3.45	0.8567	4.07	0.5305	6.99	0.9408	3.58
		1.462	3.4	1.027	4.03	0.6343	7.01	1.124	3.57
		1.689	3.34	1.227	4.01	0.762	6.94	1.338	3.57
		1.923	3.28	1.475	3.98	0.9082	6.91	1.59	3.58
		2.163	3.22	1.769	3.95	1.087	6.89	1.901	3.56



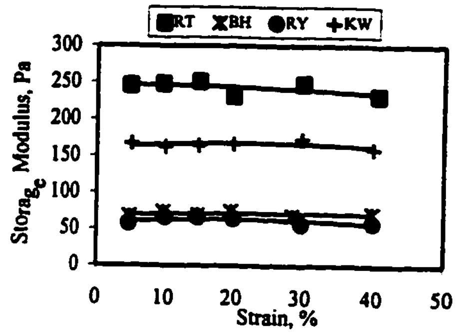
a) Fresh at 64 C



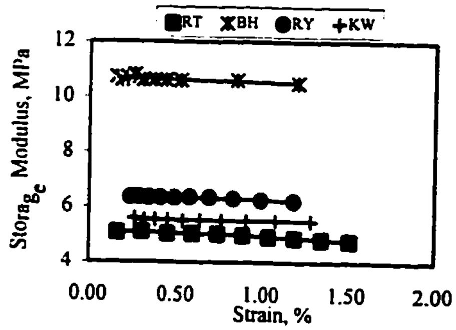
b) Fresh at 70 C



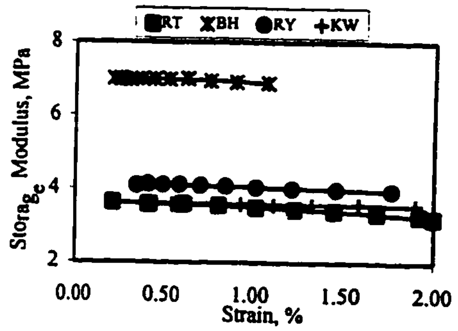
c) RTFOT residue at 64 C



d) RTFOT residue at 70 C



e) PAV residue at 22 C



f) PAV residue at 25 C

Figure 4.8: Strain Sweep Test to Identify the Linear Visco-Elastic Limit for Dynamic Meachanical Testing of all NAABs.

Table 4.5: Summary of Rheological characterization Test Results of NAABs - RT and RY

Test	Ras Tanura Refinery, Saudi Arabia							Riyadh Refinery, Saudi Arabia						
	1	2	3	4	5	Average	Standard Deviation	1	2	3	4	5	Average	Standard Deviation
Complex shear modulus (G*) of fresh binder @ 64C, kPa	1.74	1.42	1.37	1.54	1.51	1.52	0.15	1.31	1.31	1.41	1.23	1.44	1.34	0.08
Complex shear modulus (G*) of fresh binder @ 70C, kPa	0.68	0.69	0.67	0.70	0.72	0.69	0.02	0.64	0.67	0.69	0.61	0.68	0.66	0.03
Complex shear modulus (G*) of RTFOT residue @ 64C, kPa	3.77	3.13	3.24	3.92	2.94	3.40	0.42	2.73	3.60	3.90	3.01	4.39	3.53	0.67
Complex shear modulus (G*) of RTFOT residue @ 70C, kPa	1.81	1.50	1.63	1.94	1.45	1.66	0.21	1.29	1.70	1.74	1.47	1.97	1.63	0.26
Phase angle of fresh binder @ 64C, degrees	83.30	83.60	84.00	83.00	82.60	83.30	0.54	88.00	87.20	87.10	87.30	86.80	87.28	0.44
Phase angle of fresh binder @ 70C, degrees	85.90	85.70	85.90	84.80	84.80	85.42	0.57	89.10	88.40	88.40	88.40	87.90	88.44	0.43
Phase angle of RTFOT residue @ 64C, degrees	79.20	79.00	80.10	77.40	79.40	79.02	1.00	85.50	84.00	84.10	83.80	83.80	84.24	0.72
Phase angle of RTFOT residue @ 70C, degrees	82.10	82.50	82.60	81.10	82.30	82.12	0.60	87.10	85.60	85.80	85.60	85.70	85.96	0.64
G*/sin(delta) of fresh binder @ 64C	1.75	1.43	1.37	1.55	1.52	1.53	0.15	1.31	1.31	1.41	1.23	1.44	1.34	0.09
G*/sin(delta) of fresh binder @ 70C	0.68	0.69	0.67	0.71	0.72	0.70	0.02	0.64	0.67	0.69	0.61	0.68	0.66	0.03
G*/sin(delta) of RTFOT residue @ 64C	3.84	3.19	3.29	4.02	2.99	3.47	0.44	2.74	3.62	3.92	3.03	4.42	3.54	0.68
G*/sin(delta) of RTFOT residue @ 70C	1.82	1.51	1.64	1.96	1.46	1.68	0.21	1.29	1.71	1.74	1.47	1.98	1.64	0.26
Complex shear modulus of PAV residue @ 22C, kPa	3605	4754	4145	5200	4110	4362.72	620.51	7226	8831	8228	5230	5966	7096.16	1505.55
Complex shear modulus of PAV residue @ 25C, kPa	2051	2996	2363	3840	2100	2670.00	754.57	4524	6466	5937	3452	3840	4843.72	1310.76
Phase angle of PAV residue @ 22C, degrees	39.70	38.10	38.90	36.90	37.70	38.26	1.08	43.50	41.10	40.60	41.10	42.30	41.72	1.18
Phase angle of PAV residue @ 25C, degrees	42.00	39.00	41.10	38.30	40.10	40.10	1.50	45.70	43.00	43.20	43.00	44.10	43.80	1.16
G*xsin(delta) of PAV residue @ 22C	2302.50	2933.39	2602.91	3122.19	2513.38	2694.87	329.71	4974.05	5805.15	5354.57	3438.07	4015.19	4717.41	972.73
G*xsin(delta) of PAV residue @ 25C	1372.39	1885.44	1553.38	2379.95	1352.66	1708.76	431.80	3237.79	4409.53	4064.16	2354.26	2672.31	3347.61	879.77
Flexural creep stiffness of PAV residue @ -12C, MPa	102.00	96.72	92.80	99.80	101.00	98.46	3.74	153.70	193.00	164.00	144.30	147.60	160.52	19.64
Flexural creep slope of PAV residue @ -12C	0.35	0.34	0.34	0.33	0.35	0.34	0.01	0.33	0.34	0.32	0.33	0.32	0.33	0.01
Flexural creep stiffness of PAV residue @ -18C, MPa	180.70	179.70	184.65	170.65	174.50	178.04	5.49	336.90	336.90	351.40	302.20	326.90	330.86	18.25
Flexural creep slope of PAV residue @ -18C	0.30	0.30	0.29	0.32	0.32	0.30	0.01	0.26	0.29	0.27	0.27	0.26	0.27	0.01

Table 4.5: Summary of Rheological characterization Test Results of NAABs - BH and KW

Test	BAPCO Refinery, Bahrain							Al-Ahmadi Refinery, Kuwait						
	1	2	3	4	5	Average	Standard Deviation	1	2	3	4	5	Average	Standard Deviation
Complex shear modulus (G*) of fresh binder @ 64C, kPa	1.31	1.46	1.24	1.32	1.23	1.31	0.09	1.82	1.50	1.58	1.47	1.54	1.58	0.14
Complex shear modulus (G*) of fresh binder @ 70C, kPa	0.64	0.70	0.62	0.67	0.60	0.65	0.04	0.86	0.73	0.81	0.76	0.80	0.79	0.05
Complex shear modulus (G*) of RTFOT residue @ 64C, kPa	2.99	2.83	2.78	2.77	2.62	2.80	0.13	3.31	3.70	3.60	3.74	3.55	3.58	0.17
Complex shear modulus (G*) of RTFOT residue @ 70C, kPa	1.45	1.36	1.33	1.31	1.20	1.33	0.09	1.64	1.73	1.75	1.91	1.66	1.74	0.11
Phase angle of fresh binder @ 64C, degrees	88.00	87.90	87.70	87.50	88.10	87.84	0.24	85.40	86.20	85.90	86.60	86.00	86.02	0.44
Phase angle of fresh binder @ 70C, degrees	89.00	88.80	88.60	88.60	88.70	88.74	0.17	87.00	87.90	87.30	86.90	87.50	87.32	0.40
Phase angle of RTFOT residue @ 64C, degrees	85.50	85.50	85.80	85.10	85.40	85.46	0.25	82.60	82.40	82.40	82.50	82.60	82.50	0.10
Phase angle of RTFOT residue @ 70C, degrees	87.10	87.20	87.30	87.00	87.30	87.18	0.13	84.60	84.60	84.90	84.50	84.70	84.66	0.15
G*/sin(delta) of fresh binder @ 64C	1.31	1.46	1.24	1.32	1.23	1.31	0.09	1.82	1.50	1.58	1.47	1.54	1.58	0.14
G*/sin(delta) of fresh binder @ 70C	0.64	0.70	0.62	0.67	0.60	0.65	0.04	0.86	0.73	0.81	0.76	0.80	0.79	0.05
G*/sin(delta) of RTFOT residue @ 64C	3.00	2.84	2.79	2.78	2.63	2.81	0.13	3.34	3.73	3.83	3.77	3.58	3.61	0.17
G*/sin(delta) of RTFOT residue @ 70C	1.45	1.36	1.33	1.31	1.20	1.33	0.09	1.65	1.74	1.76	1.92	1.67	1.75	0.11
Complex shear modulus of PAV residue @ 22C, kPa	7690	6803	6875	5062	6007	6487.36	994.76	6401	6639	6916	8583	6225	6952.84	947.55
Complex shear modulus of PAV residue @ 25C, kPa	5404	4952	3540	3551	4635	4416.48	840.80	2822	2955	3011	4487	2570	3169.08	756.13
Phase angle of PAV residue @ 22C, degrees	41.90	44.00	42.10	44.50	44.40	43.38	1.28	45.20	44.80	44.00	44.20	44.20	44.48	0.50
Phase angle of PAV residue @ 25C, degrees	44.50	46.10	45.00	47.90	46.10	45.92	1.31	48.50	47.90	48.00	46.30	47.10	47.56	0.86
G*xsin(delta) of PAV residue @ 22C	5135.50	4725.76	4609.18	3548.00	4202.88	4444.26	601.21	4541.98	4678.21	4804.26	5983.77	4339.85	4869.61	646.19
G*xsin(delta) of PAV residue @ 25C	3787.99	3568.17	2503.16	2634.76	3339.75	3166.77	570.17	2113.55	2192.84	2237.61	3243.95	1882.64	2334.12	526.68
Flexural creep stiffness of PAV residue @ -12C, MPa	191.95	206.70	221.30	194.50	184.50	199.79	14.44	194.00	191.00	208.00	217.90	198.70	201.92	11.01
Flexural creep slope of PAV residue @ -12C	0.36	0.33	0.31	0.34	0.35	0.34	0.02	0.35	0.35	0.33	0.34	0.37	0.35	0.01
Flexural creep stiffness of PAV residue @ -18C, MPa	372.50	397.60	383.60	340.50	405.00	379.84	25.32	368.70	372.40	371.80	410.80	344.00	373.54	23.92
Flexural creep slope of PAV residue @ -18C	0.30	0.27	0.27	0.28	0.28	0.28	0.01	0.28	0.28	0.25	0.27	0.29	0.27	0.01

4.2.3.1 High Temperature Behavior

The high temperature behavior of the NAABs were assessed by studying the visco-elastic parameters of fresh and RTFOT-aged samples at 70°C and 64°C. The following observations can be stated:

1. The G* of the fresh NAABs varies over a narrow range from 1.31 kPa to 1.58 kPa at 64°C and from 0.79 to 0.65 at 70°C. Similarly, the RTFOT-aged samples ranged from 2.8 kPa to 3.58 at 64°C and from 1.33 kPa to 1.74 kPa at 70°C.
2. Although the asphalt binder from BH was graded 40/50 based on the penetration grading system, it shows the least mean G* at 64°C value of 1.31 kPa. This supports the argument that the strain-stress-temperature relationships of the asphalt binder are complex and cannot be simply characterized by the penetration test. This is very clear by comparing the penetration grades of the RT samples, which were identified as 60/70 grade with the BH samples, which were identified as 40/50 grade. This comparison indicates that RT asphalt binder is *softer* than BH asphalt binder. However, comparing their mean G* at 64°C values indicates that RT, which has a mean G* of 1.52 kPa, is *harder* than BH asphalt binder, which has a mean G* of. 1.31 kPa. This observation is also true for the G* at 70°C.
3. The phase angle of the fresh NAABs ranged over a narrow range from 83.3° to 87.84° at 64°C and from 85.42° to 88.74° at 70°C. For RTFOT residue, the phase angle ranged from 79.02° to 85.4 at 64°C and from 82.12° to 87.18 at 70°C.

4. The temperature has a remarkable influence on the G* value; as the temperature increases G* decreases. A 6°C increase in the temperature (i.e from 64°C to 70°C) resulted in about a 50% reduction in the G* for all sources.

5. Contrary to the effect of the temperature on G*, the increase in temperature increases the phase angle. However, it is interesting to note that the effect of the temperature on the phase angle is not as clear as that on G*. A 6°C increase in the temperature (i.e from 64°C to 70°C) resulted in only about a 4% to 1 % increase in the phase angle for fresh and aged samples of all sources.

6. It is very important to note that the aging of the asphalt binder in the laboratory affected G* of the binder more than it did the phase angle. G* at 64°C, for example, increased about two to three fold, while the phase angle decreased to less than 5% due to RTFOT aging as shown below:

Property	**G*, kPa**				**Phase angle, degrees**			
Source	RT	RY	BH	KW	RT	RY	BH	KW
Fresh at 64°C	1.52	1.34	1.23	1.58	83	87	88	86
RTFOT at 64°C	3.4	3.53	2.62	3.58	79	84	85	83

This simply means that laboratory aging has a more pronounced effect on the *strength* as measured by the complex shear modulus than *elasticity* as measured by the phase angle of the asphalt binder (see Figures 2.3 and 2.4), and, hence, laboratory aging did not improve the visco-elastic behavior of the asphalt binder.

Based on this, specifying G* as the lone criterion to control the participation of the asphalt binder towards high temperature distresses such as rutting is not enough. Moreover, such a behavior explains the reasons behind the selection of the parameter G*/sin(δ) as the criterion.

7. G*/sin(δ) followed the same trends of the G* due to the fact that the phase angle was very high and close to 90°, for which the sine is unity.

8. All fresh asphalt binders from all sources exhibited G*/sin δ values at 70°C of less than 1.0 kPa, which means that the asphalt binders did not have enough visco-elastic balance at this temperature to resist high temperature effects such as rutting.

9. All fresh asphalt binders exhibited G*/sin(δ) values at 64°C of more than 1.0 kPa, which means that the asphalt binders did have enough visco-elastic balance at this temperature to resist the high temperature effects such as rutting. Using the NAABs in a region where the maximum seven day pavement temperature is less than or equal to 64°C seems to be adequate. However, a large area of the Gulf countries experience a temperature of more than 64°C (see Figure 4.5), which means that the NAABs need to be modified to satisfy the Gulf countries' performance requirements. This is further validated by G*/sin(δ) of the RTFOT residue, where it was less than 2.2 kPa at 70°C but more at 64°C for all sources.

4.2.3.2 Intermediate Temperature Behavior

The intermediate temperature behavior of the NAABs was assessed by studying the visco-elastic parameters of PAV-aged samples at 22°C and 25°C as shown in Table 4.5.

1. The G* of the PAV-aged samples varied over a wide range from 4362 MPa to 7096 MPa. at 22°C and from 2670 MPa to 4843 MPa at 25°C.
2. The phase angle of the PAV residue ranged from 38.26° to 44.48° at 22°C and from 40.1° to 47.56° at 25°C.
3. At a temperature of 22°C, all NAABs exhibited an adequate amount of the affective portion of the G*, which is the $G^* \times \sin \delta$ specified to control the participation of the asphalt binder on fatigue resistance.

4.2.3.3 Low Temperature Behavior

The low temperature behavior of the NAABs was assessed by analyzing the flexural creep stiffness (S) and the rate of change in the creep (m-value) at −22°C and −28°C as shown in Table 4.5.

1. The S of the PAV-aged samples ranged from 98.46 MPa to 201.92 at −22°C and from 178.04 MPa to 379.84 MPa at −28°C. As the temperature increased, the S value decreased.
2. It is interesting to note that the S value of RT asphalt binder at −22°C and −28°C, which was 98.46 MPa and 178.04 MPa respectively, is considerably lower than that of the other sources at −22°C and at −28°C, which are very close to each

other. The values are 160.52 and 330.86 MPa for RY, 199.79 and 379.84 MPa for BH, and 201.92 MPa and 373.54 MPa for KW. This implies that RT asphalt binder is less susceptible to low temperature cracking than asphalt binders from other sources.

3. The m-value ranged from 0.33 to 0.35 at –22°C and from 0.27 to 0.30 at –28°C. As the temperature increased the m-value increased.

4. All NAABs featured an adequate value of S at –22°C, which must be less than 300 MPa. Only the RT asphalt binder showed an acceptable S value of 178.04 MPa at –28°C, indicating that it can resist low temperature cracking at temperatures as low as –28°C.

4.2.4 Findings

Based on extensive physical, consistency, and rhoeological characterization of asphalt binders produced in the Gulf countries, the following findings can be stated:

1. Four refineries in the Gulf countries produce paving grade asphalt binders. These binders exhibit different physical, consistency, temperature susceptibility, age hardening, and rheological characteristics.

2. Conventional testing, including penetration, viscosity, and ductility, do not appropriately model the complex nature of the asphalt binder in a given stress-strain-temperature domain.

3. It is evident from rheological characterization of the NAABs that they do not exhibit adequate visco-elastic properties to resist high temperature distresses in areas where the pavement temperature exceeds 64°C.
4. Mechanical modification by physically aging the asphalt binder does not improve the visco-elastic properties of the asphalt binder; it increases the complex shear modulus but only marginally improves the elasticity of the asphalt binder.
5. The temperature zoning of the Gulf countries indicates that more than half of the Gulf areas as shown in Figure 4.5 experience a maximum seven day pavement temperature of 76°C. On the other hand, the actual rheological properties of locally produced asphalt binders indicates that NAABs do not have adequate visco-elastic balance at 70°C. This clearly indicates that the NAABs need to be modified to be able to perform adequately in the Gulf countries' environmental conditions. With this finding, the main objective of the NAABs characterization work was achieved.
6. It is important to note that although the low temperature performance requirement of asphalt binders in the Gulf countries (−10°C) was satisfied by the NAABs, the polymer modified binders must be evaluated for their low temperature behavior to ascertain that the modification does not affect their behavior at low temperature as a trade off for the improvement of their behavior at high temperature.
7. Consistency, rheology, and computed temperature indices clearly indicate that the produced asphalt binders within the Gulf countries exhibited some variability

even within the same refinery. This supports the fact that polymer modification is needed.

4.3 CHARACTERIZATION OF POLYMER MODIFIED ASPHALT BINDERS

4.3.1 Introduction

In the research methodology outlined in chapter 3, the polymer modification work was divided into two phases. The first phase handled the identification of potential polymers, and the second phase focused on optimization of the four leading polymers that were identified in the first phase.

As established in section 4.1, asphalt binder performance in a specific site is controlled by the minimum and the average seven day maximum pavement design temperatures. Temperature zoning of the Gulf countries (as shown in Figure 4.5) has resulted in identifying -10°C as the minimum pavement temperature and 76°C as the maximum pavement temperature. On the other hand, the collected asphalt binder samples from the four asphalt producing refineries were determined to have the minimum required $G^*/\sin(\delta)$, which is 1.0 kPa at 64°C. This means that locally produced asphalt binders do not meet the performance requirements of about half of the Gulf countries. Locally produced asphalt binders can be used without modification in the western parts of Riyadh and in the Qassim regions, eastern and southern parts of Makkah, and all the southern regions in Saudi Arabia, while other areas within the Gulf countries require asphalt modification. Polymer modification is needed to qualify locally produced asphalt binders for other areas in the Gulf countries, including the eastern parts of Riyadh, the northern

border regions, and the Eastern Province of Saudi Arabia, all of Kuwait, Bahrain, Qatar, UAE, and Oman. Based on this, it was concluded that polymer modification is required to upgrade the rheological and performance-related properties of the NAABs

In this regard, the producers of polymer materials in the Gulf countries were approached, including the Saudi Basic Industries Company (SABIC) and some local and international manufacturers of polymers.

SABIC was contacted to provide background information to identify polymers that can possibly be added to asphalt binders to achieve the stated objectives. The tentative information received indicated that Polyethylene (PE), Polystyrene (PS), Polypropylene (PP), and Polyvinyl Chloride (PVC) polymers are produced by SABIC, and some grades can be used to modify the asphalt binder. A more detailed technical discussion with SABIC technical staff has identified more specifically the polymers that can be used for the modification of locally produced asphalt binders.

Moreover, some other local polymer producers and dealers were contacted, among them were BITUMAT, AWAZEL, and ASTER. Samples of Styrene-Butadiene-Styrene (SBS) were collected from each.

Other international polymer producers were also contacted. Exxon Chemicals was contacted. Samples of Polybilt® polymers, which are manufactured by Exxon Chemicals specifically to modify asphalt binders, were obtained and used to modify the locally produced asphalt binders.

Table 4.6 shows the candidate polymers that were collected and included in the first phase. Thirteen polymer samples were collected.

Table 4.6: Candidate Polymers Investigated in the Potential Polymer Identification Phase

Manufacturer	Code	Polymer Type	Grade	Source
Saudi Basic Industrial Corporation (SABIC)	LLDPEX	Liner Low Density Polyethylen	1182	SABIC
	LLDPEM	Liner Low Density Polyethylen	M200024	SABIC
	HDPEF	High Density Polyethylene	F00952	SABIC
	HDPEB	High Density Polyethylene	B4660	SABIC
	HDPEM	High Density Polyethylene	M80064	SABIC
	GPPS	General Purpose Polystyrene	PS125	SABIC
	EPS	Expandable Polystyrene	650FF	SABIC
	HIPS	High Impact Polystyrene	330	SABIC
	WC	High Impact Polystyrene	Waste Cups	SABIC
	PPU	Polypropylene	500U	SABIC
Shell Chemicals	SBS	Styrene-Butadiene-Styrene	-	Local Market
Dammam Industrial City	CR	Crumb Rubber	-	Manufacturer
Exxon Chemicals	PB	PolyBelt	101	Local Market

The overall objective of the polymer modification work was to identify an appropriate polymer(s) to modify Arab asphalts to satisfy the performance requirements in the Gulf countries. The specific objectives are as follows:

1. To determine the visco-elastic behavior of polymer modified asphalt binders.
2. To develop a procedure to modify Arab asphalt binders.

In this chapter, a detailed description of the asphalt modification work, modification methodology, statistical analysis, and results are presented.

4.3.2 Identification of Potential Polymers

The first phase of the modification work focused on the identification of potential polymers. Once the polymer samples were received at the laboratory, blending with asphalt from the Riyadh refinery, since it is the main supplier of asphalt binder in the Gulf countries, was performed. A special blender was assembled composed of a high shear blade, a heating oil bath, and a DC-motor capable of producing up to 3,000 rpm as shown in Plate 4.1. The cited literature coupled with manufacturer's recommendations were employed to identify the tentative polymer concentrations, blending times, and temperatures for each of the collected polymers. These parameters were controlled during the blending process as shown in Table 4.7. Each polymer type was blended with 500 gm of asphalt binder to produce the polymer modified asphalt binder (PMAB). The quantity and concentration of each polymer are shown in Table 4.7.

Visual inspection using an optical microscope and softening point testing was used to evaluate the homogeneity of the blend at 20 minute intervals from the beginning of the blending operation. Once homogeneity of the PMAB was achieved, blending was continued for an additional 15 minutes to insure blend homogeneity. While the blend

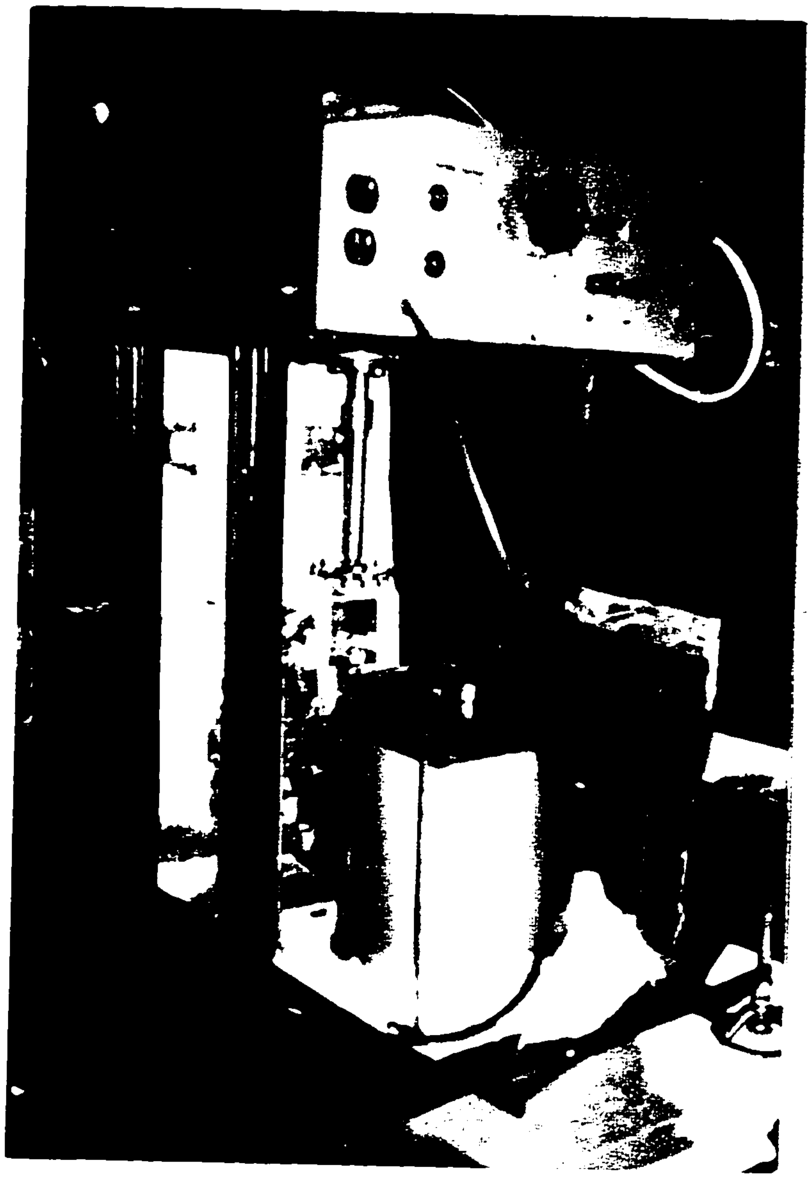


Plate 4.1: High Shear Blender.

Table 4.7: Polymer Concentrations, Blending Times and Temperatures

Polymer Type	Concentration								Blending Time minutes	Blending Temperature °C
	Recommended by others		Low		Medium		High			
	%	Weight gms	%	Weight gms	%	Weight gms	%	Weight gms		
Low Density Polyethylene (all grades)	6	31.92	-	-	-	-	-	-	60-120	150-160
High Density Polyethylene (all grades)	6	31.92	-	-	-	-	-	-	60-120	150-160
Polypropylene	-	-	3	15.46	6	31.92	9	49.45	60-120	150-160
General Purpose Polystyrene	-	-	3	15.46	6	31.92	9	49.45	60-120	150-160
Expandable Polystyrene	-	-	3	15.46	6	31.92	9	49.45	60-120	150-160
High Impact Polystyrene	-	-	3	15.46	6	31.92	9	49.45	60-120	150-160
High Impact Polystyrene - Waste Cups	-	-	3	15.46	6	31.92	9	49.45	60-120	160-170
Styrene - Butadiene - Styrene	6	31.92	-	-	-	-	-	-	30-60	170-190
Crumb Rubber (tires)	10	125	-	-	-	-	-	-	60-120	160-170
Polybelt	5	26.32	-	-	-	-	-	-	60-90	150-160

was still hot, testing was performed. Softening point, complex shear modulus, and phase angle at 70°C and 10 radian/sec frequency for five samples from each blend were determined.

To identify the storage stability of the PMAB, three test tubes were filled with the blend, properly marked, and stored for two weeks in the following storing conditions:

1. the first tube was stored at room temperature,
2. the second tube was quickly cooled in a refrigerator and then stored at room temperature, and
3. the third tube was stored in an oven maintained at 130°C.

At the end of the two week storing period, the top and bottom portions of the samples obtained from the test tube for each storing condition were tested individually using the dynamic shear rheometer to measure the complex shear modulus at 70°C and a frequency of 10 rad/sec.

To ascertain the similarity of the binders and secure the validity of the statistical analysis, the neat asphalt binder (i.e. control) was subjected to the same blending process for the same time but without polymer modification. This was done since asphalt binder rheological and physical properties may change due to aging that may take place during blending where temperature, time, and air are present. With this, the statistical differences, if any, between the neat binder and any other polymer modified binders can only be attributed to the polymer modification.

The collected data for each blend, including the control (neat asphalt), were statistically compared. Those polymers that showed significant increases in softening

point and complex shear modulus of the asphalt binder, had acceptable storage stability, and were economically feasible were utilized in the second phase. The four leading polymers were selected.

It is important to mention that blending of the asphalt binder with all polystyrene polymers (PS), including expandable (EPS), high impact (HIPS), and high impact waste cups, could not be achieved. These polymers cannot be blended with the asphalt binder and cannot be dispersed within it. Different methods were tried without success. The Saudi Basic Industrial Corporation (SABIC) was consulted for this matter, their advice did not result in any solution. Therefore, these polymers were exempted from the testing program.

4.3.2.1 Analysis and Discussion of Potential Polymer Identification Results

This phase provided valuable information from which important blending parameters, unique to each polymer, were identified. These parameters included blending time, blending temperature mixer speed, and others. The control for the identification of these parameters was the homogeneity of the asphalt polymer blend. The homogeneity was monitored during the blending operation by measuring the softening point and visually inspecting a sample from the blend using an optical microscope at intervals of 20 minutes. The softening point versus time of blending for each asphalt-polymer blend is shown in Table 4.8 and graphically presented in Figure 4.9.

It is rationalized that the softening point of the asphalt binder will exhibit an increase as the asphalt binder molecular association due to polymer addition increases. Once a uniform dispersion of the polymer within the body of the asphalt is achieved, the

Table 4.8: Softening Point Measured during Blending Operation of Various PMA

Elapsed Time from Beginning of Blending (minutes)	Softening Point for Asphalt-Polymer Blend, °C								
	LLDPEM @ 6%			LLDPE @ 6%			HDPEM @ 6%		
	1	2	Avg.	1	2	Avg.	1	2	Avg.
20	56	58	57	58	63	60.5	58	58	58
40	58	61	59.5	80	85	82.5	60	60	60
60	59	60	59.5	86	94	90	61	63	62
80	60	61	60.5	90	96	93	62	64	63
100	61	62	61.5	96	98	97	65	66	65.5
120	61	61	61	105	107	106	-	-	-

	HDPEB @ 6%			HDPEF @ 6%			PPU @ 3%		
	1	2	Avg.	1	2	Avg.	1	2	Avg.
20	61	62	61.5	50	50	50	50	51	50.5
40	78	78	78	53	53	53	53	54	53.5
60	87	94	90.5	55	57	56	57	58	57.5
80	98	109	103.5	60	63	61.5	58	59	58.5
100	109	118	113.5	62	67	64.5	59	59	59
120	118	120	119	83	85	84	60	62	61
140	-	-	-	-	-	-	61	62	61.5
160	-	-	-	-	-	-	61	62	61.5

	PB101 @ 5%			SBS @ 6%			CRT @ 10%		
	1	2	Avg.	1	2	Avg.	1	2	Avg.
20	59	60	59.5	87	89	88	55	56	55.5
40	59	60	59.5	95	94	94.5	56	57	56.5
60	61	61	61	97	99	98	57	58	57.5
80	61	61	61	97	98	97.5	57	58	57.5
100	-	-	-	98	99	98.5	58	58	58
120	-	-	-	-	-	-	58	58	58

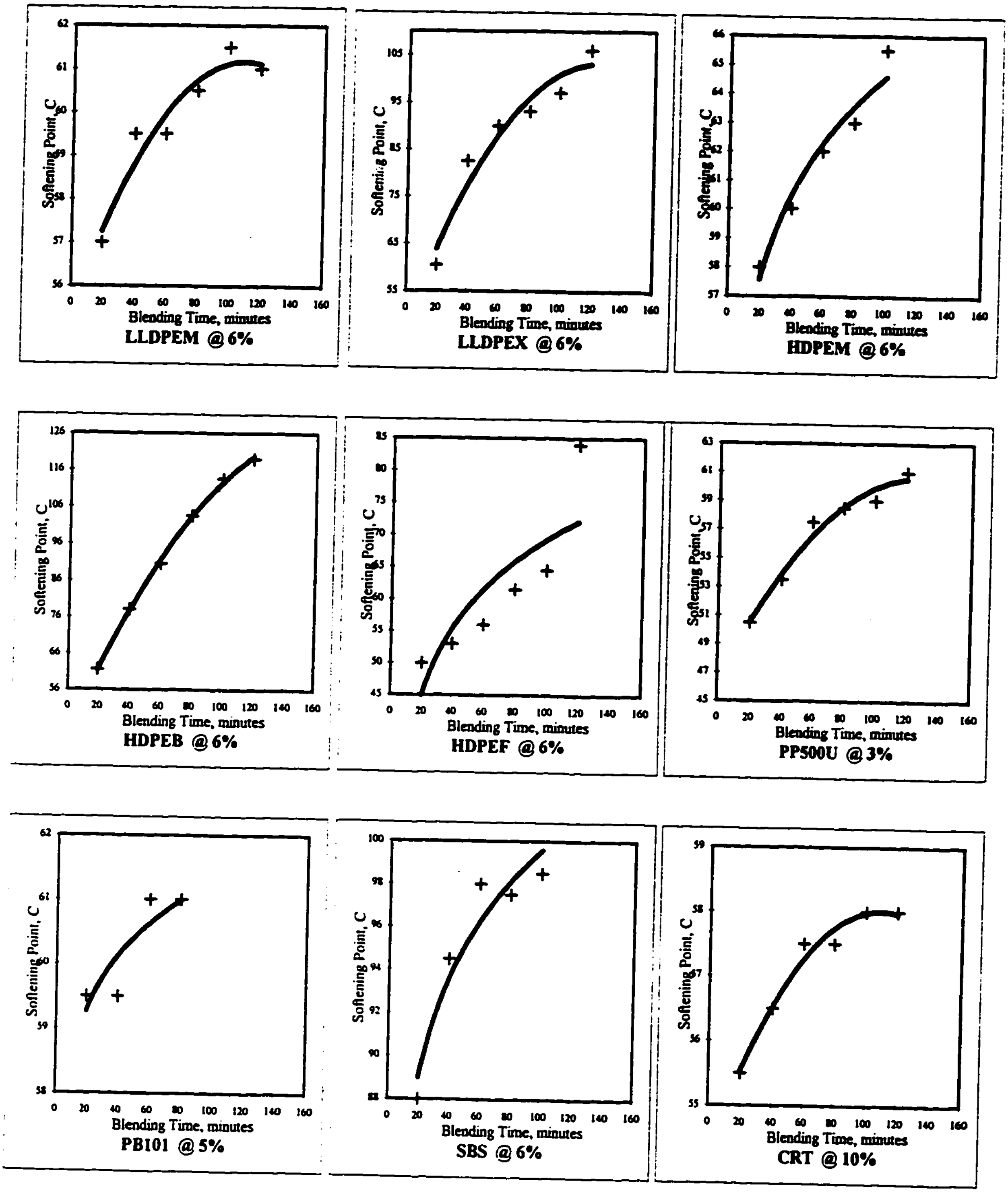


Figure 4.9: Homogeneity of PMABs Measured by the Softening Point

softening point will stabilize and become steady. An example of this behavior is shown in Figure 4.9 for PMABs containing linear low density polyethylene grade M at 6% (LLDPEM at 6%). Examining this figure, it can be seen that after about 100 minutes of blending time, the softening point starts to stabilize at about 61°C; this means that the minimum blending time necessary to produce a homogeneous blend for the polymer LLDPEM at a concentration of 6% was 100 minutes. This concept was used to identify the minimum blending times for all of the asphalt polymer blends.

In order to identify the potential polymers from among the candidate polymers, the PMABs were thoroughly examined and evaluated for the following aspects:

1. Improvement in the asphalt's rheological and performance properties,
2. Storage stability of the asphalt-polymer blends, and
3. Cost effectiveness of the polymer modification.

4.3.2.1.1 Improvement in the asphalt rheological and performance properties

The basic assumption of the role of the polymer in improving the rheological properties of the asphalt was verified by performing comparisons between the neat and the polymer modified asphalts with respect to their softening point, G*, and G*/sin δ at 70°C and 10 rad/sec. The statistical comparisons were made to test the following hypothesis:

$$H_o: \quad \mu_m = \mu_n$$

$$H_1: \quad \mu_m \neq \mu_n$$

where

μ_m = mean of the response variable of the modified asphalt

μ_n = mean of the response variable of the neat asphalt

Since the choice of the test statistic to test the above hypothesis depends on the equality of the variances of the two populations from which the samples were drawn, it is important to test the equality of the variances of the two populations in advance. To accomplish this, the two samples' variances was used to test the two-sided alternative:

$$H_o : \quad \sigma_m = \sigma_n$$

$$H_1 : \quad \sigma_m \neq \sigma_n$$

using the fact that the statistic

$$F_o = \frac{S_m^2}{S_n^2} \tag{4.2}$$

is distributed as F, with n_m-1 and n_n-1 degrees of freedom, the null hypothesis H_o will be rejected if

$$F_o > F_{\alpha/2,\, n_m-1,\, n_n-1}$$

and conclude that the two population variances are unequal and use the approximate t^* test as follows:

$$t* = \frac{\mu_m - \mu_n}{\left[\dfrac{S_m^2}{n_m} + \dfrac{S_n^2}{n_n}\right]^{1/2}} \tag{4.3}$$

which is distributed approximately as t with degrees of freedom given by

$$\nu = \frac{\dfrac{S_m^2}{n_m} + \dfrac{S_n^2}{n_n}}{\dfrac{(S_m^2 / n_m)^2}{n_m + 1} + \dfrac{(S_n^2 / n_n)^2}{n_n + 1}} - 2 \tag{4.4}$$

where

ν = degrees of freedom;

S_m^2 = the variance of the polymer modified binder for the subject property;

S_n^2 = the variance of the neat binder for the subject property;

n_m = the number of samples of the polymer modified binder; and

n_n = the sample number of the neat binder for the subject property

However, the null hypothesis will be accepted if

$$F_o < F(\alpha/2, n_m - 1, n_n - 1)$$

and conclude that the two population variances are equal and use the exact t-test with degrees of freedom $n_m + n_n - 2$ (Montgomery, 1984).

The test results are summarized in Table 4.9. From this table, it is evident that all polymers significantly improve the rheological and performance-related properties of the asphalt binder. This is further supported by the statistical analysis as shown in Tables 4.10 and 4.11.

4.3.2.1.2 Storage stability of the asphalt-polymer blend

Polymer modified asphalt binders are generally multi-phase systems in which the polymer is dispersed into the body of the asphalt binder. Such systems require a certain amount of incompatibility between their ingredients to ascertain that the polymer is not dissolved in the asphalt binder but rather is dispersed into it. However, excessive incompatibility is not beneficial and is not desirable for proper storage and handling.

Table 4.9: Summary of Potential Polymer Identification Test Results

Sample #	Polymer Type and Concentration										
	Neat Asphalt	LLDPEM 6%	LLDPEX 6%	HDPEM 6%	HDPEB 6%	HDPEF 6%	PP500U 3%	PP500U 6%	SBS 6%	CRT 10%	PB101 5%
1. Complex Shear Modulus (G*) @ 70 °C, Pa											
1	703.0	3,323.5	9,926.0	2,475.3	5,338.7	5,483.0	2,589.4	14,039.0	5,903.1	2,720.5	1,917.0
2	751.0	4,063.7	8,162.2	2,734.6	5,667.8	5,772.1	1,948.0	13,364.0	6,386.4	2,743.1	1,510.5
3	753.0	3,450.9	8,978.5	2,730.4	5,208.9	10,171.0	2,632.2	15,448.0	6,962.8	2,678.4	1,210.8
4	737.0	3,217.4	10,002.1	3,493.5	5,519.5	5,564.7	2,659.8	15,129.0	8,125.5	2,437.4	1,515.7
5	741.0	3,261.9	11,259.0	2,995.6	9,629.5	7,216.3	2,953.9	15,070.0	4,762.5	2,896.3	1,070.3
2. Phase Angle (Delta) @ 70 °C, Degrees											
1	88.1	84.3	60.2	84.3	76.2	74.0	80.4	69.4	66.8	74.7	83.4
2	87.9	84.0	66.1	85.1	82.8	75.6	83.7	69.2	57.9	73.1	83.7
3	88.6	84.6	64.6	85.1	83.8	54.3	80.7	67.9	51.5	73.2	84.6
4	88.2	84.6	64.8	84.4	80.6	74.1	80.3	69.6	44.3	72.1	82.8
5	88.3	84.5	64.9	84.6	75.2	72.7	80.8	68.9	64.9	74.7	84.9
3. G*/sin delta @ 70 °C											
1	702.6	3,307.1	8,613.4	2,463.1	5,184.6	5,270.6	2,553.1	13,141.3	5,425.7	2,624.1	1,904.3
2	750.5	4,041.4	7,462.3	2,724.6	5,623.1	5,590.8	1,936.2	12,493.0	5,410.1	2,624.6	1,501.4
3	752.8	3,435.6	8,110.6	2,720.4	5,178.4	8,259.7	2,597.6	14,313.0	5,449.1	2,564.1	1,205.4
4	736.6	3,203.1	9,050.2	3,476.8	5,445.4	5,351.8	2,621.8	14,180.1	5,675.0	2,319.4	1,503.7
5	740.7	3,246.9	10,195.8	2,982.3	9,310.0	6,889.8	2,915.9	14,059.6	4,312.8	2,793.6	1,066.1
4. Softening Point, C											
1	48.0	59.0	103.0	62.0	115.0	80.0	63.0	>130	89.0	58.0	60.0
2	49.0	61.0	104.0	63.0	117.0	94.0	63.0	>130	90.0	59.0	61.0
3	48.0	61.0	107.0	62.0	120.0	78.0	60.0	>130	87.0	58.0	60.0
4	50.0	62.0	109.0	62.0	120.0	89.0	60.0	>130	92.0	58.0	60.0
5	50.0	61.0	105.0	62.0	121.0	81.0	63.0	>130	88.0	58.0	60.0

Table 4.10: Statistical analysis of Phase II results - test of variance equality

Sample #	Neat asphalt	LLDPEM 6%	LLDPEX 6%	HDPEM 6%	HDPEB 6%	HDPEF 6%	PP500U 3%	PP500U 6%	SBS 6%	CRT 10%	PB101 5%
	Polymer Type and Concentration										
1. Complex Shear Modulus (G*) @ 70C, kPa											
Average	737.0	3,463.5	9,665.6	2,885.9	6,272.9	6,841.4	2,556.7	14,610.0	6,428.1	2,695.1	1,444.9
Standard Dev.	20.1	346.8	1,167.5	386.3	1,884.5	1,990.3	369.4	874.9	1,246.9	165.9	326.8
Variance	406	120,302	1,363,070	149,219	3,551,337	3,961,351	136,421	765,441	1,554,665	27,530	106,831
F_o	-	296.31	3,357.32	367.53	8,747.13	9,757.02	336.01	1,885.32	3,829.22	67.81	263.13
$F_{(0.025,4,4)}$	-	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60
Variance of the modified is greater than unmodified	-	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Use to test the equality of means	-	t*	t*	t*	t*	t*	t*	t*	t*	t*	t*
2. Phase Angle (Delta) @ 70C , Degrees											
Average	88.2	84.4	64.1	84.7	80.9	70.1	81.2	68.8	57.1	73.6	83.9
Standard Dev.	0.3	0.3	2.3	0.4	3.4	8.9	1.4	0.7	9.4	1.1	0.9
Variance	0.067	0.065	5.147	0.145	11.397	79.463	2.027	0.445	87.692	1.268	0.747
F_o	-	0.970	76.821	2.164	170.100	1,186.015	30.254	6.642	1,308.836	18.925	11.149
$F_{(0.025,4,4)}$	-	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60
Variance of the modified is greater than unmodified	-	NO	YES	NO	YES	YES	YES	NO	YES	YES	YES
Use to test the equality of means	-	t	t*	t	t*	t*	t*	t	t*	t*	t*

t is the exact t-test

t* is the approximated t-test

Table 4.10: Cont'd...

3. G*/sin delta @ 70C

Average	736.6	3,446.8	8,686.5	2,873.4	6,148.3	6,272.5	2,524.9	13,637.4	5,254.5	2,585.2	1,436.2
Standard Dev.	20.2	343.7	1,030.3	384.0	1,777.3	1,289.0	358.8	788.2	537.4	171.5	323.3
Variance	407	118,148	1,061,463	147,476	3,158,949	1,661,586	128,719	621,246	288,765	29,401	104,546
F_o	-	291	2,611	363	7,769	4,087	317	1,528	710	72	257
$F_{(0.025,4,4)}$	-	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60
Variance of the modified is greater than unmodified	-	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
Use to test the equality of means	-	t*	t*	t*	t*	t*	t*	t*	t*	t*	t*

4. Softening Point, C

Average	49.0	60.8	105.6	62.2	118.6	84.4	61.8	>130	89.2	58.2	60.2
Standard Dev.	1.0	1.1	2.4	0.4	2.5	6.8	1.6	#DIV/0!	1.9	0.4	0.4
Variance	1.000	1.200	5.800	0.200	6.300	46.300	2.700	#DIV/0!	3.700	0.200	0.200
F_o	-	1.200	5.800	0.200	6.300	46.300	2.700	#DIV/0!	3.700	0.200	0.200
$F_{(0.025,4,4)}$	-	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60	9.60
Variance of the modified is greater than unmodified	-	NO	NO	NO	NO	YES	NO	-	NO	NO	NO
Use to test the equality of means	-	t	t	t	t	t*	t	-	t	t	t

t is the exact t-test

t* is the approximated t-test

Table 4.11: Statistical analysis of Phase II Results - Test of Means Equality

Sample #	Neat asphalt	LLDPEM 6%	LLDPEX 6%	HDPEM 6%	HDPEB 6%	HDPEF 6%	PP500U 3%	PP500U 6%	SBS 6%	CRT 10%	PB101 5%
	Polymer Type and Concentration										
1. Complex Shear Modulus (G*) @ 70 C, kPa											
Average	737.0	3,463.5	9,665.6	2,885.9	6,272.9	6,841.4	2,556.7	14,610.0	6,428.1	2,695.1	1,444.9
Standard Dev.	20.1	346.8	1,167.5	386.3	1,884.5	1,990.3	369.4	874.9	1,246.9	165.9	326.8
to or to*	-	-17.55	-17.10	-12.42	-6.57	-6.86	-11.00	-35.45	-10.20	-26.20	-4.83
Degrees of freedom (v)	-	4.04	4.00	4.03	4.00	4.00	4.04	4.01	4.00	4.18	4.05
$t_{(0.025,v)}$	-	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78
Difference is Significant if (to<-$t_{(0.025,v)}$)	-	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
2. Phase Angle (Delta) @ 70 C, Degrees											
Average	88.2	84.4	64.1	84.7	80.9	70.1	81.2	68.8	57.1	73.6	83.9
Standard Dev.	0.3	0.3	2.3	0.4	3.4	8.9	1.4	0.7	9.4	1.1	0.9
to or to*	-	20.03	23.53	16.14	4.85	4.53	10.79	59.21	7.43	28.09	10.56
Degrees of freedom (v)	-	10.00	4.15	4.00	4.34	6.26	4.06	4.01	6.48	4.04	4.02
$t_{(0.025,v)}$	-	2.23	2.78	2.78	2.78	2.45	2.78	2.78	2.45	2.78	2.78
Difference is Significant if (to<-$t_{(0.025,v)}$)	-	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Table4.11: Cont'd...

Sample #	Neat asphalt	LLDPEM 6%	LLDPEX 6%	HDPEM 6%	HDPEB 6%	HDPEF 6%	PP500U 3%	PP500U 6%	SBS 6%	CRT 10%	PB101 5%
3. G*/sin delta @ 70C											
Average	736.6	3,446.8	8,686.5	2,873.4	6,148.3	6,272.5	2,524.9	13,637.4	5,254.5	2,585.2	1,436.2
Standard Dev.	20.2	343.7	1,030.3	384.0	1,777.3	1,289.0	358.8	788.2	537.4	171.5	323.3
to or to*	-	-17.60	-17.25	-12.42	-6.81	-9.60	-11.13	-36.59	-18.79	-23.94	-4.83
Degrees of freedom (v)	-	4.04	4.00	4.03	4.00	4.00	4.04	4.01	4.02	4.17	4.05
$t_{(0.025,v)}$	-	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78	2.78
Difference is Significant if (to<-$t_{(0.025,v)}$)	-	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
4. Softening Point, C											
Average	49.0	60.8	105.6	62.2	118.6	84.4	61.8	>130	89.2	58.2	60.2
Standard Dev.	1.0	1.1	2.4	0.4	2.5	6.8	1.6	-	1.9	0.4	0.4
to or to*	-	-17.79	-48.53	-26.94	-57.60	-11.51	-14.88	-	-41.46	-18.78	-22.86
Degrees of freedom (v)	-	9.90	6.01	6.31	5.86	4.26	7.91	-	7.02	6.31	6.31
$t_{(0.025,v)}$	-	2.23	2.45	2.45	2.45	2.78	2.31	-	2.37	2.78	2.78
Difference is Significant if (to<-$t_{(0.025,v)}$)	-	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

Therefore, the storage stability of the PMABs for various polymers was evaluated for the following storing conditions for a period of two weeks:

1. Room temperature
2. Hot storage at 130°C
3. Quick cooling then storing at room temperature

Although storage stability can be evaluated using the recommended SHRP method, which involves storing the PMABs for 48 h at 165°C, it was decided at this stage to subject the PMABs to various storage conditions to investigate the effect of changing the storage conditions on the storage stability and to explore the possibility of determining adequate storing conditions.

A sample of the blend was poured into a test tube, appropriately marked, and stored in a suitable location to provide the required storing conditions. The test tube was maintained in a vertical position during the two week storing period.

At the end of two weeks, the storage stability of the PMABs was evaluated by measuring and comparing the complex shear modulus, G*, of a sample from the top and a sample from the bottom portions of the test tube. Table 4.12 summarizes the test results from which the following observations are made:

1. For the same polymer blend, the blend storage stability is different for different storing conditions.
2. Quick cooling of the test tube followed by storing at room temperature has the least affect on storage stability as the complex shear modulus of the top and bottom portions are comparable. This is evident since eight blends out of eleven

Table 4.12: Storage Stability of Various PMABs at Various Storage Conditions

PMAB	Storage Condition (for two weeks)					
	Hot at 130 °C		Room temperature		Quick cooling then room temperature	
	G* @ 70 °C & 10 rad/sec, Pa		G* @ 70 °C & 10 rad/sec, Pa		G* @ 70 °C & 10 rad/sec, Pa	
	Top	Bottom	Top	Bottom	Top	Bottom
LLDPEM @ 6%	169,850	12,207	5,844	5,658	6,677	5,058
LLDPEX @ 6%	HARD	SOFTER	42,452	7,882	12,817	6,421
HDPEM @ 6%	HARD	8,230	3,330	5,543	3,602	4,117
HDPEB @ 6%	589,250	5,282	74,402	6,469	6,325	7,433
HDPEF @ 6%	HARD	SOFTER	138,720	14,366	11,174	10,325
PP500U @ 3%	HARD	SOFTER	27,141	1,930	7,768	1,856
PP500U @ 6%	635,660	17,444	4,441	8,019	5,630	4,419
SBS @ 6%	HARD	SOFTER	5,737	4,683	6,201	6,051
CRT @ 10%	3,627	2,425	2,834	3,201	2,783	2,997
PB101 @ 5%	554	2,668	1,499	1,490	1,486	1,498

were stable at this storing condition. The stable blends at this storing condition were LLDPEM, HDPEM, HDPEB, HDPEF, PP500U at 6%, SBS, CRT, and PB.

3. Room storage has a moderate effect on the storage stability of the blends. This is evident since five blends out of eleven were found to be stable at this condition. The stable blends at this storing condition were LLDPEM, HDPEM, SBS, CRT, and PB.

4. Hot storage has the most adverse effect on blend storage stability. This is evident since only one polymer blend out of eleven showed stability at this condition. The stable blend at this storing condition is the CRT.

5. Some blends that were stored under a hot storing condition were too hard to allow measuring the complex shear modulus. These blends were LLDPEX, HDPEF, PP500U, and SBS. On the other hand, the top portion of HDPEM 6% was very hard while the bottom portion was soft enough to allow measurement of the G*. This behavior clearly indicates excessive separation between the polymer and the asphalt binder at this storing condition.

6. In general, all asphalt polymer blends after storage exhibit an increase in the G* (top or bottom) in comparison to the freshly tested blends (unstored), which could be attributed partially to an increase in the molecular association between the polymer and the asphalt binder and partially to the aging of the asphalt binder due to prolonged storing. An exception to this behavior, some PMABs showed a G* value which is less than that of the fresh such as LLDPEX, HDPEB, PP500U, SBS, and PB. This could be attributed to the degradation of the polymer due to prolonged storing.

4.3.2.1.3 Cost effectiveness of polymer modification

The cost effectiveness of polymer modification for each asphalt-polymer blend was evaluated by comparing the equivalent annual cost ($/km) of constructing asphalt concrete pavements built using various asphalt polymer blends. Life cycle cost analysis of these pavements was estimated using the Asphalt Institute Pavement Life Cycle Cost Analysis computer program.

The additional life of the pavement structure due to the polymer modification process was estimated as follows:

a) The measured shear modulus , G*, for each PMAB at 70°C and 10 rad/sec was used to estimate the stiffness modulus, S_b of the PMAB at 45°C using Van Der Pool's nomograph (Roberts 1991). S_b of each PMAB at 45°C was used to estimate the asphalt mix stiffness modulus (S_m) using the following formula (Yoder and Wiczak, 1975):

$$S_m = S_b\left[1+\left(\frac{2.5}{n}\right)\left(\frac{C_v}{1-C_v}\right)\right]^n \qquad (4.5)$$

where

S_m = mix stiffness (kg/cm^2) at 45°C

S_b = asphalt-polymer blend stiffness measured at 45°C (kg/cm^2)

$n = 0.83 \log [(4 \times 10^5 / S_b]$

$$C_v = \frac{\text{Volume of aggregate}}{V_{aggregate} + V_{asphalt}}$$

The estimated mix stiffness at a temperature of 45°C is shown in Table 4.13.

Teble 4.13: Estimation of the Hot Mixture Asphalt Concrete Stiffness (S_m) from the Measured Asphalt Stiffness at 45 °C

Asphalt-Polymer blend	%	S_b at 45C, kg/cm^2	n = 0.83 log (400,000/S_b)	$S_m = S_b (1 + [(2.5/n) \times (C_v / 1-C_v)]^n$ kg/cm^2	S_m, psi
Neat Asphalt	0	917	2.191	39,401	560,396
Linear Low Density Polyethylene - Grade M	6	2038	1.903	66,748	949,335
Linear Low Density Polyethylene - Grade X	6	5096	1.573	117,607	1,672,691
High Density Polyethylene - Grade M	6	1529	2.007	55,396	787,877
High Density Polyethylene - Grade B	6	3058	1.757	86,256	1,226,803
High Density Polyethylene - Grade F	6	4077	1.653	102,901	1,463,527
Polyporylene - Grade 500U	3	1732	1.962	60,090	854,646
Polyporylene - Grade 500U	6	7136	1.451	143,032	2,034,311
Styrene-Butidiene-Stymene	6	3568	1.701	94,872	1,349,333
Crumb Rubber	10	1427	2.032	52,939	752,943
Polybelt- Grade 101	5	1020	2.153	42,336	602,135

b) The estimated S_m values were used in the ELSYM5 program along with other required input data to determine the compressive and tensile strains at critical locations within the pavement as shown in Figure 4.10. The determined compressive and tensile strains are shown in Table 4.14.

c) The determined strains were then used to predict the fatigue and rutting life (N_r and N_f) for the assumed pavements. The following Shell equations for estimating the allowable number of load repetitions, (N_f), to limit rutting and fatigue, were used (Huang, 1993):

For rutting (rut depth = 0.5 in.):

$$N_r = 1.05 \times 10^{-7} (\varepsilon_r)^{-4.0} \tag{4.6}$$

where

N_r = number of load repetitions to failure

ε_r = compressive strain at the top of the sub-grade

For fatigue (20% area cracked):

$$N_f = 0.0685 (\varepsilon_f)^{-5.671} (S_m)^{-2.363} \tag{4.7}$$

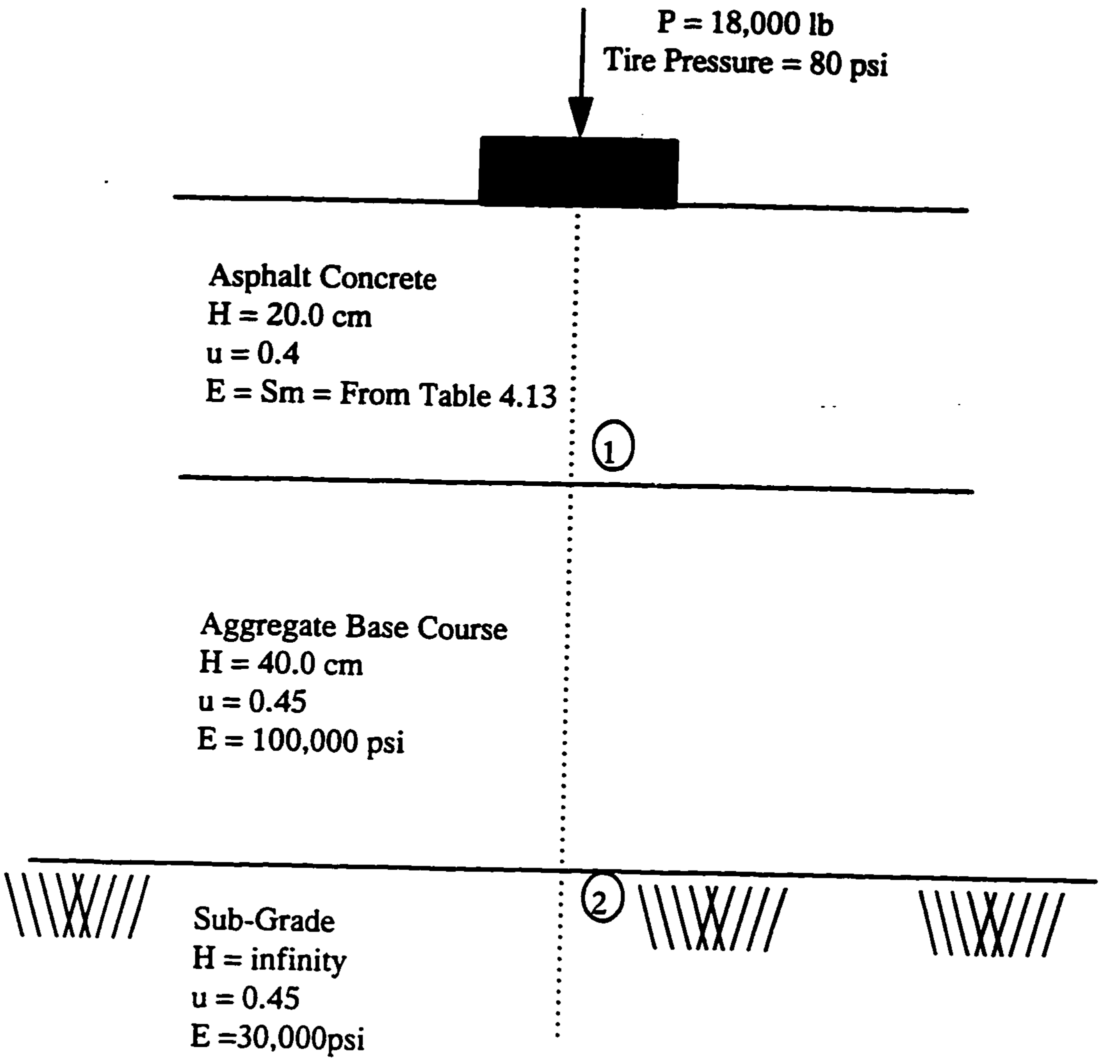
where

N_f = number of load repetitions to failure

ε_f = tensile strain at the bottom of the asphalt bound layers

S_m = mix stiffness (psi)

The predicted number of load repetitions for fatigue and rutting were then converted to years using Figure 4.11. Results are shown in Table 4.15.



1. Critical Location for fatigue

2. Critical location for rutting

Figure 4.10: Typical Pavement Cross-Section Showing Critical Locations for Rutting and Fatigue

Table 4.14: Estimated Compressive and Tensile Strains at Critical Locations within the Pavement Structure for Various PMABs under Standard 18 kip Axle

Asphalt-Polymer blend	Fatigue $\varepsilon_t \times 10^{-3}$ (Bottom of AC layer)	Rutting $\varepsilon_t \times 10^{-3}$ (Top of Subgrade)
Neat Asphalt	0.10990	0.17330
Linear Low Density Polyethylene - Grade M	0.08713	0.14910
Linear Low Density Polyethylene - Grade X	0.06450	0.12280
High Density Polyethylene - Grade M	0.09512	0.15780
High Density Polyethylene - Grade B	0.07650	0.13720
High Density Polyethylene - Grade F	0.06954	0.12890
Polypropylene - Grade 500U @ 3%	0.09161	0.15400
Polypropylene - Grade 500U @ 6%	0.05752	0.11380
Styrene - Butadiene - Styrene	0.07270	0.13270
Crumb Rubber	0.09709	0.15990
Polybelt- Grade 101	0.10680	0.17010

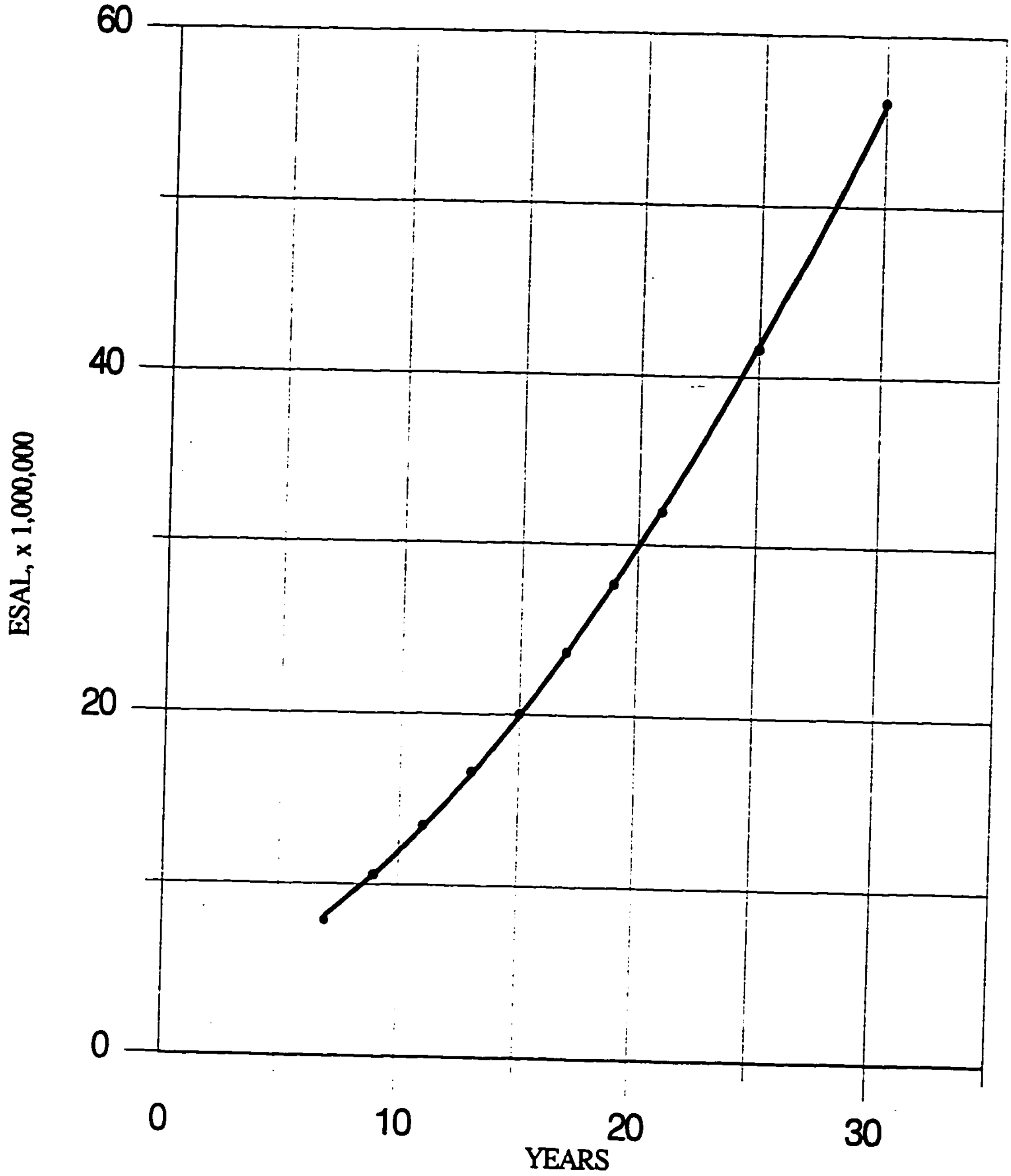


Figure 4.11: Projection of ESAL with Years (Initial ESAL = 1,000,000 Growth Rate = 4%) Based on AASHTO DNPS86 Program

Table 4.15: Estimated Rutting and Fatigue Life of Various PMABs.

Asphalt-Polymer blend	Fatigue		Rutting	
	$N_f \times 10^{-6}$	Years	$N_f \times 10^{-6}$	Years
Neat Asphalt	50.52	27	7.88	7
Linear Low Density Polyethylene - Grade M	54.24	29	14.38	12
Linear Low Density Polyethylene - Grade X	78.30	>30	31.25	21
High Density Polyethylene - Grade M	51.24	28	11.46	10
High Density Polyethylene - Grade B	61.89	>30	20.06	15
High Density Polyethylene - Grade F	70.07	>30	25.74	18
Polypropylene - Grade 500U @ 3%	52.32	28	12.64	11
Polypropylene - Grade 500U @ 6%	94.39	>30	42.37	27
Styrene - Butadiene - Styrene	65.98	>30	22.92	17
Crumb Rubber	50.77	27	10.87	9
Polybelt- Grade 101	50.14	27	8.49	8

The cost of producing and constructing one cubic meter of the mix is based on the current unit rates of hot mix asphalt concrete in the region. Saudi Aramco's current road maintenance contracts specify the neat asphalt hot mix cost to be about 180 SR/m^3, which includes all production, paving, compacting, controlling, and other overhead costs. Based on this, the additional cost due to polymer modification is computed from the current polymer cost per ton as identified from the local market and the additional preparation cost. It is further assumed that construction of asphalt concrete pavements containing polymer modified asphalt binders will not require unusual procedures in any part of the construction process.

The LCCOST-CP5 computer program was then used to compute the equivalent uniform annual cost (EUAC) of each asphalt polymer blend as shown in Table 4.16.

4.3.2.2 Polymer selection for detailed analysis and optimization

The main objective of the first phase was to identify the potential polymers that are technically and economically qualified to be carried out to the second phase for thorough evaluation and optimization. Based on the technical and economical analysis performed in the first phase and summarized in Table 4.16, the potential polymers were the following:

1. Polypropylene Grade 500U (PP500U)
2. Linear low density polyethylene Grade 1182 (LLDPEX)
3. High density polyethylene Grade F (HDPEF)

As can be noticed, two polyethylene polymers differing in density and grade came to be in the leading polymers list. However, to cover a wider range of polymers and to

Table 4.16: Equivalent Uniform Annual Cost (EUAC) of Flexible Pavements Built with Various PMABs.

Asphalt-Polymer blend	EUAC, $/km	Rank
Polypropylene - Grade 500U @ 6%	2464	1
Linear Low Density Polyethylene - Grade X	2868	2
High Density Polyethylene - Grade F	3178	3
High Density Polyethylene - Grade B	3619	4
Styrene - Butadiene - Styrene	4089	5
Polypropylene - Grade 500U @ 3%	4175	6
Linear Low Density Polyethylene - Grade M	4287	7
High Density Polyethylene - Grade M	4961	8
Neat Asphalt	5850	9
Crumb Rubber	6395	10
Polybelt- Grade 101	6519	11

secure diversity in the polymers to be optimized in the second phase, high density polyethylene was replaced by a Styrene-Butadiene-Styrene polymer since it came next in the ranking shown in Table 4.17 and because of the international acceptance of this polymer as a leader among many asphalt modifiers.

Although the original plan was to carry only three polymers to the second phase, it was decided to include a fourth. The fourth polymer was crumb rubber, which is waste from the tire shredding industry. The reason behind the addition of this polymer was the fact that a large number of waste tires are available. Using this polymer as an asphalt binder modifier could provide significant economical and environmental benefit.

In conclusion, the following polymers were carried to the second phase:

1. Polypropylene Grade 500U (PP500U)
2. Linear low density polyethylene Grade 1182 (LLDPEX)
3. Styrene-Butadiene-Styrene (SBS)
4. Crumb rubber tires (CRT)

4.4 OPTIMIZATION OF THE SELECTED POLYMERS

The second phase of the present study aims to optimize the selected polymers. The four leading polymers identified in the first phase were thoroughly evaluated and examined within a wide range of concentrations, various asphalt binder sources, various aging conditions, and testing temperatures. The resulting PMABs were subjected to extensive testing with respect to rutting, fatigue, and low temperature cracking potential for the local environmental conditions of the Gulf countries. The established criteria for the performance requirements of the Gulf countries, described in detail in section 4.1,

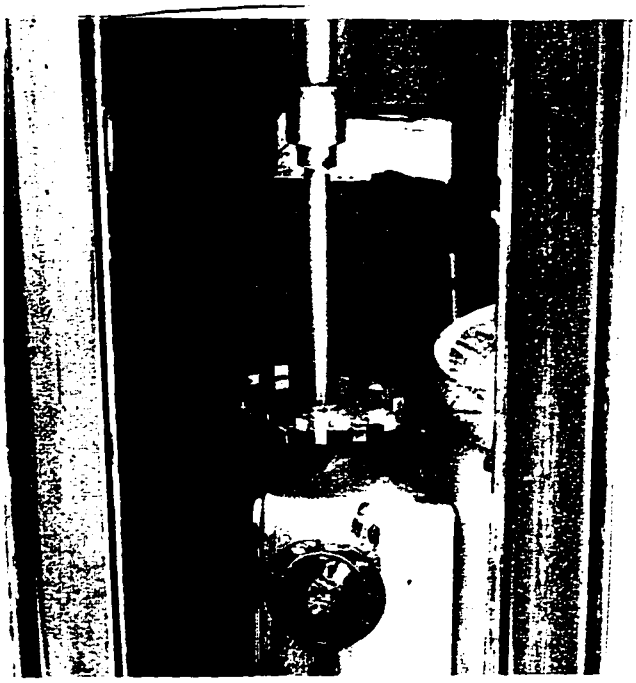
were utilized to provide the selection basis for the most appropriate polymer type and concentration for the locally produced Arab asphalt binders.

4.4.1 Suggested Polymer Modification Procedure

Information and experience gained in the first phase were activated to put together general guidelines by which asphalt binders can be blended with polymer modifiers. It is important to bear in mind, however, that these guidelines should not be considered prescriptive, some modifications may be needed to the stated recommendations. This depends on the actual instrumentation and capabilities of the laboratory performing the blending, the polymer type, and asphalt source.

1. *Blending Mechanism:* Blending of asphalt binders with high molecular weight materials such as polymers is not a steady or easy operation since two heterogeneous materials are forced together to form a two phase system. The polymer is required to disperse and not dissolve in the base asphalt binder. Therefore, it is recommended that the blender be cable of providing a high shear rate. The configuration of the blender head (i.e. blade) and the speed of blending defines the level of the shear rate that the blender induces into the asphalt binder. To insure that high shear blending is obtained, the recommended speed should not be less than 2,500 rpm and a blade similar to the one shown in Plate 4.2 must be used. However, some polymers such as SBS do not require high shear blenders; although blending time can be reduced by their use.

2. *Blending Time:* The blending time, which depends greatly on the blending shear rate and blending temperature, should be kept to a minimum since economical, practical,



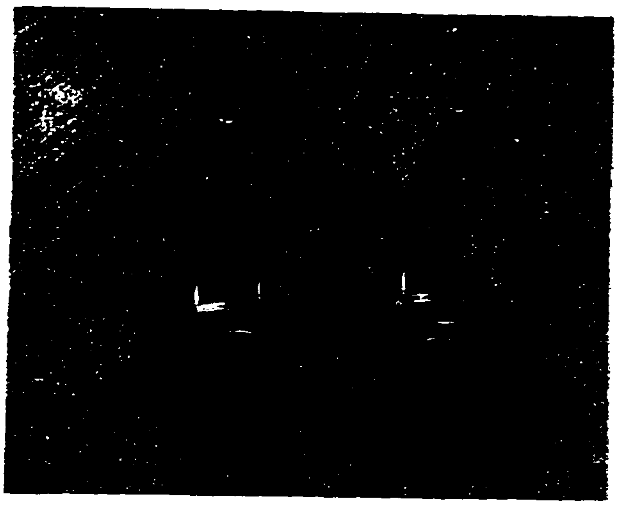


Plate 4.2: Blender Blade.

and technical issues could be affected by unnecessarily long blending times. It was found that prolonged blending time besides being uneconomical is detrimental to the rheological properties of the modified binder (Brule et. al., 1988). The suggested optimum blending times, which were identified from the first phase testing and analysis, are shown in Table 4.17.

Since blending time is dependent on the blender configuration and polymer type, it is recommended to identify the optimum blending time for a specific polymer type, blender head configuration, and speed by monitoring the increase in consistency of the PMAB by measuring the softening point at uniform time intervals during the blending process (say every 20 minutes). Once the softening point stabilizes and does not show significant increase with time, the blending process can be ceased. A plot between the blending time and the softening point such as that shown in Figure 4.12 can be generated from which the optimum blending time can be determined. The softening point is recommended as the criteria to define the relative homogeneity of the blend and the optimum blending time for the following reasons:

1. The fact that the softening point defines the beginning of the fluidity of the asphalt binder, which identifies a very critical point in the physical state of the asphalt binder.
2. Fatani et al. (1992) found that the softening point correlates with the performance of flexible pavements in the local Gulf countries' environmental conditions with respect to rutting (see Table 2.1).

Table 4.17: Recommended Blending Time for the Polymers Selected from the First Phase

Polymer Type	**Recommended Blending Time minutes**	**Maximum Blending Time minutes**
Linear Low Density Polyethylene (LLDPE)	120	135
Polypropylene (PP)	120	135
Styrene-Butadiene-Styrene (SBS)	60	75
Crumb Rubber (CRT)	80	95

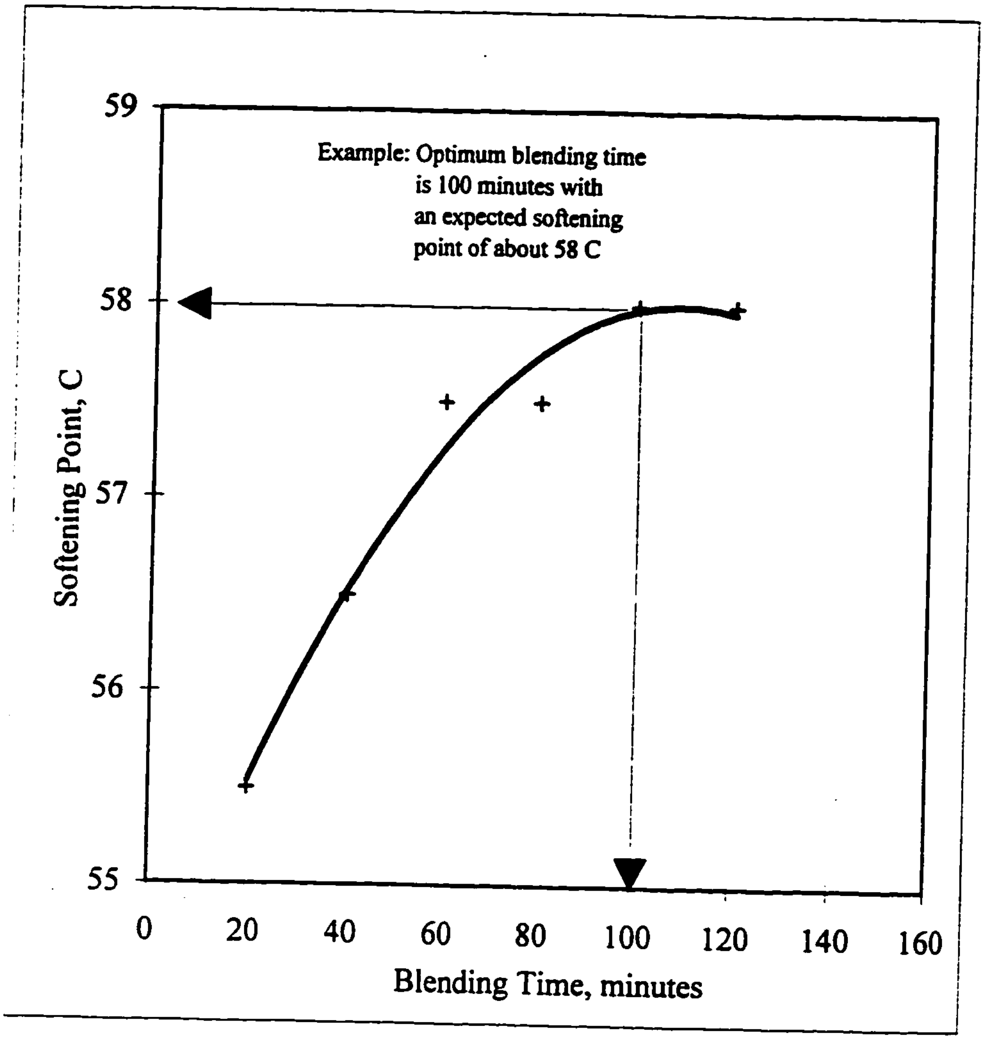


Figure 4.12: Determination of the Optimum Blending Time of PMABs Using the Softening Point

3. The limited variability of the softening point noticed in the first phase testing, where the coefficient of variation, which is equal to $(s / \overline{X}) * 100$, was found to be only 8.1%.
4. The past experience of using this test by leaders in the asphalt binder polymer modification field such as Exxon and Shell chemicals (Shell, 1994).
5. The relative low cost, ease, and simplicity of the test set up required to measure the softening point, which consists of a heating element, a beaker, standard rings and balls, and a thermometer.

3. ***Blending Temperature:*** The blending temperature greatly depends on the molecular weight of the polymer. Generally, higher molecular weight polymers such as high density polyethylene require higher temperatures than lower molecular weight polymers such as SBS. Table 4.18 provides a recommended blending temperature for the selected polymers.

4.4.2 Preparation of the Polymer Modified Asphalt Binders (PMABs)

The work in this phase involved preparing the polymer modified blends for the following factors:

1. Four asphalt sources (RT, RY, BH, and KW)
2. Four polymer types (LLDPEX, PP500U, SBS, and CRT)
3. Four polymer concentrations (Zero, Low, Medium, and High)

Table 4.18: Recommended Blending Temperature for the Selected Polymers from the First Phase

Polymer Type	**Recommended Blending Temperature °C**	**Maximum Blending Temperature °C**
Linear Low Density Polyethylene (LLDPE)	160 - 170	200
Polypropylene (PP)	170-180	200
Styrene-Butadiene-Styrene (SBS)	160-170	200
Crumb Rubber (CRT)	170-180	200

The total number of treatment combinations for the second phase was 64, representing a 4^3 factorial design with three factors at four levels. The matrix of the experimental design is shown in Table 4.19.

The work flow chart for blend preparation is shown in Figure 4.13. Asphalt samples from the asphalt producing refineries in the Gulf countries were prepared in suitable containers of 500 gms each. The selected polymers (LLDPE-X, PP500U, SBS, and CRT) were blended individually with the asphalt binder following the suggested polymer modification guidelines. A complete cycle from the beginning of blending to the end of the testing for each combination required an average of three days. Once a PMAB was obtained, it was divided and reduced to the sample sizes and scheme shown in Figure 4.13.

4.4.3 Laboratory Aging of the Polymer Modified Asphalt Binders (PMABs)

In order to obtain PMAB samples that represent various age conditions of the asphalt binder during various stages of its life, the prepared PMABs were subjected to the following laboratory aging tests:

1 Short-term aging using the Rolling Thin Film Oven Test (RTFOT), which simulates the aging effect of the asphalt mixture during production and construction.

2. Long-term aging using the Pressure Aging Vessel (PAV), which represents the in-service aging effect of about 7 to 8 years.

Table 4.19: Experimental Design Matrix of the Polymer Optimization

		Asphalt Source			
Polymer Type	**Polymer Concentration**	**Ras Tanura Refinery Saudi Arabia**	**Riyadh Refinery Saudi Arabia**	**BAPCO Refinery Bahrain**	**Al-Ahmadi Refinery Kuwait**
CRT	0%	x	x	x	x
	5%	x	x	x	x
	10%	x	x	x	x
	15%	x	x	x	x
LLDPE-X	0%	x	x	x	x
	3%	x	x	x	x
	6%	x	x	x	x
	9%	x	x	x	x
PP-500U	0%	x	x	x	x
	1.5%	x	x	x	x
	3%	x	x	x	x
	4.5%	x	x	x	x
SBS	0%	x	x	x	x
	3%	x	x	x	x
	6%	x	x	x	x
	9%	x	x	x	x

(x) represents results of three tests.

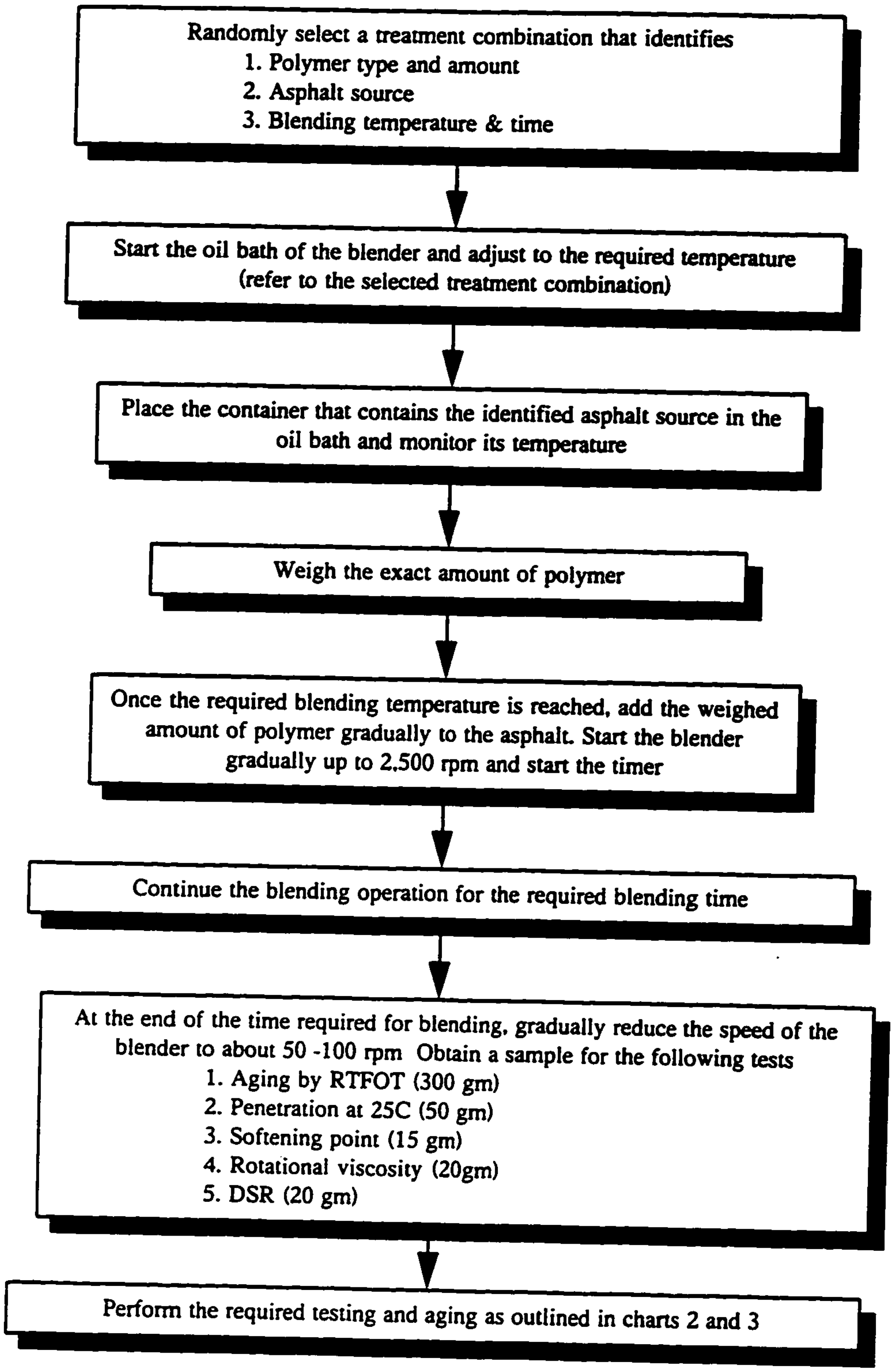


Figure 4.13: Flow Chart of the PMABs Preparation and Blending for Polymer Optimization

The work flow chart for sample aging is summarized in Figure 4.14. The obtained samples from the two aging methods were subjected to extensive rheological and performance characterization.

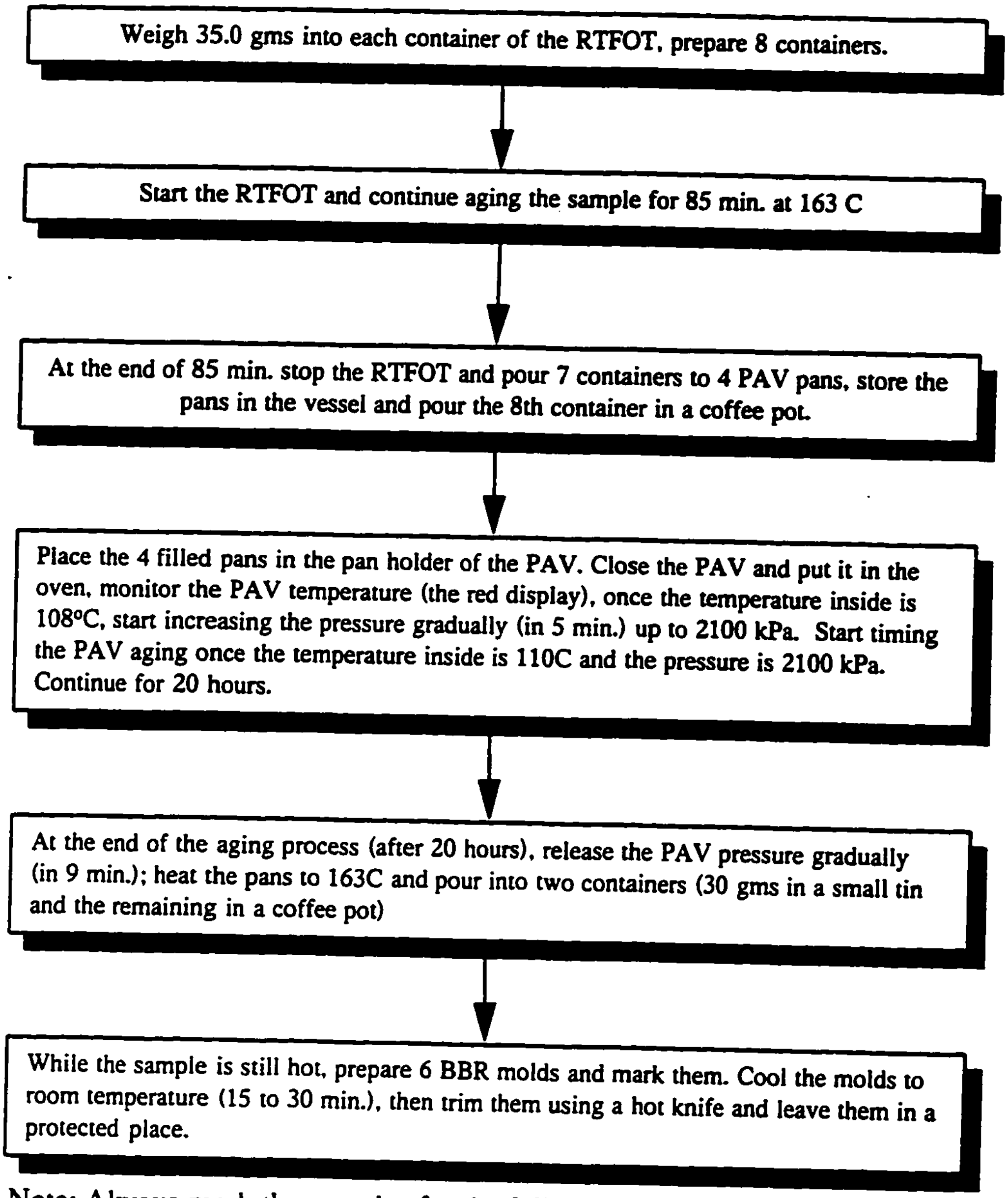
4.4.4 Characterization of the Polymer Modified Asphalt Binders (PMABs)

The obtained PMABs were subjected to extensive characterization to examine the influence of the polymer addition on the modified binder's rheological properties, age hardening, and temperature susceptibility characteristics. Rheological testing comprises the determination of the visco-elastic parameters of the PMABs at various temperatures and aging conditions. Rheological testing included the following tests:

1. Complex shear modulus (G*)
2. Phase angle (δ)
3. Flexural creep stiffness (S)
4. Slope of flexural creep curve (m-value)

The performance-based rheological properties of PMAB samples were determined using the Dynamic Shear Rheometer (DSR) to measure the complex shear modulus and phase angle, the Bending Beam Rheometer (BBR) to measure the flexural creep stiffness and creeping slope, the rolling thin-film-oven test (RTFOT) to simulate short-term aging, and the pressure aging vessel (PAV) to simulate long-term aging. Consistency testing of the PMABs included the determination of the following tests:

1. Rotational viscosity at 135°C
2. Penetration at 25°C



Note: Always mark the samples for the following:

1. Polymer type
2. %
3. Asphalt source

Figure 4.14: Flow Chart of the PMABs Aging Using RTFOT and PAV

3. Softening point

The work flow chart for the testing of the PMABs is summarized in Figure 4.15. An extensive amount of data was collected from this phase. Table 4.20 summarizes the collected data, which are shown in tabular and graphical forms in Appendix C. Collected data were thoroughly and carefully analyzed to examine the effects of asphalt source, polymer type, and concentration on the rheological and performance properties of the locally produced Arab asphalt binders.

4.4.5 Statistical Analysis and Discussion of the Test Results

Extensive testing were performed in this study to provide a concrete basis from which the stated objectives could be fulfilled.

Statistical analysis was performed to study the significance of the main effects included in the experiment, namely asphalt source, polymer type, and polymer concentration, and to examine the presence of interactions between them. The STATGRAPH package was used to perform the analysis. The following summarizes the statistical analysis approach used in this study:

1 The main effects were coded to simplify the analysis as shown in Table 4.21.

2 Multi-level analysis of variance were performed to test the significance of the main effects (three factors) and their interactions. (2nd and 3rd order interactions).

3 If the analysis of variance was significant at 5%, then the Least Significant Difference (LSD) method was used to identify exactly which means were

Perform the required testing on three replicates

↓

On the fresh blend, the following tests are required:

1. Softening point
2. Penetration @ 25C
3. Rotational viscosity @ 135C
4. DSR @ 76C
5. DSR @ 70C OR 82 depending on the G* over sin delta:
   - 5.1 If G* over sin delta @ 76C is < 1.0 kPa then test @ 70C
   - 5.2 If G* over sin delta @ 76C is > 1.0 kPa then test @ 82C

↓

On the RTFOT residue, the following tests are required:

1. DSR @ 76C
5. DSR @ 70C **OR** 82 depending on the G* over sin delta:
   - 5.1 If G* over sin delta @ 76C is < 2.2 kPa then test @ 70C
   - 5.2 If G* over sin delta @ 76C is > 2.2 kPa then test @ 82C

↓

On the PAV residue, the following tests are required:

1. DSR @ 25C
2. DSR @ 22C OR 28 depending on the G* x sin delta:
   - 2.1 If G* x sin delta @ 25C is < 5.0 MPa then test @ 22C
   - 2.2 If G* x sin delta @ 25C is > 5.0 MPa then test @ 28C
3. BBR @ -18 C
4. BBR @ -12C **OR** -24C depending on the S and the m values
   - 4.1 If S ≤ 300 MPa & m ≥ 0.300 then no further testing
   - 4.2 If S 300< S<600 MPa & m ≥ 0.300 then DTT
   - 4.3 If S ≥ 600 MPa **OR** m < 0.300 then BBR @ -12C

Figure 4.15: Flow Chart of the PMABs Testing

Table 4.20: Summary of Polymer Optimization Test Results

Response Variable	Polymer Type	Polymer Conc.	Ras Tanura Refinery	Riyadh Refinery	BAPCO Refinery	Al-Ahmadi Refinery
G* @ 76C, Pa FRESH	CRT	0.0%	750	905	618	995
		5.0%	788	940	1464	2198
		10.0%	1356	1646	1080	1846
		15.0%	5491	3304	1819	4330
	LLDPE-X	0.0%	1682	1501	1024	1433
		3.0%	19096	2501	10199	4492
		6.0%	5574	10016	7636	6414
		9.0%	25891	24120	23317	82001
	PP-500U	0.0%	1682	1501	1024	1433
		1.5%	11833	5352	7165	5033
		3.0%	12307	4691	6408	4498
		4.5%	7174	7930	9420	8307
	SBS	0.0%	750	905	618	995
		3.0%	1466	2161	1105	1012
		6.0%	4709	5225	2733	2833
		9.0%	9680	6708	7815	10227
DELTA @ 76C degrees, FRESH	CRT	0.0%	80	82	84	84
		5.0%	76	75	83	78
		10.0%	73	72	79	68
		15.0%	56	63	65	61
	LLDPE-X	0.0%	80	84	80	81
		3.0%	65	83	77	74
		6.0%	72	64	67	75
		9.0%	47	47	49	23
	PP-500U	0.0%	80	84	80	81
		1.5%	67	78	77	77
		3.0%	68	80	81	78
		4.5%	74	78	80	74
	SBS	0.0%	80	82	84	84
		3.0%	79	79	83	83
		6.0%	64	67	69	74
		9.0%	51	52	39	59
G*/SIN(DELTA) @ 76C, FRESH	CRT	0.0%	761	914	621	1000
		5.0%	811	972	1476	2245
		10.0%	1421	1727	1101	1985
		15.0%	6590	3704	2009	4938
	LLDPE-X	0.0%	1706	1510	1039	1452
		3.0%	21013	2519	10475	4666
		6.0%	5872	11156	8322	6645
		9.0%	35344	32820	30974	208723
	PP-500U	0.0%	1706	1510	1039	1452
		1.5%	12836	5473	7350	5176
		3.0%	13314	4757	6494	4599
		4.5%	7450	8101	9569	8639
	SBS	0.0%	761	914	621	1000
		3.0%	1495	2204	1113	1020
		6.0%	5241	5666	2918	2945
		9.0%	12398	8513	12453	11977
G* @ 76C, Pa RTFOT	CRT	0.0%	1370	2208	1387	2514
		5.0%	1826	2123	1951	4058
		10.0%	2947	2210	1932	4272
		15.0%	10110	5315	4038	5845
	LLDPE-X	0.0%	3073	3663	2100	3622
		3.0%	26091	4290	14224	8166
		6.0%	8685	7414	27340	90037
		9.0%	52338	12939	31132	102243
	PP-500U	0.0%	3073	3663	2100	3622
		1.5%	19336	11260	13230	7768
		3.0%	17600	11655	16737	15315
		4.5%	14516	17869	20287	59095
	SBS	0.0%	1370	2208	1387	3622
		3.0%	3122	3955	2204	2553
		6.0%	5736	7687	4944	7567
		9.0%	9105	11597	11057	10858

Table 4.20: Summary of Polymer Optimization Test Results

Response Variable	Polymer Type	Polymer Conc.	Ras Tanura Refinery	Riyadh Refinery	BAPCO Refinery	Al-Ahmadi Refinery
DELTA @ 76C degrees, RTFOT	CRT	0.0%	77	81	82	78
		5.0%	78	79	82	74
		10.0%	67	77	77	65
		15.0%	49	59	60	58
	LLDPE-X	0.0%	77	81	82	78
		3.0%	61	83	74	75
		6.0%	72	81	32	26
		9.0%	39	67	50	27
	PP-500U	0.0%	77	81	82	78
		1.5%	64	74	74	73
		3.0%	63	75	74	60
		4.5%	69	73	73	68
	SBS	0.0%	77	81	82	78
		3.0%	73	76	83	81
		6.0%	66	65	68	69
		9.0%	46	53	43	60
G*/SIN (DELTA) @ 76C, RTFOT	CRT	0.0%	1407	2237	1401	2566
		5.0%	1865	2165	1970	4218
		10.0%	3196	2264	1981	4708
		15.0%	13458	6170	4675	6925
	LLDPE-X	0.0%	3156	3711	2121	3697
		3.0%	29831	4326	14810	8437
		6.0%	9128	7505	51688	204415
		9.0%	82988	14091	40941	228344
	PP-500U	0.0%	3156	3711	2121	3697
		1.5%	21544	11736	13791	8116
		3.0%	19747	12095	17402	17763
		4.5%	15538	18676	21184	63964
	SBS	0.0%	1407	2237	1401	3697
		3.0%	3266	4085	2223	2584
		6.0%	6276	8509	5317	8104
		9.0%	12637	14605	16284	12567
G* @ 80C, Pa FRESH	CRT	0.0%	292	404	390	614
		5.0%	307	420	895	1360
		10.0%	897	1091	716	1085
		15.0%	3948	2274	1422	3169
	LLDPE-X	0.0%	1040	914	646	885
		3.0%	11983	1481	5966	2939
		6.0%	3429	6593	4969	3756
		9.0%	18546	17506	17241	72514
	PP-500U	0.0%	1040	914	646	885
		1.5%	7316	3228	4371	3294
		3.0%	7910	2857	3858	2840
		4.5%	4090	4781	5417	5136
	SBS	0.0%	292	404	390	614
		3.0%	902	1378	632	627
		6.0%	3038	3485	1849	1897
		9.0%	6968	4893	6965	6931
DELTA @ 80C degrees, FRESH	CRT	0.0%	82	82	85	85
		5.0%	76	76	84	79
		10.0%	74	74	80	72
		15.0%	59	66	68	63
	LLDPE-X	0.0%	82	84	83	82
		3.0%	68	84	79	76
		6.0%	72	62	66	77
		9.0%	45	47	44	22
	PP-500U	0.0%	82	84	83	82
		1.5%	69	80	80	78
		3.0%	70	82	82	80
		4.5%	76	80	81	76
	SBS	0.0%	82	82	85	85
		3.0%	80	81	83	82
		6.0%	67	68	70	75
		9.0%	54	53	32	61

Table 4.20: Summary of Polymer Optimization Test Results

Response Variable	Polymer Type	Polymer Conc.	Ras Tanura Refinery	Riyadh Refinery	BAPCO Refinery	Al-Ahmadi Refinery
G*/SIN (DELTA) @ 80C, FRESH	CRT	0.0%	295	408	391	616
		5.0%	317	433	900	1383
		10.0%	934	1135	727	1144
		15.0%	4584	2489	1532	3556
	LLDPE-X	0.0%	1052	919	651	895
		3.0%	12921	1490	6080	3033
		6.0%	3600	7441	5430	3863
		9.0%	26289	23911	24628	196404
	PP-500U	0.0%	1052	919	651	895
		1.5%	7814	3277	4445	3365
		3.0%	8438	2885	3893	2886
		4.5%	4209	4853	5478	5292
	SBS	0.0%	295	408	391	616
		3.0%	915	1397	638	633
		6.0%	3313	3754	1971	1964
		9.0%	8599	6116	13205	7902
G* @ 80C, Pa RTFOT	CRT	0.0%	521	1021	875	1615
		5.0%	525	623	1229	2667
		10.0%	1954	1476	856	3015
		15.0%	7250	3785	2949	4223
	LLDPE-X	0.0%	1857	2310	1449	2328
		3.0%	17740	2782	8680	4887
		6.0%	6759	5233	24512	87318
		9.0%	34338	10596	24949	76358
	PP-500U	0.0%	1857	2310	1449	2328
		1.5%	12883	6614	8400	5313
		3.0%	12167	7841	10038	11940
		4.5%	9593	11806	12088	36896
	SBS	0.0%	521	1021	875	1615
		3.0%	1966	2528	1440	1731
		6.0%	4221	5396	3266	4977
		9.0%	7233	8363	8789	7355
DELTA @ 80C degrees, RTFOT	CRT	0.0%	79	81	84	80
		5.0%	80	80	83	75
		10.0%	69	79	79	67
		15.0%	50	61	61	59
	LLDPE-X	0.0%	79	81	84	80
		3.0%	63	84	77	78
		6.0%	73	83	29	19
		9.0%	41	64	49	23
	PP-500U	0.0%	79	81	84	80
		1.5%	66	76	75	76
		3.0%	65	77	76	58
		4.5%	72	75	76	70
	SBS	0.0%	79	81	84	80
		3.0%	76	78	84	83
		6.0%	68	65	72	73
		9.0%	49	56	42	63
G*/SIN DELTA RTFOT, 80	CRT	0.0%	531	1034	880	1638
		5.0%	533	632	1237	2756
		10.0%	2091	1504	873	3284
		15.0%	9469	4328	3367	4916
	LLDPE-X	0.0%	1893	2339	1457	2362
		3.0%	19916	2797	8926	5004
		6.0%	7050	5277	50719	270950
		9.0%	52131	11830	32876	194624
	PP-500U	0.0%	1893	2339	1457	2362
		1.5%	14120	6809	8683	5488
		3.0%	13388	8061	10329	14080
		4.5%	10089	12207	12467	39198
	SBS	0.0%	531	1034	880	1638
		3.0%	2025	2586	1448	1746
		6.0%	4543	5935	3439	5202
		9.0%	9550	10091	13110	8248

Table 4.20: Summary of Polymer Optimization Test Results

Response Variable	Polymer Type	Polymer Conc.	Ras Tanura Refinery	Riyadh Refinery	BAPCO Refinery	Al-Ahmadi Refinery
G* @ 22C, MPa PAV	CRT	0.0%	5646	9269	8457	8469
		5.0%	3880	5549	5545	3192
		10.0%	2543	4885	4906	2934
		15.0%	1522	2316	1914	2692
	LLDPE-X	0.0%	5944	9759	8902	8916
		3.0%	11323	10975	17926	16446
		6.0%	1018	4475	16241	12184
		9.0%	2866	8744	7986	13759
	PP-500U	0.0%	5944	9759	8902	8916
		1.5%	10411	11570	18965	9984
		3.0%	15735	17377	38784	17626
		4.5%	10163	1025	25179	10526
	SBS	0.0%	5646	9269	8457	8469
		3.0%	3493	8015	8221	3754
		6.0%	2529	4212	6892	6220
		9.0%	950	2304	4751	5059
DELTA @ 22C degrees, PAV	CRT	0.0%	36	37	40	38
		5.0%	38	40	40	38
		10.0%	39	41	42	40
		15.0%	40	44	46	43
	LLDPE-X	0.0%	34	35	38	38
		3.0%	25	33	29	32
		6.0%	42	34	29	31
		9.0%	28	29	31	28
	PP-500U	0.0%	34	35	38	38
		1.5%	26	30	31	37
		3.0%	23	31	27	33
		4.5%	29	21	25	33
	SBS	0.0%	36	37	40	38
		3.0%	38	33	40	48
		6.0%	34	33	39	37
		9.0%	39	36	34	33
G*XSIN (DELTA) @ 22 C, PAV	CRT	0.0%	3308	5569	5432	5109
		5.0%	2390	3552	3547	1968
		10.0%	1597	3228	3297	1886
		15.0%	987	1619	1378	1841
	LLDPE-X	0.0%	3338	5625	5468	5538
		3.0%	4779	5897	8596	8601
		6.0%	683	2483	7866	6220
		9.0%	1331	4279	4113	6443
	PP-500U	0.0%	3338	5625	5468	5538
		1.5%	4487	5814	9699	5985
		3.0%	6061	8941	17470	9701
		4.5%	4875	361	10521	5712
	SBS	0.0%	3308	5569	5432	5109
		3.0%	2162	4377	5284	2798
		6.0%	1431	2298	4291	3726
		9.0%	595	1338	2643	2775
G* @25C, MPa PAV	CRT	0.0%	4085	6585	5979	6156
		5.0%	2894	3428	2980	4977
		10.0%	2318	3442	3573	3101
		15.0%	1061	1859	1231	1877
	LLDPE-X	0.0%	4329	6932	6294	6480
		3.0%	8767	8944	14923	13485
		6.0%	2349	4326	13022	9807
		9.0%	2639	6500	6195	11116
	PP-500U	0.0%	4329	6932	6294	6480
		1.5%	8714	8778	10695	7163
		3.0%	11895	13462	29043	13768
		4.5%	6847	1449	20762	7858
	SBS	0.0%	4085	6585	5979	6156
		3.0%	2794	5886	4788	2750
		6.0%	1882	2781	5420	4410
		9.0%	876	2007	3804	3838

Table 4.20: Summary of Polymer Optimization Test Results

Response Variable	Polymer Type	Polymer Conc.	Ras Tanura Refinery	Riyadh Refinery	BAPCO Refinery	Al-Ahmadi Refinery
DELTA @ 25C degrees, PAV	CRT	0.0%	38	40	42	39
		5.0%	40	43	43	39
		10.0%	40	43	45	45
		15.0%	41	45	48	44
	LLDPE-X	0.0%	36	38	42	40
		3.0%	26	34	30	33
		6.0%	30	34	31	32
		9.0%	26	30	31	29
	PP-500U	0.0%	36	38	42	40
		1.5%	27	32	32	39
		3.0%	25	32	30	36
		4.5%	31	34	26	35
	SBS	0.0%	38	40	42	39
		3.0%	38	35	43	50
		6.0%	36	35	40	39
		9.0%	38	35	36	34
G* X SIN DELTA @ 25 C, PAV	CRT	0.0%	2523	4212	3972	3863
		5.0%	1870	2333	2019	3148
		10.0%	1492	2339	2504	2184
		15.0%	702	1305	921	1302
	LLDPE-X	0.0%	2563	4264	4247	4203
		3.0%	3902	5040	7364	7309
		6.0%	1173	2400	6642	5192
		9.0%	1138	3292	3212	5423
	PP-500U	0.0%	2563	4264	4247	4203
		1.5%	3915	4703	5683	4553
		3.0%	5051	7206	14565	8002
		4.5%	3502	815	9232	4477
	SBS	0.0%	2523	4212	3972	3863
		3.0%	1708	3362	3241	2100
		6.0%	1097	1600	3503	2775
		9.0%	535	1157	2216	2150
STIFFNESS, MPa @ -18 C, PAV	CRT	0.0%	209	282	326	381
		5.0%	132	269	273	342
		10.0%	122	182	223	269
		15.0%	80	133	143	172
	LLDPE-X	0.0%	221	297	343	401
		3.0%	167	357	233	303
		6.0%	113	253	290	222
		9.0%	112	268	287	212
	PP-500U	0.0%	221	297	343	401
		1.5%	195	320	269	287
		3.0%	184	320	299	425
		4.5%	246	315	408	396
	SBS	0.0%	209	282	326	381
		3.0%	170	280	250	318
		6.0%	124	248	249	315
		9.0%	111	159	219	214
m-VALUE @ -18C	CRT	0.0%	0.220	0.191	0.204	0.197
		5.0%	0.303	0.270	0.257	0.223
		10.0%	0.281	0.291	0.283	0.283
		15.0%	0.307	0.302	0.319	0.286
	LLDPE-X	0.0%	0.231	0.201	0.215	0.204
		3.0%	0.245	0.248	0.109	0.234
		6.0%	0.265	0.247	0.230	0.246
		9.0%	0.260	0.220	0.286	0.230
	PP-500U	0.0%	0.231	0.201	0.215	0.204
		1.5%	0.224	0.237	0.258	0.230
		3.0%	0.220	0.217	0.233	0.241
		4.5%	0.236	0.208	0.198	0.219
	SBS	0.0%	0.220	0.191	0.204	0.197
		3.0%	0.263	0.255	0.250	0.284
		6.0%	0.282	0.257	0.210	0.250
		9.0%	0.265	0.247	0.230	0.223

Table 4.20: Summary of Polymer Optimization Test Results

Response Variable	Polymer Type	Polymer Conc.	Ras Tanura Refinery	Riyadh Refinery	BAPCO Refinery	Al-Ahmadi Refinery
STIFFNESS, MPa @ -12 C, PAV	CRT	0.0%	100	154	148	195
		5.0%	65	106	129	211
		10.0%	49	90	111	113
		15.0%	36	65	61	78
	LLDPE-X	0.0%	102	163	156	205
		3.0%	124	162	170	214
		6.0%	89	178	204	153
		9.0%	86	175	164	159
	PP-500U	0.0%	102	163	156	205
		1.5%	141	246	217	196
		3.0%	144	218	232	208
		4.5%	146	218	292	274
	SBS	0.0%	100	154	148	195
		3.0%	89	156	155	122
		6.0%	88	139	167	155
		9.0%	58	122	119	146
m-VALUE @ -12C	CRT	0.0%	0.271	0.275	0.285	0.292
		5.0%	0.355	0.334	0.313	0.283
		10.0%	0.335	0.351	0.349	0.359
		15.0%	0.354	0.357	0.379	0.338
	LLDPE-X	0.0%	0.283	0.291	0.300	0.307
		3.0%	0.259	0.303	0.168	0.278
		6.0%	0.275	0.274	0.263	0.282
		9.0%	0.270	0.260	0.304	0.260
	PP-500U	0.0%	0.283	0.291	0.300	0.307
		1.5%	0.243	0.268	0.270	0.293
		3.0%	0.239	0.260	0.257	0.307
		4.5%	0.268	0.231	0.242	0.278
	SBS	0.0%	0.271	0.275	0.285	0.292
		3.0%	0.305	0.301	0.304	0.375
		6.0%	0.299	0.299	0.269	0.311
		9.0%	0.301	0.279	0.294	0.290
PENETRATION @ 25C, 0.1 mm	CRT	0.0%	58	52	49	46
		5.0%	57	36	31	19
		10.0%	46	42	33	38
		15.0%	36	36	39	35
	LLDPE-X	0.0%	33	39	36	30
		3.0%	10	26	11	13
		6.0%	25	24	8	15
		9.0%	3	18	15	2
	PP-500U	0.0%	33	39	36	30
		1.5%	8	9	10	20
		3.0%	7	18	20	21
		4.5%	21	2	7	7
	SBS	0.0%	58	52	49	46
		3.0%	43	25	50	44
		6.0%	35	18	22	28
		9.0%	26	15	32	24
SOFTENING POINT, C	CRT	0.0%	59	60	60	57
		5.0%	59	61	60	63
		10.0%	62	59	58	62
		15.0%	75	69	68	71
	LLDPE-X	0.0%	60	62	61	59
		3.0%	83	67	74	70
		6.0%	94	96	110	82
		9.0%	114	117	116	113
	PP-500U	0.0%	60	62	61	59
		1.5%	76	72	72	68
		3.0%	79	68	69	69
		4.5%	80	74	76	74
	SBS	0.0%	59	60	60	57
		3.0%	60	64	60	58
		6.0%	86	75	82	72
		9.0%	94	93	92	85

Table 4.20: Summary of Polymer Optimization Test Results

Response Variable	Polymer Type	Polymer Conc.	Ras Tanura Refinery	Riyadh Refinery	BAPCO Refinery	Al-Ahmadi Refinery
ROTATIONAL VISCOSITY @ 135C, cP	CRT	0.0%	990	992	766	1201
		5.0%	1381	1399	1085	1865
		10.0%	2743	1641	1604	3649
		15.0%	11193	7170	5401	9003
	LLDPE-X	0.0%	1000	1004	1101	1244
		3.0%	9860	2033	4600	2905
		6.0%	6477	5381	4060	5631
		9.0%	5150	8372	6868	6973
	PP-500U	0.0%	1000	1004	1101	1244
		1.5%	4565	2152	2965	2837
		3.0%	5960	2180	3166	2973
		4.5%	7108	6814	6858	6717
	SBS	0.0%	990	992	766	1201
		3.0%	1436	1562	1372	1354
		6.0%	4169	4526	3241	3462
		9.0%	6077	4359	4491	9333
FLASH POINT, C	CRT	0.0%	308	324	338	298
		5.0%	300	316	322	304
		10.0%	300	294	320	296
		15.0%	304	306	316	306
	LLDPE-X	0.0%	310	326	339	301
		3.0%	322	310	350	350
		6.0%	314	338	354	354
		9.0%	334	350	340	344
	PP-500U	0.0%	310	1004	339	301
		1.5%	337	326	340	320
		3.0%	324	336	347	324
		4.5%	334	352	358	354
	SBS	0.0%	308	324	338	298
		3.0%	308	328	332	296
		6.0%	304	330	336	306
		9.0%	310	324	330	310

Table 4.21: Coding of the Experiment Variables

Code	Asphalt Source	Polymer Type	Polymer Concentration
0	Ras Tanura refinery, Saudi Arabia	Crumb rubber (CRT)	Zero
1	Riyadh refinery, Saudi Arabia	Linear low density polyethylene (LLDPE)	Low
2	BAPCO refinery, Bahrain	Polypropylene (PP)	Medium
3	Al-Ahmadi refinery, Kuwait	Styrene-Butadiene-Styrene (SBS)	High

Example:

0 0 0 = Asphalt binder from Ras Tanura Refinery modified with CRT at zero concentration
0 2 3 = Asphalt binder from Ras Tanura Refinry modified with Polypropylene at high concnetration

different (Montgomery, 1984). The LSD method uses the t statistic assuming a two-sided alternative to test which pairs of means would be declared as significantly different. The LSD value for a balanced experiment (i.e $n_1 = n_2$):is given by

$$LSD = t_{\alpha/2,\, N-a}(2MS_E/n)^{1/2}$$

To use the LSD method, the observed difference between each pair of means is compared against the corresponding LSD. If $(\mu_1 - \mu_2) > LSD$, then one can conclude that the population means μ_1 and μ_2 are different.

4 In case interactions of any two variables are significant when three factors are considered together, then a two way analysis of variance was performed for two factors, namely polymer type and concentration fixing the other factor which is the asphalt source. Fixing the asphalt source in the two way ANOVA is based on the following reasons:

i) The objective of the research was to identify polymer types that can be used to modify Arab asphalt binder, so fixing the asphalt source in the two way ANOVA allowed interpretation of the applicable results for each source without the effect of variation of the asphalt binder from other sources.

ii) From a practical perspective, each asphalt source represented a unique identity since each source used different asphalt production methods and also used different sources of crude oil.

The ANOVA tables for the three factors analysis are shown in Appendix D. Examining the three factor ANOVA tables shown in Appendix D, one concludes that the main affects of asphalt source, polymer type, and polymer concentration are significant. Furthermore, all 2nd and 3rd order interactions are also significant.

To assist in interpreting the practical and physical meaning of significant interactions, interaction plots of asphalt source by polymer type, asphalt source by polymer concentration, and polymer type by polymer concentration for G* / sin (δ) at 76 °C of fresh modified asphalt binder were constructed as shown in Figures 4.16 through 4.18. The significant interaction is indicated by the lack of parallelism of the lines in all of these plots. The physical meaning of a significant interaction is that the level of influence of one variable on the measured response depends on the level of the other variable. This can be illustrated by examining the interaction of the asphalt source with the polymer type for G* at 76 °C as shown in Figure 4.16, it is clear that the influence of different polymer types (codes 0, 1, 2 and 3 refer to Table 4.21) is different for different asphalt source. For example, asphalt binder from KW (asphalt source number 3, refer to Table 4.21) showed the highest increase in G* value when modified with LLDPE-X (polymer code number 1, refer to Table 4.21) but the least increase when modified with PP-500U (polymer code 2, refer to Table 4.21). The same interpretation can be stated about Figures 4.17 and 4.18 where the interaction lines cross each other. °C

To identify which means are different, Multiple Range Analysis using the LSD was performed for all response variables three factors each at a time as shown in

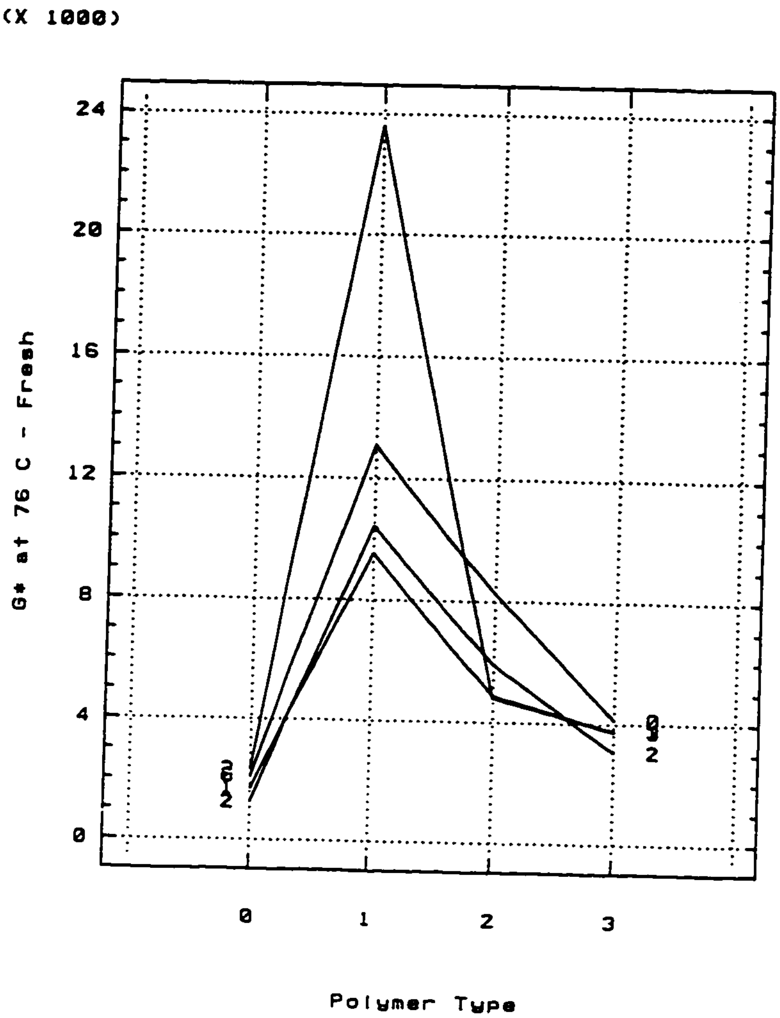


Figure 4.16: Plot of Interactions for Asphalt Source by Polymer Type - G* at 76 °C of Fresh Blend

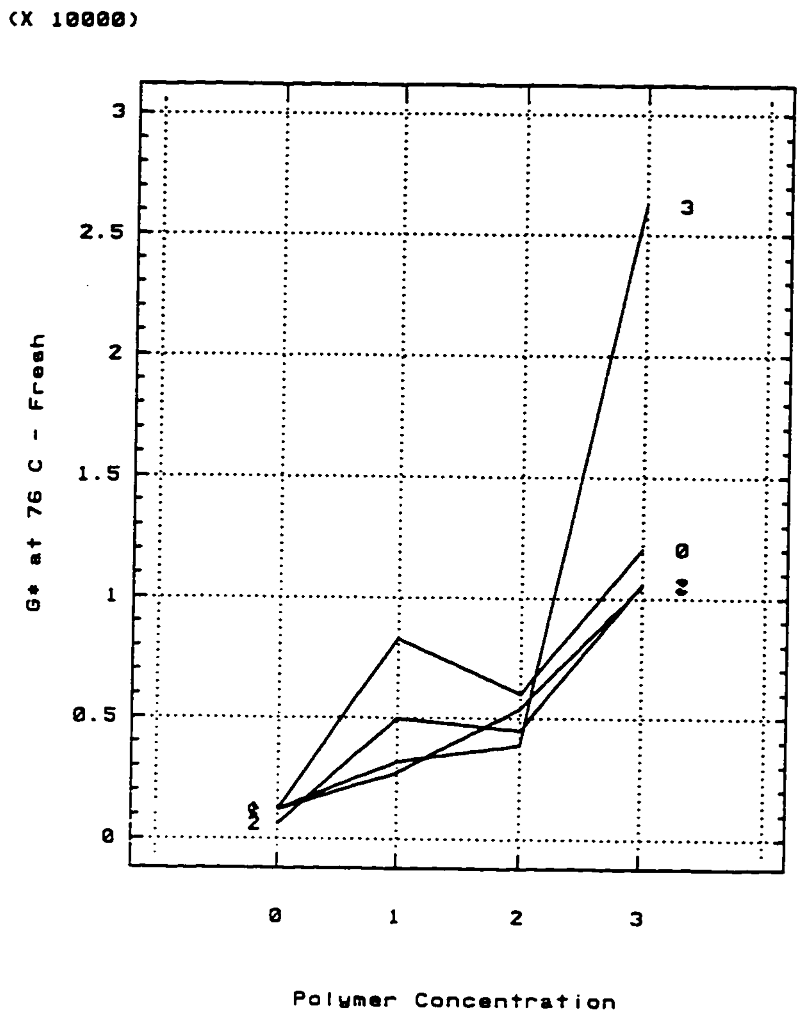


Figure 4.17: Plot of Interactions for Asphalt Source by Polymer Concentration - G* at 76 °C of Fresh Blend

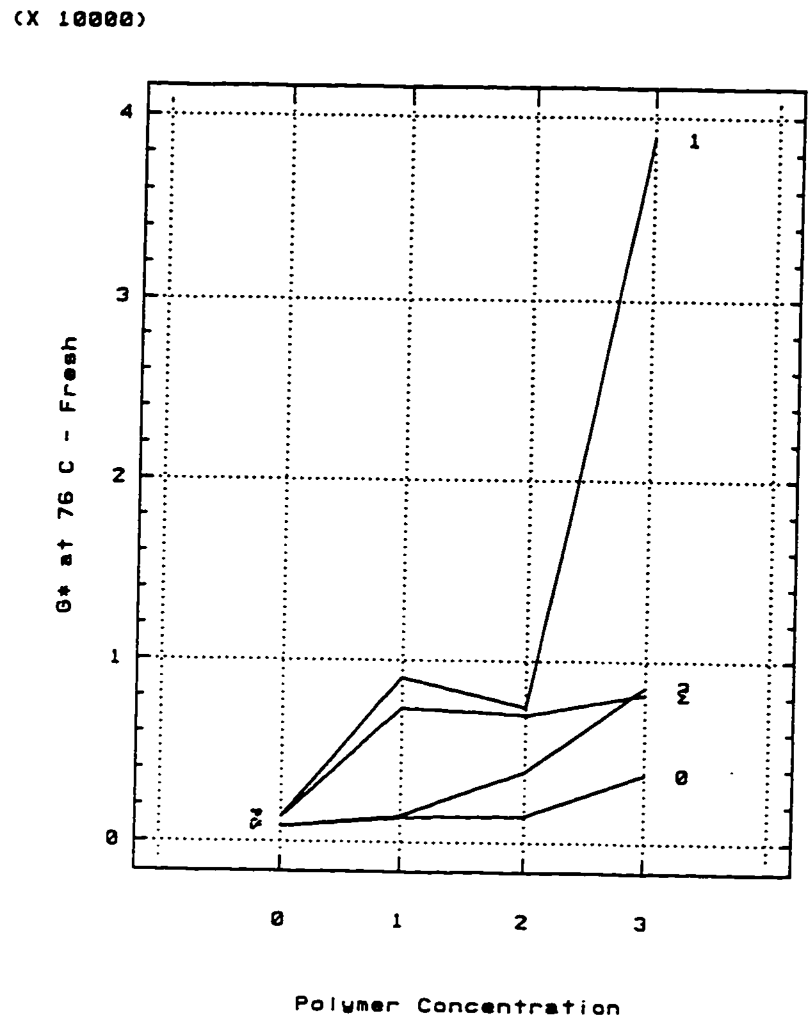


Figure 4.18: Plot of Interactions for Polymer Type by Polymer Concentration - G* at 76 °C of Fresh Blends

Appendix E. To explain the LSD analysis, the multiple range analysis for G* at 76 °C of fresh blends for asphalt source is shown below:

Contrast	Actual (μ_1 - μ_2)	Critical (LSD)	Statistically significant difference
0 - 1 (RT vs. RY)	1926.38	390.24	Yes
0 - 2 (RT vs. BH)	1724.74	390.24	Yes
0 - 3 (RT vs. KW)	1738.65	390.24	Yes
1 - 2 (RY vs. BH)	201.64	390.24	No
1 - 3 (RY vs. KW)	3665.02	390.24	Yes
2 -3 (BH vs. KW)	3463.38	390.24	Yes

This mean that all asphalt sources exhibited statistically different G at 76 °C values except asphalt binder from Riyadh and BAPCO refineries. This could be attributed to the fact that both refineries use crude oil from similar sources. Examining the LSD analysis, the following observations can be stated:

1 For the G* and G*/sin δ at 76°C of fresh blends:

i) RY and BH are similar with no statistically significant difference. Other asphalt sources are significantly different.

ii) All polymer types are different.

iii) Low and medium polymer concentrations are similar with no statistically significant difference. This has an economical advantage since the low

concentration costs less as a less polymer quantity is used. Other concentrations are significantly different.

2 For the phase angle at 76°C of fresh blends, all sources, types, and concentrations are statistically different.

3 For the G* and phase angle at 76°C of RTFOT residue, all sources, types, and concentrations are statistically different.

4 For G*/sin (δ) at 76°C of RTFOT residue:

i) RT and BH are similar with no statistically significant difference. Other sources are significantly different.

ii) CRT and SBS polymer types are similar with no statistically significant difference. Other polymer types are different. This is practically true since CRT contains a considerable amount of synthetic rubber, which is SBS.

iii) All polymer concentrations are different.

5 For G*, phase angle, and G*/ sin (δ) at 80°C of fresh blends, all sources, polymer types, and concentrations are different.

6 For G* and phase angle at 80°C of RTFOT residue, all sources, polymer types, and concentrations are different.

7 For G*/ sin (δ) at 80°C of RTFOT residue:

i) RT and BH are similar with no statistically significant difference. Other sources are significantly different.

ii) All polymer types and concentrations are significantly different.

8 For G^* and phase angle at 22°C and at 25°C of PAV residue, all sources, polymer types, and concentrations are different.

9 For Phase angle at 22°C of PAV residue:

i) All sources and polymer types are significantly different.

ii) Low and medium polymer concentrations are similar with no statistically significant difference. Other concentrations are different.

10 For $G^* \times \sin(\delta)$ at 22°C and at 25°C of PAV residue:

i) All sources and polymer types are significantly different.

ii) At 22°C, zero, low, and medium polymer concentrations are similar with no statistically significant difference. High concentrations are different.

iii) At 25°C, zero and low polymer concentrations are similar with no statistically significant difference. High concentrations are different.

11 For flexural creep stiffness at −18°C of PAV residue, all sources, polymer types, and concentrations are different.

12 For rate of change in creep stiffness (m-value) at −18°C of PAV residue:

i) BH is similar to KW, and KW is similar to RY with no statistically significant differences. Other sources are significantly different.

ii) Polymer types are significantly different.

iii) Medium and high polymer concentrations are similar with no statistically significant difference. Other polymer concentrations are different.

13 For flexural creep stiffness at −12°C of PAV residue:

i) All source and polymer types are significantly different.

ii) Zero and low polymer concentrations are similar with no statistically significant difference. Other polymer concentrations are different.

14 For rate of change in creep stiffness (m-value) at -12 °C of PAV residue:

i) RT and BH are similar with no statistically significant difference. Other sources are significantly different.

ii) LLDPEX and PP500U are similar with no statistically significant difference. Other polymer types are significantly different.

iii) Zero, Medium, and high polymer concentrations are similar with no statistically significant difference. Low polymer concentrations are different.

15 For rotational viscosity at 135°C and softening point of fresh blends, all asphalt sources, polymer types, and polymer concentrations are significantly different.

16 For penetration at 25 °C of fresh blend:

i) RY and BH are similar with no statistically significant difference. Other sources are significantly different.

ii) Polymer types and concentrations are significantly different.

Since all of the interactions in the three way analysis of variance are significant, then a two way analysis of variance was performed for each asphalt source separately. The ANOVA tables are shown in Appendix F. It is obvious from the two way analysis of variance that the polymer type and concentration significantly affect all response variables for all asphalt binder sources.

4.4.6 Findings and Observations

Based on the extensive data analysis and examining various tables, graphs, interactions plots, and statistical analysis the following findings and observations can be stated:

1 The four asphalt sources that were included in this study (RT, RY, BH, and KW) exhibit different consistency and rheological properties when modified with the same polymer type.

2 The four polymer types that were included in this study (CRT, LLDPE, PP, and SBS) have different amount of influence, decreasing or increasing, in the consistency and rheological properties of the asphalt binder of the same asphalt binder source.

3 Most of the relationships, shown in Appendix B, between polymer concentration and the various measured properties for various polymer types and asphalt sources are not linear and are not proportionally additive (i.e. the value of the property does not increase twice if the polymer concentration is doubled).

4 High temperature behavior of the PMABs is different than low temperature behavior. At the high temperature range, as the polymer concentration increases, the complex shear modulus (G*) increases, while at the low temperature range, the increase in polymer concentration resulted in a decrease in the G*.

5 G* generally increases with increasing polymer concentration for all polymers and sources except BH + 10% CRT, KW + CRT10%, RT + 6% LLDPE, BH + 6% LLDPE, RT + PP4.5%, RY + PP3%, BH + PP3%, and KW + PP3%, where a decrease in the G* compared to the G* measured at a concentration below the

stated concentration was observed. These eight treatments represent about 16% of the total treatment combinations in this study. This unexpected behavior might be attributed to the fact that the initial increase in the G* (at low polymer concentration) was a result of a chemical reaction between the polymer and some compounds in the asphalt binder; this reaction ceased and became inactive with additional quantities of the polymer at medium concentrations. At this stage, the polymer started to dominate, and an inversion point occurred where a reduction in the G* resulted. Increasing the polymer concentration resulted in a polymer phase where most of the G* is contributed by the polymer itself (Brule, 1988; Reese, 1994).

6 The G* at 76°C is always higher than that at 80°C for all polymer types, concentrations, and asphalt sources.

7 The smallest increase in G* was observed for RT + 5% CRT (788 Pa at 76°C), and the largest increase was observed with KW + 9% LLDPE (82,001 Pa at 76°C).

8 CRT has the smallest increase in G* and the smallest reduction in the phase angle followed by SBS, then PP at low concentration and LLDPE at high concentration.

9 The elasticity of the PMABs as measured by the phase angle is always improved by increasing polymer concentration for all polymer types and asphalt sources. This is evidenced by the decrease in the phase angle with increasing polymer concentration. This behavior is desirable since the recovery of the strains is improved with increasing elasticity.

10 G* of the fresh and RTFOT residue increases with increasing polymer concentration for all test temperatures. The fresh blend exhibited less G* value than the RTFOT residue.

11 In general, flexural creep stiffness decreases with increasing polymer concentration. However, this is considered marginal if compared with the improvement the polymer addition provided within the high temperature range. This behavior is desirable since polymer addition has not made the asphalt too stiff at low temperature leading to low temperature cracking.

12 The m-value, which is the rate of change in the creep stiffness, is decreasing with increasing polymer concentration except for all CRT blends, LLDPEX at 3%, and SBS at 6%. The increase in the m-value is desirable since it is an indicator of the rate at which the asphalt binder relaxes thermal stresses; a lower value indicates a slower relaxing asphalt binder.

13 Penetration at 25°C generally decreases as the polymer concentration increases for all treatment combinations except RT LLDPEX at 6% and PP500U at 4.5%; RY CRT at 10% and PP 500U at 3%; BH LLDPEX at 9%, PP 500U at 3% and SBS at 9% and KW CRT at 10% and LLDPEX at 6%. This means that the asphalt binder for these combinations at the stated concentrations is *softer* than that of a lower concentration. Similar behavior were noticed for the G* (see point 5).

14 Both the Softening point and the rotational viscosity at 135°C increased as polymer concentration increased.

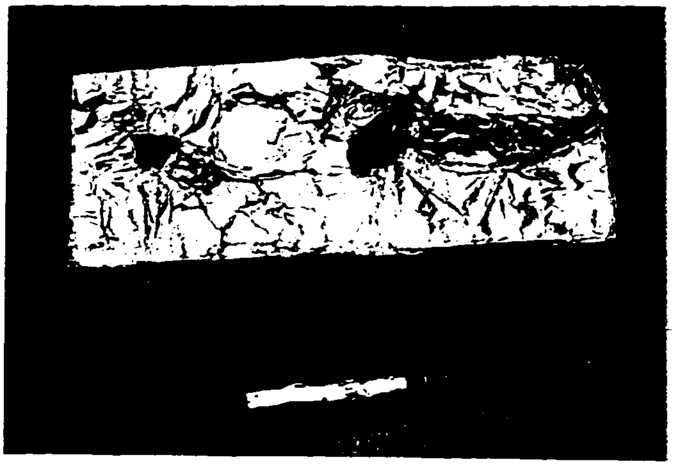
15 The flash point generally increases with increasing polymer concentration. Since the flash point is a safety test, this increase is desirable as it provides more protection against possible firing during asphalt mixture production.

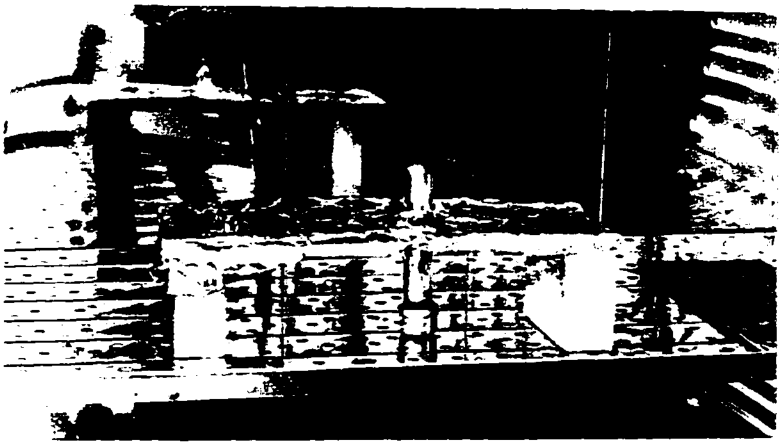
4.4.7 Storage Stability

The storage stability of some PMABs was evaluated by measuring and statistically comparing the G* at 76°C and 10 rads/sec. This was done by using the DSR of the top and bottom portions of a sample of the blend stored in a vertical position for 48 hours in a special storage device.

The storage device consisted of three 50 mm long by 19.1 mm diameter pipes attached to each other using heavy duty, heat resistant aluminum tape as shown in Plate 4.3. After filling the device with the sample, it was stored in a vertical position in an oven at 165°C for 48 hours. At the end of the storing period, the device were transferred to a refrigerator and kept there for 4 hours to solidify the sample. After 4 hours, the device was cut into three pieces using a hot knife. The top and bottom portions were placed in a container separately to collect the PMAB sample. The sample was heated until sufficiently fluid and poured into the silicon mold of the DSR.

The DSR was used to test the samples at 76°C and 10 rads/sec. The test results are shown in Table 4.22 and Figure 4.19. The storage stability testing indicated that there was no significant difference between the top and bottom portions of the PMAB sample for RT CRT at 10%. All other tested blends showed significant difference between top and bottom portions of the sample.





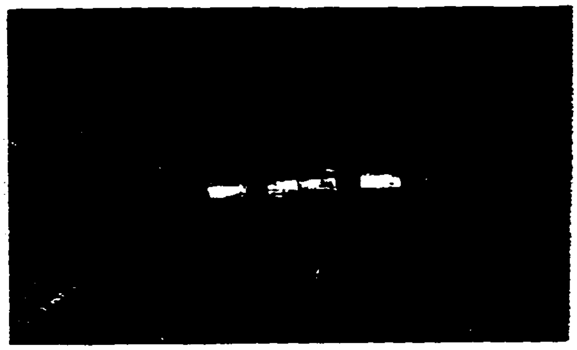


Plate 4.3: Storage Stability Device.

Table 4.22: Complex Shear Modulus at 76 °C and 10 rad/sec of some PMABs after Storing for 48 hrs at 165 °C

Asphalt Source	Code	Polymer Type	Polymer Concentration %	Top	Bottom	
				G*, kPa	G*, kPa	Difference is significant
Ras Tanura Refinery, Saudi Arabia	1	CRT	10	1.633	1.569	NO
Riyadh Refinery, Saudi Arabia	2	CRT	10	1.204	2.666	Yes
	3	LLDPEX	3	6.439	1.779	Yes
	4	SBS	3	5.221	1.285	Yes
BAPCO Refinery, Bahrain	5	PP500U	1.5	15.221	2.1752	Yes
Al-Ahmadi Refinery, Kwuiat	6	PP500U	1.5	17.329	9.601	Yes

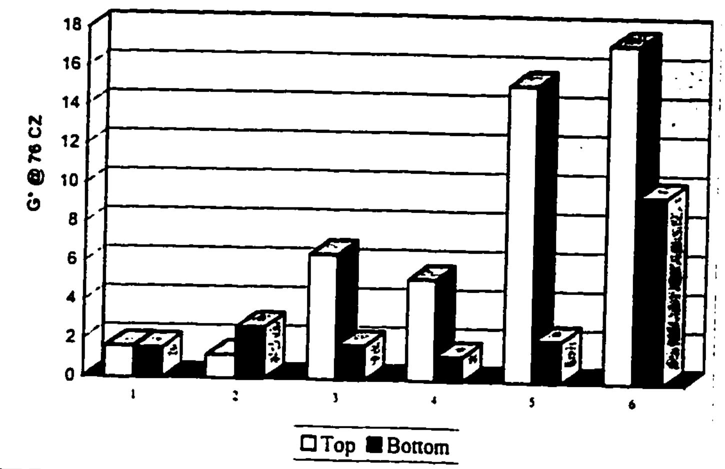


Figure 4.19: Complex Shear Modulus at 76 °C after Storage for 48 h at 165 °C

It is interesting to note that RT and RY samples blended with CRT at 10% opposed each other in that the G* of RT's top portion was more than that of the bottom portion, while for RY, the top portion was less than that of the bottom portion. This can be explained by the difference in the specific gravity of the base asphalt from RT, which is 1.019, compared to that from RY, which is 1.024. RT asphalt binder is lighter than RY asphalt binder; therefore, most of the CRT polymer floated to the top portion of the RT sample, while most of CRT polymer settled to the bottom portion of the RY sample. Other polymer types floated to the top portion because they are lighter than the asphalt binder from all sources. Their density is less than 1.0.

4.4.8 Preliminary Evaluation of Hot Mixtures Containing Modified Binders

For the purpose of gaining some feeling and confidence on the role that the polymer plays in the complex behavior of hot asphalt concrete mixtures, some mixtures were prepared with some PMABs and tested using the Transport and Road Research Laboratory (TRRL) wheel tracking machine (WTM).

4.4.8.1 Description of Materials and Test Procedure

The selected mixture gradation is the latest Ministry of Communication (MOC) wearing coarse mix. This mix was designed using Marshall Method (AASHTO T 245 and the Asphalt Institute MS-2) yielding the Marshall properties shown in Table 4.23. The PMABs of 10 % CRT and 3 % LLDPEX using asphalt from Riyadh refinery as the base asphalt, since it is the main source of asphalt binder in the region, were prepared using the suggested polymer modification procedure outlined in section 4.4.1. A total of

Table 4.23: Mixture Gradation and Marshall Properties

Property	Test result
Sieve analysis	
3/4" (19.0 mm)	100
1/2" (12.5 mm)	84
3/8" (9.5 mm)	71.5
# 4 (4.75 mm)	52.5
# 8 (2.0 mm)	30
# 40 (0.425 mm)	13.5
# 80 (0.180 mm)	9
# 200 (0.075 mm)	5.5
Optimum asphalt content, %	4.5
Marshall stability, kg	1900
Air voids, %	5.3
Voids filled with asphalt, %	65
VMA, %	15.44
Flow, mm	3.8
Marshall density, gm/cc	2.351

six slabs composed of two slabs of each of the hot mixtures containing the CRT and LLDPEX polymer modified asphalt binder and the neat binder were mixed and compacted.

Fresh blends of the PMABs were prepared following the suggested polymer modification procedure as outlined in section 4.4.1. Mixing of the asphalt binder with the heated aggregate were accomplished using a mechanical mixer shown in Plate 4.4; mixing were continued ,while monitoring the temperature, until a uniform coating of the aggregate particles were obtained. Then the mixture were immediately placed in the mold, roded 25 times, and compacted using static load of about 30,000 lb. for 4 minutes.

The WTM, as shown in Plate 4.5, consists a loaded wheel and a frame on which three 14.0 x 40.5 x 10.0 cm steel molds containing the asphalt slabs is firmly restrained on its four sides. A 204 mm diameter by 47 mm wide wheel with a tire of solid rubber (80 on the Dunlop hardness scale) applies a total of 525 N and indents a straight track in the specimen, the depth of the track is recorded at the mid point of its length. The contact area between the wheel and the specimen is about 1000 mm^2 giving a mean normal pressure of about 520-550 kN/m^2. A motor and a reciprocating device gives the wheel a to-and-from motion of 42 passes a minute with a distance of travel of 25.0 cm. The temperature of the sample is being maintained at 60 $^{\circ}$C by submerging the slab during the test in the testing machine reservoir which contains hot water at 60 $^{\circ}$C. From the deformation vs. number of passes curve the wheel tracking rate is determined and expresses in mm/h.

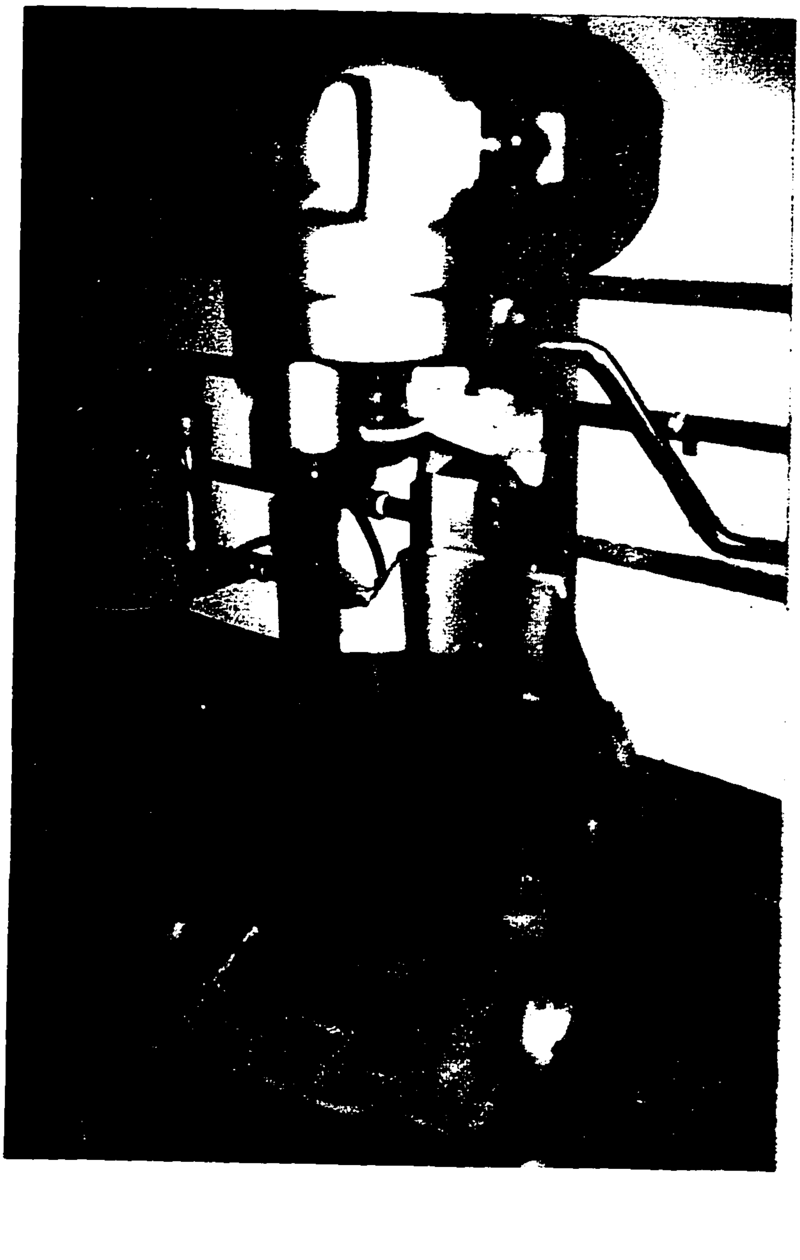


Plate 4.4: Mechanical Mixer .

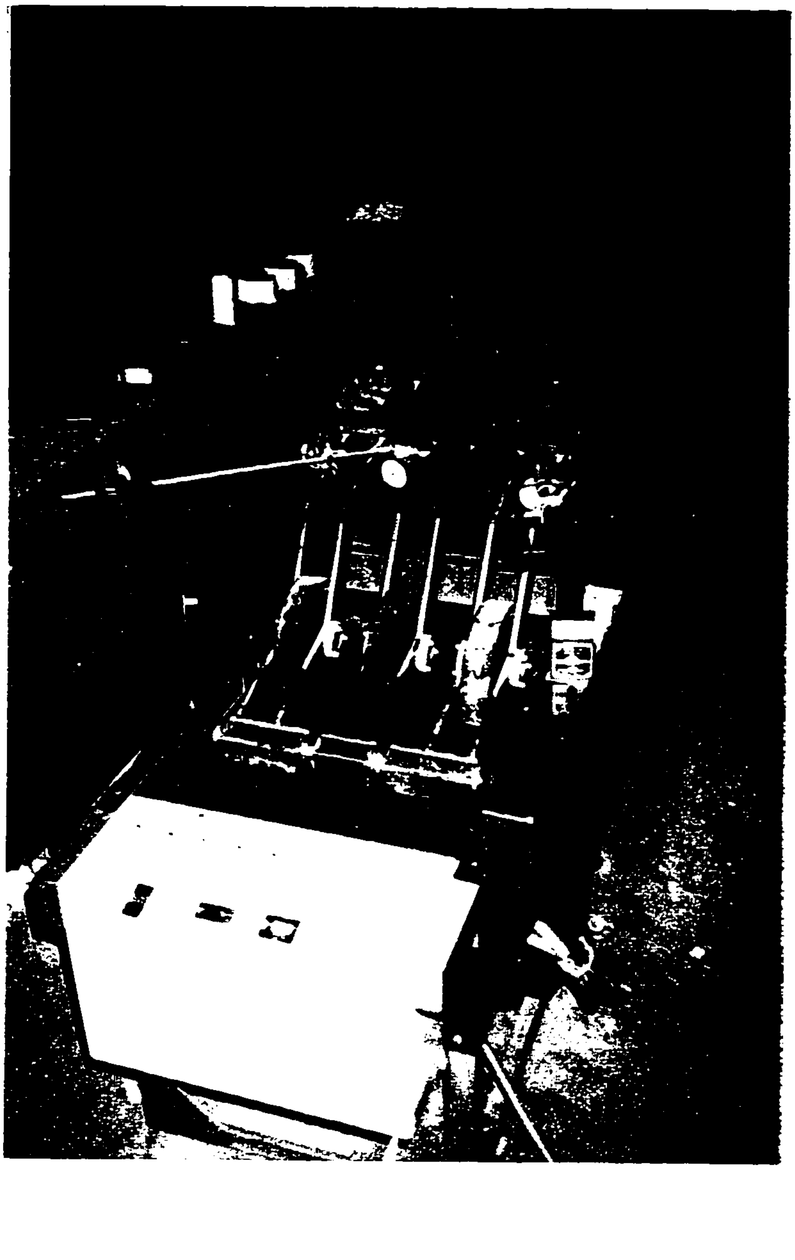


Plate 4.5: Wheel Tracking Machine (WTM).

4.4.8.2 Results and Analysis

The test results are summarized in Table 4.24. The rut depth vs. number of passes are shown in Figure 4.20. The wheel tracking rate of the three mixtures were determined to be as follows:

Mixture type	Wheel Tracking Rate mm/h
Control mixture with neat asphalt binder	1.0133
Mixture containing LLDPEX asphalt binder	0.2027
Mixture containing CRT asphalt Binder	2.1584

It is obvious that the mixture containing LLDPEX has the lowest wheel tracking rate. Furthermore and unexpectedly it was found out that the mixture containing the CRT asphalt binder has the highest wheel tracking rate. The following are some explanation for this behavior:

1. The wheel tracking test is performed while the sample is submerged in the water to maintain the test temperature; the presence of the hot water led to the occurrence of the stripping phenomena where the film of the asphalt surrounding the aggregate particles is being damaged and peeled-off. It was noticed during the test that the fine material starts to disintegrate from the sample after about 2000 passes (about 50 minutes of continuos testing) in the CRT mixture. It is believed that the wheel tracking test do not only test the rutting resistance of the mixture but rather test the stripping

Table 4.24: Rut Depth of Hot Mixutres Made with Neat, LLDPEX and CRT Asphalt Binders

# of Passes	Time, h.	Neat	LLDPEX	CRT
0	0.000	0	0	0
50	0.019	0.254	0.240	1.016
150	0.058	0.635	0.381	1.143
200	0.078	0.700	0.390	1.060
300	0.116	0.762	0.500	1.448
400	0.155	0.770	0.540	1.580
500	0.194	0.889	0.570	1.651
700	0.271	1.016	0.591	2.032
900	0.349	1.200	0.600	2.286
1000	0.388	1.320	0.610	2.320
1600	0.620	1.820	0.780	3.430
2800	1.085	2.530	0.980	4.280
5200	2.016	3.220	1.370	8.220
10000	3.876	6.430	2.000	15.920
16118	6.247	12.250	2.280	26.610
37174	14.409	14.600	2.921	31.100
	Wheel Tracking Rate mm/h	**1.0133**	**0.2027**	**2.1584**

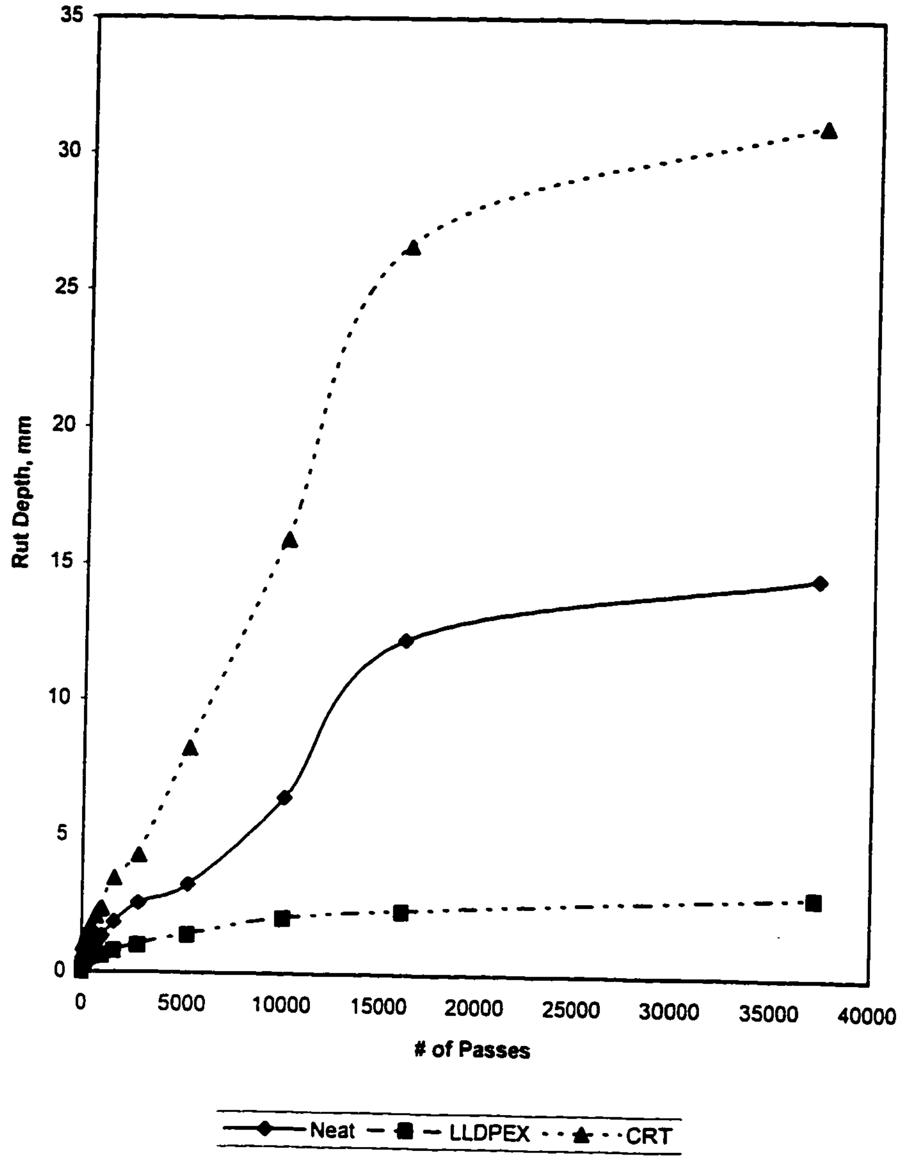


Figure 4.20 Rutting Curves of Hot Mixuters Containing Neat and PMABs of LLDPEX and CRT

characteristics of the mixture as well. From this, it is obvious that CRT mixture does not have an adequate resistance to water damage.

2. The mixture containing the CRT modified binders needs to be redesigned using the Marshall method so that the asphalt content is adjusted based on the actual design parameters. It is expected that the asphalt content will increase due to the CRT modification which will, certainly, improve the resistance to stripping.

3. This finding is extremely important as it pinpoints the complex behavior of the hot mixtures containing modified asphalt binders. Also, ascertain that the evaluation of the asphalt characteristics by itself is not enough to produced a guaranteed performance in the filed. This means that the evaluation and improvement efforts should cover the aggregate and the mixture in addition to the asphalt evaluation and improvement by polymer modification.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

The main objectives of this research were to characterize Arab asphalt binders, assess their need for modification, identify the potential polymers to improve their visco-elastic properties, and optimize the leading polymers for the Arabian Gulf countries' environmental conditions.

5.1 CONCLUSIONS

Based on a comprehensive analysis of the collected data and the experience gained from the performance of the tests and observing the actual behavior of the neat and polymer modified asphalt binders, the following findings can be stated:

1. Visco-elastic characterization of the locally produced neat asphalt binders demonstrated that the neat Arab asphalt binders (NAABs) meet the performance requirements, considering rutting and low temperature cracking, of areas where the maximum pavement temperature at a depth of 20 mm from the pavement surface does not exceed 64 °C and the minimum pavement temperature at the surface of the pavement does not go below -22 ° C.
2. The properties of asphalt binders produced in the Gulf countries are variable even within the same refinery. Refineries need to practice more strict control on the quality aspects and production monitoring to eliminate the production variability

and produce the asphalt binder meeting the designated specifications. This variability, however, supports the fact that Arab asphalt binders need to be modified since polymer modification will improve the visco-elastic properties of the asphalt binder to perform satisfactorily.

3. Temperature study of the environmental conditions of the Gulf countries revealed that the Gulf countries encounter a seven days maximum pavement design temperature of 76 °C and a minimum pavement design temperature of -10 °C. Based on the performance requirements of the Gulf countries (i.e 76 °C) and the temperature at which the locally produced asphalt binders will perform satisfactorily (i.e 64 °C), it is necessary to modify the neat Arab asphalt binders to satisfy the performance requirements of the Gulf countries.

4. Polymer modification is capable and effective in improving the reheological properties of the NAABs so that they satisfy the performance requirements of the Gulf countries. Further, life cycle cost analysis of various polymer modified mixtures indicates that the polymer modification is feasible and is economically justified.

5. Examining the 2nd order interaction of the asphalt source, polymer type and polymer concentration For:

   1) the G*/sin(d) at 76 °C, since this parameter controls the contribution of the asphalt binder towards rutting, the dominating distress in the Gulf countries;

   2) the rotational viscosity at 135 °C, since it controls the workability of the binder during mixing and production and;

3) economical considerations.

The most promising polymer types and concentrations are as follows:

a) **For asphalt from Ras Tanura refinery, Saudi Arabia:**

i) Styrene-Butadiene-Styrene (SBS) at 3 % by total weight of the blend.

ii) Crumb Rubber Tires (CRT) with a concentration of about 10% by total weight of the blend.

b) **For asphalt from Riyadh refinery, Saudi Arabia:**

i) Linear low density polyethylene-Grade 1182 at a concentration of 3 % by total weight of the blend.

ii) Crumb Rubber Tires (CRT) with a concentration of about 10% by total weight of the blend.

iii) Polypropylene-Grade 500U at a concentration of 1.5% by weight of the total blend.

c) **For asphalt from BAPCO refinery, Bahrain:**

i) Polypropylene-Grade 500U at a concentration of 1.5% by weight of the total blend.

ii) Styrene-Butadiene-Styrene (SBS) at 3 % by total weight of the blend.

d) **For asphalt from Al-Ahmadi refinery, Kuwait:**

i) Linear low density polyethylene-Grade 1182 at a concentration of 3 % by total weight of the blend.

ii) Crumb Rubber Tires (CRT) with a concentration of about 5% by total weight of the blend.

iii) Polypropylene-Grade 500U at a concentration of 1.5% by weight of the total blend.

6. The storage stability indicated that most polymer modifiers separate from the base asphalt if stored in elevated temperatures except the CRT modifier. This places a handling and storage limitation on the polymer modified asphalt binders. Blends must always be prepared freshly. Alternatively, continuos blending during hot storage may minimize the polymer separation.

7. The performance of the asphalt concrete mixtures is complex and is being affected by more than one factor. Although the improvement of the rheological properties of the asphalt binder due to polymer modification is very attractive, other important characteristics such as the adhesion and stickiness of the asphalt binder to the aggregate need to be evaluated. The wheel tracking test, indicated that the presence of water has led to the disintegration of the asphalt concrete mixture made with polymer modified asphalt binder of 10 % CRT. The mixture containing polymer modified asphalt binder must be carefully designed and evaluated for stripping and some anti-stripping agents may be used to improve the mixture resistance to water damage.

8. Blending of all of the polystyrene polymers including general purpose, high impact and expandable grades fails and a homogenous dispersion of the polymer within the body of the asphalt binder is not possible.

5.2 RECOMMENDATIONS

Although the present work tries to be very comprehensive in studying the physical and rheological properties of both neat and polymer modified asphalt binders covering all asphalt source within the Gulf countries, including a wide range of polymer types and three polymer concentrations, some important areas for future research do exist. Among the most important ones are:

1. **Laboratory characterization of modified and unmodified hot mix asphalt concrete:** Various asphalt concrete mixtures containing neat asphalt binders from all sources within the Gulf countries and the suggested polymer types and concentrations can be prepared using the SHRP gyratory compactor. These mixtures can then be subjected to a comprehensive laboratory evaluation including:
   a) Rutting resistance evaluation using the modified wheel tracking machine.
   b) Shear and stiffness behavior using the SUPERPAVE® shear test device.
   c) Creep compliance and strength using indirect tensile loading techniques.
   d) Fatigue life using the repeated flexural bending.
   e) Moisture sensitivity characteristics.
2. **Field characterization of modified and unmodified hot mix asphalt concrete:** The outcome of the laboratory characterization phase can be expanded to the field. Pavement sections of various thickness and about 100 m long can be constructed and monitored to collect data to fine tune and assess the polymer modification process.

3. Determination of a storing mechanism by which the polymer-asphalt separation is minimized or eliminated and the effect of prolonged storing in the rheological properties of the blends from which a practical shelf life can be identified.
4. Determining the impact of the polymer modification in the environmental and health considerations during mixture production and construction and during long term service.

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Appendix A

Description of Tests Used in this Research

DESCRIPTION OF TESTS USED IN THIS RESEARCH

In order to provide a common platform for the readers of this dissertation, physical, consistency, rheological, performance related and aging tests used in this research are briefly described in this chapter.

A.1 Physical and Consistency tests

Physical and consistency tests include penetration, viscosity, specific gravity, ductility, softening point and flash point:

Penetration In the penetration test (ASTM D 545), a sample of about 50 g is poured in a tin, and placed in a water bath at 25 °C for 2 hours, then tested using a standard needle loaded with 100 g and allowed to penetrate the sample for a period of 5 seconds. The distance that the needle moved is recorded as the penetration in 0.1 mm. Penetration is also performed at other temperatures such as 4 °C and subjected to a loading of 200 g for 60 seconds; to compute the asphalt binder temperature susceptibility. Plate A.1 shows the penetration test setup.

Viscosity Three viscosity tests were performed, kinematic, absolute and low temperature viscosity tests. Absolute viscosity (ASTM D 2171) was performed at 60 °C using the Asphalt Institute vacuum capillary viscometer. The test starts by pouring a sample into the viscometer up to

Plate A.1: Penetration Test Set-up.

the fill line, connecting a vacuum of 300 ± mm of mercury, conditioning the sample for a period of 30 min., then starting the flow and measuring the time required to for the asphalt binder to pass between successive pairs of timing marks. The viscosity in Poises (P) is computed by multiplying the recorded time by the viscometer constant. Plate A.2 shows the absolute viscosity test setup.

The Kinematic viscosity (ASTM D 2170) is measured using the Zeitfuchs cross-arm viscometer at 135 °C by pouring the sample to the fill line, conditioning the sample for 15 minuets at the test temperature then starting the flow and measuring the time required to pass between the time marks. The kinematic viscosity in centistokes (cSt) is obtained by multiplying the measured time by the viscometer constant. Plate A.2 shows the kinematic viscosity test setup.

Low temperature viscosity was measured at 25 °C using the sliding plate viscometer (ASTM D 3570).

Specific Gravity Asphalt binder specific gravity was determined using the pycnometer method. The pycnometer is weighed empty, filled with water, weighed, charged with the sample approximately 5 g, weighed with the sample, filled with water and weighed. These weights are used to compute the specific gravity.

Ductility The ability of the asphalt binder to stretch is measured using the ductility test (ASTM D 113) at 25 °C. The test starts by preparing the molds with the sample, placing the molds in the testing machine, conditioning for 30 minuets at 25 °C, then starting stretching the sample at a rate of 1.0 cm per

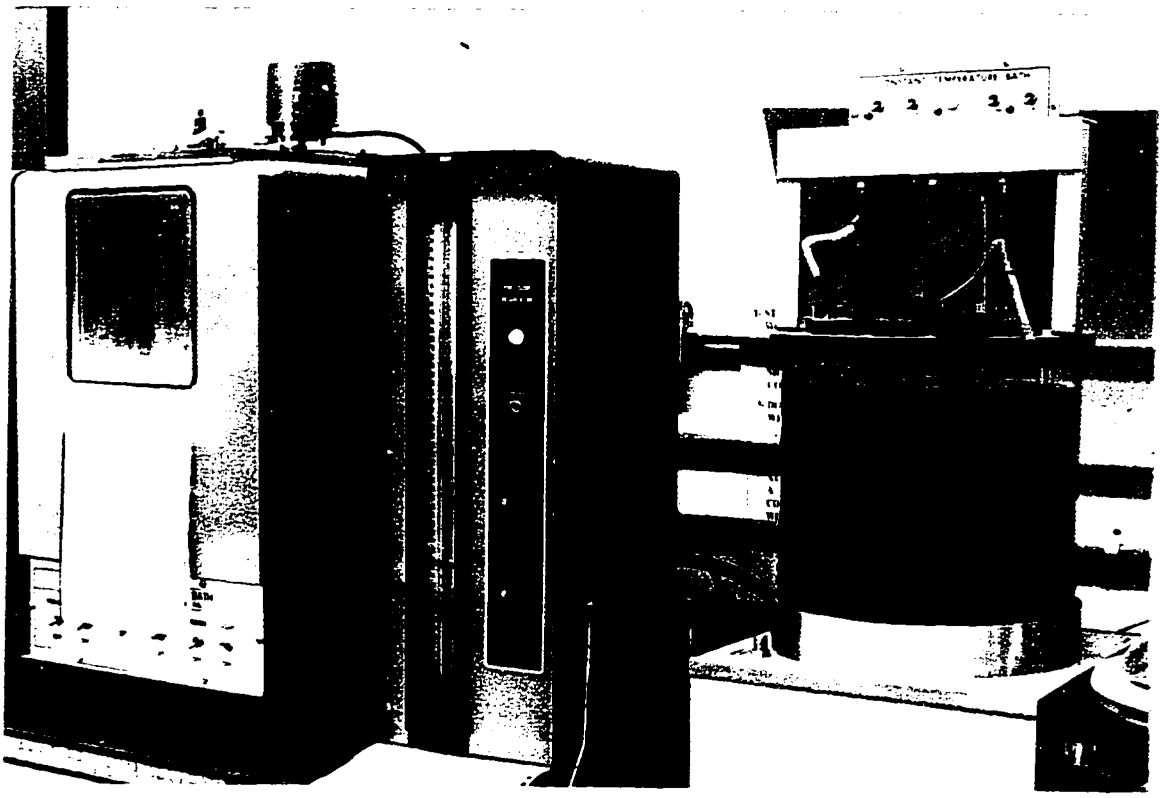


Plate A.2: Absolute and Kinematic Viscosity Tests Set-up.

minuet. Once the sample brakes, the distance is measured in cm and reported as the ductility at 25 °C.

Softening point The softening point (ASTM D 36) measures the temperature at which the asphalt binder starts to flow. A special molds is filled with the sample, conditioned in a refrigerator for 15 minuets, placed in the testing beaker mounting the standard ball on the top, then the heating started at a rate of 5.0 °C per minute, the sample is observed until the ball penetrate through the sample and hit the bottom plate, this temperature is recorded in °C and reported as the softening point. Plate A.3 shows the softening point test setup.

Flash point In this test, a sample of the asphalt binder is poured into the open cup, placed in the testing set up, the heat is started at a rate of 15 °C per minute, passing a flame right above the sample regularly, once flashing is observed, the temperature is recorded in °C and reported as the flash point. This test is considered a safety precaution against firing while heating of the asphalt binder during asphalt mixture production.

A.2 Rheological and performance tests

Rheological and performance tests include rotational viscosity, complex shear modulus, phase angle, flexural creep stiffness and rate of creep.

Rotational viscosity High temperature workability of the asphalt binder during pumping and mixing is characterized by the rotational viscosity (ASTM D-4402). This viscosity is measured using the Brookfield apparatus which is a rotational coaxial cylinder viscometer. Asphalt binder sample of 10.5 g is

Plate A.3: Softening Point Test Set-up.

heated to 135^{o}C then a spindle is submerged into it. A 15 minute conditioning period is required to retain the testing temperature. The rotational viscosity is determined by measuring the torque required to maintain a constant speed of the spindle. The read-out unit in the apparatus will display the rotational viscosity in (cP) when stabilized, three readings are recorded at 1 minute interval. Plate A.4 shows the rotational viscosity test setup

Complex shear modulus and phase angle The viscous and elastic behavior of asphalt binder are characterized by the dynamic shear rheometer (DSR). This characterization is accomplished by measuring the shear modulus ,G*, and the phase angle, δ, of the asphalt binder at high and intermediate temperature ranges (16 to 80 ^{o}C). The test starts by pouring the sample into a silicon molds, sandwiching the asphalt binder between a fixed plate and a plate that rotates in an oscillatory manner (back and forth) at a frequency of 10 radians per second (1.59 Hz), trimming the excess material in the sides, conditioning the sample for 15 minutes so that testing temperature is achieved, then starting the test. Ten cycles are applied to condition the sample followed by another ten to measure G* and δ. Plate A.5 shows the dynamic shear rheometer setup.

Flexural creep stiffness Low temperature (0 to -18 ^{o}C) flexural creep stiffness is measured by the bending beam rheometer (BBR). The constant loading resistance is measured by the flexural creep stiffness. In addition, the change in the stiffness with time is measured by the m-value which is the slope of the log creep stiffness vs. log loading time curve at 60 seconds.

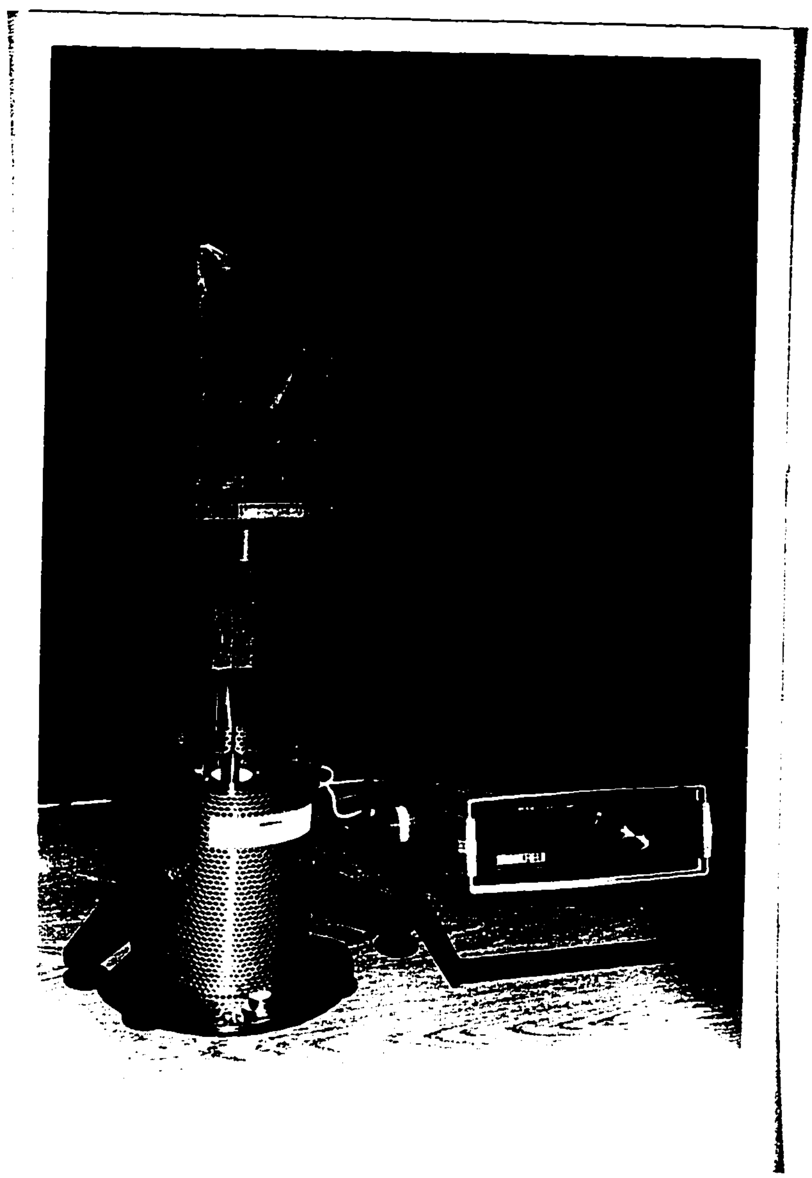


Plate A.4: Brookfield Rotational Viscometer.

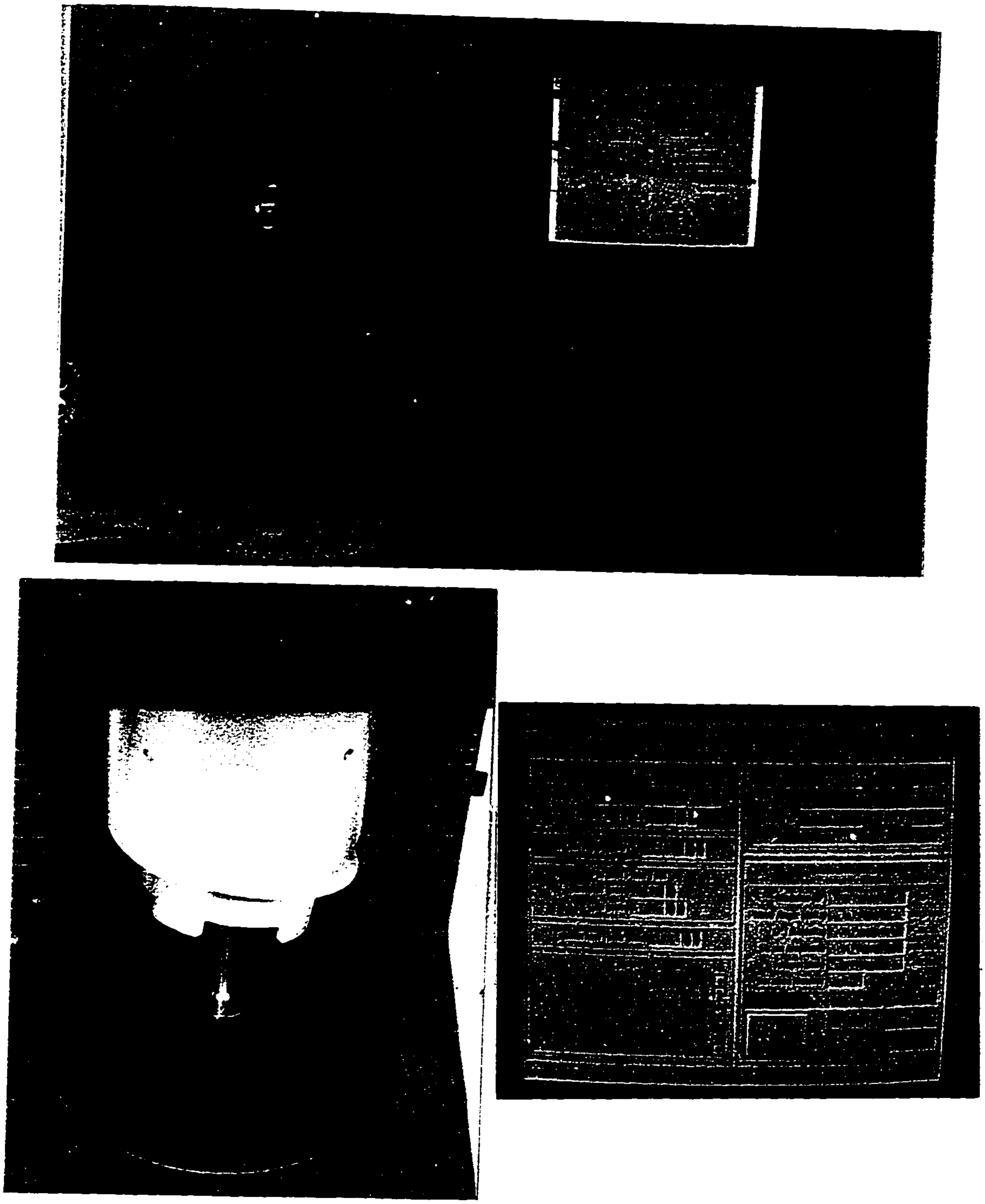


Plate A.5: Dynamic Shear Rheometer.

The test starts by pouring the sample into a beam mold, trimming the excess material, conditioning the sample at room temperature for 2 hours, demolding the sample, conditioning the sample at the testing temperature for 1 hour, loading the beam of the asphalt binder with a 100 g load for a period of 240 seconds, during which the deflection of the beam is recorded. This deflection is plotted against time in a log-log graph and used to calculate the flexural creep stiffness and the m value. Plate A.6 shows the bending beam rheometer setup.

A.3 Aging Tests

The aging tests were performed to simulate the real aging process that take place during mixing and production of the asphalt mixture and during the service life of the pavement. Rolling thin Film Oven Test (RTFOT) is used to simulate short term aging and the Pressure Aging Vessel (PAV) to simulate the long term aging.

RTFOT This test (ASTM D 2872) is performed to obtain an asphalt binder sample that exhibits similar properties of the same asphalt binder if obtained right behind the paving machine. It starts by pouring a 35 g into the test glass bottles, placing the bottles with the sample in the oven rack, starting the timer and the sample rack rotation after attaining the test temperature of 163 °C and continuing the aging process for 85 minuets. Plate A.7 shows the RTFOT setup.

PAV This test is performed to obtain an asphalt binder sample that exhibits similar properties of the same asphalt binder obtained after 7 to 8 years in service. It starts by pouring a 50 g form the RTFOT residue into the test pan, placing the pan in the pan holder, placing the pan holder with the

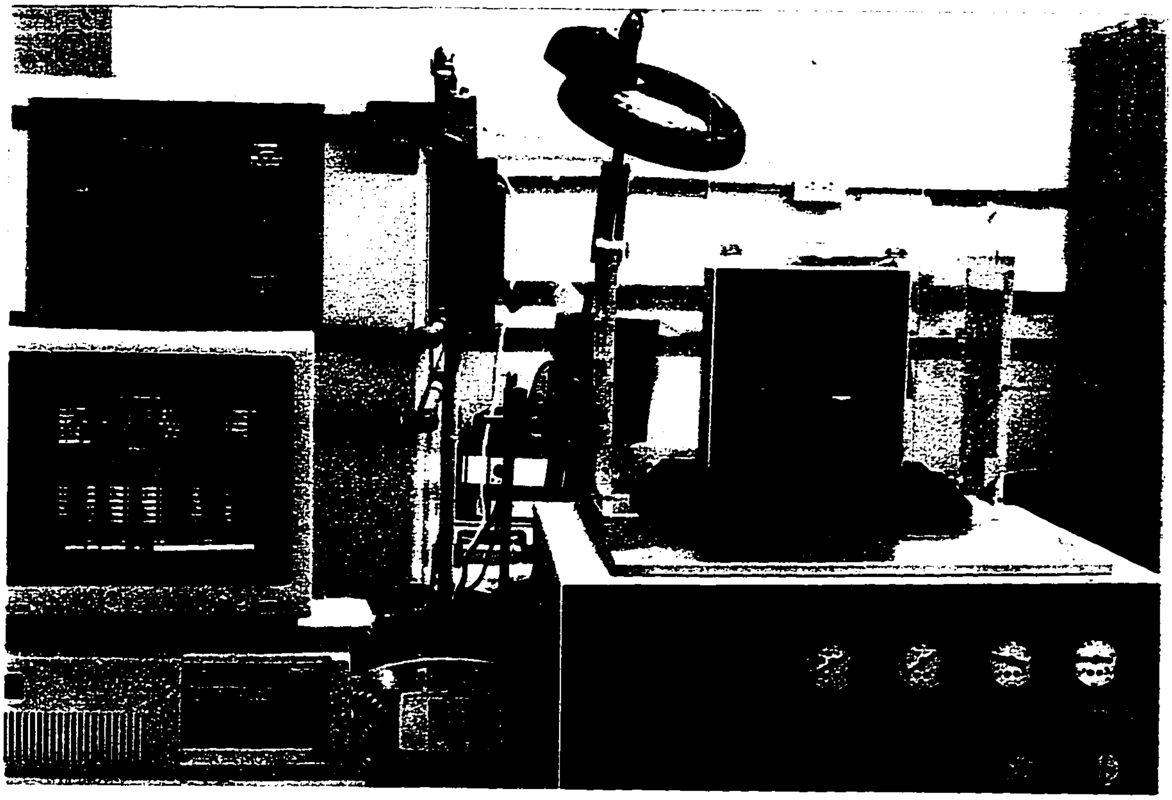


Plate A.6: Bending Beam Rheometer.

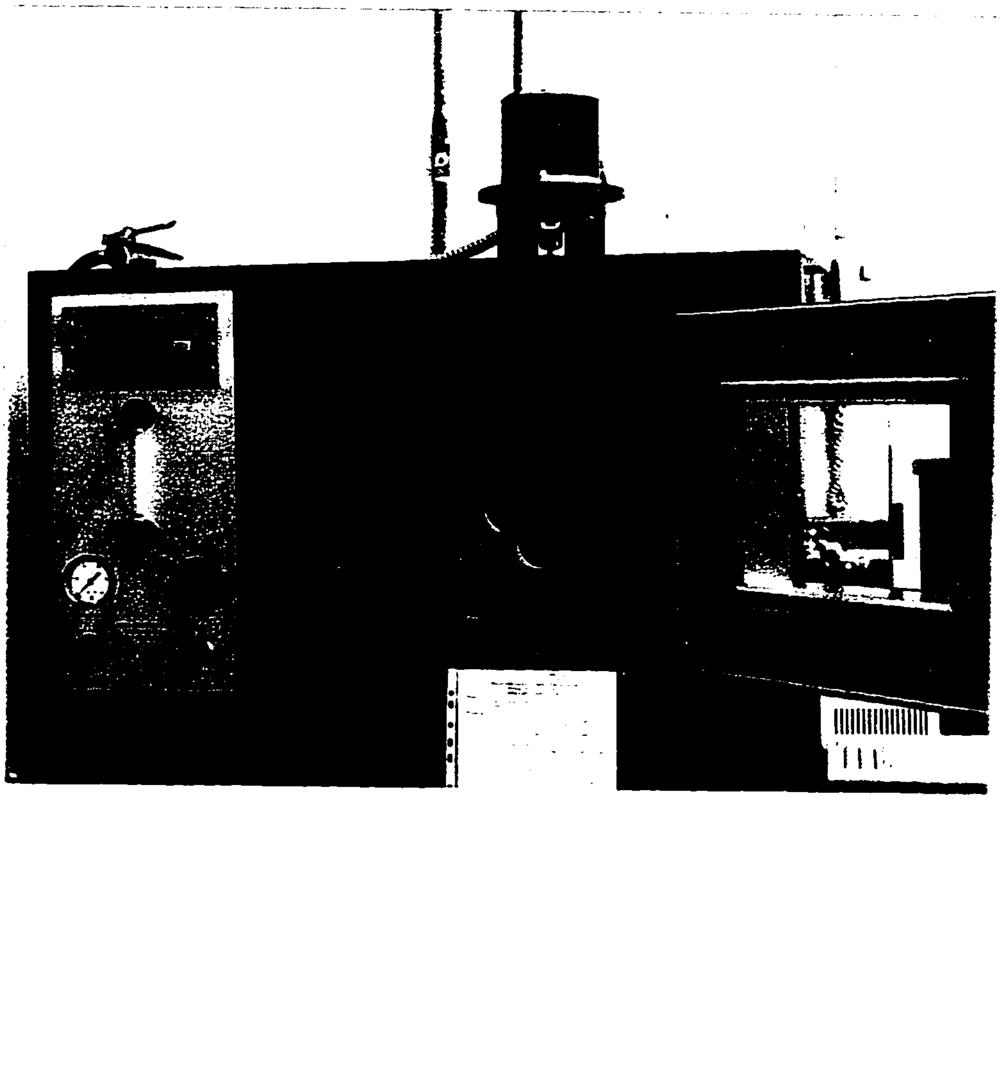


Plate A.7: Rolling Thin Film Oven (RTFOT).

filled pans in the vessel, placing the vessel in the oven, connecting the temperature probe and the pressure nozzle, applying a pressure of 2070 kPa, starting the timer after attaining the test temperature of 110 °C and continuing the aging process for 20 hours. Plate A.8 shows the PAV setup.

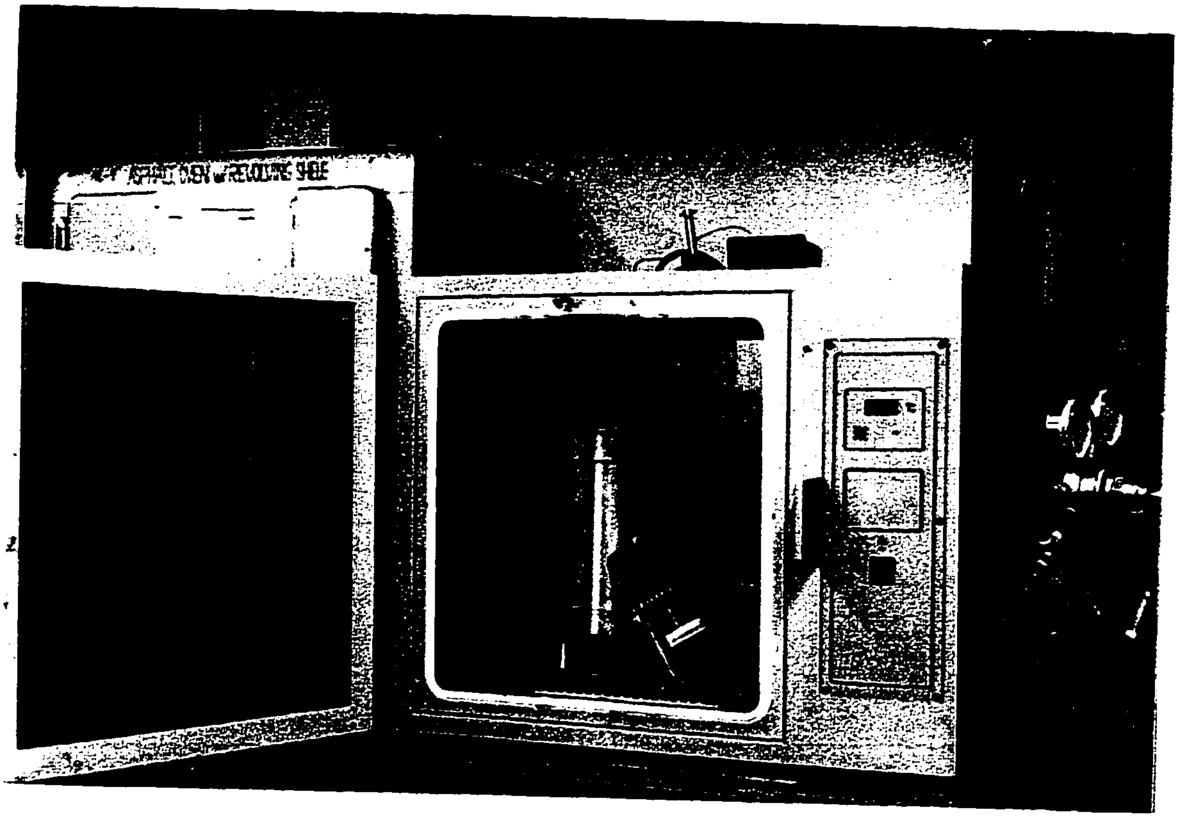


Plate A.8: Pressure Aging Vessel (PAV).

Appendix B

Test Results of Neat Asphalt Binder Characterization

Table B-1: Summary of Physical Testing

Sample #	Pentration @ 25 C, 50gms, 5sec						Pentration @ 4 C, 200 gms, 60 sec						
	1	2	3	4	5	Average	1	2	3	4	5	6	Average
RT1	59.50	60.00	60.00	59.50	x	59.75	29.50	29.00	29.00	x	x	x	29.17
RT2	62.50	63.00	64.00	64.00	63.50	63.40	29.00	29.50	29.25	29.50	29.25	x	29.30
RT3	55.00	56.00	54.50	56.50	56.00	55.60	31.00	31.00	31.00	29.00	x	x	30.50
RT4	51.00	49.50	50.50	51.50	x	50.63	31.50	32.00	32.50	x	x	x	32.00
RT5	55.50	57.00	57.00	56.50	56.00	56.40	32.00	32.50	31.00	32.50	x	x	32.00
RT1R	54.00	53.00	54.00	x	x	53.67	26.00	25.75	26.00	26.25	26.25	x	26.05
RT2R	54.00	53.50	55.00	54.00	55.50	54.40	26.00	27.50	26.00	27.00	x	x	26.63
RT3R	49.50	50.00	49.50	49.00	x	49.50	24.50	26.00	25.00	26.00	x	x	25.38
RT4R	45.00	47.00	46.00	46.00	x	46.00	25.00	26.00	27.00	27.00	x	x	26.25
RT5R	52.00	51.50	52.00	52.00	x	51.88	29.00	30.00	29.00	29.50	x	x	29.38
BH1	44.00	45.00	47.00	44.50	46.00	45.30	17.00	16.50	16.00	16.50	17.00	17.00	16.67
BH2	46.00	47.00	48.00	47.00	47.50	47.10	16.50	16.00	16.50	16.50	17.00	17.00	16.58
BH3	48.50	48.00	48.00	48.00	x	48.13	21.00	22.00	23.00	23.00	22.50	x	22.30
BH4	50.00	50.50	51.00	50.00	49.50	50.20	20.00	22.00	21.50	21.00	x	x	21.13
BH5	48.50	48.00	48.50	x	x	48.33	21.00	23.00	23.00	24.00	23.50	x	22.90
BH1R	34.50	34.00	35.00	34.50	x	34.50	16.00	15.50	16.00	x	x	x	15.83
BH2R	35.00	36.00	35.00	35.50	x	35.38	15.50	14.50	16.00	16.50	x	x	15.63
BH3R	38.00	39.00	38.00	38.00	x	38.25	17.50	16.50	18.00	18.50	x	x	17.63
BH4R	39.00	40.00	40.00	41.50	41.00	40.30	16.50	17.00	16.00	16.50	x	x	16.50
BH5R	38.00	37.50	38.00	37.00	37.00	37.50	17.00	16.00	17.00	17.50	x	x	16.88
RY1	54.00	55.00	53.50	54.50	x	54.25	21.00	22.00	20.50	21.50	x	x	21.25
RY2	56.00	56.50	57.00	x	x	56.50	22.00	21.50	23.00	23.50	x	x	22.50
RY3	50.00	49.00	50.00	49.50	x	49.63	21.00	21.50	20.50	x	x	x	21.00
RY4	55.00	54.00	54.00	x	x	54.33	22.50	23.00	23.50	22.00	x	x	22.75
RY5	50.00	51.00	50.55	51.50	x	50.76	21.00	20.50	20.00	x	x	x	20.50
RY1R	41.00	42.50	43.00	x	x	42.17	19.00	18.00	18.50	19.00	x	x	18.63
RY2R	38.00	39.50	39.00	x	x	38.83	18.00	19.00	18.50	x	x	x	18.50
RY3R	38.00	40.00	39.00	x	x	39.00	16.00	16.50	16.00	16.50	x	x	16.25
RY4R	41.50	42.00	43.00	42.50	x	42.25	18.00	18.00	17.25	19.00	x	x	18.06
RY5R	35.00	36.00	35.50	x	x	35.50	19.00	19.50	18.50	x	x	x	19.00
KW1	52.50	53.00	52.50	53.50	x	52.88	23.00	24.00	25.00	24.00	x	x	24.00
KW2	50.50	50.00	50.50	51.00	x	50.50	22.50	22.50	24.00	23.00	x	x	23.00
KW3	54.00	55.50	54.00	54.00	x	54.38	24.00	25.00	25.50	26.00	x	x	25.13
KW4	56.00	55.50	57.00	56.00	x	56.13	24.00	26.00	25.00	24.00	26.00	x	25.00
KW5	55.00	55.00	54.50	x	x	54.83	23.50	24.00	25.00	25.00	x	x	24.38
KW1R	39.50	39.00	38.50	x	x	39.00	15.00	15.00	16.00	17.00	x	x	15.75
KW2R	31.00	32.00	32.50	32.00	x	31.88	19.00	20.00	18.50	20.00	x	x	19.38
KW3R	34.00	35.00	34.50	35.00	x	34.63	17.00	18.00	18.50	18.00	x	x	17.88
KW4R	35.00	36.00	37.00	36.00	x	36.00	19.00	18.50	19.00	19.50	x	x	19.00
KW5R	29.00	28.00	29.00	28.00	28.50	28.50	17.00	19.00	17.50	18.00	x	x	17.88

Table B-2: Summary of Physical Testing

Sample #	Absolute Viscosity @ 60 C												
	1st Viscometer						2nd Viscometer						
	B	C	D	E	F	Average	B	C	D	E	F	Average	Avg. Avg.
RT1	3036.58	3129.89	3082.80	3229.80	3373.50	3170.51	3475.80	3578.20	3200.50	2930.60	2695.40	3176.10	3173.31
RT2	3184.70	3161.00	3271.80	3239.40	3275.90	3226.56	3098.70	3267.40	3179.40	3203.70	3163.20	3182.48	3204.52
RT3	3345.40	3325.70	3402.80	3416.40	3438.10	3385.68	3339.40	3293.50	3305.40	3342.50	3295.70	3315.30	3350.49
RT4	3434.60	3507.30	3607.20	3579.40	3616.60	3549.02	3602.40	3492.20	3492.80	3665.20	3580.20	3566.56	3557.79
RT5	2946.70	2907.60	3005.30	3015.30	2993.90	2973.76	2948.90	3003.50	3016.90	3013.40	3009.30	2998.40	2986.08
RT1R	x	x	x	5097.60	5068.40	5083.00	x	x	x	5199.20	5076.90	5138.05	5110.53
RT2R	5523.00	5557.20	5667.90	5782.00	5729.90	5652.00	5586.50	5656.40	5537.80	5855.60	5763.30	5679.92	5665.96
RT3R	5672.60	5746.80	5902.30	5867.90	5978.50	5833.62	5923.00	5986.90	6100.80	6059.90	6071.30	6028.38	5931.00
RT4R	8658.40	8690.90	9202.10	9080.60	9111.60	8948.72	8636.20	8876.30	9077.40	9147.40	9120.00	8971.46	8960.09
RT5R	6819.90	6909.50	7172.40	7215.10	7236.80	7070.74	6840.60	6927.60	7056.60	7057.60	7096.80	6995.84	7033.29
BH1	3409.60	3410.70	3474.00	3371.90	3407.90	3414.82	3341.80	3398.10	3421.20	3383.20	3370.60	3382.98	3398.90
BH2	3098.14	2984.10	3046.20	3028.30	3038.20	3038.99	3115.40	3059.00	3019.40	3039.00	2999.40	3046.44	3042.71
BH3	2828.80	2823.10	2895.20	2843.30	2888.30	2855.74	2833.30	2858.40	2876.40	2840.10	2832.20	2848.08	2851.91
BH4	2975.80	2955.40	3012.50	2972.90	2983.10	2979.94	2961.10	2992.90	2995.20	2978.40	2955.70	2976.66	2978.30
BH5	2908.50	2858.60	3608.10	2810.40	2865.50	3010.22	2830.20	2904.40	2820.00	2834.70	2886.40	2855.14	2932.68
BH1R	5828.30	5750.00	5635.20	5772.70	5405.40	5678.32	5318.20	5450.90	5550.80	5572.80	5528.40	5484.22	5581.27
BH2R	6592.40	5905.80	6059.20	6027.70	6148.90	6146.80	6081.40	6105.60	6183.90	6114.20	6140.90	6125.20	6136.00
BH3R	4952.60	5044.60	5143.40	4971.20	5095.70	5041.50	5057.40	5127.10	5169.40	4646.40	5046.60	5009.38	5025.44
BH4R	5233.30	5258.70	5225.90	5231.70	5333.20	5256.56	5129.50	5087.20	5175.60	5187.90	5153.70	5146.78	5201.67
BH5R	4966.70	4975.30	4934.30	5001.80	5088.00	4993.22	4940.60	5005.50	4979.00	4951.30	5085.40	4992.36	4992.79
RY1	2686.30	2567.60	2643.20	2617.30	2607.50	2624.38	2687.90	2619.80	2608.70	2615.90	2570.10	2620.48	2622.43
RY2	2767.40	2731.60	2738.50	2655.30	2659.80	2710.52	2696.60	2675.00	2657.30	2666.50	2679.40	2674.96	2692.74
RY3	3090.70	3039.30	3143.90	3108.90	3060.30	3088.62	3127.10	3086.10	3130.20	3111.70	3069.20	3104.86	3096.74
RY4	2682.20	2574.50	2661.70	2593.70	2601.90	2622.80	2689.80	2625.48	2647.60	2630.20	2607.40	2640.10	2631.45
RY5	2954.10	2985.10	2979.90	2873.40	2910.60	2940.62	2920.60	2948.40	2923.70	2901.10	2957.60	2930.28	2935.45
RY1R	4660.60	4694.60	4658.60	4697.00	4634.40	4669.04	4650.20	4671.30	4640.90	4620.10	4633.10	4643.12	4656.08
RY2R	5868.10	5858.90	5971.20	5949.70	5923.10	5914.20	5804.60	5951.70	5922.20	5915.90	5934.60	5905.80	5910.00
RY3R	6195.20	6101.80	6232.50	6614.90	9234.80	6875.84	6197.80	6231.90	6241.90	6217.40	6190.90	6215.98	6545.91
RY4R	5104.90	5176.50	5168.90	5013.70	5064.40	5105.68	5109.90	5083.10	5077.40	5039.20	5128.60	5087.64	5096.66
RY5R	5680.00	5836.20	5854.60	5720.20	5801.20	5778.44	5647.14	5721.40	5747.80	5760.30	5610.90	5697.51	5737.97
KW1	3281.70	2969.60	3290.90	3175.60	3201.10	3183.78	3215.80	3196.90	3201.70	3174.70	3157.30	3189.28	3186.53
KW2	3371.40	3462.60	3501.40	3420.80	3489.60	3449.16	3547.75	3419.20	3438.30	3407.60	3469.60	3456.49	3452.83
KW3	3840.40	3796.60	3879.60	3836.10	3864.00	3843.34	3991.50	3854.70	3912.90	3825.30	3848.90	3886.66	3865.00
KW4	3298.80	3316.40	3319.00	3296.40	3260.80	3298.28	3335.60	3343.40	3308.20	3291.40	3265.90	3308.90	3303.59
KW5	3588.30	3456.70	3544.90	3485.50	3528.00	3520.68	3944.60	3547.60	3482.40	3517.70	3522.10	3602.88	3561.78
KW1R	6515.70	5781.50	6475.90	6630.20	6592.80	6399.22	6597.60	6559.30	6671.30	6604.20	6574.70	6601.42	6500.32
KW2R	6008.30	6013.70	5949.80	6019.60	x	5997.85	5983.70	5971.50	6024.80	6041.50	x	6005.38	6001.61
KW3R	6987.70	7056.30	7233.90	7092.10	x	7092.50	6815.60	6972.30	6861.30	6916.90	x	6891.53	6992.01
KW4R	7702.50	7633.70	7918.70	7885.20	x	7785.03	7399.60	7487.30	7483.50	7536.50	x	7476.73	7630.88
KW5R	5789.80	5872.20	5964.90	5835.70	5894.70	5871.46	5712.50	5805.50	5816.00	5799.30	5897.20	5806.10	5838.78

Table B-3: Summary of Physical Testing

Sample #	Rotational Viscosity @135C	Kinematic Viscosity @ 135 C			Viscosity @ 25C By Sliding Plate			Softening Point, C					Flash Point
		1	2	Average	1	2	Average	1	2	3	4	Average	1
RT1	468.00	413.34	402.89	408.12	129256	143564	136410.00	50.00	50.00	50.00	51.00	50.25	310.00
RT2	460.00	504.40	480.30	492.35	80582	67917	74249.50	50.00	51.00	50.00	52.00	50.75	308.00
RT3	460.00	473.00	510.10	491.55	72666	68334	70500.00	50.00	50.00	50.00	50.00	50.00	308.00
RT4	480.00	502.61	476.03	489.32	81021	71782	76401.50	50.00	50.00	51.00	52.00	50.75	309.00
RT5	445.00	461.75	419.44	440.60	94731	71066	82898.50	50.00	51.00	51.00	51.00	50.75	306.00
RT1R	x	573.43	534.31	553.87	272925	267323	270124.00	54.60	54.60	54.60	55.00	54.70	x
RT2R	x	583.70	591.06	587.38	157920	143429	150674.50	53.00	53.00	54.00	54.00	53.50	x
RT3R	x	553.07	582.00	567.54	118078	106676	112377.00	56.00	57.00	54.00	55.00	55.50	x
RT4R	x	658.30	691.90	675.10	340152	348366	344259.00	55.00	56.00	56.00	56.00	55.75	x
RT5R	x	567.09	569.03	568.06	130389	120581	125485.00	54.00	55.00	55.00	55.00	54.75	x
BH1	465.00	469.43	494.44	481.94	92233	87589	89911.00	50.00	49.00	50.00	51.00	50.00	338.00
BH2	485.00	491.98	480.97	486.48	107618	99857	103737.50	50.00	49.00	49.00	50.00	49.50	336.00
BH3	460.00	479.46	423.21	451.34	121170	116563	118866.50	49.00	49.00	48.00	50.00	49.00	334.00
BH4	455.00	458.31	445.28	451.80	113794	113794	113794.00	49.00	50.00	50.00	50.00	49.75	336.00
BH5	450.00	432.02	462.74	447.38	95551	89726	92638.50	50.00	50.00	51.00	49.00	50.00	335.00
BH1R	x	631.40	587.31	609.36	208723	202184	205453.50	56.00	57.00	57.00	57.00	56.75	x
BH2R	x	612.30	625.40	618.85	216460	209615	213037.50	57.00	57.00	56.00	56.00	56.50	x
BH3R	x	659.95	597.61	628.78	153036	135497	144266.50	55.00	56.00	55.00	55.00	55.25	x
BH4R	x	600.70	595.84	598.27	209794	209615	209704.50	55.00	55.00	55.00	54.00	54.75	x
BH5R	x	552.29	593.58	572.94	119111	111325	115218.00	54.00	54.00	54.00	55.00	54.25	x
RY1	530.00	401.80	421.90	411.85	94582	96403	95492.50	49.00	49.00	49.00	50.00	49.25	332.00
RY2	490.00	424.50	453.10	438.80	90033	91991	91012.00	50.00	50.00	50.00	49.00	49.75	324.00
RY3	x	456.80	479.60	468.20	112551	114970	113760.50	50.00	50.00	50.00	49.00	49.75	322.00
RY4	x	517.20	528.70	522.95	72323	66898	69610.50	50.00	50.00	50.00	50.00	50.00	320.00
RY5	x	537.33	574.70	556.02	101051	96638	98844.50	52.00	51.00	51.00	51.00	51.25	326.00
RY1R	x	549.90	536.50	543.20	156809	149179	152994.00	53.00	53.00	53.00	53.00	53.00	x
RY2R	x	540.60	561.20	550.90	192428	209795	201111.50	54.00	54.00	55.00	55.00	54.50	x
RY3R	x	560.30	609.40	584.85	157010	169372	163191.00	55.00	56.00	56.00	56.00	55.75	x
RY4R	x	510.90	583.10	547.00	159046	162417	160731.50	52.00	53.00	53.00	54.00	53.00	x
RY5R	x	570.70	577.20	573.95	145462	161881	153671.50	56.00	56.00	56.00	56.00	56.00	x
KW1	555.00	533.41	526.59	530.00	63388	57141	60264.50	50.00	50.00	50.00	51.00	50.25	294.00
KW2	565.00	560.19	608.19	584.19	81558	84598	83078.00	51.00	51.00	50.00	52.00	51.00	298.00
KW3	575.00	506.79	553.96	530.38	74748	84598	79673.00	51.00	51.00	52.00	52.00	51.50	290.00
KW4	590.00	520.51	544.61	532.56	106630	90564	98597.00	50.00	50.00	50.00	50.00	50.00	284.00
KW5	565.00	558.73	587.56	573.15	69240	85662	77451.00	50.00	51.00	50.00	51.00	50.50	288.00
KW1R	x	785.07	687.25	736.16	136402	127138	131770.00	56.00	56.00	56.00	56.00	56.00	x
KW2R	x	676.36	696.63	686.50	150921	191303	171112.00	55.00	55.00	56.00	56.00	55.50	x
KW3R	x	782.15	738.61	760.38	181666	215132	198399.00	56.00	56.00	55.00	55.00	55.50	x
KW4R	x	822.36	759.29	790.83	137318	163937	150627.50	56.00	56.00	56.00	55.00	55.75	x
KW5R	x	696.01	755.44	725.73	186360	222752	204556.00	54.00	55.00	55.00	55.00	54.75	x

Table B-4: Summary of Physical Testing

Sample #	Ductility				Specific Gravity
	1	2	3	Average	1
RT1	115.00	135.00	150.00	133.33	1.0238
RT2	104.00	130.00	145.00	126.33	1.0186
RT3	150+	150+	150+	#DIV/0!	1.0194
RT4	114.00	118.00	125.00	119.00	1.0188
RT5	95.00	107.00	112.00	104.67	1.0189
RT1R	x	x	x	x	x
RT2R	x	x	x	x	x
RT3R	x	x	x	x	x
RT4R	x	x	x	x	x
RT5R	x	x	x	x	x
BH1	150+	150+	150+	150+	1.0293
BH2	150+	150+	150+	150+	1.0253
BH3	150+	150+	150+	150+	1.021
BH4	150+	150+	150+	150+	1.0305
BH5	150+	150+	150+	150+	1.0245
BH1R	x	x	x	x	x
BH2R	x	x	x	x	x
BH3R	x	x	x	x	x
BH4R	x	x	x	x	x
BH5R	x	x	x	x	x
RY1	150+	150+	150+	150+	1.033
RY2	150+	150+	150+	150+	1.024
RY3	150+	150+	150+	150+	1.028
RY4	150+	150+	150+	150+	1.03
RY5	150+	150+	150+	150+	1.024
RY1R	x	x	x	x	x
RY2R	x	x	x	x	x
RY3R	x	x	x	x	x
RY4R	x	x	x	x	x
RY5R	x	x	x	x	x
KW1	150+	150+	150+	150+	1.0374
KW2	150+	150+	150+	150+	1.0324
KW3	150+	150+	150+	150+	1.04
KW4	150+	150+	150+	150+	1.0329
KW5	150+	150+	150+	150+	1.0332
KW1R	x	x	x	x	x
KW2R	x	x	x	x	x
KW3R	x	x	x	x	x
KW4R	x	x	x	x	x
KW5R	x	x	x	x	x

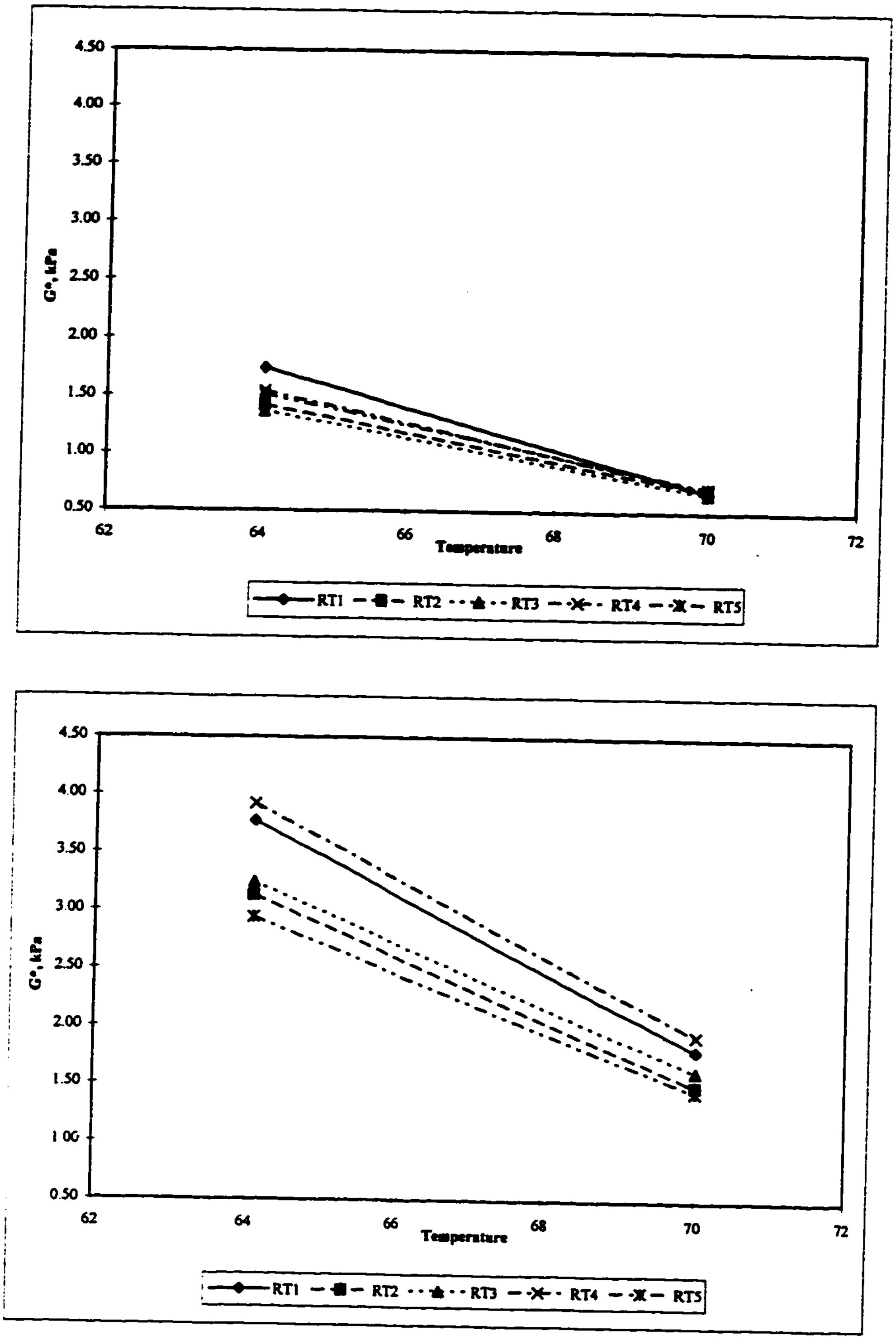
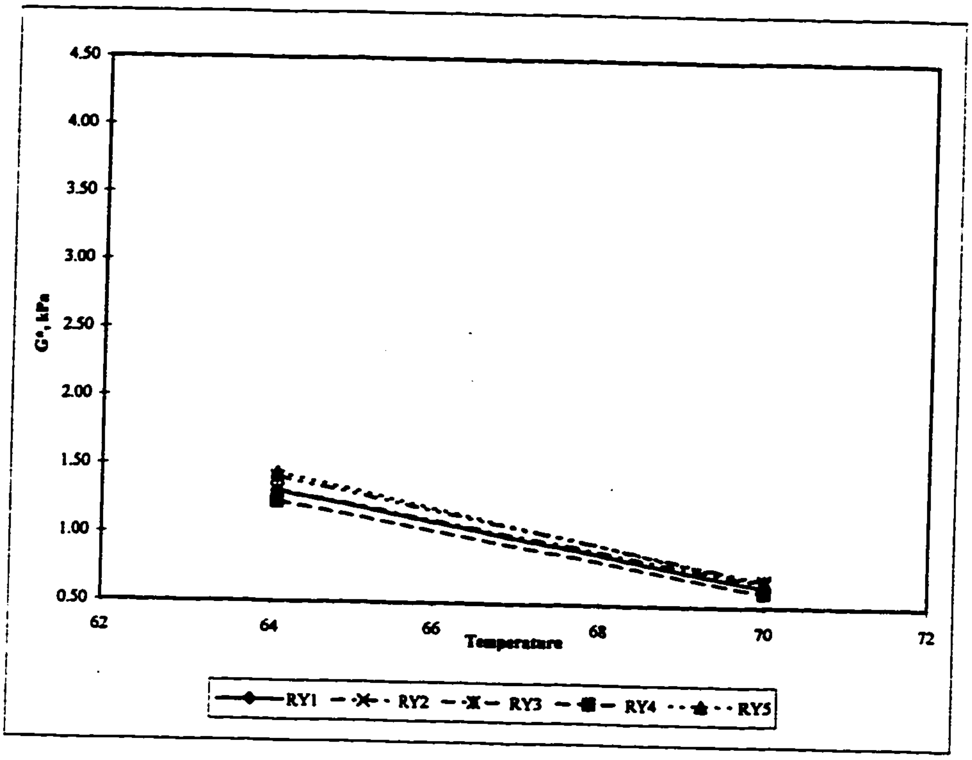


Figure B-1: Variation of G* with Temperature and Age for Various Samples of Ras Tanura Refinery.



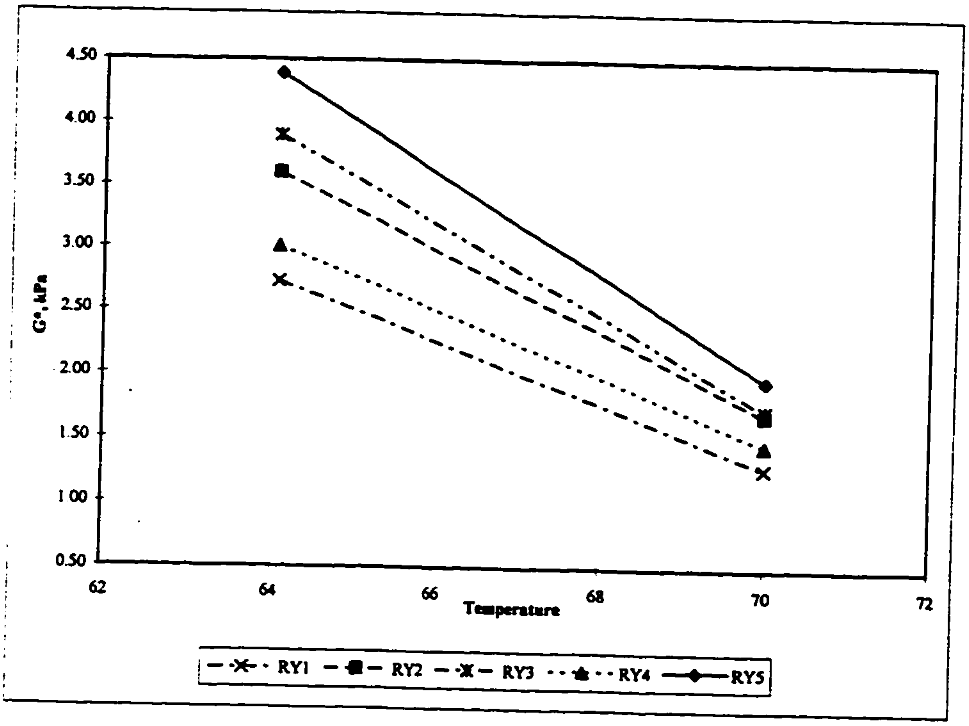
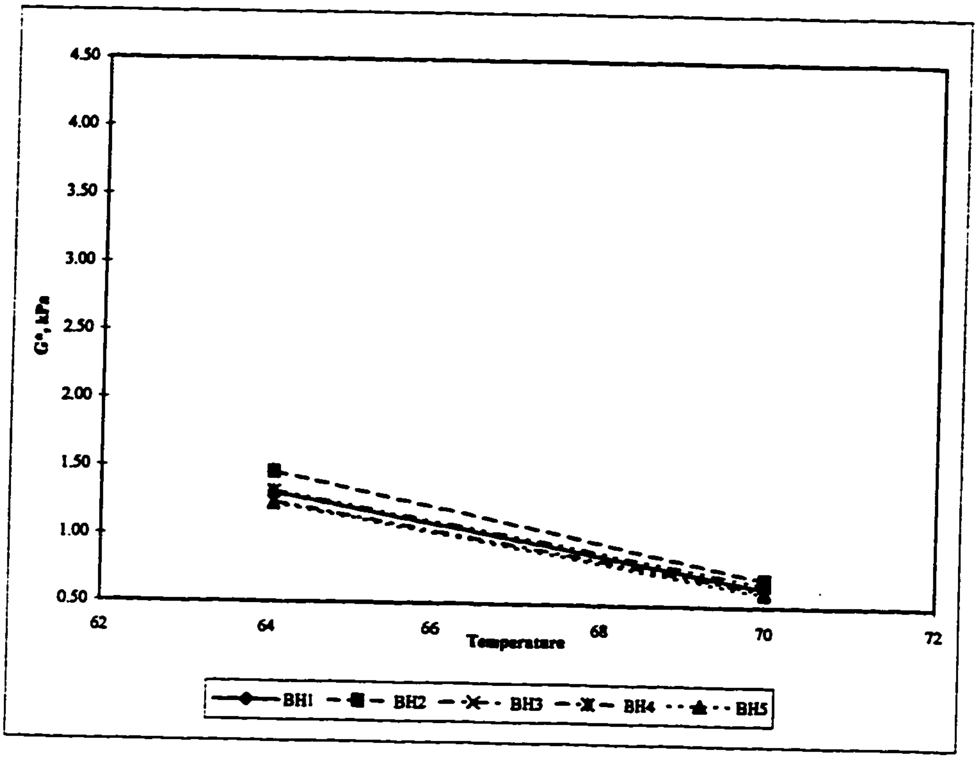


Figure B-2: Variation of G* with Temperature and Age for Various Samples of Riyadh Refinery.



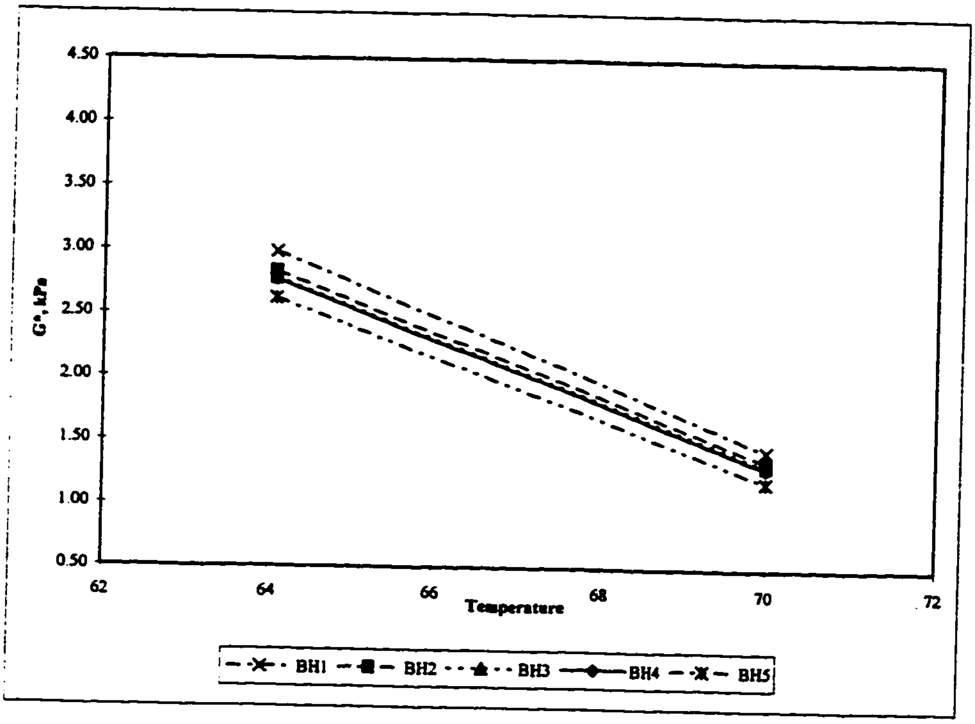
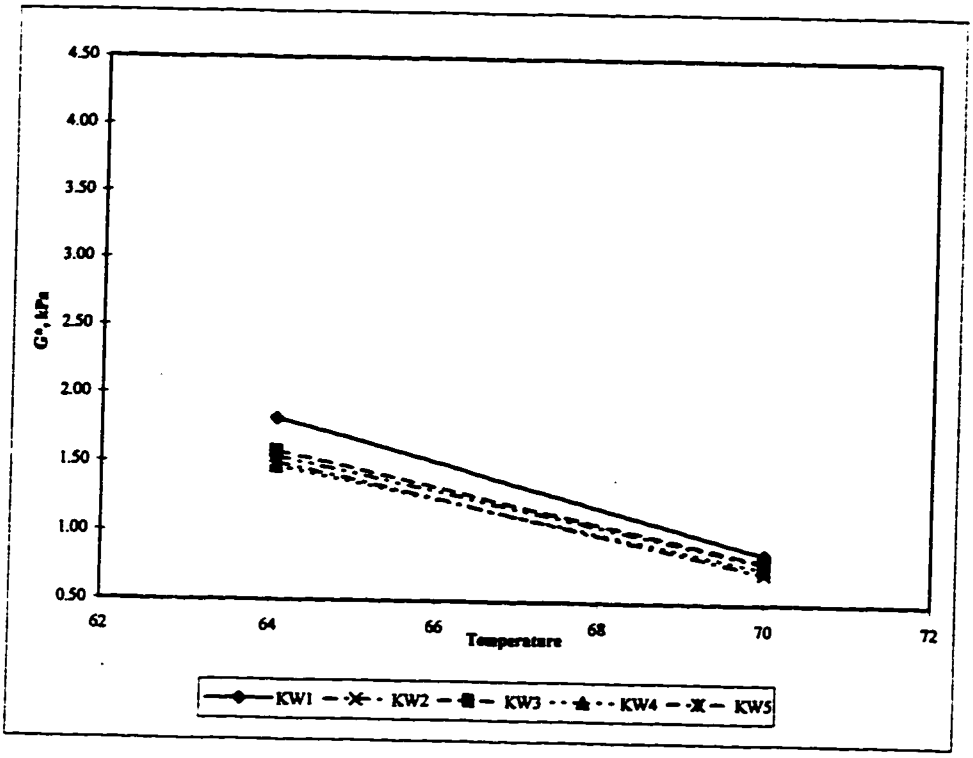


Figure B-3: Variation of G* with Temperature and Age for Various Samples of BAPCO Refinery.



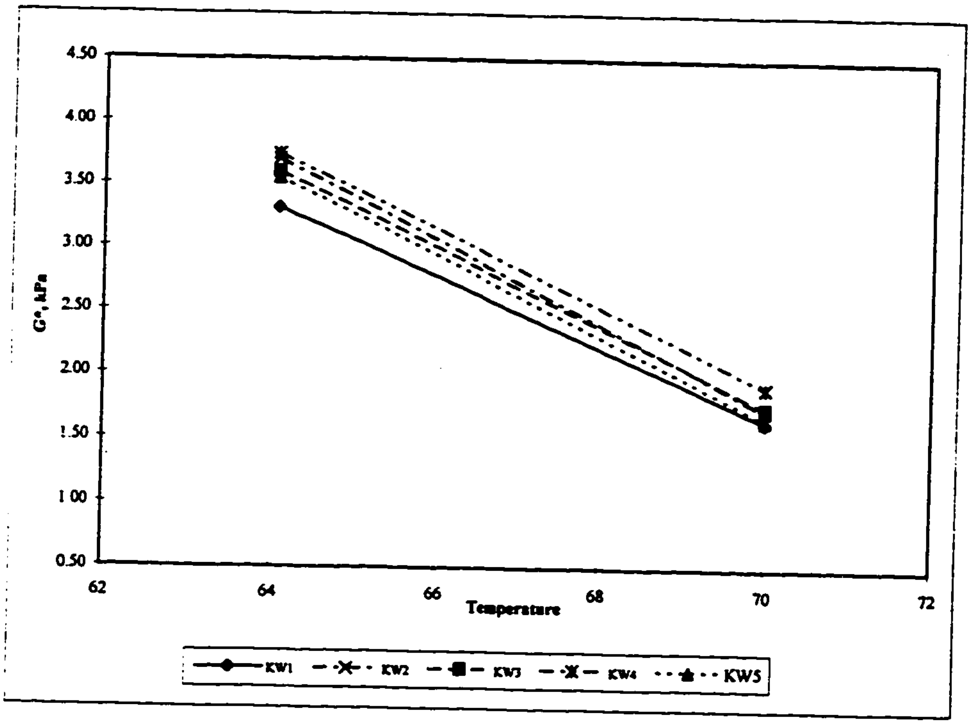
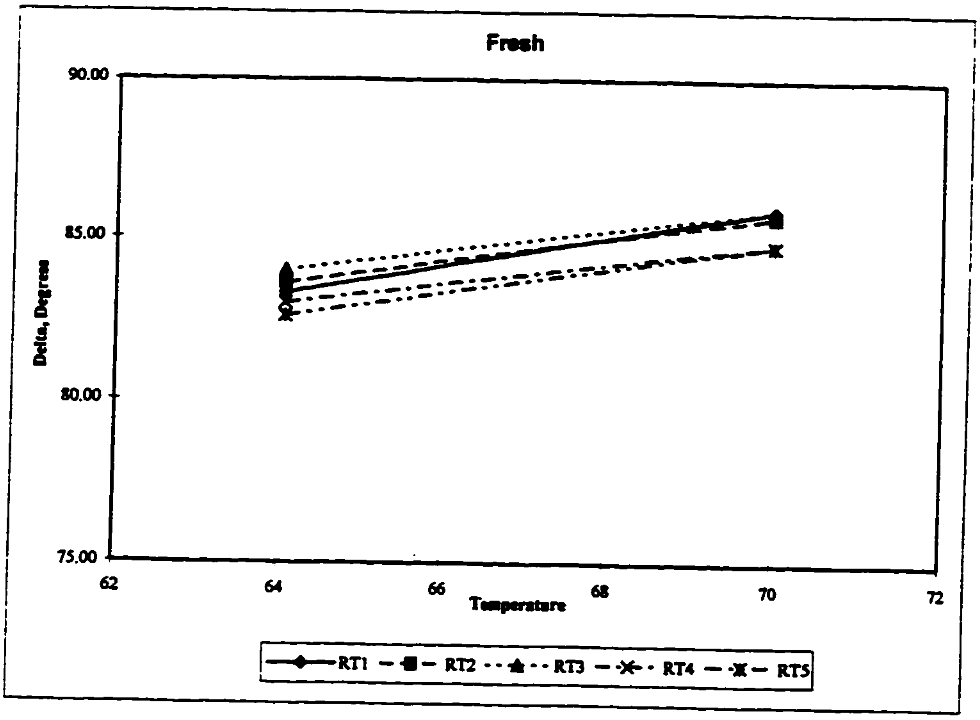


Figure B-4: Variation of G* with Temperature and Age for Various Samples of Al-Ahmadi Refinery.



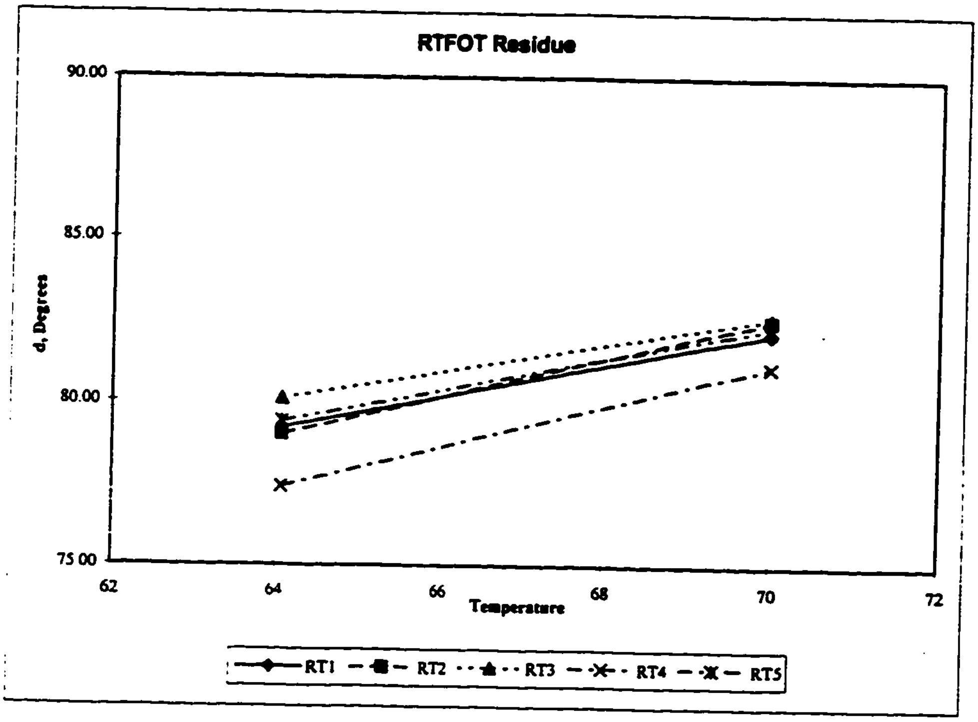
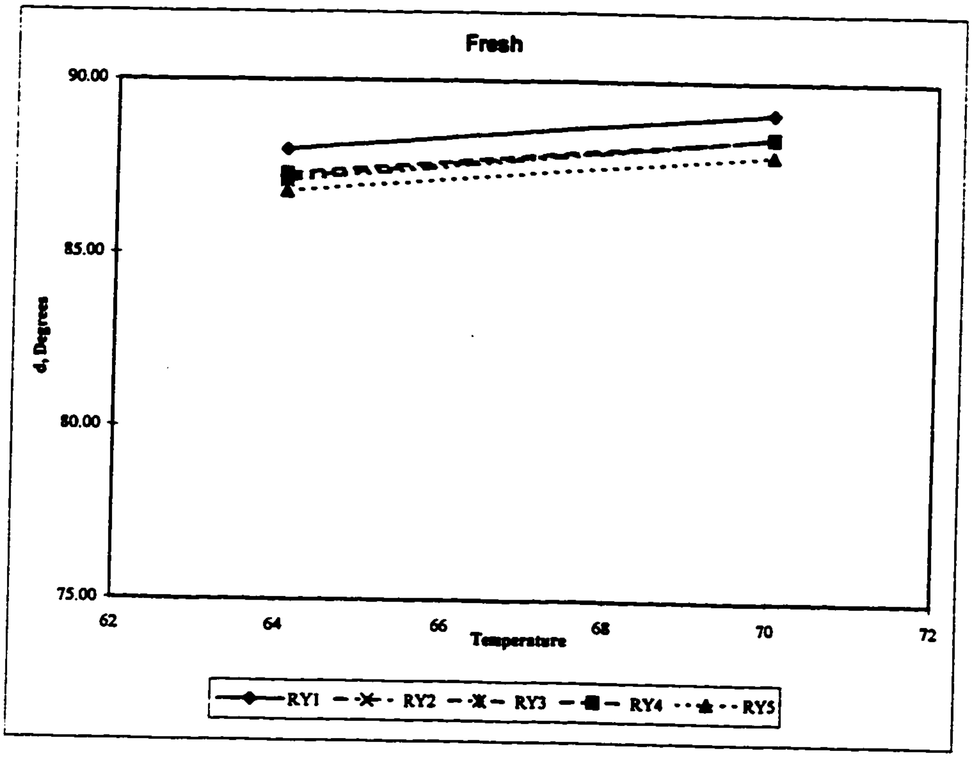


Figure B-5: Variation of δ with Temperature and Age for Various Samples of Ras Tanura Refinery.



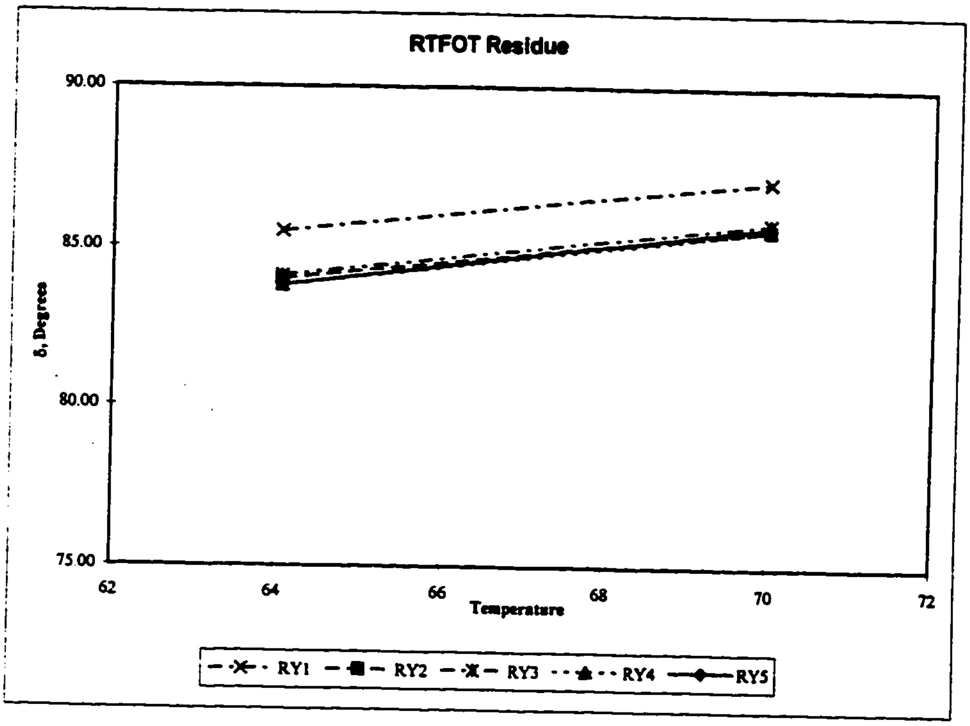
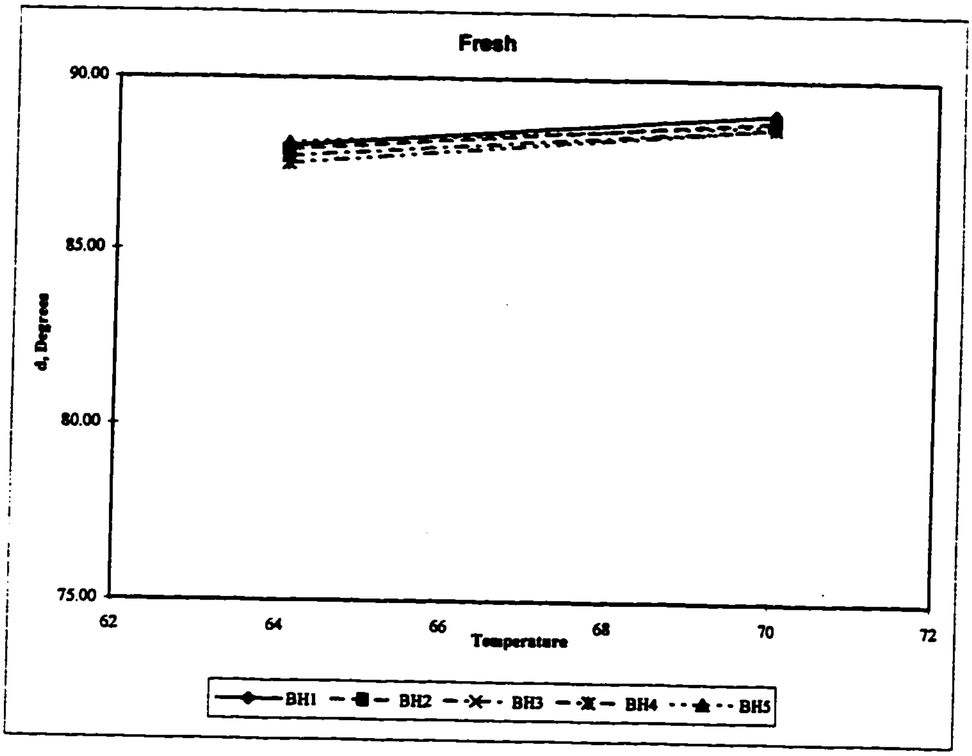


Figure B-6: Variation of δ with Temperature and Age for Various Samples of Riyadh Refinery.



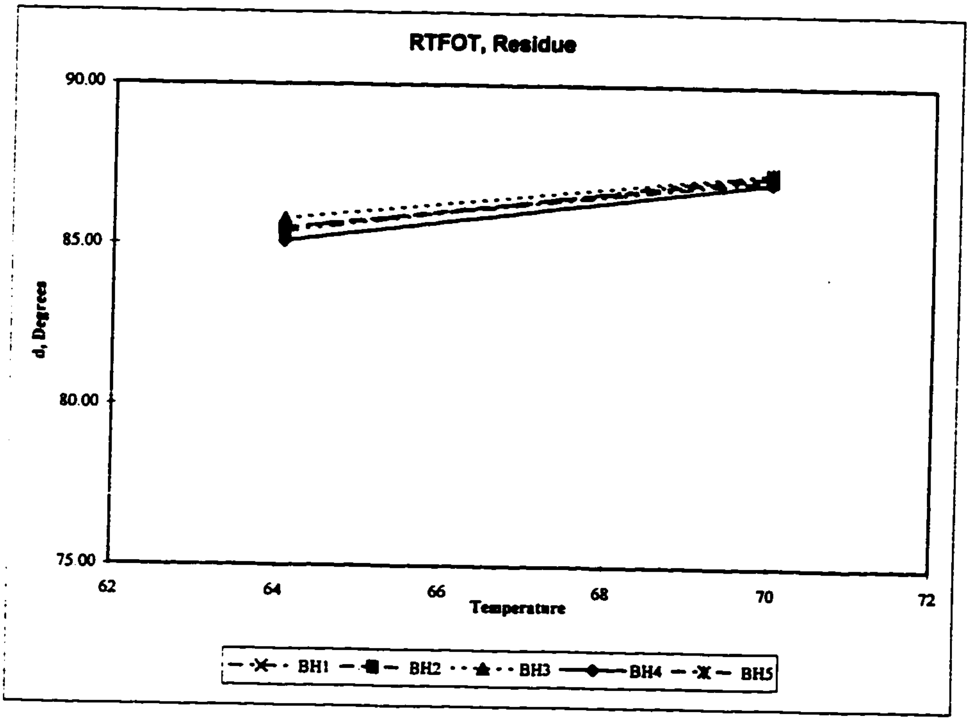


Figure B-7: Variation of δ with Temperature and Age for Various Samples of BAPCO Refinery.

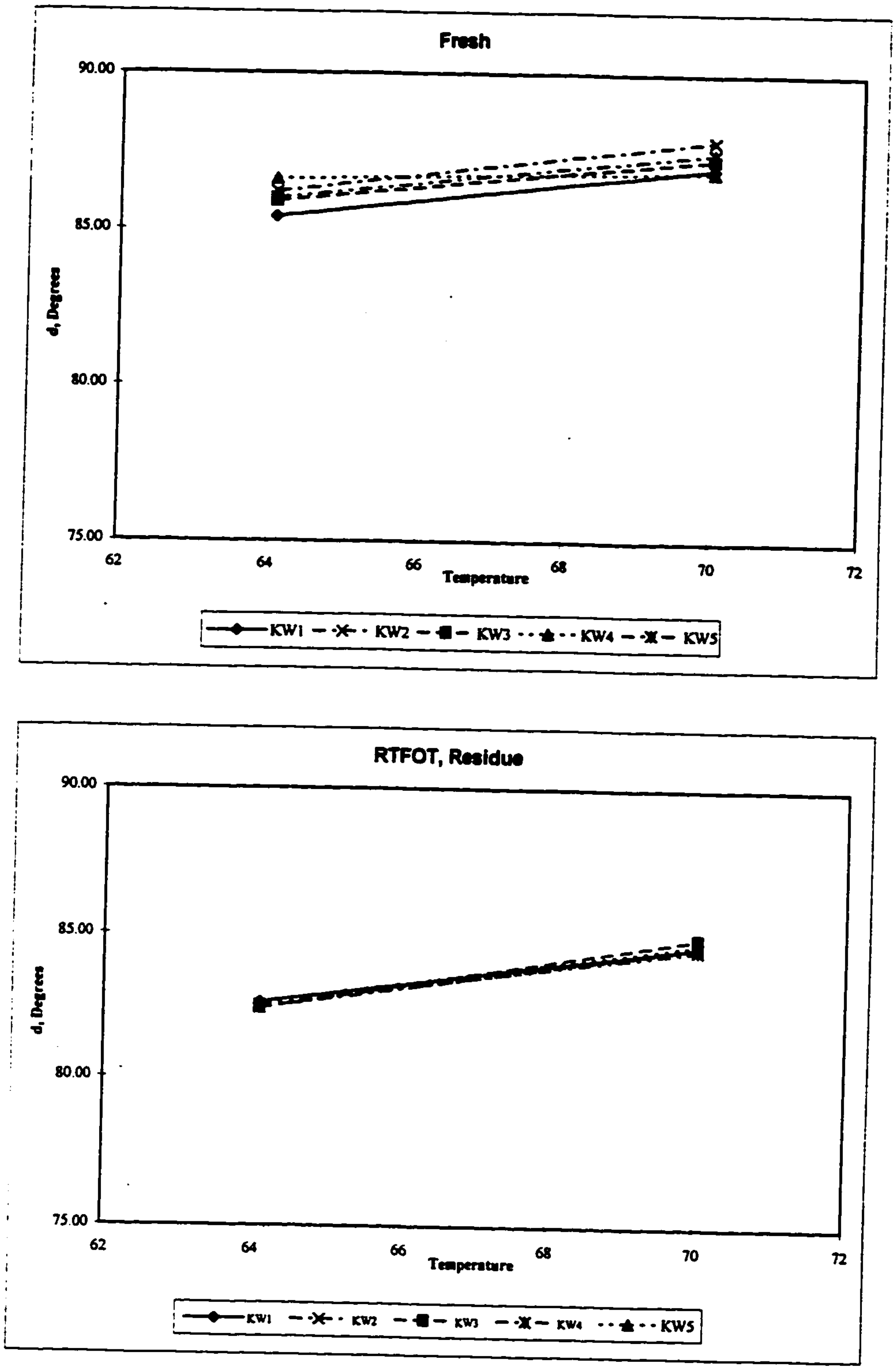


Figure B-8: Variation of δ with Temperature and Age for Various Samples of Al-Ahmadi Refinery.

Appendix C

Test Results of Polymer Optimization

Table C-1: Complex Shear Modulus, G*, (Pa) @ 76 °C, Fresh Blends of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	741	758	752	750	907	897	910	905	619	613	623	618	994	991	999	995
	5.0%	793	794	776	788	924	919	977	940	1470	1487	1436	1464	2417	2099	2077	2198
	10.0%	1357	1349	1361	1356	1649	1656	1634	1646	1089	1076	1075	1080	1869	1885	1784	1846
	15.0%	5834	5309	5329	5491	3328	3310	3275	3304	1781	1844	1832	1819	4330	4339	4321	4330
LLDPE-X	0.0%	1696	1671	1678	1682	1509	1502	1493	1501	635	608	610	618	1470	1403	1427	1433
	3.0%	19396	19188	18704	19096	2519	2483	2500	2501	10236	10131	10231	10199	4544	4455	4478	4492
	6.0%	5639	5588	5496	5574	10108	9984	9955	10016	7736	7656	7516	7636	6057	6596	6588	6414
	9.0%	26481	25783	25409	25891	24250	24084	24025	24120	24153	23109	22690	23317	73192	86301	86511	82001
PP-500U	0.0%	1696	1671	1678	1682	1509	1502	1493	1501	635	608	610	618	1470	1403	1427	1433
	1.5%	11840	11751	11907	11833	5428	5321	5307	5352	7097	7160	7238	7165	4916	5133	5050	5033
	3.0%	12277	12316	12327	12307	4608	4746	4719	4691	6320	6403	6500	6408	4550	4475	4468	4498
	4.5%	7340	7148	7034	7174	8026	7866	7898	7930	9471	9413	9376	9420	8324	8261	8336	8307
SBS	0.0%	741	758	752	750	907	897	910	905	619	613	623	618	994	991	999	995
	3.0%	1426	1457	1516	1466	2188	2158	2138	2161	1122	1095	1097	1105	1018	997	1021	1012
	6.0%	4762	4693	4673	4709	5239	5206	5230	5225	2771	2714	2713	2733	2844	2797	2859	2833
	9.0%	9722	9696	9622	9680	6771	6676	6678	6708	7953	7693	7798	7815	10182	9887	10611	10227

Table C-2: Phase Angle, delta, (Degrees) @ 76 oC, Fresh Blends of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	80.2	79.8	80.1	80.0	82.1	81.9	82.0	82.0	84.1	84.0	84.0	84.0	83.8	84.1	84.0	84.0
	5.0%	76.3	76.2	76.3	76.3	75.5	75.3	75.1	75.3	82.6	83.1	82.8	82.8	77.9	78.3	78.4	78.2
	10.0%	72.5	72.6	72.5	72.5	72.1	72.6	72.7	72.5	78.6	78.9	78.9	78.8	67.8	68.4	69.2	68.5
	15.0%	56.2	56.6	56.5	56.4	62.8	63.1	63.5	63.1	64.5	64.9	65.3	64.9	61.2	61.0	61.6	61.3
LLDPE-X	0.0%	80.2	80.2	80.5	80.3	82.1	81.9	81.6	81.9	80.2	80.5	80.5	80.4	80.9	80.8	80.6	80.8
	3.0%	65.6	65.2	65.2	65.3	82.7	83.2	83.1	83.0	77.1	76.6	76.8	76.8	73.5	74.6	74.8	74.3
	6.0%	71.4	71.8	71.8	71.7	63.9	63.9	63.8	63.9	66.8	66.7	66.2	66.6	74.7	74.8	75.0	74.8
	9.0%	47.1	47.1	47.1	47.1	47.2	47.4	47.3	47.3	48.4	49.2	48.9	48.8	24.8	22.2	22.4	23.1
PP-500U	0.0%	80.2	80.2	80.5	80.3	82.1	81.9	81.6	81.9	80.2	80.5	80.5	80.4	80.9	80.8	80.6	80.8
	1.5%	67.2	67.2	67.2	67.2	78.1	78.0	77.7	77.9	77.1	77.1	77.2	77.1	76.6	76.7	76.2	76.5
	3.0%	67.5	67.8	67.4	67.6	80.3	80.4	80.6	80.4	80.1	81.0	80.9	80.7	77.9	78.1	77.9	78.0
	4.5%	74.2	74.5	74.4	74.4	78.0	78.4	78.2	78.2	79.7	79.9	80.0	79.9	74.2	73.9	74.1	74.1
SBS	0.0%	80.2	79.8	80.1	80.0	82.1	81.9	82.0	82.0	84.1	84.0	84.0	84.0	83.8	84.1	84.0	84.0
	3.0%	78.4	78.9	79.0	78.8	78.4	78.8	78.8	78.7	82.9	83.0	83.1	83.0	82.7	82.8	82.4	82.6
	6.0%	64.0	64.1	63.8	64.0	67.3	67.1	67.3	67.2	69.7	69.3	69.4	69.5	74.0	74.2	74.3	74.2
	9.0%	51.0	51.5	51.5	51.3	51.8	51.9	52.3	52.0	36.2	41.1	39.3	38.9	58.2	59.1	58.6	58.6

Table C-3: G*/sin delta @ 76 oC, Fresh Blends of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	752	770	763	762	916	906	919	914	622	616	626	622	1000	996	1005	1000
	5.0%	817	817	799	811	954	950	1011	972	1482	1498	1447	1476	2472	2144	2120	2245
	10.0%	1427	1415	1423	1422	1733	1735	1711	1727	1112	1096	1096	1101	2018	2027	1909	1985
	15.0%	7021	6360	6391	6591	3742	3712	3659	3704	1974	2037	2016	2009	4941	4960	4913	4938
LLDPE-X	0.0%	1721	1696	1701	1706	1523	1517	1509	1517	644	616	618	626	1489	1421	1446	1452
	3.0%	21372	21069	20604	21015	2540	2501	2518	2519	10516	10131	10231	10293	4740	4622	4641	4668
	6.0%	5949	5882	5785	5872	11256	11118	11095	11156	8457	8333	8180	8323	6278	6836	6822	6645
	9.0%	36147	35186	34676	35336	33050	32719	32691	32820	32292	30653	29991	30979	174650	228530	227430	210203
PP-500U	0.0%	1721	1696	1701	1706	1523	1517	1509	1517	644	616	618	626	1489	1421	1446	1452
	1.5%	12840	12746	12918	12835	5547	5440	5432	5473	7424	7346	7281	7350	5053	5275	5199	5176
	3.0%	13290	13306	13354	13317	4675	4813	4783	4757	6416	6483	6583	6494	4652	4574	4570	4599
	4.5%	7627	7419	7302	7449	8205	8030	8069	8101	9625	9560	9519	9568	8650	8599	8670	8640
SBS	0.0%	752	770	763	762	916	906	919	914	622	616	626	622	1000	996	1005	1000
	3.0%	1453	1485	1548	1495	2234	2200	2180	2204	1104	1105	1130	1113	1026	1005	1030	1020
	6.0%	5308	5216	5201	5242	5679	5651	5669	5666	2961	2901	2893	2918	2958	2906	2971	2945
	9.0%	12293	12389	12461	12381	8616	8484	8440	8513	13460	11691	12325	12492	11976	11527	12426	11976

Table C-4: Complex Shear Modulus, G*, (Pa) @ 76 oC, RTFOT Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	1375	1350	1386	1370	2245	2180	2200	2208	1396	1378	1388	1387	2498	2524	2519	2514
	5.0%	1869	1798	1810	1826	2119	2092	2159	2123	2003	1934	1916	1951	4040	4057	4078	4058
	10.0%	2901	2920	3019	2947	2201	2159	2271	2210	1941	1928	1927	1932	4278	4279	4260	4272
	15.0%	10047	10159	10125	10110	5332	5306	5306	5315	4055	4045	4013	4038	5819	5738	5977	5845
LLDPE-X		3023	3078	3119	3073	3744	3614	3630	3663	1400	1395	1367	1387	3701	3643	3523	3622
	3.0%	25876	25936	26461	26091	4225	4319	4325	4290	14403	14243	14027	14224	8104	8176	8218	8166
	6.0%	8815	8593	8646	8685	7251	7580	7411	7414	26691	26791	28537	27340	96268	71213	102630	90037
	9.0%	52918	52462	51635	52338	13239	12998	12580	12939	29780	31832	31783	31132	101400	102100	103230	102243
PP-500U		3023	3078	3119	3073	3744	3614	3630	3663	1400	1395	1367	1387	3701	3643	3523	3622
	1.5%	19059	19753	19197	19336	11449	11074	11257	11260	13042	13392	13255	13230	7754	7766	7784	7768
	3.0%	17599	17597	17605	17600	11936	11655	11373	11655	16760	16800	16650	16737	15459	15210	15277	15315
	4.5%	14383	14420	14745	14516	17856	17681	18070	17869	20611	20719	19532	20287	62571	58076	56638	59095
SBS		1375	1350	1386	1370	2245	2180	2200	2208	1396	1378	1388	1387	2498	2524	2519	2514
	3.0%	2961	3228	3176	3122	3981	3919	3964	3955	2162	2225	2224	2204	2579	2542	2539	2553
	6.0%	5843	5704	5662	5736	7482	7752	7826	7687	4966	4978	4888	4944	7465	7729	7507	7567
	9.0%	9028	9149	9139	9105	11710	11594	11487	11597	11005	11065	11102	11057	10964	10837	10773	10858

Table C-5: Phase Angle, delta, (Degrees) @ 76 oC, RTFOT Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	77.1	77.0	77.1	77.1	81.2	81.0	80.9	81.0	82.2	81.9	82.0	82.0	77.9	78.0	78.0	78.0
	5.0%	78.1	78.4	78.0	78.2	78.9	78.9	78.5	78.8	82.4	81.9	81.9	82.1	74.3	74.1	74.2	74.2
	10.0%	67.2	67.4	67.0	67.2	77.4	77.5	77.5	77.5	77.3	77.3	76.9	77.2	65.2	65.3	65.0	65.2
	15.0%	48.9	48.6	48.6	48.7	59.7	59.3	59.4	59.5	59.7	59.6	59.9	59.7	57.7	57.3	57.7	57.6
LLDPE-X		76.9	76.8	76.8	76.8	80.7	80.8	80.8	80.8	85.5	85.4	85.4	85.4	78.6	78.6	78.2	78.5
	3.0%	61.3	60.9	60.8	61.0	82.7	82.6	82.4	82.6	73.8	73.9	73.8	73.8	75.3	75.4	75.6	75.4
	6.0%	72.0	72.0	72.2	72.1	81.2	81.0	81.0	81.1	32.9	32.0	30.9	31.9	23.0	34.5	20.9	26.1
	9.0%	39.1	38.9	39.3	39.1	66.6	66.7	66.7	66.7	50.2	49.3	49.0	49.5	27.1	26.9	25.8	26.6
PP-500U		76.9	76.8	76.8	76.8	80.7	80.8	80.8	80.8	85.5	85.4	85.4	85.4	78.6	78.6	78.2	78.5
	1.5%	64.1	63.7	63.7	63.8	73.7	73.7	73.5	73.6	73.6	73.4	73.8	73.6	73.0	73.3	73.2	73.2
	3.0%	63.3	62.9	62.9	63.0	74.4	74.4	74.7	74.5	74.1	74.0	74.2	74.1	60.1	59.3	59.3	59.6
	4.5%	69.3	69.0	69.0	69.1	72.8	73.2	73.3	73.1	73.3	73.2	73.3	73.3	67.5	67.5	67.5	67.5
SBS		77.1	77.0	77.1	77.1	81.2	81.0	80.9	81.0	82.2	81.9	82.0	82.0	77.9	78.0	78.0	78.0
	3.0%	73.1	72.8	72.8	72.9	75.3	75.6	75.6	75.5	82.5	82.5	82.5	82.5	81.2	81.2	81.1	81.2
	6.0%	66.1	65.9	66.2	66.1	65.2	64.1	64.5	64.6	68.3	68.5	68.4	68.4	68.5	69.0	69.6	69.0
	9.0%	45.9	46.1	46.3	46.1	52.2	52.5	53.0	52.6	42.7	42.8	42.8	42.8	59.7	59.9	59.7	59.8

Table C-6: G*/sin delta @ 76 oC, RTFOT Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	1411	1386	1422	1406	2272	2207	2228	2236	1409	1392	1402	1401	2555	2580	2575	2570
	5.0%	1909	1835	1851	1865	2159	2132	2203	2165	2021	1935	1953	1970	4197	4219	4237	4218
	10.0%	3146	3161	3280	3196	2255	2211	2326	2264	1990	1976	1978	1981	4712	4709	4701	4707
	15.0%	13328	13552	13458	13446	6176	6171	6164	6170	4698	4689	4637	4675	6885	6821	7071	6926
LLDPE-X		3104	3162	3204	3156	3794	3661	3677	3711	1404	1400	1371	1392	3775	3716	3599	3697
	3.0%	29498	29670	30309	29826	4260	4355	4363	4326	14999	14827	14609	14812	8379	8449	8483	8437
	6.0%	9269	9033	9083	9128	7337	7674	7503	7505	49156	49323	56539	51673	246230	125640	287270	219713
	9.0%	83911	83490	81581	82994	14425	14152	13697	14092	38776	42179	41921	40959	222380	225620	237400	228467
PP-500U		3104	3162	3204	3156	3794	3661	3677	3711	1404	1400	1371	1392	3775	3716	3599	3697
	1.5%	21191	22029	21422	21547	11928	11538	11740	11736	13595	13977	13804	13792	8111	8109	8130	8117
	3.0%	19707	19769	19769	19748	12393	12101	11791	12095	17427	17477	17304	17403	17825	17681	17769	17758
	4.5%	15380	15450	15797	15542	18692	18469	18866	18676	21515	21643	20388	21182	67716	62852	61321	63963
SBS		1411	1386	1422	1406	2272	2207	2228	2236	1409	1392	1402	1401	2555	2580	2575	2570
	3.0%	3095	3378	3324	3266	4116	4046	4093	4085	2181	2244	2244	2223	2610	2572	2570	2584
	6.0%	6392	6248	6190	6277	8242	8618	8671	8510	5343	5350	5256	5316	8026	8281	8008	8105
	9.0%	12568	12706	12641	12638	14820	14614	14383	14606	16218	16286	16338	16281	12695	12523	12480	12566

Table C-7: Complex Shear Modulus, G*, (Pa) @ 80 oC, Fresh Blends of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	290	296	289	292	400	410	401	404	384	389	398	390	616	619	608	614
	5.0%	312	320	290	307	383	396	480	420	890	918	878	895	1359	1357	1363	1360
	10.0%	882	905	904	897	1102	1079	1093	1091	723	714	710	716	1080	1060	1115	1085
	15.0%	3962	3949	3934	3948	2337	2255	2231	2274	1457	1411	1399	1422	3188	3160	3160	3169
LLDPE-X	0.0%	1060	1023	1038	1040	906	934	901	914	395	382	392	390	889	889	877	885
	3.0%	12187	11866	11895	11983	1502	1465	1476	1481	6083	6022	5793	5966	3009	2911	2897	2939
	6.0%	3508	3396	3382	3429	6474	6632	6672	6593	5121	4884	4903	4969	3954	3653	3662	3756
	9.0%	18743	18553	18341	18546	16509	18997	17012	17506	16515	18001	17208	17241	72212	71778	73551	72514
PP-500U	0.0%	1060	1023	1038	1040	906	934	901	914	395	382	392	390	889	889	877	885
	1.5%	7348	7315	7284	7316	3258	3212	3213	3228	4352	4389	4372	4371	3277	3364	3242	3294
	3.0%	7853	7963	7915	7910	2875	2817	2879	2857	3870	3800	3905	3858	2820	2826	2873	2840
	4.5%	4106	4125	4039	4090	4786	4764	4792	4781	5526	5374	5350	5417	5154	5084	5170	5136
SBS	0.0%	290	296	289	292	400	410	401	404	384	389	398	390	616	619	608	614
	3.0%	894	888	924	902	1387	1406	1340	1378	640	632	625	632	625	625	632	627
	6.0%	3138	2941	3036	3038	3464	3470	3521	3485	1848	1859	1840	1849	1901	1907	1882	1897
	9.0%	7005	6898	7002	6968	4873	4913	4892	4893	6952	6962	6981	6965	7037	6910	6847	6931

Table C-8: Phase Angle, delta, (Degrees) @ 80 oC, Fresh Blends of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	82.1	82.0	82.0	82.0	82.0	82.0	82.0	82.0	85.2	85.0	84.9	85.0	85.0	85.1	85.0	85.0
	5.0%	75.8	75.9	75.8	75.8	75.8	75.8	75.9	75.8	84.0	84.2	84.3	84.2	79.4	79.4	79.6	79.5
	10.0%	73.8	73.7	73.8	73.8	73.8	74.1	74.4	74.1	80.1	79.9	80.1	80.0	71.0	71.8	71.7	71.5
	15.0%	59.4	59.4	59.6	59.5	65.3	66.3	66.5	66.0	67.9	68.1	68.5	68.2	62.9	62.9	63.3	63.0
LLDPE-X	0.0%	81.5	81.8	81.6	81.6	81.8	82.3	82.1	82.1	82.6	82.5	83.5	82.9	81.6	81.6	81.6	81.6
	3.0%	68.1	67.9	68.1	68.0	83.7	83.6	83.8	83.7	79.0	78.8	78.9	78.9	75.5	75.5	76.2	75.7
	6.0%	72.0	72.3	72.4	72.2	62.6	62.3	62.2	62.4	66.1	66.3	66.3	66.2	76.1	76.5	77.0	76.5
	9.0%	44.9	45.0	44.7	44.9	48.6	44.4	48.2	47.1	44.9	44.2	44.2	44.4	21.7	21.7	21.6	21.7
PP-500U	0.0%	81.5	81.8	81.6	81.6	81.8	82.3	82.1	82.1	82.6	82.5	83.5	82.9	81.6	81.6	81.6	81.6
	1.5%	69.4	69.3	69.6	69.4	80.0	80.1	79.9	80.0	79.4	79.6	79.6	79.5	78.3	78.3	78.2	78.3
	3.0%	69.9	69.5	69.5	69.6	82.0	81.9	82.1	82.0	82.1	82.5	82.3	82.3	79.8	79.7	79.7	79.7
	4.5%	76.3	76.3	76.4	76.3	80.1	80.3	79.8	80.1	81.5	81.2	81.5	81.4	75.8	76.2	76.1	76.0
SBS	0.0%	82.1	82.0	82.0	82.0	82.0	82.0	82.0	82.0	85.2	85.0	84.9	85.0	85.0	85.1	85.0	85.0
	3.0%	80.6	80.5	80.2	80.4	80.7	80.6	80.4	80.6	82.5	82.6	82.5	82.5	82.4	82.6	82.4	82.5
	6.0%	66.0	66.7	66.8	66.5	68.3	68.1	68.1	68.2	69.6	69.6	69.9	69.7	74.8	74.9	75.2	75.0
	9.0%	54.2	54.0	54.2	54.1	52.8	53.3	53.3	53.1	32.2	31.6	31.7	31.8	60.8	61.6	61.5	61.3

Table C-9: G*/sin delta @ 80 oC, Fresh Blends of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	293	299	292	295	404	414	405	408	385	390	400	392	618	621	610	617
	5.0%	322	330	299	317	395	408	495	433	895	923	882	900	1383	1381	1386	1383
	10.0%	919	943	941	934	1148	1122	1135	1135	734	725	721	727	1142	1116	1175	1144
	15.0%	4603	4586	4562	4584	2572	2463	2433	2489	1572	1521	1504	1532	3582	3550	3536	3556
LLDPE-X	0.0%	1072	1034	1049	1052	915	942	910	922	398	385	395	393	899	899	887	895
	3.0%	13135	12811	12816	12921	1511	1474	1485	1490	6198	6140	5902	6080	3108	3007	2982	3032
	6.0%	3689	3564	3548	3600	7292	7490	7543	7442	5602	5332	5355	5430	3759	4073	3758	3863
	9.0%	26555	26253	26090	26299	22009	27152	22820	23994	23377	25811	24684	24624	195150	193760	199900	196270
PP-500U	0.0%	1072	1034	1049	1052	915	942	910	922	398	385	395	393	899	899	887	895
	1.5%	7852	7822	7771	7815	3308	3261	3264	3277	4427	4463	4445	4445	3346	3436	3312	3365
	3.0%	8362	8503	8452	8439	2903	2845	2907	2885	3907	3833	3941	3893	2865	2873	2872	2870
	4.5%	4226	4246	4156	4209	4858	4833	4869	4853	5588	5439	5410	5479	5316	5234	5325	5292
SBS	0.0%	293	299	292	295	404	414	405	408	385	390	400	392	618	621	610	617
	3.0%	900	894	937	910	1405	1425	1359	1397	645	632	630	636	631	630	638	633
	6.0%	3434	3304	3199	3312	3728	3740	3795	3754	1972	1983	1960	1972	1969	1976	1947	1964
	9.0%	8641	8528	8630	8600	6118	6128	6101	6116	13060	13277	13294	13210	8063	7856	7795	7905

Table C-10: Complex Shear Modulus, G*, (Pa) @ 80 oC, RTFOT Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	520	519	523	521	1014	1030	1020	1021	871	880	875	875	1618	1621	1605	1615
	5.0%	610	475	490	525	595	560	714	623	1208	1242	1236	1229	2724	2578	2699	2667
	10.0%	1949	1951	1963	1954	1498	1436	1493	1476	812	905	851	856	2996	3012	3036	3015
	15.0%	7248	7209	7294	7250	3789	3812	3754	3785	2964	2949	2935	2949	4212	4233	4224	4223
LLDPE-X	0.0%	1889	1842	1841	1857	2368	2268	2294	2310	884	881	860	875	2279	2339	2367	2328
	3.0%	16831	18122	18267	17740	2824	2731	2790	2782	8871	8575	8595	8680	5215	4689	4758	4887
	6.0%	7041	6636	6599	6759	5266	5073	5360	5233	24617	24294	24624	24512	83707	87736	90511	87318
	9.0%	37045	33383	32587	34338	10886	10505	10398	10596	25022	25036	24790	24949	75934	75880	77241	76358
PP-500U	0.0%	1889	1842	1841	1857	2368	2268	2294	2310	884	881	860	875	2279	2339	2367	2328
	1.5%	12885	12799	12964	12883	6662	6427	6754	6614	8327	8465	8408	8400	5547	5227	5165	5313
	3.0%	12245	12096	12159	12167	7759	8027	7736	7841	9670	10244	10200	10038	11973	12026	11822	11940
	4.5%	9645	9618	9517	9593	12065	11559	11794	11806	12393	11879	11993	12088	37922	36790	35977	36896
SBS	0.0%	520	519	523	521	1014	1030	1020	1021	871	880	875	875	1618	1621	1605	1615
	3.0%	1967	1928	2003	1966	2513	2575	2495	2528	1443	1438	1438	1440	1720	1781	1693	1731
	6.0%	4413	4103	4146	4221	5430	5396	5362	5396	3244	3300	3255	3266	5201	4894	4836	4977
	9.0%	7173	7308	7218	7233	8329	8368	8391	8363	8768	8813	8787	8789	7320	7381	7365	7355

Table C-11: Phase Angle, delta, (Degrees) @ 80 oC, RTFOT Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	79.0	79.1	79.0	79.0	80.9	81.1	81.1	81.0	84.0	84.0	84.1	84.0	80.0	80.1	80.0	80.0
	5.0%	80.0	80.6	79.9	80.2	80.4	80.4	79.8	80.2	83.1	83.6	83.2	83.3	75.8	75.2	75.3	75.4
	10.0%	69.3	69.0	69.3	69.2	78.9	78.7	78.8	78.8	78.8	78.9	78.3	78.7	66.3	66.8	66.8	66.6
	15.0%	49.9	50.2	49.8	50.0	61.0	60.9	61.1	61.0	60.9	61.0	61.6	61.2	59.2	59.1	59.3	59.2
LLDPE-X		78.6	78.9	79.0	78.8	82.6	83.0	83.0	82.9	86.6	86.7	86.6	86.6	80.2	80.3	80.4	80.3
	3.0%	63.5	62.9	62.5	63.0	83.9	84.1	84.2	84.1	76.7	76.6	76.3	76.5	77.6	77.3	77.9	77.6
	6.0%	72.9	73.8	73.7	73.5	82.4	82.7	82.6	82.6	28.2	29.4	29.1	28.9	19.8	18.6	18.0	18.8
	9.0%	40.9	41.2	41.5	41.2	63.4	63.7	63.7	63.6	49.3	49.3	49.5	49.4	23.2	23.1	23.0	23.1
PP-500U		78.6	78.9	79.0	78.8	82.6	83.0	83.0	82.9	86.6	86.7	86.6	86.6	80.2	80.3	80.4	80.3
	1.5%	65.7	66.0	65.8	65.8	76.3	76.5	76.0	76.3	75.6	75.2	75.2	75.3	75.0	75.7	75.8	75.5
	3.0%	65.2	65.3	65.5	65.3	77.6	76.7	75.4	76.6	76.2	76.5	76.4	76.4	59.2	57.9	56.9	58.0
	4.5%	72.1	71.8	72.0	72.0	75.3	75.2	75.3	75.3	75.7	76.0	75.8	75.8	70.4	70.5	69.9	70.3
SBS		79.0	79.1	79.0	79.0	80.9	81.1	81.1	81.0	84.0	84.0	84.1	84.0	80.0	80.1	80.0	80.0
	3.0%	76.2	76.3	76.0	76.2	77.9	77.8	77.8	77.8	84.0	84.1	84.0	84.0	82.6	82.6	82.5	82.6
	6.0%	67.6	68.4	68.9	68.3	65.6	65.4	65.2	65.4	71.3	72.1	71.9	71.8	72.8	73.1	73.4	73.1
	9.0%	49.1	49.2	49.4	49.2	55.9	56.0	56.0	56.0	42.2	42.0	42.1	42.1	63.0	63.2	63.1	63.1

Table C-12: G*/sin delta @ 80 oC, RTFOT Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	530	529	533	530	1027	1043	1032	1034	876	885	880	880	1643	1646	1630	1639
	5.0%	619	481	498	533	603	568	725	632	1217	1250	1245	1237	2810	2666	2790	2756
	10.0%	2084	2090	2098	2091	1527	1464	1522	1504	828	922	869	873	3272	3277	3303	3284
	15.0%	9475	9383	9550	9469	4332	4363	4288	4328	3392	3372	3337	3367	4904	4933	4912	4916
LLDPE-X	0.0%	1927	1877	1875	1893	2388	2285	2311	2328	886	882	862	877	2313	2373	2401	2362
	3.0%	18807	20357	20594	19919	2840	2746	2804	2797	9115	8815	8847	8926	5340	4807	4866	5004
	6.0%	7367	6910	6875	7051	5313	5114	5405	5277	52094	49488	50632	50738	247114	275070	292900	271695
	9.0%	56580	50681	49179	52147	12175	11718	11599	11830	33005	33023	32601	32876	192805	193405	197683	194631
PP-500U	0.0%	1927	1877	1875	1893	2388	2285	2311	2328	886	882	862	877	2313	2373	2401	2362
	1.5%	14138	14010	14213	14120	6857	6610	6961	6809	8597	8755	8697	8683	5743	5394	5328	5488
	3.0%	13489	13314	13362	13388	7944	8248	7994	8062	9957	10535	10494	10329	13939	14196	14112	14082
	4.5%	10136	10125	10007	10089	12473	11956	12193	12207	12789	12243	12371	12468	40254	39029	38310	39198
SBS	0.0%	530	529	533	530	1027	1043	1032	1034	876	885	880	880	1643	1646	1630	1639
	3.0%	2025	1984	2064	2025	2570	2634	2553	2586	1451	1446	1446	1448	1734	1796	1708	1746
	6.0%	4773	4413	4444	4543	5963	5935	5907	5935	3425	3468	3424	3439	5444	5115	5046	5202
	9.0%	9490	9654	9506	9550	10058	10094	10121	10091	13053	13171	13107	13110	8215	8269	8259	8248

Table C-13: Complex Shear Modulus, G*, (kPa) @ 22 oC for PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	5592	5629	5718	5646	9472	9110	9225	9269	8694	8352	8326	8457	8437	8510	8460	8469
	5.0%	3963	3794	3882	3880	5498	5538	5611	5549	5522	5588	5524	5545	4923	4986	5022	4977
	10.0%	2528	2579	2521	2543	4774	4679	5203	4885	5275	4678	4766	4906	3101	3107	3096	3101
	15.0%	1533	1519	1514	1522	2281	2325	2342	2316	1893	1936	1913	1914	2678	2709	2690	2692
LLDPE-X	0.0%	5886	5926	6019	5944	9971	9595	9710	9759	9151	8792	8764	8902	8881	8959	8907	8916
	3.0%	11280	11261	11427	11323	10949	11603	10374	10975	18165	18528	17086	17926	13810	17611	17918	16446
	6.0%	882	1024	1147	1018	4630	4352	4444	4475	16146	16271	16306	16241	12240	12361	11951	12184
	9.0%	2872	2851	2876	2866	8803	8680	8750	8744	8058	7819	8080	7986	14250	13621	13406	13759
PP-500U	0.0%	5886	5926	6019	5944	9971	9595	9710	9759	9151	8792	8764	8902	8881	8959	8907	8916
	1.5%	10493	10554	10185	10411	11781	11534	11396	11570	22557	21781	12557	18965	10226	9821	9905	9984
	3.0%	16311	15027	15868	15735	17370	17033	17727	17377	38001	39200	39150	38784	16967	17685	18226	17626
	4.5%	10245	10129	10114	10163	1057	1046	972	1025	25084	25207	25246	25179	10485	10558	10536	10526
SBS	0.0%	5592	5629	5718	5646	9472	9110	9225	9269	8694	8352	8326	8457	8437	8510	8460	8469
	3.0%	3498	3396	3585	3493	7984	8010	8051	8015	8308	8158	8196	8221	3767	3716	3778	3754
	6.0%	2513	2537	2538	2529	4149	4242	4245	4212	7010	6830	6837	6892	6218	6252	6191	6220
	9.0%	920	964	966	950	2235	2345	2333	2304	4665	4792	4797	4751	5034	5039	5104	5059

Table C-14: Phase Angle, delta, (Degrees) @ 22 oC for PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source: Ras Tanura Refinery, Saudi Arabia — Replicate Number 1	2	3	Average	Riyadh Refinery, Saudi Arabia — Replicate Number 1	2	3	Average	BAPCO Refinery, Bahrain — Replicate Number 1	2	3	Average	Al-Ahmadi Refinery, Kuwait — Replicate Number 1	2	3	Average
CRT	0%	36.0	35.8	35.8	35.9	36.6	37.0	37.2	36.9	39.6	40.2	40.1	40.0	37.0	37.2	37.1	37.1
	5.0%	37.9	38.2	38.0	38.0	39.9	39.7	39.8	39.8	39.7	39.9	39.7	39.8	38.4	38.0	37.7	38.0
	10.0%	38.9	39.0	38.8	38.9	41.2	41.7	41.2	41.4	41.8	42.5	42.4	42.2	39.9	40.1	40.0	40.0
	15.0%	40.3	40.6	40.4	40.4	44.5	44.2	44.4	44.4	46.2	46.1	45.9	46.1	43.1	43.1	43.2	43.1
LLDPE-X	0%	34.3	34.1	34.1	34.2	34.9	35.2	35.5	35.2	37.6	38.1	38.0	37.9	38.4	38.3	38.5	38.4
	3.0%	25.0	25.1	24.8	25.0	32.6	32.5	32.4	32.5	28.0	28.8	29.2	28.7	32.4	31.3	31.1	31.6
	6.0%	43.2	41.5	42.0	42.2	33.5	33.7	33.9	33.7	28.9	28.8	29.2	29.0	30.6	30.6	30.9	30.7
	9.0%	27.7	27.6	27.7	27.7	29.3	29.2	29.4	29.3	31.2	30.9	30.9	31.0	27.4	28.2	28.2	27.9
PP-500U	0%	34.3	34.1	34.1	34.2	34.9	35.2	35.5	35.2	37.6	38.1	38.0	37.9	38.4	38.3	38.5	38.4
	1.5%	25.4	25.6	25.6	25.5	30.2	30.1	30.2	30.2	30.6	30.9	30.8	30.8	36.8	36.9	36.8	36.8
	3.0%	21.9	24.4	21.8	22.7	30.7	31.2	31.0	31.0	26.2	27.1	27.0	26.8	33.7	33.3	33.2	33.4
	4.5%	28.4	28.9	28.7	28.7	23.2	18.9	19.8	20.6	24.7	25.0	24.4	24.7	33.0	32.8	32.8	32.9
SBS	0%	36.0	35.8	35.8	35.9	36.6	37.0	37.2	36.9	39.6	40.2	40.1	40.0	37.0	37.2	37.1	37.1
	3.0%	38.1	38.3	38.3	38.2	33.1	33.0	33.2	33.1	39.4	40.3	40.3	40.0	48.5	48.3	47.8	48.2
	6.0%	34.5	34.5	34.4	34.5	33.0	33.1	33.1	33.1	38.5	38.4	38.6	38.5	36.9	36.8	36.7	36.8
	9.0%	39.3	38.4	38.6	38.8	35.8	35.3	35.4	35.5	33.9	33.7	33.8	33.8	33.2	33.4	33.2	33.3

Table C-15: G* x sin delta @ 22 oC for PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	3287	3293	3345	3308	5647	5483	5577	5569	5542	5391	5363	5432	5078	5145	5103	5109
	5.0%	2434	2346	2390	2390	3527	3537	3592	3552	3527	3584	3529	3547	3058	3070	3071	3066
	10.0%	1587	1623	1580	1597	3145	3113	3427	3228	3516	3160	3214	3297	1989	2001	1990	1993
	15.0%	992	989	981	987	1599	1621	1639	1619	1366	1395	1374	1378	1830	1851	1841	1841
LLDPE-X	0%	3317	3322	3374	3338	5705	5531	5639	5625	5583	5425	5396	5468	5516	5553	5545	5538
	3.0%	4767	4777	4793	4779	5899	6234	5559	5897	8528	8926	8336	8596	7400	9149	9255	8601
	6.0%	604	679	767	683	2555	2415	2479	2483	7803	7839	7955	7866	6231	6292	6137	6220
	9.0%	1335	1321	1337	1331	4308	4235	4295	4279	4174	4015	4149	4113	6558	6437	6335	6443
PP-500U	0%	3317	3322	3374	3338	5705	5531	5639	5625	5583	5425	5396	5468	5516	5553	5545	5538
	1.5%	4501	4560	4401	4487	5926	5784	5732	5814	11482	11185	6430	9699	6126	5897	5933	5985
	3.0%	6084	6208	5893	6061	8868	8824	9130	8941	16778	17857	17774	17470	9414	9709	9980	9701
	4.5%	4873	4895	4857	4875	416	339	329	361	10482	10653	10429	10521	5711	5719	5707	5712
SBS	0%	3287	3293	3345	3308	5647	5483	5577	5569	5542	5391	5363	5432	5078	5145	5103	5109
	3.0%	2158	2105	2222	2162	4360	4363	4408	4377	5273	5277	5301	5284	2821	2775	2799	2798
	6.0%	1423	1437	1434	1431	2260	2317	2318	2298	4364	4242	4265	4291	3733	3745	3700	3726
	9.0%	583	598	603	595	1307	1355	1351	1338	2602	2639	2669	2643	2756	2774	2795	2775

Table C-16: Complex Shear Modulus, G*, (kPa) @ 25 oC for PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	4010	4136	4110	4085	6614	6528	6612	6585	5953	6007	5977	5979	6253	6113	6102	6156
	5.0%	2893	2903	2885	2894	3376	3469	3439	3428	2872	3043	3026	2980	3449	3262	2866	3192
	10.0%	2321	2344	2290	2318	3444	3445	3437	3442	3569	3567	3582	3573	2940	2930	2932	2934
	15.0%	1055	1070	1059	1061	1843	1869	1865	1859	1224	1243	1226	1231	1879	1874	1878	1877
LLDPE-X	0%	4306	4354	4326	4329	6963	6872	6960	6932	6266	6324	6292	6294	6582	6435	6424	6480
	3.0%	8724	8622	8954	8767	8921	9216	8695	8944	14848	14954	14968	14923	11454	12824	16176	13485
	6.0%	2122	2220	2705	2349	4293	4362	4324	4326	12966	13026	13075	13022	9853	9891	9676	9807
	9.0%	2627	2637	2654	2639	6279	6700	6520	6500	6225	6151	6209	6195	11341	11100	10906	11116
PP-500U	0%	4306	4354	4326	4329	6963	6872	6960	6932	6266	6324	6292	6294	6582	6435	6424	6480
	1.5%	8927	8744	8471	8714	8908	8761	8664	8778	12546	12086	7454	10695	7341	6999	7149	7163
	3.0%	12114	11633	11938	11895	13484	13472	13429	13462	28670	29270	29190	29043	13672	13755	13877	13768
	4.5%	6887	6891	6763	6847	1443	1452	1451	1449	20761	20746	20780	20762	7824	7892	7857	7858
SBS	0%	4010	4136	4110	4085	6614	6528	6612	6585	5953	6007	5977	5979	6253	6113	6102	6156
	3.0%	2823	2821	2739	2794	5931	5874	5852	5886	4688	4836	4841	4788	2769	2719	2761	2750
	6.0%	1878	1881	1886	1882	2806	2792	2745	2781	5313	5401	5546	5420	4372	4422	4437	4410
	9.0%	877	880	872	876	2001	2009	2011	2007	3784	3877	3750	3804	3800	3839	3874	3838

Table C-17: Phase Angle, delta, (Degrees) @ 25 oC for PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	38.0	38.1	38.3	38.1	39.8	39.6	39.9	39.8	41.5	41.6	41.8	41.6	39.0	38.9	38.7	38.9
	5.0%	40.2	40.3	40.3	40.3	43.1	42.8	42.8	42.9	42.6	43.1	42.2	42.6	39.1	39.1	39.5	39.2
	10.0%	40.4	40.0	39.8	40.1	42.5	43.0	42.9	42.8	44.6	44.4	44.5	44.5	45.0	44.6	44.7	44.8
	15.0%	41.3	41.5	41.4	41.4	44.7	44.5	44.6	44.6	48.7	48.5	48.2	48.5	44.0	44.0	43.8	43.9
LLDPE-X	0%	36.2	36.3	36.4	36.3	37.9	37.9	38.1	38.0	42.4	42.6	42.3	42.4	40.3	40.6	40.4	40.4
	3.0%	26.5	26.5	26.3	26.4	34.4	34.3	34.2	34.3	29.7	29.6	29.4	29.6	33.4	34.0	31.5	33.0
	6.0%	30.9	30.7	28.6	30.1	33.8	33.5	33.8	33.7	30.6	30.7	30.7	30.7	31.9	31.9	32.1	32.0
	9.0%	25.5	25.5	25.6	25.5	30.4	29.8	31.1	30.4	31.4	31.2	31.1	31.2	29.1	29.2	29.3	29.2
PP-500U	0%	36.2	36.3	36.4	36.3	37.9	37.9	38.1	38.0	42.4	42.6	42.3	42.4	40.3	40.6	40.4	40.4
	1.5%	26.6	26.6	26.9	26.7	32.4	32.4	32.4	32.4	32.0	32.2	32.1	32.1	39.2	39.4	39.8	39.5
	3.0%	24.9	25.7	24.8	25.1	32.3	32.3	32.5	32.4	30.2	30.1	30.0	30.1	35.5	35.5	35.6	35.5
	4.5%	30.3	31.3	30.7	30.8	35.3	33.3	34.1	34.2	26.3	26.5	26.4	26.4	34.7	34.9	34.6	34.7
SBS	0%	38.0	38.1	38.3	38.1	39.8	39.6	39.9	39.8	41.5	41.6	41.8	41.6	39.0	38.9	38.7	38.9
	3.0%	37.7	37.6	37.7	37.7	34.9	34.8	34.8	34.8	42.6	42.6	42.6	42.6	49.9	49.8	49.7	49.8
	6.0%	35.5	35.8	35.7	35.7	35.2	35.0	35.2	35.1	40.6	40.2	40.0	40.3	39.2	38.9	38.9	39.0
	9.0%	37.6	37.7	37.6	37.6	35.2	35.2	35.2	35.2	35.6	35.5	35.8	35.6	34.0	34.0	34.2	34.1

Table C-18: G* x sin delta @ 25 oC for PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source: Ras Tanura Refinery, Saudi Arabia – Replicate Number 1	2	3	Average	Riyadh Refinery, Saudi Arabia – Replicate Number 1	2	3	Average	BAPCO Refinery, Bahrain – Replicate Number 1	2	3	Average	Al-Ahmadi Refinery, Kuwait – Replicate Number 1	2	3	Average
CRT	0%	2469	2552	2547	2523	4234	4161	4241	4212	3945	3988	3984	3972	3935	3839	3815	3863
	5.0%	1867	1878	1866	1870	2307	2357	2337	2333	1944	2079	2033	2019	2175	2057	1823	2018
	10.0%	1504	1507	1466	1492	2327	2349	2340	2339	2506	2496	2511	2504	2079	2057	2062	2066
	15.0%	696	709	700	702	1296	1310	1310	1305	920	931	914	921	1305	1302	1300	1302
LLDPE-X	0%	2543	2578	2567	2563	4277	4221	4295	4264	4225	4281	4235	4247	4257	4188	4164	4203
	3.0%	3893	3847	3967	3902	5040	5193	4887	5040	7357	7386	7348	7364	6305	7171	8452	7309
	6.0%	1090	1133	1295	1173	2388	2408	2405	2400	6600	6650	6675	6642	5207	5227	5142	5192
	9.0%	1131	1135	1147	1138	3177	3330	3368	3292	3243	3186	3207	3212	5516	5415	5337	5423
PP-500U	0%	2543	2578	2567	2563	4277	4221	4295	4264	4225	4281	4235	4247	4257	4188	4164	4203
	1.5%	3997	3915	3833	3915	4773	4694	4642	4703	6648	6440	3961	5683	4640	4442	4576	4553
	3.0%	5100	5045	5007	5051	7205	7199	7215	7206	14422	14679	14595	14565	7939	7988	8078	8002
	4.5%	3475	3580	3453	3502	834	797	813	815	9199	9257	9240	9232	4454	4515	4462	4477
SBS	0%	2469	2552	2547	2523	4234	4161	4241	4212	3945	3988	3984	3972	3935	3839	3815	3863
	3.0%	1726	1721	1675	1708	3393	3352	3340	3362	3173	3273	3277	3241	2118	2077	2106	2100
	6.0%	1091	1100	1101	1097	1617	1601	1582	1600	3458	3486	3565	3503	2763	2777	2786	2775
	9.0%	535	538	532	535	1153	1158	1159	1157	2203	2251	2194	2216	2125	2147	2178	2150

Table C-19: Flexural Creep Stiffness, S, (MPa) @ - 28 oC, PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	221.5	196.1	210.0	209.2	250.0	302.1	293.6	281.9	330.2	314.4	333.5	326.0	411.3	358.4	372.4	380.7
	5.0%	116.4	144.2	135.2	131.9	274.8	258.7	272.0	268.5	271.9	288.5	259.5	273.3	359.3	345.2	322.8	342.4
	10.0%	118.2	128.1	120.5	122.3	190.0	168.2	187.3	181.8	218.9	216.8	234.5	223.4	264.8	278.3	264.3	269.1
	15.0%	82.7	77.2	79.6	79.8	137.5	126.7	136.2	133.5	152.4	145.4	131.8	143.2	180.7	159.7	174.9	171.8
LLDPE-X	0%	233.2	206.4	222.0	220.5	262.5	318.1	309.0	296.5	347.6	331.0	351.0	343.2	432.9	377.3	392.0	400.7
	3.0%	168.8	166.2	164.6	166.5	325.0	385.0	360.1	356.7	234.5	234.1	229.3	232.6	314.7	293.0	300.4	302.7
	6.0%	89.2	119.9	129.8	113.0	259.2	243.2	255.3	252.6	272.1	324.7	274.2	290.3	220.7	216.7	227.6	221.7
	9.0%	95.4	136.4	105.1	112.3	285.0	256.1	261.5	267.5	288.6	284.1	287.7	286.8	249.8	169.7	217.3	212.3
PP-500U	0%	233.2	206.4	222.0	220.5	262.5	318.1	309.0	296.5	347.6	331.0	351.0	343.2	432.9	377.3	392.0	400.7
	1.5%	192.7	195.1	197.3	195.0	300.8	348.4	309.9	319.7	279.3	268.6	260.1	269.3	292.3	281.2	288.3	287.3
	3.0%	189.3	172.0	190.8	184.0	333.8	293.4	332.4	319.9	295.1	301.2	299.2	298.5	375.9	460.9	439.1	425.3
	4.5%	255.1	220.5	261.2	245.6	280.2	334.0	329.3	314.5	410.9	407.0	405.3	407.7	398.7	391.7	396.1	395.5
SBS	0%	221.5	196.1	210.0	209.2	250.0	302.1	293.6	281.9	330.2	314.4	333.5	326.0	411.3	358.4	372.4	380.7
	3.0%	175.3	165.7	170.3	170.4	283.3	275.3	281.9	280.2	298.2	228.2	224.9	250.4	309.9	293.3	351.3	318.2
	6.0%	135.3	99.2	137.0	123.8	242.7	255.3	244.8	247.6	244.8	288.3	215.0	249.4	318.3	318.4	308.6	315.1
	9.0%	104.9	111.6	116.6	111.0	153.1	164.4	159.6	159.0	213.4	225.4	219.6	219.5	232.1	203.9	207.3	214.4

Table C-20: Flexural Creep Slope (m-value) @ - 28 oC, PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	0.225	0.216	0.219	0.220	0.186	0.197	0.191	0.191	0.212	0.209	0.190	0.204	0.212	0.185	0.195	0.197
	5.0%	0.298	0.307	0.303	0.303	0.260	0.271	0.278	0.270	0.263	0.255	0.253	0.257	0.213	0.235	0.221	0.223
	10.0%	0.276	0.284	0.283	0.281	0.295	0.296	0.282	0.291	0.287	0.281	0.280	0.283	0.281	0.287	0.282	0.283
	15.0%	0.307	0.301	0.312	0.307	0.313	0.286	0.307	0.302	0.319	0.320	0.319	0.319	0.285	0.283	0.290	0.286
LLDPE-X	0%	0.237	0.227	0.230	0.231	0.196	0.207	0.201	0.201	0.223	0.220	0.201	0.215	0.224	0.187	0.200	0.204
	3.0%	0.247	0.244	0.243	0.245	0.258	0.232	0.253	0.248	0.104	0.110	0.114	0.109	0.234	0.231	0.237	0.234
	6.0%	0.281	0.245	0.270	0.265	0.241	0.251	0.248	0.247	0.236	0.221	0.233	0.230	0.236	0.252	0.250	0.246
	9.0%	0.262	0.255	0.264	0.260	0.203	0.223	0.233	0.220	0.279	0.296	0.282	0.286	0.225	0.235	0.231	0.230
PP-500U	0%	0.237	0.227	0.230	0.231	0.196	0.207	0.201	0.201	0.223	0.220	0.201	0.215	0.224	0.187	0.200	0.204
	1.5%	0.229	0.218	0.224	0.224	0.237	0.235	0.239	0.237	0.249	0.264	0.260	0.258	0.223	0.238	0.230	0.230
	3.0%	0.211	0.236	0.214	0.220	0.210	0.229	0.211	0.217	0.230	0.231	0.238	0.233	0.233	0.243	0.247	0.241
	4.5%	0.229	0.236	0.244	0.236	0.209	0.208	0.208	0.208	0.182	0.216	0.197	0.198	0.227	0.211	0.220	0.219
SBS	0%	0.225	0.216	0.219	0.220	0.186	0.197	0.191	0.191	0.212	0.209	0.190	0.204	0.212	0.185	0.195	0.197
	3.0%	0.262	0.264	0.264	0.263	0.257	0.258	0.250	0.255	0.259	0.236	0.254	0.250	0.271	0.295	0.287	0.284
	6.0%	0.264	0.290	0.292	0.282	0.262	0.250	0.260	0.257	0.208	0.205	0.218	0.210	0.242	0.258	0.249	0.250
	9.0%	0.260	0.269	0.265	0.265	0.250	0.241	0.249	0.247	0.229	0.229	0.231	0.230	0.224	0.219	0.226	0.223

Table C-21: Flexural Creep Stiffness, S, (MPa) @ - 22 oC, PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Ras Tanura Refinery, Saudi Arabia – Replicate 1	Ras Tanura – 2	Ras Tanura – 3	Ras Tanura – Average	Riyadh Refinery, Saudi Arabia – Replicate 1	Riyadh – 2	Riyadh – 3	Riyadh – Average	BAPCO Refinery, Bahrain – Replicate 1	BAPCO – 2	BAPCO – 3	BAPCO – Average	Al-Ahmadi Refinery, Kuwait – Replicate 1	Al-Ahmadi – 2	Al-Ahmadi – 3	Al-Ahmadi – Average
CRT	0%	100.9	99.0	100.1	100.0	152.0	160.0	151.0	154.3	159.0	140.1	144.6	147.9	196.1	194.0	194.8	195.0
	5.0%	66.0	63.8	64.3	64.7	110.7	100.5	105.3	105.5	130.3	127.3	129.7	129.1	215.5	214.7	201.7	210.6
	10.0%	54.0	43.0	50.2	49.1	87.4	93.6	90.1	90.4	112.7	109.4	112.1	111.4	116.6	110.5	113.0	113.4
	15.0%	34.5	36.1	35.9	35.5	62.3	66.4	65.0	64.6	58.3	65.5	59.1	61.0	85.1	70.4	79.1	78.2
LLDPE-X	0%	106.3	99.2	102.0	102.5	160.6	168.5	161.0	163.4	167.9	147.5	152.2	155.9	206.4	204.3	205.0	205.2
	3.0%	125.6	123.2	124.1	124.3	161.5	188.8	136.3	162.2	180.7	138.2	190.0	169.6	220.9	207.8	211.9	213.5
	6.0%	79.2	93.0	93.7	88.6	174.6	180.3	177.6	177.5	200.7	217.1	194.6	204.1	156.6	149.4	152.0	152.7
	9.0%	77.8	96.5	83.6	86.0	184.9	167.8	170.8	174.5	144.2	174.9	171.4	163.5	177.6	134.3	164.1	158.7
PP-500U	0%	106.3	99.2	102.0	102.5	160.6	168.5	161.0	163.4	167.9	147.5	152.2	155.9	206.4	204.3	205.0	205.2
	1.5%	140.8	141.0	142.3	141.4	246.7	250.1	242.0	246.3	226.6	204.1	220.1	216.9	197.0	194.5	196.0	195.8
	3.0%	148.2	136.9	148.2	144.4	226.2	206.0	221.8	218.0	230.9	232.8	231.8	231.8	189.3	233.7	201.8	208.3
	4.5%	132.6	154.8	149.6	145.7	214.3	221.4	219.1	218.3	293.5	291.8	290.9	292.1	273.7	275.2	273.0	274.0
SBS	0%	100.9	99.0	100.1	100.0	152.0	160.0	151.0	154.3	159.0	140.1	144.6	147.9	196.1	194.0	194.8	195.0
	3.0%	86.4	90.5	91.3	89.4	160.3	160.2	146.8	155.8	187.6	127.3	150.2	155.0	131.1	108.5	125.2	121.6
	6.0%	91.6	77.7	95.2	88.2	141.6	137.5	139.0	139.4	164.5	184.2	152.3	167.0	154.6	154.2	155.0	154.6
	9.0%	55.6	60.0	58.4	58.0	119.5	123.2	122.6	121.8	129.3	111.4	115.2	118.6	155.2	141.1	142.8	146.4

Table C-22: Flexural Creep Slope (m-value) @ - 22 oC, PAV Residue of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source: Ras Tanura Refinery, Saudi Arabia – Replicate Number 1	2	3	Average	Riyadh Refinery, Saudi Arabia – Replicate Number 1	2	3	Average	BAPCO Refinery, Bahrain – Replicate Number 1	2	3	Average	Al-Ahmadi Refinery, Kuwait – Replicate Number 1	2	3	Average
CRT	0%	0.277	0.264	0.272	0.271	0.278	0.272	0.276	0.275	0.281	0.288	0.286	0.285	0.294	0.291	0.292	0.292
	5.0%	0.356	0.358	0.350	0.355	0.331	0.337	0.335	0.334	0.323	0.302	0.315	0.313	0.278	0.297	0.273	0.283
	10.0%	0.333	0.336	0.337	0.335	0.358	0.354	0.341	0.351	0.351	0.346	0.350	0.349	0.352	0.365	0.360	0.359
	15.0%	0.353	0.354	0.354	0.354	0.364	0.346	0.360	0.357	0.374	0.383	0.379	0.379	0.332	0.342	0.340	0.338
LLDPE-X	0%	0.289	0.275	0.286	0.283	0.293	0.288	0.291	0.291	0.296	0.302	0.301	0.300	0.309	0.306	0.307	0.307
	3.0%	0.263	0.255	0.258	0.259	0.307	0.295	0.307	0.303	0.187	0.139	0.179	0.168	0.277	0.279	0.279	0.278
	6.0%	0.283	0.263	0.278	0.275	0.272	0.278	0.273	0.274	0.266	0.258	0.265	0.263	0.279	0.284	0.282	0.282
	9.0%	0.270	0.270	0.271	0.270	0.255	0.262	0.264	0.260	0.302	0.302	0.307	0.304	0.259	0.260	0.260	0.260
PP-500U	0%	0.289	0.275	0.286	0.283	0.293	0.288	0.291	0.291	0.296	0.302	0.301	0.300	0.309	0.306	0.307	0.307
	1.5%	0.245	0.241	0.243	0.243	0.259	0.273	0.271	0.268	0.266	0.273	0.271	0.270	0.298	0.292	0.290	0.293
	3.0%	0.232	0.252	0.233	0.239	0.258	0.270	0.253	0.260	0.251	0.261	0.258	0.257	0.300	0.312	0.310	0.307
	4.5%	0.269	0.266	0.270	0.268	0.233	0.230	0.230	0.231	0.233	0.252	0.241	0.242	0.282	0.277	0.276	0.278
SBS	0%	0.277	0.264	0.272	0.271	0.278	0.272	0.276	0.275	0.281	0.288	0.286	0.285	0.294	0.291	0.292	0.292
	3.0%	0.306	0.302	0.308	0.305	0.306	0.305	0.292	0.301	0.307	0.300	0.305	0.304	0.376	0.377	0.371	0.375
	6.0%	0.295	0.296	0.307	0.299	0.293	0.304	0.300	0.299	0.266	0.273	0.269	0.269	0.313	0.311	0.310	0.311
	9.0%	0.301	0.301	0.300	0.301	0.279	0.278	0.279	0.279	0.292	0.294	0.295	0.294	0.291	0.285	0.293	0.290

Table C-23: Penetration @ 25 oC (0.1 mm) of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	59.0	57.0	58.0	58.0	52.0	51.0	50.0	51.0	48.0	49.0	48.0	48.3	46.0	46.0	46.0	46.0
	5.0%	56.0	57.0	58.0	57.0	34.0	36.0	38.0	36.0	31.0	31.0	32.0	31.3	19.0	20.0	19.0	19.3
	10.0%	45.0	47.0	47.0	46.3	41.0	42.0	43.0	42.0	34.0	32.0	34.0	33.3	38.0	37.0	39.0	38.0
	15.0%	36.0	37.0	36.0	36.3	36.0	35.0	37.0	36.0	38.0	39.0	40.0	39.0	34.0	35.0	36.0	35.0
LLDPE-X	0%	33.0	33.0	34.0	33.3	39.0	39.0	40.0	39.3	35.0	36.0	36.0	35.7	30.0	30.0	29.0	29.7
	3.0%	10.0	10.0	10.0	10.0	26.0	26.0	27.0	26.3	11.0	11.0	11.0	11.0	13.0	13.0	12.0	12.7
	6.0%	25.0	24.0	26.0	25.0	24.0	24.0	25.0	24.3	8.0	7.0	8.0	7.7	15.0	15.0	15.0	15.0
	9.0%	3.0	3.0	4.0	3.3	18.0	18.0	17.0	17.7	16.0	15.0	15.0	15.3	2.0	2.0	3.0	2.3
PP-500U	0%	33.0	33.0	34.0	33.3	39.0	39.0	40.0	39.3	35.0	36.0	36.0	35.7	30.0	30.0	29.0	29.7
	1.5%	9.0	8.0	8.0	8.3	10.0	10.0	8.0	9.3	10.0	10.0	10.0	10.0	20.0	20.0	21.0	20.3
	3.0%	7.0	7.0	7.0	7.0	17.0	17.0	19.0	17.7	20.0	21.0	20.0	20.3	22.0	21.0	21.0	21.3
	4.5%	20.0	21.0	22.0	21.0	2.0	2.0	2.0	2.0	7.0	7.0	8.0	7.3	7.0	7.0	7.0	7.0
SBS	0%	59.0	57.0	58.0	58.0	52.0	51.0	50.0	51.0	48.0	49.0	48.0	48.3	46.0	46.0	46.0	46.0
	3.0%	43.0	43.0	42.0	42.7	25.0	24.0	25.0	24.7	49.0	50.0	50.0	49.7	44.0	43.0	44.0	43.7
	6.0%	35.0	36.0	35.0	35.3	18.0	17.0	18.0	17.7	23.0	22.0	22.0	22.3	28.0	28.0	28.0	28.0
	9.0%	26.0	25.0	26.0	25.7	15.0	14.0	15.0	14.7	31.0	33.0	33.0	32.3	24.0	25.0	24.0	24.3

Table C-24: Softening Point (C) of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	59.0	59.0	59.0	59.0	60.0	60.1	60.0	60.0	60.0	60.0	60.0	60.0	57.0	57.1	57.1	57.1
	5.0%	59.0	60.0	57.0	58.7	60.0	62.0	61.0	61.0	60.0	60.0	60.0	60.0	62.0	63.0	63.0	62.7
	10.0%	62.0	63.0	62.0	62.3	59.0	59.0	60.0	59.3	58.0	58.0	59.0	58.3	62.0	62.0	62.0	62.0
	15.0%	75.0	75.0	75.0	75.0	69.0	69.0	69.0	69.0	68.0	68.0	67.0	67.7	70.0	71.0	71.0	70.7
LLDPE-X	0%	60.0	60.0	60.0	60.0	62.0	62.0	63.0	62.3	61.0	61.0	62.0	61.3	59.0	59.0	60.0	59.3
	3.0%	84.0	83.0	83.0	83.3	68.0	68.0	66.0	67.3	74.0	74.0	74.0	74.0	70.0	70.0	70.0	70.0
	6.0%	94.0	94.0	95.0	94.3	96.0	99.0	92.0	95.7	110.0	110.0	110.0	110.0	82.0	82.0	83.0	82.3
	9.0%	114.0	114.0	114.0	114.0	116.0	118.0	118.0	117.3	116.0	116.0	116.0	116.0	113.0	113.0	113.0	113.0
PP-500U	0%	60.0	60.0	60.0	60.0	62.0	62.0	63.0	62.3	61.0	61.0	62.0	61.3	59.0	59.0	60.0	59.3
	1.5%	76.0	76.0	76.0	76.0	72.0	72.0	72.0	72.0	72.0	72.0	73.0	72.3	68.0	68.0	68.0	68.0
	3.0%	79.0	78.0	79.0	78.7	68.0	68.0	68.0	68.0	69.0	69.0	70.0	69.3	69.0	69.0	68.0	68.7
	4.5%	80.0	80.0	80.0	80.0	74.0	74.0	75.0	74.3	75.0	76.0	76.0	75.7	74.0	75.0	74.0	74.3
SBS	0%	59.0	59.0	59.0	59.0	60.0	60.1	60.0	60.0	60.0	60.0	60.0	60.0	57.0	57.1	57.1	57.1
	3.0%	60.0	60.0	60.0	60.0	64.0	64.0	64.0	64.0	60.0	60.0	61.0	60.3	58.0	58.0	57.0	57.7
	6.0%	86.0	86.0	85.0	85.7	75.0	75.0	75.0	75.0	82.0	82.0	82.0	82.0	71.0	72.0	72.0	71.7
	9.0%	94.0	94.0	94.0	94.0	93.0	93.0	93.0	93.0	92.0	92.0	91.0	91.7	85.0	85.0	85.0	85.0

Table C-25: Rotational Viscosity @ 135 oC (cP) of Various Asphalt-Polymer Blends and Asphalt Sources

Polymer Type	Polymer Concentration	Asphalt Source															
		Ras Tanura Refinery, Saudi Arabia				Riyadh Refinery, Saudi Arabia				BAPCO Refinery, Bahrain				Al-Ahmadi Refinery, Kuwait			
		Replicate Number				Replicate Number				Replicate Number				Replicate Number			
		1	2	3	Average	1	2	3	Average	1	2	3	Average	1	2	3	Average
CRT	0%	998.0	986.0	987.0	990.3	990.0	994.0	992.0	992.0	768.0	770.0	760.0	766.0	1200.0	1198.0	1204.0	1200.7
	5.0%	1375.0	1402.0	1366.0	1381.0	1400.0	1412.0	1385.0	1399.0	1087.0	1049.0	1120.0	1085.3	1862.0	1852.0	1882.0	1865.3
	10.0%	2743.0	2736.0	2750.0	2743.0	1633.0	1603.0	1687.0	1641.0	1612.0	1600.0	1601.0	1604.3	3625.0	3629.0	3692.0	3648.7
	15.0%	11300.0	11366.0	10912.0	11192.7	7200.0	7102.0	7209.0	7170.3	5412.0	5390.0	5402.0	5401.3	9012.0	9078.0	8920.0	9003.3
LLDPE-X	0%	1000.0	987.5	1012.0	999.8	1012.0	1000.0	1000.0	1004.0	762.5	772.0	762.0	765.5	1337.0	1137.0	1257.0	1243.7
	3.0%	9875.0	9812.0	9892.0	9859.7	2043.0	2001.0	2055.0	2033.0	4612.0	4600.0	4589.0	4600.3	2925.0	2989.0	2802.0	2905.3
	6.0%	6456.0	6400.0	6575.0	6477.0	5387.0	5399.0	5358.0	5381.3	4075.0	4005.0	4100.0	4060.0	5612.0	5702.0	5580.0	5631.3
	9.0%	5137.0	5203.0	5109.0	5149.7	8387.0	8430.0	8300.0	8372.3	6970.0	6930.0	6705.0	6868.3	6987.0	6902.0	7029.0	6972.7
PP-500U	0%	1000.0	987.5	1012.0	999.8	1012.0	1000.0	1000.0	1004.0	762.5	772.0	762.0	765.5	1337.0	1137.0	1257.0	1243.7
	1.5%	4587.0	4512.0	4595.0	4564.7	2162.0	2105.0	2190.0	2152.3	2962.0	2930.0	3002.0	2964.7	2812.0	2800.0	2898.0	2836.7
	3.0%	5975.0	5912.0	5992.0	5959.7	2162.0	2198.0	2180.0	2180.0	3107.0	3205.0	3185.0	3165.7	2950.0	3008.0	2962.0	2973.3
	4.5%	7100.0	7212.0	7012.0	7108.0	6819.0	6830.0	6794.0	6814.3	6850.0	6895.0	6830.0	6858.3	6712.0	6709.0	6729.0	6716.7
SBS	0%	998.0	986.0	987.0	990.3	990.0	994.0	992.0	992.0	768.0	770.0	760.0	766.0	1200.0	1198.0	1204.0	1200.7
	3.0%	1430.0	1412.0	1465.0	1435.7	1575.0	1509.0	1602.0	1562.0	1370.0	1350.0	1395.0	1371.7	1337.0	1312.0	1412.0	1353.7
	6.0%	4170.0	4185.0	4152.0	4169.0	4525.0	4500.0	4552.0	4525.7	3225.0	3200.0	3297.0	3240.7	3475.0	3412.0	3498.0	3461.7
	9.0%	6075.0	6100.0	6057.0	6077.3	4337.0	4401.0	4339.0	4359.0	4500.0	4469.0	4503.0	4490.7	9325.0	9302.0	9372.0	9333.0

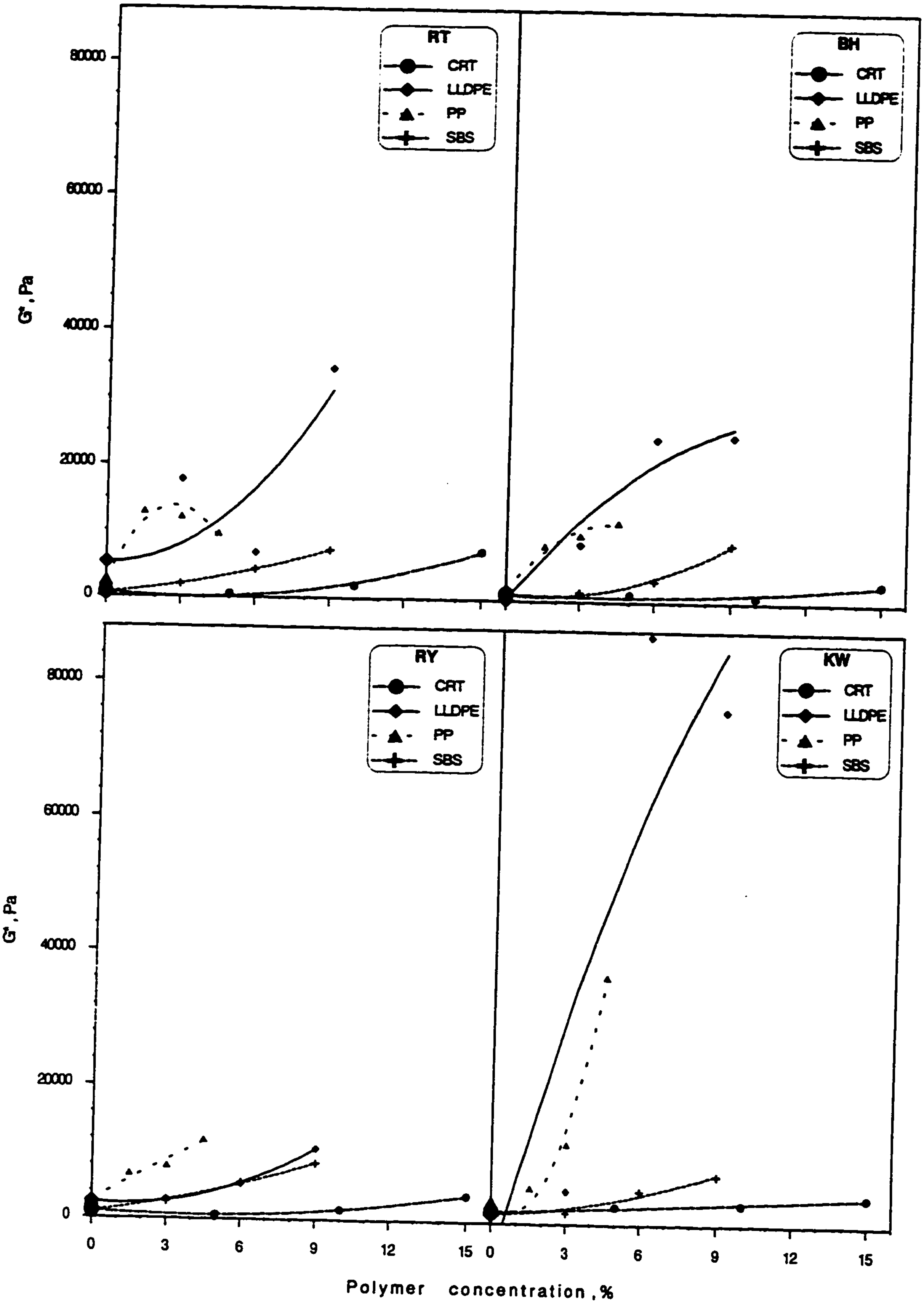


Figure C-1: Complex shear modulus (G*) at 80 C - RTFOT residue of different polymers and sources

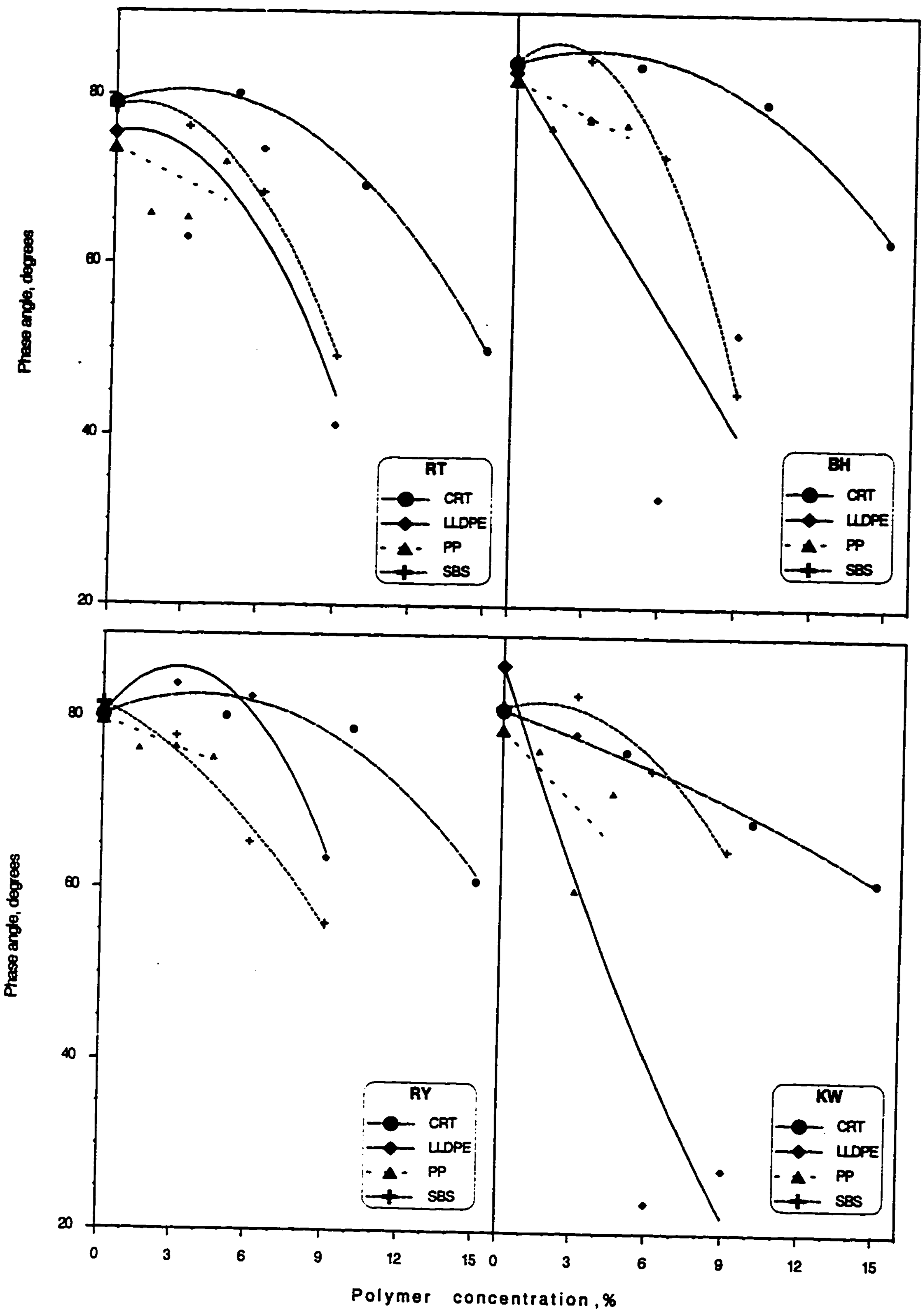


Figure C-2: Phase angle @ 80 C - RTFOT residue of different polymers and sources

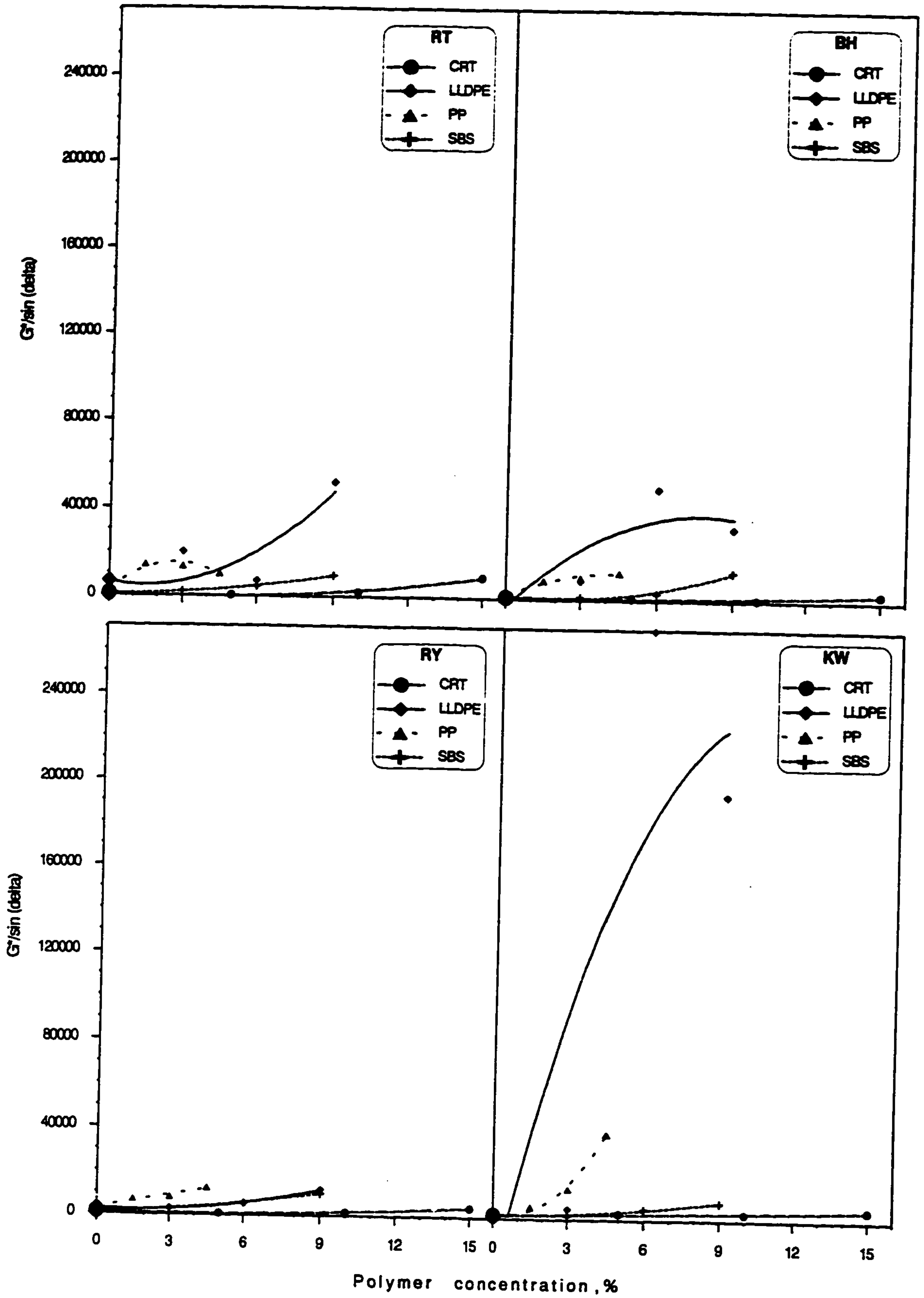


Figure C-3: G*/sin (delta) at 80 C - RTFOT residue of different polymers and sources

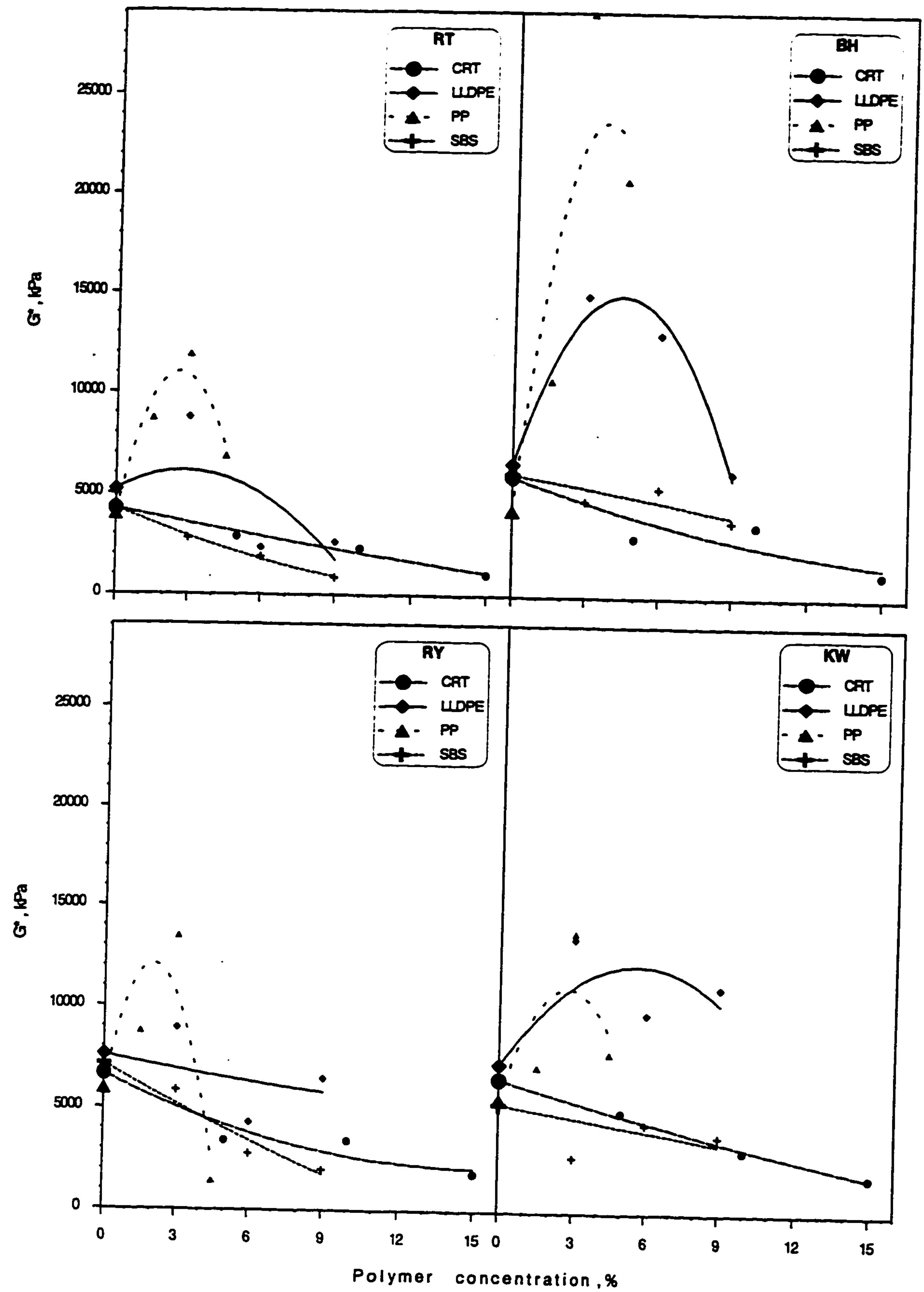


Figure C-4: Complex shear modulus (G*) at 25 C - PAV residue of different polymers and sources

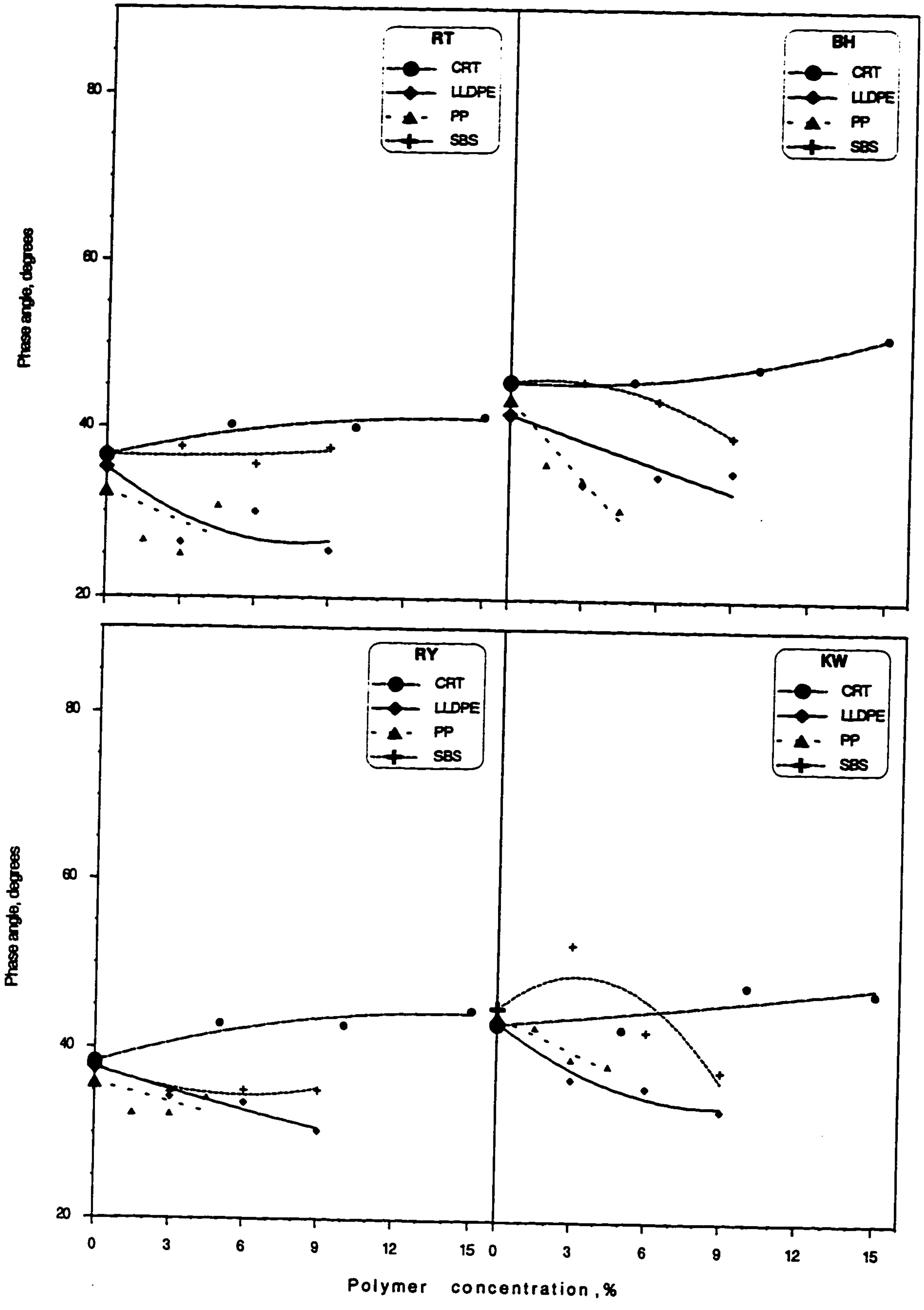


Figure C-5: Phase angle @ 25 C - PAV residue of different polymers and sources

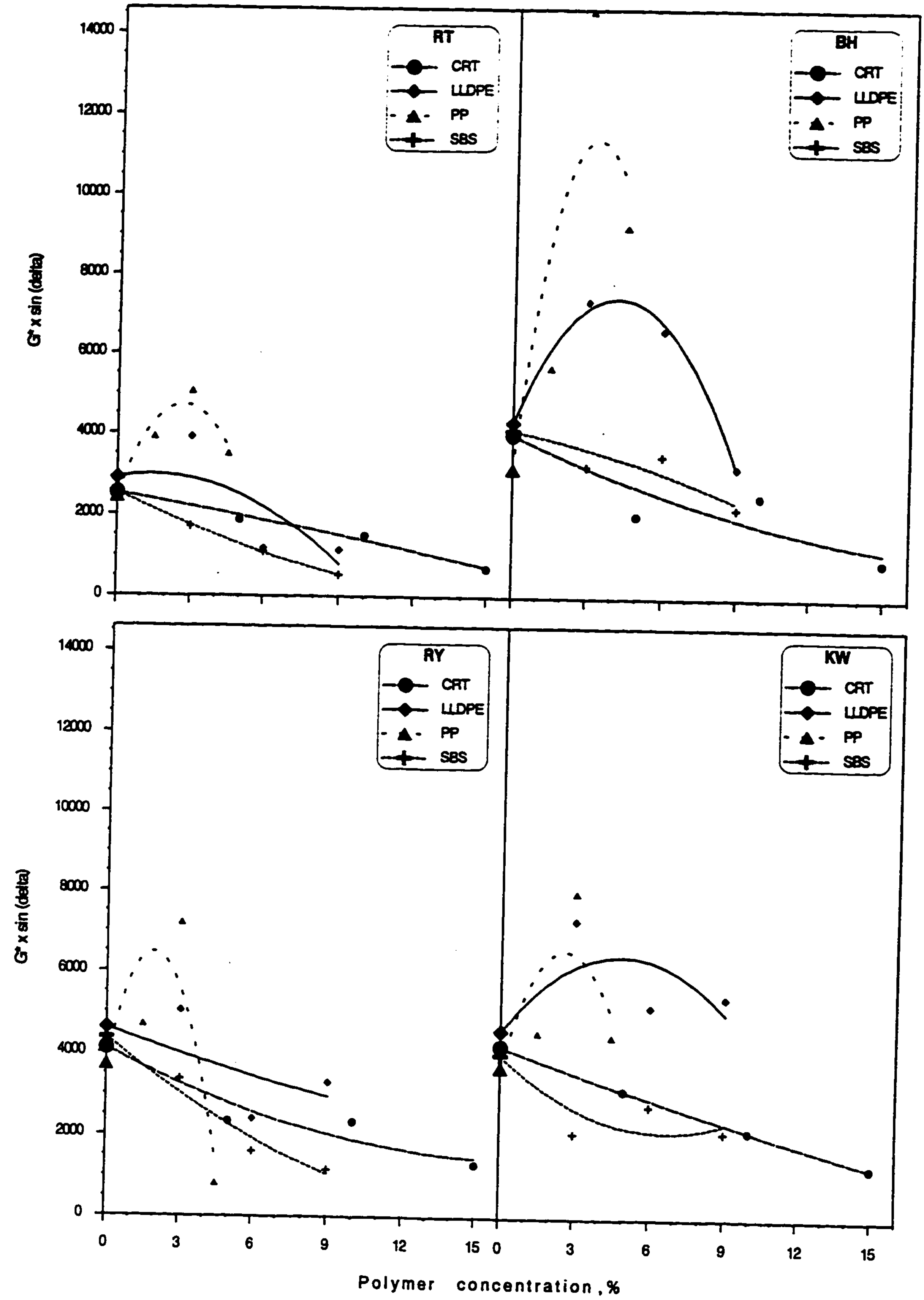


Figure C-6: G* x sin (delta) at 25 C - PAV residue of different polymers and sources

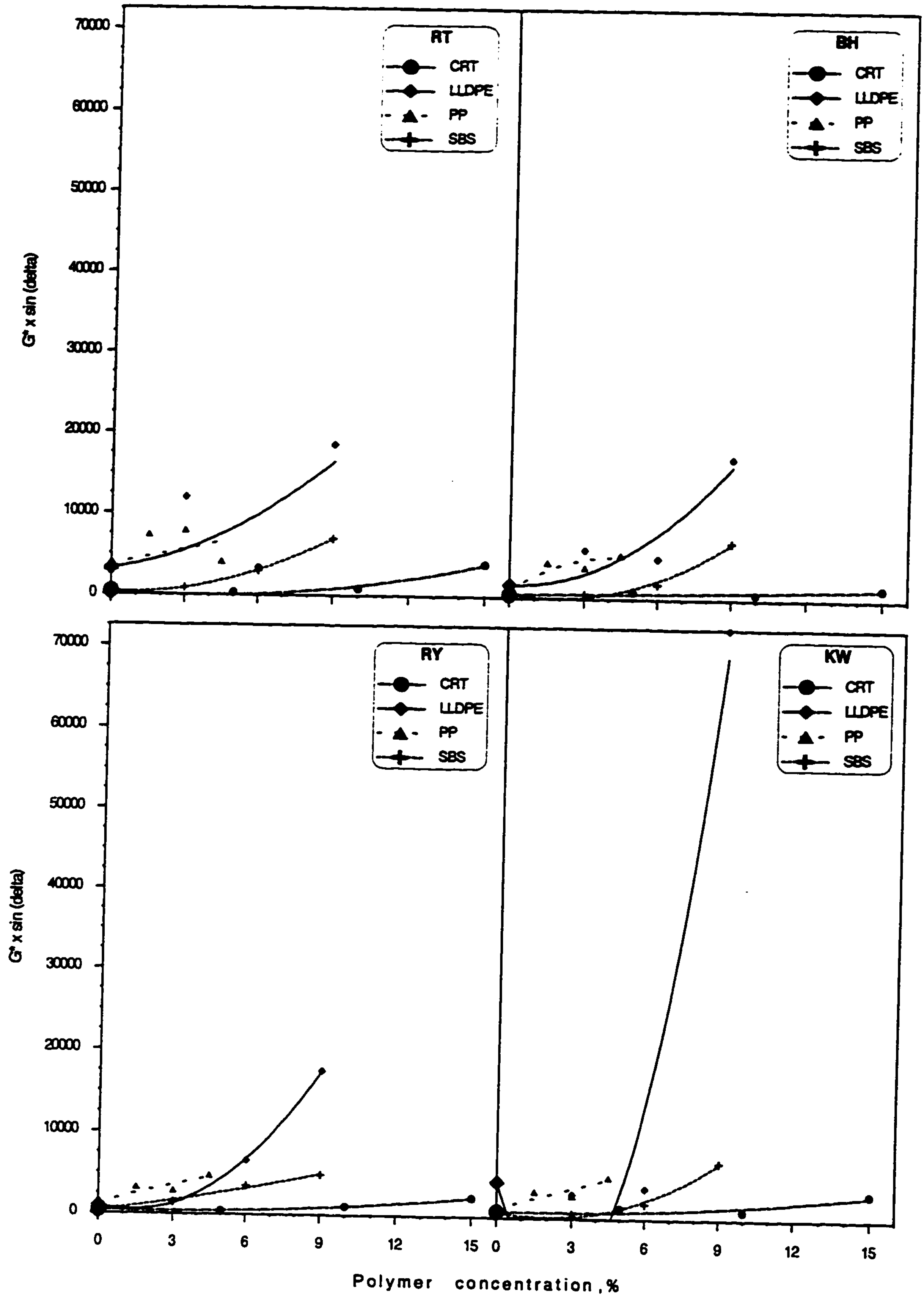


Figure C-7: Complex shear modulus (G*) at 80 C - Fresh of different polymers and sources

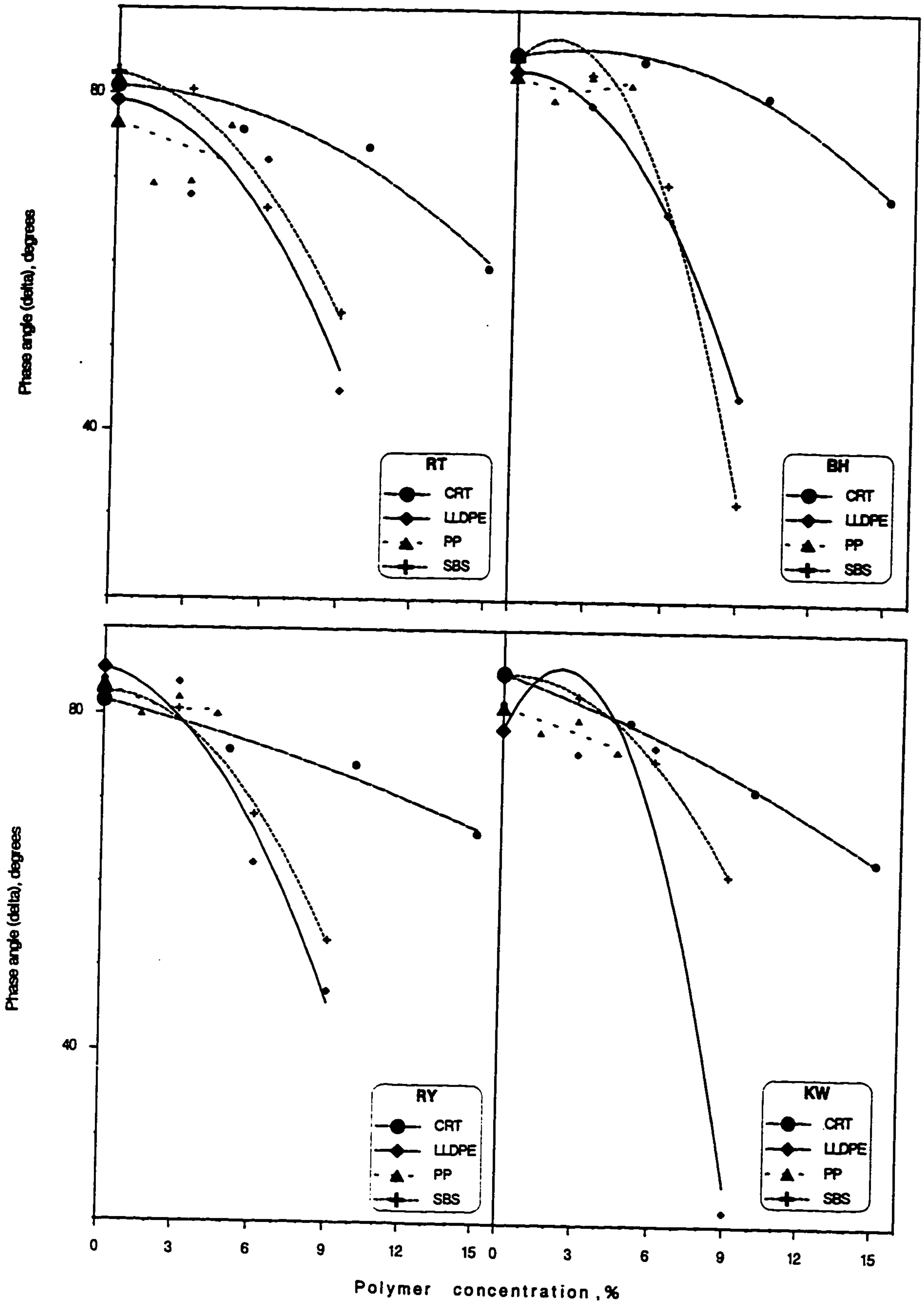


Figure C-8: Phase angle (delta) at 80 C - Fresh of different polymers and sources

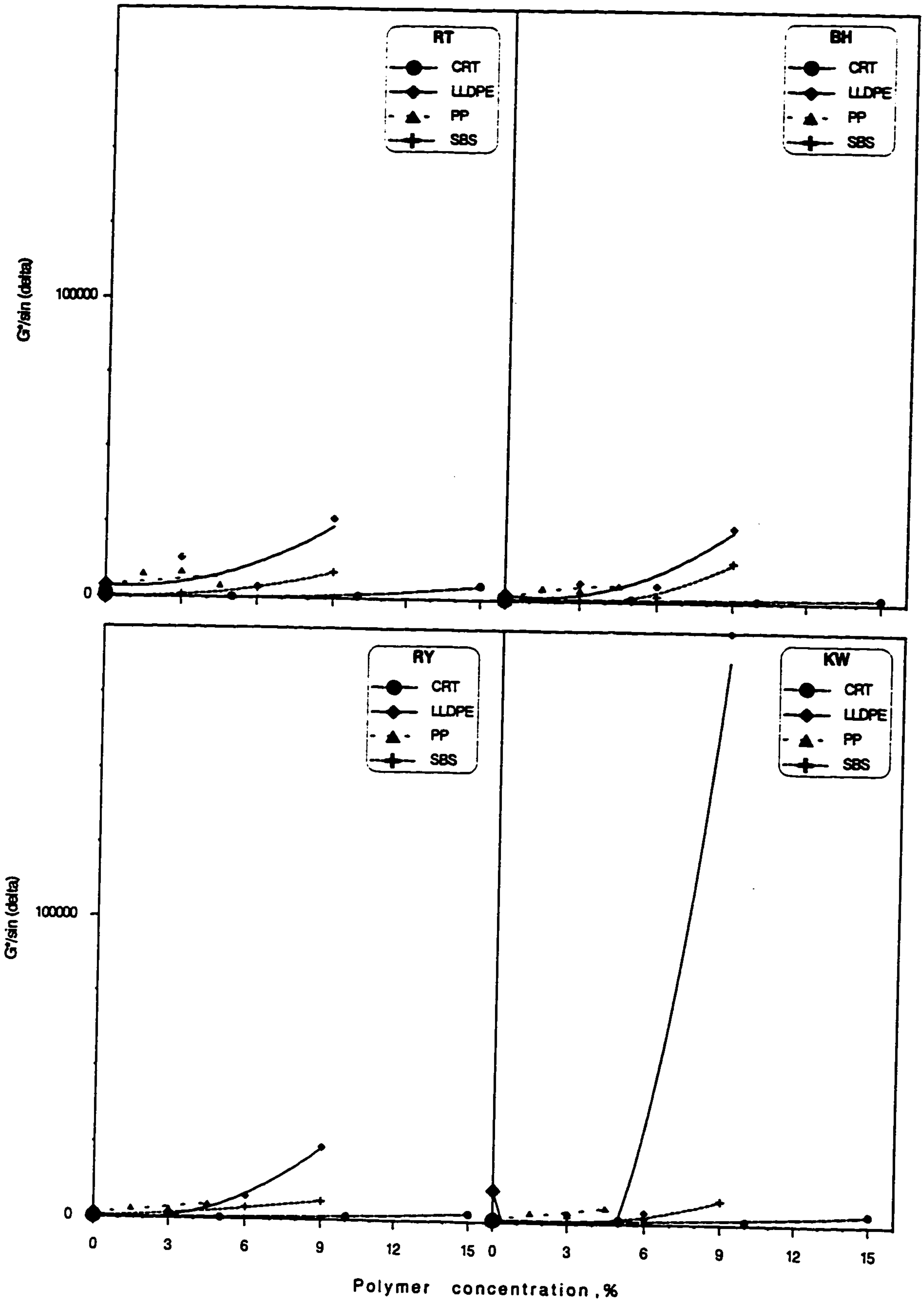


Figure C-9: G*/sin (delta) at 80 C - Fresh of different polymers and sources

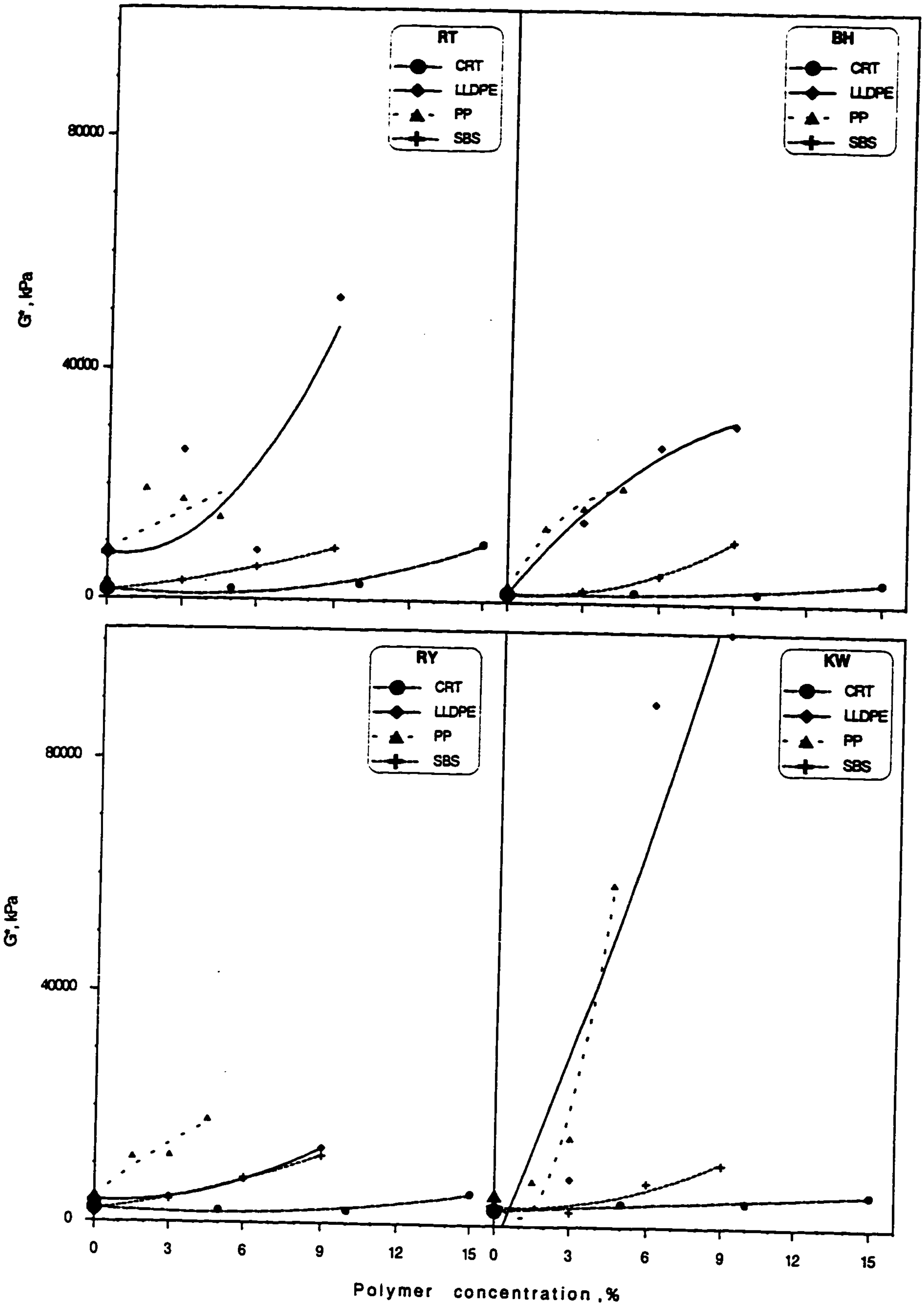


Figure C-10: Complex shear modulus (G*) at 76 C - RTFOT residue of different polymers and sources

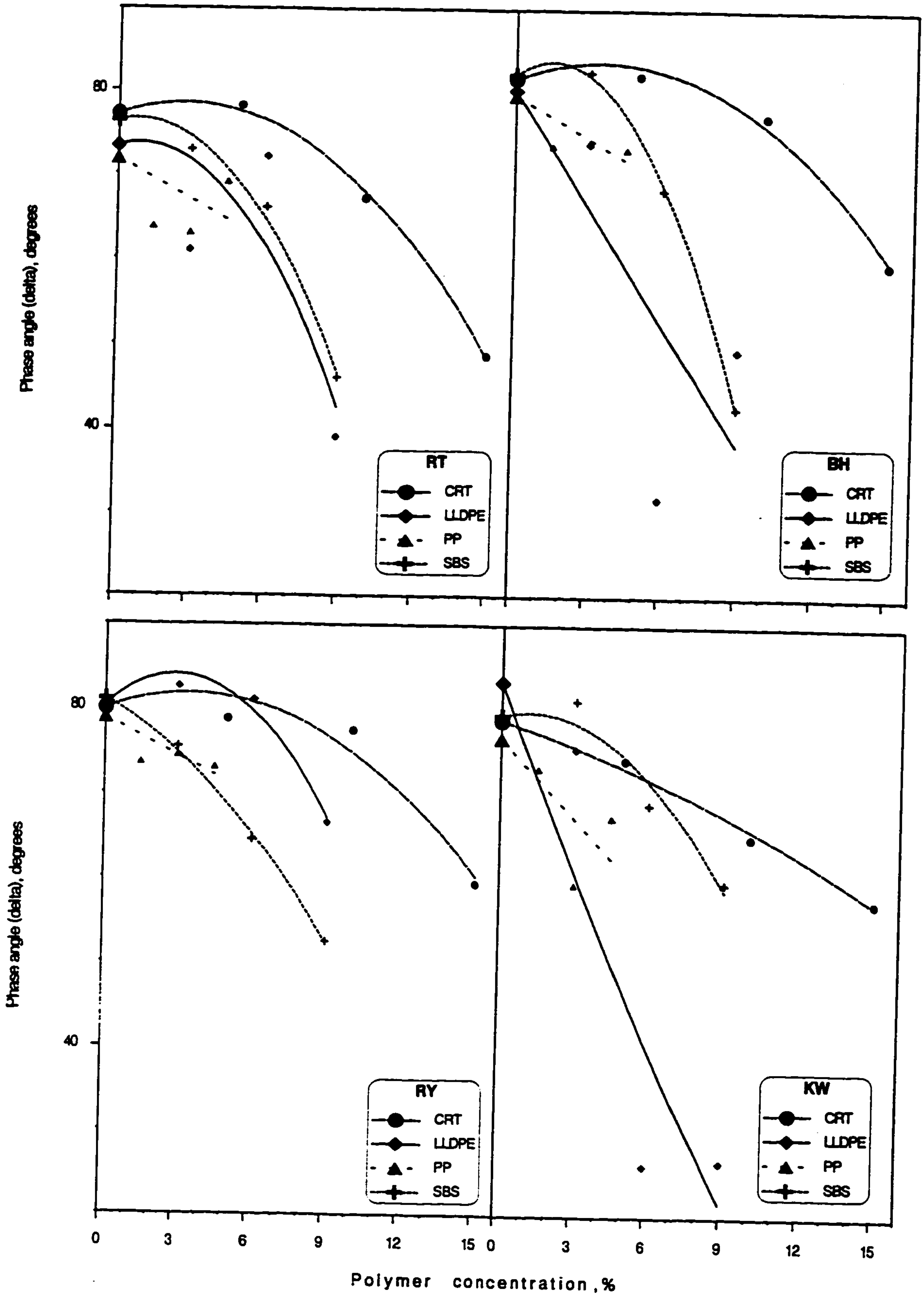


Figure C-11: Phase angle (delta) at 76 C - RTFOT residue of different polymers and sources

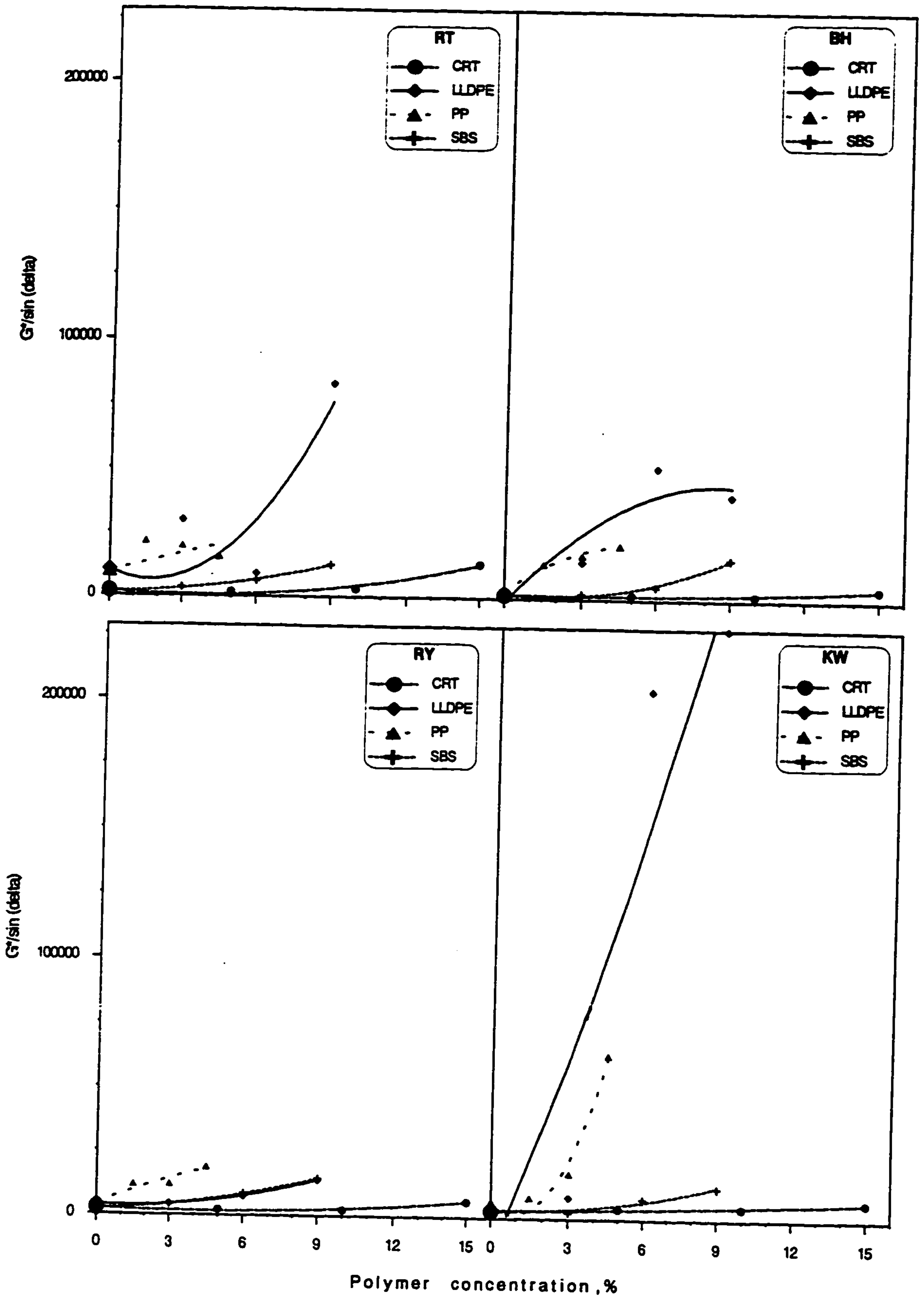


Figure C-12: G*/sin (delta) at 76 C - RTFOT residue of different polymers and sources

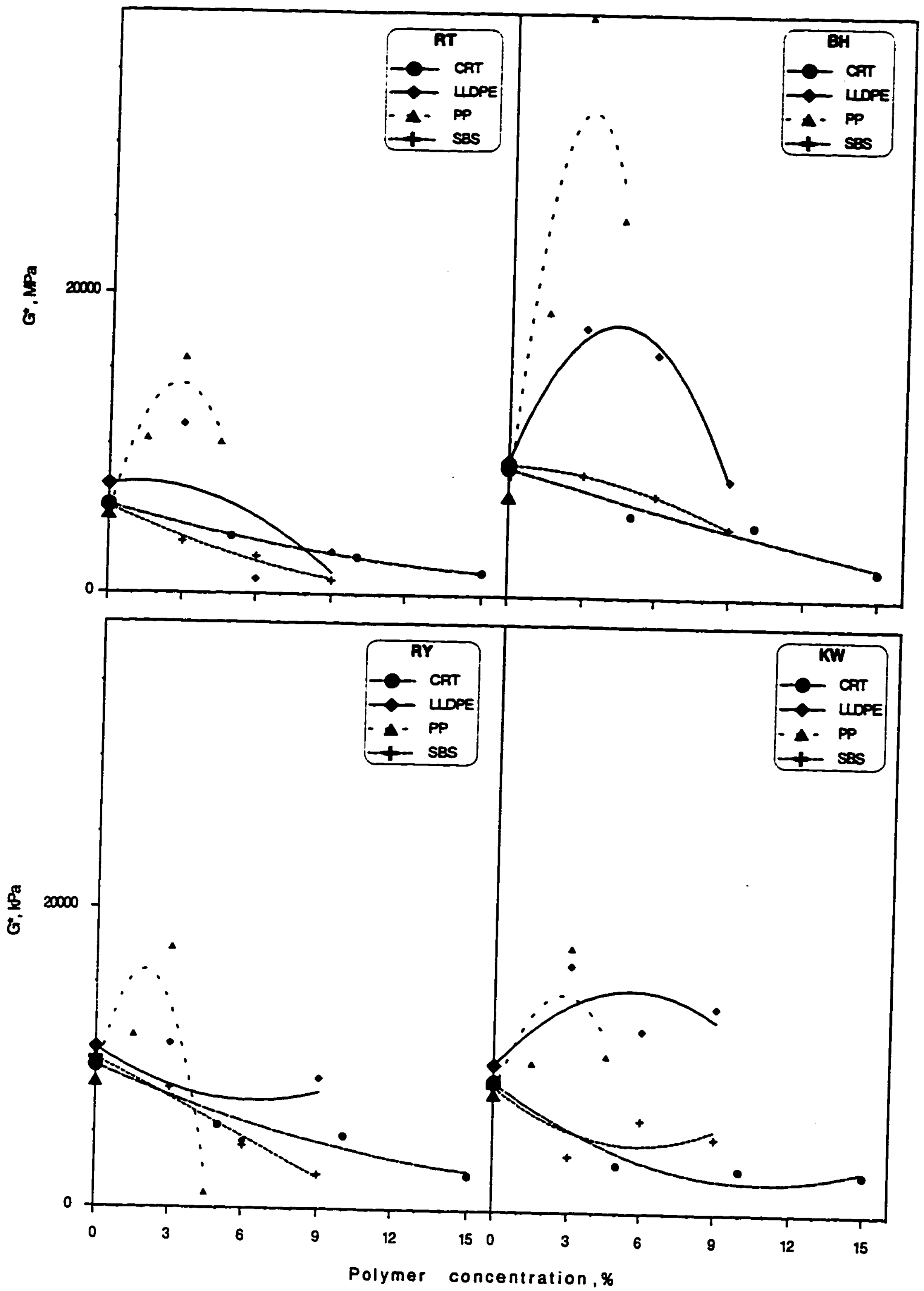


Figure C-13: Complex shear modulus (G*) at 22 C - PAV residue of different polymers and sources

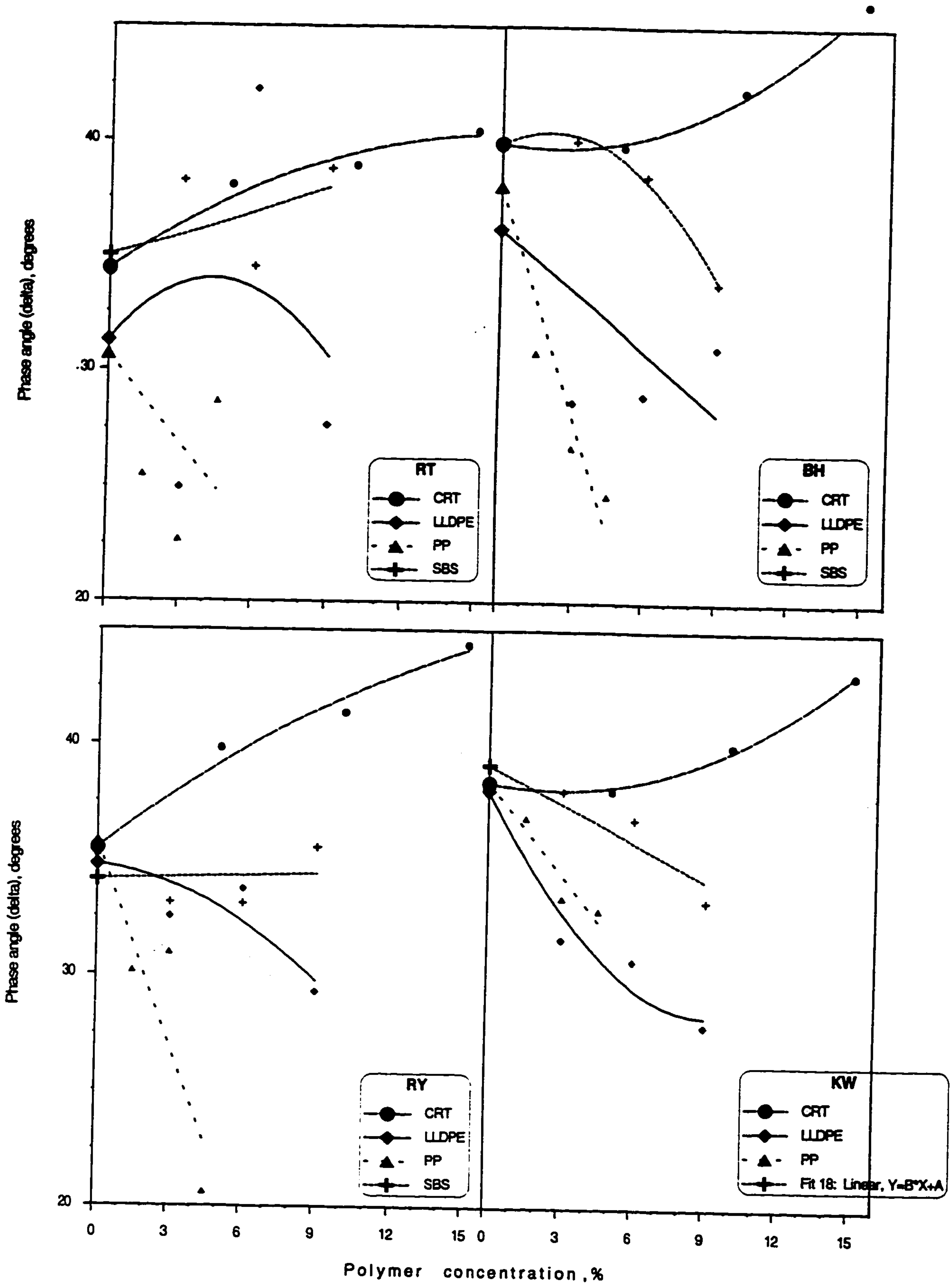


Figure C-14: Phase angle (delta) at 22 C - PAV residue of different polymers and sources

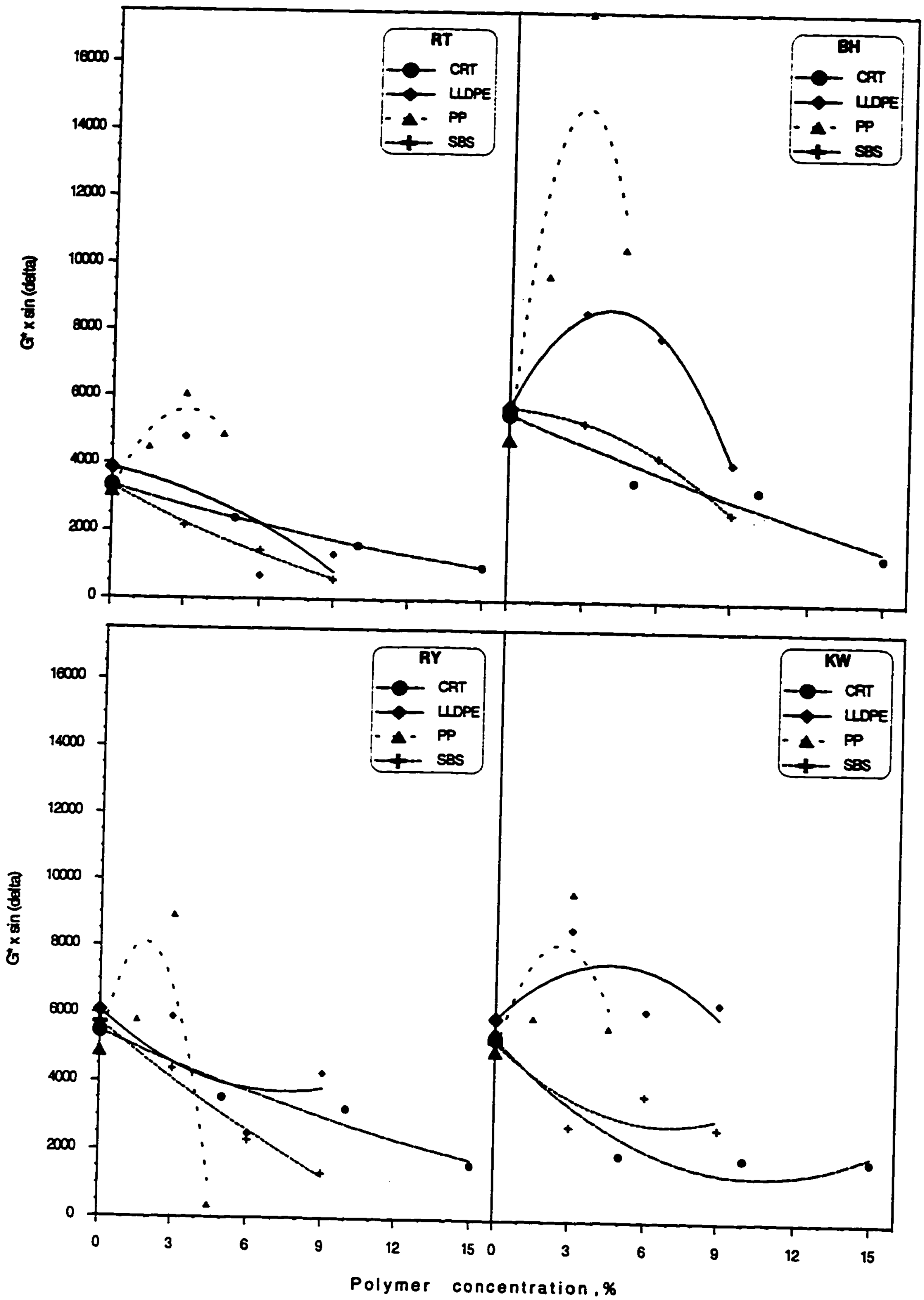


Figure C-15: G* x sin (delta) at 22 C - PAV residue of different polymers and sources

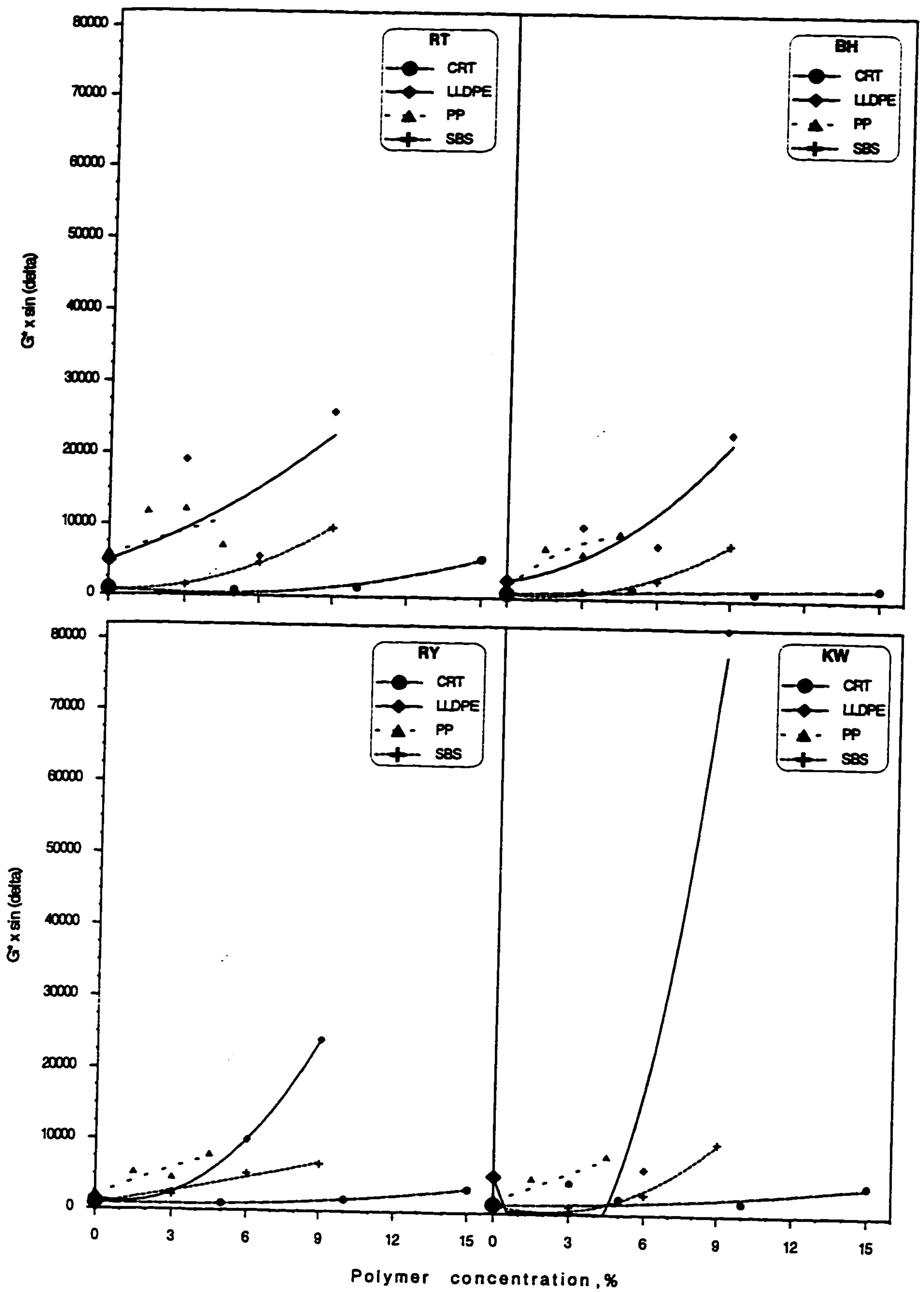


Figure C-16: Complex shear modulus (G*) at 76 C - Fresh of different polymers and sources

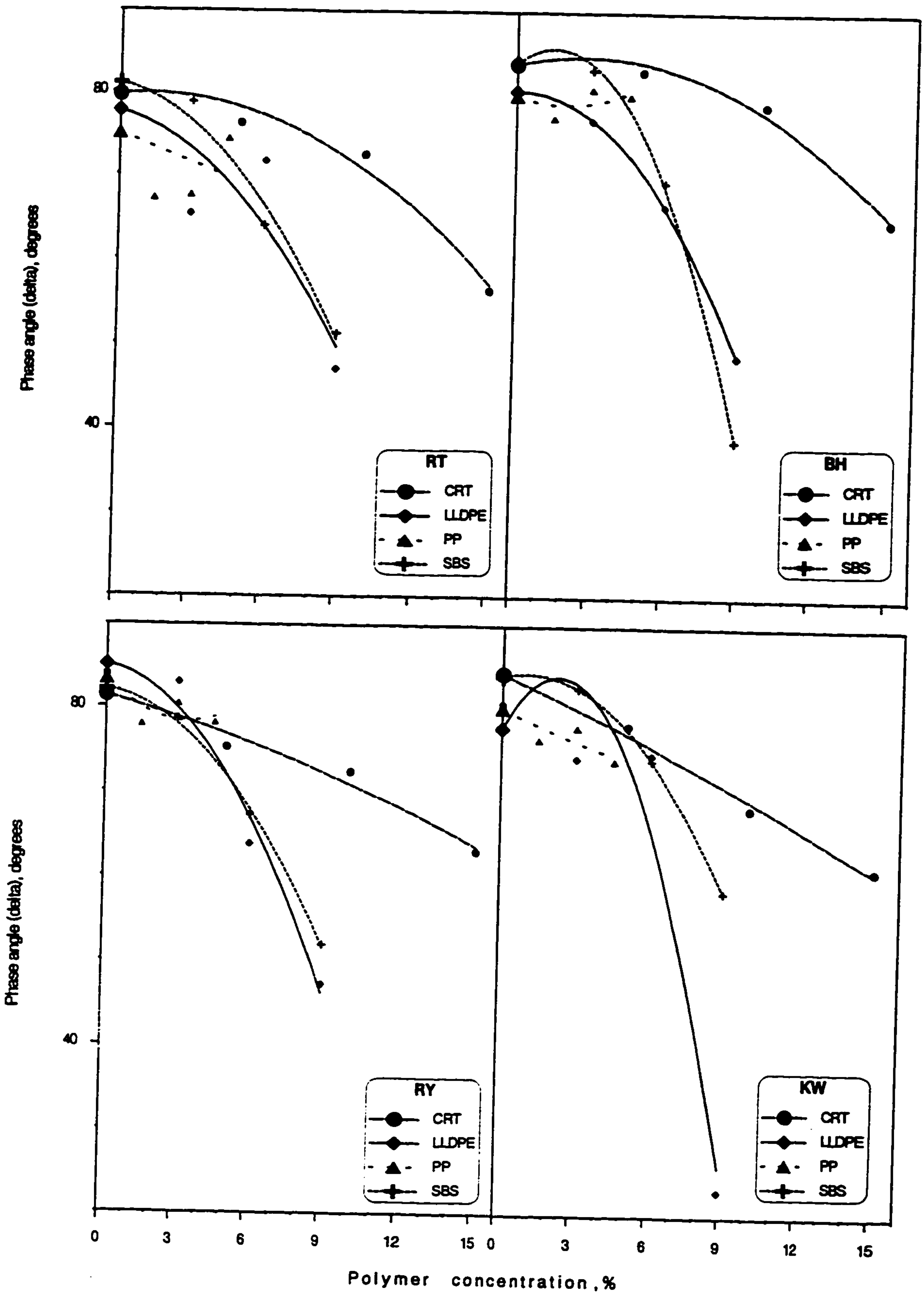


Figure C-17: Phase angle (delta) at 76 C - Fresh of different polymers and sources

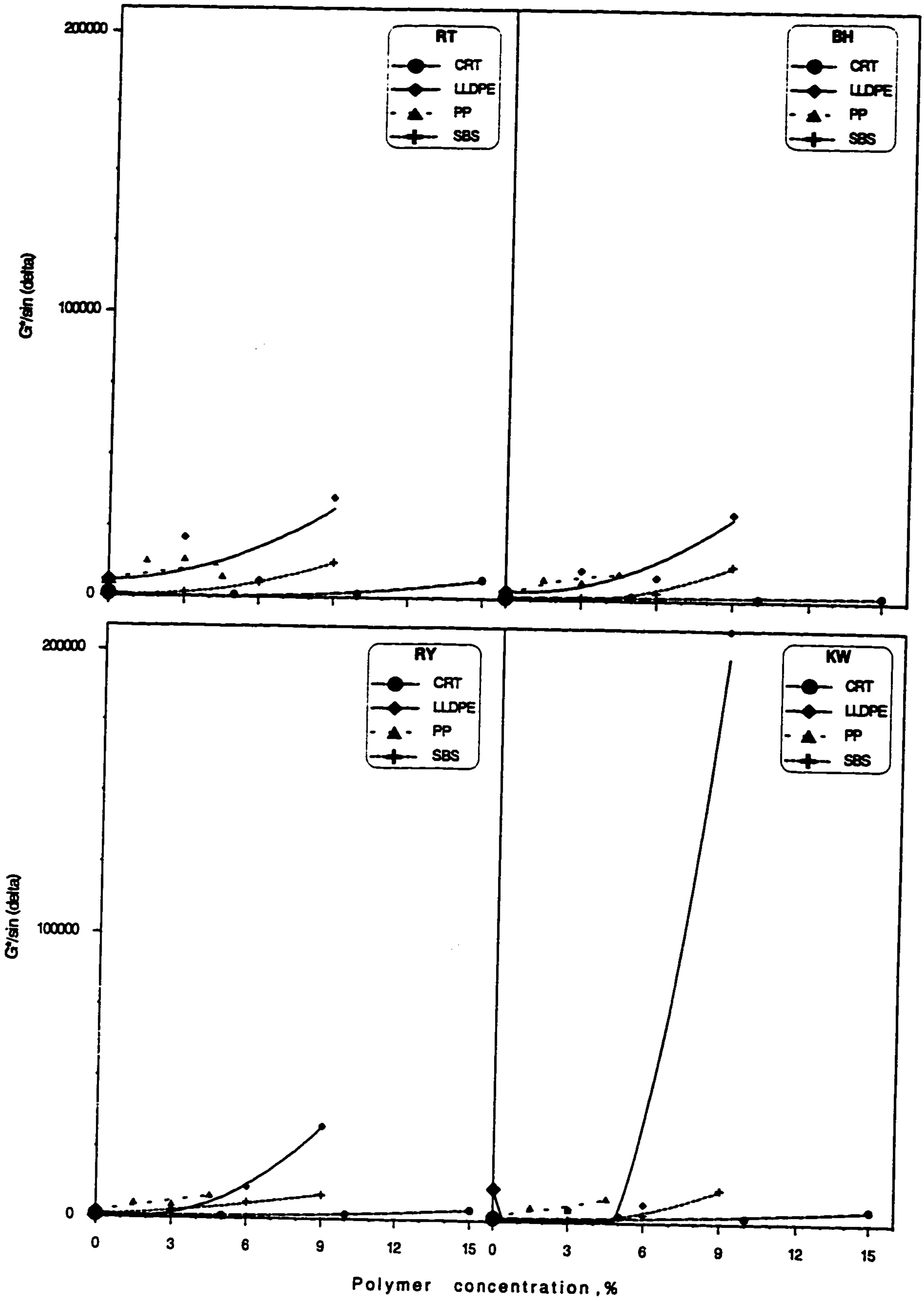


Figure C-18: G*/sin (delta) at 76 C - Fresh of different polymers and sources

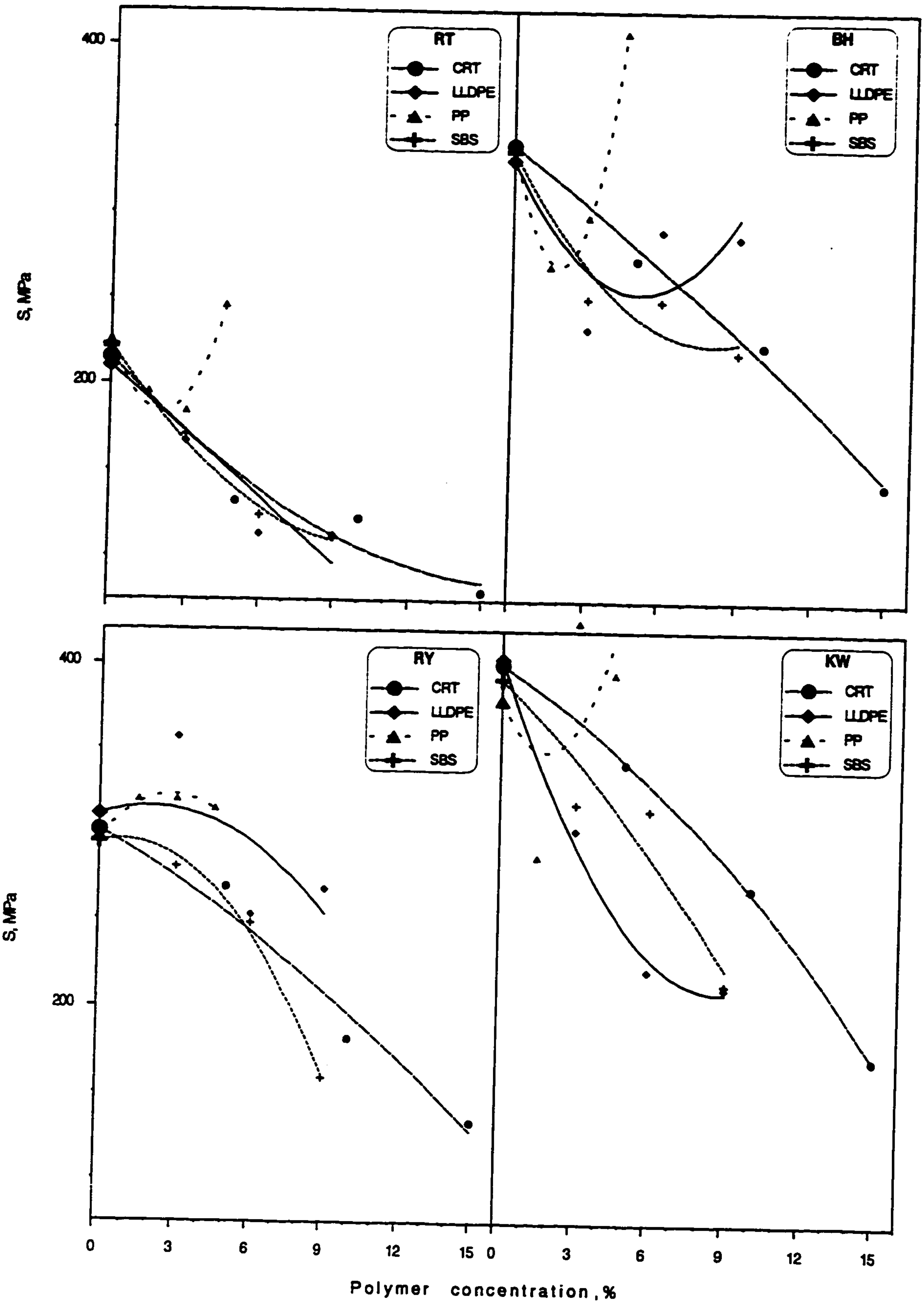


Figure C-19: Flexural creep stiffness @ -28 C - PAV residue of different polymers and sources

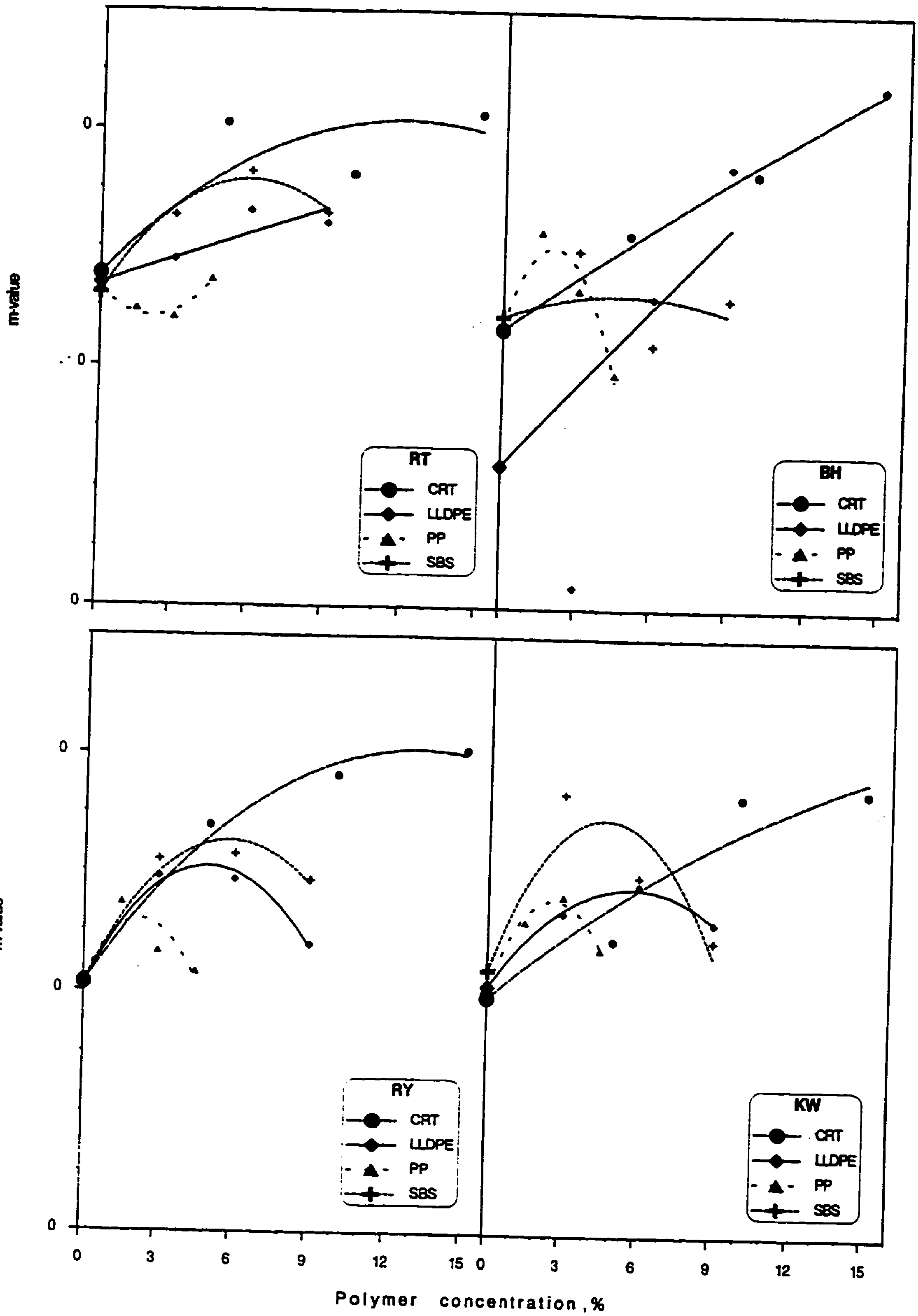


Figure C-20: Flexural creep slope (m-value) @ -28 C - PAV residue of different polymers and sources

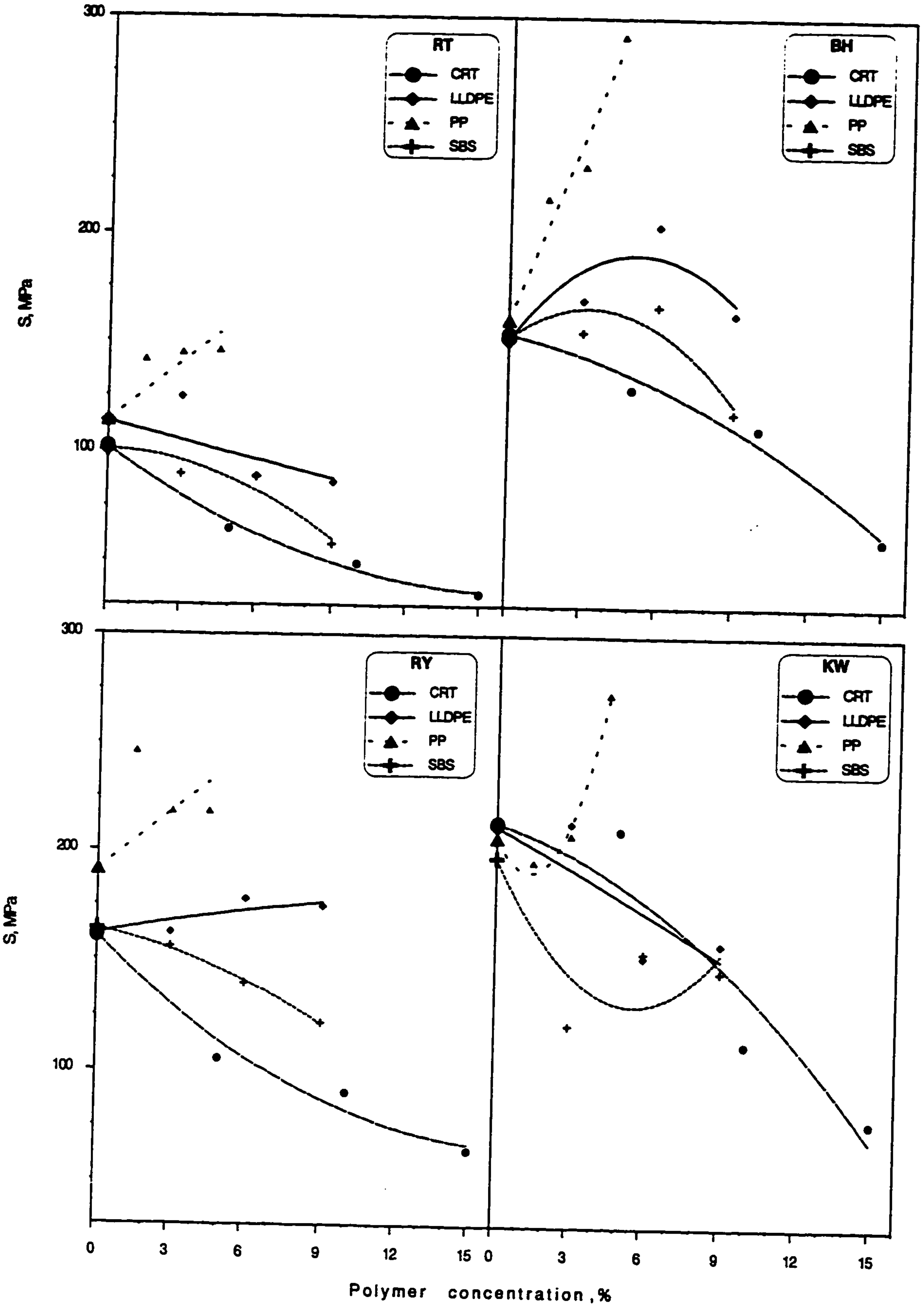


Figure C-21: Flexural creep stiffness @ -22 C - PAV residue of different polymers and sources

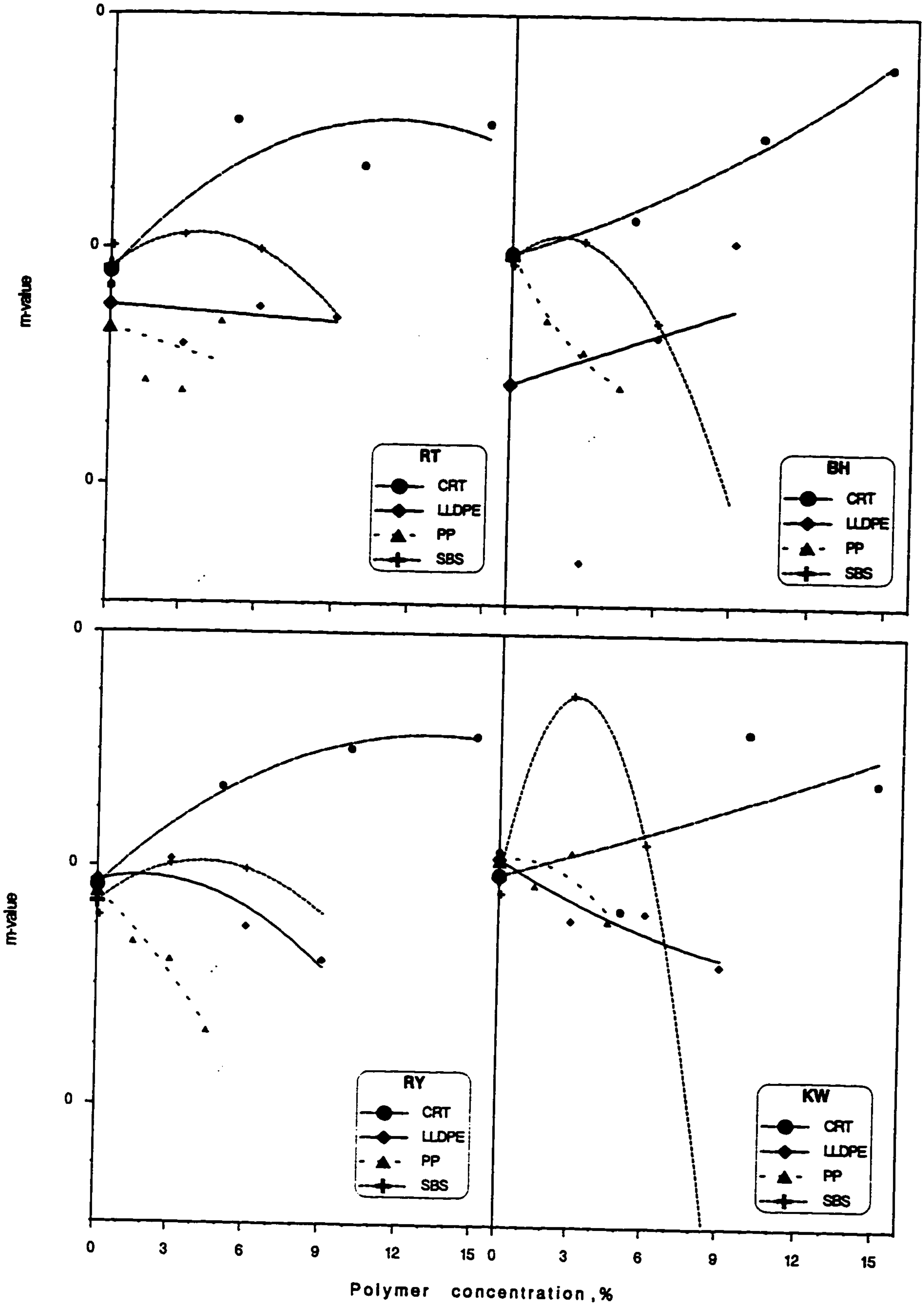


Figure C-22: Flexural creep slope (m-value) @ -22 C - PAV residue of different polymers and sources

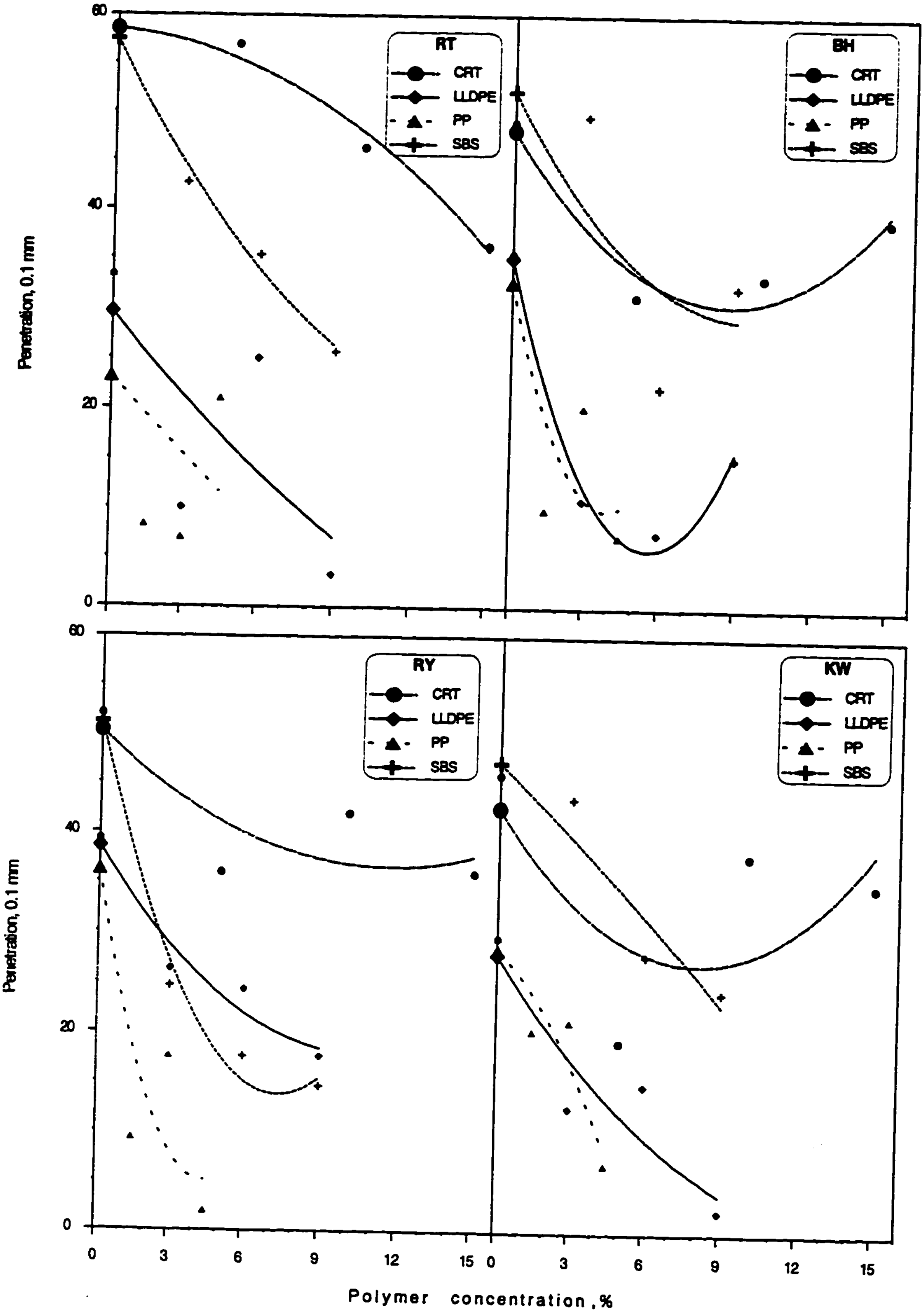


Figure C-23: Penetration @ 25 C of different polymers and sources

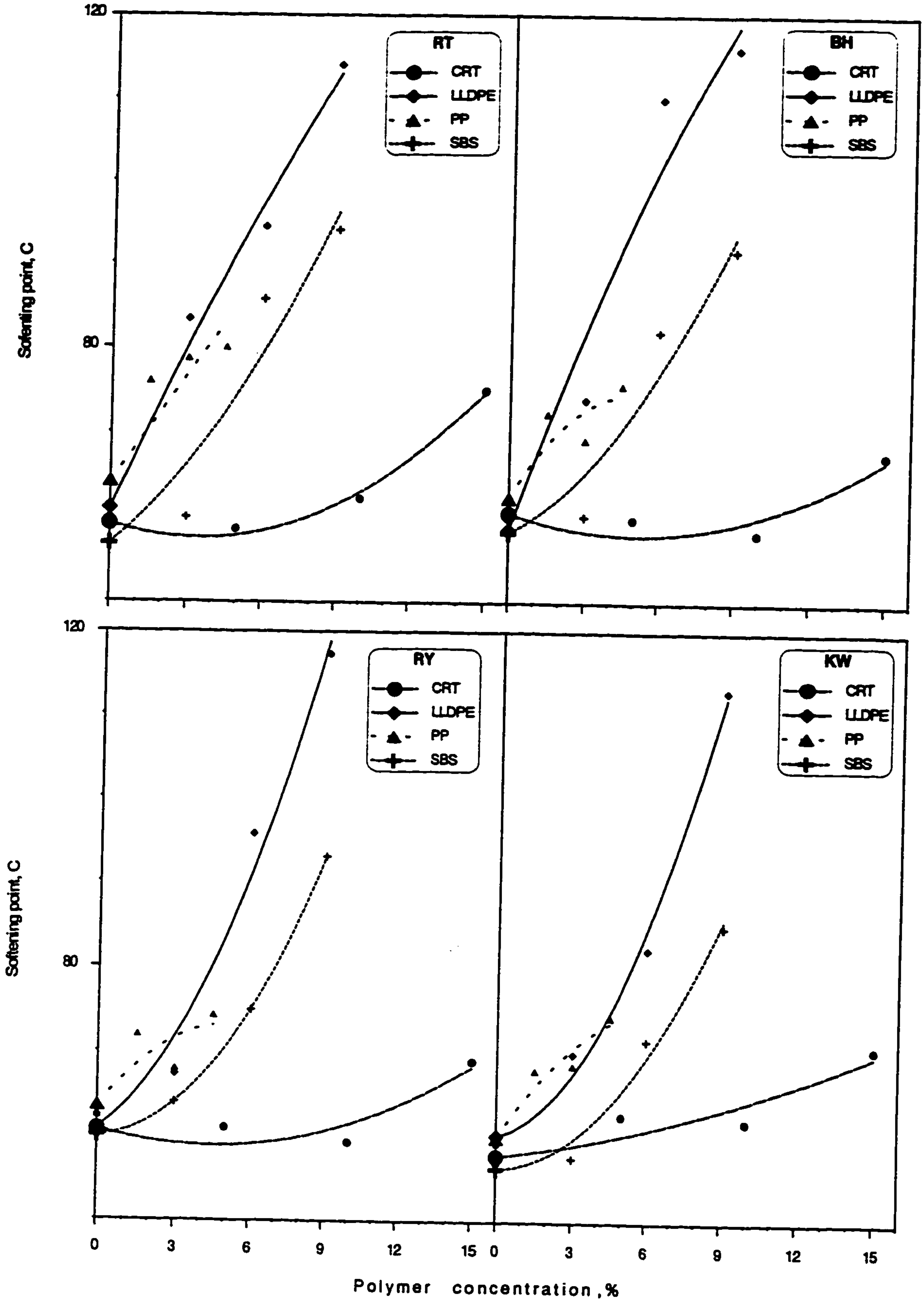


Figure C-24: Sotening point of different polymers and sources

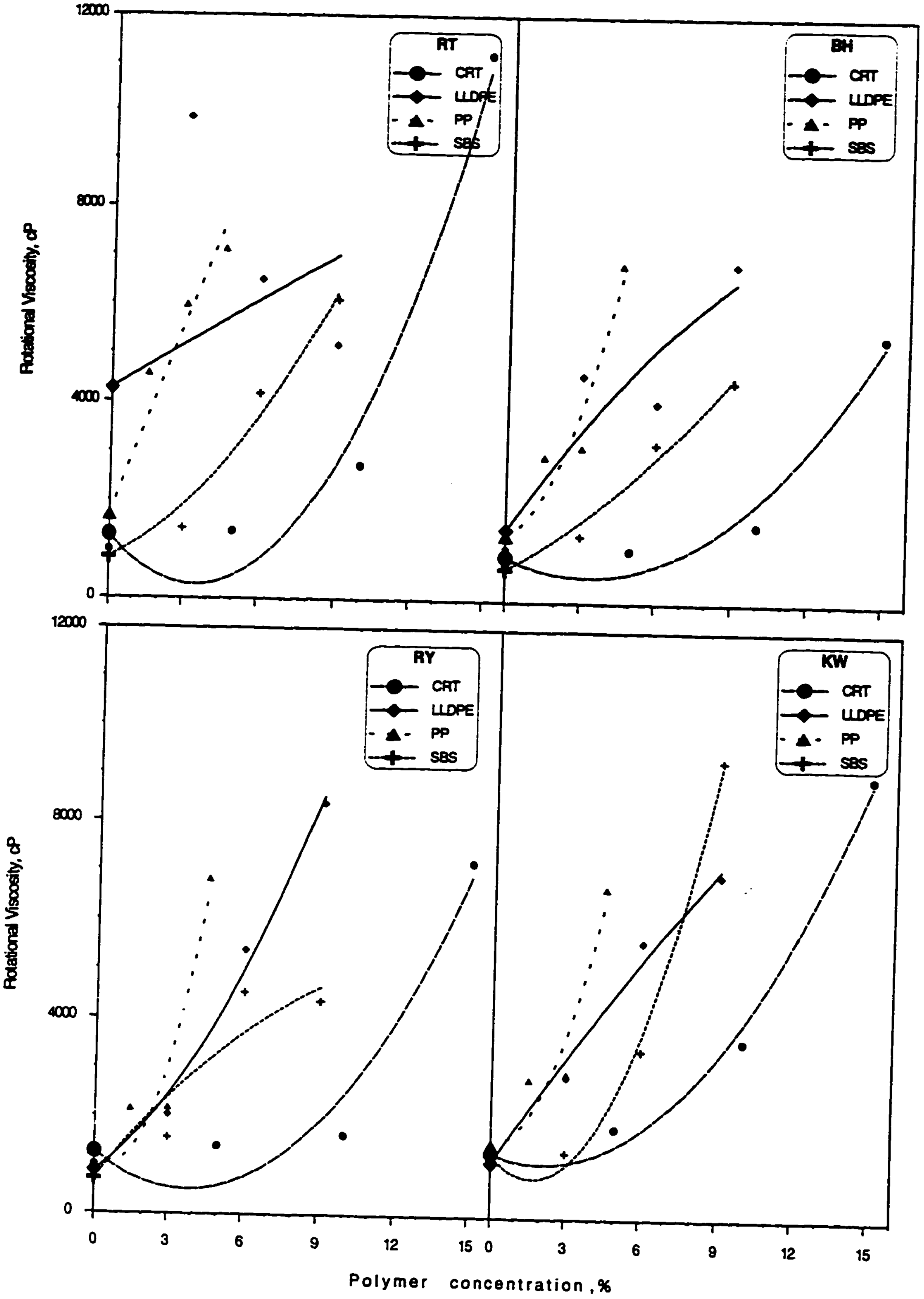


Figure C-25: Rotational viscosity @ 135 C of different polymers and sources

Appendix D

Three Way Analysis of Variance Tables of Polymer Optimization Test Results

Table D-1: Analysis of Variance for G* @ 76C - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	4.2212E8	3	1.4071E8	150.790	0.0000
B:PH31.Type	4.2463E9	3	1.4154E9	1516.865	0.0000
C:PH31.Percent	5.0170E9	3	1.6723E9	1792.197	0.0000
INTERACTIONS					
AB	1.1894E9	9	1.3216E8	141.631	0.0000
AC	1.9285E9	9	2.1428E8	229.637	0.0000
BC	5.9934E9	9	6.6593E8	713.659	0.0000
ABC	4.7448E9	27	1.7573E8	188.327	0.0000
RESIDUAL	1.1944E8	128	933127.42		
TOTAL (CORRECTED.)	2.3661E10	191			

Table D-2: Analysis of Variance for Phase angle at 76C - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	439.896	3	146.6320	771.113	0.0000
B:PH31.Type	2937.072	3	979.0241	5148.524	0.0000
C:PH31.Percent	15888.221	3	5296.0737	27851.168	0.0000
INTERACTIONS					
AB	784.6015	9	87.17794	458.454	0.0000
AC	482.6694	9	53.62993	282.031	0.0000
BC	6145.8931	9	682.87701	3591.136	0.0000
ABC	2296.8165	27	85.06728	447.355	0.0000
RESIDUAL	24.340000	128	0.1901562		
TOTAL (CORRECTED)	28999.510	191			

Table D-3: Analysis of Variance for G*/sin(delta) at 76C -Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	04E9	3	1.3101E9	88.080	0.0000
B:PH31.Type	1607E10	3	8689E9	327.330	0.0000
C:PH31.Percent	1.7273E10	3	5.7577E9	38784	0.0000
INTERACTIONS					
AB	1.2366E10	9	1.3740E9	92.374	0.0000
AC	1.4481E10	9	1.6090E9	108.173	0.0000
BC	2.9894E10	9	3.3216E9	223.305	0.0000
ABC	4.0903E10	27	1.49E9	101.847	0.0000
RESIDUAL	1.9039E9	128	14874510		
TOTAL (CORRECTED)	3536E11	191			

Table D-4: Analysis of Variance for G* @ 76 C - RTFOT residue-Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	5.1177E9	3	1.7059E9	375.864	0.0000
B:PH31.Type	1.3818E10	3	4.6061E9	1014.881	0.0000
C:PH31.Percent	1.2043E10	3	4.0144E9	884.509	0.0000
INTERACTIONS					
AB	8.2359E9	9	9.1510E8	201.626	0.0000
AC	6.5156E9	9	7.2396E8	159.511	0.0000
BC	8.1276E9	9	9.0306E8	198.974	0.0000
ABC	1.2277E10	27	4.5472E8	100.190	0.0000
RESIDUAL	5.8094E8	128	4538603.3		
TOTAL (CORRECTED)	6.6717E10	191			

Table D-5:Analysis of Variance for Delat @ 76C-RTFOT residue-Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	2290.622	3	763.5407	844.858	0.0000
B:PH31.Type	2634.532	3	878.1774	971.704	0.0000
C:PH31.Percent	16862.909	3	5620.9696	6219.607	0.0000
INTERACTIONS					
AB	3363.9600	9	73.77333	413.580	0.0000
AC	2071.2600	9	230.14000	254.650	0.0000
BC	4639.8183	9	15.53537	570.440	0.0000
ABC	5149.1179	27	190.70807	211.019	0.0000
RESIDUAL	115.68000	128	0.9037500		
TOTAL (CORRECTED)	37127.899	191			

Table D-6:Analysis of Variance for G*/sin(delta) @ 76C-RTFOT residue Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	2.5647E10	3	8.5490E9	76.297	0.0000
B:PH31.Type	5.1882E10	3	1.7294E10	154.341	0.0000
C:PH31.Percent	3.3425E10	3	1.1142E10	99.435	0.0000
INTERACTIONS					
AB	5.7431E10	9	6.3812E9	56.950	0.0000
AC	2.9183E10	9	3.2425E9	28.938	0.0000
BC	3.9650E10	9	4.4055E9	39.318	0.0000
ABC	6.7568E10	27	2.5025E9	22.334	0.0000
RESIDUAL	1.4342E10	128	1.1205E8		
TOTAL (CORRECTED)	3.1913E11	191			

Tsable D-7: Analysis of Variance for G* @ 80C - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	3.6964E8	3	1.2321E8	2344.217	0.0000
B:PH31.Type	2.5395E9	3	8.4649E8	16104.946	0.0000
C:PH31.Percent	3.1894E9	3	1.0631E9	20226.783	0.0000
INTERACTIONS					
AB	1.1102E9	9	1.2336E8	2346.984	0.0000
AC	1.5293E9	9	1.6992E8	3232.790	0.0000
BC	4.3363E9	9	4.8181E8	9166.702	0.0000
ABC	4.0713E9	27	1.5079E8	2868.871	0.0000
RESIDUAL	6727756.0	128	52560.594		
TOTAL (CORRECTED)	1.7152E10	191			

Table D-8: Analysis of Variance for Phase angle @ 80C - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	260.548	3	86.8494	627.118	0.0000
B:PH31.Type	3902.472	3	1300.8241	9392.938	0.0000
C:PH31.Percent	16722.158	3	5574.0527	40248.895	0.0000
INTERACTIONS					
AB	1047.7930	9	116.42144	840.651	0.0000
AC	680.2588	9	75.58431	545.776	0.0000
BC	7316.6496	9	812.96107	5870.197	0.0000
ABC	2685.0610	27	99.44670	718.081	0.0000
RESIDUAL	17.726667	128	0.1384896		
TOTAL (CORRECTED)	32632.667	191			

Table D-9: Analysis of Variance for G*/sin(delta) @ 80C - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	3.7445E9	3	1.2482E9	345.040	0.0000
B:PH31.Type	1.0726E10	3	3.5753E9	12446.215	0.0000
C:PH31.Percent	1.3014E10	3	4.3379E9	15100.984	0.0000
INTERACTIONS					
AB	1.1879E10	9	1.3199E9	4594.659	0.0000
AC	1.2886E10	9	1.4317E9	4984.101	0.0000
BC	2.4664E10	9	2.7404E9	9539.891	0.0000
ABC	3.8106E10	27	1.4113E9	4913.036	0.0000
RESIDUAL	6769364	128	287260.65		
TOTAL (CORRECTED)	1.1505E11	191			

Table D-10: Analysis of Variance for G* @ 80C-RTFOT residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	3.5111E9	3	1.1704E9	3685.781	0.0000
B:PH31.Type	8.7928E9	3	2.9309E9	9230.179	0.0000
C:PH31.Percent	6.7411E9	3	2.2470E9	7076.425	0.0000
INTERACTIONS					
AB	6.2771E9	9	6.9745E8	2196.440	0.0000
AC	3.9738E9	9	4.4154E8	1390.503	0.0000
BC	5.4751E9	9	6.0835E8	1915.838	0.0000
ABC	8.9319E9	27	3.3081E8	1041.802	0.0000
RESIDUAL	40644709	128	317536.79		
TOTAL (CORRECTED)	4.3744E10	191			

Table D-11: Analysis of Variance for Phase angle-RTFOT residue-Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	2216.506	3	738.8353	6675.595	0.0000
B:PH31.Type	3624.335	3	1208.1117	10915.645	0.0000
C:PH31.Percent	17812.912	3	5937.6374	53648.301	0.0000
INTERACTIONS					
AB	4115.9835	9	457.33150	4132.125	0.0000
AC	2526.2731	9	280.69701	2536.180	0.0000
BC	5816.0773	9	646.23081	5838.885	0.0000
ABC	6491.0656	27	240.40984	2172.174	0.0000
RESIDUAL	14.166667	128	0.1106771		

Table D-12: Analysis of Variance for G*/sin (delta) @ 80C - RTFOT residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	2.7586E10	3	9.1954E9	1051.780	0.0000
B:PH31.Type	4.8704E10	3	1.6235E10	1856.933	0.0000
C:PH31.Percent	2.5256E10	3	8.4186E9	962.926	0.0000
INTERACTIONS					
AB	6.8774E10	9	7.6416E9	874.054	0.0000
AC	3.0821E10	9	3.4245E9	391.699	0.0000
BC	4.1787E10	9	4.6430E9	531.071	0.0000
ABC	8.2516E10	27	3.0561E9	349.564	0.0000
RESIDUAL	1.1191E9	128	8742696.9		
TOTAL (CORRECTED)	3.2656E11	191			

Table D-13: Analysis of Variance for G* @ 22C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	1.0524E9	3	3.5081E8	567.184	0.0000
B:PH31.Type	2.4797E9	3	8.2657E8	1336.402	0.0000
C:PH31.Percent	3.5967E8	3	1.1989E8	193.837	0.0000
INTERACTIONS					
AB	9.2414E8	9	1.0268E8	166.016	0.0000
AC	4.3904E8	9	4.8782E7	78.872	0.0000
BC	1.6567E9	9	1.8408E8	297.620	0.0000
ABC	7.0650E8	27	2.6167E7	42.306	0.0000
RESIDUAL	79168604	128	618504.72		
TOTAL (CORRECTED)	7.6974E9	191			

Table D-14: Analysis of Variance for Phase angle (delta) @ 22C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	291.0538	3	97.01792	515.139	0.0000
B:PH31.Type	2602.3021	3	867.43403	4605.844	0.0000
C:PH31.Percent	277.1829	3	92.39431	490.589	0.0000
INTERACTIONS					
AB	372.2142	9	41.35713	219.595	0.0000
AC	309.5650	9	34.39611	182.634	0.0000
BC	1391.4667	9	154.60741	820.924	0.0000
ABC	911.2288	27	33.74921	179.199	0.0000
RESIDUAL	24.106667	128	0.1883333		
TOTAL (CORRECTED)	6179.1200	191			

Table D-15: Analysis of Variance for G*xsin(delta) @ 22C-PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	3.2227E8	3	1.0742E8	682.075	0.0000
B:PH31.Type	4.4670E8	3	1.4890E8	945.421	0.0000
C:PH31.Percent	1.2871E8	3	4.2905E7	272.417	0.0000
INTERACTIONS					
AB	1.5754E8	9	17504234	111.141	0.0000
AC	8.0900E7	9	8988838	57.074	0.0000
BC	3.1181E8	9	34645508	219.978	0.0000
ABC	1.2770E8	27	4729537	30.030	0.0000
RESIDUAL	20159432	128	157495.56		
TOTAL (CORRECTED)	1.5958E9	191			

Table D-16: Analysis of Variance for G* @ 25C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	5.1315E8	3	1.7105E8	749.409	0.0000
B:PH31.Type	1.5106E9	3	5.0352E8	2206.044	0.0000
C:PH31.Percent	2.0443E8	3	6.8144E7	298.559	0.0000
INTERACTIONS					
AB	4.8912E8	9	5.4347E7	238.107	0.0000
AC	2.6179E8	9	2.9087E7	127.439	0.0000
BC	1.0248E9	9	1.1387E8	498.892	0.0000
ABC	4.7108E8	27	1.7448E7	76.442	0.0000
RESIDUAL	29215327	128	228244.74		
TOTAL (CORRECTED)	4.5042E9	191			

Table D-17: Analysis of Variance for Phase angle (delta) @ 25C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	587.2879	3	195.76264	1874.635	0.0000
B:PH31.Type	2750.9679	3	916.98931	8781.144	0.0000
C:PH31.Percent	472.8158	3	157.60528	1509.238	0.0000
INTERACTIONS					
AB	323.8617	9	35.98463	344.591	0.0000
AC	224.4771	9	24.94190	238.845	0.0000
BC	1199.6738	9	133.29708	1276.461	0.0000
ABC	483.7617	27	17.91710	171.575	0.0000
RESIDUAL	13.366667	128	0.1044271		
TOTAL (CORRECTED)	6056.2125	191			

Table D-18: Analysis of Variance for G* x sin(delta) @ 25C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	1.7625E8	3	5.8749E7	1048.609	0.0000
B:PH31.Type	3.1939E8	3	1.0646E8	1900.292	0.0000
C:PH31.Percent	7.2716E7	3	2.4239E7	432.638	0.0000
INTERACTIONS					
AB	9.8171E7	9	10907842	194.694	0.0000
AC	5.8868E7	9	6540936	116.749	0.0000
BC	2.3276E8	9	25862119	461.613	0.0000
ABC	9.5500E7	27	3537039	63.133	0.0000
RESIDUAL	7171266.6	128	56025.521		
TOTAL (CORRECTED)	10608E9	191			

Table D-19: Analysis of Variance for S @ -18C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	618960.11	3	206320.04	552.148	0.0000
B:PH31.Type	179090.82	3	59696.94	159.759	0.0000
C:PH31.Percent	253469.11	3	84489.70	226.109	0.0000
INTERACTIONS					
AB	31203.50	9	3467.056	9.278	0.0000
AC	64916.19	9	7212.910	19.303	0.0000
BC	192807.39	9	21423.043	57.332	0.0000
ABC	62672.98	27	2321.221	6.212	0.0000
RESIDUAL	47829.528	128	373.66819		
TOTAL (CORRECTED)	1450949.6	191			

Table D-20: Analysis of Variance for m-value @ -18C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	0.0144227	3	0.0048076	54.823	0.0000
B:PH31.Type	0.0512189	3	0.0170730	194.691	0.0000
C:PH31.Percent	0.0505467	3	0.0168489	192.136	0.0000
INTERACTIONS					
AB	0.0096389	9	0.0010710	12.213	0.0000
AC	0.0126408	9	0.0014045	16.017	0.0000
BC	0.0421916	9	0.0046880	53.459	0.0000
ABC	0.0502411	27	0.0018608	21.219	0.0000
RESIDUAL		0.0112247	128	8.76927E-5	
TOTAL (CORRECTED)	0.2421255	191			

Table D-21: Analysis of Variance for S @ -12C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	195299.67	3	65099.891	682.663	0.0000
B:PH31.Type	204085.14	3	68028.379	713.372	0.0000
C:PH31.Percent	12436.70	3	4145.567	43.472	0.0000
INTERACTIONS					
AB	10511.68	9	1167.964	12.248	0.0000
AC	16039.93	9	1782.215	18.689	0.0000
BC	102310.54	9	11367.838	119.208	0.0000
ABC	38509.99	27	1426.296	14.957	0.0000
RESIDUAL	12206.292	128	95.361654		
TOTAL (CORRECTED)	591399.94	191			

Table D-22: Analysis of Variance for m-value @ -12C - PAV residue - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	0.0086399	3	0.0028800	75.489	0.0000
B:PH31.Type	0.1109814	3	0.0369938	969.666	0.0000
C:PH31.Percent	0.0007039	3	0.0002346	6.150	0.0006
INTERACTIONS					
AB	0.0146342	9	0.0016260	42.621	0.0000
AC	0.0188346	9	0.0020927	54.854	0.0000
BC	0.0562170	9	0.0062463	163.726	0.0000
ABC	0.0401199	27	0.0014859	38.948	0.0000
RESIDUAL	0.0048833	128	3.81510E-5		
TOTAL (CORRECTED)	0.2550143	191			

Table D-23: Analysis of Variance for Rotational Viscosity @ 135C - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	5.3539E7	3	1.7846E7	5861.819	0.0000
B:PH31.Type	5.9147E7	3	1.9716E7	6475.820	0.0000
C:PH31.Percent	9.1810E8	3	3.0603E8	100519.223	0.0000
INTERACTIONS					
AB	2.4826E7	9	2758408	906.024	0.0000
AC	4.3435E7	9	4826104	1585.177	0.0000
BC	1.1926E8	9	13251444	4352.555	0.0000
ABC	1.6550E8	27	6129619	2013.328	0.0000
RESIDUAL	389698.67	128	3044.5208		
TOTAL (CORRECTED)	1.3842E9	191			

Table D-24: Analysis of Variance for Softening point - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	675.486	3	225.1619	526.951	0.0000
B:PH31.Type	14017.944	3	4672.6478	10935.500	0.0000
C:PH31.Percent	21761.222	3	7253.7408	16976.088	0.0000
INTERACTIONS					
AB	475.1273	9	52.7919	123.550	0.0000
AC	391.4235	9	43.4915	101.784	0.0000
BC	9940.5973	9	1104.5108	2584.911	0.0000
ABC	1274.2819	27	47.1956	110.453	0.0000
RESIDUAL	54.693333	128	0.4272917		
TOTAL (CORRECTED)	48590.775	191			

Table D-25: Analysis of Variance for Penetration @ 25C - Fresh - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:PH31.Source	659.057	3	219.6858	405.574	0.0000
B:PH31.Type	18731.557	3	6243.8524	11527.112	0.0000
C:PH31.Percent	14050.016	3	4683.3385	8646.163	0.0000
INTERACTIONS					
AB	3069.3802	9	341.04225	629.616	0.0000
AC	738.5885	9	82.06539	151.505	0.0000
BC	2139.2552	9	237.69502	438.822	0.0000
ABC	3865.5573	27	143.16879	264.312	0.0000
RESIDUAL	69.333333	128	0.5416667		
TOTAL (CORRECTED)	43322.745	191			

Appendix E

Multiple Range Analysis Tables Using Least Significant Difference (LSD) for Polymer Optimization Test Results

Table E-1: LSD Table for G* at 76 C - Fresh Blends

Multiple range analysis for PH31.GS76F by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	4962.8958	X
2	48	5164.5333	X
0	48	6889.2708	X
3	48	8627.9167	X

contrast	difference	+/- limits	
0 - 1	1926.38	390.243	*
0 - 2	1724.74	390.243	*
0 - 3	-1738.65	390.243	*
1 - 2	-201.638	390.243	
1 - 3	-3665.02	390.243	*
2 - 3	-3463.38	390.243	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS76F by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	1845.604	X
3	48	3683.896	X
2	48	5959.417	X
1	48	14155.700	X

contrast	difference	+/- limits	
0 - 1	-12310.1	390.243	*
0 - 2	-4113.81	390.243	*
0 - 3	-1838.29	390.243	*
1 - 2	8196.28	390.243	*
1 - 3	10471.8	390.243	*
2 - 3	2275.52	390.243	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS76F by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	1062.750	X
1	48	4800.313	X
2	48	4935.679	X
3	48	14845.875	X

contrast	difference	+/- limits	
0 - 1	-3737.56	390.243	*
0 - 2	-3872.93	390.243	*
0 - 3	-13783.1	390.243	*
1 - 2	-135.367	390.243	
1 - 3	-10045.6	390.243	*
2 - 3	-9910.20	390.243	*

* denotes a statistically significant difference.

Table E-2: LSD Table for Phase angle at 76 C - Fresh Blends

Multiple range analysis for PH31.DEL76F by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	69.575000	X
3	48	72.102083	X
1	48	72.954167	X
2	48	73.539583	X

contrast	difference	+/- limits	
0 - 1	-3.37917	0.17617	*
0 - 2	-3.96458	0.17617	*
0 - 3	-2.52708	0.17617	*
1 - 2	-0.58542	0.17617	*
1 - 3	0.85208	0.17617	*
2 - 3	1.43750	0.17617	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL76F by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	66.631250	X
3	48	70.547917	X
0	48	73.789583	X
2	48	77.202083	X

contrast	difference	+/- limits	
0 - 1	7.15833	0.17617	*
0 - 2	-3.41250	0.17617	*
0 - 3	3.24167	0.17617	*
1 - 2	-10.5708	0.17617	*
1 - 3	-3.91667	0.17617	*
2 - 3	6.65417	0.17617	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL76F by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	57.464583	X
2	48	71.916667	X
1	48	77.118750	X
0	48	81.670833	X

contrast	difference	+/- limits	
0 - 1	4.55208	0.17617	*
0 - 2	9.75417	0.17617	*
0 - 3	24.2062	0.17617	*
1 - 2	5.20208	0.17617	*
1 - 3	19.6542	0.17617	*
2 - 3	14.4521	0.17617	*

* denotes a statistically significant difference.

Table E-3: LSD Table for G*/sin (δ) at 76 C - Fresh Blends

Multiple range analysis for PH31.GOS76F by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	5779.620	X
2	48	6038.273	X
0	48	8043.821	X
3	48	16871.545	X

contrast	difference	+/- limits	
0 - 1	2264.20	1558.07	*
0 - 2	2005.55	1558.07	*
0 - 3	-8827.72	1558.07	*
1 - 2	-258.653	1558.07	
1 - 3	-11091.9	1558.07	*
2 - 3	-10833.3	1558.07	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS76F by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2017.333	X
3	48	4454.023	X
2	48	6191.209	X
1	48	24070.693	X

contrast	difference	+/- limits	
0 - 1	-22053.4	1558.07	*
0 - 2	-4173.88	1558.07	*
0 - 3	-2436.69	1558.07	*
1 - 2	17879.5	1558.07	*
1 - 3	19616.7	1558.07	*
2 - 3	1737.19	1558.07	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS76F by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	1074.820	X
1	48	5041.577	X
2	48	5260.546	X
3	48	25356.315	X

contrast	difference	+/- limits	
0 - 1	-3966.76	1558.07	*
0 - 2	-4185.73	1558.07	*
0 - 3	-24281.5	1558.07	*
1 - 2	-218.969	1558.07	
1 - 3	-20314.7	1558.07	*
2 - 3	-20095.8	1558.07	*

* denotes a statistically significant difference.

Table E-4: LSD Table for G* at 76 C - RTFOT

Multiple range analysis for PH31.GS76R by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	6878.438	X
2	48	9664.021	X
0	48	11268.750	X
3	48	20628.146	X

contrast	difference	+/- limits	
0 - 1	4390.31	860.649	*
0 - 2	1604.73	860.649	*
0 - 3	-9359.40	860.649	*
1 - 2	-2785.58	860.649	*
1 - 3	-13749.7	860.649	*
2 - 3	-10964.1	860.649	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS76R by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	3381.667	X
3	48	5491.542	X
2	48	14775.875	X
1	48	24790.271	X

contrast	difference	+/- limits	
0 - 1	-21408.6	860.649	*
0 - 2	-11394.2	860.649	*
0 - 3	-2109.88	860.649	*
1 - 2	10014.4	860.649	*
1 - 3	19298.7	860.649	*
2 - 3	9284.33	860.649	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS76R by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2403.167	X
1	48	7884.792	X
2	48	14504.854	X
3	48	23646.542	X

contrast	difference	+/- limits	
0 - 1	-5481.63	860.649	*
0 - 2	-12101.7	860.649	*
0 - 3	-21243.4	860.649	*
1 - 2	-6620.06	860.649	*
1 - 3	-15761.8	860.649	*
2 - 3	-9141.69	860.649	*

* denotes a statistically significant difference.

Table E-5: LSD Table for Phase Angle at 76 C - RTFOT

Multiple range analysis for PH31.DEL76R by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	65.510417	X
0	48	65.941667	X
2	48	70.237500	X
1	48	73.968750	X

contrast	difference	+/- limits
0 - 1	-8.02708	0.38405 *
0 - 2	-4.29583	0.38405 *
0 - 3	0.43125	0.38405 *
1 - 2	3.73125	0.38405 *
1 - 3	8.45833	0.38405 *
2 - 3	4.72708	0.38405 *

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL76R by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	62.962500	X
3	48	68.716667	X
0	48	71.485417	X
2	48	72.493750	X

contrast	difference	+/- limits
0 - 1	8.52292	0.38405 *
0 - 2	-1.00833	0.38405 *
0 - 3	2.76875	0.38405 *
1 - 2	-9.53125	0.38405 *
1 - 3	-5.75417	0.38405 *
2 - 3	3.77708	0.38405 *

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL76R by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	55.718750	X
2	48	64.843750	X
1	48	75.145833	X
0	48	79.950000	X

contrast	difference	+/- limits
0 - 1	4.80417	0.38405 *
0 - 2	15.1063	0.38405 *
0 - 3	24.2313	0.38405 *
1 - 2	10.3021	0.38405 *
1 - 3	19.4271	0.38405 *
2 - 3	9.12500	0.38405 *

* denotes a statistically significant difference.

Table E-6: LSD Table for G*/sin (δ) at 76 C - RTOFT

Multiple range analysis for PH31.GOS76R by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	7382.590	X
2	48	12370.792	X
0	48	14287.830	X
3	48	37395.787	X

contrast	difference	+/- limits	
0 - 1	6905.24	4276.33	*
0 - 2	1917.04	4276.33	
0 - 3	-23108.0	4276.33	*
1 - 2	-4988.20	4276.33	*
1 - 3	-30013.2	4276.33	*
2 - 3	-25025.0	4276.33	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS76R by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	3825.515	X
3	48	6504.480	X
2	48	15844.571	X
1	48	45262.435	X

contrast	difference	+/- limits	
0 - 1	-41436.9	4276.33	*
0 - 2	-12019.1	4276.33	*
0 - 3	-2678.96	4276.33	
1 - 2	29417.9	4276.33	*
1 - 3	38758.0	4276.33	*
2 - 3	9340.09	4276.33	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS76R by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2446.053	X
1	48	8435.477	X
2	48	24730.345	X
3	48	35825.125	X

contrast	difference	+/- limits	
0 - 1	-5989.42	4276.33	*
0 - 2	-22284.3	4276.33	*
0 - 3	-33379.1	4276.33	*
1 - 2	-16294.9	4276.33	*
1 - 3	-27389.6	4276.33	*
2 - 3	-11094.8	4276.33	*

* denotes a statistically significant difference.

Table E-7: LSD Table for G* at 80 C - Fresh Blends

Multiple range analysis for PH31.GS80F by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	3288.7708	X
2	48	3491.3958	X
0	48	4499.8958	X
3	48	6784.1875	X

contrast	difference	+/- limits	
0 - 1	1211.12	92.6179	*
0 - 2	1008.50	92.6179	*
0 - 3	-2284.29	92.6179	*
1 - 2	-202.625	92.6179	*
1 - 3	-3495.42	92.6179	*
2 - 3	-3292.79	92.6179	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS80F by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	1205.333	X
3	48	2579.104	X
2	48	3645.375	X
1	48	10634.438	X

contrast	difference	+/- limits	
0 - 1	-9429.10	92.6179	*
0 - 2	-2440.04	92.6179	*
0 - 3	-1373.77	92.6179	*
1 - 2	6989.06	92.6179	*
1 - 3	8055.33	92.6179	*
2 - 3	1066.27	92.6179	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS80F by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	616.083	X
1	48	2943.667	X
2	48	3141.896	X
3	48	11362.604	X

contrast	difference	+/- limits	
0 - 1	-2327.58	92.6179	*
0 - 2	-2525.81	92.6179	*
0 - 3	-10746.5	92.6179	*
1 - 2	-198.229	92.6179	*
1 - 3	-8418.94	92.6179	*
2 - 3	-8220.71	92.6179	*

* denotes a statistically significant difference.

Table E-8: LSD Table for Phase Angle at 80 C - Fresh Blends

Multiple range analysis for PH31.DEL80F by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	71.125000	X
3	48	73.372917	X
1	48	73.822917	X
2	48	74.064583	X

contrast	difference	+/- limits	
0 - 1	-2.69792	0.15034	*
0 - 2	-2.93958	0.15034	*
0 - 3	-2.24792	0.15034	*
1 - 2	-0.24167	0.15034	*
1 - 3	0.45000	0.15034	*
2 - 3	0.69167	0.15034	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL80F by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	66.870833	X
3	48	71.239583	X
0	48	75.343750	X
2	48	78.931250	X

contrast	difference	+/- limits	
0 - 1	8.47292	0.15034	*
0 - 2	-3.58750	0.15034	*
0 - 3	4.10417	0.15034	*
1 - 2	-12.0604	0.15034	*
1 - 3	-4.36875	0.15034	*
2 - 3	7.69167	0.15034	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL80F by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	58.060417	X
2	48	73.110417	X
1	48	78.431250	X
0	48	82.783333	X

contrast	difference	+/- limits	
0 - 1	4.35208	0.15034	*
0 - 2	9.67292	0.15034	*
0 - 3	24.7229	0.15034	*
1 - 2	5.32083	0.15034	*
1 - 3	20.3708	0.15034	*
2 - 3	15.0500	0.15034	*

* denotes a statistically significant difference.

Table E-9: LSD Table for G*/sin (δ) at 80 C - Fresh Blends

Multiple range analysis for PH31.GOS80F by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	3870.304	X
2	48	4406.423	X
0	48	5289.049	X
3	48	14653.296	X

contrast	difference	+/- limits	
0 - 1	1418.74	216.522	*
0 - 2	882.626	216.522	*
0 - 3	-9364.25	216.522	*
1 - 2	-536.119	216.522	*
1 - 3	-10783.0	216.522	*
2 - 3	-10246.9	216.522	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS80F by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	1302.796	X
3	48	3257.410	X
2	48	3756.119	X
1	48	19902.746	X

contrast	difference	+/- limits	
0 - 1	-18599.9	216.522	*
0 - 2	-2453.32	216.522	*
0 - 3	-1954.61	216.522	*
1 - 2	16146.6	216.522	*
1 - 3	16645.3	216.522	*
2 - 3	498.708	216.522	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS80F by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	621.493	X
1	48	3064.898	X
2	48	3336.255	X
3	48	21196.426	X

contrast	difference	+/- limits	
0 - 1	-2443.41	216.522	*
0 - 2	-2714.76	216.522	*
0 - 3	-20574.9	216.522	*
1 - 2	-271.357	216.522	*
1 - 3	-18131.5	216.522	*
2 - 3	-17860.2	216.522	*

* denotes a statistically significant difference.

Table E-10: LSD Table for G* at 80 C - RTFOT

Multiple range analysis for PH31.GS80R by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	4606.542	X
2	48	6918.604	X
0	48	7586.563	X
3	48	15910.479	X

contrast	difference	+/- limits	
0 - 1	2980.02	227.647	*
0 - 2	667.958	227.647	*
0 - 3	-8323.92	227.647	*
1 - 2	-2312.06	227.647	*
1 - 3	-11303.9	227.647	*
2 - 3	-8991.88	227.647	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS80R by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2161.500	X
3	48	3831.063	X
2	48	9559.396	X
1	48	19470.229	X

contrast	difference	+/- limits	
0 - 1	-17308.7	227.647	*
0 - 2	-7397.90	227.647	*
0 - 3	-1669.56	227.647	*
1 - 2	9910.83	227.647	*
1 - 3	15639.2	227.647	*
2 - 3	5728.33	227.647	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS80R by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	1425.333	X
1	48	5000.479	X
2	48	11935.479	X
3	48	16660.896	X

contrast	difference	+/- limits	
0 - 1	-3575.15	227.647	*
0 - 2	-10510.1	227.647	*
0 - 3	-15235.6	227.647	*
1 - 2	-6935.00	227.647	*
1 - 3	-11660.4	227.647	*
2 - 3	-4725.42	227.647	*

* denotes a statistically significant difference.

Table E-11: LSD Table for Phase Angle at 80 C - RTFOT

Multiple range analysis for PH31.DEL80R by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	66.497917	X
0	48	68.095833	X
2	48	71.543750	X
1	48	75.333333	X

contrast	difference	+/- limits	
0 - 1	-7.23750	0.13440	*
0 - 2	-3.44792	0.13440	*
0 - 3	1.59792	0.13440	*
1 - 2	3.78958	0.13440	*
1 - 3	8.83542	0.13440	*
2 - 3	5.04583	0.13440	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL80R by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	63.175000	X
3	48	70.856250	X
0	48	72.991667	X
2	48	74.447917	X

contrast	difference	+/- limits	
0 - 1	9.81667	0.13440	*
0 - 2	-1.45625	0.13440	*
0 - 3	2.13542	0.13440	*
1 - 2	-11.2729	0.13440	*
1 - 3	-7.68125	0.13440	*
2 - 3	3.59167	0.13440	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL80R by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	57.020833	X
2	48	65.741667	X
1	48	77.112500	X
0	48	81.595833	X

contrast	difference	+/- limits	
0 - 1	4.48333	0.13440	*
0 - 2	15.8542	0.13440	*
0 - 3	24.5750	0.13440	*
1 - 2	11.3708	0.13440	*
1 - 3	20.0917	0.13440	*
2 - 3	8.72083	0.13440	*

* denotes a statistically significant difference.

Table E-12: LSD Table for G*/sin (δ) at 80 C - RTFOT

Multiple range analysis for PH31.GOS80R by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	4923.937	X
0	48	9360.779	X
2	48	9437.905	X
3	48	35265.806	X

contrast	difference	+/- limits	
0 - 1	4436.84	1194.50	*
0 - 2	-77.1257	1194.50	
0 - 3	-25905.0	1194.50	*
1 - 2	-4513.97	1194.50	*
1 - 3	-30341.9	1194.50	*
2 - 3	-25827.9	1194.50	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS80R by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2442.122	X
3	48	4500.371	X
2	48	10149.018	X
1	48	41896.917	X

contrast	difference	+/- limits	
0 - 1	-39454.8	1194.50	*
0 - 2	-7706.90	1194.50	*
0 - 3	-2058.25	1194.50	*
1 - 2	31747.9	1194.50	*
1 - 3	37396.5	1194.50	*
2 - 3	5648.65	1194.50	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GOS80R by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	1442.961	X
1	48	5294.264	X
2	48	25468.349	X
3	48	26782.853	X

contrast	difference	+/- limits	
0 - 1	-3851.30	1194.50	*
0 - 2	-24025.4	1194.50	*
0 - 3	-25339.9	1194.50	*
1 - 2	-20174.1	1194.50	*
1 - 3	-21488.6	1194.50	*
2 - 3	-1314.50	1194.50	*

* denotes a statistically significant difference.

Table E-13: LSD Table for G* at 22 C - PAV

Multiple range analysis for PH31.GS22P by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	5637.900	X
1	48	7530.208	X
3	48	8874.500	X
2	48	12057.458	X

contrast	difference	+/- limits	
0 - 1	-1892.31	317.714	*
0 - 2	-6419.56	317.714	*
0 - 3	-3236.60	317.714	*
1 - 2	-4527.25	317.714	*
1 - 3	-1344.29	317.714	*
2 - 3	3182.96	317.714	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS22P by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	4834.417	X
3	48	5620.075	X
1	48	9841.512	X
2	48	13804.063	X

contrast	difference	+/- limits	
0 - 1	-5007.10	317.714	*
0 - 2	-8969.65	317.714	*
0 - 3	-785.659	317.714	*
1 - 2	-3962.55	317.714	*
1 - 3	4221.44	317.714	*
2 - 3	8183.99	317.714	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS22P by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	6359.8254	X
0	48	8380.0833	X
1	48	9439.5958	X
2	48	9920.5625	X

contrast	difference	+/- limits	
0 - 1	-1059.51	317.714	*
0 - 2	-1540.48	317.714	*
0 - 3	2020.26	317.714	*
1 - 2	-480.967	317.714	*
1 - 3	3079.77	317.714	*
2 - 3	3560.74	317.714	*

* denotes a statistically significant difference.

Table E-14: LSD Table for Phase Angle at 22 C - PAV

Multiple range analysis for PH31.DEL22P by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	33.579167	X
1	48	34.079167	X
2	48	35.693750	X
3	48	36.647917	X

contrast	difference	+/- limits	
0 - 1	-0.50000	0.17532	*
0 - 2	-2.11458	0.17532	*
0 - 3	-3.06875	0.17532	*
1 - 2	-1.61458	0.17532	*
1 - 3	-2.56875	0.17532	*
2 - 3	-0.95417	0.17532	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL22P by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
2	48	30.733333	X
1	48	32.310417	X
3	48	36.964583	X
0	48	39.991667	X

contrast	difference	+/- limits	
0 - 1	7.68125	0.17532	*
0 - 2	9.25833	0.17532	*
0 - 3	3.02708	0.17532	*
1 - 2	1.57708	0.17532	*
1 - 3	-4.65417	0.17532	*
2 - 3	-6.23125	0.17532	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL22P by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	33.631250	X
2	48	34.672917	X
1	48	34.762500	X
0	48	36.933333	X

contrast	difference	+/- limits	
0 - 1	2.17083	0.17532	*
0 - 2	2.26042	0.17532	*
0 - 3	3.30208	0.17532	*
1 - 2	0.08958	0.17532	
1 - 3	1.13125	0.17532	*
2 - 3	1.04167	0.17532	*

* denotes a statistically significant difference.

Table E-15: LSD Table for G* x sin (δ) at 22 C - PAV

Multiple range analysis for PH31.GXS22P by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2795.6465	X
1	48	4167.9862	X
3	48	5063.4350	X
2	48	6348.4373	X

contrast	difference	+/- limits	
0 - 1	-1372.34	160.324	*
0 - 2	-3552.79	160.324	*
0 - 3	-2267.79	160.324	*
1 - 2	-2180.45	160.324	*
1 - 3	-895.449	160.324	*
2 - 3	1285.00	160.324	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GXS22P by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	3044.6319	X
3	48	3370.9919	X
1	48	5094.4248	X
2	48	6865.4564	X

contrast	difference	+/- limits	
0 - 1	-2049.79	160.324	*
0 - 2	-3820.82	160.324	*
0 - 3	-326.360	160.324	*
1 - 2	-1771.03	160.324	*
1 - 3	1723.43	160.324	*
2 - 3	3494.46	160.324	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GXS22P by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	3175.8152	X
0	48	5054.5741	X
1	48	5064.7563	X
2	48	5080.3595	X

contrast	difference	+/- limits	
0 - 1	-10.1822	160.324	
0 - 2	-25.7853	160.324	
0 - 3	1878.76	160.324	*
1 - 2	-15.6031	160.324	
1 - 3	1888.94	160.324	*
2 - 3	1904.54	160.324	*

* denotes a statistically significant difference.

Table E-16: LSD Table for Phase Angle at 25 C - PAV

Multiple range analysis for PH31.DEL25P by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	33.908333	X
1	48	36.547917	X
2	48	37.743750	X
3	48	38.525000	X

contrast	difference	+/- limits	
0 - 1	-2.63958	0.13055	*
0 - 2	-3.83542	0.13055	*
0 - 3	-4.61667	0.13055	*
1 - 2	-1.19583	0.13055	*
1 - 3	-1.97708	0.13055	*
2 - 3	-0.78125	0.13055	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL25P by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	35.216667	X
2	48	35.733333	X
1	48	36.491667	X
0	48	39.283333	X

contrast	difference	+/- limits	
0 - 1	2.79167	0.13055	*
0 - 2	3.55000	0.13055	*
0 - 3	4.06667	0.13055	*
1 - 2	0.75833	0.13055	*
1 - 3	1.27500	0.13055	*
2 - 3	0.51667	0.13055	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.DEL25P by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	32.700000	X
2	48	33.566667	X
3	48	38.414583	X
0	48	42.043750	X

contrast	difference	+/- limits	
0 - 1	9.34375	0.13055	*
0 - 2	8.47708	0.13055	*
0 - 3	3.62917	0.13055	*
1 - 2	-0.86667	0.13055	*
1 - 3	-5.71458	0.13055	*
2 - 3	-4.84792	0.13055	*

* denotes a statistically significant difference.

Table E-17: LSD Table for G* x sin (δ) at 25 C - PAV

Multiple range analysis for PH31.GXS25P by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2270.9843	X
1	48	3288.1893	X
3	48	4011.1792	X
2	48	4880.5760	X

contrast	difference	+/- limits	
0 - 1	-1017.21	95.6220	*
0 - 2	-2609.59	95.6220	*
0 - 3	-1740.19	95.6220	*
1 - 2	-1592.39	95.6220	*
1 - 3	-722.990	95.6220	*
2 - 3	869.397	95.6220	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GXS25P by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	2259.3507	X
3	48	2545.0486	X
1	48	4210.2044	X
2	48	5436.3251	X

contrast	difference	+/- limits	
0 - 1	-1950.85	95.6220	*
0 - 2	-3176.97	95.6220	*
0 - 3	-285.698	95.6220	*
1 - 2	-1226.12	95.6220	*
1 - 3	1665.16	95.6220	*
2 - 3	2891.28	95.6220	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GXS25P by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	2586.1739	X
0	48	3819.1559	X
1	48	3820.0913	X
2	48	4225.5077	X

contrast	difference	+/- limits	
0 - 1	-0.93541	95.6220	
0 - 2	-406.352	95.6220	*
0 - 3	1232.98	95.6220	*
1 - 2	-405.416	95.6220	*
1 - 3	1233.92	95.6220	*
2 - 3	1639.33	95.6220	*

* denotes a statistically significant difference.

Table E-18: LSD Table for G* at 25 C - PAV

Multiple range analysis for PH31.GS25P by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	4396.9583	X
1	48	5661.7083	X
3	48	6757.3750	X
2	48	8850.8542	X

contrast	difference	+/- limits	
0 - 1	-1264.75	193.004	*
0 - 2	-4453.90	193.004	*
0 - 3	-2360.42	193.004	*
1 - 2	-3189.15	193.004	*
1 - 3	-1095.67	193.004	*
2 - 3	2093.48	193.004	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS25P by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	3426.521	X
3	48	4079.396	X
1	48	7881.708	X
2	48	10279.271	X

contrast	difference	+/- limits	
0 - 1	-4455.19	193.004	*
0 - 2	-6852.75	193.004	*
0 - 3	-652.875	193.004	*
1 - 2	-2397.56	193.004	*
1 - 3	3802.31	193.004	*
2 - 3	6199.88	193.004	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.GS25P by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	4994.8958	X
0	48	6008.6667	X
1	48	6886.3125	X
2	48	7777.0208	X

contrast	difference	+/- limits	
0 - 1	-877.646	193.004	*
0 - 2	-1768.35	193.004	*
0 - 3	1013.77	193.004	*
1 - 2	-890.708	193.004	*
1 - 3	1891.42	193.004	*
2 - 3	2782.13	193.004	*

* denotes a statistically significant difference.

Table E-19: LSD Table for S at -28 C - PAV

Multiple range analysis for PH31.S18 by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	164.86771	X
1	48	267.97688	X
2	48	282.32917	X
3	48	317.41396	X

contrast	difference	+/- limits	
0 - 1	-103.109	7.80922	*
0 - 2	-117.461	7.80922	*
0 - 3	-152.546	7.80922	*
1 - 2	-14.3523	7.80922	*
1 - 3	-49.4371	7.80922	*
2 - 3	-35.0848	7.80922	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.S18 by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	225.12813	X
3	48	245.00104	X
1	48	254.74896	X
2	48	307.70958	X

contrast	difference	+/- limits	
0 - 1	-29.6208	7.80922	*
0 - 2	-82.5815	7.80922	*
0 - 3	-19.8729	7.80922	*
1 - 2	-52.9606	7.80922	*
1 - 3	9.74792	7.80922	*
2 - 3	62.7085	7.80922	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.S18 by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	217.15042	X
2	48	239.86083	X
1	48	260.32646	X
0	48	315.25000	X

contrast	difference	+/- limits	
0 - 1	54.9235	7.80922	*
0 - 2	75.3892	7.80922	*
0 - 3	98.0996	7.80922	*
1 - 2	20.4656	7.80922	*
1 - 3	43.1760	7.80922	*
2 - 3	22.7104	7.80922	*

* denotes a statistically significant difference.

Table E-20: LSD Table for m-value at -28 C - PAV

Multiple range analysis for PH31.M18 by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
2	48	0.2325833	X
3	48	0.2353125	XX
1	48	0.2376875	X
0	48	0.2547708	X

contrast	difference	+/- limits	
0 - 1	0.01708	0.00378	*
0 - 2	0.02219	0.00378	*
0 - 3	0.01946	0.00378	*
1 - 2	0.00510	0.00378	*
1 - 3	0.00238	0.00378	
2 - 3	-0.00273	0.00378	

* denotes a statistically significant difference.

Multiple range analysis for PH31.M18 by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
2	48	0.2233125	X
1	48	0.2294167	X
3	48	0.2416667	X
0	48	0.2659583	X

contrast	difference	+/- limits	
0 - 1	0.03654	0.00378	*
0 - 2	0.04265	0.00378	*
0 - 3	0.02429	0.00378	*
1 - 2	0.00610	0.00378	*
1 - 3	-0.01225	0.00378	*
2 - 3	-0.01835	0.00378	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.M18 by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	0.2127500	X
1	48	0.2430625	X
2	48	0.2522708	X
3	48	0.2522708	X

contrast	difference	+/- limits	
0 - 1	-0.03031	0.00378	*
0 - 2	-0.03952	0.00378	*
0 - 3	-0.03952	0.00378	*
1 - 2	-0.00921	0.00378	*
1 - 3	-0.00921	0.00378	*
2 - 3	0.00000	0.00378	

* denotes a statistically significant difference.

Table E-21: LSD Table for S at -22 C - PAV

Multiple range analysis for PH31.S12 by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	95.32000	X
1	48	157.96958	X
2	48	165.23208	X
3	48	178.04042	X

contrast	difference	+/- limits	
0 - 1	-62.6496	3.94504	*
0 - 2	-69.9121	3.94504	*
0 - 3	-82.7204	3.94504	*
1 - 2	-7.26250	3.94504	*
1 - 3	-20.0708	3.94504	*
2 - 3	-12.8083	3.94504	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.S12 by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	108.77063	X
3	48	133.91458	X
1	48	156.38646	X
2	48	197.49042	X

contrast	difference	+/- limits	
0 - 1	-47.6158	3.94504	*
0 - 2	-88.7198	3.94504	*
0 - 3	-25.1440	3.94504	*
1 - 2	-41.1040	3.94504	*
1 - 3	22.4719	3.94504	*
2 - 3	63.5758	3.94504	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.S12 by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	137.28875	X
2	48	146.17542	X
1	48	156.35958	X
0	48	156.73833	X

contrast	difference	+/- limits	
0 - 1	0.37875	3.94504	
0 - 2	10.5629	3.94504	*
0 - 3	19.4496	3.94504	*
1 - 2	10.1842	3.94504	*
1 - 3	19.0708	3.94504	*
2 - 3	8.88667	3.94504	*

* denotes a statistically significant difference.

Table E-22: LSD Table for m-value at -22 C - PAV

Multiple range analysis for PH31.M12 by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
2	48	0.2881458	X
0	48	0.2897708	X
1	48	0.2925000	X
3	48	0.3052083	X

contrast	difference	+/- limits	
0 - 1	-0.00273	0.00250	*
0 - 2	0.00163	0.00250	
0 - 3	-0.01544	0.00250	*
1 - 2	0.00435	0.00250	*
1 - 3	-0.01271	0.00250	*
2 - 3	-0.01706	0.00250	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.M12 by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
2	48	0.2711250	X
1	48	0.2735625	X
3	48	0.3004792	X
0	48	0.3304583	X

contrast	difference	+/- limits	
0 - 1	0.05690	0.00250	*
0 - 2	0.05933	0.00250	*
0 - 3	0.02998	0.00250	*
1 - 2	0.00244	0.00250	
1 - 3	-0.02692	0.00250	*
2 - 3	-0.02935	0.00250	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.M12 by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
1	48	0.2907708	X
3	48	0.2939583	X
0	48	0.2952500	X
2	48	0.2956458	X

contrast	difference	+/- limits	
0 - 1	0.00448	0.00250	*
0 - 2	-0.00040	0.00250	
0 - 3	0.00129	0.00250	
1 - 2	-0.00487	0.00250	*
1 - 3	-0.00319	0.00250	*
2 - 3	0.00169	0.00250	

* denotes a statistically significant difference.

Table E-23: LSD Table for Rotational Viscosity at 135 C - Fresh Blends

Multiple range analysis for PH31.VIS135 by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
2	48	3048.3958	X
1	48	3223.8958	X
3	48	3849.3958	X
0	48	4381.1042	X

contrast	difference	+/- limits	
0 - 1	1157.21	22.2907	*
0 - 2	1332.71	22.2907	*
0 - 3	531.708	22.2907	*
1 - 2	175.500	22.2907	*
1 - 3	-625.500	22.2907	*
2 - 3	-801.000	22.2907	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.VIS135 by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	3083.0625	X
0	48	3255.2708	X
2	48	3644.2083	X
1	48	4520.2500	X

contrast	difference	+/- limits	
0 - 1	-1264.98	22.2907	*
0 - 2	-388.938	22.2907	*
0 - 3	172.208	22.2907	*
1 - 2	876.042	22.2907	*
1 - 3	1437.19	22.2907	*
2 - 3	561.146	22.2907	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.VIS135 by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	995.2500	X
1	48	2710.6458	X
2	48	3803.8958	X
3	48	6993.0000	X

contrast	difference	+/- limits	
0 - 1	-1715.40	22.2907	*
0 - 2	-2808.65	22.2907	*
0 - 3	-5997.75	22.2907	*
1 - 2	-1093.25	22.2907	*
1 - 3	-4282.35	22.2907	*
2 - 3	-3189.10	22.2907	*

* denotes a statistically significant difference.

Table E-24: LSD Table for Softening Point - Fresh Blends

Multiple range analysis for PH31.SOFT by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	62.672917	X
2	48	70.020833	X
3	48	72.256250	X
1	48	86.270833	X

contrast	difference	+/- limits	
0 - 1	-23.5979	0.26407	*
0 - 2	-7.34792	0.26407	*
0 - 3	-9.58333	0.26407	*
1 - 2	16.2500	0.26407	*
1 - 3	14.0146	0.26407	*
2 - 3	-2.23542	0.26407	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.SOFT by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	69.925000	X
1	48	72.545833	X
2	48	73.750000	X
0	48	75.000000	X

contrast	difference	+/- limits	
0 - 1	2.45417	0.26407	*
0 - 2	1.25000	0.26407	*
0 - 3	5.07500	0.26407	*
1 - 2	-1.20417	0.26407	*
1 - 3	2.62083	0.26407	*
2 - 3	3.82500	0.26407	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.SOFT by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
0	48	59.887500	X
1	48	66.708333	X
2	48	76.458333	X
3	48	88.166667	X

contrast	difference	+/- limits	
0 - 1	-6.82083	0.26407	*
0 - 2	-16.5708	0.26407	*
0 - 3	-28.2792	0.26407	*
1 - 2	-9.75000	0.26407	*
1 - 3	-21.4583	0.26407	*
2 - 3	-11.7083	0.26407	*

* denotes a statistically significant difference.

Table E-25: LSD Table for Penetration at 25 C - Fresh Blends

Multiple range analysis for PH31.PEN by PH31.Source

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	26.145833	X
2	48	27.979167	X
1	48	28.062500	X
0	48	31.291667	X

contrast	difference	+/- limits	
0 - 1	3.22917	0.29732	*
0 - 2	3.31250	0.29732	*
0 - 3	5.14583	0.29732	*
1 - 2	0.08333	0.29732	
1 - 3	1.91667	0.29732	*
2 - 3	1.83333	0.29732	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.PEN by PH31.Type

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
2	48	18.104167	X
1	48	19.291667	X
3	48	35.270833	X
0	48	40.812500	X

contrast	difference	+/- limits	
0 - 1	21.5208	0.29732	*
0 - 2	22.7083	0.29732	*
0 - 3	5.54167	0.29732	*
1 - 2	1.18750	0.29732	*
1 - 3	-15.9792	0.29732	*
2 - 3	-17.1667	0.29732	*

* denotes a statistically significant difference.

Multiple range analysis for PH31.PEN by PH31.Percent

Method: 95 Percent LSD

Level	Count	LS Mean	Homogeneous Groups
3	48	19.958333	X
2	48	25.083333	X
1	48	25.770833	X
0	48	42.666667	X

contrast	difference	+/- limits	
0 - 1	16.8958	0.29732	*
0 - 2	17.5833	0.29732	*
0 - 3	22.7083	0.29732	*
1 - 2	0.68750	0.29732	*
1 - 3	5.81250	0.29732	*
2 - 3	5.12500	0.29732	*

* denotes a statistically significant difference.

Appendix F

Two Way Analysis of Variance Tables of Polymer Optimization Test Results

F-1 Asphalt Binder From Ras Tanura Refinery, Saudi Arabia

F-2 Asphalt Binder From Riyadh Refinery, Saudi Arabia

F-3 Asphalt Binder From BAPCO Refinery, Bahrain

F-4 Asphalt Binder From Al-Ahmadi Refinery, Kuwait

Appendix F-1

Asphalt Binder from Ras Tanura Refinery Saudi Arabia

Table F-1.1: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - Fresh Blends

Analysis of Variance for RT.GS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	8.4486E8	3	2.8162E8	8130.787	0.0000
B:RT.PERCENT	7.4045E8	3	2.4682E8	7125.927	0.0000
INTERACTIONS					
AB	8.3578E8	9	92864522	2681.122	0.0000
RESIDUAL	1108366.0	32	34636.438		
TOTAL (CORRECTED)	2.4222E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.DEL76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	287.5017	3	95.8339	2643.693	0.0000
B:RT.PERCENT	3221.1983	3	1073.7328	29620.215	0.0000
INTERACTIONS					
AB	1542.8900	9	171.43222	4729.165	0.0000
RESIDUAL	1.1600000	32	0.0362500		
TOTAL (CORRECTED)	5052.7500	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.GOS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	1.2597E9	3	4.1991E8	7443.788	0.0000
B:RT.PERCENT	1.2547E9	3	4.1823E8	7413.998	0.0000
INTERACTIONS					
AB	1.4551E9	9	1.6168E8	2866.100	0.0000
RESIDUAL	1805144.4	32	56410.761		
TOTAL (CORRECTED)	3.9713E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.2: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - RTFOT

Analysis of Variance for RT.GS76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	2.7133E9	3	9.0444E8	18984.239	0.0000
B:RT.PERCENT	2.3403E9	3	7.8009E8	16374.178	0.0000
INTERACTIONS					
AB	2.8080E9	9	3.1200E8	6548.823	0.0000
RESIDUAL	1524535.3	32	47641.729		
TOTAL (CORRECTED)	7.8631E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.DEL76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	267.4433	3	89.1478	2971.593	0.0000
B:RT.PERCENT	4349.9250	3	1449.9750	48332.500	0.0000
INTERACTIONS					
AB	1924.1683	9	213.79648	7126.549	0.0000
RESIDUAL	0.9600000	32	0.0300000		
TOTAL (CORRECTED)	6542.4967	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.GOS76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	5.3539E9	3	1.7846E9	13260.544	0.0000
B:RT.PERCENT	5.4098E9	3	1.8033E9	13399.048	0.0000
INTERACTIONS					
AB	7.5918E9	9	8.4354E8	6267.821	0.0000
RESIDUAL	4306632.3	32	134582.26		
TOTAL (CORRECTED)	1.8360E10	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.3: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - Fresh Blends

Analysis of Variance for RT.GS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	3.7376E8	3	1.2459E8	20348.721	0.0000
B:RT.PERCENT	3.6809E8	3	1.2270E8	20040.170	0.0000
INTERACTIONS					
AB	4.1478E8	9	46087084	7527.469	0.0000
RESIDUAL	195920.67	32	6122.5208		
TOTAL (CORRECTED)	1.1568E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.DEL80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	387.8067	3	129.2689	4308.963	0.0000
B:RT.PERCENT	3296.7300	3	1098.9100	36630.333	0.0000
INTERACTIONS					
AB	1574.9133	9	174.99037	5833.012	0.0000
RESIDUAL	0.9600000	32	0.0300000		
TOTAL (CORRECTED)	5260.4100	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.GOS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	6.0450E8	3	2.0150E8	25227.698	0.0000
B:RT.PERCENT	6.5448E8	3	2.1816E8	27313.716	0.0000
INTERACTIONS					
AB	7.9154E8	9	87949390	11011.230	0.0000
RESIDUAL	255591.84	32	7987.2451		
TOTAL (CORRECTED)	2.0508E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.4: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - RTFOT

Analysis of Variance for RT.GS80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	1.2239E9	3	4.0797E8	1020.212	0.0000
B:RT.PERCENT	1.1084E9	3	3.6947E8	923.946	0.0000
INTERACTIONS					
AB	1.1559E9	9	1.2843E8	321.169	0.0000
RESIDUAL	12796364	32	399886.38		
TOTAL (CORRECTED)	3.5010E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.DEL80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	285.8275	3	95.2758	1056.176	0.0000
B:RT.PERCENT	4244.3442	3	1414.7814	15683.489	0.0000
INTERACTIONS					
AB	1987.8808	9	220.87565	2448.506	0.0000
RESIDUAL	2.8866667	32	0.0902083		
TOTAL (CORRECTED)	6520.9392	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.GOS80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	2.2130E9	3	7.3767E8	719.322	0.0000
B:RT.PERCENT	2.3177E9	3	7.7256E8	753.343	0.0000
INTERACTIONS					
AB	2.8559E9	9	3.1732E8	309.425	0.0000
RESIDUAL	32816298	32	1025509.3		
TOTAL (CORRECTED)	7.4194E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.5: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 22 C - PAV

Analysis of Variance for RT.GS22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	4.1849E8	3	1.3950E8	4192.886	0.0000
B:RT.PERCENT	7.1025E7	3	2.3675E7	711.602	0.0000
INTERACTIONS					
AB	3.2884E8	9	36537496	1098.214	0.0000
RESIDUAL	1064637.7	32	33269.927		
TOTAL (CORRECTED)	8.1942E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.DEL22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	744.71750	3	248.23917	1172.783	0.0000
B:RT.PERCENT	59.90417	3	19.96806	94.337	0.0000
INTERACTIONS					
AB	806.74417	9	89.638241	423.488	0.0000
RESIDUAL	6.7733333	32	0.2116667		
TOTAL (CORRECTED)	1618.1392	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.GXS22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	60120816	3	20040272	6527.293	0.0000
B:RT.PERCENT	18874171	3	6291390	2049.161	0.0000
INTERACTIONS					
AB	45651323	9	5072369.3	1652.115	0.0000
RESIDUAL	98247.267	32	3070.2271		
TOTAL (CORRECTED)	1.2474E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.6: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 25 C - PAV

Analysis of Variance for RT.GS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	2.3249E8	3	77498269	4974.335	0.0000
B:RT.PERCENT	5.2460E7	3	17486546	1122.398	0.0000
INTERACTIONS					
AB	1.5381E8	9	17089538	1096.916	0.0000
RESIDUAL	498548.00	32	15579.625		
TOTAL (CORRECTED)	4.3926E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.DEL25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	912.29167	3	304.09722	2076.339	0.0000
B:RT.PERCENT	100.91667	3	33.63889	229.682	0.0000
INTERACTIONS					
AB	390.96167	9	43.440185	296.604	0.0000
RESIDUAL	4.6866667	32	0.1464583		
TOTAL (CORRECTED)	1408.8567	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.GXS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	38715635	3	12905212	6512.006	0.0000
B:RT.PERCENT	12794734	3	4264911	2152.086	0.0000
INTERACTIONS					
AB	24620925	9	2735658.4	1380.421	0.0000
RESIDUAL	63416.217	32	1981.7568		
TOTAL (CORRECTED)	76194711	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.7: ANOVA Table for S and m-value at -28 C - PAV

Analysis of Variance for RT.S12 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	31768.367	3	10589.456	325.655	0.0000
B:RT.PERCENT	4178.760	3	1392.920	42.836	0.0000
INTERACTIONS					
AB	13185.277	9	1465.0308	45.054	0.0000
RESIDUAL	1040.5585	32	32.517452		
TOTAL (CORRECTED)	50172.963	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.M12 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	0.0374974	3	0.0124991	361.203	0.0000
B:RT.PERCENT	0.0014517	3	0.0004839	13.984	0.0000
INTERACTIONS					
AB	0.0144100	9	0.0016011	46.269	0.0000
RESIDUAL	0.0011073	32	3.46042E-5		
TOTAL (CORRECTED)	0.0544665	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.8: ANOVA Table for S and m-value at -22 C - PAV

Analysis of Variance for RT.S18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	36640.529	3	12213.510	65.540	0.0000
B:RT.PERCENT	56552.377	3	18850.792	101.156	0.0000
INTERACTIONS					
AB	27995.369	9	3110.5966	16.692	0.0000
RESIDUAL	5963.3037	32	186.35324		
TOTAL (CORRECTED)	127151.58	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.M18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	0.0171451	3	0.0057150	84.615	0.0000
B:RT.PERCENT	0.0092172	3	0.0030724	45.489	0.0000
INTERACTIONS					
AB	0.0082069	9	9.11873E-4	13.501	0.0000
RESIDUAL	0.0021613	32	6.75417E-5		
TOTAL (CORRECTED)	0.0367305	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-1.9: ANOVA Table for Rotational Viscosity, Penetration and Softening Point

Analysis of Variance for RT.VIS135 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	3.8153E7	3	12717722	2300.883	0.0000
B:RT.PERCENT	2.4820E8	3	82732184	14967.843	0.0000
INTERACTIONS					
AB	1.9515E8	9	21683287	3922.913	0.0000
RESIDUAL	176874.33	32	5527.3229		
TOTAL (CORRECTED)	4.8168E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.SOFT - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	3543.5000	3	1181.1667	4724.667	0.0000
B:RT.PERCENT	6553.5000	3	2184.5000	8738.000	0.0000
INTERACTIONS					
AB	2181.0000	9	242.33333	969.333	0.0000
RESIDUAL	8.0000000	32	0.2500000		
TOTAL (CORRECTED)	12286.000	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RT.PEN - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RT.TYPE	9398.2500	3	3132.7500	5569.333	0.0000
B:RT.PERCENT	3748.4167	3	1249.4722	2221.284	0.0000
INTERACTIONS					
AB	1921.2500	9	213.47222	379.506	0.0000
RESIDUAL	18.000000	32	0.5625000		
TOTAL (CORRECTED)	15085.917	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Appendix F-2

Asphalt Binder From Riyadh Refinery Saudi Arabia

Table F-2.1: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - Fresh Blends

Analysis of Variance for RY.GS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	3.9639E8	3	1.3213E8	48695.154	0.0000
B:RY.PERCENT	6.0124E8	3	2.0041E8	73860.200	0.0000
INTERACTIONS					
AB	5.1858E8	9	57620540	21235.419	0.0000
RESIDUAL	86829.333	32	2713.4167		
TOTAL (CORRECTED)	1.5163E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.DEL76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	825.5558	3	275.1853	5949.952	0.0000
B:RY.PERCENT	3377.7608	3	1125.9203	24344.222	0.0000
INTERACTIONS					
AB	1433.7825	9	159.30917	3444.523	0.0000
RESIDUAL	1.4800000	32	0.0462500		
TOTAL (CORRECTED)	5638.5792	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.GOS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	6.8549E8	3	2.2850E8	46560.661	0.0000
B:RY.PERCENT	1.0331E9	3	3.4435E8	70168.989	0.0000
INTERACTIONS					
AB	1.0566E9	9	1.1740E8	23923.690	0.0000
RESIDUAL	157039.21	32	4907.4753		
TOTAL (CORRECTED)	2.7753E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-2.2: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - RTFOT

Analysis of Variance for RY.GOS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	6.8549E8	3	2.2850E8	46560.661	0.0000
B:RY.PERCENT	1.0331E9	3	3.4435E8	70168.989	0.0000
INTERACTIONS					
AB	1.0566E9	9	1.1740E8	23923.698	0.0000
RESIDUAL	157039.21	32	4907.4753		
TOTAL (CORRECTED)	2.7753E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.DEL76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	570.5773	3	190.19243	3756.888	0.0000
B:RY.PERCENT	2195.4673	3	731.82243	14455.752	0.0000
INTERACTIONS					
AB	728.19054	9	80.910949	1598.241	0.0000
RESIDUAL	1.6200000	32	0.0506250		
TOTAL (CORRECTED)	3495.8631	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.GOS76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	4.1789E8	3	1.3930E8	4885.530	0.0000
B:RY.PERCENT	7.0539E8	3	2.3513E8	8246.748	0.0000
INTERACTIONS					
AB	1.4335E8	9	15927827	558.636	0.0000
RESIDUAL	912384.57	32	28512.018		
TOTAL (CORRECTED)	1.2675E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-2.3: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - Fresh Blends

Analysis of Variance for RY.GS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	2.0188E8	3	6.7292E7	614.114	0.0000
B:RY.PERCENT	3.1597E8	3	1.0532E8	961.183	0.0000
INTERACTIONS					
AB	2.8319E8	9	31465562	287.156	0.0000
RESIDUAL	3506444.0	32	109576.38		
TOTAL (CORRECTED)	8.0454E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.DEL80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	1029.9023	3	343.3008	876.979	0.0000
B:RY.PERCENT	3126.8840	3	1042.2947	2662.594	0.0000
INTERACTIONS					
AB	1629.2519	9	181.02799	462.445	0.0000
RESIDUAL	12.526667	32	0.3914583		
TOTAL (CORRECTED)	5798.5648	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.GOS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	3.6431E8	3	1.2144E8	253.105	0.0000
B:RY.PERCENT	5.4457E8	3	1.8152E8	378.343	0.0000
INTERACTIONS					
AB	5.8931E8	9	65478923	136.476	0.0000
RESIDUAL	15353093	32	479784.16		
TOTAL (CORRECTED)	1.5135E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-2.4: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - RTFOT

Analysis of Variance for RY.GS80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	1.8235E8	3	6.0783E7	4301.057	0.0000
B:RY.PERCENT	3.2643E8	3	1.0881E8	7699.447	0.0000
INTERACTIONS					
AB	53961281	9	5995697.9	424.264	0.0000
RESIDUAL	452224.00	32	14132.000		
TOTAL (CORRECTED)	5.6319E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.DEL80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	507.4167	3	169.13889	1604.480	0.0000
B:RY.PERCENT	2298.6517	3	766.21722	7268.464	0.0000
INTERACTIONS					
AB	698.76500	9	77.640556	736.511	0.0000
RESIDUAL	3.3733333	32	0.1054167		
TOTAL (CORRECTED)	3508.2067	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.GOS80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	1.8714E8	3	6.2381E7	3810.794	0.0000
B:RY.PERCENT	4.2647E8	3	1.4216E8	8684.287	0.0000
INTERACTIONS					
AB	64981537	9	7220170.7	441.076	0.0000
RESIDUAL	523821.83	32	16369.432		
TOTAL (CORRECTED)	6.7912E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-2.5: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 22 C - PAV

Analysis of Variance for RY.GS22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	1.4923E8	3	49744533	993.554	0.0000
B:RY.PERCENT	2.7261E8	3	90869642	1814.950	0.0000
INTERACTIONS					
AB	4.0255E8	9	44727361	893.345	0.0000
RESIDUAL	1602153.3	32	50067.292		
TOTAL (CORRECTED)	8.2599E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.DEL22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	751.83417	3	250.61139	687.784	0.0000
B:RY.PERCENT	53.15750	3	17.71917	48.629	0.0000
INTERACTIONS					
AB	490.88750	9	54.543056	149.689	0.0000
RESIDUAL	11.660000	32	0.3643750		
TOTAL (CORRECTED)	1307.5392	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.GXS22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	26530377	3	8843459	627.837	0.0000
B:RY.PERCENT	93883750	3	31294583	2221.743	0.0000
INTERACTIONS					
AB	1.0043E8	9	11159296	792.248	0.0000
RESIDUAL	450739.26	32	14085.602		
TOTAL (CORRECTED)	2.2130E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-2.6: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 25 C - PAV

Analysis of Variance for RY.GS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	1.1567E8	3	38557748	4228.596	0.0000
B:RY.PERCENT	1.2328E8	3	41066911	4503.774	0.0000
INTERACTIONS					
AB	2.2340E8	9	24822181	2722.219	0.0000
RESIDUAL	291786.67	32	9118.3333		
TOTAL (CORRECTED)	4.6256E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.DEL25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	508.22729	3	169.40910	1623.081	0.0000
B:RY.PERCENT	32.30729	3	10.76910	103.177	0.0000
INTERACTIONS					
AB	208.50521	9	23.167245	221.962	0.0000
RESIDUAL	3.3400000	32	0.1043750		
TOTAL (CORRECTED)	752.37979	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.GXS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	25694565	3	8564855	2964.586	0.0000
B:RY.PERCENT	47984289	3	15994763	5536.328	0.0000
INTERACTIONS					
AB	59174637	9	6574959.6	2275.816	0.0000
RESIDUAL	92449.795	32	2889.0561		
TOTAL (CORRECTED)	1.3295E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-2.7: ANOVA Table for S and m-value at -28 C - PAV

Analysis of Variance for RY.S18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	65074.905	3	21691.635	48.399	0.0000
B:RY.PERCENT	60269.965	3	20089.988	44.825	0.0000
INTERACTIONS					
AB	45197.241	9	5021.9157	11.205	0.0000
RESIDUAL	14341.881	32	448.18377		
TOTAL (CORRECTED)	184883.99	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.M18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	0.0163601	3	0.0054534	77.975	0.0000
B:RY.PERCENT	0.0217204	3	0.0072401	103.523	0.0000
INTERACTIONS					
AB	0.0095079	9	0.0010564	15.105	0.0000
RESIDUAL	0.0022380	32	6.99375E-5		
TOTAL (CORRECTED)	0.0498263	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-2.8: ANOVA Table for Rotational Viscosity, Penetration and Softening Point

Analysis of Variance for RY.VIS135 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	1.5537E7	3	5179069	4581.727	0.0000
B:RY.PERCENT	2.2802E8	3	76006127	67239.745	0.0000
INTERACTIONS					
AB	40490763	9	4498973.7	3980.072	0.0000
RESIDUAL	36172.000	32	1130.3750		
TOTAL (CORRECTED)	2.8400E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.SOFT - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	3454.9675	3	1151.6558	1062.658	0.0000
B:RY.PERCENT	5118.8692	3	1706.2897	1574.431	0.0000
INTERACTIONS					
AB	3220.4025	9	357.82250	330.171	0.0000
RESIDUAL	34.680000	32	1.0837500		
TOTAL (CORRECTED)	11828.919	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for RY.PEN - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:RY.TYPE	3562.7292	3	1187.5764	1425.092	0.0000
B:RY.PERCENT	5102.3958	3	1700.7986	2040.958	0.0000
INTERACTIONS					
AB	901.02083	9	100.11343	120.136	0.0000
RESIDUAL	26.666667	32	0.8333333		
TOTAL (CORRECTED)	9592.8125	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Appendix F-3

Asphalt Binder From BAPCO Refinery Bahrain

Table F-3.1: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - Fresh Blends

Analysis of Variance for BH.GS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	5.7791E8	3	1.9264E8	4973.597	0.0000
B:BH.PERCENT	6.0792E8	3	2.0264E8	5231.904	0.0000
INTERACTIONS					
AB	4.2910E8	9	47677560	1230.973	0.0000
RESIDUAL	1239411.4	32	38731.607		
TOTAL (CORRECTED)	1.6162E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.DEL76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	1242.9706	3	414.3235	931.580	0.0000
B:BH.PERCENT	4252.3690	3	1417.4563	3186.787	0.0000
INTERACTIONS					
AB	2259.5619	9	251.06243	564.449	0.0000
RESIDUAL	14.233333	32	0.4447917		
TOTAL (CORRECTED)	7769.1348	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.GOS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	8.1570E8	3	2.7190E8	1904.209	0.0000
B:BH.PERCENT	1.1003E9	3	3.6678E8	2568.719	0.0000
INTERACTIONS					
AB	8.2612E8	9	91791127	642.847	0.0000
RESIDUAL	4569227.3	32	142788.35		
TOTAL (CORRECTED)	2.7467E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.2: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - RTFOT

Analysis of Variance for BH.GS76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	1.9863E9	3	6.6210E8	3576.942	0.0000
B:BH.PERCENT	1.5547E9	3	5.1825E8	2799.771	0.0000
INTERACTIONS					
AB	8.8245E8	9	98049512	529.702	0.0000
RESIDUAL	5923296.7	32	185103.02		
TOTAL (CORRECTED)	4.4294E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.DEL76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	2022.9975	3	674.3325	6434.982	0.0000
B:BH.PERCENT	5880.2692	3	1960.0897	18704.634	0.0000
INTERACTIONS					
AB	3773.8325	9	419.31472	4001.413	0.0000
RESIDUAL	3.3533333	32	0.1047917		
TOTAL (CORRECTED)	11680.453	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.GOS76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	4.2714E9	3	1.4238E9	1461.245	0.0000
B:BH.PERCENT	3.0473E9	3	1.0158E9	1042.479	0.0000
INTERACTIONS					
AB	2.8940E9	9	3.2155E8	330.006	0.0000
RESIDUAL	31180077	32	974377.40		
TOTAL (CORRECTED)	1.0244E10	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.3: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - Fresh Blends

Analysis of Variance for BH.GS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	2.5603E8	3	8.5342E7	2246.303	0.0000
B:BH.PERCENT	3.4249E8	3	1.1416E8	3004.916	0.0000
INTERACTIONS					
AB	2.4785E8	9	27538866	724.858	0.0000
RESIDUAL	1215746.0	32	37992.062		
TOTAL (CORRECTED)	8.4758E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.DEL80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	1982.0256	3	660.6752	8883.028	0.0000
B:BH.PERCENT	5520.7673	3	1840.2558	24742.935	0.0000
INTERACTIONS					
AB	3166.8569	9	351.87299	4731.065	0.0000
RESIDUAL	2.3800000	32	0.0743750		
TOTAL (CORRECTED)	10672.030	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.GOS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	4.2703E8	3	1.4234E8	1468.905	0.0000
B:BH.PERCENT	7.9599E8	3	2.6533E8	2738.078	0.0000
INTERACTIONS					
AB	6.0848E8	9	67608489	697.683	0.0000
RESIDUAL	3100935.9	32	96904.247		
TOTAL (CORRECTED)	1.8346E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.4: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - RTFOT

Analysis of Variance for BH.GS80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	1.2352E9	3	4.1173E8	24744.264	0.0000
B:BH.PERCENT	9.1007E8	3	3.0336E8	18231.258	0.0000
INTERACTIONS					
AB	7.1739E8	9	79709585	4790.425	0.0000
RESIDUAL	532459.33	32	16639.354		
TOTAL (CORRECTED)	2.8632E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.DEL80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	2432.9940	3	810.9980	12203.104	0.0000
B:BH.PERCENT	6294.0523	3	2098.0174	31568.914	0.0000
INTERACTIONS					
AB	4707.5652	9	523.06280	7870.537	0.0000
RESIDUAL	2.1266667	32	0.0664583		
TOTAL (CORRECTED)	13436.738	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.GOS80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	3.3522E9	3	1.1174E9	8985.156	0.0000
B:BH.PERCENT	2.1147E9	3	7.0491E8	5668.350	0.0000
INTERACTIONS					
AB	3.0822E9	9	3.4247E8	2753.854	0.0000
RESIDUAL	3979511.9	32	124359.75		
TOTAL (CORRECTED)	8.5531E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.5: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 22 C - PAV

Analysis of Variance for BH.GS22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	2.2611E9	3	7.5369E8	373.121	0.0000
B:BH.PERCENT	4.3600E8	3	1.4536E8	71.962	0.0000
INTERACTIONS					
AB	1.3041E9	9	1.4490E8	71.734	0.0000
RESIDUAL	64638582	32	2019955.7		
TOTAL (CORRECTED)	4.0659E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.DEL22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	1014.2523	3	338.08410	3207.122	0.0000
B:BH.PERCENT	297.4956	3	99.16521	940.698	0.0000
INTERACTIONS					
AB	522.70688	9	58.078542	550.943	0.0000
RESIDUAL	3.3733333	32	0.1054167		
TOTAL (CORRECTED)	1837.8281	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.GXS22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	3.8411E8	3	1.2804E8	238.138	0.0000
B:BH.PERCENT	8.3586E7	3	2.7862E7	51.821	0.0000
INTERACTIONS					
AB	2.1398E8	9	23776042	44.221	0.0000
RESIDUAL	17205056	32	537657.98		
TOTAL (CORRECTED)	6.9889E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.6: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 25 C - PAV

Analysis of Variance for BH.GS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	1.2701E9	3	4.2336E8	837.724	0.0000
B:BH.PERCENT	2.7403E8	3	9.1345E7	180.747	0.0000
INTERACTIONS					
AB	8.9978E8	9	99975855	197.826	0.0000
RESIDUAL	16171900	32	505372.13		
TOTAL (CORRECTED)	2.4601E9	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.DEL25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	1140.4106	3	380.13688	10733.276	0.0000
B:BH.PERCENT	362.6256	3	120.87521	3412.947	0.0000
INTERACTIONS					
AB	552.56854	9	61.396505	1733.548	0.0000
RESIDUAL	1.1333333	32	0.0354167		
TOTAL (CORRECTED)	2056.7381	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.GXS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	2.5657E8	3	85521683	602.252	0.0000
B:BH.PERCENT	6.1952E7	3	20650501	145.423	0.0000
INTERACTIONS					
AB	1.8616E8	9	20684801	145.664	0.0000
RESIDUAL	4544098.8	32	142003.09		
TOTAL (CORRECTED)	5.0922E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.7: ANOVA Table for S and m-value at -28 C - PAV

Analysis of Variance for BH.S18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	46727.489	3	15575.830	49.892	0.0000
B:BH.PERCENT	59859.824	3	19953.275	63.914	0.0000
INTERACTIONS					
AB	80913.189	9	8990.3543	28.798	0.0000
RESIDUAL	9990.1072	32	312.19085		
TOTAL (CORRECTED)	197490.61	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.M18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	0.0226140	3	0.0075380	89.583	0.0000
B:BH.PERCENT	0.0146598	3	0.0048866	58.073	0.0000
INTERACTIONS					
AB	0.0603072	9	0.0067008	79.633	0.0000
RESIDUAL	0.0026927	32	8.41458E-5		
TOTAL (CORRECTED)	0.1002737	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.8: ANOVA Table for S and m-value at -22 C - PAV

Analysis of Variance for BH.S12 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	76663.239	3	25554.413	133.204	0.0000
B:BH.PERCENT	3763.121	3	1254.374	6.538	0.0014
INTERACTIONS					
AB	46871.983	9	5207.9981	27.147	0.0000
RESIDUAL	6139.0349	32	191.84484		
TOTAL (CORRECTED)	133437.38	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.M12 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	0.0424321	3	0.0141440	220.212	0.0000
B:BH.PERCENT	0.0120064	3	0.0040021	62.310	0.0000
INTERACTIONS					
AB	0.0426902	9	0.0047434	73.850	0.0000
RESIDUAL	0.0020553	32	6.42292E-5		
TOTAL (CORRECTED)	0.0991840	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-3.9: ANOVA Table for Rotational Viscosity, Penetration and Softening Point

Analysis of Variance for BH.VIS135 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	2.6840E7	3	8946670	4337.363	0.0000
B:BH.PERCENT	1.6397E8	3	54657741	26498.100	0.0000
INTERACTIONS					
AB	18604258	9	2067139.7	1002.153	0.0000
RESIDUAL	66006.333	32	2062.6979		
TOTAL (CORRECTED)	2.0948E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.SOFT - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	5301.6667	3	1767.2222	9425.185	0.0000
B:BH.PERCENT	5464.5000	3	1821.5000	9714.667	0.0000
INTERACTIONS					
AB	3764.8333	9	418.31481	2231.012	0.0000
RESIDUAL	6.0000000	32	0.1875000		
TOTAL (CORRECTED)	14537.000	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for BH.PEN - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:BH.TYPE	4905.7292	3	1635.2431	3567.803	0.0000
B:BH.PERCENT	3272.0625	3	1090.6875	2379.682	0.0000
INTERACTIONS					
AB	1716.5208	9	190.72454	416.126	0.0000
RESIDUAL	14.666667	32	0.4583333		
TOTAL (CORRECTED)	9908.9792	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Appendix F-4

Asphalt Binder From Al-Ahmadi Refinery Kuwait

Table F-4.1: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - Fresh Blends

Analysis of Variance for KW.GS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	3.6166E9	3	1.2055E9	329.699	0.0000
B:KW.PERCENT	4.9960E9	3	1.6653E9	455.450	0.0000
INTERACTIONS					
AB	8.9548E9	9	9.9497E8	272.116	0.0000
RESIDUAL	1.1701E8	32	3656428.2		
TOTAL (CORRECTED)	1.7684E10	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.DEL76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	1365.6456	3	455.2152	1950.922	0.0000
B:KW.PERCENT	5519.5623	3	1839.8541	7885.089	0.0000
INTERACTIONS					
AB	3206.4752	9	356.27502	1526.893	0.0000
RESIDUAL	7.4666667	32	0.2333333		
TOTAL (CORRECTED)	10099.150	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.GOS76F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	2.4212E10	3	8.0706E9	136.112	0.0000
B:KW.PERCENT	2.8366E10	3	9.4554E9	159.466	0.0000
INTERACTIONS					
AB	6.7459E10	9	7.4954E9	126.412	0.0000
RESIDUAL	1.8974E9	32	59293933		
TOTAL (CORRECTED)	1.2193E11	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-4.2: ANOVA Table for G*, Phase angle and G*/sin (δ) at 76 C - RTFOT

Analysis of Variance for KW.GS76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	1.6952E10	3	5.6507E9	315.694	0.0000
B:KW.PERCENT	1.4144E10	3	4.7145E9	263.390	0.0000
INTERACTIONS					
AB	1.6590E10	9	1.8433E9	102.984	0.0000
RESIDUAL	5.7278E8	32	17899366		
TOTAL (CORRECTED)	4.8259E10	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.DEL76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	3137.4740	3	1045.8247	304.942	0.0000
B:KW.PERCENT	6508.5073	3	2169.5024	632.585	0.0000
INTERACTIONS					
AB	3362.7369	9	373.63743	108.945	0.0000
RESIDUAL	109.74667	32	3.4295833		
TOTAL (CORRECTED)	13118.465	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.GOS76R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	9.9270E10	3	3.3090E10	74.016	0.0000
B:KW.PERCENT	5.3445E10	3	1.7815E10	39.849	0.0000
INTERACTIONS					
AB	9.6589E10	9	1.0732E10	24.006	0.0000
RESIDUAL	1.4306E10	32	4.4706E8		
TOTAL (CORRECTED)	2.6361E11	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-4.3: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - Fresh Blends

Analysis of Variance for KW.GS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	2.8180E9	3	9.3934E8	16610.417	0.0000
B:KW.PERCENT	3.6921E9	3	1.2307E9	21762.522	0.0000
INTERACTIONS					
AB	7.4618E9	9	8.2908E8	14660.719	0.0000
RESIDUAL	1809645.3	32	56551.417		
TOTAL (CORRECTED)	1.3974E10	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.DEL80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	1550.5306	3	516.8435	8891.932	0.0000
B:KW.PERCENT	5458.0356	3	1819.3452	31300.563	0.0000
INTERACTIONS					
AB	3630.6885	9	403.40984	6940.384	0.0000
RESIDUAL	1.8600000	32	0.0581250		
TOTAL (CORRECTED)	10641.115	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.GOS80F - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	2.1209E10	3	7.0696E9	12526.643	0.0000
B:KW.PERCENT	2.3904E10	3	7.9681E9	14118.670	0.0000
INTERACTIONS					
AB	6.0780E10	9	6.7534E9	11966.264	0.0000
RESIDUAL	18059743	32	564366.95		
TOTAL (CORRECTED)	1.0591E11	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-4.4: ANOVA Table for G*, Phase angle and G*/sin (δ) at 80 C - RTFOT

Analysis of Variance for KW.GS80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	1.2428E10	3	4.1428E9	4934.896	0.0000
B:KW.PERCENT	8.3700E9	3	2.7900E9	3323.442	0.0000
INTERACTIONS					
AB	1.2480E10	9	1.3866E9	1651.771	0.0000
RESIDUAL	26863661	32	839489.42		
TOTAL (CORRECTED)	3.3305E10	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.DEL80R - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	4514.0806	3	1504.6935	8330.483	0.0000
B:KW.PERCENT	7502.1373	3	2500.7124	13844.775	0.0000
INTERACTIONS					
AB	4912.9319	9	545.88132	3022.180	0.0000
RESIDUAL	5.7800000	32	0.1806250		
TOTAL (CORRECTED)	16934.930	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.DEL22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	463.71229	3	154.57076	2150.550	0.0000
B:KW.PERCENT	176.19063	3	58.73021	817.116	0.0000
INTERACTIONS					
AB	482.35687	9	53.595208	745.672	0.0000
RESIDUAL	2.3000000	32	0.0718750		
TOTAL (CORRECTED)	1124.5598	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-4.5: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 22 C - PAV

Analysis of Variance for KW.GXS22P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	1.3348E8	3	44491859	591.896	0.0000
B:KW.PERCENT	1.3269E7	3	4423018	58.841	0.0000
INTERACTIONS					
AB	79437717	9	8826413.0	117.422	0.0000
RESIDUAL	2405389.7	32	75168.428		
TOTAL (CORRECTED)	2.2859E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.GS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	3.8142E8	3	1.2714E8	332.036	0.0000
B:KW.PERCENT	1.6524E7	3	5.5081E6	14.385	0.0000
INTERACTIONS					
AB	2.1892E8	9	24324537	63.526	0.0000
RESIDUAL	12253084	32	382908.88		
TOTAL (CORRECTED)	6.2912E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.DEL25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	513.90000	3	171.30000	1303.074	0.0000
B:KW.PERCENT	201.44333	3	67.14778	510.791	0.0000
INTERACTIONS					
AB	531.40000	9	59.044444	449.149	0.0000
RESIDUAL	4.2066667	32	0.1314583		
TOTAL (CORRECTED)	1250.9500	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-4.6: ANOVA Table for G*, Phase Angle and G*xsin (δ) at 25 C - PAV

Analysis of Variance for KW.GXS25P - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	96589915	3	32196638	416.903	0.0000
B:KW.PERCENT	8854262	3	2951421	38.217	0.0000
INTERACTIONS					
AB	58300356	9	6477817.3	83.879	0.0000
RESIDUAL	2471301.9	32	77228.183		
TOTAL (CORRECTED)	1.6622E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.S18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	61851.39	3	20617.132	37.626	0.0000
B:KW.PERCENT	141703.13	3	47234.378	86.203	0.0000
INTERACTIONS					
AB	101374.57	9	11263.841	20.557	0.0000
RESIDUAL	17534.236	32	547.94488		
TOTAL (CORRECTED)	322463.33	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.M18 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	0.0047387	3	0.0015796	12.231	0.0000
B:KW.PERCENT	0.0175901	3	0.0058634	45.401	0.0000
INTERACTIONS					
AB	0.0144109	9	0.0016012	12.398	0.0000
RESIDUAL	0.0041327	32	1.29146E-4		
TOTAL (CORRECTED)	0.0408723	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-4.7: ANOVA Table for S and m-value at -22 C - PAV

Analysis of Variance for KW.S12 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	35769.176	3	11923.059	136.087	0.0000
B:KW.PERCENT	16987.287	3	5662.429	64.629	0.0000
INTERACTIONS					
AB	54095.839	9	6010.6487	68.604	0.0000
RESIDUAL	2803.6397	32	87.613742		
TOTAL (CORRECTED)	109655.94	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.M12 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	0.0136783	3	0.0045594	209.829	0.0000
B:KW.PERCENT	0.0034984	3	0.0011661	53.667	0.0000
INTERACTIONS					
AB	0.0242739	9	0.0026971	124.124	0.0000
RESIDUAL	6.95333E-4	32	2.17292E-5		
TOTAL (CORRECTED)	0.0421459	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Table F-4.8: ANOVA Table for Rotational Viscosity, Penetration and Softening Point

Analysis of Variance for KW.VIS135 - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	3.4426E6	3	1.1475E6	331.878	0.0000
B:KW.PERCENT	3.2135E8	3	1.0712E8	30978.858	0.0000
INTERACTIONS					
AB	30518832	9	3390981.3	980.708	0.0000
RESIDUAL	110646.00	32	3457.6875		
TOTAL (CORRECTED)	3.5542E8	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.SOFT - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	2192.9367	3	730.9789	3889.910	0.0000
B:KW.PERCENT	5015.7767	3	1671.9256	8897.165	0.0000
INTERACTIONS					
AB	2048.6433	9	227.62704	1211.319	0.0000
RESIDUAL	6.0133333	32	0.1879167		
TOTAL (CORRECTED)	9263.3700	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Analysis of Variance for KW.PEN - Type III Sums of Squares

Source of variation	Sum of Squares	d.f.	Mean square	F-ratio	Sig. level
MAIN EFFECTS					
A:KW.TYPE	3934.2292	3	1311.4097	4196.511	0.0000
B:KW.PERCENT	2665.7292	3	888.5764	2843.444	0.0000
INTERACTIONS					
AB	1466.0208	9	162.89120	521.252	0.0000
RESIDUAL	10.0000000	32	0.3125000		
TOTAL (CORRECTED)	8075.9792	47			

0 missing values have been excluded.
All F-ratios are based on the residual mean square error.

Appendix G

Practical Implications of the Research

Practical Implications of the Research

This research provided a deep insight in to the physical, rheological and performance related properties of both neat and polymer modified Arab asphalt binders. The output of this research is a modification methodology along with a criteria to evaluate the effectiveness of the modification and a polymer modified asphalt binder that satisfies the performance requirements of the Gulf countries environmental conditions. The modified asphalt binder have the double behavior characteristics required to resist high temperature related distresses (i.e. permanent deformation) and low temperature and fatigue related distresses (i.e. cracking). Once the asphalt binder is modified to satisfy compatible the environmental conditions of the Gulf countries, savings in highway maintenance cost and efforts are anticipated since pavement structures built using the modified asphalt binder is expected to have a better performance and hence a longer life. Maintenance (either minor such as crack filling or major such as surfacing) will not be required so frequently.

To simplify and allow the implementation of the research findings, the following sections summarizes the main items required for the implementation.

G.1 NEED FOR MODIFICATION

Asphalt binder performance in a specific site is controlled by the minimum and the average seven day maximum pavement design temperatures. Temperature zoning of the Gulf countries has concluded in identifying -10 °C as the minimum pavement temperature and 76°C as the maximum pavement temperature. On the other hand, the collected asphalt binder samples from the four asphalt producing refineries were determined to have the minimum required $G^*/\sin(\delta)$, which is 1.0 kPa at 64°C. This means that locally produced asphalt

binders do not meet the performance requirements of about half of the Gulf countries. Locally produced asphalt binders can be used without modification in the western parts of Riyadh and in the Qassim regions, eastern and southern parts of Makkah, and all the southern regions in Saudi Arabia, while other areas within the Gulf countries require asphalt modification. Polymer modification is needed to qualify locally produced asphalt binders for other areas in the Gulf countries, including the eastern parts of Riyadh, the northern border regions, and the Eastern Province of Saudi Arabia, all of Kuwait, Bahrain, Qatar, UAE, and Oman. Based on this, it was concluded that polymer modification is required to upgrade the rheological and performance-related properties of the NAABs

G.2 THE SELECTED POLYMERS

The analysis of the collected data have indicated that the polymer types differ for different asphalt source. also, the optimum polymer concentration varies for different asphalt source and different polymer types. Table G.1 provides information about the most appropriate polymer type and concentration for each asphalt source within the Gulf countries.

Table G.1: Recommended Polymer Types and Concentrations for Various Asphalt Source in the Gulf Countries

Asphalt Source	Polymer Type			
	CRT	**LLDPE-X**	**PP 500U**	**SBS**
Ras Tanura Refinery	10%	-	-	3%
Riyadh Refinery	10%	3%	1.5%	-
BAPCO Refinery	-	-	1.5%	3%
Al-Ahmadi Refinery	5%	3%	1.5%	-

The selected polymers are two locally produced by SABIC these are LLDPE-X and PP 500U, one industrial waste available locally which is CRT and one manufactured by Shell chemicals which is SBS. Table G.2 summarizes some important physical properties of the selected polymers.

Table G.2: Some Important Physical Properties of the Selected Polymers

Physical Property	Polymer Type			
	CRT	**LLDPE-X**	**PP 500U**	**SBS**
Grade	-	1182	500U	-
Density, g/cc	1.1	0.918	0.89-0.91	0.92
Melting Index, g/10 min	-	1.00	3.00	-

G.3 POLYMER MODIFICATION PROCEDURE

Information and experience gained in the first phase were activated to put together general guidelines by which asphalt binders can be blended with polymer modifiers. It is important to bear in mind, however, that these guidelines should not be considered prescriptive, some modifications may be needed to the stated recommendations. This depends on the actual instrumentation and capabilities of the laboratory performing the blending, the polymer type, and asphalt source.

1. *Blending Mechanism* The blender be cable of providing a high shear rate. The configuration of the blender head (i.e. blade) and the speed of blending defines the level of the shear rate that the blender induces into the asphalt binder. To insure

that high shear blending is obtained, the recommended speed should not be less than 2,500 rpm and a blade similar to the one shown in Plate 4.2 must be used..

2. ***Blending Time*** The blending time, which depends greatly on the blending shear rate and blending temperature, should be kept to a minimum since economical, practical, and technical issues could be affected by unnecessarily long blending times. It was found that prolonged blending time besides being uneconomical is detrimental to the rheological properties of the modified binder. The suggested optimum blending times are shown Table G.3.

Table G.3: Recommended Blending Time for the Polymers Selected from the First Phase

Polymer Type	**Recommended Blending Time** minutes	**Maximum Blending Time** minutes
Linear Low Density Polyethylene (LLDPE)	120	135
Polypropylene (PP)	120	135
Styrene-Butadiene-Styrene (SBS)	60	75
Crumb Rubber (CRT)	80	95

Since blending time is dependent on the blender configuration and polymer type, it is recommended to identify the optimum blending time for a specific polymer type, blender head configuration, and speed by monitoring the increase in consistency of the PMAB by measuring the softening point at uniform time intervals during the blending process (say every 20 minutes). Once the softening point stabilizes and does not show significant increase with time, the blending process can be ceased. A plot

between the blending time and the softening point can be generated from which the optimum blending time can be determined.

3. *Blending Temperature* The blending temperature greatly depends on the molecular weight of the polymer. Table G.4 provides a recommended blending temperature for the selected polymers.

Table G.4: Recommended Blending Temperature

Polymer Type	Recommended Blending Temperature °C	Maximum Blending Temperature °C
Linear Low Density Polyethylene (LLDPE)	160 - 170	200
Polypropylene (PP)	170-180	200
Styrene-Butadiene-Styrene (SBS)	160-170	200
Crumb Rubber (CRT)	170-180	200