LABORATORY STUDY OF TEST METHODS FOR POLYMER MODIFIED ASPHALT IN HOT MIX PAVEMENT

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16. Abstract

Increasing use of asphalt binders modified with elastomeric or plastic modifiers makes the specification of binders a difficult task. Ideally, a generic specification would allow various suppliers and additives to compete based on expected performance differences in the hot mix pavements resulting from the use of these binders. This paper describes research whose objectives were to investigate unique characteristics of polymer modified hot mix and to determine if there are binder tests and properties which could be used to predict mix performance whether the binders used are conventional or modified. Two mix designs incorporating three conventional asphalts and six different modified asphalts were tested during two phases of testing. The objective was to determine what binder tests had promising correlations with important mix properties. Fraass Point and PVN showed the most promise for controlling temperature susceptibility of the hot mix at low temperatures. Penetration at 25°C and force ductility areas, particularly "peak area," showed the most promise for predicting strength properties of mixes. The best prediction of fatigue life and permanent deformation as measured by diametral testing resulted from a combination of penetration at 25°C and force ductility area values as independent variables in multiple regression analysis.

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DISCLAIMER

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1.0 INTRODUCTION

1.1 Problem Statement

Polymer additives to asphalt materials are being advocated as having high potential for improving long-term pavement performance through their ability to enhance the properties of the asphalt binder, and of the resulting asphalt concrete mix. Claims have been made that polymer additives to asphalt can improve adhesion and cohesion, temperature susceptibility, modulus, resistance to fatigue, resistance to rutting, and durability (Terrel and Walter 1986). Improvements to these qualities in hot mix pavements have the potential to lengthen pavement service life. Because these additives are relatively new to hot mix pavement construction in the U.S., work is needed to determine their effect on asphalt pavements, to identify appropriate properties which relate to performance, to select testing procedures to aid in design and construction of these pavements, and to develop tests to predict the long-term behavior of the pavements.

1.2 Objectives

The objectives of this study are to:

1) conduct a literature review on the use of, test procedures for, and specifications used in the design of polymer modified asphalt hot mixes,
2) identify the important properties required for polymer modified hot mixes and to determine the best method to measure them, and
3) recommend interim specifications and test methods for polymer modified asphalt and polymer modified hot mixes.

To expand upon these objectives, it is important to determine what research has been conducted on the use of polymer additives for hot mix pavements. Specifically, it is essential to determine any differences from conventional

asphalts exhibited by polymer modified binders in laboratory testing which may affect performance in the field. Can polymer modified asphalts be tested just like any other asphalt cement? Are there routine tests which give misleading results when polymer modified asphalts are used? Are non-conventional tests required to properly design and construct with polymer modified asphalts? These questions need to be answered for both binder tests, and for tests of hot mix using the modified binders.

To answer the above questions, the logical starting point is "the literature." For this reason, the first task of this investigation was a thorough search of existing literature dealing with polymer modified hot mix, testing of polymer modified asphalts, and testing of hot mix using polymer modified asphalts.

1.3 Research Methodology

The literature search was conducted through a search of the Transportation Research Information Service (TRIS) Database, as well as reference lists from various publications and reports dealing with polymer modified asphalts. Promising documents were obtained and reviewed.

Several reports summarizing laboratory testing programs were obtained. The results of these programs were analyzed. A testing program was developed utilizing promising binder and mix tests considering time and manpower budgets and laboratory test equipment accessibility.

The laboratory investigation used tests which were identified as highly likely to predict field performance of polymer modified asphalts. Two phases of laboratory investigation were undertaken. The initial laboratory investigation proposed in Chapter 4 of this report was designed to "prototype" in the OSU Laboratory the most promising tests suggested by the literature using the modified binders specified by ODOT. A second phase of testing, the final testing program, was designed to further investigate these promising tests with sufficient numbers of specimens of the modified binders and local aggregates to provide a sound basis for evaluation of binder, hot mix, and pavement properties.

1.4 Organization of the Report

This report begins with a brief discussion of the various polymer types, expected and reported effects on binder properties, and expected and reported effects on mix properties. Chapter 3 presents an evaluation of test procedures, and proposes test methods for further study. The preliminary laboratory testing program and test results are presented in Chapter 4. Chapter 5 presents the test results and analysis from the final testing program. Chapter 6 discusses the results of the testing programs and Chapter 7 provides conclusions and recommendations. The appendices provide detailed information on test procedures and data on the asphalt mixture preparation.

2.0 ELASTOMERIC AND PLASTIC ADDITIVES USED TO MODIFY ASPHALT MIXTURES

The purpose of this chapter is to present the results of a literature review on: 1) the types and classification of asphalt additives; 2) the effect of the additives on binder properties; and 3) the effect of the additives on mix properties.

2.1 Types and Classification of Additives

Several additives have been used in recent years to modify the properties of asphalt binders. The reasons for their increased use include (King, Muncy, and Prudhomme 1985):

1) To prevent premature failure of roadways due to rutting and cracking.
2) To reduce the potential for stripping.
3) To prevent asphalt bleeding.
4) To prevent ravelling.
5) To prevent "tender" mixes (hard-to-place mixes) during construction.

Examples of additives which have been used are included in Table 2.1 (Terrel and Walter, 1986). This report will focus on the use of rubbers and plastics. Specifically, EVA (ethylene-vinyl-acetate), SBS (styrene-butadiene-styrene), SBR (styrene-butadiene-rubber), and SB (styrene-butadiene) will be discussed.

Before discussion of specific additives, a few words about polymers in general are in order. It should be noted that the term polymer can be applied to many chemically crosslinked structures, each of which has its own chemical and physical properties. Polymers may be defined as large molecules composed of a repetition of smaller, normally organic, structural units called monomers (King, Muncy, and Prudhomme, 1986). A diblock or triblock copolymer is a polymer that consists of two or three monomers, respectively.

Some additives used in the asphalt industry are identified as polyolefins. Although some researchers refer to polyolefins as simply plastics (Krater, Wolfe, and Epps, 1987), the proper definition is a compound composed of a chain

Table 2.1. Binder Additive

Additive	Examples
Mineral Fillers	dust, lime, portland cement, sulfur, carbon black
Extenders	sulfur, lignin
Rubbers	natural latex, synthetic latex (SB or SBR), block copolymer (SBS), reclaimed rubber
Plastics	polyethylene, polypropylene, EVA polyvinyl chloride
Combinations	
Fibers	asbestos, rock wool, polypropylene, polyester
Oxidants	manganese and other mineral salts
Antioxidants	lead compounds, carbon, calcium salts
Hydrocarbons	aromatic oils and rejuvenating
Antistrip Materials	lime, sulfur

of olefin monomers. The olefin monomers have names that end with -ene, -ylene, or -diene, such as propylene, ethylene, and butadiene (Patton 1976).

Although additives may be classified as SBS, SBR, etc., it should be noted that variations within a classification occur. For example, Button and Little (1987) reported considerably different properties for EVA supplied by Exxon and supplied by Dupont (Elvax 150). Collins (1986) reported at least nine different blends of Kraton. Generally, however, distinctions in behavior may be made based on these generic designations.

2.1.1 SB (Styrene-Butadiene)

This additive is a diblock copolymer of styrene and butadiene. "Styrelf," the most widely used form of SB, produces a unique modified binder by blending using a proprietary means of cross-linking the polymer and binder system (Shuler 1987).

2.1.2 SBR (Styrene-Butadiene Rubber)

Styrene Butadiene Rubber is a synthetic rubber and is usually provided in a latex form. This additive can either be added to the binder before mixing with the aggregate or after. Some manufacturers recommend that this modifier be added to the binder just after mixing with the aggregate since it has a tendency to degrade with high temperatures (Button and Little 1987).

2.1.3 SBS (Styrene-Butadiene-Styrene)

This additive is a triblock copolymer of styrene and butadiene. The styrene ends of this polymer are attracted towards each other forming a solid lattice while the butadiene strands flex and stretch to give flexibility.

2.1.4 EVA (Ethylene-Vinyl-Acetate)

This modifier is a flexible thermoplastic. It differs from the thermoplastic rubbers, (the polystyrene group) in that it forms a stiffer, stronger mix with better resistance to rutting, but lacks the flexibility and resiliency that the others offer (King, Muncy, and Prudhomme, 1986).

2.1.5 Polychloroprene (Neoprene)

Neoprene is a generic name for elastomeric polymers of chloroprene (synthetic rubber) of which there are several types in both dry and latex forms. The latex form is a water dispersion of neoprene particles about .2 microns in diameter (Terrel and Epps, 1988).

2.1.6 Polyethylene

This additive is classified as a plastic. Polyethylene is unusual in the way it mixes with asphalt. Other polymers are processed to produce a complete and homogeneous dissolution of the additive in the asphalt cement. Polyethylene does not, however, dissolve in asphalt but forms a uniform dispersion of small (micron size) particles under high shearing forces (Terrel and James, 1988).

2.2 Effect of Additives on Binder Properties

This section presents an evaluation of the effect of the various additives on binder performance. Binder properties are determined through laboratory testing. The tests most commonly run on conventional asphalt binders include:

1) penetration at 4°C and 25°C (ASTM D5, AASHTO T49)
2) viscosity vs temperature at 60°C (ASTM D2170, AASHTO T201) and 135°C (ASTM D2171, AASHTO T202)
3) ductility (ASTM D113, AASHTO T51)
4) durability — that is, properties 1 to 3 after aging using TFOT (ASTM D1744) or RTFOT (ASTM D2872, AASHTO T240)

To this list has been added a number of other non-standard tests such as:

1) toughness and tenacity
2) tension test
3) Fraass test
4) force ductility
5) others

All of these tests are discussed in Chapter 3, and a detailed description of the nonstandard test procedures is given in Appendix C.

Tables 2.2 through 2.5 compare binder effects, as reported in the most significant research reports obtained through the literature search, for the four polymers studied in both the preliminary and final lab testing. Table 2.2 shows findings of researchers working with SB. All researchers found decreases in penetration at 25°C after modification, and increases in viscosities at 60°C and 135°C. Moderate and high temperature consistency is increased through addition of the modifier. Those reporting penetration at 4°C indicated slight increases, indicating that the modifier had made the material slightly more compliant at low temperatures. Low temperature ductility was reported to have increased by two researchers and to have decreased by one. Force ductility also showed contradiction. Although only one researcher reported on toughness and tenacity, he found both to be increased after modification.

Table 2.3 summarizes reported SBR binder properties. Consistency increased except at 4°C, where results were mixed. Toughness, tenacity, and force ductility values increased. Conventional ductility data were inconclusive.

Table 2.2. Effects of "Styrelf" (SB Modifier) on Binder Properties

Test	Puzinauskas AC-10	O'Leary 85/100 pen	Schuler AC-10	Lee AC-5 (3%)*
Penetration @ 39.2°F (4°C)	Incr	-	Incr	Incr
@ 77°F (25°C)	Decr	Decr	Decr	Decr
Viscosity @ 140°F	Incr	Incr	Incr	Incr
@ 275°F	Incr	Incr	Incr	Incr
Ductility @ 39°F	Incr	Incr	-	Decr
@ 60°F	Decr	-	-	-
Force Ductility (39°F)	-	-	Incr	Decr
Toughness (77°F)	-	-	-	Incr
Tenacity (77°F)	-	-	-	Incr

*Percent additive of binder

Table 2.3. Effects of an SBR Modifier on Binder Properties

Test	Button & Little AC-5 (5%)*	Schuler AC-10 (3%)	Reinke (3%)
Penetration @ 39.2°F (4°C)	Decr	Incr	-
@ 77°F (25°C)	Decr	Decr	Decr
Viscosity @ 140°F	Incr	Incr	Incr
@ 275°F	Incr	Incr	-
Ductility @ 39.2°F	N/C**	-	Incr
@ 77°F	N/C	-	
Force Ductility	Incr	Incr	-
Toughness	-	-	Incr
Tenacity	-	-	Incr

*Percent additive of binder
**No change

Table 2.4 summarizes findings for SBS modified binders. The effects of SBS modifiers on binder properties were varied. The majority of researchers reported penetration increases at 4°C. Penetration results at 25°C were about evenly split between increases and decreases. All researchers reported viscosity increases at 60°C and 135°C. The majority of researchers showed ductility increases at 4°C and all reported changes in ductility at 25°C were decreases. All reports of modifier effects on force ductility, toughness, and tenacity showed increases.

Table 2.4. Effects of an SBS Modifier on Binder Properties

Test	Button & Little AC-5 (5%)*	Schuler AC-10 (3%)	Krivohlavek 85/100 pen (5%)	Carpenter
Penetration @ 39.2°F (4°C)	Decr	Incr	Incr	-
@ 77°F (25°C)	N/C**	Decr	Incr	Decr
Viscosity @ 140°F (60°C)	Incr	Incr	Incr	-
@ 275°F (130°C)	Incr	Incr	Incr	Incr
Ductility @ 39.2°F	Decr	-	Incr	Incr
@ 77°F	Decr	-	Decr	-
Force Ductility	Incr	Incr	-	-
Toughness	-	-	-	Incr
Tenacity	-	-	-	Incr

*Percent additive of binder
**No change

The reported effects of an EVA type modifier on a binder's properties were varied (Table 2.5). The reports all showed increases in viscosities, force ductility, toughness and tenacity. Ductility and penetration effects showed mixed performance at both 4°C and 25°C.

When all four additives just discussed are considered, a few points stand out. No researcher reported decreases in viscosity at 60°C or 135°C as a result of use of any of the additives. Only one researcher reported an increase in penetration at 25°C. Penetrations at 4°C were reported to either increase or

Table 2.5. Effects of an EVA Modifier on Binder Properties

Test	Button & Little AC-5 (5%)*	Chow AC-10
Penetration @ 39.2°F (4°C)	Decr	-
@ 77°F (25°C)	Decr	-
Viscosity @ 140°F (60°C)	Incr	-
@ 275°F (130°C)	Incr	-
Ductility @ 39.2°F	Decr	-
@ 77°F	Decr	-
Force Ductility	Incr	-
Toughness	-	Incr
Tenacity	-	Incr

*Percent additive of binder

decrease slightly. Generalizing, consistency remained essentially constant at low temperature. At higher temperatures the addition of polymer additives increased consistency. Figure 2.1 shows the typical effect of a polymer additive on binder consistency as plotted on a bitumen test data chart (BTDC). No researcher reported decreases in toughness and tenacity. Only one researcher reported a decrease in force ductility values. Little published information regarding polychloroprene (neoprene) and polyethylene was found in the literature.

2.3 Effect of Additives on Mixture Properties

This section presents the results of lab and field studies showing the effects of additives on mix properties. The mix properties most commonly evaluated through laboratory testing include:

1) Stability — Marshall or Hveem
2) Modulus
3) Tensile Strength
4) Fatigue resistance
5) Resistance to permanent deformation

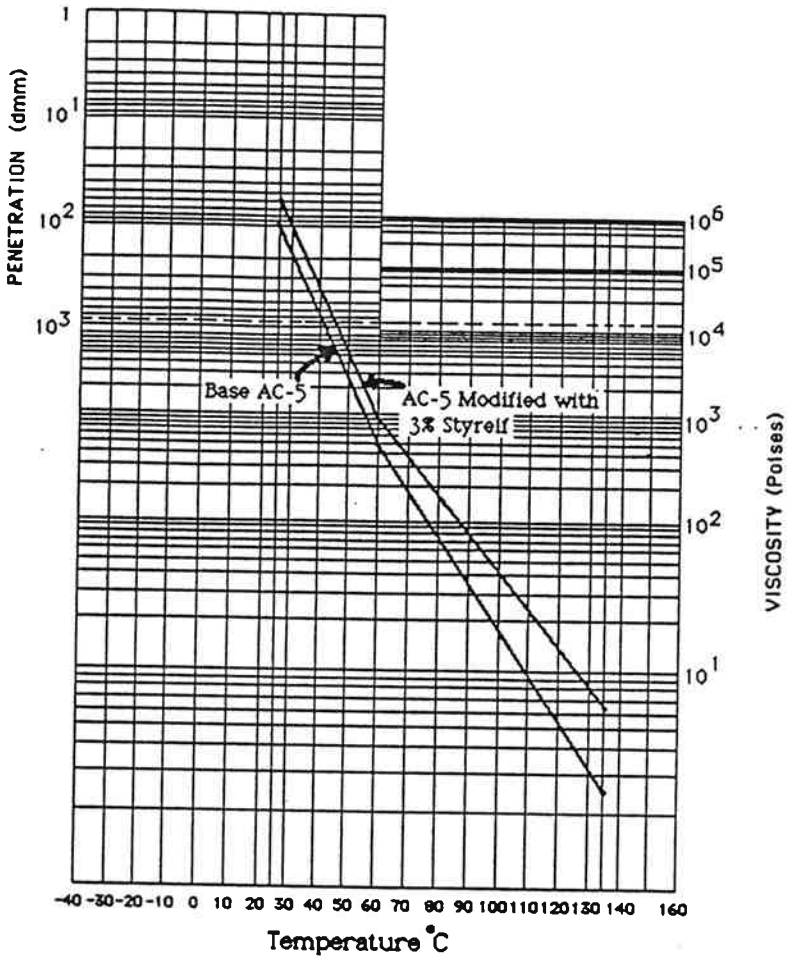


Figure 2.1. BTDC (Bitumen Test Data Chart) of Styrelf-Modified AC-5 and Base AC-5 (after Lee and Demirel, 1987)

6) Moisture sensitivity

7) Aging resistance

All of these tests are discussed in Chapter 3, and a detailed description of the nonstandard test procedures is given in Appendix C.

2.3.1 Laboratory Studies

Tables 2.6 through 2.9 summarize test results for mixture tests, as reported in the most significant research reports obtained through the literature search, for the four binders tested on both preliminary and final testing.

Review of Tables 2.6 through 2.9 shows near complete agreement on modifier effects for all four types of additives. No researcher reported a decrease in modulus at 25°C. Tensile strength increased at 25°C for all researchers.

Table 2.6. Effects of Styrelf Modifiers on Mix Properties

	Button	King	Puzinauskas	O'Leary	Lee
Modulus @ 77°F	Incr	Incr	–	Incr	N/C*
Tensile Strength @ 77°F	Incr	Incr	–	–	Incr
Fatigue Resistance	Incr	Incr	Incr	Incr	Incr
Performance Deformation Resistance	Incr	Incr	–	Incr	Incr
Moisture Sensitivity	Decr	Decr	Decr	Decr	Decr
Aging Sensitivity	–	–	–	–	–

*No change

Table 2.7. Effects of SBR–Modified Binders on Mix Properties

	Button	Krater	Lee
Modulus @ 77°F	N/C*	Incr	Incr
Tensile Strength @ 77°F	Incr	Incr	Incr
Fatigue Resistance	Incr	–	Incr
Permanent Deformation Resistance	Incr	–	Incr
Moisture Sensitivity	Decr	–	Decr
Aging Sensitivity	Incr	–	–

*No change

Table 2.8. Effects of SBS–Modified Binders on Mix Properties

	Button	Carpenter
Modulus @ 77°F	Incr	Incr
Tensile Strength @ 77°F	Incr	Incr
Fatigue Resistance	Incr	Incr
Permanent Deformation Resistance	Incr	Incr
Moisture Sensitivity	Decr	N/C*
Aging Sensitivity	Incr	–

*No change

Table 2.9. Effects of EVA-Modified Binders on Mix Properties

	Button	Afshar
Modulus @ 77°F	Incr	-
Tensile Strength @ 77°F	Incr	Incr
Fatigue Resistance	Incr	Incr
Permanent Deformation Resistance	Incr	-
Moisture Sensitivity	Decr	-
Aging Sensitivity	Incr	-

Fatigue resistance increased in all cases. Figure 2.2 shows the typical effect on fatigue curves at a given temperature through the addition of a polymer additive. Permanent deformation resistance also increased in all cases. Moisture sensitivity was reported as either a decrease or as no effect. Only one research team investigated mixture aging sensitivity. Button and Little (1987) showed significant aging effect in fatigue testing for EVA and SBS, and to a lesser extent SBR. This appears to be an area requiring further study.

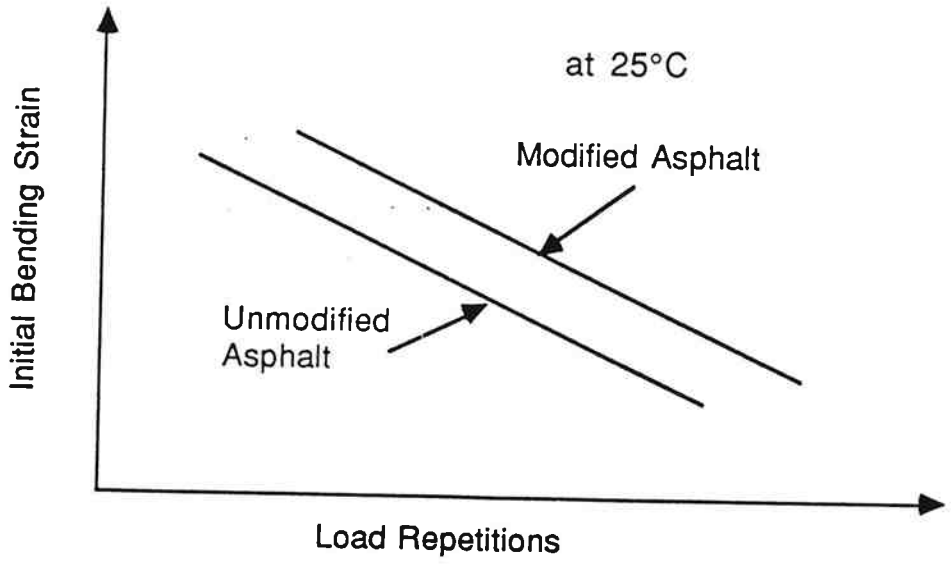


Figure 2.2. Typical Modifier Effect on Fatigue Resistance

2.4 Relation Between Binder and Mix Properties

Improvements made to asphalt binders by the addition of polymers may not always correlate well with improvements in modified asphalt mixes. According to J.L. Goodrich (1988), who studied three types of asphalts and two types of additives ("P1" and "P2"), the following tests correlated well with flexural fatigue life at 25°C:

1) Penetration (4°C,200g,60sec)
2) Force Ductility
3) Temperature of equivalent binder stiffness (138GPa [200 psi], 1000sec)

Tests that did not correlate well with flexural fatigue life include:

1) Penetration Viscosity Number (25-135°C)
2) RTFO Ductility @ 4°C
3) RTFO Force Ductility: Asphalt-Polymer Modulus @ 4°C
4) RTFO Tenacity @ 25°C

He went on to state that:

> We must distinguish those tests which merely characterize the presence of modifiers in asphalt binders from those tests which provide data which correlate with improved asphalt concrete mix performance. Some "conventional" asphalt tests have been shown to be usefully related to mix performance properties; other tests which are in use, especially those involving very high strains, do not. (Goodrich 1988)

Binder tests that incorporate high strain rates (e.g., toughness and tenacity) have been shown to have low correlations with mix properties in modified asphalts. One explanation for this is that a high strain rate in a binder test develops the strength of the polymer more than would actually be seen in working conditions and therefore gives an exaggerated value. This may be the case with ductility-type tests.

In contrast, King, Muncy, and Prudhomme (1986) argue that "elastic binder characteristics, especially improved temperature susceptibility and stress-strain behavior, should correlate with desirable mix capabilities." O'leary, King, and King (1986) present the argument that, ". . . improvements in fatigue response and dynamic modulus are directly related to the creep response of the binder as measured by tensile strength and elastic recovery."

It should be noted that in all cases good mix design or construction practices must be followed to insure improved mix performance. A polymer

modifier will be useless unless the binders are used in well-designed mixes and on properly constructed roads.

3.0 EVALUATION OF TEST PROCEDURES BASED ON LITERATURE REVIEW

This chapter attempts to evaluate the various test procedures used to characterize binders and mixes, particularly as they might relate to field performance of polymer modified asphalt hot mix. In addition, other factors used to evaluate the procedures include:

1) ease of operation,
2) cost of equipment, and
3) repeatability.

Table 3.1 presents a summary of binder tests encountered in the literature and evaluations of the tests based on the above-mentioned criteria. Table 3.2 presents similar information for mixture tests. The binder and mixture tests are discussed in Sections 3.1 and 3.2, respectively. Section 3.3 presents a list of test methods suggested for further study. Descriptions of nonstandard tests are presented in Appendices A and B.

3.1 Binder Tests

As indicated in Chapter 2, a number of test methods have been used to evaluate modified binders. A discussion for each of these binder tests is presented below.

3.1.1 Consistency Tests

Penetration tests, viscosity tests, softening point and Fraass point have been used for polymer modified binders (Table 3.3). Penetration tests were reported by the majority of researchers. This is no doubt because of their simplicity and widespread usage in specifications and temperature susceptibility criteria. Penetration tests at 4°C, 41°F, and 25°C were reported. Generally, penetration test results were reported only as a means to determine penetration index, penetration viscosity number, or to plot temperature vs. consistency on BTDC (bitumen test data charts). Goodrich (1988), however, has cited penetration at 4°C as having high correlation with fatigue and permanent deformation testing of mixture specimens using polymer modified binders.

Table 3.1. Evaluation of Binder Tests

Test Method	Skill Level Required	Equipment Cost	Repeatability
Consistency Tests:			
Penetration	L	L	H
Conventional Viscosities	M	M	H
Sliding Plate Viscosities	H	M	M
Brookfield Viscosities	M	M	H
Softening Point	L	L	H
Fraass Test	M	L	M
Tests of Tensile, Ductile, and Resilient Properties:			
Conventional Ductility ASTM D113	M	M	H
Force Ductility	M	M	H
Toughness and Tenacity	M	M	M
Rubber Industry Tensile Tests ASTM D412	L	M	H
Dropping Ball	M	M	L
Tests of Aging and Durability:			
TFOT	L	L	M
RTFOT	L	M	H
LTD	L	M	H
Krivohlavek Accelerated Weathering	L	M	H
POB	M	M	H
Other Tests of Binders:			
Dynamic Shear Analysis	H	H	H
Flashpoint	L	L	H
Loss on Heating	L	L	H
Ash Content	L	L	H
Solubility in Trichlorethylene	M	L	H

Note: H = high
M = moderate
L = low

Table 3.2. Evaluation of Mixture Tests

Test Method	Skill Level Required	Equipment Cost	Repeatability
Stabilities:			
Marshall Stability	L	L	H
Hveem Stability	L	L	H
Modulus Tests:			
Dynamic Resilient	L	M	H
Fatigue Tests:			
Flexural Beam	M	M	M
Diametral Model	L	M	H
Overlay Tester	M	M	H
Permanent Deformation Tests:			
Uniaxial Compression Creep	M	H	H
Diametral Mode	M	M	H
Rutting Resistance (LCPC)	L	H	H
Tensile Strength Test:			
Indirect Tensile	L	M	H
Moisture Sensitivity Tests:			
Modified Lottman	M	M	M
Retained Marshall	L	L	M
Immersion Compression	M	M	M
Aging:			
Texas A&M Method	L	L	H
POB	M	M	H
Other Mixture Tests:			
Microwave "Zapping"	L	L	H
Vialit	M	M	M

Note: H = high
M = moderate
L = low

Table 3.3. Consistency Tests Employed by Polymer Modified Asphalt Researchers

Researcher	Penetration	Viscosities	Softening Point	Fraas Test
Button & Little (TTI)	4°C, 100 g, 5 sec 4°C, 200 g, 60 sec 25°C, 100 g, 5 sec	25°C 60°C 135°C		
Goodrich (Chevron Research)	X 4°C, 200 g, 60 sec	60°C 135°C		
Shuler (NMERI)	X	60°C 135°C	X	
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)				
Salter & Rafati-Ashar (U. of Bradford)				
Lee & Demirel (Iowa State U.)	X 5°C 25°C	25°C 60°C 135°C	X	
O'Leary, King, & King (ELF Aquitaine Asphalt)	X 25°C, 100 g, 5 sec	60°C 135°C		
King, Muncy, & Prudhomme (ELF Aquitaine)	X 25°C	60°C 135°C	X	X
Brule, Brion, & Tanguay (French Central Public Works)	X 25°C		X	X
Krivohlavek	4°C, 200 g, 5 sec 25°C, 100 g, 5 sec	60°C 135°C Modified Koppers @ 60°C Brookfield Model RVT Viscometer (71.1-171°C)	X	X
Fleckenstein & Allen	X	X		
Collins (Shell Development Co.)	25°C	60°C 80°C 100°C 120°C (Brookfield)	X	
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)	4°C 25°C	4°C 25°C 60°C 135°C		
Krater, Wolfe, & Epps (U. of Nevada-Reno)				
Chow (SRI International for Dupont)	25°C			

Viscosity tests at 25°C, 60°C, 176°F, 212°F, 248°F, and 135°C were reported. The most common tests were at 60°C and 135°C as would be expected because of their frequent use in specifications, in computing pen-vis numbers, and for plotting curves on BTDC.

There is disagreement regarding the validity of standard viscosities for polymer modified binders. Puzinauskas and Harrigan (1987) reported high dependency between **stiffness modulus** of mixture and **viscosity** of binder when testing Styrelf binders. Shuler (1987) reported that viscosity at 60°C and kinematic viscosity at 135°C "have limited or doubtful application for characterizing" Styrelf, Kraton (SBS), and asphalts modified with SBR. Actual field overlay installations of SBS modified mix reported by Krivohlavek (1988) would seem to substantiate this, as high kinematic viscosity at 135°C did not result in batch plant or field lay down and compaction problems.

Shuler's skepticism regarding the use of conventional viscosities is based on testing of "apparent viscosity" and determination of "shear susceptibility" using the Schweyer Rheometer. These tests show that modified binders are more shear susceptible than conventional asphalts. Viscosity measurements at the same temperature will vary more with changes in shear rate for modified binders than for conventional binders.

Polymer modified binders are "shear thinning." Viscosity drops with increasing shear rate. Shuler (1987) explains:

> Shear thinning behavior can present problems in measurement and analysis if the shear rate at which viscosity is measured is unknown or incorrectly assumed. For example, if the shear rate varies during a test of two materials of different shear susceptibility, a true comparison of viscosity at a given temperature is not possible. This becomes a problem when testing viscosity in capillary tube viscometers. The shear rate in the viscometer varies with the material being evaluated. This is not a problem for 'more' Newtonian fluids, such as most asphalts, because these materials are not especially shear sensitive. However, polymer modified binders, like those used in this study, are shear sensitive, in this case becoming less viscous as more shear is applied. Therefore, for these materials, unless the shear rate during the viscosity test is known or can be made constant for any given material, the relative viscosity between materials cannot be determined.

Conceptually, it would seem to make more sense to try to relate mix and field results "to apparent viscosities" determined at appropriate shear rates than to correlate to conventional viscosities. This will have to be a long-term

development. In the short term, conventional viscosities will continue to be measured.

Krivohlavek (1988) suggests that a **Brookfield Model RVT viscometer** may be "a sensitive and useful tool in examining modified binders." He based this conclusion on the fact that plots of viscosity vs temperature using this instrument picked up an inflection point that conventional viscosity measurement did not. Collins (1986) also reported Brookfield Viscosity results at 60°C, 80°C, 94.4°C, and 120°C, but without discussion.

Krivohlavek (1988) used "modified Koppers viscosity" at 60°C when measured conventional absolute viscosities produced values too high to be valid. This is the recommended procedure.

Button and Little (1987) tested for viscosity at 25°C using the sliding glass plate microviscometer (ASTM D3570-77). They indicated that this test is inappropriate for "binders containing granular materials with particle sizes approaching the binder film thickness." This would apply to polyethylene fibers, but not to the other modifiers being investigated in this research.

The softening point test was reported by several researchers (Shuler 1987; Lee and Demirel 1987; King, Muncy and Prudhomme 1986; Krivohlavek 1988; and Collins 1986), but not discussed. The inference is that softening point values were used to plot BTDC's for use in temperature susceptibility evaluations. One research report (Brule, Brion, and Tanguay 1988), used the temperature range between Fraass Temperature (see next paragraph) and softening point as an indicator of relative plasticity of various binders.

Several researchers (King, Muncy, and Prudhomme 1986; Brule, Brion, and Tanguay 1988; and Krivohlavek 1988) reported using the Fraass Test. The test was used to evaluate temperature susceptibility and as an indicator of brittleness at low temperatures.

3.1.2 Tests for Tensile, Ductile, and Resilient Properties

Five types of tests which evaluate tensile strength of binders were reported in the literature (Table 3.4). These were conventional ductility (ASTM D113), force ductility, rubber industry tensile tests similar to ASTM D412, and the dropping ball test. Force ductility was the most widely used, followed by conventional ductility, toughness and tenacity, rubber industry tensile tests, and the dropping ball test, in that order.

Table 3.4. Tensile, Ductile, and Resilient Property Tests Employed by Researchers

Researcher	Ductility ASTM D-113	Force Ductility	Toughness and Tenacity	Rubber Industry Tests Similar to ASTM D-412	Dropping Ball Test
Button & Little (TTI)	X	1 cm/min	–	–	–
Goodrich (Chevron Research)	X	X	X	–	–
Shuler (NMERI)		X	–	–	–
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)		–	–	–	–
Salter & Rafati-Ashar (U. of Bradford)		–	–	–	–
Lee & Demirel (Iowa State U.)		5 cm/min @ 10°C	constant strain method @ 25°C	20°C, 800% elong. 50 cm/min	–
O'Leary, King, & King (ELF Aquitaine Asphalt)		X	X	X	–
King, Muncy, & Prudhomme (ELF Aquitaine)		X	X	X	X
Brule, Brion, & Tanguay (French Central Public Works)		–	–	–	–
Krivohlavek	5 cm/min, 25°C	X	–	–	–
Fleckenstein & Allen	25°C (4°C for recovery)	–	–	–	–
Collins (Shell Development Co.)	(4°C for recovery)	–		–	–
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)	4°C 15.5°C 5 cm/min	–	–	–	–
Krater, Wolfe, & Epps (U. of Nevada-Reno)	–	–	–	–	–
Chow (SRI International for DuPont)	4°C		X	–	–

Force Ductility. Force ductility is a refinement of the conventional ductility test. Two force cells are added to the loading chain, and the mold is modified to produce a specimen with constant cross-sectional area through the gage length. Stress strain data are plotted (see Fig. 3.1) to determine maximum tensile stress, asphalt (binder) modulus, and total work to failure. Button and Little (1987) have indicated that the presence of a secondary loading curve when this test is run may indicate good asphalt/polymer compatibility. The Kraton (SBS) curve of Fig. 3.1 illustrates such a secondary loading curve.

The majority of researchers seem to believe that this test is a significant binder test, and an improvement over the conventional ductility test. Button and Little go as far as to state that, "a relationship exists between maximum engineering stress of the binders and tensile strength of corresponding mixtures . . . It appears that the force ductility test may be useful in predicting changes in mixture tensile strength when asphalt additives are used." Goodrich (1988), on the other hand, reported that force ductility test results did not correlate well with low-temperature creep or with fatigue test results for the binder-aggregate mixture.

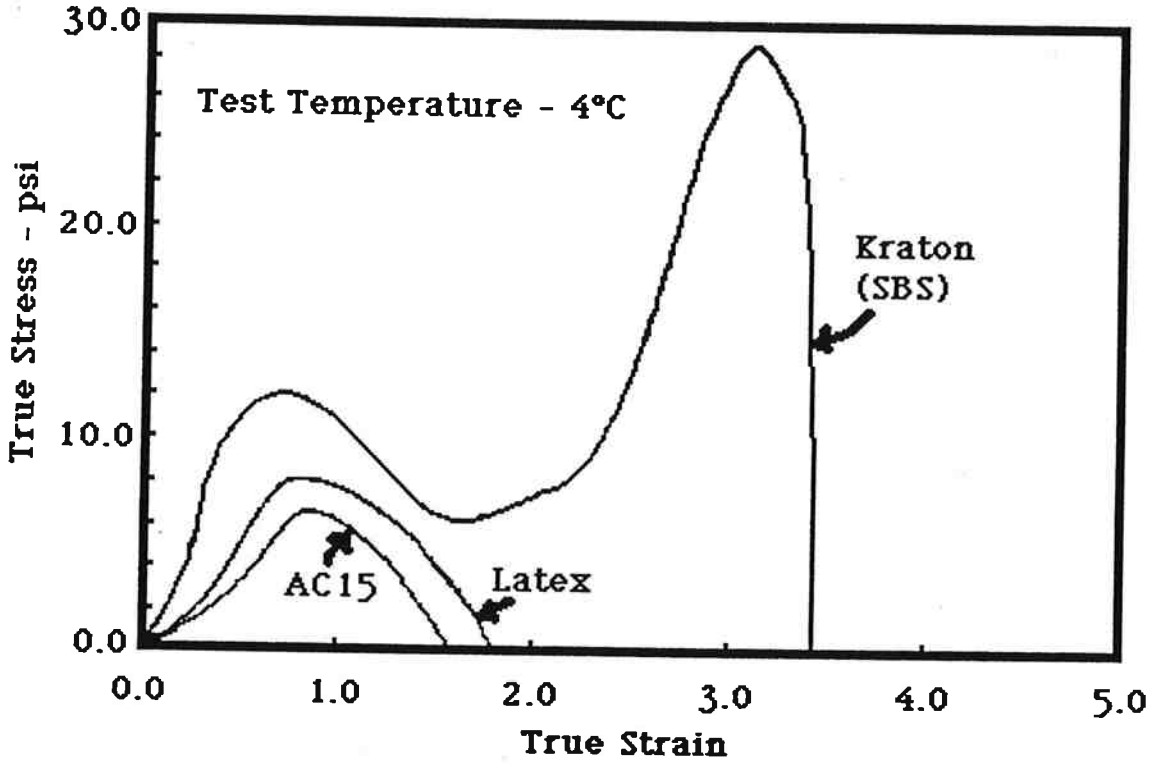


Figure 3.1. Typical Force Ductility Results (after Button and Little, 1987)

Ductility and Elastic Recovery. Conventional ductility testing (ASTM D113) is used to determine material properties similar to those determined by force ductility. This test is still being used because it is a standard test, and the equipment is simpler than force ductility, and more readily accessible. This test procedure is also used to test for "elastic recovery." To test elastic recovery, the standard ductility specimen is stretched to 20 cm, held for 5 minutes, and cut in the middle. After an hour the combined length of the two segments is noted, and percent recovery computed.

Krivohlavek (1988) tested elastic recovery at 10°C, while Fleckenstein and Allen's (1987) specification for modified asphalt requires the test at 4°C. Chow (1987) takes issue with this test, indicating that "ductility at 4°C, . . . does not seem to correlate with any other quantities at all. Although this test is becoming more popular in the asphalt community, it should be examined in more detail to obtain a better understanding of the merit of this engineering testing method."

Toughness and Tenacity. The toughness and tenacity test records tensile strength at constant strain. A metallic hemispherical head embedded in asphalt is pulled from the asphalt at a rate of 20 in/min. at controlled temperature. Toughness and tenacity are derived from the plot of the resulting load-deformation curve (see Fig. 3.2). Toughness is the total area under the load deformation curve and denotes the total work done on the binder. Tenacity is only the work performed in pulling the binder away from the tension head to maximum extension. Reinke and O'Connell (1985) indicate that in addition to toughness and tenacity values, the shape of the toughness and tenacity curve is important and highly variable. They describe seven types of curves.

O'Leary, King, and King (1986) report negatively on the toughness and tenacity test. They indicate that, "test results and data interpretation vary significantly, indicating this test is not as reliable . . ." as the force ductility and traditional rubber industry tensile tests. They continue that, "Lack of repeatability is due in part to the non-uniform cross-section of the test specimen. Thus it is recommended that this test should not be used for specification purposes."

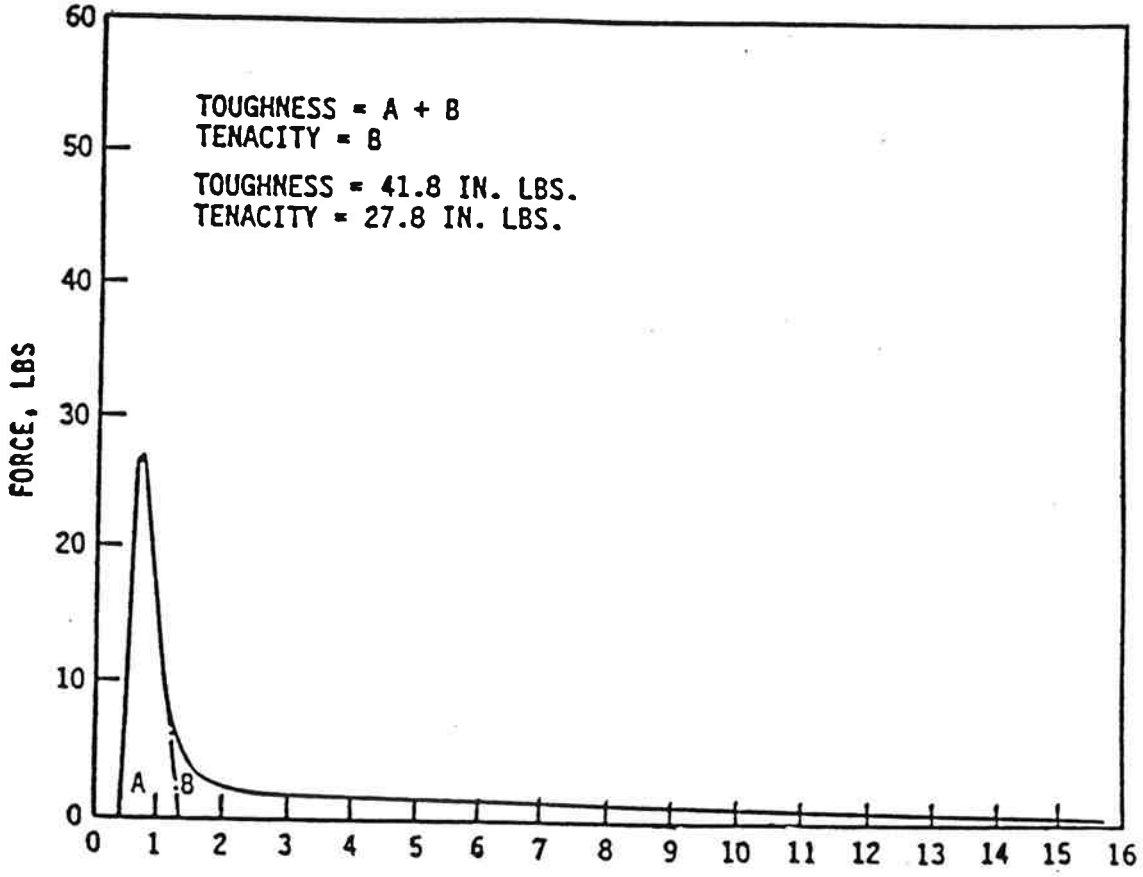


Figure 3.2. Toughness and Tenacity (after Lee and Demirel, 1987)

Goodrich (1988) reports that toughness and tenacity does not correlate well with mixture fatigue and creep tests. On the other hand, Chow (1987) reports that "a qualitative correlation does exist between toughness/tenacity and dynamic moduli within the range of polymer modification chosen for this investigation. . . . Therefore, toughness/tenacity may be regarded as a comparative method of assessing the effects of polymer modifier."

Tensile Test. Two reports (O'Leary, King, and King 1986; King, Muncy, and Prudhomme 1986) advocated rubber industry tensile tests for binders. These reports were prepared by researchers working predominantly with Styrelf. The other researchers (Lee and Demirel 1987) reporting this test included Styrelf in their study and had the tests done at the Elf Aquitaine Asphalt Laboratory. The modified test stretches the specimen to 800% elongation (or fracture) at a

rate of 50 cm/min with an Instron tensile tester. O'Leary, King, and King (1986) indicate that this test generates a stress/strain curve which is virtually identical to that produced by the force ductility test.

Dropping Ball Test. The least reported test of binder tensile properties was the dropping ball test, a test developed in the Elf Aquitaine research labs in France. It is intended to provide a "rough relationship of a material's elasticity or tensile strength after elongation to its original viscosity." (Lee and Demirel 1987).

3.1.3 Aging Tests

Rolling Thin Film Oven Test (RTFOT) and Thin Film Oven Test (TFOT) both are reported and both are generally accepted (Table 3.5). The choice of method is probably a matter of available equipment, the RTFOT being preferred if available. Button and Little (1987) refer to "crusting" and "scumming" problems with TFOT, particularly with some modified asphalts.

All authors reporting on effects of aging on binder properties generally indicated less aging effect on polymer modified binders than on conventional asphalts. Some additives even produced binders that resulted in lower viscosities with aging, probably due to degradation of the polymer. Goodrich (1988) reported on the use of the extended tilt-oven durability test or long-term durability (LTD) test. This is an extension of the RTFOT utilizing 7-day exposure at 111°C. The test was designed to "approximate the properties of asphalt recovered from cores aged for two years in the California desert." His testing indicated that his polymer 2 blend did not experience viscosity increases after RTFO and LTD aging. Apparently, this polymer degraded concurrent with the normal oxidation of the asphalt, resulting in a fairly stable viscosity. Since polymer modified asphalts may be stored at elevated temperatures for long periods of time, this type of testing may become very important.

Button and Little (1987) tested for "heat stability" to investigate the possibility of degradation problems due to prolonged storage of modified binders at elevated temperatures. They placed binder samples in covered penetration tins and exposed them to 176.6°C for 48 hours, 162.7°C for 24 hours, and 260°C for 2 hours. In each case they observed the effect on appearance, and tested for penetration before and after. Definite changes in appearance were noted for the longer tests. Most binders experienced decreased penetration, while two binders

Table 3.5. Aging Procedure Employed by Researchers

	RTFOT	FTOT	LTD	Krivohlavek's "Accelerated Weathering Instrument"
Button & Little (TTI)	X			
Goodrich (Chevron Research)	X		X	
Shuler (NMERI)	X			
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)				
Salter & Rafati-Ashar (U. of Bradford)				
Lee & Demirel (Iowa State U.)		X		
O'Leary, King, & King (Elf Aquitaine Asphalt)	X	X		
King, Muncy, & Prudhomme (ELF Aquitaine)	X			
Brule, Brion, & Tanguay (French Central Public Works)				
Krivohlavek	X			X
Fleckenstein & Allen		X		
Collins (Shell Development Co.)				
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)		X		
Krater, Wolfe, & Epps (U. of Nevada-Reno)				
Chow (SRI International for Dupont)				

experienced increased penetration. Unpublished Shell and Cal DOT data were cited as indicating "reduction in viscosity after prolonged exposure to temperatures greater than 176.6°C for SBR and SBS modified asphalts."

Krivohlavek (1988) tested to simulate "accelerated weathering" utilizing modified equipment available commercially to test in accordance with ASTM G53-84. The picture of this apparatus indicates that it is essentially a "tanning booth" for binders. It utilizes banks of tubular light fixtures. He reported "radical changes in the modified koppers viscosity, ring and ball softening point, and PVN as compared to the RTFOT data."

Although reporting only on conventional binders, Kim, Bell, Wilson, and Boyle (1986) indicate promise for use of the Pressure Oxygen Bomb (POB) in combination with the previously mentioned Fraass test to measure the durability of asphalt. Kim placed Fraass samples in a bomb with oxygen at 100 psi at a temperature of 60°C. This type of testing should be equally applicable to modified binders.

3.1.4 Other Binder Tests

A summary of less well known binder tests used by researchers can be found in Table 3.6.

The most frequently cited "other" binder test is referred to as "dynamic shear" analysis, "dynamic mechanical" analysis, or rheological mechanical spectroscopy. Goodrich (1988) reports excellent correlations with fatigue and creep performance determined from tests of mixtures. O'Leary, King, and King (1986) tested "for cohesion and flexibility by dynamic modulus . . . over a range of expected road temperatures," but state that they do not believe that these tests are superior to simpler tests for tensile strength and elastic recovery. King, Muncy, and Prudhomme (1986) reiterate this opinion by stating that, "although research tools such as a modified sliding plate rheometer and a Rheometrics mechanical spectrometer are available to measure the entire creep response curve for polymer modified binders, simpler tests are more convenient." The simpler tests listed are tensile strength by modified ASTM D412, force ductility, toughness and tenacity, and dropping ball.

Chow (1987) places more value on dynamic shear analysis, however, using it as the standard against which the usefulness of toughness and tenacity tests was

Table 3.6. Other Binder Tests Employed by Researchers

Researcher	Dynamic Shear Analysis	Flash Point	ASTM D1370 Heptane Xylene Equiv.	High Pressure Liquid Chromatography	Reflected Fluorescence Microscopy	X-Ray Diffraction	ASTM D2007 "Clay Gel" Procedure	Gel Permeation Chromatography	Loss on Heating	Ash Content	Stability in Trichloroethylene
Button & Little (TTI)		X									
Goodrich (Chevron Research)	X										
Shuler (NMERI)			X								
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)											
Salter & Rafati-Ashar (U. of Bradford)											
Lee & Demirel (Iowa State U.)				X	X	X					
O'Leary, King, & King (ELF Aquitaine Asphalt)	X										
King, Muncy, & Prudhomme (ELF Aquitaine)											
Brule, Brion, & Tanguay (French Civil Public Works CAB)					X			X			
Krivohlavek	X	X							X	X	
Aerckerstein & Allen		X									X

Table 3.6. Other Binder Tests Employed by Researchers (continued)

Researcher	Dynamic Shear Analysis	Flash Point	ASTM D1370 Heptane Xylene Equiv.	High Pressure Liquid Chromatography	Reflected Fluorescence Microscopy	X-Ray Diffraction	ASTM D2007 "Clay Gel" Procedure	Gel Permeation Chromatography	Loss on Heating	Ash Content	Stability in Trichloroethylene
Collins (Shell Development Co.)											
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)		X									
Krater, Wolfe, & Epps (U. of Nevada-Reno)											
Chow (SRI International for DuPont)	X										

evaluated. In other words, toughness/tenacity tests would be evaluated favorably if the results correlated with dynamic shear analysis.

Krivohlavek (1988) refers to "rheological mechanical spectroscopy" as a test method to "check compatibility" as well as "to relate binder rheology to potential performance." This test methodology certainly possesses a very sound fundamental approach and would appear to be a very promising test for evaluating any binder, modified or conventional.

Numerous other binder test results have been reported in the literature for modified binders. These include routine tests such as flashpoint, loss on heating, ash content, and solubility in trichloroethylene, and more specialized testing such as heptane–xylene equivalent, high–pressure liquid chromatography, reflected fluorescence microscopy, x–ray diffraction, composition by clay gel procedure, and gel permeation chromatography. None of these tests were indicated to be essential for analysis of modified binders, at least not by user agencies.

3.2 Mixture Tests

Binder properties are investigated because it is hoped that they will provide a simple means of predicting hot mix pavement performance. To determine the usefulness of tests of polymer modified binder, it is necessary to test mixtures utilizing the binders to determine if binder tests are useful indicators of mixture performance in the lab and in the field. Mixture tests to be discussed include stability, modulus, fatigue, permanent deformation, tensile strength, moisture sensitivity, aging, and miscellaneous other tests.

3.2.1 Stability Tests

Both the Marshall and Hveem methods of mix design have their own method for testing stability. Although researchers used these methods for mix design and compaction of specimens, most researchers did not report stability results (Table 3.7).

Button and Little (1987) reported stabilities for both methods. Marshall stabilities showed clear increases for modified asphalts over the base asphalts whereas Hveem stabilities did not.

Lee and Demirel (1987) reported only Marshall stabilities. They reported that two modifiers increased Marshall stabilities from that of the base AC–5 asphalt to values comparable to those of AC–20 mixes without additives.

Table 3.7. Stability Tests Employed by Researchers

Researcher	Marshall	Hveem
Button & Little (TTI)	X	X
Goodrich (Chevron Research)		
Shuler (NMERI)		
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)	for mix design	
Salter & Rafati-Ashar (U. of Bradford)		
Lee & Demirel (Iowa State U.)	X	
O'Leary, King, & King (ELF Aquitaine Asphalt)		
King, Muncy, & Prudhomme (ELF Aquitaine)	Discuss	Discuss
Brule, Brion, & Tanguay (French Central Public Works)		
Krivohlavek		X
Fleckenstein & Allen		
Collins (Shell Development Co.)		
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)	for mix design	
Krater, Wolfe, & Epps (U. of Nevada-Reno)		
Chow (SRI International for Dupont)		

Krivohlavek (1988) reported only Hveem stabilities. He reports that Hveem mix design produced the same binder content for both conventional asphalt and modified asphalt. He further indicated that the modified binder had "slightly higher" Hveem stability than the control, although his graphical comparison of stability values shows no perceptible difference between control asphalt and modified asphalt values.

King, Muncy, and Prudhomme (1986) commented that, "it is not uncommon for Hveem or Marshall stability tests to show little distinction between an asphalt before and after polymer modification." They continue that, "pavement design procedures for conventional asphalt mixes should be reevaluated for each type of polymer." Button and Little do not agree. They concluded that "either Marshall or Hveem is acceptable for mix design with polymer modified binders." They did conclude however, that "the Marshall procedure is much more sensitive to binder properties than the Hveem." This is because "Hveem stability is largely dependent upon interparticle friction of the aggregate and does not correlate well with binder properties . . . As one might expect, there were no correlations between Hveem stability and the additives utilized . . ."

The general consensus is that either Marshall or Hveem will produce acceptable mix designs for polymer modified asphalts at the usual levels of modification. Other tests give better indications of potential improvements in pavement from modifiers than stabilities, particularly Hveem stabilities, where little difference can be observed.

3.2.2 Modulus Tests

The Dynamic Resilient Modulus test was used widely by researchers testing mix properties (Table 3.8). Button and Little (1987) present a good example of this usage — using it both to evaluate mixture temperature susceptibility (see Figure 3.3) and as a general quality control measure for mixture preparation and testing throughout their study. To evaluate temperature susceptibility, they tested modified and control mixtures at -23.3°C, .55°C, 20°C, 25°C, and 40°C. They state that "although pavement performance data based on resilient modulus has not been established, it appears that the ideal binder should provide low mixture stiffness at low temperatures to improve flexibility and reduce cracking and or provide higher mixture stiffness at high temperatures to reduce permanent deformation." They report that this test shows no clear differences between low

Table 3.8. Modulus Testing Employed by Researchers

	-23.3	-12.2	-10	0	4.4	20	22.2	25	37.8	40 (°C)
Button & Little (TTI)	X			X		X		X		X
Goodrich (Chevron Research)										
Shuler (NMERI)										
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)					X		X		X	
Salter & Rafati-Ashar (U. of Bradford)										
Lee & Demirel (Iowa State U.)								X		
O'Leary, King, & King (ELF Aquitaine Asphalt)										
King, Muncy, & Prudhomme (ELF Aquitaine)			X							X
Brule, Brion, & Tanguay (French Central Public Works)										
Krivohlavek										
Fleckenstein & Allen										
Collins (Shell Development Co.)										
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)										
Krater, Wolfe, & Epps (U. of Nevada-Reno)		X		X				X		X
Chow (SRI International for DuPont)										
Scholz and Hicks (OSU)				X				X		

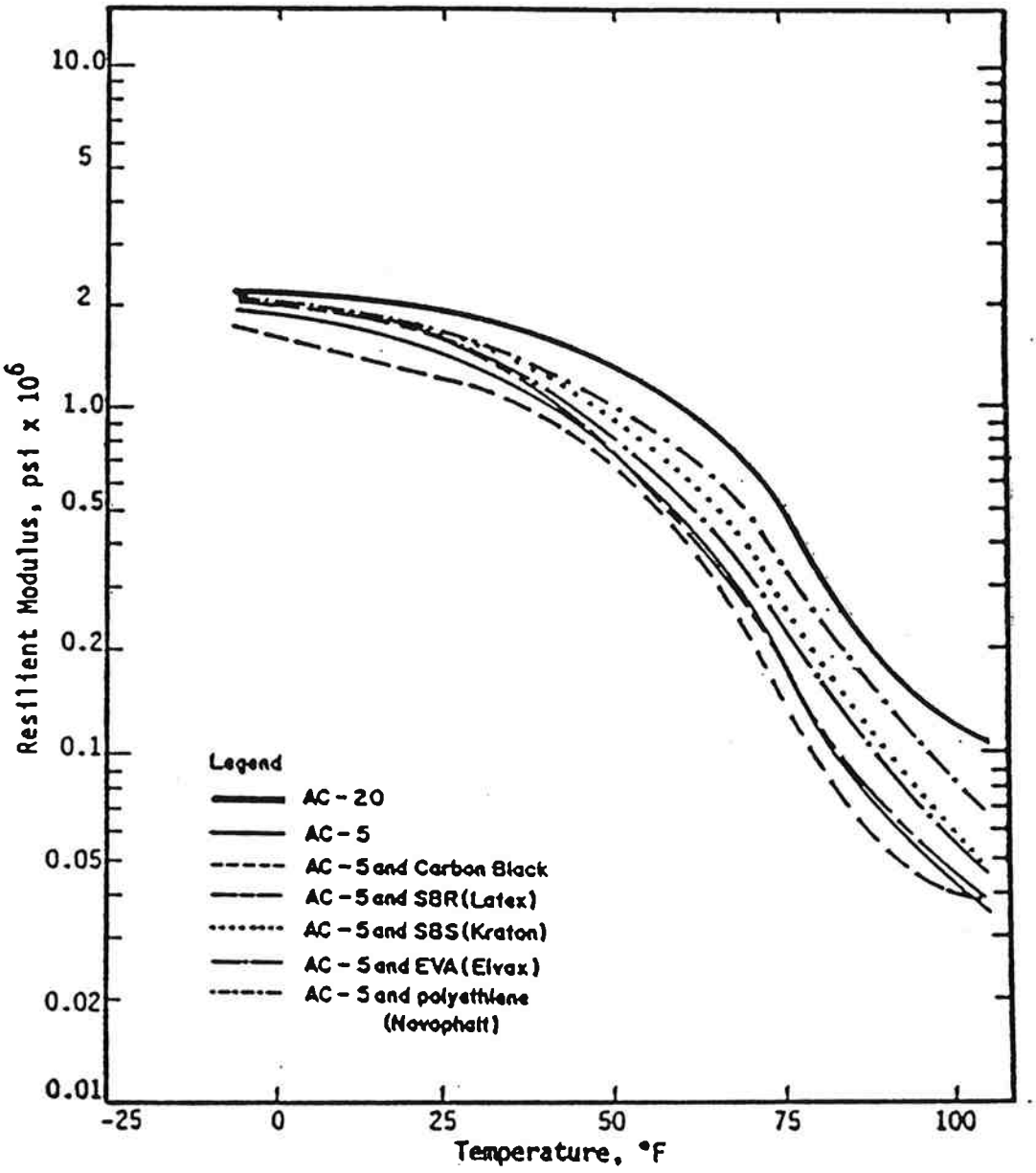


Figure 3.3. Resilient Modulus to Evaluate Temperature Susceptibility (after Button and Little)

temperature performance of conventional and polymer modified binders. They indicate that resilient modulus values for all mixes, conventional and modified, approached a "limiting value of about 2 million psi" at low temperatures. But O'Leary, King and King (1986) reported 17% lower complex moduli at -10°C and 10% higher modulus at 40°C for their tests of Styrelf.

Krater, Wolfe, and Epps also tested resilient modulus over a broad temperature spectrum, testing at -12.2°C, 1.11°C, 25°C, and 40°C. Low temperature testing generally showed a slight advantage for modified asphalts vs the control, with results of all mixtures within 10% of each other. High temperature testing showed a clear advantage to the polymer modified mixtures.

Carpenter and Van Dam (1987) tested at 4.44°C, 22.2°C, and 37.8°C, and extrapolated values for temperatures below 4.44°C. Lee and Demirel's (1987) results with resilient modulus are not conclusive. They did indicate that modulus values were more sensitive to moisture induced damage than indirect tensile strength values.

3.2.3 Fatigue Tests

Significant variations in test methods for fatigue strength are reported in the literature (Table 3.9), but it is generally agreed that fatigue strength is an essential property for successful pavement performance. The most commonly reported fatigue tests were flexural fatigue tests utilizing beam-type test specimens. Button and Little (1988) and Puzinauskas and Harrigan (1987) used 3 in. x 3 in. x 15 in. specimens. Goodrich (1988) used 1.5 in. x 1.5 in. x 15 in. specimens, and King Muncy and Prudhomme (1986) used trapezoidal beam specimens 56 mm x 25 mm at the base, 25 mm x 25 mm at the top, and with height of 250 mm.

Button and Little (1988) reported on the use of an "overlay tester," which simulates the loading condition in an overlay over an existing crack. Salter and Rafati-Afshar (1987) used the indirect tensile test apparatus to test specimens to fatigue failure. Fatigue test temperatures of 0°C, 4.44°C, 10°C, 18.3°C, 20°C, 22.2°C, and 25°C were reported.

Lee and Demirel (1987) did not perform fatigue testing, but instead estimated fatigue strength based on the Shell France method (function of mix stiffness, penetration index, and percent by volume of binder), Brown Method (function of softening point and volume percent of bitumen), and the Maupin

Table 3.9. Fatigue Testing Employed by Researchers

	Flex Beam Tests		Trapezoidal Beam	Ovely Test	Indirect Tensile Test	Inference (Shell France)	Inference (Brown)	Inference (Maupin)
	1.5x1.5x15 in.	3x3x15 in.						
Button & Little (TTI)		controlled stress 0°C, 20°C		25°C				
Goodrich (Chevron Research)	controlled stress 25°C							
Shuler (NMERI)								
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)								X
Salter & Rafati-Ashar (U. of Bradford)					22.8°C			
Lee and Demirel (Iowa State U.)						X	X	X
O'Leary, King, & King (ELF Aquitaine Asphalt)								
King, Muncy, & Prudhomme (ELF Aquitaine)			10°C					
Brule, Brion, & Tanguay (French Central Public Works)								
Krivohlavek								
Fleckenstein & Allen								
Collins (Shell Development Co.)								
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)		4.4°C, 18.3°C, 29.4°C						
Krater, Wolfe, & Epps (U. of Nevada-Reno)								
Chow (SRI International for DuPont)								

method (function of indirect tensile strength). Carpenter and Van Dam (1987) also used the Maupin method to estimate fatigue strength rather than performing fatigue tests.

3.2.4 Permanent Deformation Tests

Three types of permanent deformation testing were reported — uniaxial compression creep, diametral creep, and rutting resistance through wheel load simulation (Table 3.10). The most frequently reported test is the uniaxial compression creep test. Results for this test were reported at 4.44°C, 21.1°C, 22.2°C, 37.8°C, and 40°C.

King, Muncy, and Prudhomme (1986) reported on a method for testing rutting resistance developed by the French Highway Department Central Laboratory for Roads and Bridges (LCPC). This test utilizes a 40-cm wheel with a 50 kg (1124 lbs) load and a 6 bar (90 psi) tire pressure.

3.2.5 Tensile Strength Tests

The indirect tensile test, or split tension test, is another widely reported test (Table 3.11). Tests have been reported at temperatures of -28.9°C, -26.1°C, -17.8°C, -12.2°C, 2-17.8°C, .55°C, 4.44°C, 22.2°C, and 25°C. This test seems to show polymer additives favorably. However, Button and Little (1988) distinguish between results at high loading rates and low loading rates for low-temperature testing. They deduce potential for increased resistance to traffic-induced cracking because of good high loading rate performance, but no appreciable effect on thermally induced cracking due to no increase in tensile strength or strain at failure at low loading rates. Their conclusion is that "based solely on the results of these indirect tension tests, any increase in service life would be modest and cost effectiveness would be questionable."

The test was also used extensively to determine retained tensile strengths after conditioning for moisture susceptibility tests. As discussed previously, this test is also used to estimate fatigue strength.

3.2.6 Moisture Sensitivity

Three tests for moisture sensitivity were reported using modified asphalts (Table 3.12). These tests were the modified Lottman procedure, utilizing indirect tensile test results with and without the procedure to determine a

Table 3.10. Permanent Deformation Testing Employed by Researchers

	Uniaxial Comp. Creep 8 in.x4in. Cylinder Compression	Diametral Creep	Rutting Resistance W/Wheel*
Button & Little (TTI)	4.4°C, 21.1°C 37.8°C		
Goodrich (Chevron Research)	40°C		
Shuler (NMERI)			
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)	22.2°C, 37.8°C		
Salter & Rafati-Ashar (U. of Bradford)			
Lee & Demirel (Iowa State U.)	60°C		
O'Leary, King, & King (ELF Aquitaine Asphalt)			
King, Muncy, & Prudhomme (ELF Aquitaine)			60°C
Brule, Brion, & Tanguay (French Central Public Works)			
Krivohlavek			
Fleckenstein & Allen			
Collins (Shell Development Co.)			
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)			
Krater, Wolfe, & Epps (U. of Nevada-Reno)			
Chow (SRI International for Dupont)			

*40 cm wheel, 50 kg load, 90 psi tire pressure
specimen 16 cm x 14 cm x 100 cm

Table 3.11. Tensile Strength Testing by Researchers

Button & Little (TTI)	-26.1, .6, 25°C 0.02 in/min, 0.2 in/min, 2 in/min
Goodrich (Chevron Research)	
Shuler (NMERI)	
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)	2 in/min @ 22.2°C 0.05 in/min @ -28.9, -17.8, -6.7, 4.4°C
Salter & Rafati-Ashar (U. of Bradford)	
Lee & Demirel (Iowa State U.)	25°C 2 in/min
O'Leary, King, & King (ELF Aquitaine Asphalt)	
King, Muncy, & Prudhomme (ELF Aquitaine)	
Brule, Brion, & Tanguay (French Central Public Works)	
Krivohlavek	used for retained strength
Fleckenstein & Allen	
Collins (Shell Development Co.)	
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)	
Krater, Wolfe, & Epps (U. of Nevada-Reno)	-12.2°C, 25°C
Chow (SRI International for Dupont	

Table 3.12. Moisture Sensitivity Testing by Researchers

	Modified Lottman	24 hr Marshall Immersion	Immersion Compression
Button & Little (TTI)	X		
Goodrich (Chevron Research)			
Shuler (NMERI)			
Carpenter & Van Dam (U. of Illinois for Shell Development Co.)			
Salter & Rafati-Ashar (U. of Bradford)			
Lee & Demirel (Iowa State U.)	X	X	
O'Leary, King, & King (ELF Aquitaine Asphalt)		X	X
King, Muncy, & Prudhomme (ELF Aquitaine)	X		X
Brule, Brion, & Tanguay (French Central Public Works)			
Krivohlavek			X (modified)
Fleckenstein & Allen			
Collins (Shell Development Co.			X (modified)
Puzinauskas & Harrigan (Asphalt Institute for ELF Aquitaine)		X	
Krater, Wolfe, & Epps (U. of Nevada-Reno)	X		
Chow (SRI International for Dupont)			

tensile strength ratio; the "retained Marshall" method testing stability before and after 24-hr immersion in a 60°C bath; and immersion compression (ASTM 1075) with modifications, testing unconfined compressive strength before and after conditioning. These are the same tests as used for conventional hot mix samples.

The majority of researchers considered moisture sensitivity of such importance that some type of procedure was utilized. The methodology in all three procedures is generally the same. Specimens are tested for a strength property dry, voids are filled with water (by vacuum saturation if necessary), specimens are conditioned for a specified period of time at a specified temperature, specimens are tested again, and finally an index of retained strength is determined as a ratio of after conditioning value to before conditioning value.

Published results vary widely. Research funded by Styrelf (O'leary, King, and King 1986; King, Muncy, and Prudhomme 1986; Puzinauskas and Harrigan 1987) indicates improved retained strength values for modified asphalts. Krivohlavek (1988) indicated improvement for the modified asphalt over conventional asphalt. Krater, Wolfe, and Epps (1987) indicated that results for retained modulus were about the same with and without modifiers, but noted that the absolute values of modulus after conditioning were about 50% higher for the modified asphalt mixes. Lee and Demirel (1987) found improvement for some modifier-asphalt combinations, but not for others. Button and Little (1988) concluded that "generally, the additives have little effect on moisture susceptibility of the mixtures. . ."

3.2.7 Aging

Interestingly, the only report of procedures for aging of hot mix in the laboratory in the studies involving modified asphalts was made by Button and Little (1987). They reported that, "No standard procedure has been documented to simulate post-construction oxidative aging in the field. However, laboratory testing at Texas A&M has revealed that aging at 60°C substantially changes material properties such as resilient modulus and indirect tensile strength and, furthermore, that essentially all detectable changes in mixture properties occur within a 14-day period." For this reason, they aged some of their flexural fatigue beam specimens in accordance with the above described procedure, and compared fatigue results with and without aging.

The results are very interesting. SBS and EVA demonstrated severe decreases in fatigue response with aging. Aging effects on SBR and polyethylene were not as severe, but still significant. On the other hand, aging actually improved the fatigue response of AC-20 mixtures. This would appear to be an area where additional study is needed.

Button and Little's results indicate the potential importance of simulating mixture aging in the laboratory — particularly for modified asphalts. Because of this, and because of the virtual absence of published information on aging of modified asphalt mixtures, the literature search was expanded to explore other techniques for laboratory simulation of hot mix aging.

A study of "Effect of Moisture and Aging On Asphalt Pavement Life," reported by Kim, Bell, Wilson, and Boyle (1986) indicates promise for use of the Pressure Oxygen Bomb in simulating mixture aging. These researchers worked with a reduced pressure version of the European test. Samples were placed in a bomb and subjected to pure oxygen at 100 psi at a temperature of 60°C for 1 to 5 days. Tests of important mix properties were made before and after aging and compared with similar results of field cores utilizing the same design mixes. These researchers concluded that, "The POB should be considered as a suitable device to condition mixtures to represent field oxidative aging."

3.2.8 Other Mixture Tests

Microwave heating of pavement materials, particularly if modifiers are present, has indicated the possibility of improved mixture modulus and tensile strength, as well as improved stripping resistance (Terrel 1987). Microwave treatment of hot mix for short durations ("zapping") appears to allow migration or activation of polar compounds in the binder to the aggregate surface, improving the bond between aggregate and binder.

Terrel also discusses the potential effects of additives. "Additives can be used to alter the heating behavior of binders and mixtures in the presence of MW." "The effectiveness of chemical additives or modifiers can be enhanced or extended when the mixture is exposed to MW."

He also concludes that it is only a matter of time before microwave construction equipment is "in common use." Thus, it would appear that the evaluation of the true potential of an asphalt additive should be evaluated by

microwave "zapping." The combination of additive and microwave "zapping" may produce higher quality pavement than either treatment by itself.

King, Muncy, and Prudhomme (1986) report on the "Vialit Test" from Elf France. This test might be considered to test binder adhesive properties. However, its current use is confined to chip seal emulsions. A binder-chip mixture containing 100 chips is maintained at 100% humidity and room temperature for 20 minutes and subjected to the dropping of a 500 g ball. Numbers of chips retained and lost are determined and a value of adhesion is determined.

Carpenter and Van Dam (1987) reported on determining the coefficient of thermal expansion for modified hot mix samples. Cylindrical samples formed with the kneading compactor were used. They indicated that "these coefficients are typical of any dense-graded mixture and do not appear to be affected by the asphalt grade used or type of polymer treatment." It should be noted that only Kraton mixtures were studied.

3.3 Current and Proposed Polymer Modified Binder Specifications

The literature search uncovered several specifications which have been used or are proposed for use with polymer modified binders. Table 3.13 summarizes the binder test procedures utilized in these specifications. These specifications were supplied by the various material suppliers. The Kentucky specification was included in a paper by Fleckinstein and Allen (1987) reporting on the use of Kraton. The proposed New Mexico specification is based on input from both Styrelf and Chevron. MAC-30 and MAC-45 specifications have just been released by Chevron, and vary considerably from the Chevron CAP-1 and CAP-2 specifications.

The specification identified as ODOT AC-20R is the most widely used polymer modified binder specification. This specifications has been used by the FAA, the FHWA and several western states. The ODOT CAP-1 and CAP-2 tests utilize the same battery of tests as the AC-20R specification, with the addition of toughness and tenacity requirements for the aged binders. The proposed New Mexico specification, the Kentucky DOH specification, and the Styrelf specification make no attempt to measure tensile, ductile and resilient properties of the unaged binder, measuring these properties only with the aged binders. The majority of specifications require testing of ductilities at 4°C and 25°C even though researchers generally do not hold the test of conventional ductility in high

Table 3.13. Comparison of Tests Incorporated in Specifications for Polymer Modified Asphalt

	ODOT AC-20R (1988)	ODOT CAP-1 (1988)	ODOT CAP-2 (1988)	ODOT STYRELF (1988)	KY PAC (1987)	NM MAC (1988)	CHEVRON MAC 30/45 (1988)
Raw Binder							
Pen. (4C,200g,60s), dmm						range	range
Pen. (25C,100g,5s), dmm		min	min	min	range		
Abs. Vis. @ 60°C, poise	range	range	min	range	min	min	min
Vis. @ 135°C, cSt	min	min	min	min	min	range	range
R&B softening pt., degrees						min	
Flash pt., degrees	min	min	min	min	min		min
Sol. in trichloroethylene, %				min	min		
Ductility @ 25°C, cm	min	min	min				
Ductility @ 4°C, cm	min	min	min				
Toughness, in-lb	min	min	min				
Tenacity, in-lb	min	min	min				
RTFOT or TFOT Residues							
Pen. (4C,200g,60s), dmm						min	min
% orig. pen. (25C,100g,5s), dmm				min			
Abs. Vis. @ 60°C, poise	max	max	max		max		
Vis. ratio @ 60°C				max		max	max
Ductility @ 4°C, cm	min	min	min		min	min	
Ductility @ 25°C, cm	min	min	min		min		
Tens. Stress @ 20°C, psi				min			
Toughness, in-lb		min	min				
Tenacity, in-lb		min	min				
Elastic recovery @ 4°C, %				min	min		
Ball pen. resilience, % (ASTM D3407)					min		
Weight Loss, %						max	max

esteem. Only Kentucky DOH and the Styrelf specifications require testing of elastic recovery or resilience. Only Styrelf requires tensile strength testing of binder. None of the specifications require testing for force ductility maximum tensile strength, even though this test is highly regarded by researchers (Button and Little 1987; Shuler 1987). The most recent specifications, New Mexico MAC and Chevron MAC-30 and MAC-45 introduce the use of penetration at 4°C, 200 g, and 60 seconds. The inclusion in specifications of this penetration test is based on research by Goodrich (1988) indicating high correlation of this test with important mix properties. The MAC-30 and MAC-45 specifications are the only specifications which do not include some type of ductility or tensile test. It is expected that the MAC-30 and MAC-45 specifications will allow competition between AC-20R, EVA, Kraton, and Styrelf modified binders, as well as others.

Review of the literature and of the current polymer modified asphalt specifications indicates that penetrations and/or viscosities have generally been specified. Some measure of consistency is clearly needed. Various binder properties have been specified for aged and/or unaged binders. Aged properties should be of most interest, since it is aged binder that must perform in the pavement. Although elastic recovery testing and conventional ductilities have been included in specifications, there is little evidence to demonstrate their relevance.

3.4 Test Methods Proposed for Further Study

The objectives for polymer modification of asphalt for hot mix are to improve the pavement life through reduction of load induced and environment induced failures. For reduction of load-induced failures, consideration of mix modulus, tensile strength, fatigue strength, and creep resistance are required. There is no reason that the tests used on conventional hot mix will not be appropriate here. The ability to run modulus, indirect tensile tests, fatigue and permanent deformation utilizing the same equipment makes the diametral mode of testing very attractive.

Ideally, binder tests could be identified which would predict modified binder effect on modified mixture performance in these important test situations. Goodrich (1988) and others (Krivohlavek, 1988; Chow, 1987) cite dynamic shear analysis as a very promising binder test because of its reliance on fundamental rheological properties. Currently this is an expensive test to run — one not

readily available to highway agencies. If simpler tests can prove to be good predictors of pavement performance, this would be highly desirable.

King, Muncy, and Prudhomme (1986) state that such tests are available in the form of force ductility, toughness and tenacity, tensile strength test similar to ASTM D 412, and dropping ball test. Of these, dropping ball has seldom been reported and appears to have little to argue for it over other methods. Tensile strength test similar to ASTM D412 appears promising, but is not as well known among pavement researchers as other tests. O'Leary, King, and King (1986) indicate that the curves produced by this test and force ductility are "virtually identical." Therefore, the tensile test has little to argue for it over the more widely known force ductility test.

Chow (1987) advocates toughness/tenacity and is critical of "ductility at 4C," stating that it "does not seem to correlate with any other quantities at all." But O'Leary, King, and King state that the toughness and tenacity test lacks repeatability, and is not as reliable as force ductility or the tensile test.

Obviously, the choice of tests is not clear. All things considered, force ductility seems to be developing the most acceptance of these tests of tensile, ductile, and resilient properties.

For evaluation of potential for temperature induced failures, some measures of temperature susceptibility of the mix and of the binder are required. For the mix, the approach of Button and Little (1987) and Krater, Wolfe, and Epps (1987) seems most appropriate. This approach tests dynamic resilient modulus over a wide range of temperatures — from subfreezing temperatures to temperatures in excess of 37.8°C. This evaluation of stiffness provides a good indication of flexibility at low temperatures, and ability to resist wheel loads at higher temperatures.

For temperature susceptibility of the binder, an analogous procedure is dynamic shear analysis over a range of temperatures. Long term, this approach would seem to hold the most promise. To utilize simpler tests, plots of BTDC utilizing data from penetration, viscosity, softening point, and Fraass point tests may be made to evaluate temperature susceptibility. Computation of PI (Penetration Index) and PVN (Penetration Viscosity Number) are alternate methods of evaluating temperature susceptibility. There is some question regarding the validity of conventional viscosity values for polymers, but at least for

evaluation of temperature susceptibility over in-service temperatures, conventional methods appear to be acceptable.

For evaluation of durability over time, moisture susceptibility and oxidative aging must be considered. Moisture susceptibility testing is discussed first.

Testing for tensile strength and modulus before and after the modified Lottman procedure has gained the greatest acceptance for evaluating stripping potential. This procedure is appropriate for mixes utilizing polymer modified binders.

Durability during long-term exposure to heat and oxygen is another important consideration. For both mix and binder testing, the Pressure Oxygen Bomb (Kim, Bell, Wilson, and Boyle, 1986) appears to offer great promise. The Texas A&M 14-day, 60°C treatment (Button and Little, 1987) for mixtures appears to be simpler and equally promising.

Historically, degradation during exposure to ultraviolet radiation has been a problem for polymers exposed to sunlight over long periods of time. Although this has not been shown to be a concern for polymer modified asphalts, "tanning booth" testing similar to that discussed by Krivohlavek (1988) would seem to be an appropriate means for making an evaluation.

A very exciting possibility for improved durability of hot mix pavement properties is the use of microwave "zapping" (Terrel 1988), with or without polymer modifiers, to improve pavement properties — particularly antistripping properties. Since this procedure is so promising, the behavior under microwave treatment of mixes utilizing various polymer modifiers should be investigated. Simply testing modulus, tensile strength, fatigue strength, and deformation resistance before and after microwave conditioning should provide useful information. Testing after Lottman conditioning will address the stripping question.

Table 3.14 summarizes this discussion of test methods proposed for further study. Binder and mixture tests are classified as load resistance tests, temperature susceptibility tests, and durability tests. Distinctions between ideal and practical tests are also made.

After considering all of the factors just discussed, a preliminary laboratory testing program utilizing the tests listed in Table 3.14 was formulated. This testing program and the results obtained are discussed further in Chapter 4.

Table 3.14. Tests Recommended for Further Study

Binder Tests

I. Load resistance
   A. Force ductility
   B. Toughness and tenacity
   C. Dynamic mechanical analysis (for basic understanding and future use)

II. Temperature susceptibility
   A. Conventional viscosities (275°F and 140°F)
   B. Penetrations (77°F and 39.2°F)
   C. Fraass point

III. Durability
   A. TFOT (or RTFOT if equipment is available) to simulate mix preparation effects
   B. Pressure oxygen bomb with Fraass specimens to simulate long-term effects

Mixture Tests

I. Load resistance
   A. Wheel loads
      1) Diametral fatigue and permanent deformation over temperature range
      2) Uniaxial compression creep at 104°F
      3) Diametral resilient modulus at different temperatures
      4) Indirect tensile test at 77°F and 2 in./min. strain rate
   B. Thermal loading
      1) Indirect tensile test at 14°F and 32°F and 0.05 in./min. strain rate

II. Temperature susceptibility
   A. Diametral resilient modulus over temperature range

III. Durability
   A. Moisture and susceptibility
      1) Indirect tensile strength before and after modified Lottman conditioning
   B. Heat/oxygen stability
      1) Indirect tensile test before and after pressure oxygen bomb
      2) Indirect tensile test before and after maintaining specimens at 140°F for 14 days (Texas A&M method)

4.0 PRELIMINARY TESTING

4.1 Objectives

The preliminary testing program was intended to provide a broad base of test results from which promising procedures could be further investigated in the final testing program. The literature review provided some clues as to which tests might be helpful in evaluating the performance of polymer modified asphalts as indicated in the previous section. This testing program had a broad scope and many test procedures were explored. An outline of the testing program can be found in Figures 4.1 and 4.2.

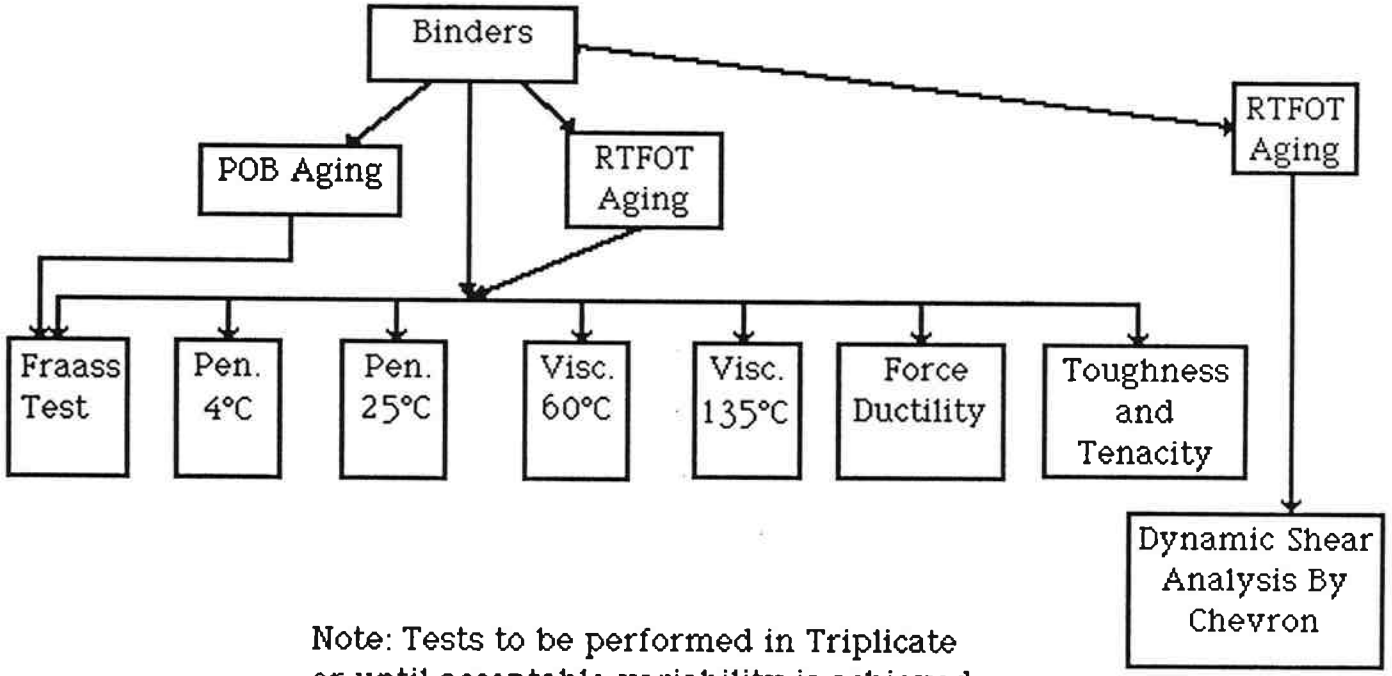
4.2 Methodology

The preliminary testing investigated five different asphalt binder types. The asphalts were blended with polymer additives to resemble an AC20 with respect to viscosity measurements. One asphalt was unmodified while the other four were modified with either an EVA, SBS, SB, or SBR additive. The asphalts were arbitrarily assigned names A1 through E1 for each additive type (see Table 4.1).

Table 4.1. Additive Summary

Code	Additive
A1	None
B1	EVA
C1	SBS
D1	SBR
E1	SB

In order to reduce the number of variables in the test results, the asphalt mix design and sample preparation were done by the Oregon Department of Transportation (ODOT). By having the samples mass-produced in this manner by professionals, uniform samples were attained.



Note: Tests to be performed in Triplicate or until acceptable variability is achieved

Figure 4.1. Binder Specimen Flow Chart

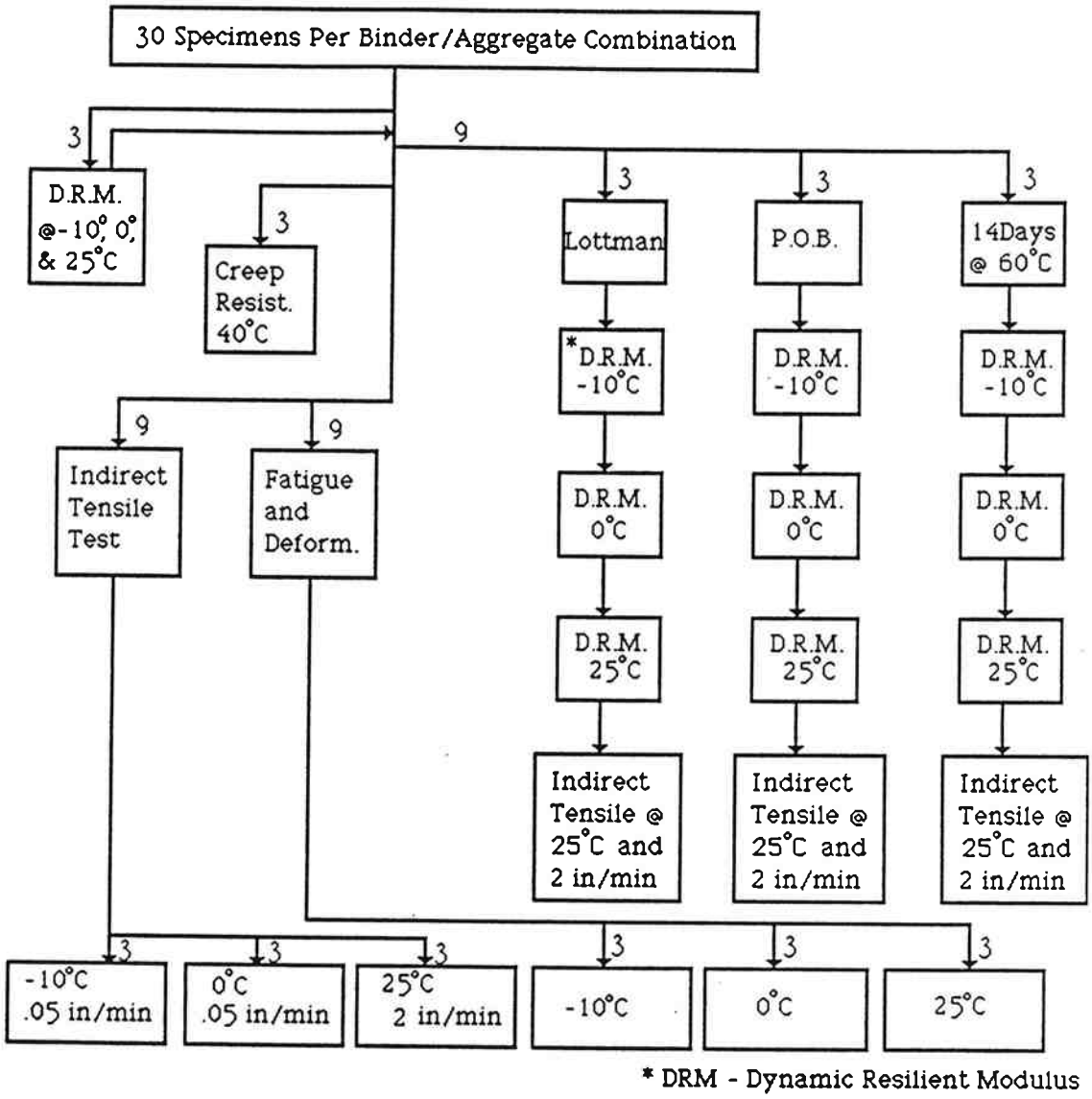


Figure 4.2. Mixture Specimen Flow Chart

ODOT also performed some of the testing of binder properties. They aged the asphalt in a Rolling Thin Film Oven (RTFO) and performed all kinematic viscosity, absolute viscosity, and force ductility testing. Chevron Research, USA, was kind enough to run a dynamic shear test on the five binders used in the preliminary testing.

The remainder of the test program was accomplished in the OSU asphalt lab. These tests included:

1) Binder Tests: Penetration at 4°C (60 sec) and 25°C (5 sec)
   Toughness and Tenacity at 25°C
   Fraass Brittle Point
2) Mixture Tests: Modulus at 25°C, 0°C, and -10°C
   Split Tensile at 25°C at 2in/min, 0°C and -10°C at .05 in/min
   Diametral Fatigue at 25°C and 0°C

The mixtures were also subjected to various conditioning procedures such as Lottman moisture conditioning, Pressure Oxygen Bomb (POB) aging, and aging 14 days at 60°C in a forced draft oven. Descriptions of these aging procedures can be found in Appendix A. The results of the testing of these conditioned specimens can be found in Section 4.3.3. For more information about the flow of test specimens, see Figures 4.1 and 4.2.

Tests for penetration, viscosity and low temperature brittle point (Fraass point) are parameters that help identify the temperature susceptibility of an asphalt and were deemed important properties that should be included in this testing program. Force ductility, toughness and tenacity, and dynamic mechanical analysis are tests that provide information about load resistance and were included for that reason.

Resilient modulus is a generally accepted measure of mixture stiffness and can also give insights into the temperature susceptibility of an asphalt mixture if tested at different temperatures. For these reasons and the fact that it is a non-destructive test, it was included in the test program at three different temperatures.

Indirect tensile strength is used to predict both mixture stiffness and fatigue properties. The test can be run at various temperatures and strain rates. This project included testing at 25°C and a standard loading rate of 2 in./min to determine tensile strength at ambient temperatures. Testing at cold

temperatures and slow loading rates (.05 in./min) was included to evaluate thermal cracking potential.

Fatigue testing was included in the test schedule to provide a direct way of measuring an asphalt's ability to resist repeated loading. Permanent deformation data were collected during the fatigue testing to evaluate the mixture's ability to resist rutting. Static, uniaxial creep was also included in the testing program to further investigate rutting potential in the asphalt mixtures.

4.3 Test Results

4.3.1 Binder Properties

4.3.1.1 Penetration. This test was performed according to the ASTM D5 procedure at both 25°C and 4°C on all asphalt samples. Test results are presented in Table 4.2.

Penetration Index (PI) and Penetration Viscosity Number (PVN) were calculated to evaluate the temperature susceptibility of the binders. PI was first proposed by Pfeiffer and Van Doormaal and is calculated by means of the following equation:

$$PI = \frac{30}{1 + 90\ (PTS)} - 10 \qquad \text{Eq. (4.1)}$$

where

$$PTS = \text{Penetration - Temp. - Susceptibility} = \frac{\log 800 - \log Pen_{77}}{T_{R\&B} - T_{pen_{77}}}$$

Pen_{77} = penetration at 77°F (25°C)
$T_{R\&B}$ = softening point
$T_{Pen_{77}}$ = 77°F

Table 4.2. Penetration Results

	A1	B1	C1	D1	E1
Original Binder					
PEN @ 25°C (dmm)	75	77	122	91	95
PEN @ 4°C (dmm)	20	22	39	27	36
PI	-1.6	-0.72	4.85	-0.46	0.56
PVN	-0.92	0.11	0.91	0.56	0.24
RTFO Residues					
PEN @ 25°C (dmm)	36	36	74	46	55
PEN @ 4°C (dmm)	11	15	30	18	30
PI	-1.41	-1.19	6.48	-0.002	0.43
PVN	-1.08	-0.1	0.52	0.35	0.006

From this relationship it is apparent that an increase in the PI number indicates a decrease in temperature susceptibility of a material.

PVN is another means of evaluating the temperature susceptibility. It is defined by the following equation:

$$PVN = \frac{4.258 - .7967\ (\log P) - \log V}{.7591 - .1858\ (\log P)} \cdot (-1.5) \qquad \text{Eq. (4.2)}$$

where

P = penetration at 77°F (25°C)
V = kinematic viscosity (at 135°C)

Again, a high value of PVN would indicate a material that has a low temperature susceptibility.

Temperature susceptibility of the modified binders was significantly lower than the conventional binder when comparing the penetration index (PI) or the penetration viscosity number (PVN). These two measurements, however, are somewhat questionable when used for polymer modified asphalts. Penetration Index has limited validity because the penetration at the softening point of modified asphalts may not be 800, as assumed. A measurement of penetration at two

temperatures would be a more reliable way of measuring PI (Shuler, 1988). PVN also has limited validity when applied to polymer modified asphalts because the procedure assumes linearity for temperature susceptibility between 25°C (pen) and 135°C (kinematic viscosity). For some of the modified binders tested temperature susceptibility was clearly curvilinear and as a result, PVN results may be misleading. PVN evaluated at 25°C and 60°C may provide a better estimate of temperature susceptibility, but caution must still be exercised (Shuler, 1988).

4.3.1.2 Viscosity. Both kinematic and absolute viscosities were measured by ODOT according to ASTM D2170 and D2171 following their normal laboratory procedures. There is some discussion as to the validity of a Cannon Manning tube viscosity measurement, as was used here, for the measurement of polymer modified asphalt viscosities. As discussed in Section 3.1.1, this is because of "shear thinning." Some polymer additives produce erroneous values of viscosity using this type of tube and it has been suggested that other types of viscosity measurement be conducted. It is likely that a straight walled tube would produce more consistent results than a Cannon Manning tube. A summary of the viscosity values can be found in Table 4.3. It is obvious that the viscosity of C1, measured by the Cannon Manning tube, is well out of the acceptable range for AC-20 grade asphalts.

Table 4.3. Viscosity Data

	A1	B1	C1	D1	E1
Original Binder					
Visc @ 60°C (poise)	1390	1730	15900	2300	2830
Visc @ 135°C (cst)	326	610	661	700	557
RTFO Residue					
Visc @ 60°C (poise)	3850	4140	62900	6830	7080
Visc @ 135°C (cst)	478	967	815	1090	747

4.3.1.3 Toughness and Tenacity. This test was performed according to the procedure outlined in Appendix A. The total area under the force-extension curve was calculated and reported as Toughness. The declining side of the curve was extended to the horizontal axis in a straight line and the area to the right of

this line was reported as Tenacity. Although not defined in the literature, the difference between the toughness and tenacity was found to be a significant property. This is called "Peak Area" and is shown as area A in Figure 4.3.

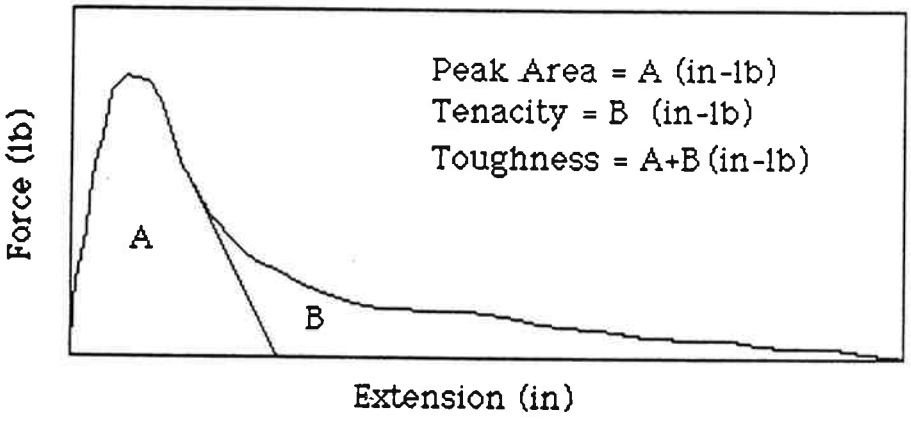


Figure 4.3. Typical Toughness and Tenacity Curve

Each of the five asphalts were tested in triplicate and the averaged values are shown in Table 4.4.

The asphalt with an SBS modifier (C1) was the only one of the five asphalts tested that had a significant secondary peak. All of the other binders, including the conventional binder, had curves with one primary peak and no other

Table 4.4. Toughness and Tenacity Data

	A1	B1	C1	D1	E1
Original Binder					
Toughness (in-lbs)	221.5	276.8	112.7	290.3	148.3
Tenacity (in-lb)	165.1	244.2	96.1	257.7	118.8
Peak Area (in-lb)	56.5	32.6	16.5	32.6	29.4
RTFO Residues					
Toughness (in-lb)	204.3	278.2	119.3	149.1	106.2
Tenacity (in-lb)	135.2	180.1	93.1	75.7	77.5
Peak Area (in-lb)	69.1	98.1	26.2	73.9	28.7

increase in load before failure. The shapes of these curves were similar to the force ductility curves with respect to primary and secondary peaks.

4.3.1.4 Force Ductility. This non-standard test was performed by ODOT according to the procedure outlined in Appendix A. Although the test is normally run at 4°C, for this testing program it was run at both 4°C and 25°C to compare results with Toughness and Tenacity testing. It was more convenient to conduct both tests at 25°C rather than at 4°C due to temperature control limitations. The raw data was collected on an XY plotter and reduced by graphical means. An example of the force vs. extension force ductility curve in presented in Figure 4.4. Most asphalts develop one primary peak and have the load continue to decrease to failure. Some of the modified asphalts had a secondary peak. That is, after the primary peak the load decreased for a period of time and then began to increase again before failure. Refer to Shuler, 1985, for more information.

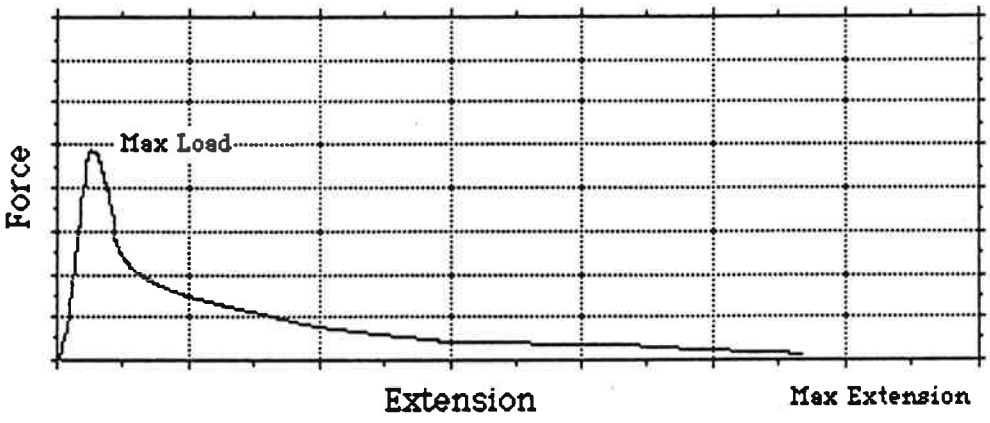


Figure 4.4. Typical Force Ductility Curve

The maximum load was converted to maximum engineering stress by dividing the load by the original cross-sectional area. For the force ductility test this area is one cm^2 or .15 in^2.

$$\text{Engineering Stress} = \sigma = \frac{P_{max}}{A_o} \qquad \text{Eq. (4.3)}$$

Maximum true stress was also calculated by the use of a modified cross-sectional area given by (Dekker):

$$A = \frac{L_o}{L} A_o \qquad \text{Eq. (4.3)}$$

where

A = Modified Cross sectional Area
A_o = Original Cross sectional Area
L = Length at Failure
L_o = Original Length

Maximum strain was calculated by dividing the length at failure of the specimen by the original length (3 cm). Area under the curve was also calculated by integrating the force vs. extension curve. This was then converted to an area under the stress strain curve and these are the values reported in Table 4.5.

All of the above mentioned properties have been suggested as being important properties for evaluating an asphalt's performance. For the sake of comparison with toughness and tenacity data, areas analogous to "tenacity" and "peak area" were also computed. Total area is the same as "toughness." All of these values for the preliminary testing are presented in Table 4.5.

4.3.1.5 Dynamic Shear Analysis. A description of this test can be found in Appendix A along with a sample of the graphical output of the results. The analysis was performed on only RTFO residues.

4.3.1.6 The Fraass Test. This test measures the cold temperature flexibility of an asphalt. The procedure is outlined in Appendix A and the results are presented in Table 4.6. As would be expected, the unmodified A1 had the highest Fraass point of all of the binders. Since all of the polymer modified asphalts had lower Fraass points it would imply that the modified asphalts are more flexible at cold temperatures since, by definition, the lower the Fraass point, the more flexible the binder.

Table 4.5. Force Ductility Data

	A1	B1	C1	D1	E1
Original Binder					
Total Area @ 4°C (psi)	276.4	683.6	1004.8	258.2	511.3
Peak Area @ 4°C (psi)	204.6	164.5	75.9	120.5	65.5
FDTenacity @ 4°C (psi)	71.8	519.1	928.9	137.7	445.8
Engr Stress @ 4°C (psi)	121.3	71.0	49.9	57.6	44.1
True Stress @ 4°C (psi)	1451	1036	1779	1581	1959
Max Strain 4°C (in/in)	10.8	14.3	34.6	26.4	43.6
Curve Area @ 25°C (psi)	4.4*	3.4*	29.1*	7.4*	12.5*
Engr Stress @ 25°C (psi)	0.92	0.45	1.18	0.61	0.69
True Stress @ 25°C (psi)	46.3	21.4	38.8	28.4	32.3
Max Strain 25°C (in/in)	46.6*	46.6*	30.8	46.6*	46.6*
RTFO Residues					
Total Area @ 4°C (psi)	**	926.1	1222	807.5	469.9
Peak Area @ 4°C (psi)	–	293.7	126.5	210.1	116.6
FDTenacity @ 4°C (psi)	–	632.4	1095.5	597.4	353.3
Engr Stress @ 4°C (psi)	**	126.7	67.7	101.5	67.7
True Stress @ 4°C (psi)	**	1345	2024	1845	1240
Max Strain 4°C (in/in)	0.5	9.8	28.7	17.2	17.0
Curve Area @ 25°C (psi)	10.3*	10.1*	121.9	24.5*	29.3*
Engr Stress @ 25°C (psi)	1.14	1.81	6.0	1.83	1.66
True Stress @ 25°C (psi)	53.7	85.2	200.8	85.8	77.8
Max Strain 25°C (in/in)	46.6*	46.6*	32.7	46.6*	46.6*

*Indicates that extension exceeded machine's capacity

**Indicates brittle failure – missing data

Table 4.6. Fraass Point Data

	A1	B1	C1	D1	E1
Original Binder					
Fraass point (°C)	-2.9	-6.8	-23.4	-15.8	-18.6
RTFO Residues					
Fraass point(°C)	-9.4	-12	-12.2	-14.3	-19
POB Fraass point (°C)	-0.51	-1.7	-12.3	-14.7	-9.2

It should be noted that the procedure used here is very operator dependent. While the operator is monitoring temperature and pouring solid carbon dioxide into the acetone bath, he is also watching, listening, and feeling for a crack to develop on the plaque. With some of these asphalts, the crack was easily detected by a loud snap, but the more flexible asphalts such as the C1 and the D1 developed hairline cracks very quietly and were hard to detect.

The original asphalt and the RTFO residues were tested first. Then a set of RTFO residues were treated in the POB for five days and tested. These results are referred to as POB Fraass point in Table 4.6.

4.3.2 Mixture Tests

4.3.2.1 Dynamic Resilient Modulus. The asphalt specimens were all standard Marshall test specimens 2.5 in. high with a diameter of 4 in., and were compacted with a California Kneading Compactor. The mixture contained aggregate from the Farewell Bend ODOT construction project in eastern Oregon coated with 1% lime. The asphalt content was 5% and the gradation was a "C" mix. The breakdown of the percent passing sieve sizes can be found in Appendix C.

Three unaged specimens and three conditioned specimens from each conditioning process were tested for modulus at 25°C, 0°C, and -10°C, to determine temperature susceptibility of the mixtures. An ideal mixture would be stiff at high temperatures and flexible at low temperatures. The test procedure is outlined in Appendix B and results for the unconditioned mixtures are presented in Table 4.7. The results of the conditioned specimens are presented in Section

Table 4.7 - Dynamic Resilient Modulus Data (KSI)

	A1	B1	C1	D1	E1
Original					
Modulus @ 25°C	195	220	162	191	136
Modulus @ 0°C	2904	2876	2098	2060	1515
Modulus @ -10C	4560	4518	3570	3236	3849

4.3.3, Table 4.11. The values reported in these tables are the average of three specimens that were tested on two axes.

The modulus values for all five unaged asphalts increased dramatically with decreasing temperature as would be expected. The plots of the moduli vs. temperature can be found in Figure 4.5. The A1 and B1 plots are virtually on top of one another and show the greatest temperature susceptibility. C1 and D1 show the least temperature susceptibility over the -10°C to 25°C range.

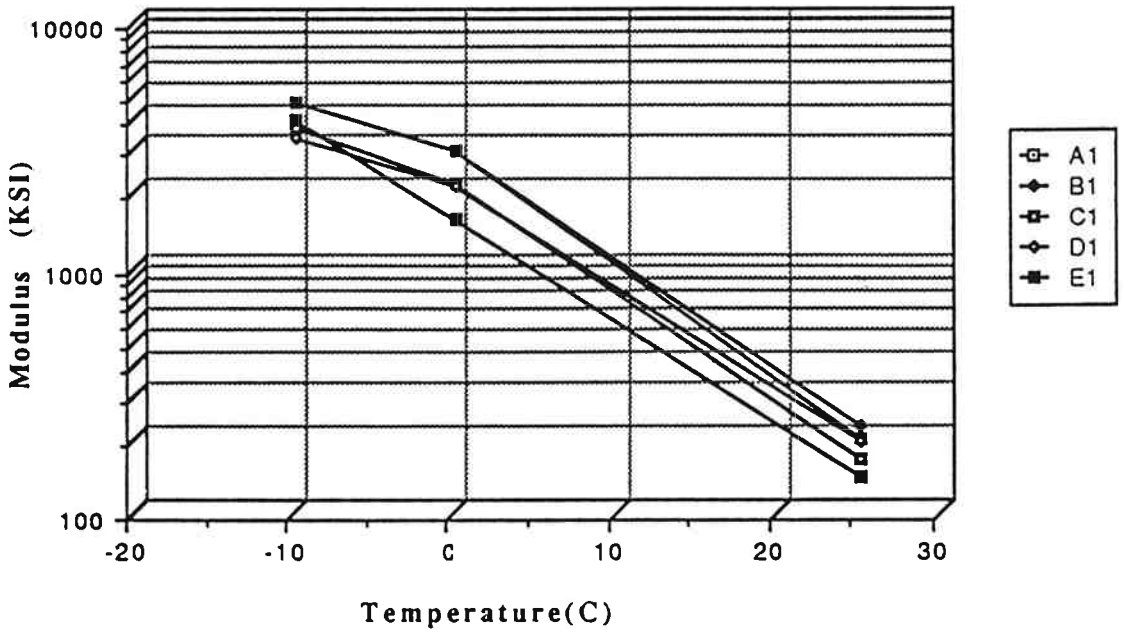
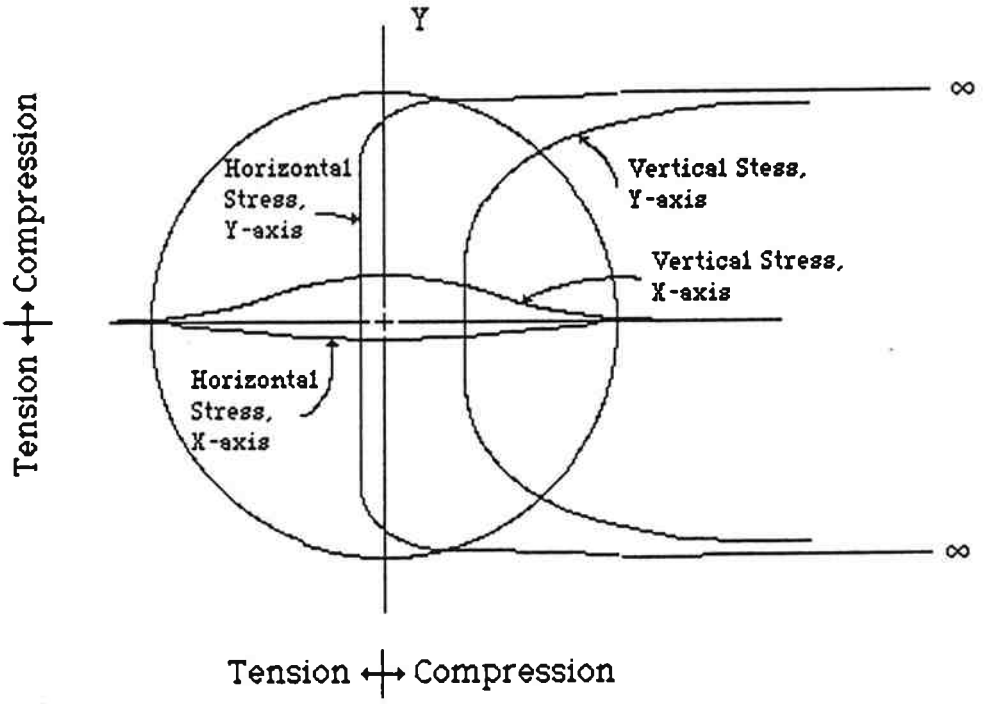


Figure 4.5. Modulus Variation with Temperature

4.3.2.2 Indirect Tensile Test. The same specimens that were used for modulus testing were finally broken in this test. Three specimens of each binder and each conditioned group were loaded diametrally at 25°C and at a rate of 2 in/min. Three more unaged specimens of each binder were loaded at 0°C and .05 in/min. A final group of unaged specimens were tested at -10°C and .05 in/min. Each test was recorded on an XY plotter with pounds vs. extension on the axis. The peak loading was converted to stress by applying Equation (4.5) which is based on the stress distribution shown in Figure 4.6. Note from the stress distribution that a fairly uniform tensile stress is developed along the y-axis. This is the mode of failure for this test.



$$\text{Tensile Strength} = S_t = \frac{2P_{max}}{\pi t d} \qquad \text{(Eq. 4.5)}$$

P_{max} = maximum load
t = specimen thickness
d = specimen diameter

Figure 4.6. Stress Distribution of Indirect Tensile Test (after Yoder and Witzack, 1975)

Strain at failure for this test is of interest. Since it was not practical to measure or compute tensile strain with the laboratory equipment available, compressive strain was computed instead. Compressive strain at failure is the total diametral strain in the specimen at the maximum load in the direction of the load. This was attained using Equation (4.5) with a specimen thickness of 2.5 in. and a diameter of 4 in. (Kennedy, 1977).

$$\text{Compressive Strain} = e_c = Y_t(.1485) \qquad \text{(Eq. 4.6)}$$

where

Y_t = deformation in Y direction

This procedure is outlined in Appendix B and the results for the unconditioned specimens are presented in Table 4.8. The conditioned specimen results are presented in Section 4.3.3.

Table 4.8 – Indirect Tensile Test Data

	A1	B1	C1	D1	E1
Unconditioned Mix					
Ind. Tens @ 25°C (psi)	107	169	84	134	107
Ind. Tens @ 0°C (psi)	106	116	71	70	73
Ind. Tens @ -10°C (psi)	189	226	135	176	123
Work to Fail @ 25 (ft-lb)	10.5	13.4	6.5	11.9	9.2
Work to Fail @ 0 (ft-lb)	6.2	7.3	4.4	5.3	5.0
Work to Fail -10 (ft-lb)	7.1	8.1	7.9	9.3	6.9
Comp. Strain @ 25°C (%)	1.63	1.63	1.63	1.78	1.78
Comp. Strain @ 0°C (%)	1.34	1.34	1.34	1.63	1.49
Comp. Strain @ -10°C (%)	1.04	1.19	1.63	1.34	1.34

Work to failure was also calculated by integrating the area under the force vs. extension curve to the left of the maximum load. Work to failure at low temperatures should give an indication of the mixture's ability to deform without cracking under induced tensile stresses.

4.3.2.3 Fatigue Life. Although beam fatigue is used by many researchers to determine the fatigue life of asphalt concrete, this study chose to use diametral fatigue to determine this parameter. Since the diametral fatigue uses the same specimens that are used in resilient modulus and indirect tensile testing, the time spent fabricating new specimens is saved and a more direct comparison of these three properties is possible.

Fatigue life for the diametral fatigue test was defined by a set amount of horizontal deformation. The specimens were wrapped with foil tape and a loop of 7/64 in. was placed on each side to allow the same amount of deformation for all specimens before the tape was broken. When the tape broke, the machine was shut down and the fatigue life was recorded at that point.

Three specimens of each binder were tested at 25°C with an initial strain of 200 $\mu\epsilon$. The specimens tested at 25°C employed a pneumatic loading system in a temperature control cabinet with a simple loading frame and a Bellefram piston. This type of system, since it uses air as the driving force, has a cushioning effect on the load waveform (see Figure 4.7).

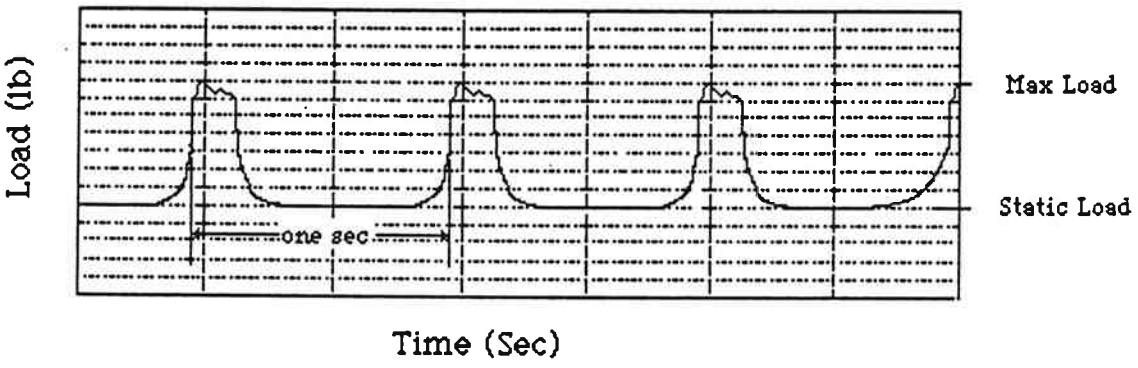


Figure 4.7. Pneumatic Load Waveform

The specimens that were tested at 0°C were tested in an MTS machine since the pneumatic system could not generate enough load to produce an initial strain of 200 $\mu\epsilon$ at low temperatures. This machine is a hydraulic system capable of producing very large loads and a variety of waveforms. A square wave was first attempted to simulate the pneumatic system, but since the liquid used in the hydraulic system is not compressible, the machine was impacting the specimens to a high degree. This was determined to be unacceptable so a haversine wave

was used instead (see Figure 4.8). Temperature control was maintained for a small area around the specimens using an insulated cabinet and injecting liquid nitrogen as needed.

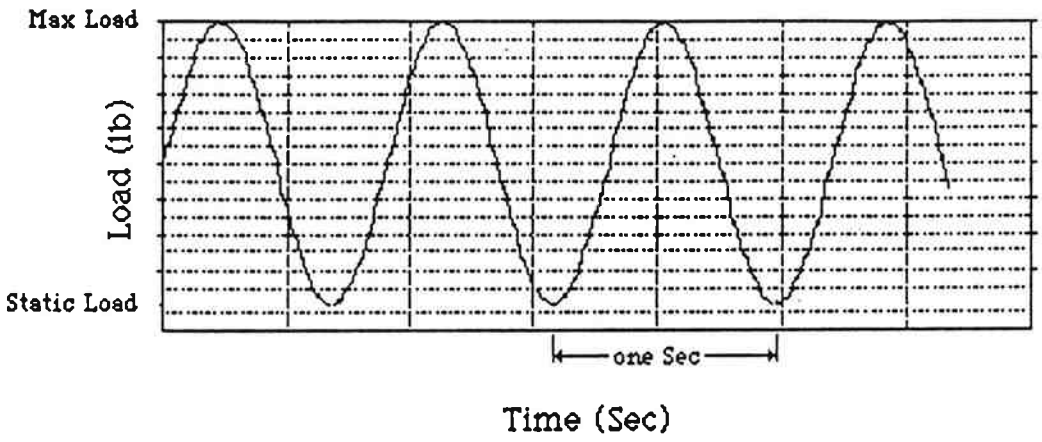


Figure 4.8. Haversine Waveform

Permanent deformation was measured by the use of an LVDT attached to the actuator which was connected to a computer. Every 100 seconds the computer shut down the system, took ten readings from the LVDT, averaged them, and stored the average on disk. The series of voltages for each specimen were converted to strain and plotted against repetitions (see Figure 4.9).

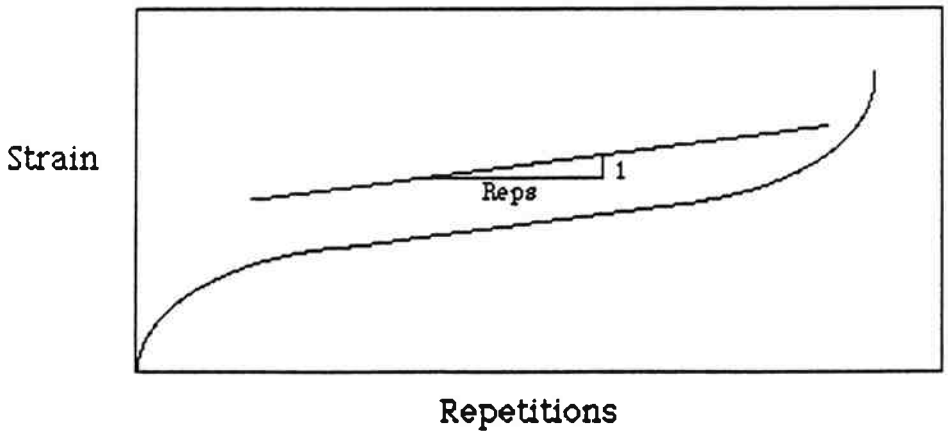


Figure 4.9. Typical Permanent Deformation Curve

As is characteristic of asphalt concrete, the first few repetitions applied to the specimen produce a high amount of strain until the initial consolidation occurs. Once the specimen has been conditioned, a fairly constant amount of strain per repetition is seen until the specimen begins to fail at which point high strains per repetition are again seen. The slope of this middle segment is constant and is what was used for comparison between the five asphalts. The steeper the slope, the greater the rate of permanent compressive deformation. As shown in Figure 4.10, the ranking of asphalt mixtures is quite apparent with asphalt C1 having the most rapid rate of deformation and asphalt E1 having the least rapid rate. Permanent deformation was not available for the conventional asphalt (A1) for this testing segment. The fatigue life, however, was measured and was the second shortest of the five. This would place it between D1 and C1 in Figure 4.10. The slopes of each permanent deformation curve and fatigue values are shown in Table 4.9.

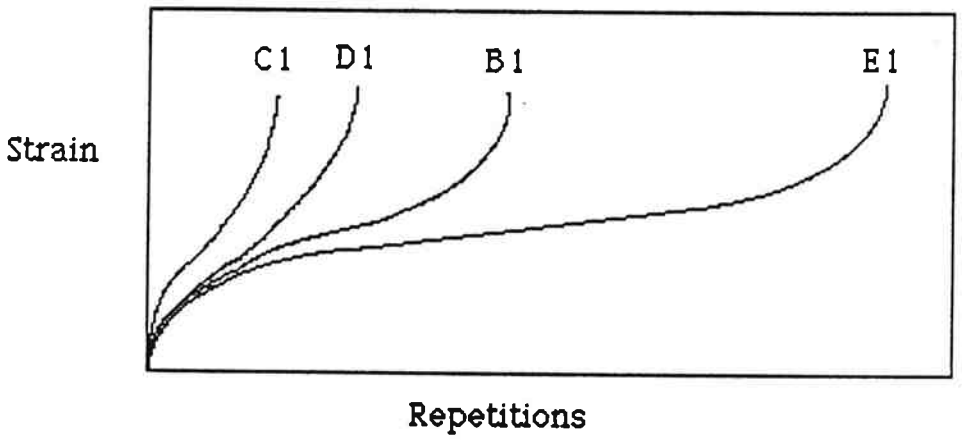


Figure 4.10. Permanent Deformation Comparisons

Table 4.9 – Fatigue Life and Permanent Deformation Slope Data

	A1	B1	C1	D1	E1
Slope (in/rep) ($x10^{-6}$)	*	.57	3.3	2.1	.26
Fatigue Life					
(reps) @ 25°C	4046	14261	2487	5893	25217
(reps) @ 0°C	541	11903	4269	1917	12779

* = Missing data

4.3.2.4 Creep. To produce a sample of the proper dimensions for this test, three Marshall specimens were cemented together with their respective binders. A load of 15 psi was placed on the specimen in the axial direction for periods ranging from one hour to three. The amount of deformation was measured at intervals of 5 minutes by the use of an LVDT and stored in a computer. The plots of deformation vs. time have the same general shape as the permanent deformation curves (Figure 4.8). As with the permanent deformation data, the slope of the straight line segment of the curve was measured and used for comparitive purposes. This slope was later correlated with the binder test data. For a full description of the test procedure, refer to Appendix B. The slope data is presented in Table 4.10.

Table 4.10. Creep Slope Data

	A1	B1	C1	D1	E1
Slope (in/min)	.0006	.0000*	.0001	.0005	.0007

*Slope was too low to measure

4.3.3 Durability

The literature review did not provide clear answers regarding the long-term durability of polymer modified asphalt binders with respect to exposure to moisture or to heat and oxygen. Because of this, a small-scale investigation of long-term durability was included in the preliminary testing.

4.3.3.1 Moisture Sensitivity. The literature indicated that polymers are probably either neutral or positive with regard to improving anti-strip properties of hot mix. To determine if anti-strip properties would be important to evaluation of polymer modified binders, Lottman conditioning was introduced into the laboratory testing program. Moduli and indirect tensile strength properties before and after Lottman conditioning were compared for samples from each group of mix specimens. Ratios of retained modulus and retained tensile strength were calculated. Results of this testing are presented in Table 4.11.

Table 4.11. Retained Modulus and Tensile Strength after Lottman Conditioning

	A1	B1	C1	D1	E1
Retained Tensile Strength @ 25°C	1.26	0.85	0.89	0.76	0.91
Retained Modulus @ 25°C	1.68	1.0	1.1	1.14	0.8
Retained Modulus @ 0°C	0.86	0.90	0.82	0.71	0.74
Retained Modulus @ -10°C	0.74	0.71	0.65	0.75	0.45

Several factors raise questions regarding the validity of these numbers and those presented in the next section for accelerated aging testing. First, the values for "before conditioning" are mean values of a random sample of three specimens for each binder type, and the values for after conditioning are mean values from three different samples. Although the variations in mean bulk specific gravities of before and after specimens were less than 2%, and in most cases, less than 1 %, results may have been affected. Second, the large numbers of retained ratios greater than 1.0 is unusual and raises questions about the validity of the test results. These factors, combined with the small numbers of specimens involved mean that it is not wise to draw conclusions regarding anti-strip properties of polymer modified asphalts based on this testing. Nevertheless, if the numbers are correct, it can be said that all polymers showed clear tensile strength reductions when tested at 25°C after modified Lottman conditioning, whereas the conventional binder showed an increase. Only binder E1 showed a clear modulus reduction when tested at 25°C.

4.3.3.2 Durability When Subjected to Heat and Oxygen. The literature raised concerns that polymers may be more subject to degradation by heat, light, and oxygen than conventional asphalt binders. To determine if resistance to heat and oxygen would be important to evaluation of polymer modified binders, two accelerated aging conditioning methods were introduced into the preliminary laboratory test program. One conditioning method consisted of placing the mix specimens in a forced draft oven at 60°C for 14 days. The other method involved the use of the Pressure Oxygen Bomb (POB) as discussed in Chapter 3. Moduli and indirect tensile strength properties before and after both types of conditioning were compared for samples from each group of mix specimens as discussed in the

previous section for modified Lottman conditioning. Ratios of retained modulus and retained tensile strength were calculated. Results of this testing are presented in Table 4.12.

Table 4.12. Retained Modulus and Tensile Strength after Accelerated Aging

	A1	B1	C1	D1	E1
14 Days @ 60°C					
Retained Tensile Strength @ 25°C	1.37	1.01	1.08	1.09	1.04
Retained Modulus @ 25°C	1.87	2.03	1.15	1.38	1.33
Retained Modulus @ 0°C	0.95	1.05	0.98	1.03	0.95
Retained Modulus @ -10°C	1.09	0.89	0.80	0.89	0.84
POB:					
Retained Tensile Strength @ 25°C	1.28	0.83	1.06	0.72	0.76
Retained Modulus @ 25°C	1.56	1.24	0.89	0.80	0.68
Retained Modulus @ 0°C	0.82	0.85	0.76	0.78	0.77
Retained Modulus @ -10°C	0.67	0.51	0.63	0.49	0.29

The POB conditioning resulted in lower ratios than the less severe conditioning for 14 days at 60°C. The latter conditioning increased the stiffness and tensile strength for all binders when tested at 25°C. POB conditioning produced decreases in either modulus or tensile strength for all of the polymer modified binders, while the conventional binder showed increases in both strength and stiffness at 25°C. Although this testing is by no means conclusive, the results do nothing to dispel concerns about the long-term durability of polymer modified asphalts when subjected to heat and oxygen. One cannot rule out the possibility that the long-term effects of heat and oxygen on polymers may offset initial gains in strength, stiffness, and fatigue life. Further research is needed in this area.

4.4 Binder/Mixture Correlations

Each of the binder properties was analyzed using statistical methods to determine which binder tests best predict mixture properties. The averaged data, which have been presented in Tables 4.2-4.10, were input into a statistical

computer package for analysis. A simple linear regression analysis was run for each binder/mixture combination to determine the strength of the relationship between the data sets.

R-squared, also called the coefficient of determination, was chosen as the statistic for comparisons between variables. R-squared can be defined as the proportion of variation in the predicted variable that has been explained by the simple linear regression model (Devore and Peck, 1986). It is important to realize that R-squared alone is not a good indicator of the strength of the relationship between two variables. For example, a small value of R-squared might indicate that one variable cannot be used very accurately to predict another, when in reality, the wrong model is being applied. As shown in Fig. 4.11, the R-squared for a simple linear model would be quite low, but in reality, there is a very clear relationship between the two variables that could be explained with a different regression model.

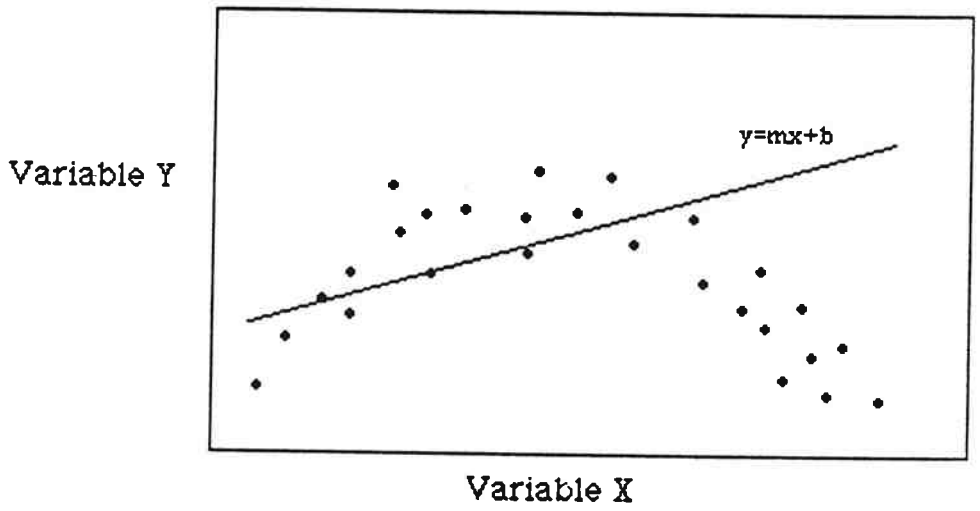


Figure 4.11. Regression Example

In this study, R-squared was computed for each combination of variables, as can be seen in Tables 4.13 and 4.14, and the plots of the data sets were reviewed to determine if the R-squared values were in fact representative of the variation within the data sets. A sample of these plots can be found in Figure 4.12. As can be seen in this figure, four of the data points appear to line up and one is far lower than the rest resulting in a low R-squared. This is an

Table 4.13. R-Squared Values for Original Binder Correlations – Preliminary Testing

	Penetration		Viscosity					Force Ductility									
								Area (in-lb)	True Stress		Engr. Stress						
	@ 4°C	@ 25°C	@ 60°C	@ 135°C	Toughness	Tenacity	T&T Peak Area	@ 4°C	@ 4°C	@ 25°C	@ 4°C	@ 25°C	Peak Area	Tenacity	Fraass Point	PI	PVN
Unconditioned Mix Property																	
Modulus @ 25°C	0.72	0.40	0.15	0.00	0.66	0.62	0.18	0.04	0.93	0.10	0.29	0.38	0.66	0.11	0.54	0.18	0.12
Modulus @ 0°C	0.68	0.36	0.07	0.22	0.26	0.18	0.35	0.01	0.76	0.00	0.64	0.24	0.85	0.07	0.70	0.02	0.37
Modulus @ -10°C	0.41	0.46	0.18	0.54	0.03	0.00	0.39	0.00	0.38	0.01	0.50	0.27	0.52	0.04	0.67	0.00	0.62
Ind. Tens σ @ 25°C	0.42	0.45	0.41	0.04	0.71	0.76	0.03	0.06	0.66	0.65	0.00	0.54	0.20	0.09	0.28	0.32	0.02
Ind. Tens σ @ 0°C	0.66	0.58	0.23	0.28	0.23	0.16	0.35	0.01	0.75	0.01	0.48	0.42	0.71	0.06	0.80	0.03	0.47
Ind. Tens σ @ -10°C	0.80	0.56	0.28	0.03	0.68	0.62	0.24	0.07	0.97	0.14	0.31	0.53	0.70	0.15	0.66	0.22	0.20
Comp. Strain 25°C	0.09	0.00	0.11	0.13	0.01	0.02	0.02	0.23	0.29	0.09	0.28	0.15	0.26	0.12	0.16	0.26	0.08
Comp. Strain 0°C	0.02	0.00	0.10	0.21	0.12	0.16	0.01	0.30	0.13	0.11	0.18	0.16	0.12	0.19	0.10	0.42	0.11
Comp. Strain -10°C	0.81	0.94	0.75	0.53	0.37	0.22	0.85	0.51	0.32	0.00	0.63	0.24	0.72	0.62	0.91	0.41	0.84
IDT Work 25°C	0.66	0.72	0.68	0.00	0.89	0.85	0.21	0.30	0.60	0.38	0.09	0.80	0.38	0.36	0.49	0.61	0.14
IDT Work 0°C	0.74	0.73	0.44	0.11	0.50	0.43	0.29	0.07	0.85	0.15	0.29	0.43	0.62	0.14	0.76	0.18	0.33
IDT Work -10°C	0.02	0.00	0.00	0.50	0.36	0.49	0.08	0.01	0.08	0.26	0.08	0.09	0.00	0.00	0.03	0.17	0.26
Fat. Life @ 25°C	0.04	0.04	0.17	0.00	0.01	0.00	0.02	0.00	0.04	0.21	0.18	0.05	0.14	0.00	0.00	0.00	0.00
Creep @ 40°C	0.00	0.06	0.22	0.20	0.00	0.02	0.23	0.54	0.31	0.17	0.03	0.07	0.00	0.44	0.00	0.22	0.17
Perm. Def. @ 25°C	0.18	0.62	0.66	0.62	0.09	0.06	0.54	0.17	0.05	0.42	0.03	0.54	0.07	0.19	0.39	0.17	0.94
Mod Diff (-10°C & 25°C)	0.37	0.44	0.17	0.56	0.02	0.00	0.38	0.00	0.33	0.02	0.48	0.03	0.88	0.03	0.64	0.00	0.62

Table 4.14. R-Squared Vales for RTFO Residue Correlations – Preliminary Testing

	Penetration		Viscosity					Force Ductility							Fraass				
								Area (in-lb)	True Stress		Engr. Stress						Loss Tan.		
	@ 4°C	@ 25°C	@ 60°C	@ 135°C	Toughness	Tenacity	T&T Peak Area	@ 4°C	@ 4°C	@ 25°C	@ 4°C	@ 25°C	Peak Area	Tenacity	Res	POB Res	@ 40°C	PI	PVN
Unconditioned Mix Property																			
Modulus @ 25°C	0.74	0.51	0.13	0.05	0.83	0.61	0.90	*	*	0.09	*	0.10	0.93	0.01	0.50	0.26	0.66	0.24	0.10
Modulus @ 0°C	0.72	0.42	0.05	0.05	0.78	0.76	0.57	*	*	0.07	*	0.05	0.79	0.09	0.79	0.59	0.88	0.17	0.38
Modulus @ -10°C	0.33	0.4	0.17	0.32	0.56	0.73	0.22	*	*	0.22	*	0.18	0.30	0.04	0.23	0.99	0.77	0.28	0.64
Ind. Tens σ @ 25°C	0.32	0.52	0.40	0.30	0.62	0.39	0.78	*	*	0.24	*	0.30	0.91	0.17	0.00	0.12	0.31	0.44	0.00
Ind. Tens σ @ 0°C	0.58	0.58	0.22	0.07	0.89	0.93	0.57	*	*	0.22	*	0.20	0.71	0.01	0.37	0.88	0.95	0.37	0.47
Ind. Tens σ @ -10°C	0.77	0.66	0.26	0.03	0.93	0.71	0.95	*	*	0.20	*	0.21	0.99	0.00	0.38	0.39	0.77	0.40	0.17
Comp. Strain 25°C	0.11	0.00	0.13	0.15	0.32	0.53	0.06	*	*	0.09	*	0.12	0.11	0.52	0.69	0.38	0.38	0.03	0.12
Comp. Strain 0°C	0.02	0.00	0.11	0.31	0.20	0.46	0.00	*	*	0.07	*	0.09	0.01	0.28	0.35	0.47	0.28	0.04	0.16
Comp. Strain -10°C	0.71	0.90	0.73	0.15	0.44	0.33	0.46	*	*	0.82	*	0.77	0.54	0.57	0.11	0.63	0.69	0.86	0.76
IDT Work 25°C	0.56	0.79	0.67	0.14	0.59	0.32	0.87	*	*	0.52	*	0.57	0.80	0.28	0.02	0.18	0.42	0.72	0.09
IDT Work 0°C	0.63	0.76	0.42	0.00	0.94	0.82	0.80	*	*	0.36	*	0.37	0.86	0.10	0.18	0.65	0.84	0.57	0.30
IDT Work -10°C	0.04	0.00	0.00	0.72	0.01	0.02	0.18	*	*	0.03	*	0.01	0.26	0.05	0.01	0.28	0.02	0.00	0.31
Fat. Life @ 25°C	0.12	0.01	0.20	0.00	0.00	0.00	0.02	*	*	0.14	*	0.17	0.01	0.70	0.64	0.00	0.03	0.11	0.00
Creep @ 40°C	0.00	0.03	0.23	0.17	0.23	0.31	0.09	*	*	0.34	*	0.31	0.28	0.49	0.18	0.00	0.05	0.14	0.15
Perm. Def. @ 25°C	0.06	0.47	0.69	0.02	0.14	0.13	0.11	*	*	0.71	*	0.70	0.09	0.77	0.30	0.43	0.20	0.67	0.93
Mod Diff (-10°C & 25°C)	0.28	0.37	0.16	0.35	0.51	0.70	0.18	*	*	0.21	*	0.18	0.25	0.04	0.19	0.98	0.73	0.27	0.63

Note: Force ductility correlations exclude values from specimens which failed immediately
* = Value not representative due to lack of accurate AC-20 values

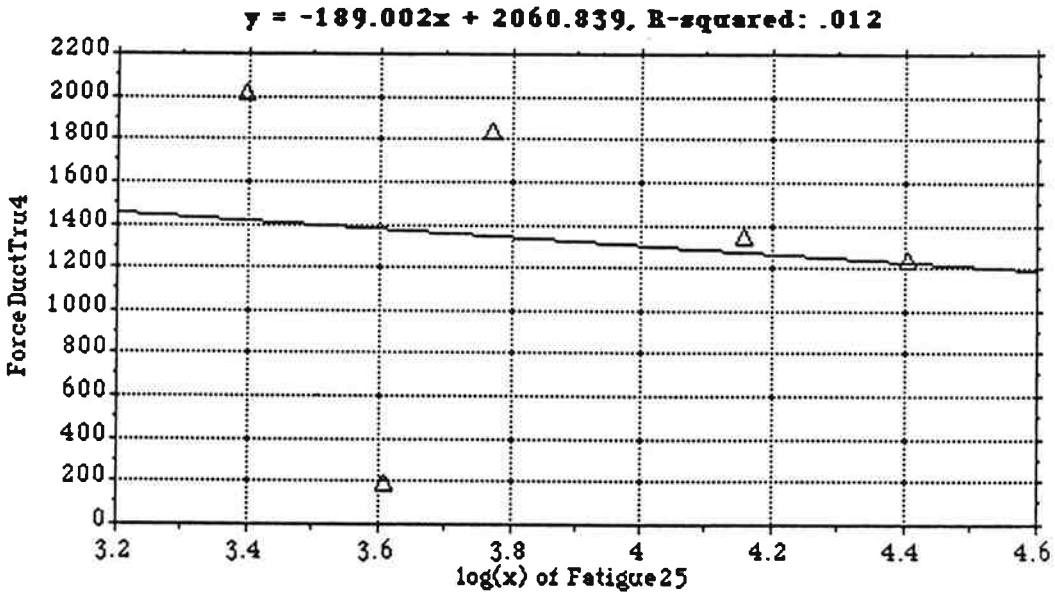


Figure 4.12. Sample Regression Plot

example of a binder property being a fairly accurate predictor of a mix property for all but one type of polymer additive.

Table 4.15 is a condensed version of Tables 4.13 and 4.14 which allows a clearer view of the properties that have correlations greater than .7. For this report, a promising correlation is one in which R-squared is greater than or equal to .7. It can be seen that penetration at 4°C and 25°C, Force Ductility true stress, and the Fraass point have the largest number of good correlations for original binders. For the RTFO residue properties, penetration at 4°C and 25°C, toughness, tenacity, toughness and tenacity (t&t) peak area, force ductility peak area, Fraass point, POB Fraass point and loss tangent at 40° have the greatest number of good correlations.

With five or less data points to work with for correlations, a multiple regression fit of the data is of little value since the number of predictors rapidly approaches the number of data points and the effect on R-squared brings doubt into the meaning of the value. For this reason, multiple regression was not attempted in the preliminary testing program.

Table 4.15. Summary of Promising R-Square Values – Preliminary Testing

	Penetration		Viscosity				T&T	Force Ductility									
								True Stress		Engr. Stress							
	@ 4°C	@ 25°C	@ 60°C	@ 135°C	Toughness	Tenacity	Peak Area	@ 4°C	@ 25°C	@ 4°C	@ 25°C	Peak Area	Tenacity	Fraass Point	POB Fraass	PI	PVN	Loss Tan @ 40°C
Original Binder																		
Modulus @ 25°C	0.72(-)							0.93(-)										N/T
Modulus @ 0°C								0.76(-)				0.85		0.70				N/T
Ind. Tens σ @ 25°C					0.71	0.76												N/T
Ind. Tens σ @ 0°C								0.75(-)				0.71		0.80				N/T
Ind. Tens σ @ -10°C	0.80(-)							0.97(-)				0.70						N/T
Comp Strain -10°C	0.81	0.94	0.75				0.85(-)					0.72(-)		0.91(-)			0.84	N/T
IDT Work 25°C		0.72(-)			0.89	0.85				0.80(-)								N/T
IDT Work 0°C	0.74(-)	0.73(-)						0.85(-)						0.76				N/T
Perm. Def. @ 25°C																	0.94	N/T
RTFO Residues																		
Modulus @ 25°C	0.74(-)				0.83		0.90					0.93						
Modulus @ 0°C	0.72(-)				0.78	0.76						0.79		0.79				0.88
Modulus @ -10°C						0.73									0.99			0.77
Ind. Tens σ @ 25°C							0.78					0.91						
Ind. Tens σ @ 0°C					0.89	0.93						0.71			0.88			0.95
Ind. Tens σ @ -10°C	0.77(-)				0.93	0.71	0.95					0.99						0.77
Comp Strain -10°C	0.71	0.90	0.73						0.82		0.77					0.86	0.76	
IDT Work 25°C		0.79(-)					0.87					0.80				0.72(-)		
IDT Work 0°C		0.76(-)			0.94	0.82	0.8					0.86						0.84
IDT Work -10°C				0.72														
Perm. Def. @ 25°C									0.71		0.70		0.77				0.93	
Fat. Life @ 25°C													0.70(-)					
Mod Diff (-10°C & 25°C)						0.70									0.98			0.73

N/T = not tested
(-) = inverse relationship

4.5 Discussion of Results of Preliminary Testing

Penetration values at both 4°C and 25°C produced promising correlations with mixture properties for both the original and RTFO residues. Viscosity at both 60°C and 135°C seem to have little or no ability to predict mix performance. Perhaps these correlations are low due to the previously discussed problems of viscosity measurement when polymers are involved.

Attempts to compare toughness and tenacity testing (normally tested at 25°C) with force ductility testing (normally tested at 4°C) were not successful. Available laboratory equipment did not allow running both tests at 4°C. Running force ductility at 25°C did not allow failure of most specimens to be reached before the extension limits of the machine were reached. Consequently, "area" values were meaningless.

With only four or five data points, the R-squared values obtained from preliminary testing can not be considered significant. The intent was to use these values to reduce the number of binder tests utilized in the final testing. Unfortunately, analysis of preliminary testing results only suggested the elimination of force ductility testing at 25°C from the final testing program. In addition, dynamic mechanical analysis had to be dropped too, due to unavailability of equipment.

5.0 FINAL TESTING

5.1 Objectives

The final testing program was intended to build on the experience of the preliminary testing by reducing the number of test procedures and increasing the number of binders tested. This makes possible a more valid statistical base for evaluating the correlations of binder/mixture properties.

5.2 Methodology

The following tests were included in the final testing program:

1) Binder tests: Pen @ 4°C and 25°C
   Viscosity @ 60°C and 135°C
   Ring and Ball Softening Point
   Force Ductility @ 4°C
   Toughness and Tenacity @ 25°C
   Fraass Brittle Point of Original Binders
2) Mixture tests: Resilient modulus @ 25°C, 0°C, and -10°C
   Indirect tensile @ 25°C 2 in/min, and -10°C .05 in/min
   Fatigue @ 25°C
   Permanent Deformation @ 25°C

Although loss tangent in the dynamic mechanical analysis showed good correlation with mix properties in the preliminary test program, it was dropped from the final testing program due to the unavailability of the test equipment. The cost of this test equipment is also prohibitive to most asphalt labs which may inhibit its use. The emphasis of this part of the project focussed on fairly conventional, easily performed test procedures.

Since researchers who use the force ductility test run it at 4°C and the correlations of true stress, engineering stress, and area under the stress/strain curve at 25°C with mixture properties were poor, only force ductility at 4°C was used in the final testing.

The number of asphalts used in the final testing program were doubled from five to ten and included two unmodified asphalts and asphalts modified with the additives SBS, SBR, SB, EVA, polychloroprene, and polyethylene. The asphalts were assigned names A2–J2 according to Table 5.1.

Table 5.1. Asphalt Designations

Code	Additive
A2	None
B2	None
C2	Polyethelene
D2	EVA
E2	SBR
F2	SB
G2	SBS
H2	Polychloroprene
I2	EVA
J2	SBS

All asphalts were received from their respective suppliers by ODOT and specimens were prepared using the California kneading compactor. All mixtures were mixed at the same asphalt content to reduce the amount of variables in the testing. The aggregate was not treated with lime and was obtained from the River Bend Pit in Oregon's Willamette Valley. The asphalt content was 5.9% and the gradation of the aggregate was a "C" mix. For more information about the specific aggregate gradation refer to Appendix C.

The original binders and RTFO residues were tested for penetration, viscosity and force ductility by ODOT as well. Toughness and tenacity tests, Fraass test, and mixture testing were performed by OSU.

No mixture moisture conditioning or long-term aging procedures were included as part of the final testing program since the study of long-term durability of polymer modified asphalts was not a major research objective. All data reported in this section for mixture properties will be for unconditioned mixtures. A flow chart of the final testing program can be found in Figures 5.1 and 5.2.

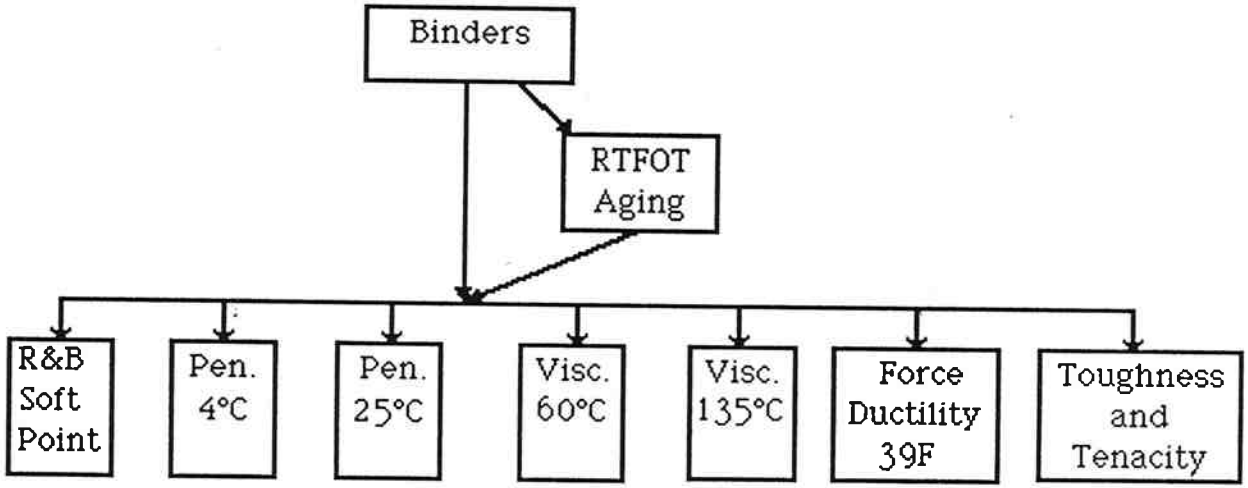


Figure 5.1. Binder Specimen Flow Chart

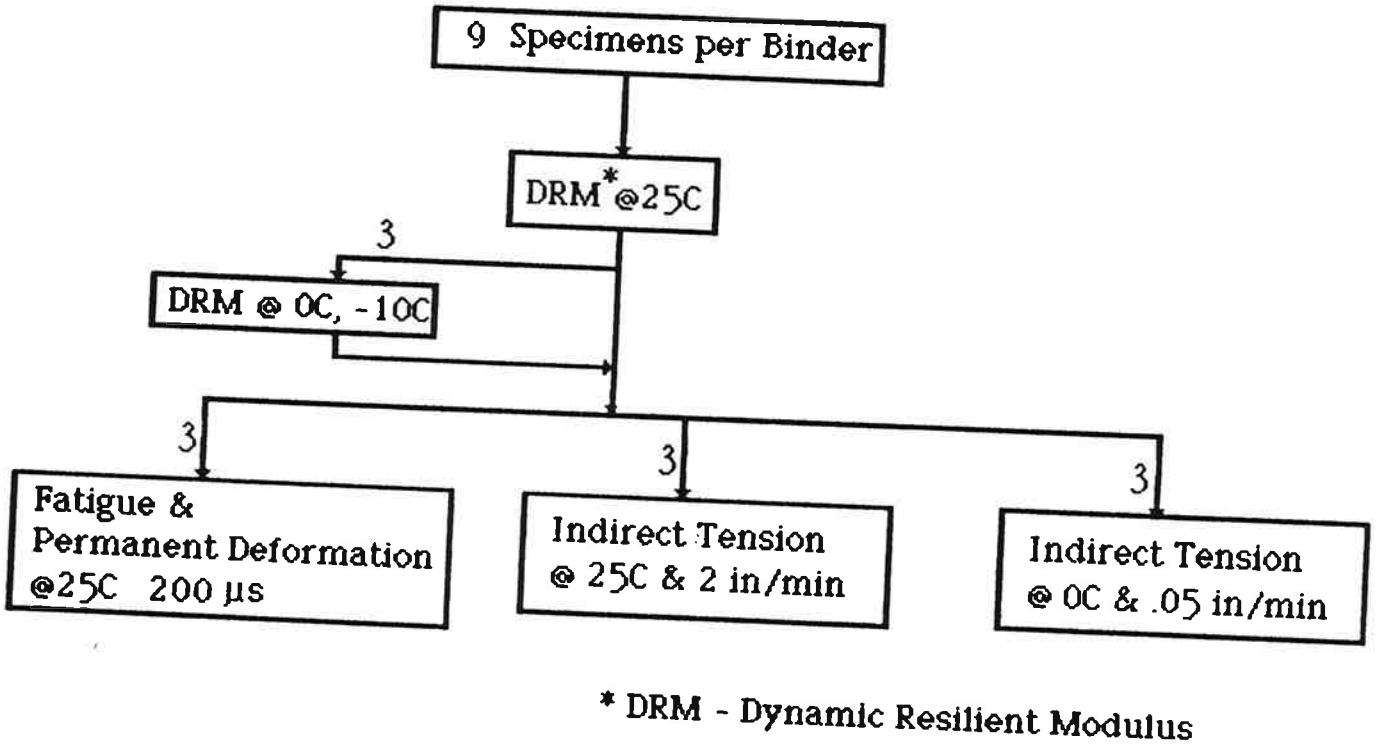


Figure 5.2. Mixture Specimen Flow Chart

5.3 Test Results

5.3.1 Binder Tests

5.3.1.1 Penetration. ODOT performed penetration tests at 4°C and 25°C on both the unaged binders and the RTFO residues. The test procedure is described in ASTM D5 and the results are shown in Table 5.2. Each of the values presented here is an average of three separate test runs.

Table 5.2. Penetration Data (dmm)

Binder	Orig Pen @ 4°C	Orig Pen @ 25°C	Res Pen @ 4°C	Res Pen @ 25°C
A2	27	70	21	38
B2	21	80	20	54
C2	23	52	22	28
D2	31	66	20	41
E2	43	98	23	60
F2	26	83	19	45
G2	63	132	43	86
H2	19	56	16	38
I2	50	106	33	76
J2	33	133	27	78

5.3.1.2 Viscosity. Both absolute viscosity (60°C) and kinematic viscosity (135°C) were measured for all binders according to ASTM D2170 and D2171. The Cannon Manning tube was once again used, as is standard ODOT procedure. This probably contributes to some of the seemingly high values (for a target of an AC-20 visc.) reported as discussed in Section 4.3.1.2. The results are presented in Table 5.3.

5.3.1.3 Force Ductility. All original binders and RTFO residues were tested at 4°C according to the procedure outlined in Appendix A. The XY plots of force vs. extension were reduced to engineering stress, true Stress, and the area under the curve by the same procedure as described in Chapter 4. Because

of the good correlations obtained for toughness, tenacity, and peak area in the preliminary testing, analogous values were computed from force ductility test results. These results are presented in Tables 5.4, 5.5, and 5.6.

Table 5.3. Viscosity Data

Binder	Orig Visc @ 60°C (poise)	Orig Visc @ 135°C (cst)	Res Visc @ 60°C (poise)	Res Visc @ 135°C (cst)
A2	1800	392	4920	569
B2	1160	177	2130	244
C2	5520	1174	19500	1910
D2	1530	591	9060	1050
E2	1940	622	5180	888
F2	1910	519	2790	735
G2	12200	803	18000	923
H2	2340	336	4760	487
I2	2040	1030	2530	1130
J2	11700	748	17000	643

Table 5.4. Force Ductility, Original Binder Data

Binder	Engr Stress (psi)	True Stress (psi)	Peak Area (psi/in/in)	Tenacity (psi/in/in)	Toughness (psi/in/in)
A2	114	4079	203	115	318
B2	160	3319	265	94	359
C2	192	1688	288	147	436
D2	82	1759	179	309	488
E2	50	1158	105	291	396
F2	110	2030	201	566	766
G2	33	559	65	139	203
H2	–	–	–	–	–
I2	67	3151	123	233	356
J2	32	519	72	142	214

Table 5.5. Force Ductility, RTFO Residue Binder Data

Binder	Engr Stress (psi)	True Stress (psi)	Peak Area (psi/in/in)	Tenacity (psi/in/in)	Toughness (psi/in/in)
A2	127	4042	235	122	357
B2	244	1554	446	92	538
C2	–	–	–	–	–
D2	184	1872	334	281	587
E2	82	2063	153	598	751
F2	177	2034	385	548	933
G2	53	1395	104	540	644
H2	–	–	–	–	–
I2	108	5238	204	466	670
J2	60	1295	126	447	573

Table 5.6. Additional Force Ductility Data

Binder	Unaged Max Strain (in/in)	Unaged Sec Mod (psi)	Residue Max Strain (in/in)	Residue Sec Mod (psi)
A2	36.4	11330	30.8	13938
B2	20.3	9219	5.8	8633
C2	7.8	6492	–	–
D2	20.7	4886	9.0	6455
E2	22.1	3217	23.9	5730
F2	17.4	11278	10.4	5650
G2	15.9	3105	25.1	6643
H2	–	–	–	–
I2	46.7	10865	46.7	18062
J2	15.3	4718	20.7	4465

It should be noted that no data is available for H2 on either the original or residue because the sample broke with no elongation. The same is true for the C2 residue. These missing values are denoted by a "–" in Tables 5.4, 5.5, and 5.6.

5.3.1.4 Toughness and Tenacity. Significant variability was noted in the RTFO residue results of this test. The original binders were very consistent and repeatable, but the residues, especially the brittle ones, varied considerably in both the ultimate strength and the area under the curve. A description of the test can be found in Appendix A and the results are shown in Table 5.7.

Table 5.7. Toughness and Tenacity Data

Binder	Original			Residue		
	Toughness (in-lb)	Tenacity (in-lb)	Peak Area (in-lb)	Toughness (in-lb)	Tenacity (in-lb)	Peak Area (in-lb)
A2	112.0	93.0	19.3	70.4	36.9	33.4
B2	127.1	104.4	22.7	52.8	3.2	49.1
C2	38.9	8.3	30.7	126.9	24.8	102.0
D2	73.6	49.4	24.3	74.5	14.0	60.4
E2	177.9	164.6	13.3	149.6	109.9	39.7
F2	146.9	120.1	26.8	98.4	47.8	50.5
G2	120.3	105.2	15.1	136.6	105.7	31.1
H2	222.4	156.9	65.5	174.0	59.1	114.8
I2	118.4	104.7	13.6	161.4	118.7	42.7
J2	102.2	89.5	12.7	126.0	102.9	23.5

5.3.1.5 Ring and Ball Softening Point, Fraass Point, PI, and PVN. The softening point test was conducted by ODOT according to AASHTO T53 (ASTM D36). This information was then used to calculate PI. Fraass Pt. was determined as for preliminary testing. Table 5.8 presents softening point, PI, PVN, and Fraass Pt. values.

Table 5.8. Softening Point, PI and PVN Data

Binder	Original				Residue		
	R&B Point (°C)	PI	PVN	Fraass Point (°C)	R&B Point (°C)	PI	PVN
A2	58.9	1.7	-0.7	-6	53	-1.1	-0.79
B2	54.4	1.1	-1.8	-1	49	-1.3	-1.7
C2	54.0	-0.15	0.61	-6	63	0.29	0.54
D2	64.4	2.6	-0.13	-10	48	-2.1	0.16
E2	57.8	2.5	0.57	-16	54	0.2	0.37
F2	62.2	2.9	-0.05	-16	50	-1.4	-0.25
G2	63.3	4.8	1.3	-16	65	3.6	0.93
H2	56.7	0.63	-1.2	-1.5	54	-0.86	-1.0
I2	61.1	3.5	1.4	-12	48	-0.7	1.0
J2	74.4	6.8	1.3	-16	68	3.8	0.21

5.3.2 Mixture Test Results

5.3.2.1 Dynamic Resilient Modulus. All specimens were tested for modulus at 25°C but only representative specimens were tested at the lower temperatures. Three specimens were selected from each binder group that had moduli near the average for the group to be tested at 0°C, and -10°C. The results are summarized in Table 5.9. The temperature vs. moduli plots for each asphalt are shown in Fig. 5.3.

5.3.2.2 **Indirect Tensile Strength.** Three specimens from each binder group were loaded to failure at 25°C and at a rate of 2 in./min. Three more from each group were loaded to failure at -10°C and at a rate of .05 in./min. The full test procedure is outlined in Appendix B. Compressive strain and work to failure were computed from the force/extension plots and are presented in Table 5.10.

Table 5.9. Dynamic Resilient Modulus Data (KSI)

Binder	Modulus @ 25°C	Modulus @ 0°C	Modulus @ -10°C
A2	311	1788	2835
B2	267	2258	3343
C2	381	1915	2957
D2	278	1534	2687
E2	244	1317	2185
F2	291	1719	2732
G2	156	1273	1995
H2	435	2703	3822
I2	191	1655	2412
J2	138	1129	1996

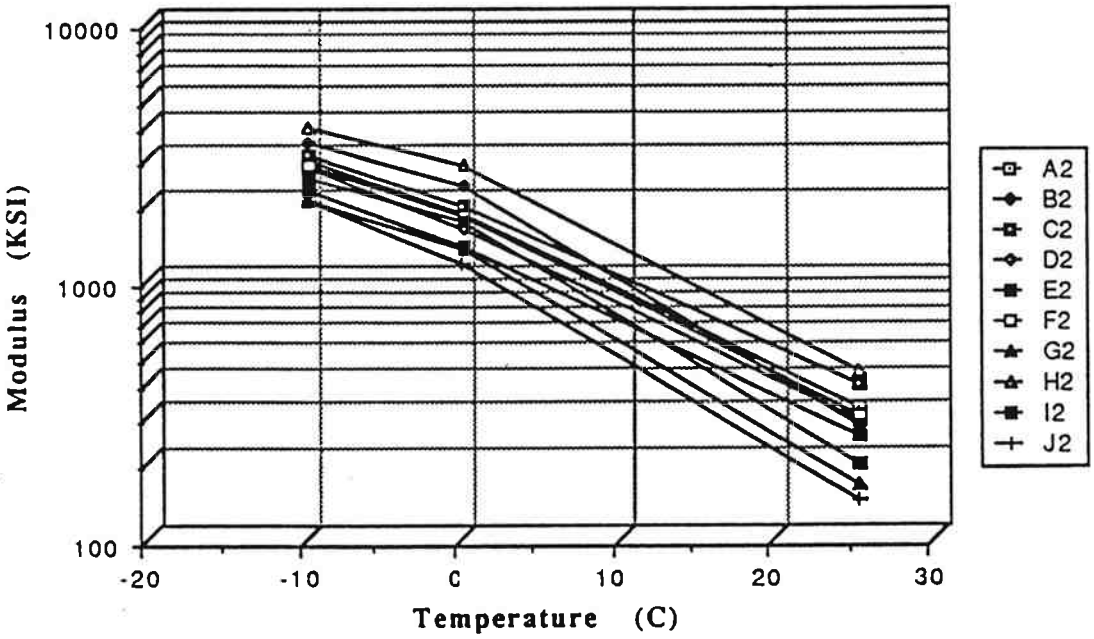


Figure 5.3. Modulus vs. Temperature Curves

5.3.2.3 Fatigue Life and Permanent Deformation. The specimens were repeatedly loaded diametrally to failure as in the preliminary testing at 25°C. The initial strain for all specimens was set at 200 $\mu\epsilon$ and the same failure criteria were used as previously. See Appendix B.

Table 5.10. Indirect Tensile Data

Binder	Strength @ 25°C (psi)	Comp Strain @ 25°C (%)	Strength @ -10°C (psi)	Comp Strain @ -10°C (%)	Work @ 25°C (in-lb)	Work @ -10°C (in-lb)
A2	58.7	1.08	177.9	.52	3.6	4.3
B2	56.8	1.26	172.0	.70	3.6	5.0
C2	71.1	0.88	200.5	.58	3.8	5.1
D2	51.5	0.89	169.1	.65	2.4	5.6
E2	51.5	1.11	150.0	.74	3.4	6.1
F2	62.0	1.05	192.5	.77	3.9	7.2
G2	30.7	1.05	115.3	.71	1.8	4.5
H2	76.4	1.10	196.4	.68	5.1	5.5
I2	36.7	0.98	150.4	.88	2.2	7.0
J2	27.9	0.99	97.4	.85	1.5	4.7

Permanent deformation data were also collected for each specimen and the slope of the straight line segment of the strain vs. repetitions curve was measured. The results are presented in Table 5.11.

Table 5.11. Fatigue Life and Permanent Deformation Data

Binder	Fatigue Life (reps)	Perm Def Slope (%/rep) ($x10^{-6}$)
A2	4657	3.6
B2	1756	9.6
C2	5834	2.8
D2	3068	4.8
E2	7773	1.9
F2	15429	0.9
G2	1400	8.9
H2	1234	13.0
I2	2942	8.2
J2	1970	7.1

5.4 Correlation of Binder and Mixture Properties

The same procedure was followed as was used in the preliminary testing to correlate properties. The number of mixture tests was reduced significantly, but the number of data points for each test was increased by a factor of 2. This allowed a more accurate and thorough statistical analysis of the data.

A simple linear regression of each binder test mixture-test combination was calculated and the R-squared value reported (as shown in Tables 5.12 and 5.13). The plots of each test combination data were reviewed to judge the validity of the R-squared value and suspect R-squared values were ignored. A sample plot is shown in Figure 5.4. This plot demonstrates again the ability of one asphalt to reduce the predicting ability of a binder test.

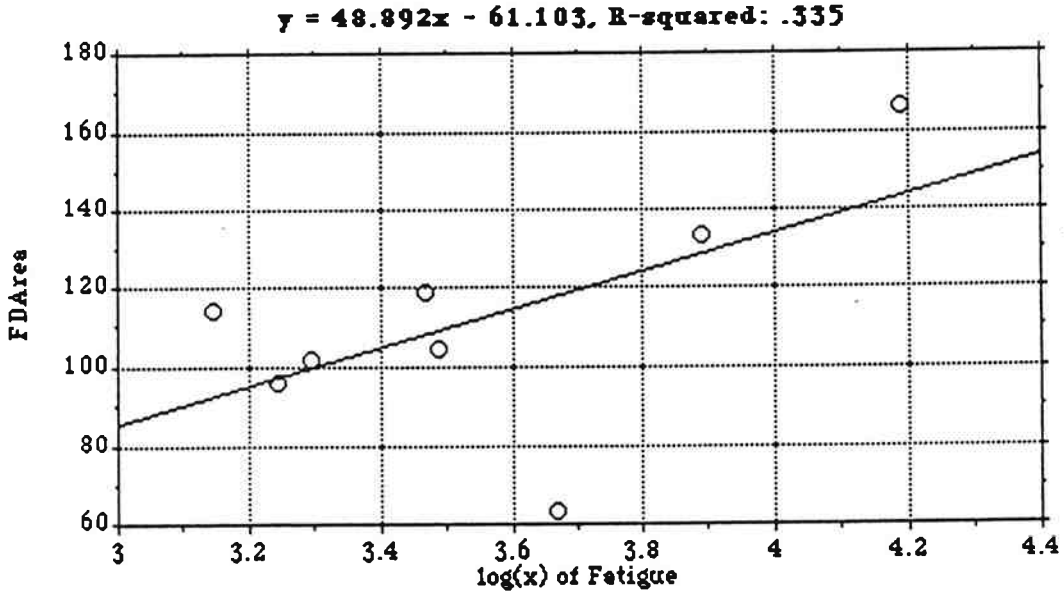


Figure 5.4. Sample Regression Plot

The full matrix of R-squared values was reduced to only those values that were higher then .7 and the resulting matrix is presented in Table 5.14. By reviewing Table 5.14 it can be seen that Pen at 25°C, T&T Peak area, Force Ductility Engr. Stress and FD peak area have the highest number of good correlations with mixture properties.

Table 5.12. R-Squared Values for Original Binder Correlations – Final Testing

	Penetration		Viscosity					Force Ductility											
	@ 4°C	@ 25°C	@ 60°C	@ 135°C	Toughness (in-lb)	Tenacity (in-lb)	T&T Peak (in-lb)	Area (in-lb) @ 4°C	Engr. Stress @ 4°C	True Stress @ 4°C	Peak Area (in-lb) @ 4°C	Tenacity (in-lb) @ 4°C	Strain (%)	Mod (psi)	R&B Soft Point (°C)	PI	PVN	Fraas Point
Modulus @ 25°C	0.54	0.87	0.31	0.07	0.04	0.00	0.70	0.31	0.74	0.19	0.79	0.02	0.04	0.13	0.39	0.78	0.41	0.50
Modulus @ 0°C	0.45	0.54	0.29	0.22	0.14	0.02	0.70	0.11	0.80	0.56	0.82	0.01	0.00	0.42	0.48	0.60	0.62	0.78
Modulus @ -10°C	0.60	0.67	0.35	0.27	0.09	0.00	0.70	0.17	0.83	0.50	0.91	0.00	0.00	0.35	0.42	0.65	0.72	0.80
Ind Tens σ @ 25°C	0.59	0.86	0.39	0.10	0.05	0.00	0.58	0.41	0.74	0.19	0.80	0.06	0.05	0.15	0.47	0.82	0.48	0.45
Ind Tens ϵ @ 25°C	0.02	0.00	0.06	0.57	0.40	0.46	0.00	0.01	0.00	0.11	0.00	0.03	0.02	0.05	0.45	0.02	0.36	0.09
Ind Tens σ @ -10°C	0.48	0.88	0.55	0.05	0.00	0.02	0.04	0.52	0.71	0.32	0.78	0.11	0.00	0.31	0.50	0.83	0.40	0.40
Ind Tens ϵ @ -10°C	0.18	0.47	0.06	0.05	0.06	0.14	0.09	0.00	0.33	0.11	0.35	0.08	0.04	0.00	0.19	0.44	0.25	0.30
IDT Work 25°C	0.49	0.63	0.39	0.20	0.23	0.07	0.60	0.38	0.59	0.25	0.62	0.07	0.01	0.23	0.54	0.70	0.52	0.40
IDT Work -10°C	0.00	0.00	0.24	0.03	0.08	0.09	0.00	0.50	0.00	0.00	0.00	0.65	0.09	0.12	0.02	0.00	0.02	0.10
Fat. Life @ 25°C	0.03	0.03	0.10	0.00	0.00	0.01	0.00	0.75	0.04	0.00	0.06	0.73	0.02	0.12	0.00	0.01	0.00	0.16
Log Fatigue 25°C	0.02	0.06	0.15	0.03	0.02	0.00	0.60	0.66	0.08	0.01	0.10	0.56	0.00	0.11	0.00	0.03	0.01	0.13
Perm Def @ 25°C	0.00	0.02	0.04	0.07	0.14	0.07	0.19	0.46	0.05	0.00	0.07	0.38	0.04	0.00	0.02	0.00	0.05	0.20
Mod Diff (-10°C & 25°C)	0.58	0.60	0.33	0.31	0.10	0.01	0.67	0.14	0.76	0.52	0.84	0.01	0.00	0.37	0.41	0.59	0.74	0.82

Note: Force ductility correlations exclude ϕ values from specimens which failed immediately

Table 5.13. R-Squared Values for RTFO Residue Binder Correlations – Final Testing

	Penetration		Viscosity					Force Ductility								
	@ 4°C	@ 25°C	@ 60°C	@ 135°C	Toughness (in-lb)	Tenacity (in-lb)	T&T Peak (in-lb)	Area (in-lb) @ 4°C	Engr. Stress @ 4°C	True Stress @ 4°C	Peak Area (in-lb) @ 4°C	Tenacity (in-lb) @ 4°C	Strain (%)	Mod (psi)	PI	PVN
Modulus @ 25°C	0.55	0.82	0.05	0.08	0.18	0.37	0.77	0.00	0.51	0.03	0.51	0.25	0.14	0.02	0.37	0.24
Modulus @ 0°C	0.35	0.37	0.20	0.00	0.35	0.29	0.57	0.04	0.76	0.06	0.71	0.51	0.07	0.16	0.33	0.47
Modulus @ -10°C	0.50	0.52	0.18	0.00	0.53	0.45	0.59	0.05	0.89	0.02	0.84	0.60	0.20	0.06	0.41	0.56
Ind Tens σ @ 25°C	0.63	0.84	0.10	0.04	0.21	0.42	0.65	0.00	0.55	0.00	0.58	0.17	0.20	0.00	0.44	0.30
Ind Tens ϵ @ 25°C	0.02	0.02	0.31	0.62	0.12	0.00	0.04	0.01	0.13	0.03	0.11	0.11	0.06	0.00	0.01	0.48
Ind Tens σ @ -10°C	0.52	0.81	0.17	0.06	0.18	0.47	0.53	0.02	0.60	0.09	0.64	0.15	0.08	0.06	0.66	0.20
Ind Tens ϵ @ -10°C	0.14	0.53	0.02	0.03	0.29	0.45	0.14	0.32	0.09	0.00	0.06	0.39	0.06	0.00	0.10	0.14
IDT Work 25°C	0.55	0.60	0.20	0.00	0.16	0.23	0.52	0.02	0.38	0.01	0.42	0.09	0.11	0.00	0.36	0.39
IDT Work -10°C	0.02	0.00	0.30	0.02	0.11	0.04	0.00	0.63	0.04	0.11	0.08	0.25	0.02	0.03	0.02	0.06
Fat. Life @ 25°C	0.10	0.10	0.07	0.00	0.00	0.00	0.00	0.52	0.04	0.00	0.10	0.16	0.05	0.05	0.10	0.00
Log Fatigue 25°C	0.10	0.14	0.05	0.05	0.00	0.01	0.00	0.33	0.02	0.03	0.07	0.10	0.00	0.00	0.13	0.02
Perm Def @ 25°C	0.04	0.10	0.00	0.07	0.00	0.01	0.05	0.17	0.00	0.00	0.01	0.08	0.02	0.06	0.10	0.07
Mod Diff (-10°C & 25°C)	0.46	0.44	0.20	0.02	0.55	0.44	0.53	0.06	0.89	0.01	0.83	0.62	0.19	0.07	0.40	0.59

Note: Force ductility correlations exclude ϕ values from specimens which failed immediately

Table 5.14. Summary of Promising R-Squared Values - Final Testing

	Pen @ 25°C	T&T Peak	Force Ductility: Area (psi/in/in) @ 4°C	Force Ductility: Engr. Str. @ 4°C	Force Ductility: Peak Area @ 4°C	Force Ductility: Tenacity @ 4°C	PI	PVN	Fraass Pt.
Original									
Modulus @ 25°C	0.87(-)	0.70		0.74	0.79		0.78(-)		
Modulus @ 0°C		0.70		0.80	0.82				0.78
Modulus @ -10°C		0.70		0.83	0.91			0.72(-)	0.80
Ind. Tens. σ @ 25°C	0.86(-)			0.74	0.8		0.82(-)		
Ind. Tens. σ @ -10°C	0.88(-)			0.71	0.78		0.83(-)		
Fatigue @ 25°C			0.75			0.73			
Mod Diff (-10°C & 25°C)				0.76	0.84			0.74(-)	0.82
RTFO Residues									
Modulus @ 25°C	0.82(-)	0.77							N/T
Modulus @ 0°C				0.76	0.71				N/T
Modulus @ -10°C				0.89	0.84				N/T
Ind. Tens. σ @ 25°C	0.84(-)								N/T
Ind. Tens. σ @ -10°C	0.81(-)								N/T
Mod Diff (-10°C & 25°C)				0.89	0.83				

N/T = not tested
(-) = inverse relationship

5.4.1 Multiple Regression of the Data

With twice as many data points per binder test as were used in the preliminary testing, a multiple regression of two binder properties on one mixture property was calculated. This allows for a more complete evaluation of which binder properties individually or cooperatively predict mixture performance. For each mixture property, one binder property was forced into the model and the computer picked the best variable from the remaining set to predict the mixture property. This process was then repeated for each binder property and then was stepped to the next mixture property.

The statistical computer package used skipped entire lines of data when a missing value was encountered in any one of the input data columns. This, in effect, deleted one whole binder class, so the program was run for the full data set (including missing values) and then run again for the data set without the binder tests that contained missing values.

The multiple regression model, to best fit the mixture property, will pick the best compliment of the binder property that was forced into the model. When applying this to asphalts, the model will pick the binder property that " fills

in the holes" left by the forced binder property. Ideally, then, the model should include binder properties from opposite ends of the spectrum. The R-squared values from the multiple regression analysis are reported in Tables 5.15 and 5.16. These tables include only the best three combinations (highest R-squared values) of binder properties for each mixture property and are the results from the full data set (all binder properties including missing values). For the full set of results refer to Appendix D which contains all of the values for the whole set as well as for the reduced set of data.

Regardless of what binder properties were forced into the model for predicting modulus at 25°C and split tensile strength at 25°C, the best complement was always penetration at 25°C. This was true for both aged and original binder as well as the full and reduced data sets. This would suggest that penetration at 25°C is the best individual predictor of modulus at 25°C and split tensile strength at 25°C of all of the binder properties examined, based on the final testing. This was also shown by simple correlation.

A review of Table D.3 (see appendix) shows that simple consistency tests of RTFO could be paired to predict modulus and strength properties at all temperatures with resulting R-squared of 0.89 or better. These simple consistency tests are Penetration at 25°C, Ring and Ball Softening Pt., and Viscosities at 60°C and 135°C.

5.5 Discussion of Results of Final Testing

Toughness and tenacity, which produced very good correlations with mixture properties in the preliminary testing, did not produce promising correlations in the final testing. Some of the binders after being aged in the RTFO became brittle and broke in brittle failure upon testing. This produced unusually shaped force vs. extension curves and probably contributed to the poor correlation of RTFO values with mixture properties. The force ductility data (all zeros) for these brittle binders were omitted from the analysis. This may help explain higher correlations for force ductility data.

Fatigue at 25°C was predicted fairly well in the final testing by both original force ductility area under the stress/strain curve and original force ductility tenacity. The same binder that produced the long fatigue lives in the preliminary testing was used again here, and it again produced the longest fatigue lives.

Table 5.15. Multiple Regression R-Squared for Original Binder

Mixture Property	Paired Binder Property	R^2
Modulus @ 25°C	Pen@25C,Visc@60C	.94
	Pen@25C,FDEngr.	.94
	Pen@25C,RDTrue	.93
Modulus @ 0°C	FDPArea,FDTrue	.90
	FDEngr.,FDTrue	.92
	FDPArea,Tenacity	.86
Modulus @ -10°C	Visc@135C,FDEngr	.94
	FDPArea,FDTrue	.95
	Visc@135C,FDPArea	.96
Ind. Tens. @ 25°C	Pen@25C,Toughness	.90
	Pen@25C,R&B	.88
	Pen@25C,Tenacity	.89
Ind. Tens. @ -10°C	Pen@25C,FDArea	.93
	Pen@25C,FDTena	.91
	Pen@25C,Toughness	.90
Comp. Strain @ 25°C	Visc@135C,Toughness	.72
	FDEngr,Tenacity	.61
	Visc@135C,Tenacity	.72
Comp. Strain @ -10°C	Pen@25C,T&TPeak	.70
	Pen@25C,FDPArea	.67
	RDEngr,T&TPeak	.65
Fatigue	R&B,FDTenacity	.79
	FDArea,Tenacity	.82
	FDArea,Toughness	.82
Perm. Def.	Pen@25C,FDTena	.57
	FDArea,T&TPeak	.55
	FDTena,T&TPeak	.57

Pen@4C = Penetration @ 4°C; Pen@25C = Penetration @ 25°C; Visc@60C = Viscosity @ 60°C; Visc@135C = Viscosity @ 135°C; FDEngr = Force Ductility Maximum Engineering Stress; FDTrue = Force Ductility Maximum True Stress; FDPArea = Force Ductility Peak Area; FRDArea = Force Ductility Total Area; FDTena = Force Ductility Tenacity; Toughness = Toughness; Tenacity = Tenacity; T&TPeak = Toughness and Tenacity Peak Area

Table 5.16. Multiple Regression R-Squared for RTFO Residue

Mixture Property	Paired Binder Property	R^2
Modulus @ 25°C	Pen@4C,Pen@25C	.94
	Pen@25C,Visc@60C	.96
	Pen@25C,R&B	.95
Modulus @ 0°C	Visc@135C,R&B	.89
	FDEngr,FDTrue	.84
	FDEngr,T&TPeak	.83
Modulus @ -10°C	Visc@60C,Toughness	.95
	FDArea,FDTena	.96
	FDPArea,FDTena	.95
Ind. Tens. @ 25°C	Pen@25C,Visc@60C	.91
	Pen@25C,FDArea	.87
	Pen@25C,FDPArea	.87
Ind. Tens. @ -10°C	Pen@25C,Visc@60C	.91
	Pen@25C,R&B	.90
	Visc@60C,Tenacity	.86
Comp. Strain @ 25°C	Visc@60C,Visc@135C	.67
	Visc@135C,Toughness	.69
	Visc@135C,FDTena	.65
Comp. Strain @ -10°C	Pen@4C,Pen@25C	.69
	FDPArea,Tenacity	.74
	Pen@25C,FDArea	.68
Fatigue	Pen@25C,FDArea	.82
	Pen@4C,RDArea	.74
	Pen@25C,FDTena	.78
Perm. Def.	Pen@25C,FDTena	.90
	Pen@25C,Toughness	.77
	Pen@25C,Tenacity	.82

Pen@4C = Penetration @ 4°C; Pen@25C = Penetration @ 25°C; Visc@60C = Viscosity @ 60°C; Visc@135C = Viscosity @ 135°C; FDEngr = Force Ductility Maximum Engineering Stress; FDTrue = Force Ductility Maximum True Stress; FDPArea = Force Ductility Peak Area; FRDArea = Force Ductility Total Area; FDTena = Force Ductility Tenacity; Toughness = Toughness; Tenacity = Tenacity; T&TPeak = Toughness and Tenacity Peak Area

Aging of the binders by the use of a rolling thin film oven had a significant effect on both the conventional binders and polymer modified binders. Some of the polymer additives have been reported to break down when exposed to high temperatures and oxygen for extended periods. This was demonstrated by a couple of the additives studied in this project when samples of stiffer asphalts (polyethylene and polychloroprene) in force ductility and T&T testing broke in brittle failure after being aged in the RTFO.

Viscosity, as discussed before, is of questionable validity when applied to polymer modified asphalts. Most of the additives used to modify binders have a tendency to thicken the base asphalt. The long chains of polymers will cause a type of coagulation to occur which will affect viscosity measurements. But this effect may be exaggerated to an extreme by using a viscosity tube that passes the asphalt through a tortuous path. Using a straight-walled tube has been suggested by some researchers, and by reviewing the results of this project, this suggestion seems worthy of investigation.

The SB, SBR, and SBS modified materials supplied for final testing were supplied to the same specifications by the same suppliers as for preliminary testing. There were, however, large variations in material properties between preliminary materials and final materials. This was particularly true for penetration at 4°C and force ductility properties for the SB and SBS modified materials.

6.0 DISCUSSION OF RESULTS

Ideally, binder tests can be identified which predict mix performance in the field. Since the scope and duration of this project did not allow for field testing, the best mix performance indicators that could be obtained were mix test results from laboratory testing. The combination of the preliminary and final testing programs provided the opportunity for one or more binder tests to illustrate their ability to predict important mix properties for two different aggregates and mix designs, regardless of the conventional or modified binder used. The preliminary testing employed five different binders and therefore generated only a maximum of five data points for correlation of binder and mix properties. Some correlations only involved four data points. The final testing, which employed ten different binders, produced a maximum of ten data points for correlation.

6.1 Variations in Polymer Modified Binders

The SB, SBR, and SBS modified binders were each supplied for the preliminary and final testing programs by the same suppliers to the same specifications. That is, for example, the SB specification and supplier were the same for both preliminary and final testing programs. In spite of this, large variation in properties occurred for the SB and SBS modified binders between materials supplied for preliminary and for final testing. Possible explanations are that the blending of small quantities of these materials makes it difficult to develop uniformity or that the modifiers were not completely compatible with the base asphalts.

6.2 Problems with Conventional Viscosity Tests

Problems occurred when conventional viscosity measurements were made with polymer modified binders at 60°C and possibly at 135°C. Absolute viscosity measurements resulted in tube-clogging in some cases. As discussed by Shuler (1987), this is due to the shear-thinning properties of polymers. One way to solve this problem is to move away from conventional viscosity testing toward constant power viscosity (Roque, Tia, and Ruth 1987) or some other method of constant stress viscosity measurement when polymers are used.

6.3 Binder Strength Tests

One of the questions hoped to be answered by the testing programs was, "Are tests such as force ductility and toughness and tenacity required?" The answer, based on preliminary and final testing would seem to be, "maybe — they show promise for predicting mix properties." These tests provided the best predictive ability for mixture strength and modulus properties.

The preliminary test program ran both of these tests at the same temperature (25°C) to see if similar results could be obtained. They could not. 25°C is not a good temperature for force ductility testing. Most binders cannot be taken to failure at this temperature in force ductility testing because of extension limits of the testing equipment. Different strain rates may also confuse the issue. Toughness and tenacity testing uses 20 cm/min. while force ductility testing uses 5 cm/min.

Toughness and tenacity testing splits the total area under the load deformation curve into two areas. Toughness is defined as the total area, and tenacity is defined as the area of the tail of the curve. What is of most interest is that the best correlations for toughness and tenacity properties were not for toughness or for tenacity, but rather were for the area which represents the difference of these two areas, which the authors have chosen to call "peak area," for lack of a better term. Developing areas analogous to toughness, tenacity, and peak area for the force ductility stress-strain curves also produces good correlations for "peak area." However, "peak area" is strongly related to engineering stress, which is easier to compute. Since the two properties showed relationship to each other with R-squared > 0.95, it may not be worth the extra effort to compute "peak area."

6.4 Long-Term Aging

Another question which the testing programs attempted to answer was, "are tests of long-term aging effects required when polymers are used?" Time and budget constraints permitted the inclusion of only a small-scale aging test in the preliminary testing program. Due to a combination of procedural errors and some values that look questionable, it is uncertain whether the results of this testing can be relied upon. If, however, the numbers can be believed, there is evidence that the polymer modified binders were affected more adversely by Pressure Oxygen Bomb (POB) conditioning than was the conventional binder. This

testing therefore does nothing to alleviate concerns regarding the long-term durability of polymers raised by Button and Little (1987), Goodrich (1988), and Krivohlavek (1988). If, in fact, polymer binders degrade more quickly than conventional binders, perceived present benefits could quickly disappear. It appears wise to develop some type of specification binder test which can be used to reject binders which may be subject to accelerated aging. The POB, Long-Term Durability (LTD) test (Goodrich 1988), and "tanning booth" described by Krivohlavek (1988) are possibilities. More research is needed.

6.5 Predicting Mix Properties From Binder Tests

Using results of binder and mix testing from both the preliminary and final testing programs, attempts were made to correlate all binder properties with all mix properties. Promising correlations were identified. For purposes of this study, a relationship was considered promising when the coefficient of determination (R-squared) was greater than or equal to 0.70.

Because of the larger number of data points in the final testing, the approach to analysis was to focus on promising relationships from the final testing. Since preliminary testing only resulted in four or five data points, its results were not given much weight. Preliminary testing served primarily to aid in planning final testing. The approach taken is that high R-squared on preliminary testing can serve as supporting evidence to high R-squared on final testing, but that low R-squared on preliminary testing does not necessarily rule-out a relationship or negate high R-squared values for final testing. This is because of the dramatic volatility of R-squared when only four or five data points are involved. Figure 6.1 illustrates the point. The R-squared for the final test data presented in Figure 6.1 is 0.75 and the relationship is positive or direct. If only A2, C2, D2, and E2 had been selected for testing, the R-squared would have been 0.10 and the relationship inverse. If only these four data points had been generated, it is easy to see how a slight shift of A2 upward and to the right could even result in a high R-squared for an inverse relationship.

The individual binder properties which appear to be the best predictors of mix performance based on simple linear regression are presented in Table 6.1 and are discussed below. Multiple regression results are discussed in a subsequent section.

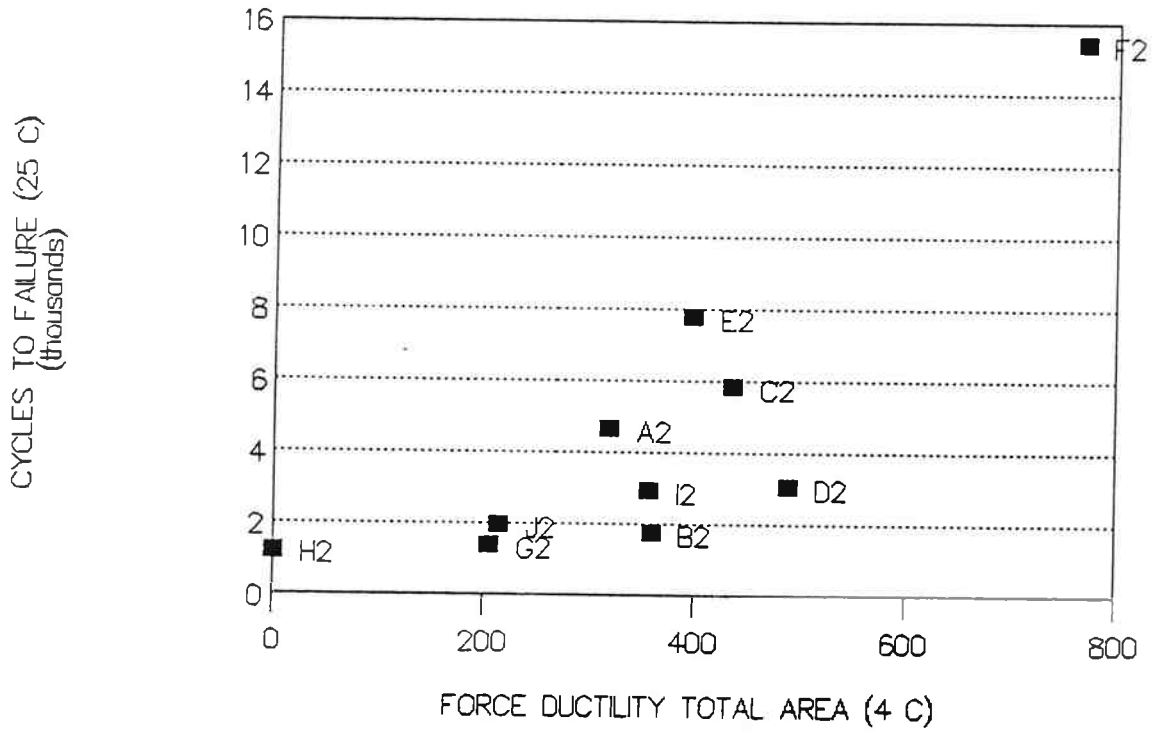


Figure 6.1. Fatigue Life vs. Original Force Ductility Total Area — Final Testing

6.5.1 Predicting Fatigue Life

The only single binder properties which showed promise for predictive ability in the final testing were original force ductility total area (R-squared = 0.75) and its component area force ductility "tenacity" (0.73).
The scattergram for fatigue cycles to failure vs original force ductility total area for final testing is shown in Figure 6.1.

Correlations with low temperature (0°C) fatigue lives were not good, and even if they had been, the results of low-temperature fatigue testing showed so much scatter that the results can not be relied upon. Because of this scatter, low-temperature fatigue testing was dropped from the final testing program.

6.5.2 Predicting Rutting Resistance

The two mix tests aimed at predicting rutting resistance were 40°C uniaxial compression creep (preliminary) and permanent deformation data from 25°C diametral fatigue testing (preliminary and final). No promising correlations

Table 6.1. Promising Predictions from Final Testing — R-Squared Values

Performance	Mix/Binder Properties	Final
Fatigue Life	Diametral Fatigue	
	Orig FD Total Area	.75
	Orig FD "Tenacity"	.73
Rutting Resistance	Uniaxial Creep	N/T
	Permanent Deformation	<.70
Low-Temperature Crack Resistance	Ind. Tens. Stress @ -10°C, .05 in/min	
	Orig. Penetration (25°C)	.88
	Orig. FD Engr Stress (4°C)	.71
	Orig. FD Peak Area (4°C)	.78*
	Orig. PI	.83
	RTFO Penetration (25°C)	.81
	Modulus @ 0°C	
	Orig. FD Engr Stress (4°C)	.80
	Orig. FD Peak Area (4°C)	.82*
	Orig. T&T Peak Area	.70
	Orig. Fraass Pt	.78*
	RTFO FD Engr Stress (4°C)	.76*
	RTFO FD Peak Area (4°C)	.71*
	Modulus @ -10°C	
	Orig. T&T Peak Area	.70
	Orig. FD Engr Stress (4°C)	.83
	Orig. FD Peak Area (4°C)	.91
	Orig. PVN	.72
	Orig. Fraass Pt.	.80
	RTFO FD Engr Stress	.89
	RTFO FD Peak Area	.84
Temperature Susceptibility at Low Temperature	Modulus Difference, -10°C, 25°C	
	Orig. FD Engr Stress (4°C)	.76
	Orig. FD Peak Area (4°C)	.84
	Orig. PVN	.74
	Orig. Fraass Pt.	.82
	RTFO FD Engr Stress (4°C)	.89
	RTFO FD Peak Area	.83
Modulus at 25°C	Diametral Resilient Modulus	
	Original Penetration (25°C)	.87
	Orig. T&T Peak Area	.70
	Orig. FD Engr Stress (4°C)	.74
	Orig. FD Peak Area (4°C)	.79
	Orig. PI	.78
	RTFO Penetration (25°C)	.82
	RTFO T&T Peak Area	.77*
Tensile Strength at 25°C	Indirect Tens. Stress @ 25°C, 2in/min	
	Orig. Penetration (25°C)	.86
	Orig. FD Engr Stress (4°C)	.74
	Orig. FD Peak Area (4°C)	.80
	Orig. PI	.82
	RTFO Penetration (25°C)	.84

N/T = Not Tested
* = > 0.70 in preliminary testing

were obtained for uniaxial compression creep testing in the preliminary testing. This test was dropped from the final testing program. No promising correlations were obtained for permanent deformation data in the final testing.

6.5.3 Predicting Resistance to Thermal Cracking

Low-temperature, low strain-rate indirect tensile testing was the mix testing procedure chosen to provide an indicator of a mix's ability to resist thermal cracking. Probably the best indicator which could be obtained from this test would be tensile strain at failure. Laboratory equipment restraints made it impractical to measure this property. Instead, maximum tensile stress, maximum compressive strain, and work to failure were determined.

Final testing produced no promising predictors for compressive strain or work to failure. However many promising predictors of tensile stress at -10°C were found. These are original (0.88) and RTFO (0.81) penetration at 25°C, original PI (0.83), and original force ductility (4°C) engineering stress (0.71) and peak area (0.78). Considering results from preliminary testing, original and RTFO penetration at 25°C and original force ductility peak area look most promising. Figures 6.2 and 6.3 show scattergrams for the relationships of penetration at 25°C and force ductility peak area with indirect tensile stress at -10°C.

Modulus at 0°C and -10°C could also be considered indicators of resistance to low-temperature thermal cracking. Low modulus at low temperature is preferred. Force ductility (4°C) properties were found which predicted these properties in final testing. These were original and RTFO peak area and maximum engineering stress. As will be discussed below, these properties also served as reasonable predictors of strength and modulus at 25°C. In these relationships larger force ductility values imply larger mix property values. At cold temperatures, since low modulus is desired, "lower force ductility values are better." Therefore, it would be preferable to find a different predictor of low-temperature modulus. Original PVN showed some promise at -10°C, but Fraass brittle point of original binders was a promising predictor of modulus at both 0°C and -10°C. Therefore, the use of Fraass point to predict cold temperature properties is preferred over force ductility properties. Scattergrams for Fraass point vs mix modulus (0°C) are shown in Figures 6.4 and 6.5.

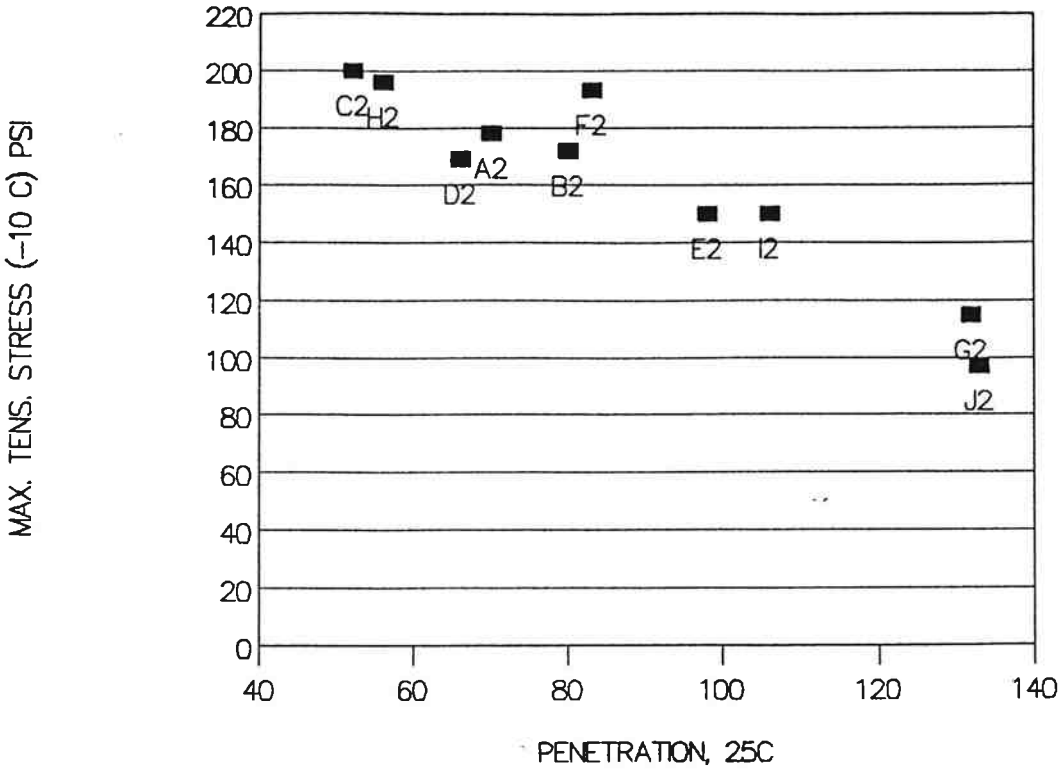


Figure 6.2. Tensile Strength (-10°C) vs. Penetration at 25°C - Final Testing

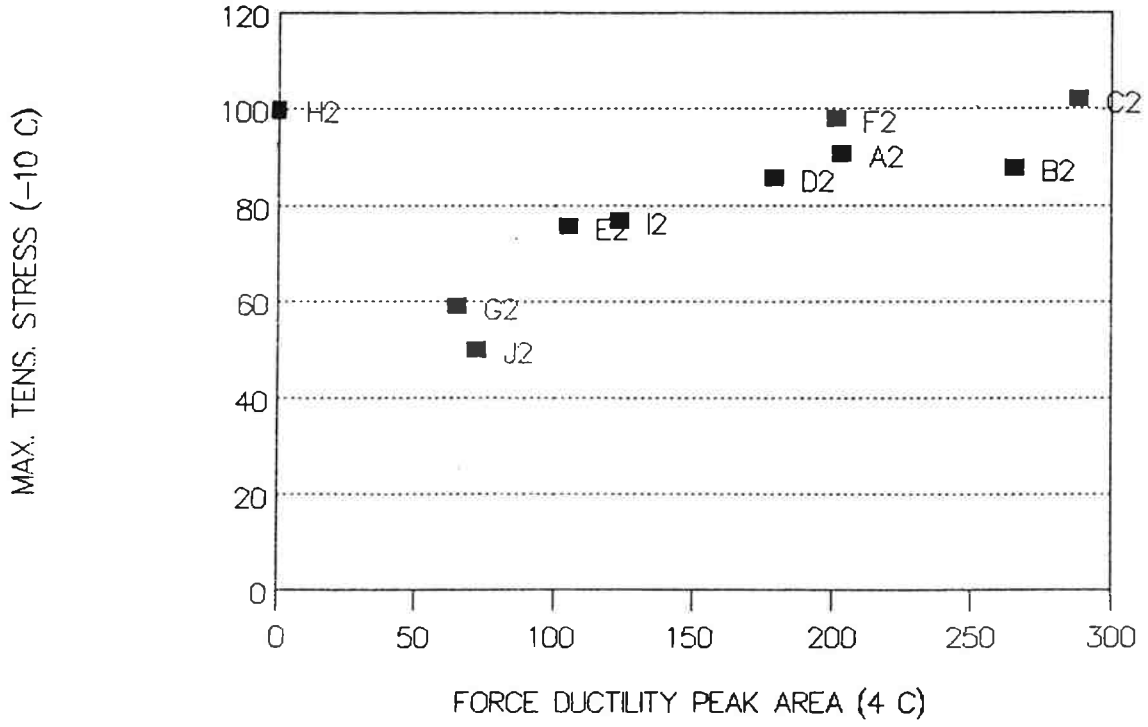


Figure 6.3. Tensile Strength (-10°C) vs. Original Force Ductility Area — Final Testing.

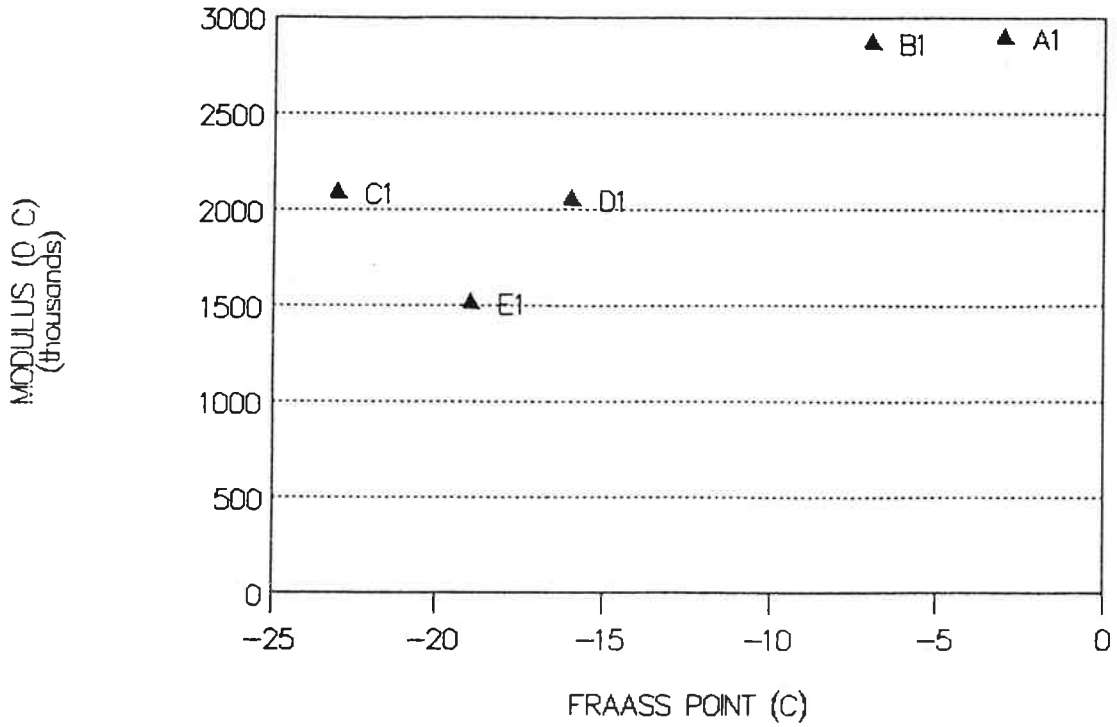


Figure 6.4. Modulus (0°C) vs. Original Fraass Point — Preliminary Testing

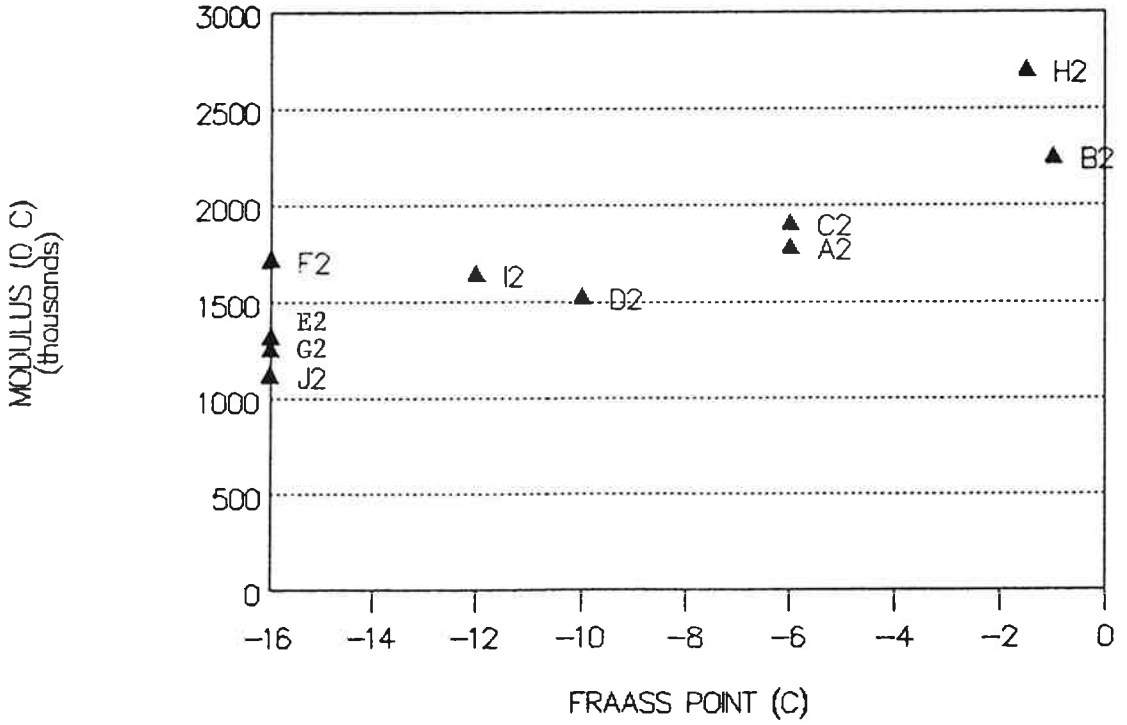


Figure 6.5. Modulus (0°C) vs. Original Fraas Point — Final Testing

It should be noted that Fraass point for RTFO residues, POB Fraass point, loss tangent at 40°C, and force ductility true stress at 25°C had promising predictions of low-temperature properties in the preliminary testing, but could not be "promising" in the final testing since, for various reasons, they were not part of the final testing program.

6.5.4 Predicting Low-Temperature Temperature Susceptibility

To further evaluate thermal-cracking potential, an evaluation of the sensitivity of mix modulus to changes in temperature at low temperatures was made. To do this, change in modulus between -10°C and 25°C was computed for each mixture. Binder properties were then correlated against these mixture values. Three binder properties warrant discussion: PI (Penetration Index); PVN (Pen-Vis Number); and Fraass brittle point.

The two most accepted measures of temperature susceptibility of asphalts are PI (Penetration Index) and PVN (Pen-Vis Number). These measures concentrate on binder consistency at temperatures of 25°C and above. They do not utilize measures of consistency below 25°C. Nonetheless, if the plot of consistency on a Bitumen Test Data Chart (BTDC) is linear, PI and PVN should also predict low-temperature temperature susceptibility of mixtures. When correlations were made with mixture modulus change, PVN correlated better than PI. Original PVN had R-squared of 0.73 for the final test program and favorable correlation in the preliminary program. Since significant problems were encountered in measuring viscosity by conventional means for some of the polymers, it is believed that PVN correlations would be better if a more accurate means of determining viscosity is used. As it was, PVN with both original binders and residues correctly identified the two most low-temperature sensitive mixes from both the preliminary and the final testing programs.

Interestingly, Fraass Brittle Point for original binders (RTFO residues were not tested in both testing phases) was a better predictor of the low-temperature sensitivity of the resulting mix as predicted by modulus versus temperature curves. Final test R-squared was 0.82 with favorable preliminary correlation. Scattergrams of this relationship are shown in Figures 6.6 and 6.7. Until routine viscosity testing for polymer modified asphalts can be improved, Fraass Brittle Point appears to be an acceptable method for predicting rate of change of mix modulus at low temperatures.

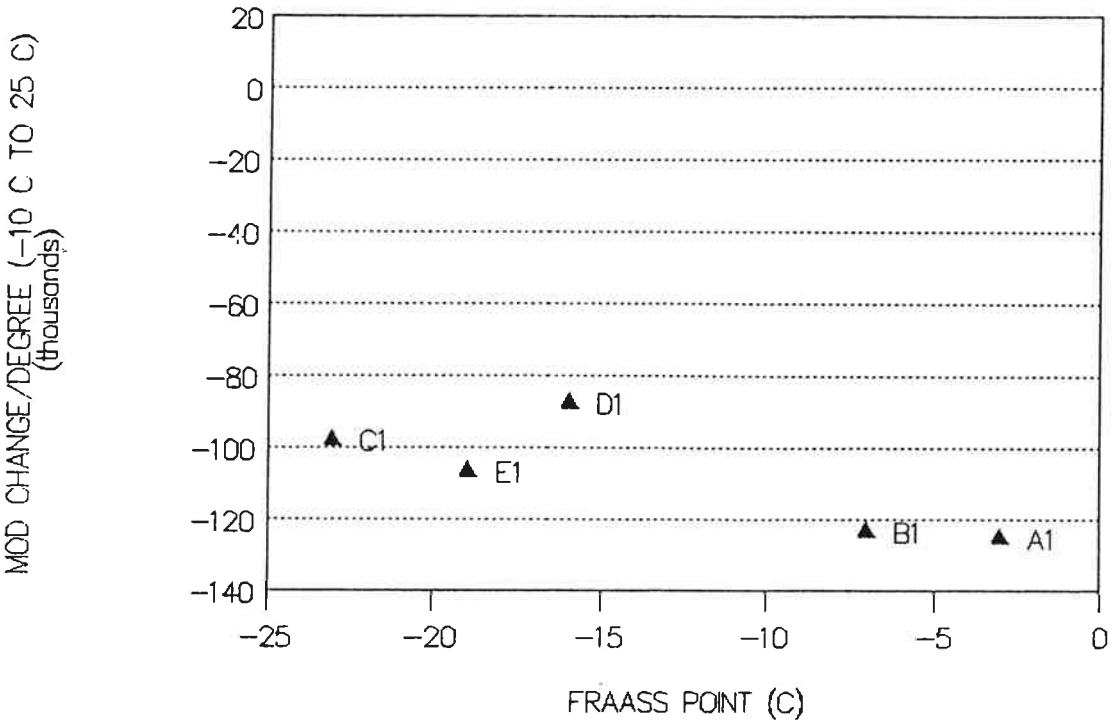


Figure 6.6. Modulus Change vs. Original Fraas Point — Preliminary Testing

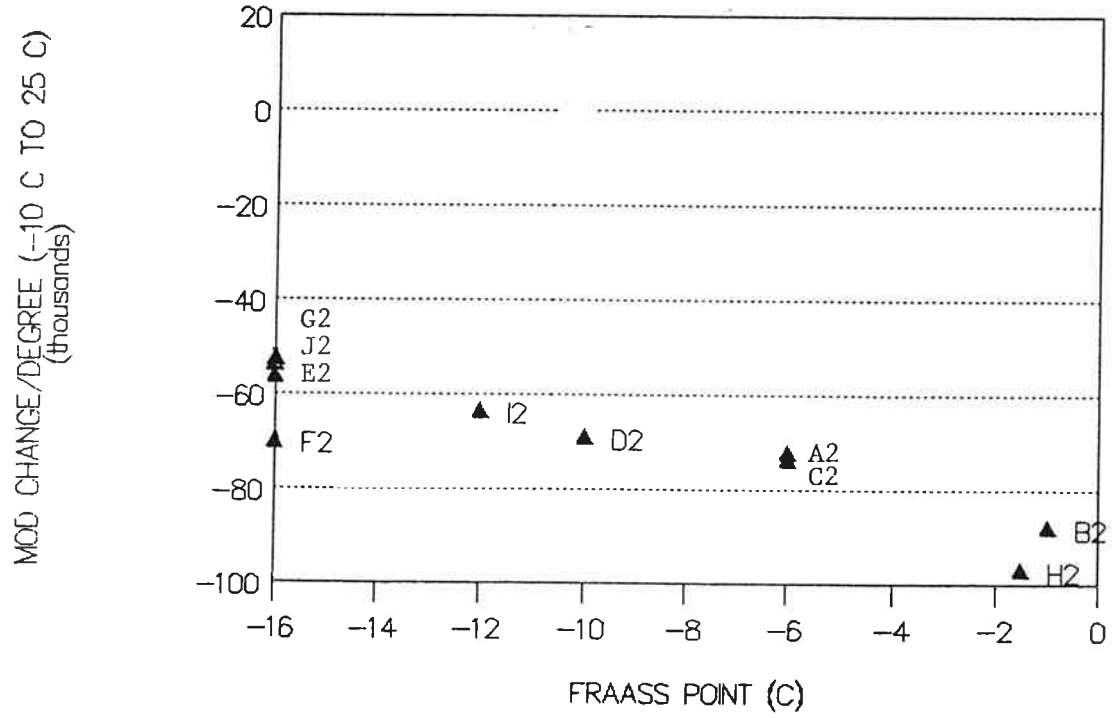


Figure 6.7. Modulus Change vs. Original Fraas Point — Final Testing

Original RTFO force ductility engineering stress and peak area also showed promise for predicting modulus change. PVN and Fraass point are of more interest because they provide indicators separate from "strength" properties.

6.5.5 Predicting Stiffness at 25°C

Modulus at 25°C is used in mechanistic pavement design, is considered a measure of quality of asphalt concrete pavement, and is used to predict other mixture properties. Correlations of all binder properties were made with modulus values at 25°C. The most promising binder properties and their final R-squared were original penetration at 25°C (0.87), RTFO penetration at 25°C (0.82), original force ductility peak area at 4°C (0.79), and RTFO toughness and tenacity peak area (0.77).

6.5.6 Predicting Tensile Strength at 25°C

Tensile strength at 25°C is considered an important measure of quality of asphalt concrete, and is used to predict fatigue life. Correlations of all binder properties were made with tensile strength values at 25°C. The most promising predictors were original and RTFO penetration at 25°C with final R-squared values of 0.86 and 0.84.

6.5.7 Predicting Mix Properties by Multiple Regression

The five data points of the preliminary testing program were clearly inadequate for multiple regression analysis. The maximum ten data points provided by the final testing are marginal for multiple regression. Twenty points would be preferred. Nevertheless, analysis was attempted for the final testing program selecting pairs of binder tests as predictor variables.

Penetration at 25°C was the most helpful variable in explaining variability when paired with other binder properties in multiple regression analysis. Two results are worthy of discussion.

The combination of penetration at 25°C and force ductility total area showed promise for predicting fatigue life (original R-squared = 0.79; FTFO = 0.82). However, a look at the plot of force ductility area vs penetration at 25°C for RTFO residues (see Figure 6.8) shows the problems in writing a specification based on this relationship. On the plot, 100% represents the binder with the longest fatigue life in the final testing program and the remaining percentages

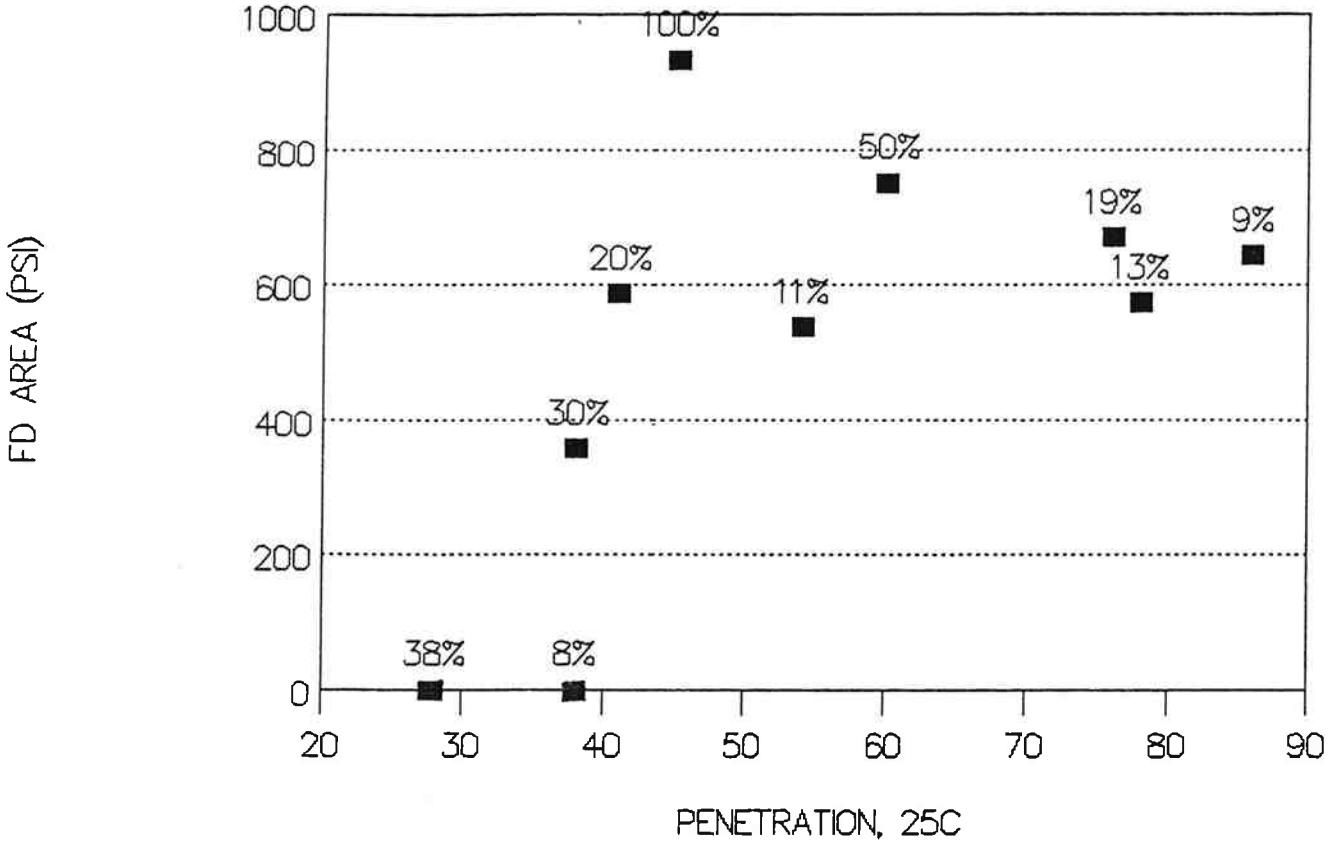


Figure 6.8. RTFO Force Ductility Total Area vs. RTFO Penetration at 25°C — Final Testing

show the relative fatigue lives of the other binders. The two best performers can easily be isolated with a maximum penetration, minimum area requirement, but separating moderate performers from poor performers is not as straightforward. When the preliminary test data is added to the plot, the usefulness of the relationship further breaks down. Ten and 20% performers become intermingled with 50 and 100% performers.

The combination of penetration at 25°C and force ductility "tenacity" or "tail area" showed promise for predicting resistance to permanent deformation (RTFO R-squared = 0.90). Figure 6.9 shows a plot of force ductility "tenacity" vs penetration at 25°C for RTFO residues. Again, the top two performers may easily be separated with a maximum penetration/minimum area requirement. The midrange performers even show some separation form the poorest performers. However, when preliminary test data is added to the plot, the relationship breaks down, with a 12% performer intermingled with 100% performers and 50% performers.

A word of caution is in order. Permanent deformation data were generated from the diametral fatigue test. Permanent deformation results are closely correlated with fatigue lives as defined in this study. Therefore, to a large

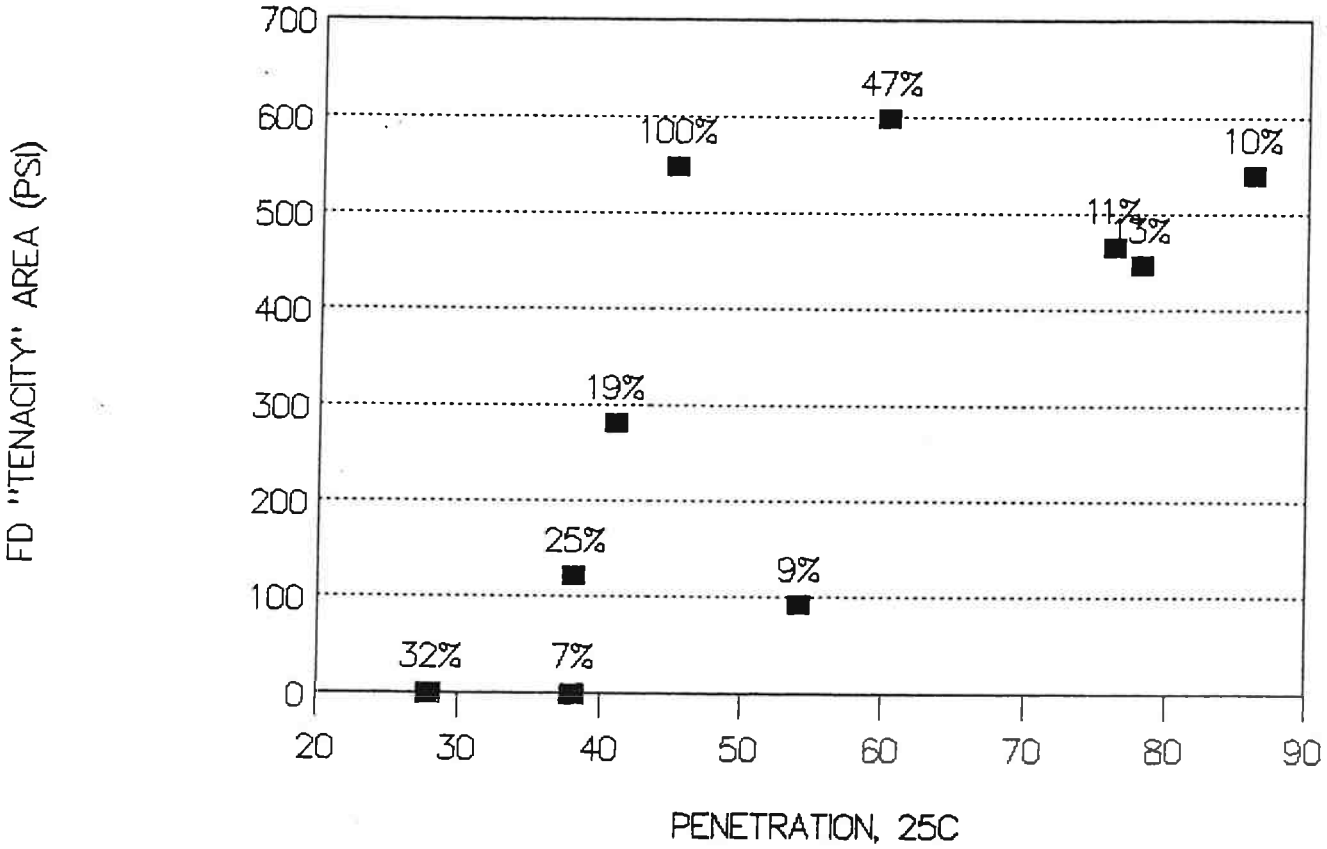


Figure 6.9. RTFO Force Ductility "Tenacity" vs. RTFO Penetration at 25°C — Final Testing

extent, predicting diametral fatigue life is also predicting permanent deformation, and vice versa.

It is really only in the area of fatigue and permanent deformation that multiple regression analysis indicates that force ductility testing contributed more to predicting mix properties than did simple binder tests already in common usage. Combinations of RTFO penetration at 25°C, viscosities at 60°C and 135°C, and ring and ball softening point produced R-squared values approximating 0.89 or better for modulus at all temperatures (-10°C, 0°C, 25°C) and maximum indirect tensile stress at both temperatures (-10°C, 25°C). See Table D.3.

6.5.8 Correlation Summary

Penetration at 25°C and force ductility peak area and maximum engineering stress appear to be the best predictors of strength and stiffness at all temperatures. In addition, Fraass point and PVN show promise for predicting low-temperature temperature susceptibility and low-temperature stiffness. Force ductility total area ("toughness") and "tenacity" or "tail area" show some

promise for predicting fatigue life, particularly when paired with penetration at 25°C. Force ductility "tenacity" shows some promise for predicting permanent deformation at 25°C when paired with penetration at 25°C.

Another way to evaluate relationships is to determine which individual correlations showed promising R-squared relationships in both preliminary testing and final testing. When this is done, the only binder properties producing R-squared of greater than 0.70 in simple linear regression in both testing programs are as follows:

1. Original force ductility (4°C) peak area predicting indirect tensile stress at -10°C.
2. Original force ductility (4°C) peak area predicting modulus at 0°C.
3. RTFO force ductility (4°C) peak area predicting modulus at 0°C.
4. RTFO force ductility (4 C) maximum engineering stress predicting modulus at 0°C
5. Original Fraass point predicting modulus at 0°C.
6. RTFO toughness and tenacity "peak area" predicting modulus at 25°C.

Of these, numbers two and six showed the strongest correlations. Five out of six of these predictions are for low-temperature mixture properties. Four of these same five predictors use low-temperature binder tests. Four of the predictors utilize force ductility testing.

In addition, RTFO loss tangent at 40°C might have been promising in both preliminary and final testing, had it been included in final testing. The equipment required for dynamic mechanical analysis upon which the computation of loss tangent is based is not commonly available for highway agency use, however.

Although force ductility peak area showed better correlations than maximum engineering stress, it should be pointed out that the two are closely related. In fact, simple linear regression of these two properties produced R-squared in excess of 0.95. Since maximum engineering stress is easier to compute, it is questionable whether the extra effort of obtaining peak area is worthwhile.

6.6 Recommendations for Specification Testing Based on This Research

Based on the laboratory testing performed for this research project, the following binder properties show promise for inclusion in a generic "premium" binder specification:

Consistency:

Fraass brittle point
Penetration at 25°C
PVN

Strength characteristics:

Force ductility testing at 4°C for "peak area", total area, "tenacity" area, and maximum engineering stress.

The results of this research are consistent with the preponderance of literature in concluding that polymer modification can improve the temperature susceptibility of asphalts. This study was only interested in temperature susceptibility at low temperatures. The two most accepted methods of measuring temperature susceptibility, PI and PVN, are based on consistency measurements only at temperatures of 25°C and above and present problems when polymer modified asphalts are encountered. Some of these binders have non-linear curves when consistency data is plotted on BTDC (bitumen test data charts). Figure 6.10 provides an example. Conventional viscosity measurements produce misleading results because of the shear susceptibility of polymers. Nevertheless, even with questionable viscosity values, the use of PVN correctly identified the binders which were most temperature-susceptible at low temperatures.

Fraass brittle point showed better correlations with mix low-temperature temperature susceptibility in this research than did PVN. Fraass brittle point offers an alternative to the use of PVN for control of low-temperature temperature susceptibility — an alternate which avoids the problem of viscosity measurement for polymer modified asphalts and concentrates on the low-temperature end of the temperature-consistency curve. Use of Fraass brittle point in conjunction with penetration grading would completely eliminate the need for viscosity testing in binder specifications. Proper use of either PVN or Fraass point in binder specifications should assure the use of either a conventional or modified asphalt with low temperature susceptibility at low temperatures.

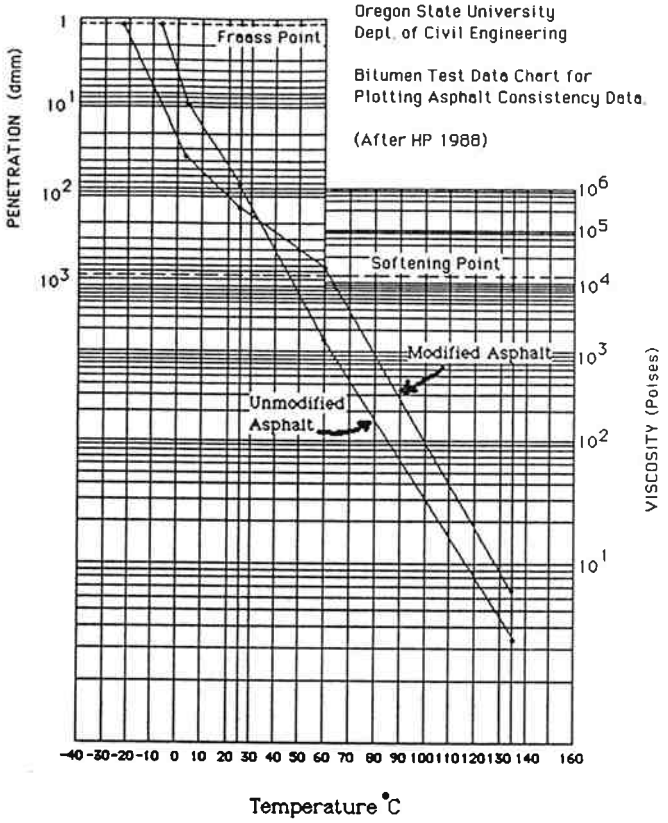


Figure 6.10. Non-Linearity of Temperature-Consistency Curve for Modified Binder

From a strength standpoint, force ductility testing appears to offer the most potential for predicting mix performance. This statement is based on limited test data, and is not universally agreed upon in the literature. For the laboratory testing in this research, however, it does show promise for predicting strength and stiffness of mixtures, particularly at low temperatures and particularly if binders with very low values (brittle materials) are rejected. Penetration at 25°C, a much simpler test, showed promise for predicting strength at both low and moderate temperatures.

In summary, PVN and Fraass point may be used to control low-temperature temperature susceptibility of hot mix. Force ductility areas may be used to eliminate brittle binders, and show promise for controlling strength and stiffness properties of hot mix (given a specific aggregate source and gradation). Penetration at 25°C was a good overall indicator of strength and stiffness and, when combined with force ductility area values, shows promise of predicting fatigue life and permanent deformation as measured by diametral testing.

7.0 CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations which follow are based on limited testing involving three conventional and six polymer modified binders with two different aggregates and design mixes. For the binders and mixes tested, the following conclusions are warranted:

1. Force ductility total area and "tenacity" area for original binders show some promise for predicting fatigue life as determined by diametral testing. The combination of penetration at 25°C and force ductility total area for RTFO residues showed the most promise for predicting fatigue life.
2. Mix permanent deformation resistance as defined in this study can <u>not</u> be predicted with any single binder test studied. The most promising basis for predicting pavement deformation resistance of the mix is the combination of force ductility "tenacity" or "tail area" with penetration at 25°C.
3. Improvements in low-temperature temperature susceptibility can be predicted with either Fraass brittle point or PVN.
4. The area under the primary peak of the force ductility stress/strain curve or the toughness and tenacity force/extension curve has better predictive ability of mixture properties than either the total area (toughness) or tail area (tenacity). However, it is only a marginally better predictor than maximum engineering stress, which is easier to compute.
5. With the exception of low-temperature modulus prediction, more force ductility peak area is better.
6. Force ductility (4°C) testing of RTFO residues <u>does</u> clearly identify the more brittle binders.
7. Penetration at 25°C shows promise for predicting modulus at 25°C and indirect tensile strength at 25°C.
8. It is only in the area of diametral fatigue and permanent deformation that multiple regression analysis indicates that force ductility testing contributed more to predicting mix properties than did simple binder tests already in common usage. Pairings of RTFO penetration at 25°C, viscosities at 60°C and

135°C, and ring and ball softening point produced R-squared values of 0.89 or better for modulus at all temperatures (-10°C, 0°C, 25°C) and maximum indirect tensile stress at both temperatures (-10°C, 25°C) tested.

9. The shear susceptibility of polymer modifiers creates problems when conventional viscosity measurements are made. Other types of viscosity measurement should be explored.
10. Testing of long-term aging effects on polymer modified binders is needed.
11. The very limited dynamic mechanical testing of binders performed in this research project showed promise for predicting mix properties.
12. Properties of the same modified binders supplied at different times for preliminary and final testing showed wide variations in physical properties.
13. The diametral fatigue testing results for SBS-modified binders in this research project showed much poorer performance than the generally outstanding beam fatigue results reported for these binders "in the literature."

8.0 IMPLEMENTATION

Force ductility testing and simple penetration at 25°C were binder tests which showed promise for predicting a great many mix properties. Fraass point showed an ability to identify the least brittle (or most brittle) binders for hot mix pavements. The combination of penetration and force ductility data showed promise for predicting fatigue and permanent deformation performance as measured by diametral testing.

Additional research aimed at generically relating binder properties with mixture properties should concentrate on studying sufficient numbers of binders to allow determination of statistically significant relationships and to allow evaluation of relationships based on multiple regression. This means that a minimum of 20 binders incorporating conventional and modified binders should be used. Such research should further explore the promising predictive ability of force ductility testing, particularly in combination with penetration at 25°C.

If additional research substantiates the ability of force ductility testing to predict important mix properties, transportation agencies may want to include force ductility requirements in specifications for "premium" binders. Fraass point may be used in specifying "premium" binders to eliminate brittle binders most prone to thermal cracking. Penetration at 25°C is already in common usage in asphalt specifications.

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APPENDICES

APPENDIX A

Binder Test Procedures

Force Ductility Test

The force–ductility test is a modification of the asphalt ductility test (ASTM D113). The principal alteration of the test consists of adding the force ductility proving ring (Figure A.1). The assembled apparatus is shown in Figure A.2. A second major alteration of the ASTM procedure involves the test specimen shape. A standard ASTM specimen is as shown in Figure A.3. The mold is modified as shown in Figure A.4 so that the specimen has a constant cross-sectional area for a distance of approximately 1.18 in. (3 cm). This mold geometry produces a deformation rate of .74 ± .01 cm/min between the gage marks of the test specimens at a fixed grips test rate of 1 cm/min (.4 in./min). The modified shape of the force ductility specimen allows computation of material stress and strain characteristics.

(Shuler, 1987; Anderson, 1976)

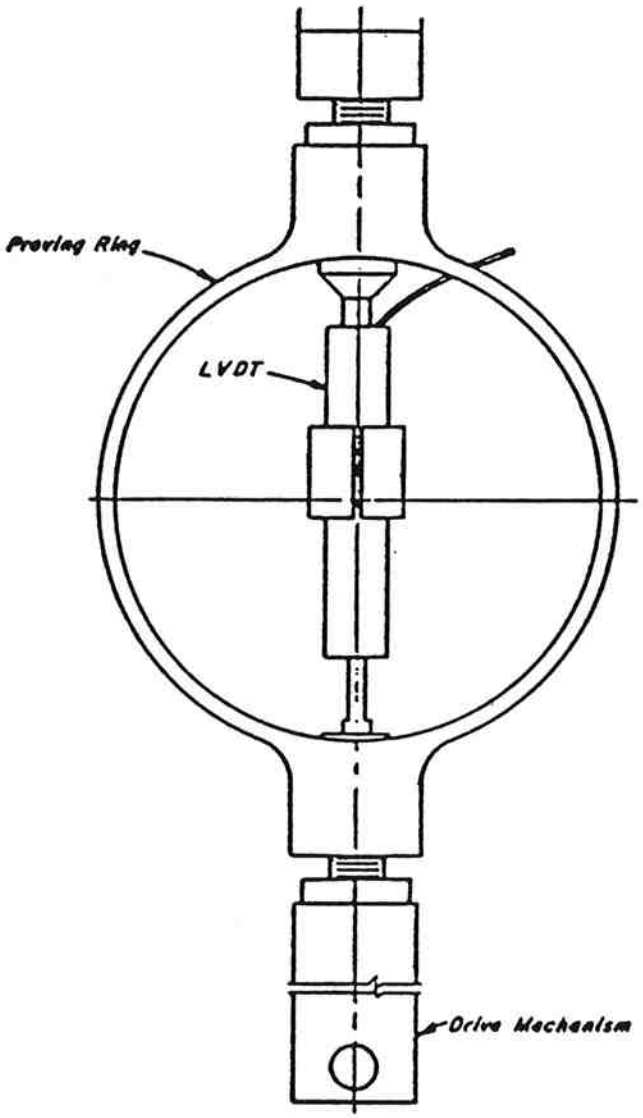


Figure A.1. Force Ductility Proving Ring (after Anderson, 1976)

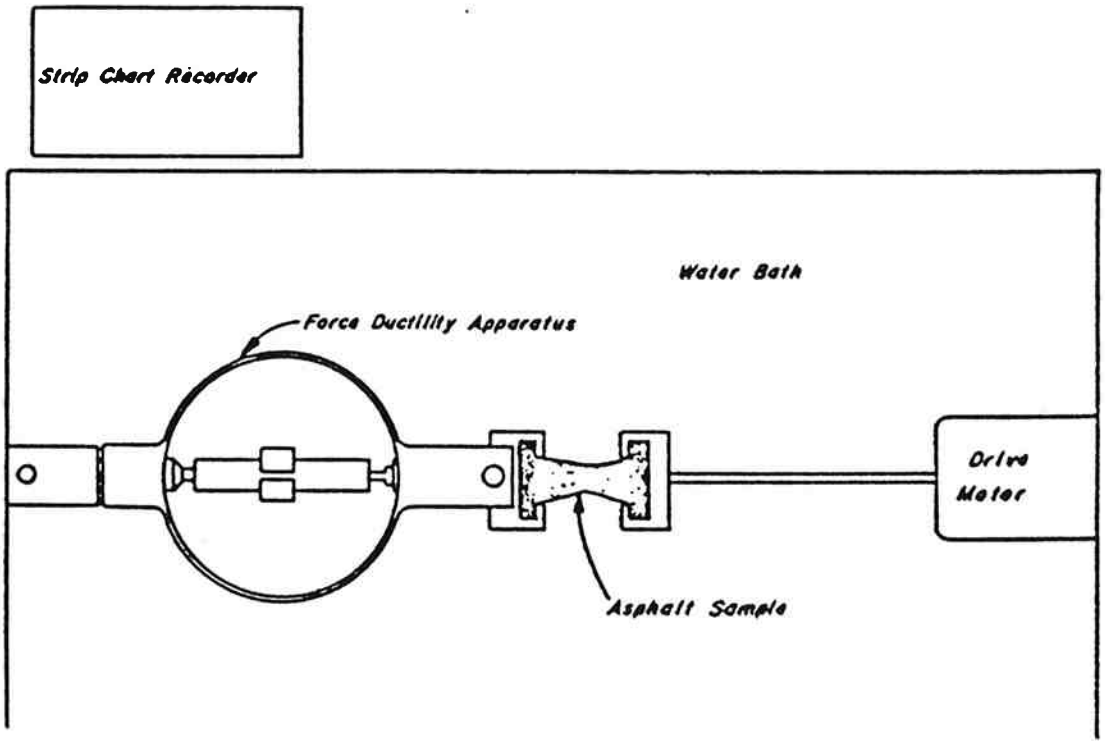


Figure A.2. Force Ductility Testing Equipment (after Anderson, 1976)

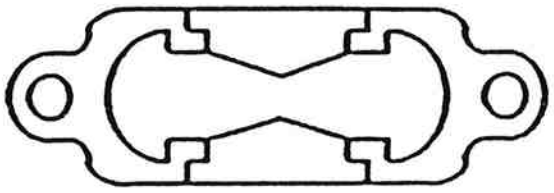


Figure A.3. ASTM D-113 Ductility Mold

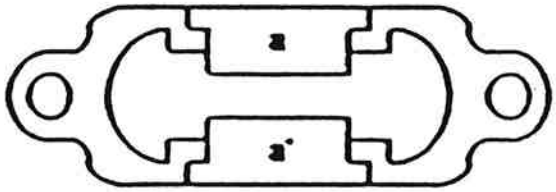


Figure A.4. Force-Ductility Mold

Dynamic Shear Test

Sample Preparation

Asphalt is heated to 150°C and poured into the mold shown in Figure A.5. The sample is cooled at room temperature for 24 hours, and then cooled slightly with ice and trimmed with a razor blade. The molds are stored in ice for about three hours; the specimens are then separated.

Test Procedure

The asphalt samples are placed in the testing apparatus (schematic shown in Figure A.6) between the two parallel disks shown in Figure A.7. "A strain profile is applied, sinusoidally in the case of a typical dynamic measurement to the sample, by a DC torque motor fed by a signal generator. A position transducer measures the actual strain, which is entered into the computer for the modulus computation. The deformation force (torque) is measured by gauges. The stress and deformation signals are amplified and fed to the computer." With this information, the various dynamic moduli, complex viscosities, and tan δ can be computed. A sample output from this procedure can be found in Figure A.8.

(Pink, Merz, and Bosniack, 1980)

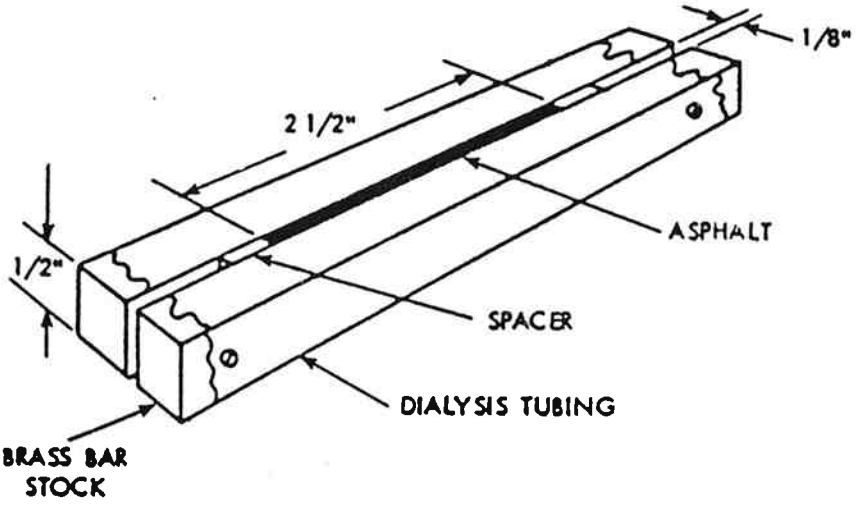


Figure A.5. Sample Mold

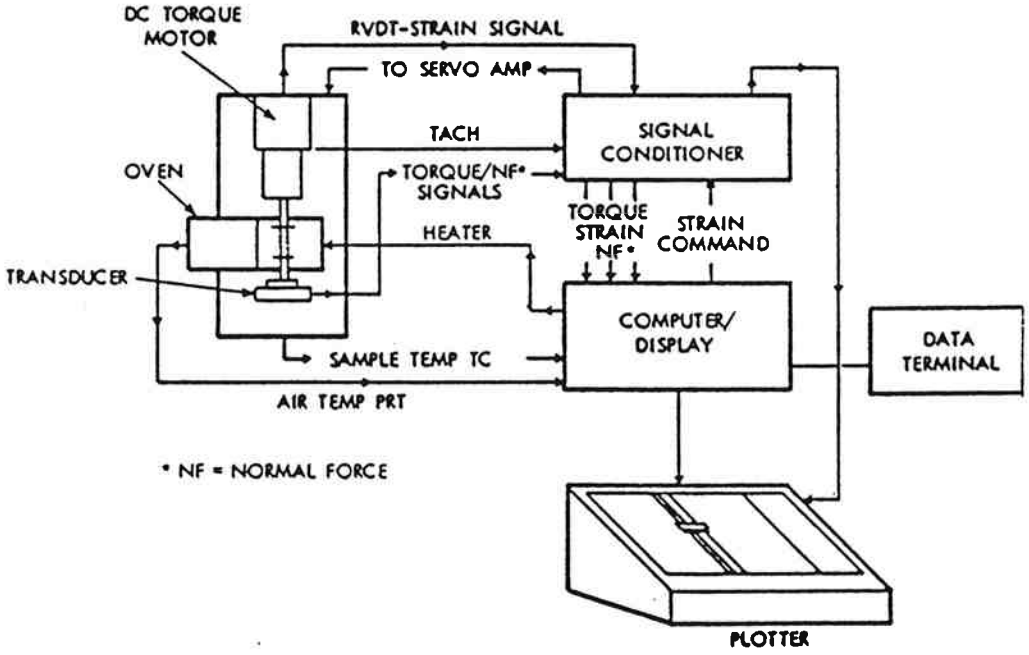


Figure A.6. Diagram of the Rheometrics Mechanical Spectrometer (Rheometrics, Inc., Union, NJ)

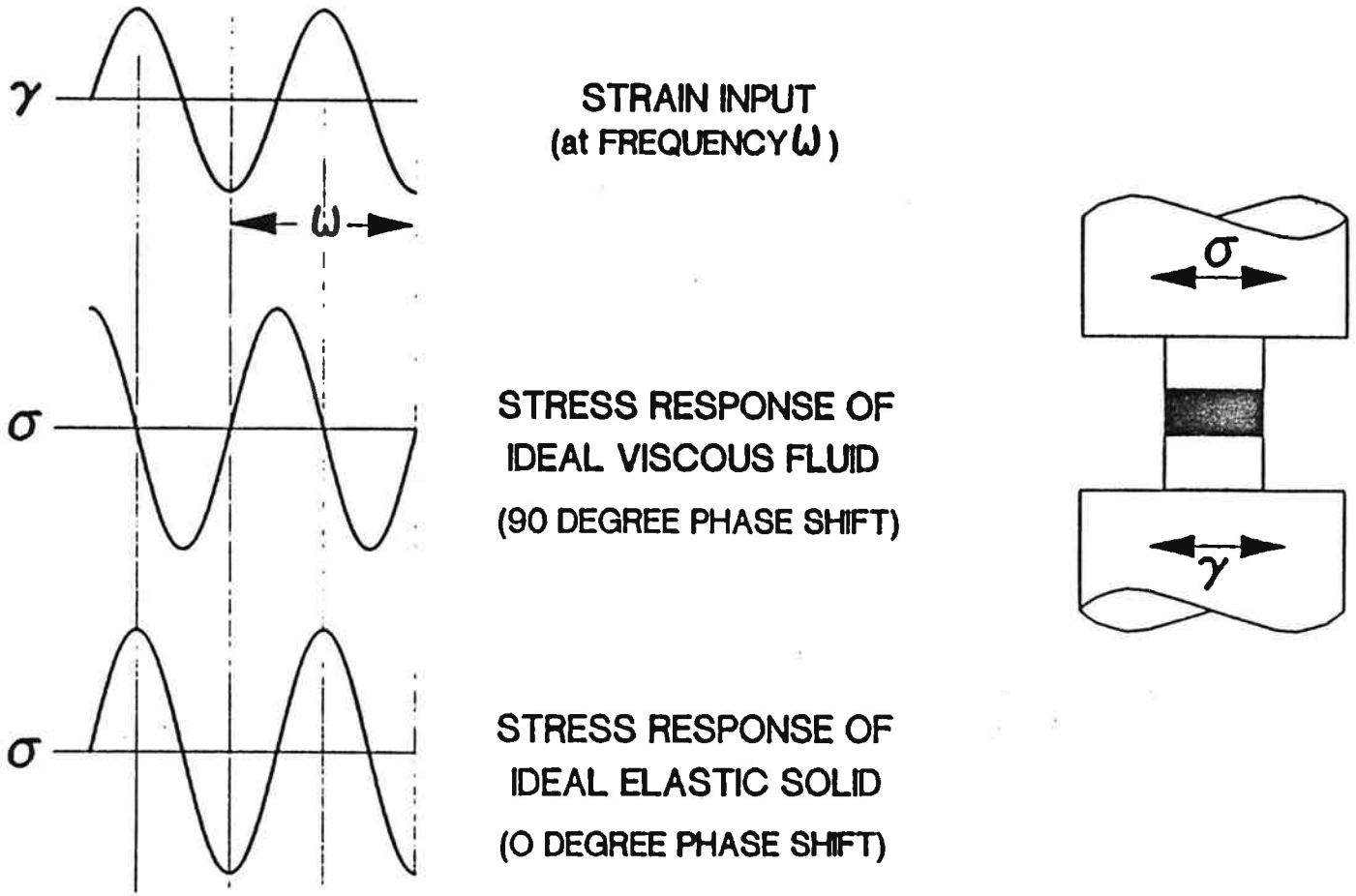


Figure A.7. Dynamic Mechanical Analysis (after Goodrich, 1988)

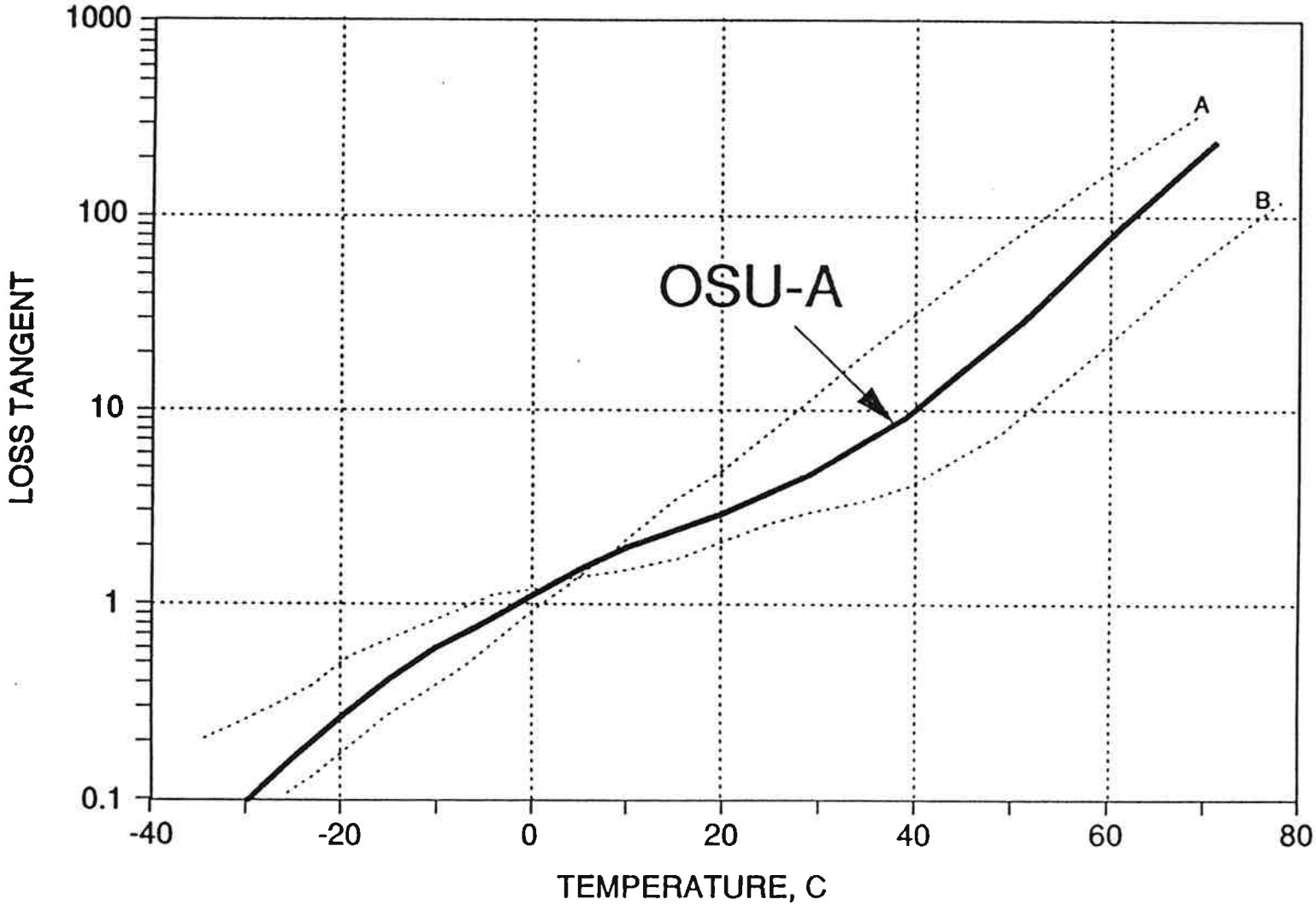


Figure A.8. Loss Tangent Versus Temperature

Toughness and Tenacity

Test Procedure

Thirty-six grams of the material to be tested are placed in a standard 3-oz. penetration tin. It is heated to 350°F. The tension head (Figure A.9) is placed into the tin so that the material is level with the diameter of the hemisphere. The sample is air cooled for 1 hour and cooled at 77°F for 1 hour. It is placed in a testing machine and the tension head is pulled at 20 in./min while the force vs. extension plot is recorded.

(Rienke, 1985)

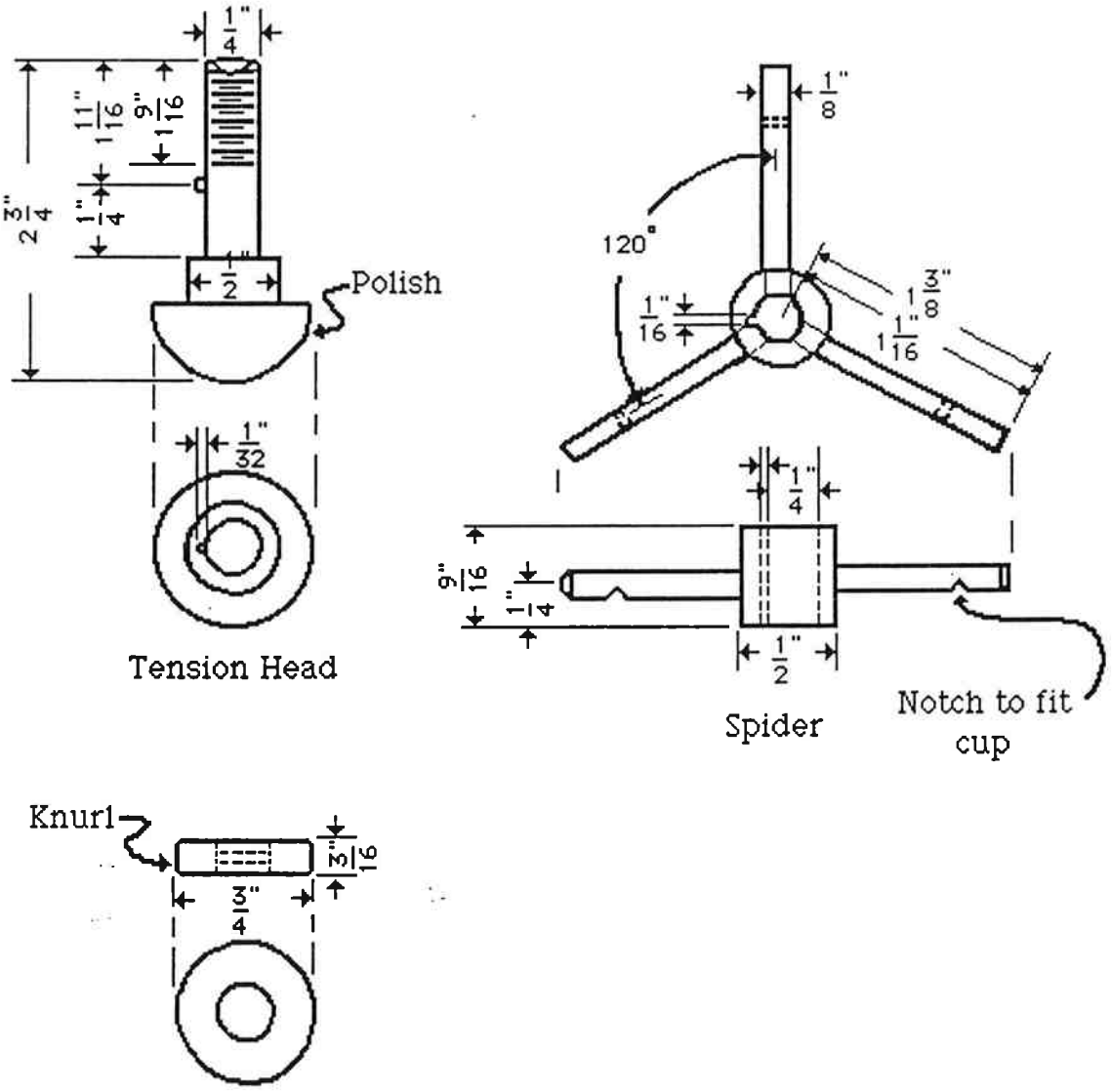


Figure A.9. Detail of Toughness and Tenacity Testing Device (after Reinke, 1985)

Fraass Test

Sample Preparation

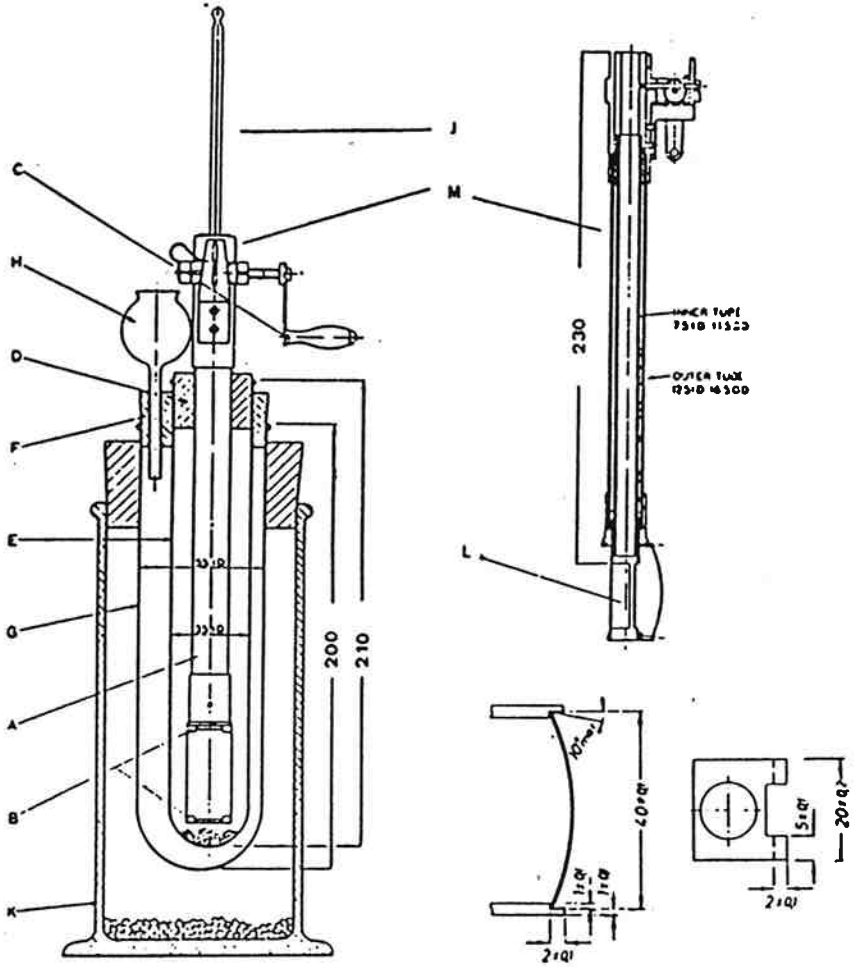
"For each test it is necessary to prepare and test three plaques such that the Fraass brittle point is determined in triplicate. According to IP 80/53, the samples should be prepared as follows:

Place an amount of the sample corresponding to .40 ± .01 g in the solid state on a clean plaque of known tare weight. Place the plaque on the heating plate and heat the baffle plate cautiously until the bitumen just flows; manipulate the plaque, replacing on the heating plate if necessary until the plaque is completely coated. Obtain the final smooth film by replacing the plaque on the heating plate for a short time."

Test Procedure

The standard steel plaque (41 mm x 20 mm) coated with a thin layer of bitumen (.5 mm) is placed in the testing apparatus (Figure A.10) and is cooled at a rate of 1°C/min by adding solid carbon dioxide to the acetone bath contained in test tube 'G' which surrounds chamber 'E' where the plaque is located. While the plaque is being cooled, the handle 'C' is turned at a rate of one revolution per second for 11 turns and then unwound at the same rate. This causes the steel plaque to bend (with the coated film outward until the ends are separated by a distance of 36.4 mm, starting initially at a distance of 39.9 mm. The temperature at which one or more cracks appear is recorded as the breaking point ("brittle temperature").

(Thenoux et al., 1985)



(dimensions in mm)

KEY

A: Concentric cylinder

B: Plaque hinges

C: Rotating handle

D: Supporter rubber bung. Seals chamber one.

E: Test-tube. Air chamber one. Contains small quantity of calcium chloride to absorb moisture.

F: Supported rubber bung

G: Test tube containing acetone

H: Funnel

J: Mercury thermometer

K: Glass cylinder. Air chamber two contains small quantity of calcium chloride to absorb moisture.

L: Location of the thermometer bulb

M: Bending apparatus

Figure A.10. Schematic of Fraass Apparatus (after Kim and Bell, 1986)

APPENDIX B

Mixture Test Procedures

Lottman Procedure

This accelerated aging process is intended to be applied to asphalt concrete specimens 2.5 in. high and 4 in, in diameter. At least nine specimens are recommended for each test. The procedure is as follows:

1. Fill a vacuum jar with distilled water at 73°F (22.8°C) and place one or more specimens flat on the bottom of the jar such that the water is 1 in. (2.5 cm) above the upper specimen.
2. Seal jar and apply a vacuum of 26 in. (66 mm) of mercury to the jar for 30 min. Gently agitate the sides of the jar to aid in air release.
3. Remove vacuum and let the specimens submerged in distilled water for another 30 min.
4. Wrap each specimen, saturated, tightly with two layers of plastic wrap and seal with tape. Place each wrapped specimen in a leak-proof plastic bag with approximately 3 ml of distilled water and seal.
5. Place each bag into an air bath freezer (−.4 ± 3.6°F (−18 ± 2°C)) for 15 hrs.
6. Remove specimens from freezer and immediately place in a water bath at 140 ± 3.6°F (60 ± 2°C) for 24 hrs. Remove plastic wrapping as surface begins to melt.
7. Remove specimens from water bath and allow to cool and dry.

This completes one cycle of the aging process. It may be repeated as many times as required, or mechanical testing can begin immediately.

Pressure Oxygen Bomb

A test sample is placed in the apparatus shown in Figure B.1. A vacuum is applied for 20 minutes and then the bomb is filled with oxygen to a pressure of 100 psi (689.5 kPa). This pressure is held for 30 minutes to ensure leak-free joints. The bomb is then placed in an oven maintained at 140°F (60°C) for a time period such as 1, 2, 3, or 5 days. After the samples have been aged, they are removed and allowed to cool for one day and two hours at room temperature. (Kim and Bell, 1986)

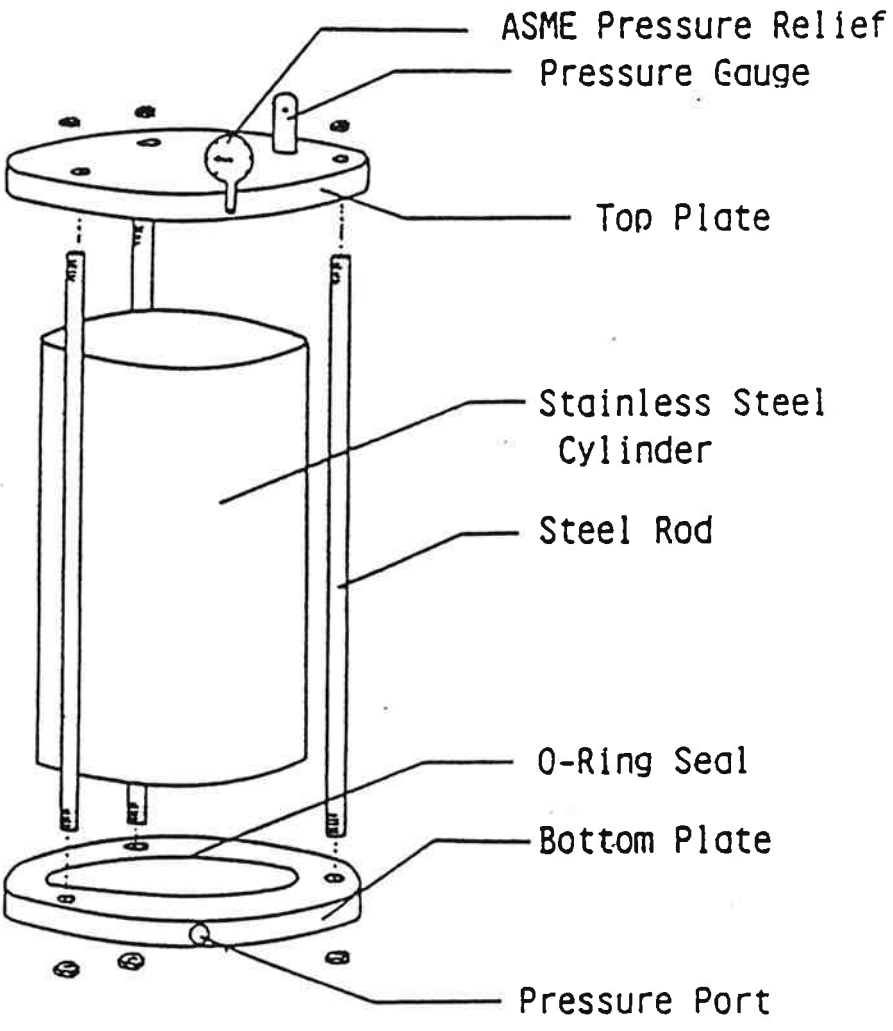


Figure B.1. Pressure Oxidation Bomb (POB)

Dynamic Resilient Modulus

A static load is applied to a cylindrical test specimen in the diametral direction to seat the specimen in the testing apparatus. A dynamic, or pulse load is then applied at regular intervals (normally from 1/3 hz to 1 hz) and the horizontal deformation is measured along the axis perpendicular to the loading direction.

LVDT's are positioned an opposite sides of the specimen, as shown in Figure B.2 and the signal from each is summed by either a chart recorder or a computer and a trace of the deformation can then be plotted.

The dynamic load can be applied to the specimen in a variety of ways. The waveform can vary from a square wave to a haversine wave and the driving system can be either pneumatic or hydraulic. The loading strip width also varies depending on the system used and the material being tested but, for asphalt concrete, 1/2 in. is the most widely used and accepted size.

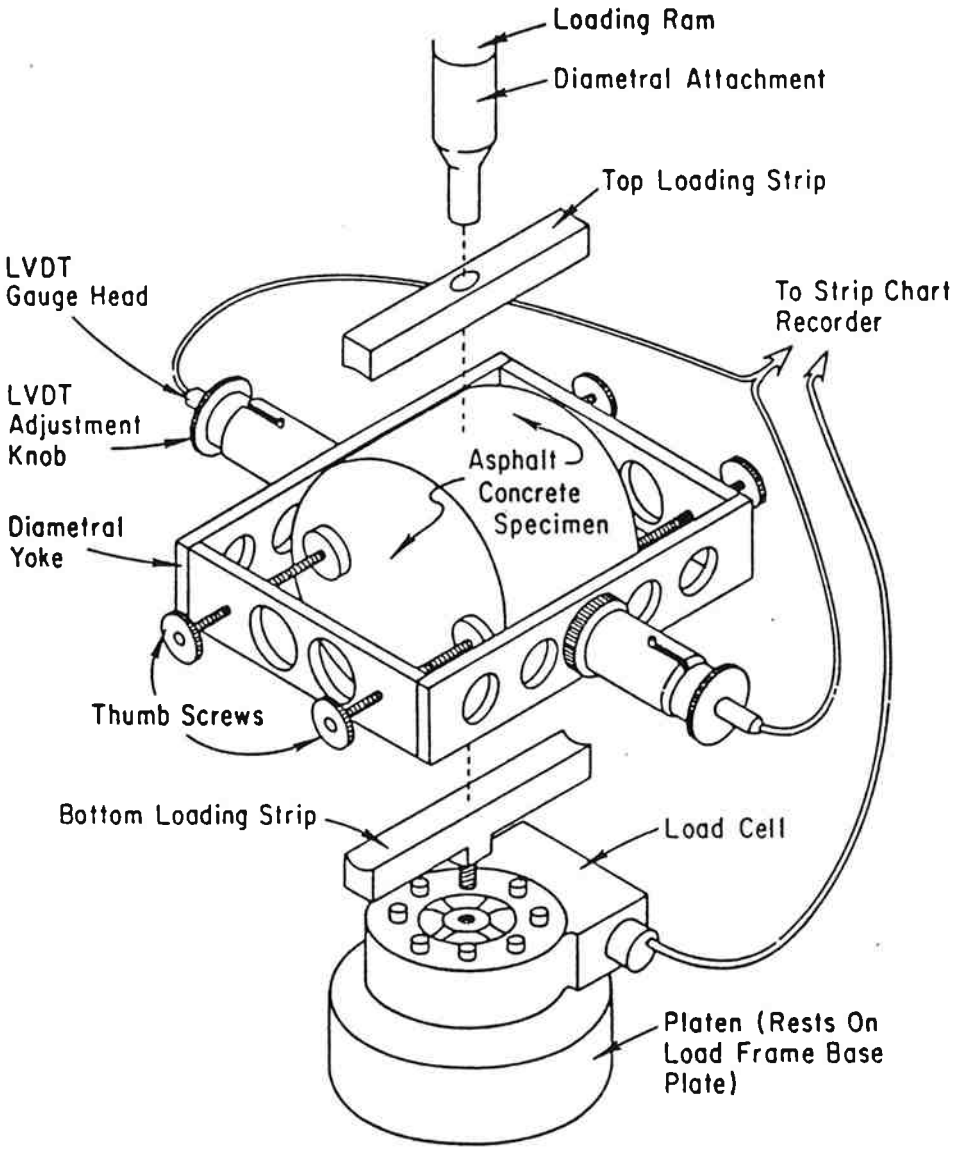


Figure B.2. Test Specimen with Diametral Yoke and Loading Ram

Indirect Tensile Test

This test is conducted by loading a cylindrical specimen with a single or repeated compressive load which acts parallel to and along the vertical diametral plane. (For this project, a single load was applied to specimens 2.5 in. high with a diameter of 4 in.) This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane, which ultimately causes the specimen to fail by splitting along the vertical diameter. See Figure B.3.

In the static test, a loading rate of 2 in./min is usually used at higher temperatures (normally 25°C) and a slower rate is used at the colder temperatures since the material behaves more elastically and since deformations associated with thermal cracking develop slowly. Horizontal and vertical deformations as well as the applied load should be measured continuously during the test. From these values, tensile strength, tensile strain, and compressive strain can be calculated.

(Kennedy, 1977)

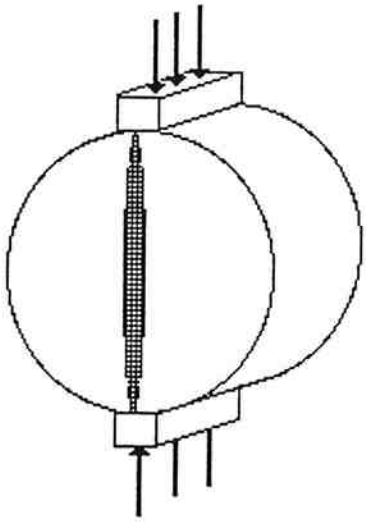


Figure B.3. Tensile Test Diagram

Fatigue Test

The indirect tensile fatigue test provides a measure of a material's ability to withstand a repeated load. A cylindrical specimen is tested by the following procedure:

1. Determine loading conditions (i.e., loading frequency and duration), test temperature, initial recoverable tensile strain, and amount of permanent horizontal deformation to be used in the determination of the fatigue life.
2. Determine the load magnitude required to induce the specified recoverable strain via ASTM D4123.
3. Place lead-based foil tape around the diametral axis perpendicular to the loading axis such that the foil tape has two loops of length corresponding to the specified amount of permanent horizontal deformation (see Figure B.4). The foil tape must not connect end-to-end since this would cause a short circuit.
4. Secure the foil tape by means of hot glue or other appropriate adhesive.
5. Solder leads to each end of the foil tape and connect the leads to a circuit that continues load applications while closed and discontinues loading when open.
6. Place the test specimen in the test apparatus such that the line of the foil tape is perpendicular to the line of loading.
7. Apply the static load that was applied when determining the load magnitude to induce the specified recoverable tensile strain.
8. Apply a repeated-load such that the magnitude of the load corresponds to that which induced the specified amount of recoverable tensile strain.
9. Count and record the number of load applications required to break the foil tape.

(Sholz, 1989)

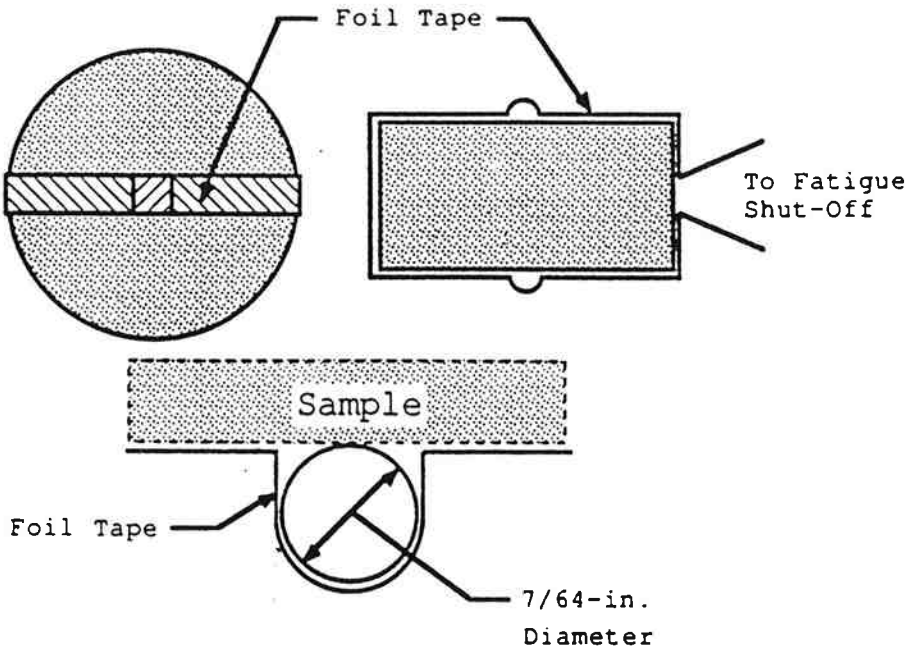


Figure B.4. Failure Criteria for Fatigue (after Scholz, 1989)

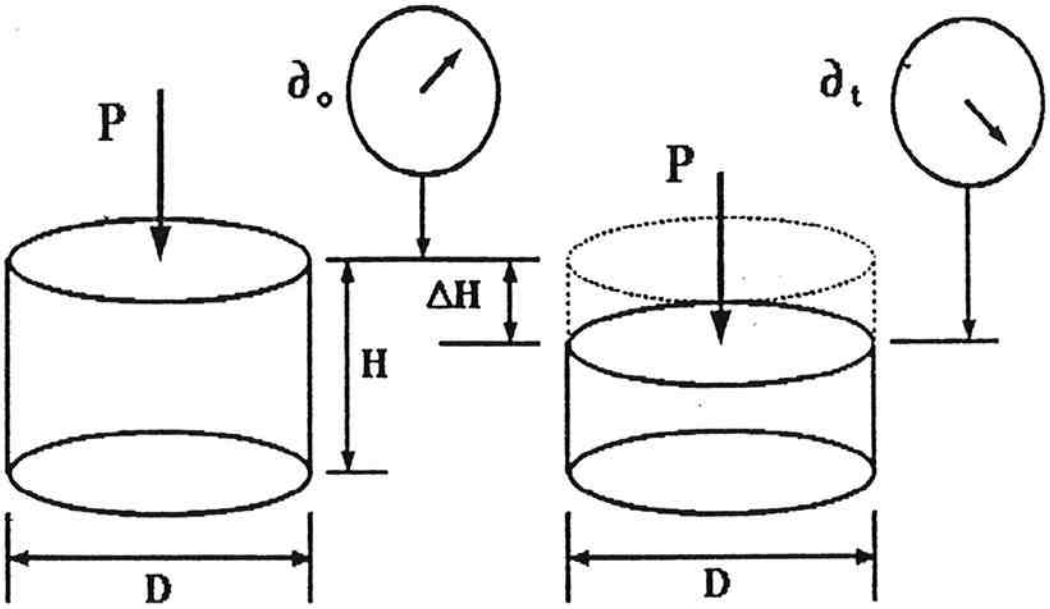
Creep Testing

Minimum specimen dimensions vary according to the aggregate size, but a minimum height-to-diameter ratio of two is recommended. Up to three specimens may be stacked to obtain the recommended specimen height. The procedure is as follows:

1. Place specimens in a controlled temperature environment and allow them to come to the specified test temperature.
2. Position specimen in the testing machine taking care that the ends of the specimen are perpendicular to the sample axis and parallel to the loading plates.
3. Attach LVDT's to either of the end plates, such that the total deformation is measured, or attach them to the middle segment of the specimen to measure a representative deformation.
4. Apply a preload of the same magnitude as the test load for a 2 min period followed by a 5 min rest period. Use a 1 min preload time for temperatures higher the 40°C.
5. Apply a step-load to produce a 20 psi compressive stress in the specimen.
6. Measure deformations for one to two hours and after that time release the load and measure rebound for one half to one hour.
7. If excessive deformations occur (greater than 3% strain), reduce load. If no measurable deformation occurs, increase loading stress.

Calculations

The calculation of creep compliance is accomplished by measuring the specimen dimensions, the load applied, the change in height of the specimen, and applying the equations shown in Figure B.5. It should be noted that if the deformation was measured in the middle of the specimen, the distance between the LVDT's is the height that should be used for calculation. Only if the total deformation is measured should the specimen height be used.



$$\text{Stress} = P / A = 4P / \pi D^2$$

$$\text{Strain} = \Delta H / H = | \partial_o - \partial_t | / H$$

$$\text{Modulus} = E_c = \text{Stress} / \text{Strain}$$

$$= 4PH / \pi D^2 | \partial_o - \partial_t |$$

$$\text{Compliance} = 1 / E_c$$

Figure B.5. Calculation of the Creep Modulus

APPENDIX C

Mixture Gradations

Preliminary Mix Aggregate Gradation

Sieve Size	% Passing
3/4"	100
1/2"	86.3
3/8"	73.5
1/4"	59
#4	49.3
#10	30
#40	12.2
#200	3.5
pan	0

Final Mix Aggregate Gradation

Sieve Size	% Passing
3/4"	100
1/2"	98.1
3/8"	84.8
1/4"	62
#4	51.6
#10	32.2
#40	13.2
#200	3.5
pan	0

APPENDIX D

Multiple Regression Results from Final Testing Program

Table D.1. Multiple Regression Data for Original Binder

Modulus @ 25°C		Modulus @ 0°C		Modulus @ - 10°C	
Pen4,Pen25	.93	Pen4,FDPArea	.84	Pen4,FDPArea	.91
Pen25,Visc60	.94	Pen25,FDPArea	.86	Pen25,FDPArea	.91
Pen25,Visc135	.93	Visc60,FDEngr	.86	Visc60,FDPArea	.93
Pen25,R&B	.94	Visc135,FDEngr	.87	Visc135,FDPArea	.96
Pen25,FDArea	.93	R&B,FDPArea	.85	R&B,FDPArea	.91
Pen25,FDPArea	.93	FDArea,FDTena	.83	FDArea,FDTena	.91
Pen25,FDTena	.93	FDPArea,FDTrue	.90	Visc135,FDPArea	.96
Pen25,FDEngr	.94	FDEngr,FDTrue	.92	Visc135,FDEngr	.94
Pen25,FDTrue	.93	FDPArea,Tough	.86	FDPArea,FDTrue	.95
Pen25,Tough	.93	FDPArea,Tenac	.86	FDPArea,Tough	.93
Pen25,Tenac	.93	FDPArea,T&TPArea	.82	FDPArea,Tenac	.93
Pen25,T&TPArea	.93			FDPArea,T&TPArea	.91
Ind Ten Str 25		**Ind Ten Str -10**		**Comp Str 25**	
Pen4,Pen25	.87	Pen4,Pen25	.87	Pen4,Visc135	.62
Pen25,Tough	.90	Pen25,FDArea	.93	Pen25,Visc135	.63
Pen25,Visc60	.86	Pen25,Visc60	.88	Visc60,Visc135	.56
Pen25,Visc135	.86	Pen25,Visc135	.87	Visc135,Tough	.72
Pen25,R&B	.88	Pen25,R&B	.89	Visc135,R&B	.62
Pen25,FDArea	.88	Pen25,FDArea	.93	Visc135,FDArea	.61
Pen25,FDPArea	.88	FDArea,FDPArea	.90	FDPArea,Tenac	.67
Pen25,FDTena	.87	Pen25,FDTena	.91	FDTena,Tough	.67
Pen25,FDEngr	.88	FDArea,FDEngr	.89	FDEngr,Tenac	.69
Visc60,FDTrue	.86	Pen25,FDTrue	.88	FDTrue,Tough	.59
Pen25,Tough	.90	Pen25,Tough	.90	Visc135,Tough	.72
Pen25,Tenac	.89	Pen25,Tenac	.89	Visc135,Tenac	.72
Pen25,T&TPArea	.86	Pen25,T&TPArea	.87	Visc135,T&TPArea	.58
Comp Str -10		**Fatigue**		**Permdef**	
Pen4,T&TPArea	.54	Pen4,FDTena	.78	Pen4,FDTena	.50
Pen25,T&TPArea	.70	Pen25,FDArea	.79	Pen25,FDTena	.57
Pen25,Visc60	.64	Visc60,FDArea	.78	Visc60,FDArea	.46
Pen25,Visc135	.51	Visc135,FDArea	.76	Visc135,FDArea	.48
R&B,T&TPArea	.65	R&B,FDTena	.80	R&B,FDArea	.46
Pen25,FDArea	.67	FDArea,Tenac	.82	FDArea,T&TPArea	.55
FDPArea,T&TPArea	.65	FDPArea,FDTena	.79	FDPArea,FDTena	.46
Pen25,FDTena	.64	FDTena,FDEngr	.81	Pen25,FDTena	.57
FDEngr,T&TPArea	.65	FDArea,FDTrue	.77	FDTena,FDEngr	.47
FDTrue,T&TPArea	.54	FDArea,Tough	.82	FDArea,FDTrue	.48
Tough,T&TPArea	.62	FDArea,Tenac	.82	FDArea,Tough	.46
Tenac,T&TPArea	.65	FDTena,T&TPArea	.79	FDArea,Tenac	.46
				FDTena,T&TPArea	.57

Table D.2. Multiple Regression Data for Original Binder (reduced data set)

Modulus @ 25°C		Modulus @ 0°C		Modulus @ −10°C	
Pen4,Pen25	.88	Pen4,R&B	.69	Pen4,R&B	.78
Pen25,Tough	.93	Pen25,Tough	.70	Pen25,Visc135	.78
Pen25,Visc60	.89	Pen25,Visc60	.54	Pen25,Visc60	.67
Pen25,Visc135	.87	Pen25,Visc135	.63	Pen25,Visc135	.78
Pen25,R&B	.88	Pen4,R&B	.69	Pen25,Tough	.78
Pen25,Tenac	.91	Tough,Tenac	.70	Pen25,Tenac	.74
Pen25,T&TPArea	.88	Pen25,T&TPArea	.54	Pen25,T&TPArea	.67
Ind Ten Str 25		**Ind Ten Str −10**		**Comp Str 25**	
Pen4,Pen25	.87	Pen4,Pen25	.89	Pen4,Visc135	.63
Pen25,Tough	.92	Pen25,R&B	.91	Pen25,Visc135	.64
Pen25,Visc60	.87	Pen25,Visc60	.90	Visc60,Visc135	.57
Pen25,Visc135	.87	Pen25,Visc135	.88	Visc135,Tenac	.69
Pen25,R&B	.88	Pen25,R&B	.91	Visc135,R&B	.62
Pen25,Tough	.92	Pen25,Tough	.90	Visc135,Tough	.64
Pen25,Tenac	.92	Pen25,Tenac	.90	Visc135,Tenac	.69
Pen25,T&TPArea	.87	Pen25,T&TPArea	.89	Visc135,T&TPArea	.60
Comp Str −10		**Fatigue**		**Permdef**	
Pen4,T&TPArea	.51	Pen4,Visc60	.10	Pen4,Tough	.15
Pen25,T&TPArea	.64	Pen25,Visc60	.11	Pen25,Tough	.16
Pen25,Visc60	.58	Visc60,Visc135	.13	Visc60,Tough	.23
Visc135,T&TPArea	.50	Visc60,R&B	.12	Visc60,Visc135	.18
R&B,T&TPArea	.61	Visc60,Tough	.10	R&B,Tough	.15
Tough,T&TPArea	.61	Visc60,Tenac	.10	Tough,Tenac	.24
Tenac,T&TPArea	.65	Visc60,T&TPArea	.12	Tough,T&TPArea	.15

Table D.3. Multiple Regression Data for RTFO Residue

Modulus @ 25°C		Modulus @ −10°C		Modulus @ 0°C	
Pen4,Pen25	.94	Pen4,FDEngr	.78	Pen4,FDEngr	.89
Pen25,visc60	.96	Pen25,FDEngr	.77	Pen25,FDEngr	.90
Pen25,Visc135	.93	Visc60,FDTena	.83	Visc60,Tough	.95
Pen25,R&B	.95	Visc135,R&B	.89	Visc135,R&B	.93
Pen25,FDArea	.93	FDArea,FDTena	.83	FDArea,FDTena	.96
Pen25,FDPArea	.93	FDPArea,FDTrue	.80	FDPArea,FDTena	.95
Pen25,FDTena	.93	FDEngr,FDTrue	.84	FDTena,FDEngr	.94
Pen25,FDEngr	.93	Visc60,Tough	.81	FDEngr,FDTrue	.92
Pen25,FDTrue	.93	Visc60,Tenac	.79	Visc60,Tough	.95
Pen25,Tough	.93	FDEngr,T&TPArea	.83	Visc60,Tenac	.94
Pen25,Tenac	.93			FDEngr,T&TPArea	.93
Pen25,T&TPArea	.93				

Ind Ten Str 25		Ind Ten Str −10		Comp Str 25	
Pen4,Pen25	.84	Pen4,R&B	.82	Pen4,Visc135	.65
Pen25,Visc60	.91	Pen25,Visc60	.91	Pen25,Visc135	.64
Pen25,Visc135	.85	Visc135,R&B	.82	Visc60,Visc135	.67
Pen25,R&B	.86	Pen25,R&B	.90	Visc135,Tough	.69
Pen25,FDArea	.87	Pen25,FDArea	.80	Visc135,R&B	.64
Pen25,FDPArea	.87	Pen25,FDPArea	.82	Visc135,FDArea	.65
Pen25,FDTena	.84	R&B,FDTena	.77	Visc135,FDPArea	.62
Pen25,FDEngr	.86	Pen25,FDEngr	.80	Visc135,FDTena	.65
Pen25,FDEngr	.86	Pen25,FDTrue	.79	Visc135,FDEngr	.62
Pen25,FDTrue	.84	R&B,Tough	.84	Visc135,FDTrue	.62
Pen25,Tough	.84	Visc60,Tenac	.86	Visc135,Tough	.69
Pen25,Tenac	.84	Pen25,T&TPArea	.81	Visc135,Tenac	.65
Pen25,T&TPArea	.84			Visc135,T&TPArea	.62

Comp Str −10		Fatigue		Permdef	
Pen4,Pen25	.69	Pen4,FDArea	.74	Pen4,FDTena	.69
Pen25,Visc60	.58	Pen25,FDArea	.82	Pen25,FDTena	.90
Visc135,Tough	.50	Visc60,FDArea	.64	Pen25,Visc60	.38
Pen25,R&B	.55	Visc135,FDArea	.58	Pen4,Visc135	.51
Pen25,FDArea	.68	R&B,FDArea	.58	Pen25,R&B	.41
FDPArea,Tenac	.74	Pen25,FDArea	.82	Pen25,FDArea	.62
Pen25,FDTena	.54	FDPArea,FDEngr	.71	Pen25,FDPArea	.56
FDEngr,Tenac	.71	Pen25,FDTena	.78	Pen25,FDEngr	.67
FDTrue,Tough	.49	FDArea,FDTrue	.54	Pen25,FDTrue	.38
FDPArea,Tough	.65	FDArea,Tough	.64	Pen25,Tough	.77
FDPArea,Tenac	.74	FDArea,Tenac	.61	Pen25,Tenac	.82
Pen25,T&TPArea	.55	FDArea,T&TPArea	.53	Pen25,T&TPArea	.41

Table D.4. Multiple Regression Data for RTFO Residue (reduced data set)

Modulus @ 25°C		Modulus @ 0°C		Modulus @ -10C	
Pen4,T&TPArea	.88	Pen4,T&TPArea	.63	Pen4,T&TPArea	.72
Pen25,T&TPArea	.94	Pen25,T&TPArea	.59	Pen25,Visc135	.66
Visc60,T&TPArea	.83	Visc60,T&TPArea	.78	Visc60,T&TPArea	.79
Pen25,Visc135	.82	Visc135,T&TPArea	.84	Visc135,T&TPArea	.85
Pen25,R&B	.82	R&B,T&TPArea	.69	R&B,T&TPArea	.72
Pen25,Tough	.91	Tough,Tenac	.64	Tough,Tenac	.74
Pen25,Tenac	.84	Visc135,T&TPArea	.84	Visc135,T&TPArea	.85
Pen25,T&TPArea	.94				
Ind Ten Str 25		**Ind Ten Str -10**		**Comp Str 25**	
Pen4,T&TPArea	.85	Pen4,Pen25	.82	Pen4,Visc135	.64
Pen25,T&TPArea	.90	Pen25,R&B	.87	Pen25,Visc135	.64
Pen25,Visc60	.86	Pen25,Visc60	.87	Visc60,Visc135	.66
Pen25,Visc135	.85	Pen25,Visc135	.81	Visc135,R&B	.65
Pen25,R&B	.84	Pen25,Tough	.82	Visc135,Tough	.64
Pen25,Tough	.89	Pen25,Tenac	.81	Visc135,Tenac	.64
Pen25,Tenac	.85	Pen25,T&TPArea	.84	Visc135,T&TPArea	.65
Pen25,T&TPArea	.90				
Comp Str -10		**Fatigue**		**Permdef**	
Pen4,Pen25	.70	Pen4,T&TPArea	.15	Pen4,Visc135	.26
Pen25,Visc60	.60	Pen25,T&TPArea	.22	Pen25,T&TPArea	.47
Pen25,Visc135	.53	Visc60,Visc135	.20	Visc60,Visc135	.22
Pen25,R&B	.58	Pen25,R&B	.21	Visc135,Tough	.36
Pen25,Tough	.58	Pen4,Tough	.19	Visc135,R&B	.20
Pen25,Tenac	.56	Pen25,Tenac	.15	Visc135,Tenac	.19
Pen25,T&TPArea	.56	Pen25,T&TPArea	.22	Pen25,T&TPArea	.47