Relating Hot-Mix Properties to Properties of Conventional or Polymer-Modified Binders

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Increasing use of asphalt binders altered 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 on the basis of expected performance differences in the hot-mix pavements resulting from the use of these binders. Unique characteristics of polymer-modified hot mix were investigated, and binder tests and properties that could be used to predict mix performance whether conventional or modified binders are used were determined. Two mix designs incorporating three conventional asphalts and six different modified asphalts were tested in two phases. The objective was to determine which binder tests had promising correlations with important mix properties. Fraass point and Pen-Vis number 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.

Highway agencies have the opportunity to improve asphalt pavement performance through the addition of various polymer additives to conventional asphalts. Polymer additives to asphalt materials are being advocated as having high potential for improving long-term pavement performance through their ability to improve the properties of the asphalt binder and 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 (*1*). 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 United States, it was necessary to determine their effect on asphalt pavements, identify appropriate properties that relate to performance, select testing procedures to aid in design and construction of these pavements, and investigate tests to predict the long-term behavior of the pavements.

Ideally, binder tests and properties would be identified that could predict mix performance, regardless of whether binders were conventional or modified with polymers. Goodrich (*2*) correlated binder properties with important properties of hot mix prepared with the binders. Three conventional and two polymer-modified binders were used. In many respects, the present research replicated Goodrich's work, expanding the number of binder and mix tests and properties as well as the number of binders and design mixes.

The objectives of this research were 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 determine the best measuring method; and
3. Recommend interim specifications and test methods for polymer-modified asphalt and polymer-modified hot mixes.

RESEARCH METHODOLOGY

The literature search was conducted using the Transportation Research Information Service (TRIS) data base, as well as from reference lists of various publications and reports dealing with polymer-modified asphalts. Promising documents were obtained and reviewed. A synthesis on polymer types, polymer-modified asphalt hot-mix properties, and testing procedures was formulated and presented in an interim report (*3*).

The laboratory investigation was conducted in two phases. The preliminary testing program focused on using tests that were identified in the literature as likely to predict field performance of polymer-modified asphalts. The initial testing included all promising binder tests and the mix tests required for the validation process. After the initial testing, the most promising binder tests were selected for further examination in a program using fewer tests, but more binders. Different aggregate sources and gradations were used for the two testing programs.

During the laboratory testing program, three conventional binders and six binders using elastomeric and plastic modifiers were tested. At the conclusion of the final laboratory testing program, correlations of various binder test properties with mix-test results were made for both the preliminary and final testing programs. Binder properties were sought that correlated well with important mix properties for the two different mix designs represented by the preliminary and final testing programs.

More detailed reports of this research were provided by Ifft (*4*) and Rogge et al. (*5*).

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TESTING PROGRAM

The laboratory testing program was conducted in two phases: preliminary and final. Table 1 presents the mix-testing procedures used to evaluate mix performance. Table 2 presents the binder test procedures used to develop binder properties to relate to the mix-test results.

The preliminary testing program was conducted with a broad range of mixture and binder tests using one conventional and four modified binders. One aggregate source and mix design was used. The dense-graded mix used lime-treated sand and gravel from eastern Oregon, with a 5 percent binder content. The tests selected for inclusion in the preliminary testing program were chosen on the basis of the extensive literature review; a questionnaire completed by experts on polymer asphalt; and a survey of practical limitations of equipment, funding, and staffing.

The final testing program presented a narrower focus for testing procedures, but expanded the number of binders to two conventional and eight modified binders. The larger number of binders allowed for more data points for correlation between binder properties and mix properties. A different aggregate source and design mix was used. Sand and gravel from a Willamette Valley pit were used without lime treatment. The asphalt content of this dense-graded mix was 5 percent.

All conventional and modified binders for both testing phases were intended to approximate an AC–20 grading. All modified binders were blended and furnished by the suppliers. In reality, several of the binders did not meet an AC–20 specification. Table 3 presents the binders used in preliminary and final testing.

RESULTS OF THE TESTING PROGRAM

Ideally, using binder tests that predict mix performance in the field is preferable. Because 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 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 10 different binders, produced a maximum of 10 data points for correlation.

Variations in Polymer-Modified Binders

The binders modified with styrene-butadiene (SB), styrene-butadiene rubber (SBR), and styrene-butadiene-styrene (SBS) were each supplied for the preliminary and final testing programs by the same suppliers to the same specifications. For example, the SB specification and supplier were the same for both the preliminary and final testing programs. Nevertheless, large variations in properties occurred for the SB- and SBS-modified binders between materials supplied for the preliminary and 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.

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. In some cases, absolute viscosity measurements resulted in clogging of tubes. As discussed by

TABLE 1 PRELIMINARY AND FINAL MIX-TESTING PROGRAMS

Performance	Mix Tests	Prel.	Final
Fatigue Life	Diametral Fatigue	X	X
Rutting Resistance	Uniaxial Creep	X	
	Permanent Deformation	X	X
Low-Temperature Crack Resistance	Ind. Tens. @ 0°C, .05 in./min.	X	
	Ind. Tens. @ -10°C, .05 in./min.	X	X
	Modulus @ 0°C	X	X
	Modulus @ -10°C	X	X
Temperature Susceptibility	Modulus vs Temp., -10°C, 0°C, 25°C	X	X
Long-Term Durability:			
Moisture Resistance	Modified Lottman Conditioning	X	
Heat/Oxygen Resistance	Pressure Oxygen Bomb	X	
	Forced Draft Oven for 14 Days @ 60°C	X	
Modulus @ 25°C	Diametral Resilient Modulus	X	X
Tensile Strength @ 25°C	Indirect Tensile Test @ 25°C, 2in/min.	X	X

TABLE 2 PRELIMINARY AND FINAL BINDER-TESTING PROGRAMS

Performance	Binder Tests	Prel.	Final
Consistency	Fraass Brittle Point	X	X
	Penetration @ 4°C	X	X
	Penetration @ 25°C	X	X
	Softening Point		X
	Viscosity at 60°C	X	X
	Viscosity at 135°C	X	X
Load Resistance	Force Ductility @ 4°C	X	X
	Force Ductility @ 25°C	X	
	Toughness and Tenacity (25°C)	X	X
	Dynamic Mechanical Analysis	X	
Durability:			
Mix Prep. Aging	RTFO	X	X
Long-Term Aging	POB	X	

TABLE 3 BINDERS USED IN PRELIMINARY AND FINAL TESTING

Preliminary Testing:

Code	Binder Type	Comments
A1	AC-20 (conventional)	
B1	EVA modified	
C1	SBS modified	
D1	SBR modified	
E1	SB modified	

Final Testing:

Code	Binder Type	Comments
A2	AC-15 (conventional)	
B2	AR-2000 (conventional)	
C2	polyethylene fiber modified	
D2	EVA modified	
E2	SBR modified	Same supplier as D1
F2	SB modified	Same supplier as E1
G2	SBS modified	Same supplier as C1
H2	neoprene modified	
I2	EVA modified	Same supplier as B1
J2	SBS modified	Same supplier as C1 & G2

Shuler and Pavlovich (*6*), this difficulty is caused by the shear-thinning properties of polymers. One solution is to move away from conventional viscosity testing toward constant-power viscosity (*7*) or another method of constant-stress viscosity measurement when polymers are used.

Binder Strength Tests

The question of whether tests such as force ductility and toughness and tenacity are required was to be answered by the testing programs. On the basis of preliminary and final testing, the answer was maybe—the tests did show promise for predicting mix properties and provided the best predictive ability for mixture strength and modulus properties.

Although 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. A temperature of 25°C is not good 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, whereas force ductility testing uses 5 cm/min.

Toughness and tenacity testing splits the total area under the load deformation curve into two areas (see Figure 1). Toughness is defined as the total area, and tenacity is defined as the tail of the curve. The best correlations for toughness and tenacity properties were not for toughness or for tenacity, but rather for the area that represented the difference of these two areas, herein called "peak area." 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. Because the two properties showed relationship to each other with $R^2 > 0.95$, computing peak area may not be worth the extra effort.

Long-Term Aging

Another question that the testing programs attempted to answer was whether tests of long-term aging effects are required when polymers are used. Time and budget constraints permitted the inclusion of only a small-scale aging test in the preliminary testing program. Because of a combination of procedural errors and some values that looked questionable, it is uncertain whether the results of this testing are reliable. The polymer-modified binders seemed to be 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 Goodrich (*2*), Button and Little (*8*), and Krivohlavek (*9*). If polymer binders degrade more quickly than conventional binders, perceived present benefits could quickly disappear. Some type of specification binder test should be developed that can be used to reject binders that may be subject to accelerated aging. The POB, long-term durability (LTD) test (*2*), and tanning booth described by Krivohlavek (*9*) are possibilities. More research is needed.

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. A relationship was considered promising when the coefficient of determination (R^2) was ≥0.70.

Because of the larger number of data points in the final testing, the analysis was focused on promising relationships from this testing. Because preliminary testing only resulted in four or five data points, those results were not given much weight. Preliminary testing served primarily to aid in planning final testing. The approach taken is that a high R^2 value on preliminary testing can serve as supporting evidence for high R^2 on final testing, but that low R^2 on preliminary testing does not necessarily rule out a relationship or negate high R^2 values for final testing. This result follows from the dramatic volatility of R^2 when only four or five data points are involved (see Figure 2). The R^2 value for the final test data shown in Figure 2 is 0.75 and the relationship is positive or direct. If only *A2*, *C2*, *D2*, and *E2* had been selected for testing, the R^2 value would have been 0.10 and the relationship would have been inverse. If only these four data points had been generated, a slight shift of *A2* upward and to the right could even result in a high R^2 value for an inverse relationship.

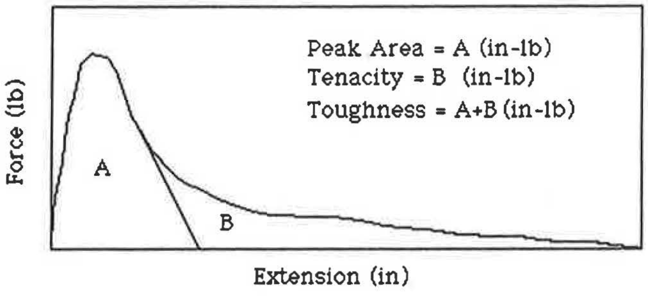

FIGURE 1 Typical toughness and tenacity curves.

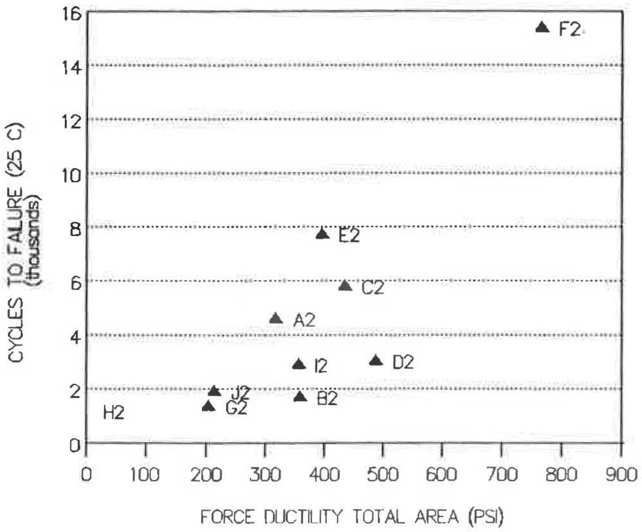

FIGURE 2 Fatigue life versus original force ductility total area—final testing.

The individual binder properties, which appear to be the best predictors of mix performance on the basis of simple linear regression, are presented in Table 4 and discussed in the following paragraphs. Multiple regression results are discussed later.

Predicting Fatigue Life

The only single-binder properties that showed promise for predictive ability in the final testing were the original force ductility total area ($R^2 = 0.75$) and its component area force ductility tenacity ($R^2 = 0.73$). The scattergram for fatigue cycles to failure versus original force ductility total area for final testing is shown in Figure 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 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.

Predicting Resistance to Thermal Cracking

Low-temperature, low-strain-rate indirect tensile testing was the mix-testing procedure chosen to provide an indication of the ability of a mix to resist thermal cracking. Probably the

TABLE 4 PROMISING CORRELATIONS FROM FINAL TESTING—R^2 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

best indicator that 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 (R^2 = 0.88) and rolling thin-film oven (RTFO) (R^2 = 0.81) penetration at 25°C, original penetration index (PI) (R^2 = 0.83), and the original force ductility (4°C) engineering stress (R^2 = 0.71) and peak area (R^2 = 0.78). Considering results from preliminary testing, original and RTFO penetration at 25°C, and original force ductility peak area look most promising. Figures 3 and 4 show scattergrams for the relationships between penetration at 25°C and force ductility peak area with indirect tensile stress at −10°C.

Modulus values 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 that predicted these properties in final testing. These properties were original and RTFO peak area and maximum engineering stress. 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, because 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. Hence, the use of Fraass point to predict cold-temperature properties is preferred over force ductility properties. Figure 5 shows a scattergram for Fraass point versus mix modulus at 0°C.

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, for various reasons, were not part of the final testing program.

Predicting Low-Temperature Temperature Susceptibility

To further evaluate potential for thermal cracking, an evaluation of the sensitivity of mix modulus to changes in temperature at low temperatures was made. To accomplish this, change in modulus values 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, PVN, and Fraass brittle point.

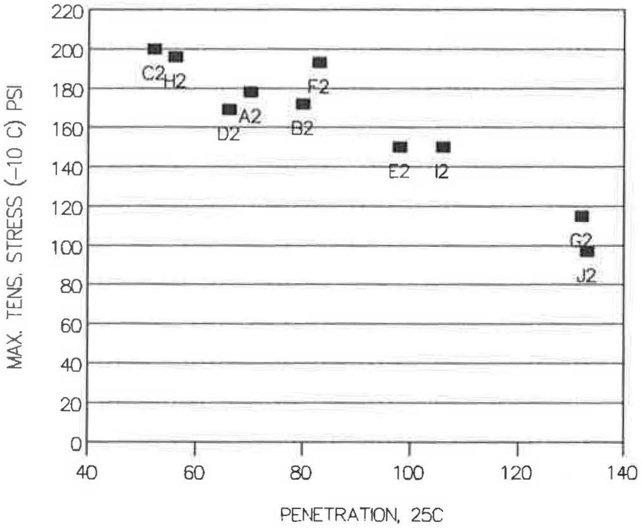

FIGURE 3 Tensile strength (−10°C) versus penetration at 25°C—final testing.

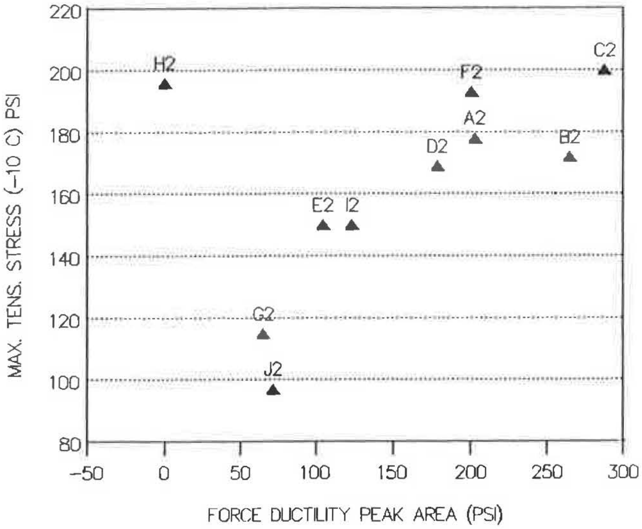

FIGURE 4 Tensile strength (−10°C) versus original force ductility peak area—final testing.

The two most accepted measures of temperature susceptibility of asphalts are PI and PVN. These measures concentrate on binder consistency at temperatures of 25°C and above. They do not use measures of consistency below 25°C. Nonetheless, if the plot of consistency on a bitumen test data chart (BTDC) is linear, PI and PVN values 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 an R^2 value of 0.73 for the final test program and favorable correlation in the preliminary program. Because significant problems were encountered in measuring viscosity by conventional means for some of the polymers, PVN correlations would be better if a more accurate means of determining viscosity is used. 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.

Fraass brittle point for original binders (RTFO residues were not tested in either phase) was a better predictor of the low-temperature sensitivity of the resulting mix as predicted by modulus-versus-temperature curves. Final test R^2 value was 0.82 with favorable preliminary correlation. A scattergram of this relationship is shown in Figure 6. 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.

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.

Predicting Stiffness at 25°C

Modulus at 25°C, which is used in mechanistic pavement design, is considered a measure of quality of asphalt concrete pave-

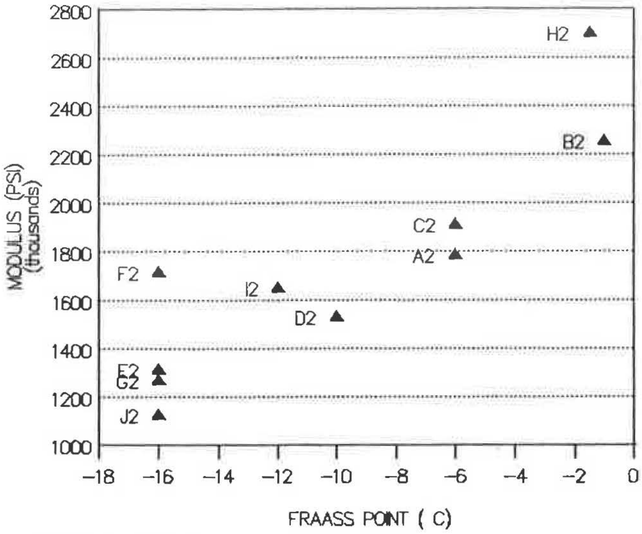

FIGURE 5 Modulus (0°C) versus original Fraass point—final testing.

ment, 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^2 values) were original penetration at 25°C ($R^2 = 0.87$), RTFO penetration at 25°C ($R^2 = 0.82$), original force ductility peak area at 4°C ($R^2 = 0.79$), and RTFO toughness and tenacity peak area ($R^2 = 0.77$).

Predicting Tensile Strength at 25°C

Tensile strength at 25°C, which is considered an important measure of quality of asphalt concrete, 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^2 values of 0.86 and 0.84.

Predicting Mix Properties by Multiple Regression

The five data points of the preliminary testing program were clearly inadequate for multiple regression analysis. The maximum 10 data points provided by the final testing are marginal for multiple regression; 20 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 $R^2 = 0.79$; RTFO $R^2 = 0.82$). However, the plot of force ductility area versus penetration at 25°C for RTFO residues (see Figure 7) shows the problems in writing a specification on the basis of this relationship. On the plot, 100 percent represents the binder with the longest fatigue life in the final testing program and the remaining percentages 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 are normalized and added to the plot, the usefulness of the relationship breaks down further. The 10 and 20 percent performers become intermingled with 50 and 100 percent performers.

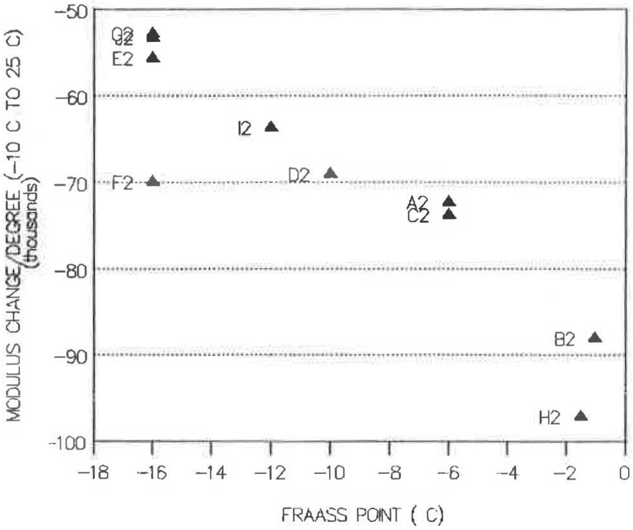

FIGURE 6 Modulus change versus original Fraass point—final testing.

The combination of penetration at 25°C and force ductility tenacity or tail area showed promise for predicting resistance to permanent deformation (RTFO $R^2 = 0.90$). Figure 8 shows a plot of force ductility tenacity versus 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 from the poorest performers. However, when preliminary test data are added to the plot, the relationship breaks down, with a 12 percent performer intermingled with 100 and 50 percent performers.

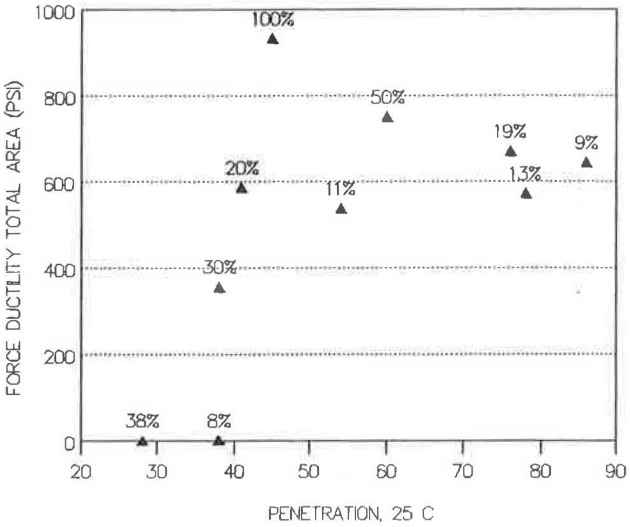

FIGURE 7 RTFO force ductility total area versus RTFO penetration at 25°C—final testing.

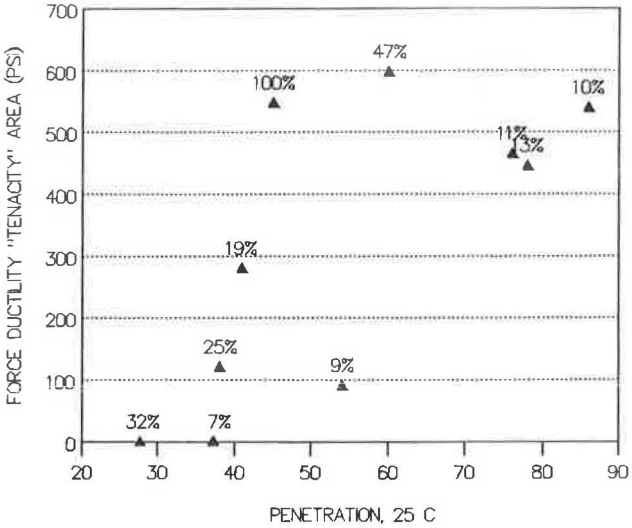

FIGURE 8 RTFO force ductility tenacity versus RTFO penetration at 25°C—final testing.

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. Therefore, predicting diametral fatigue life is equivalent to predicting permanent deformation.

Only in the area of fatigue and permanent deformation does multiple regression analysis indicate that force ductility testing contributes more to predicting mix properties than does 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^2 values approximating 0.89 or better for modulus at all temperatures (−10°C, 0°C, 25°C) and maximum indirect tensile stress at −10°C and 25°C.

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^2 relationships both in preliminary and final testing. When done, the only binder properties producing R^2 values >0.70 in simple linear regression in both testing programs were as follows:

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

Of these, Relations 2 and 6 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 used 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. However, the equipment required for dynamic mechanical analysis on which the computation of loss tangent is based is not commonly available for highway agency use.

Although force ductility peak area showed better correlations than maximum engineering stress, the two are closely related. In fact, simple linear regression of these two properties produced R^2 values that were >0.95. Because maximum engineering stress is easier to compute, it is questionable whether the extra effort of obtaining peak area is worthwhile.

Recommendations for Specification Testing Based on This Research

On the basis of 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, and
  —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. PI and PVN, the two most accepted methods of measuring temperature susceptibility, are based on consistency measurements only at temperatures ≥25°C and present problems when polymer-modified asphalts are encountered. Some of these binders have nonlinear curves when consistency data are plotted on BTDCs (see Figure 9). 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 that were most temperature susceptible at low temperatures.

Fraass brittle point showed better correlations with mix low-temperature temperature susceptibility than did PVN. Fraass brittle point offers an alternative to the use of PVN for control of low-temperature temperature susceptibility—an alternate that 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 PVN or Fraass point in binder specifications should ensure the use of either a conventional or modified asphalt with low-temperature susceptibility at low temperatures.

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 on 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, showed promise of predicting fatigue life and permanent deformation as measured by diametral testing.

CONCLUSIONS AND RECOMMENDATIONS

The recommendations that 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 show the most promise for predicting fatigue life.
2. Mix permanent deformation resistance, as defined in this study, cannot be predicted with any single binder test studied. The most promising basis for predicting permanent 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, this peak 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 clearly identifies the more brittle binders.
7. Penetration at 25°C shows promise for predicting modulus at 25°C and indirect tensile strength at 25°C.

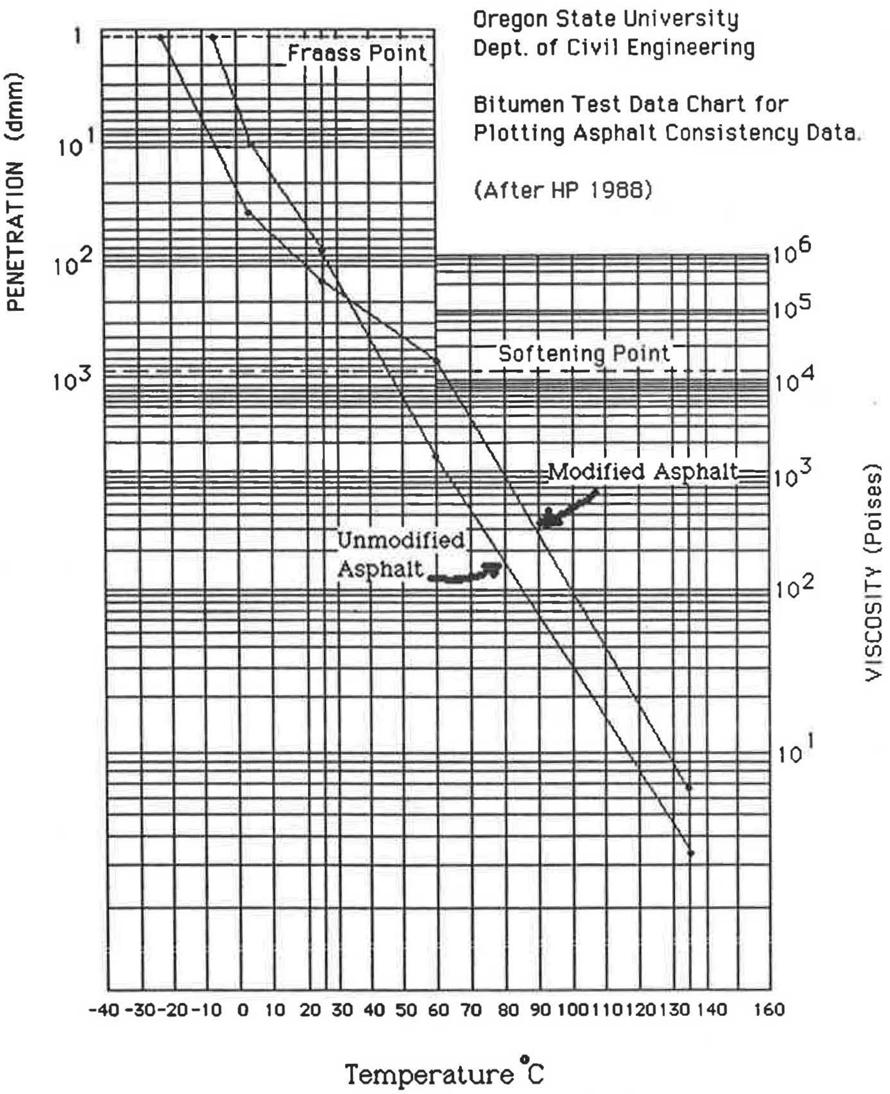

FIGURE 9 Nonlinearity of temperature-consistency curve for modified binder.

8. Only for diametral fatigue and permanent deformation, multiple regression analysis indicates that force ductility testing contributes more to predicting mix properties than do 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 produce R^2 values of 0.89 or higher for modulus at all temperatures (−10°C, 0°C, 25°C) and maximum indirect tensile stress at −10°C and 25°C.

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 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.

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