Application of Intermediate Temperature Semi-Circular Bending (SCB) Test Results to Design Mixtures with Improved Load Associated Cracking Resistance

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ABSTRACT. *This paper describes the development and practical application of regression equations to estimate the relative load associated cracking resistance of asphalt mixtures from properties that are included in specifications and controlled through current quality control and acceptance procedures. This work was part of a research study performed through the Wisconsin Highway Research Program to evaluate changes to the composition of asphalt concrete mixtures that should be considered to improve the durability of flexible pavements. Based on the findings of a synthesis of current research, a laboratory experiment was conducted to quantify the effects of: (1) effective binder volume, (2) virgin binder low temperature performance grade, (3) recycled binder content, and (4) polymer modification on the resistance of typical Wisconsin mixtures to aging and load associated cracking. For the types of mixtures normally used in Wisconsin, the laboratory experiment found mixture composition had little effect on aging; however, load associated cracking resistance was significantly affected. The laboratory experiment produced a regression equation that was used to recommend revised volumetric criteria that provide equivalent load associated cracking resistance and allow producers the flexibility to design mixtures using a range of effective binder contents, recycled binder contents, and virgin binders.*

KEYWORDS: *Load associated cracking, semi-circular bend, flexibility index, age hardening.*

1.0 Introduction

This paper describes the development and practical application of regression equations to estimate the relative load associated cracking resistance of asphalt mixtures from properties that are included in specifications and controlled through current quality control and acceptance procedures. This work was part of a research

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study performed through the Wisconsin Highway Research Program (WHRP) to evaluate changes to the composition of asphalt concrete mixtures that should be considered to improve the durability of flexible pavements. For asphalt concrete mixtures, durability refers to the ability of compacted asphalt concrete to maintain its structural integrity throughout its expected service life when exposed to the damaging effects of the environment and traffic loading (Nicholls et al., 2008). Traditionally, durability has been addressed in asphalt mixture design and construction through a combination of the following:

1. Asphalt binder specifications that limit changes in binder properties under simulated aging.
2. Aggregate specifications that limit the amount of clay and other deleterious materials and guard against breakdown of aggregates during production and under traffic and environmental effects during the service life of the pavement.
3. Limits on volumetric properties to provide a sufficient volume of asphalt binder in the mixture to properly coat the aggregates and to minimize aging and cracking during the service life of the mixture.
4. Testing and requirements to ensure that the mixture is not sensitive to moisture.
5. In-place compaction requirements to minimize permeability which minimizes water infiltration and slows the rate of age hardening in the mixture.

Although these requirements have been largely successful, highway agencies question whether the durability of asphalt concrete mixtures can be improved either through changes to mixture composition or the adoption of performance related mixture testing. This paper summarizes important elements of research that led to recommendations for improving the Wisconsin Department of Transportation's (WisDOT's) mix design and binder selection criteria.

2.0 Asphalt Mixture Design Factors Affecting Age Hardening and Resistance to Load Associated Cracking

The WHRP research included a literature review, that is published elsewhere (Bonaquist, 2014), to identify important factors affecting asphalt mixture durability and recent efforts to improve asphalt mixture durability. This literature review emphasized the effect of mixture composition on durability, but also considered other factors. The literature review found that asphalt mixture durability is affected by a number of factors associated with: (1) the environment, (2) drainage conditions, (3) construction, and (4) mixture composition.

Resistance to age hardening and load associated cracking are two important characteristics related to asphalt mixture durability. The literature review found that the following compositional factors affect these characteristics:

1. **Binder Properties.** Important binder properties include the stiffness of the binder after aging, the amount and stiffness of recycled binder, and whether the binder is polymer modified.
2. **Gradation.** The gradation affects the permeability of the mixture to air and water. Permeability affects the rate of aging and the potential for moisture damage.
3. **Air Void Content.** The in-place air void content affects the strength, stiffness, and permeability of the mixture and is primarily controlled by compaction specifications.
4. **Volume of Effective Binder (V_{be}).** The volume of effective binder controls the thickness of the asphalt binder coating the aggregate. More effective binder slows the rate of aging and improves the resistance of mixtures to cracking.

Fine graded mixtures having low permeability at typical in situ air void contents are used in Wisconsin (Schmidt et al., 2007; and Christensen et al., 2013). Several methods for improving the resistance of these mixtures to age hardening and load associated cracking were identified by the literature review. These included:

1. **Increase effective binder content for all mixtures.** This can be accomplished in a number of ways including: increase design voids in the mineral aggregate (VMA), decrease design air voids, decrease design gyration level, and use smaller nominal maximum size mixtures (McDaniel, 2007).
2. **Increase the effective binder content in proportion to the amount of recycled binder**. This addresses the question of whether all of the recycled binder in a mixture is effective. Increasing the effective binder content in mixtures with recycled binder is equivalent to placing a limit on the contribution of the recycled binder. Laboratory data from two studies showed that this approach improves the load associated cracking resistance of mixtures with recycled binder (Willis, 2012; Bennert et al., 2014).
3. **Use a softer grade of binder in recycled mixtures.** Many highway agencies have adopted this approach for mixtures having a recycled binder ratio greater than 0.25. There are conflicting results in the published literature on the effectiveness of using a softer binder to improve the load associated cracking resistance of mixtures with recycled binder. For example, a study using the Texas Overlay Tester (Mogawer et al, 2012), found the use of a softer binder was not effective in improving the cracking resistance of mixtures with recycled binder. On the other hand, a study using semi-circular bending (SCB) tests (Al-Qadi et al., 2015), showed improvement in cracking resistance when softer binders are used.

Warm mix asphalt (WMA) is a variation on the use of a softer grade of binder. The lower production temperatures associated with WMA reduce plant aging, resulting in softer binders at the time of construction. The reduction in binder stiffness depends on the temperature of the WMA, but is typically less than a one performance grade change (Bonaquist, 2011a).

4. **Use polymer modified binder.** Polymer modification has been shown to reduce all forms of pavement distress, increasing the life of flexible pavements by two to ten years (Asphalt Institute, 2005). In a recent laboratory study of the fatigue resistance of Nevada mixtures, the Western Regional Superpave Center found the fatigue resistance of mixtures with polymer modified binder with up to 30% RAP was significantly greater than that of virgin mixtures with neat binder (Hajj et al., 2009).
5. **Increase in-place compaction requirements.** There is substantial published literature related to the effect of in-place density on the performance related properties of asphalt concrete mixtures (Alderson, 2011). An interesting variation on the concept of improved compaction is the approach of matching design and in-place air voids that is being evaluated in Indiana (Hekmatfar et al., 2015). The philosophy behind this research is that mixtures should be designed in the laboratory using an air void content that is achievable during construction. The recommended target for both laboratory design and field compaction is 5.0% air voids, which represents a substantial improvement in in-place compaction.

Based on the literature review summarized above, the mixture design factors that potentially affect the resistance of asphalt mixtures to age hardening and load associated cracking are: (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification. To recommend improvements to mixture design practice, the relative effect of each of these factors on the resistance to age hardening and load associated cracking must be quantified. For example, how much additional binder or what level of modification is needed to offset the reduced cracking resistance resulting from the use of recycled binder in a mixture? The literature review did not identify that such quantitative relationships are available; therefore, the experiment described in this paper was designed, conducted, and analyzed. The results from the experiment were used to make recommendations to improve WisDOT's mix design and binder selection criteria.

3.0 Laboratory Prepared Mixtures Experiment

3.1 Statistical Considerations

The objective of this experiment was to develop regression equations quantifying the effect of (1) effective binder volume, (2) recycled binder content, (3) virgin binder low temperature grade, and (4) polymer modification on the resistance of asphalt mixtures to load associated cracking and age hardening. This type of experiment is a classical response surface experiment, which has the objective of defining the shape of the response surface in a well-defined region (NIST, 2014). The response surface can then be used to determine the combination of factors that produce an optimal or acceptable response over the region of interest. In the case of this experiment, that is the combinations of the four factors listed above that (1) provide acceptable resistance to cracking, and (2) minimize binder aging.

Since response surface experiments are often used in process improvement, partial factorial experiments with efficient designs that allow for interaction and non-linear effects have been developed. The Box-Behnken design allows a general quadratic model to be fit using data obtained from only 27 combinations of the four factors (NIST, 2014). A full factorial experiment for four factors at three levels requires testing 81 combinations. The Box-Behnken design is best visualized considering two factors at a time as shown in Figure 1. For each of the six two-factor combinations: (1) V_{be}-Recycle Content, (2) V_{be}-Virgin Low Grade, (3) V_{be}-Modification, (4) Recycle Content-Virgin Low Grade, (5) Recycle Content-Modification, and (6) Virgin Low Grade-Modification, one test is performed on mixtures representing the mid points of the sides. Tests at the overall center point are repeated three times to provide an estimate of testing error for judging the significance of effects.

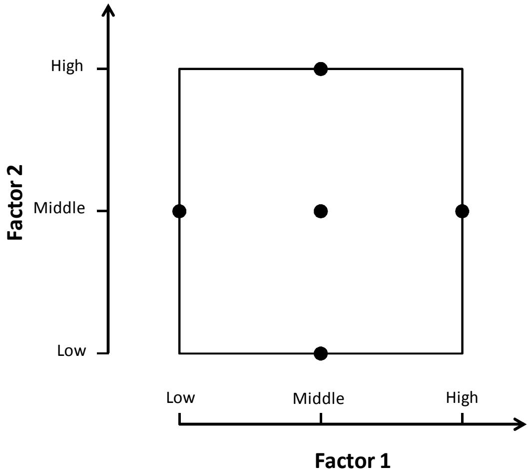

Figure 1. *Illustration of Box-Behnken design for two of the four factors.*

3.2 Materials

Since the goal of the project was to develop regression equations to be used to evaluate WisDOT specifications, materials were selected to incorporate a wide range of aggregates and binders used in Wisconsin. The variation in V_{be} was accomplished by using different nominal maximum aggregate size (NMAS) mixtures: 19.0 mm for low V_{be}, 12.5 mm for middle V_{be}, and 9.5 mm for high V_{be} mixtures. The recycle content was varied by including virgin mixtures for the low level, mixtures with 20 to 25% recycled asphalt pavement (RAP) for the middle level, and mixtures with 15 to 20% RAP plus 3% recycled asphalt shingles (RAS) for the high level. The use of RAP and RAS in combination is a common method for reaching high recycle contents; recycled binder ratios exceeding 0.30. The recycled binder ratios in Table 1 were calculated using the measured binder content of the RAP and RAS from solvent extraction. The aggregate and recycle selections resulted in the use of the nine different mix designs which are summarized in Table 1. The mixtures were typical fine graded mixtures used in Wisconsin. Except for the virgin 12.5 and 9.5 mm mixtures, the mixtures were designed per WisDOT specifications by Wisconsin producers. The virgin 12.5- and 9.5-mm mixtures required slight modification to WisDOT approved designs for mixtures with low RAP content to replace the RAP with virgin aggregate and binder.

Nine different virgin asphalt binders were used in the mixtures of Table 1 to complete the experiment. The low temperature grade of the virgin binder was varied by using PG XX-34 for the low level, PG XX-28 for the middle level, and PG XX-22 for the high level. Finally, different levels of modification were obtained by using unmodified binders for the low level, styrene-butadiene-styrene (SBS) modified binders with 35 to 60% AASHTO T 350 recovery for the middle level, and SBS modified binders with greater than 70% AASHTO T 350 recovery for the high level. Table 2 presents AASHTO M 320 and M 332 grading properties for the virgin binders used in the experiment. Commercial binder sources were used except for the middle and high modification PG XX-22 binders, which were laboratory blends based on typical commercial formulations.

Table 3 and Table 4 present properties for the RAP and RAS used in the mixtures. Four different RAP sources and two different RAS sources were used. The RAP and RAS binders were extracted and recovered in accordance with AASHTO R 59. The properties of the RAP binders were then determined in accordance with the blending chart procedure in the Appendix to AASHTO M 323. The properties for the RAS binders were determined by grading a blend of 70% PG 52-34 and 30% recovered RAS binder and then using linear extrapolation to estimate an appropriate value for the RAS binder to be used in blending chart analyses. Please note that this approach does not provide the actual grade of the RAS because the properties of RAS blends become highly non-linear at RAS binder ratios exceeding about 0.50 (Bonaquist, 2011). However, the RAS properties determined in this manner may be used to evaluate mixtures with RAS binder ratios of 0.30 or less.

Table 1. *Properties of mixtures used in the laboratory prepared mixtures experiment***.**

Type	**ID**	**Nom Max Size, mm**	**AC, wt %**	**V_{be}, vol. %**	**Recycled Binder Ratio**			**Gradation, % passing Sieve Size in mm**										
					RAP	**RAS**	**Total**	**25**	**19**	**12.5**	**9.5**	**4.75**	**2.36**	**1.18**	**0.6**	**0.3**	**0.15**	**0.075**
Virgin	8	19.0	4.8	9.9	0	0	0	100	98	87	78	57	45	32	24	12	7	4.8
	2	12.5	5.7	11.6	0	0	0	100	100	98	87	67	50	31	20	9	5	4.3
	9	9.5	6.3	11.7	0	0	0	100	100	100	100	71	53	42	32	18	9	5.3
RAP	5	19.0	4.9	8.8	0.26	0	0.26	100	100	89	82	64	48	36	26	16	9	4.8
	6	12.5	5.4	10.5	0.19	0	0.19	100	100	95	89	73	56	42	30	17	9	4.6
	1	9.5	6.1	12.0	0.25	0	0.25	100	100	100	96	81	65	48	34	16	8	5.7
RAP + RAS	3	19.0	5.1	9.2	0.21	0.16	0.37	100	98	89	79	60	49	41	33	17	7	5.0
	7	12.5	5.8	12.3	0.12	0.16	0.28	100	100	94	85	68	56	44	31	15	8	5.3
	4	9.5	5.7	11.7	0.12	0.18	0.30	100	100	100	98	74	53	38	26	13	7	5.1

Table 2. *AASHTO M 320 and AASHTO M 332 grading for the virgin binders used in the laboratory prepared mixtures experiment.*

	Low Temperature Grade	**-34**	**-34**	**-34**	**-28**	**-28**	**-28**	**-22**	**-22**	**-22**
	Modification	**None**	**Middle**	**High**	**None**	**Middle**	**High**	**None**	**Middle**	**High**
Spec	**Property**									
AASHTO M320 Continuous Grading Data	Tank High, °C	54.2	62.9	68.7	58.2	68.5	74.4	66.1	77.6	80.6
	RTFOT High, °C	55.8	65.6	69.4	59.7	69.9	75.1	67.1	78.4	82.2
	Intermediate, °C	11.9	13.1	10.5	20.2	19.1	15.8	23.7	22.8	21.9
	Stiffness Low, °C	-34.0	-36.4	-36.2	-29.8	-29.6	-32.0	-25.9	-24.2	-24.3
	m-value Low, °C	-35.6	-36.9	-36.7	-29.0	-28.9	-31.8	-25.6	-25.1	-25.3
	Grade	52-34	58-34	64-34	58-22*	64-28	70-28	64-22	76-22	76-22
AASHTO M332 Grading Data	$J_{nr3.2}$ at 58°C, 1/kPa	6.42	0.57	0.24	3.64	0.57	0.07	NA	NA	NA
	J_{nrdiff} at 58°C, %	10.1	28.7	9.2	10.3	25.3	5.6	NA	NA	NA
	%R at 58°C, %	0.0	59.6	75.1	0.0	34.6	86.0	NA	NA	NA
	$J_{nr3.2}$ at 64°C, 1/kPa	NA	NA	NA	NA	NA	NA	3.05	0.34	0.10
	J_{nrdiff} at 64°C, %	NA	NA	NA	NA	NA	NA	10.0	23.2	6.9
	%R at 64°C, %	NA	NA	NA	NA	NA	NA	0.3	49.4	79.1
	Grade	52-34 S	58-34 V	58-34 E	58-22 S*	58-28 V	58-28 E	64-22 S	64-22 V	64-22 E

** fails intermediate stiffness of 5000 kPa at 19°C*

Table 3. *Properties of recovered RAP binders.*

Property	Mix Using RAP			
	1	5&6	3&4	7
Binder Content, %	4.78	4.78	4.42	4.16
As Recovered High, °C	84.1	87.6	88.9	91.1
RTFOT High, °C	82.1	85.6	87.4	89.1
Intermediate, °C	25.5	27.1	26.3	25.8
Stiffness Low, °C	-25.1	-23.6	-24.6	-25.2
m-value Low, °C	-22.5	-19.7	-20.9	-23.3
$\Delta T_{c,}$ °C	-2.6	-3.9	-4.0	-1.9

Table 4. *Properties of recovered RAS binders.*

Property		Mix Using RAS	
		3&4	7
Binder Content, %		29.41	23.63
30/70 Blend of RAS and PG 52-34	As Blended High, °C	70.4	71.6
	RTFOT High, °C	73.3	72.6
	PAV Intermediate, °C	17.6	17.1
	PAV Stiffness Low, °C	-32.1	-32.7
	PAV m-value Low, °C	-28.8	-30.7
	PAV $\Delta T_{c,}$ °C	-3.3	-2.0
Extrapolated RAS	As Recovered High, °C	108.2	112.2
	RTFOT High, °C	114.1	111.8
	PAV Intermediate, °C	30.9	29.2
	PAV Stiffness Low, °C	-27.7	-29.7
	PAV m-value Low, °C	-12.9	-19.3
	$\Delta T_{c,}$ °C	-14.8	-10.4

3.2 Responses and Test Procedures

Table 5 presents an overall summary of the partial factorial experimental design. Since a partial factorial was used, all combinations of mixture and binder were not tested. As discussed earlier, NMAS was used as a surrogate for V_{be} with 19.0 mm mixtures for the low V_{be} level, 12.5 mm mixtures for the middle V_{be} level and 9.5 mm mixtures for the high V_{be} level. For each cell in Table 5, resistance to aging and load associated cracking was evaluated using the procedures described below.

Aging was evaluated by testing the mixtures in Table 5 for two laboratory aging conditions: short-term oven aged (STOA) and long-term oven aged (LTOA). For short-term oven aging, loose mix was conditioned in a forced draft oven for 4 hours at 135°C in accordance with AASHTO R 30. Long-term oven aging included short-term oven aging plus additional conditioning of loose mix in a forced draft oven for 120 hours at 85°C. The long-term oven aging used loose mix rather than compacted specimens to minimize aging gradients that occur when compacted specimens are conditioned in accordance with AASHTO R 30 (Kim et al., 2015).

Table 5. *Summary of experimental design.*

Run	**Mix ID**	**NMAS, mm**	**Recycle**	**Low Grade**	**Modification**[1]	**Space**
1	8	19.0	Virgin	-28	V	V_{be} – Recycle
2	9	9.5	Virgin	-28	V	
3	3	19.0	RAP+RAS	-28	V	
4	4	9.5	RAP+RAS	-28	V	
5	6	12.5	RAP	-22	S	Low Grade – Modification
6	6	12.5	RAP	-34	S	
7	6	12.5	RAP	-22	E	
8	6	12.5	RAP	-34	E	
9	6	12.5	RAP	-28	V	Center
10	5	19.0	RAP	-28	S	V_{be} – Modification
11	1	9.5	RAP	-28	S	
12	5	19.0	RAP	-28	E	
13	1	9.5	RAP	-28	E	
14	2	12.5	Virgin	-22	V	Recycle - Low Grade
15	7	12.5	RAP+RAS	-22	V	
16	2	12.5	Virgin	-34	V	
17	7	12.5	RAP+RAS	-34	V	
18	6	12.5	RAP	-28	V	Center
19	2	12.5	Virgin	-28	S	Recycle – Modification
20	7	12.5	RAP+RAS	-28	S	
21	2	12.5	Virgin	-28	E	
22	7	12.5	RAP+RAS	-28	E	
23	5	19.0	RAP	-22	V	V_{be} – Low Grade
24	1	9.5	RAP	-22	V	
25	5	19.0	RAP	-34	V	
26	1	9.5	RAP	-34	V	
27	6	12.5	RAP	-28	V	Center

[1] *S, V, and E denote AASHTO M 350 grades. H and V grades required polymer modification.*

Load associated cracking resistance was evaluated using intermediate temperature SCB tests. SCB testing was selected for the following reasons: (1) parameters from SCB tests have been related to field cracking (Mohammad et al., 2012; Al-Qadi et al., 2015), (2) test specimens can be prepared from gyratory specimens or cores with minimal effort, (3) the test does not require closed loop control or specimen mounted transducers, (4) a measure of stiffness to evaluate aging effects can be obtained from the load displacement curve, and (5) energy (area under the load-displacement curve) calculated from the test has a low coefficient of variation. Specimens for SCB testing were compacted in a gyratory compactor meeting the requirements of AASHTO T 312 to a target air void content of 7.0 ±0.5%.

Two versions of intermediate temperature SCB tests have been proposed by researchers at the Louisiana Transportation Research Center (Mohammad et al., 2012) and the Illinois Center for Transportation (Al-Qadi et al., 2015). The Louisiana version was initially selected for this project. The SCB tests were conducted at 15°C using a ram displacement rate of 0.5 mm/min. The testing temperature was reduced from 25°C to 15°C to produce critical strain energy release rates for the softer binders used in Wisconsin that were in the range of those reported in the Louisiana research (Mohammad et al, 2012) for stiffer binders. The Louisiana analysis was abandoned when comparisons of results for short-term oven aging and long-term oven aging revealed irrational trends. The irrational trends from the Louisiana analysis led to the reanalysis of the 25-mm notch depth data using the flexibility index (FI) approach recommended by research at the Illinois Center for Transportation (Al-Qadi et al., 2015). The flexibility index is equal to the fracture energy divided by the slope of the post peak load-displacement curve at the inflection point. This is shown in Figure 2. Using time-temperature superposition, the loading conditions of 15°C, 0.5 mm/min used in this project are approximately equivalent to 8.5 mm/min at 25°C, which is somewhat slower than the 50 mm/min used in the Illinois research. Also, the notch depth of 25 mm is greater than the 15-mm used in the Illinois research. Therefore, flexibility index values presented in this paper should not be compared directly with those from the Illinois research. The flexibility index values reported here are the average of three tests. The measured flexibility index values ranged from 2 to 15 for short-term oven aged mixtures and 1 to 10 for long-term oven aged mixtures. Considering the wide range in flexibility index values and the rational trend of reduced cracking resistance with long-term oven aging, the flexibility index was the response selected for final analysis.

To evaluate aging, the slope of the load displacement curve at 50% of the peak value was used to define a stiffness index (SI). The stiffness index values reported here are the average of three tests. An aging ratio was then calculated as the ratio of the stiffness index after long-term oven aging divided by the stiffness index after short-term oven aging. This aging ratio is a measure of the age hardening that occurs in the mixture.

Finally, after SCB testing, the binder in the specimens was extracted and recovered to measure properties of the binder that have been related to cracking and aging. These properties include: (1) the intermediate and low temperature continuous grade temperature, (2) the parameter ΔT_c (Anderson et al., 2011) which is the difference in the temperature where bending beam rheometer (BBR) stiffness is 300 MPa and the temperature where the BBR m-value is 0.300, and (3) the Glover-Rowe (G-R) parameter (Rowe, 2011). The binders were extracted and recovered in accordance with AASHTO R 59, and the properties were measured on the recovered binder with no additional conditioning.

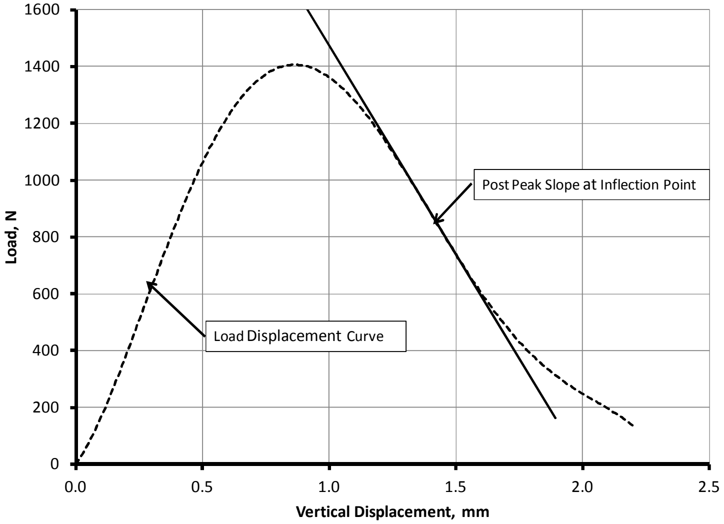

Figure 2. *Load-displacement curve and slope for calculating the flexibility index.*

3.4 Results and Analysis

3.4.1 Results and Preliminary Graphical Analysis

The intermediate temperature SCB results are presented in Table 6 and Table 7 for short- and long-term oven aged mixtures, respectively. These tables include V_{be} and apparent film thickness (AFT). The AFT was calculated by dividing the effective volume of binder by the surface area of the aggregates. The surface area of the aggregates was calculated from the aggregate gradation using surface area factors (Roberts et al., 1996). In the statistical analysis presented later, both were considered as predictors of the asphalt content effect.

Since the experiment is balanced, the effect of the primary experimental variables can be determined by averaging the data over the primary variables. Figures 3 through 6 show the effects of the primary variables on the flexibility index and the aging index. These figures show that the resistance to load associated cracking as measured by the flexibility index is significantly affected in a rational manner by the four primary experimental variables and aging. However, the four primary experimental variables have only a minor effect on the resistance to aging as measured by the aging index based on mixture stiffness. The flexibility index, which is a measure of load associated cracking resistance, increases with increasing V_{be} (Figure 3); decreasing virgin binder low temperature grade (Figure 4); decreasing recycled binder content (Figure 5); and increasing levels of modification (Figure 6). The flexibility index for long-term oven aged mixtures is approximately 50% of that for short-term oven aged mixtures implying cracking resistance decreases significantly with aging. Interestingly, the aging index based on stiffness varies over a narrow range from 1.2 to 1.4. It tends to be higher, indicating greater aging, for mixtures using the -34 virgin binder (Figure 4), and for virgin mixtures (Figure 5).

Table 6. *Intermediate temperature SCB results for short-term conditioned mixtures.*

Mix #	NMAS, mm	Recycle	Virgin Binder Grade	V_{be}, %	VTM, %	AFT, micron	SI, N/mm	FI
8	19	Virgin	58-28 V	9.9	6.9	8.31	500	6.75
9	9.5	Virgin	58-28 V	11.7	6.9	8.31	585	10.63
3	19	RAP+ RAS	58-28 V	9.2	7.1	6.77	724	2.60
4	9.5	RAP+ RAS	58-28 V	11.7	7.0	9.42	807	3.96
6	12.5	RAP	64-22 S	10.5	7.0	7.74	913	3.12
6	12.5	RAP	52-34 S	10.5	7.1	7.74	383	5.63
6	12.5	RAP	64-22 E	10.5	6.9	7.74	1141	3.44
6	12.5	RAP	58-34 E	10.5	6.9	7.74	449	9.14
6	12.5	RAP	58-28 V	10.5	7.0	7.74	819	4.01
5	19	RAP	58-28 S	8.8	6.8	6.76	619	3.70
1	9.5	RAP	58-28 S	12.0	7.2	8.14	626	7.67
5	19	RAP	58-28 E	8.8	6.9	6.76	705	4.76
1	9.5	RAP	58-28 E	12.0	7.0	8.14	720	9.93
2	12.5	Virgin	64-22 V	11.6	6.9	11.01	823	6.83
7	12.5	RAP+ RAS	64-22 V	12.3	6.9	9.14	817	5.56
2	12.5	Virgin	58-34 V	11.6	7.0	11.01	322	11.43
7	12.5	RAP+ RAS	58-34 V	12.3	6.9	9.14	385	9.98
6	12.5	RAP	58-28 V	10.5	7.0	7.74	870	4.23
2	12.5	Virgin	58-28 S	11.6	6.5	11.01	528	7.47
7	12.5	RAP+ RAS	58-28 S	12.3	6.9	9.14	568	7.42
2	12.5	Virgin	58-28 E	11.6	6.8	11.01	602	14.86
7	12.5	RAP+ RAS	58-28 E	12.3	6.9	9.14	643	8.96
5	19	RAP	64-22 V	8.8	7.0	6.76	970	2.42
1	9.5	RAP	64-22 V	12.0	7.2	8.14	965	4.53
5	19	RAP	58-34 E	8.8	7.0	6.76	522	5.61
1	9.5	RAP	58-34 E	12.0	7.1	8.14	453	11.77
6	12.5	RAP	58-28 E	10.5	7.0	7.74	882	4.46

Table 7. *Intermediate temperature SCB results for long-term conditioned mixtures.*

Mix #	NMAS, mm	Recycle	Virgin Binder Grade	V_{be}, %	VTM, %	AFT, micron	SI, N/mm	FI
8	19	Virgin	58-28 V	9.9	6.4	8.31	717	3.42
9	9.5	Virgin	58-28 V	11.1	7.0	8.31	743	5.76
3	19	RAP+ RAS	58-28 V	9.2	7.4	6.77	883	1.19
4	9.5	RAP+ RAS	58-28 V	11.7	7.0	9.42	912	1.25
6	12.5	RAP	64-22 S	10.5	7.0	7.74	1066	1.45
6	12.5	RAP	52-34 S	10.5	7.1	7.74	595	4.17
6	12.5	RAP	64-22 E	10.5	6.9	7.74	1372	1.08
6	12.5	RAP	58-34 E	10.5	6.9	7.74	658	4.63
6	12.5	RAP	58-28 V	10.5	6.9	7.74	1117	1.78
5	19	RAP	58-28 S	8.8	7.1	6.76	706	2.03
1	9.5	RAP	58-28 S	12.0	7.4	8.14	747	4.12
5	19	RAP	58-28 E	8.8	7.1	6.76	928	3.42
1	9.5	RAP	58-28 E	12.0	6.9	8.14	958	6.98
2	12.5	Virgin	64-22 V	11.6	6.8	11.01	1212	2.51
7	12.5	RAP+ RAS	64-22 V	12.3	7.0	9.14	897	2.12
2	12.5	Virgin	58-34 V	11.6	6.9	11.01	425	7.54
7	12.5	RAP+ RAS	58-34 V	12.3	7.1	9.14	548	4.99
6	12.5	RAP	58-28 V	10.5	6.8	7.74	1002	2.10
2	12.5	Virgin	58-28 S	11.6	6.5	11.01	740	6.86
7	12.5	RAP+ RAS	58-28 S	12.3	7.0	9.14	704	2.31
2	12.5	Virgin	58-28 E	11.6	7.0	11.01	828	9.62
7	12.5	RAP+ RAS	58-28 E	12.3	6.9	9.14	765	4.79
5	19	RAP	64-22 V	8.8	7.1	6.76	1132	1.39
1	9.5	RAP	64-22 V	12.0	6.9	8.14	1239	2.02
5	19	RAP	58-34 E	8.8	7.1	6.76	652	3.40
1	9.5	RAP	58-34 E	12.0	6.9	8.14	603	6.48
6	12.5	RAP	58-28 E	10.5	6.0	7.74	938	2.12

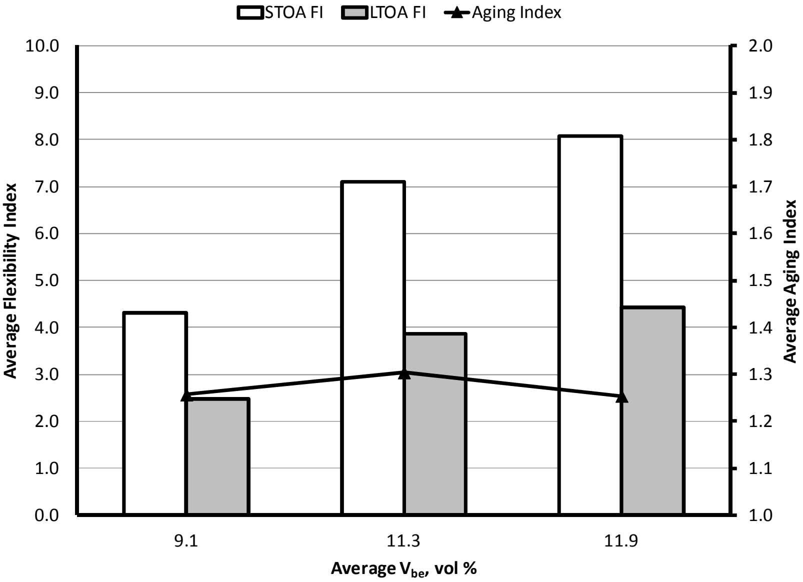

Figure 3. *Effect of V_{be} on flexibility index and aging index.*

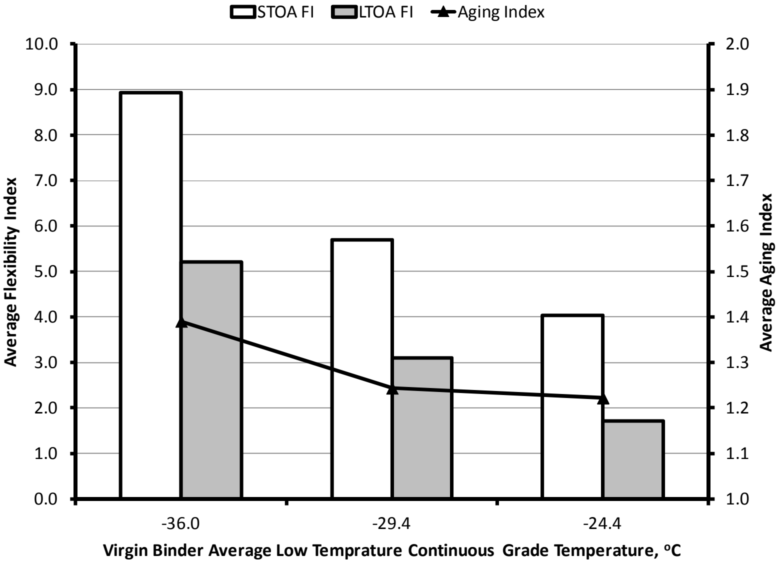

Figure 4. *Effect of virgin binder low temperature grade on flexibility index and aging index.*

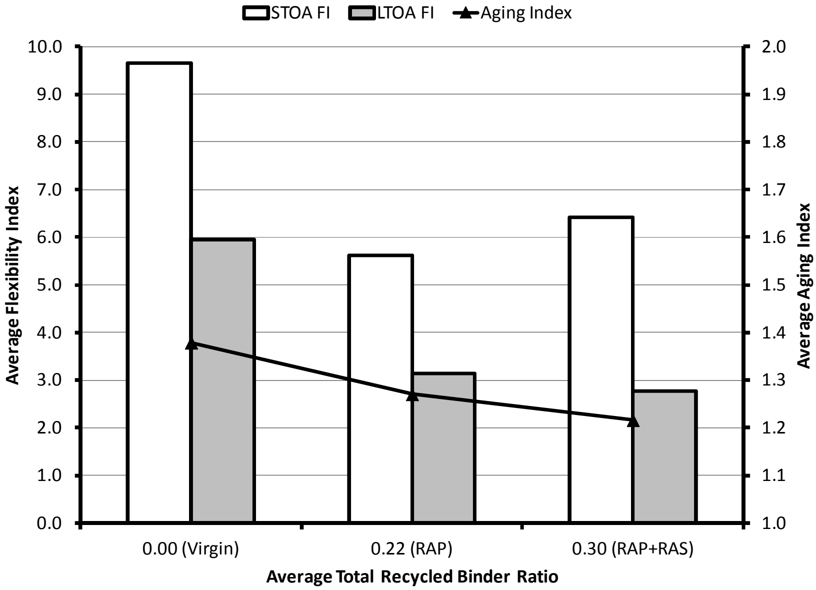

Figure 5. *Effect of recycle content on flexibility index and aging index.*

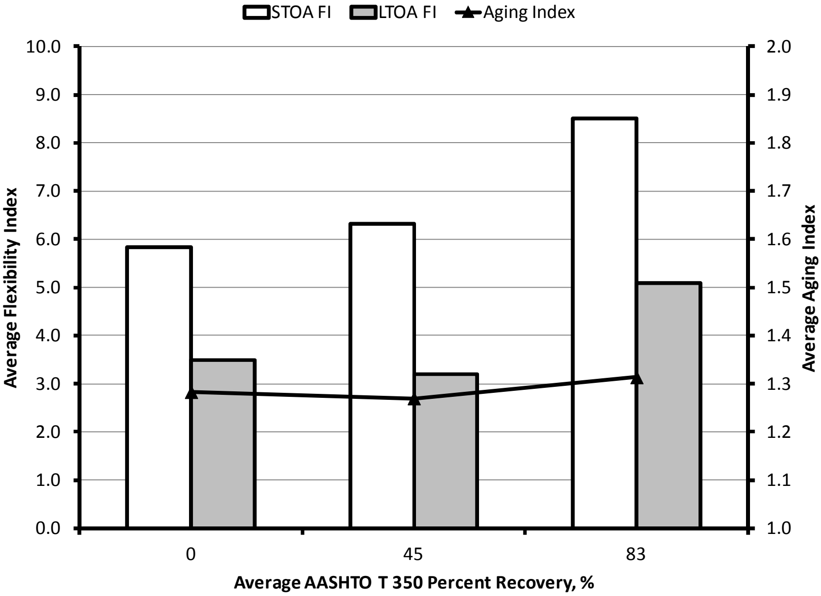

Figure 6. *Effect of polymer modification on flexibility index and aging index.*

The recovered binder results are presented in Table 8 and Table 9 for short- and long-term oven aged mixtures, respectively. The recovered binder data were collected to investigate relationships between the flexibility index and properties of the binders in the mixtures. Several binder parameters were considered including: continuous high (T_{high}), intermediate (T_{int}), and low temperature (T_{lowS} and T_{lowm}) grade temperatures, ΔT_c, and the Glover-Rowe (G-R) parameter. The strongest relationship was the linear relationship between the mixture flexibility index and the intermediate continuous grade temperature shown in Figure 7. This figure shows a definite relationship between the flexibility index and the stiffness of the binder in the mixture; however, the spread of the data around the regression line indicates the flexibility index is also affected by other properties of the mixtures.

Table 8. *Recovered binder results for short-term oven aged mixtures.*

Mix #	**NMAS, mm**	**Recycle**	**Virgin Binder Grade**	**Continuous Grade Temperature, °C**				**ΔT_c, °C**	**G-R, kPa**
				T_{high}	**T_{int}**	**T_{lowS}**	**T_{lowm}**		
8	19	Virgin	58-28 V	76.6	16.2	-31.4	-32.7	1.3	22.3
9	9.5	Virgin	58-28 V	74.9	15.8	-32.2	-33.0	0.8	21.9
3	19	RAP+ RAS	58-28 V	86.2	21.0	-28.8	-27.0	-1.8	161.8
4	9.5	RAP+ RAS	58-28 V	87.6	20.5	-29.2	-27.7	-1.5	162.1
6	12.5	RAP	64-22 S	75.6	22.3	-26.9	-27.9	1.0	54.4
6	12.5	RAP	52-34 S	64.7	14.2	-33.4	-36.8	3.4	2.5
6	12.5	RAP	64-22 E	79.2	22.5	-25.3	-26.4	1.1	70.4
6	12.5	RAP	58-34 E	70.9	11.6	-35.0	-36.0	1.0	4.5
6	12.5	RAP	58-28 V	77.2	19.0	-30.3	-30.9	0.6	21.9
5	19	RAP	58-28 S	70.7	18.1	-29.7	-29.8	0.1	21.8
1	9.5	RAP	58-28 S	69.2	17.1	-30.1	-30.3	0.2	15.3
5	19	RAP	58-28 E	81.0	17.0	-31.0	-30.5	-0.5	46.1
1	9.5	RAP	58-28 E	79.7	16.1	-31.7	-31.2	-0.5	25.3
2	12.5	Virgin	64-22 V	75.0	20.1	-26.0	-28.5	2.5	24.0
7	12.5	RAP+ RAS	64-22 V	84.9	22.8	-26.5	-26.1	-0.4	168.8
2	12.5	Virgin	58-34 V	69.7	8.1	-37.4	-39.9	2.5	3.6
7	12.5	RAP+ RAS	58-34 V	80.8	13.8	-34.4	-34.4	0.0	47.5
6	12.5	RAP	58-28 V	77.2	19.0	-30.3	-30.9	0.6	21.9
2	12.5	Virgin	58-28 S	65.3	14.8	-32.2	-33.5	1.3	6.4
7	12.5	RAP+ RAS	58-28 S	75.9	18.2	-29.9	-30.2	0.3	57.3
2	12.5	Virgin	58-28 E	78.7	13.0	-34.6	-36.2	1.6	18.0
7	12.5	RAP+ RAS	58-28 E	80.8	17.6	-32.3	-31.9	-0.4	97.5
5	19	RAP	64-22 V	78.2	23.0	-25.0	-25.9	0.9	115.5
1	9.5	RAP	64-22 V	78.8	23.2	-25.4	-26.1	0.7	83.6
5	19	RAP	58-34 E	73.1	13.7	-33.8	-35.1	1.3	12.3
1	9.5	RAP	58-34 E	72.0	14.4	-34.7	-35.7	1.3	14.5
6	12.5	RAP	58-28 E	77.2	19.0	-30.3	-30.9	0.6	21.9

Table 9. *Recovered binder results for long-term oven aged mixtures.*

Mix #	NMAS, Mm	Recycle	Virgin Binder Grade	Continuous Grade Temperature, °C				ΔT_c, °C	G-R, kPa
				T_{high}	T_{int}	T_{lowS}	T_{lowm}		
8	19	Virgin	58-28 V	82.5	19.7	-29.1	-29.8	0.7	58.7
9	9.5	Virgin	58-28 V	82.5	18.7	-30.4	-30.5	0.1	71.8
3	19	RAP+ RAS	58-28 V	90.6	23.0	-28.8	-25.1	-3.7	296.9
4	9.5	RAP+ RAS	58-28 V	90.7	21.7	-29.0	-25.2	-3.8	263.2
6	12.5	RAP	64-22 S	79.4	23.5	-25.7	-24.8	-0.9	121.8
6	12.5	RAP	52-34 S	68.9	16.6	-32.7	-35.0	2.3	7.7
6	12.5	RAP	64-22 E	83.4	23.6	-25.8	-25.6	-0.2	139.1
6	12.5	RAP	58-34 E	75.5	14.8	-33.4	-34.2	0.8	12.3
6	12.5	RAP	58-28 V	82.4	23.3	-29.9	-28.9	-1.0	76.0
5	19	RAP	58-28 S	75.2	20.1	-28.1	-27.5	-0.6	48.4
1	9.5	RAP	58-28 S	73.8	19.5	-29.2	-28.9	-0.3	47.4
5	19	RAP	58-28 E	86.0	19.8	-29.2	-27.1	-2.1	116.3
1	9.5	RAP	58-28 E	83.7	17.9	-31.4	-31.7	0.3	50.4
2	12.5	Virgin	64-22 V	80.9	23.2	-24.4	-25.1	0.7	95.8
7	12.5	RAP+ RAS	64-22 V	91.3	25.7	-25.0	-23.1	-1.9	430.3
2	12.5	Virgin	58-34 V	74.8	10.2	-37.2	-38.1	0.9	10.2
7	12.5	RAP+ RAS	58-34 V	85.9	16.1	-33.8	-32.3	-1.5	99.6
6	12.5	RAP	58-28 V	82.4	23.3	-29.9	-28.9	-1.0	76.0
2	12.5	Virgin	58-28 S	70.5	18.2	-30.5	-30.2	-0.3	21.7
7	12.5	RAP+ RAS	58-28 S	81.3	20.2	-30.0	-27.5	-2.5	161.5
2	12.5	Virgin	58-28 E	85.3	16.1	-32.2	-33.1	0.9	44.5
7	12.5	RAP+ RAS	58-28 E	93.4	20.3	-30.6	-28.4	-2.2	241.5
5	19	RAP	64-22 V	84.3	26.2	-23.5	-23.1	-0.4	241.5
1	9.5	RAP	64-22 V	81.3	25.0	-25.1	-25.3	0.2	189.7
5	19	RAP	58-34 E	77.7	16.1	-32.8	-32.1	-0.7	34.1
1	9.5	RAP	58-34 E	77.3	14.5	-33.8	-33.7	-0.1	30.9
6	12.5	RAP	58-28 E	77.2	19.0	-30.3	-30.9	0.6	21.9

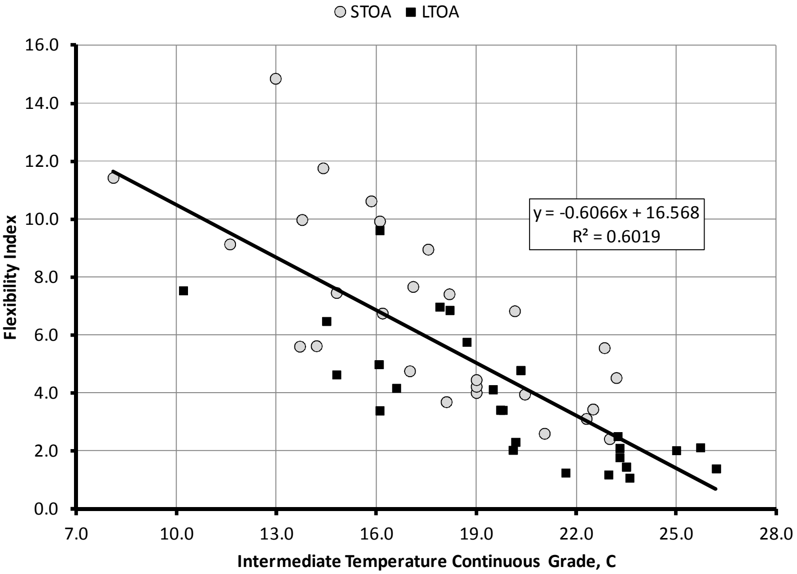

Figure 7. *Relationship between binder intermediate temperature continuous grade temperature and flexibility index.*

3.4.2 Regression Analysis for Short-Term Oven Aged Flexibility Index

Step-wise regression techniques were used to develop regression equations to estimate the short- and long-term oven aged flexibility indices from specifications properties. Both V_{be} and apparent film thickness were considered as measures of the asphalt content effect. Equations based on apparent film thickness did not show improvement compared to those based on V_{be}; therefore, V_{be} was used in the final equation. The likely reason that apparent film thickness did not improve the regression equations is all mixtures were fine graded mixtures resulting in similar calculated aggregate surface areas. Equation 1 is the final equation developed to estimate the short-term oven aged flexibility index from properties that can be controlled by specifications.

$$FI_{STOA} = -18.759 + 1.368 \times V_{be} - 0.3905 \times \left(T_{Virgin}\right)_{Low} - 10.181 \times RBR_{EFF} + 3.100 \times \left(\frac{R\%}{100}\right)^2 \quad [1]$$

Where: FI_{STOA} = short-term oven aged flexibility index

V_{be} = effective volume of binder, vol %

$(T_{Virgin})_{Low}$ = continuous low temperature grade of the virgin binder, °C

R% = percent recovery from AASHTO M 332

$$RBR_{EFF} = \text{effective RAP binder ratio} = \frac{\%RAPBinder}{\%TotalBinder} + F \times \left(\frac{\%RASBinder}{\%TotalBinder}\right) \quad [2]$$

Where: %RAPBinder = % of total mix that is RAP binder
%RASBinder = % of total mix that is RAS binder
%TotalBinder = % of the total mix that is binder (virgin+recycled)

$$F = \frac{T_{c_{RAS}} - T_{c_{Virgin}}}{T_{c_{RAP}} - T_{c_{Virgin}}} \qquad [3]$$

Where: F = factor indicating how much faster RAS changes the intermediate temperature grade of a blended binder compared to RAP
$T_{c_{RAS}}$ = continuous intermediate grade temperature for RAS binder
$T_{c_{RAP}}$ = continuous intermediate grade temperature for RAP binder
$T_{c_{Virgin}}$ = continuous intermediate grade temperature for virgin binder

The effective RAP binder ratio (RBR_{EFF}) is a new parameter introduced during this research to provide a single factor that combines the effects of both RAP and RAS. For an equal amount of recycled binder added to virgin binder, the addition of RAS will change the intermediate grade of the blended binder faster than RAP binder. The factor F in Equation 2 indicates how much faster RAS binders change the intermediate grade compared to RAP binders. It is derived from AASHTO M 323 blending chart calculations. For the RAP and RAS used in this experiment, the factor F had an average value of 1.3, indicating that the RAS increased the intermediate temperature grade 1.3 times faster than the RAP. The factor F may be different for other recycled binders.

The explained variance for Equation 1 is reasonable at 83% adjusted for the degrees of freedom. The standard error of estimate is 1.33 compared to a standard deviation of 0.88 for multiple measurements at the center point of the experiment. The analysis of the regression coefficients is shown in Table 10. The flexibility index rationally increases with: (1) increasing V_{be}, (2) decreasing virgin binder low temperature grade, (note the coefficient is negative and the low temperature grade is negative), decreasing effective RAP binder ratio, and increasing percent recovery. All of the coefficients are significant as shown by the very low p-values in Table 10. The standardized partial regression coefficients in Table 10 indicate the relative importance of the predictor variables. V_{be} and low temperature grade of the virgin binder are the most important having nearly equal standardized partial regression coefficients. These are followed by the effective RAP binder ratio and then the percent recovery.

Table 10. *Analysis of the regression coefficients for Equation 1.*

Variable	Partial Regression Coefficient	t-Statistic	p-value	Standardized Partial Regression Coefficient
Intercept	-18.759	-6.051	0.000004	NA
V_{be}	1.368	6.325	0.000002	0.52
Virgin Binder Low PG	-0.3905	-5.773	0.000008	-0.49
Effective RAP Binder Ratio	-10.181	-4.736	0.000100	-0.39
% Recovery	3.100	2.893	0.008445	0.25

Figure 8 is a plot of the predicted versus measured flexibility index values and Figure 9 is a plot of the residuals versus the predicted values. These indicate the equation may underestimate the flexibility index for conditions yielding low flexibility index values. Low values of the flexibility index are not important in this research aimed at specification changes to improve load associated cracking resistance. From Equation 1, the flexibility index for a 12.5 mm mixture with a V_{be} of 10.0, PG 58-28 S binder and no RAP is 5.9 which is near the middle of the range of flexibility index values in Figure 8. Plots of the residuals versus each of the predictor variables, which are not shown here, show the residuals are randomly distributed and do not identify a particular predictor variable that is responsible for the underestimation of low flexibility index values (Bonaquist, 2016).

3.4.3 Regression Analysis for Long-Term Oven Aged Flexibility Index

The primary experimental variables and the short-term oven aged flexibility index were evaluated as predictor variables in regression equations for the long-term oven aged flexibility index. This evaluation found that the long-term oven aged flexibility index is highly dependent on the short-term oven aged flexibility index. Equation 3 is the relationship for the long-term oven aged flexibility index that was developed from the laboratory prepared mixtures experiment.

$$FI_{LTOA} = 0.6550 \times FI_{STOA} - 0.7019 \qquad [3]$$

Where: FI_{LTOA} = long-term oven aged flexibility index
FI_{STOA} = short-term oven aged flexibility index

The explained variance for this equation is 84% and the standard error of estimate is 0.91 compared to a standard deviation of 0.37 for multiple measurements of the long-term oven aged flexibility index at the center point of the experiment. Figure 10 is a plot of the predicted versus measured long-term conditioned flexibility index values and Figure 11 is a plot of the residuals versus the predicted values. These figures show the equation provides an unbiased estimate over the range of the measured values.

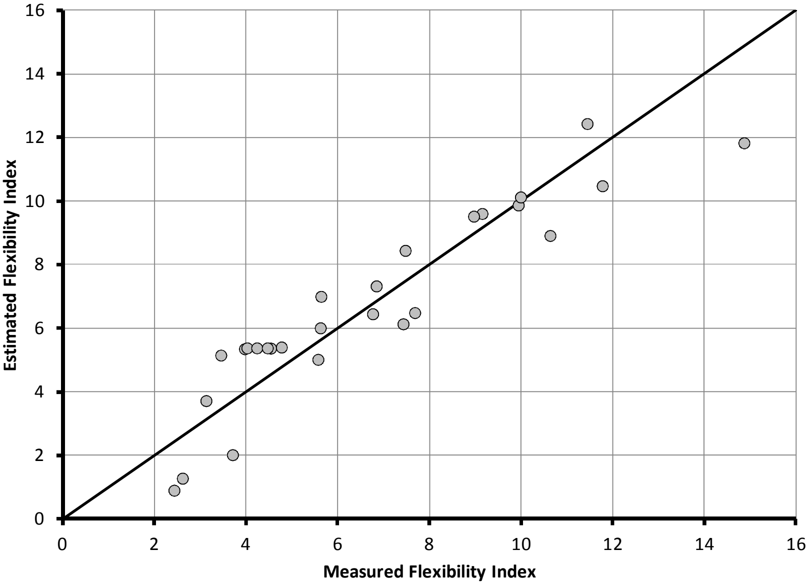

Figure 8. *Predicted versus measured short-term oven aged flexibility index.*

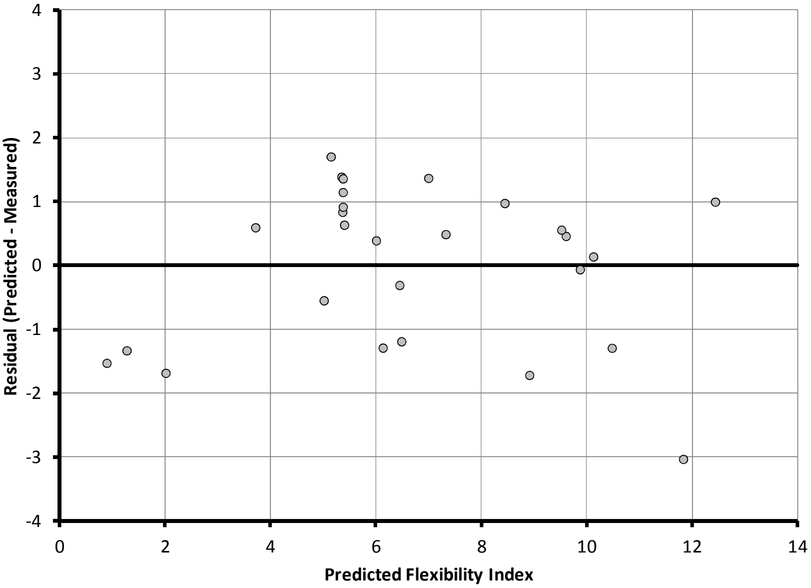

Figure 9. *Plot of residuals versus predicted short-term oven aged flexibility index.*

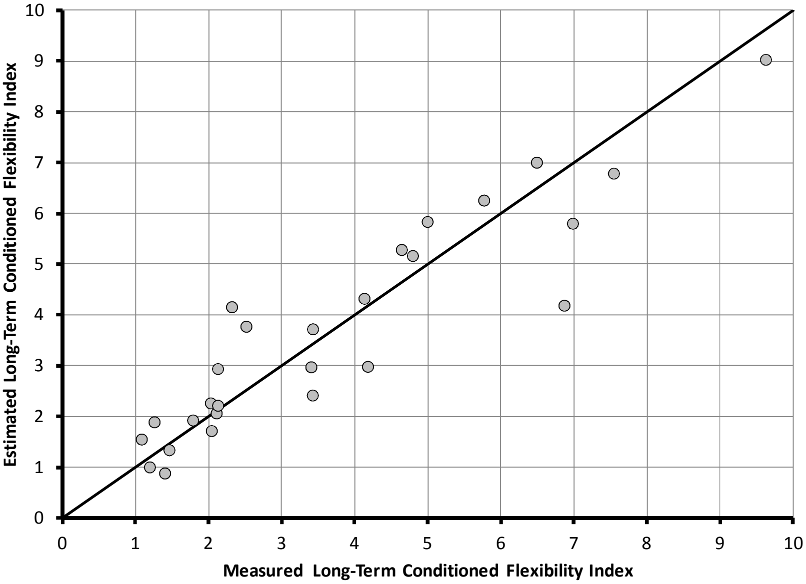

Figure 10. *Predicted versus measured long-term oven aged flexibility index.*

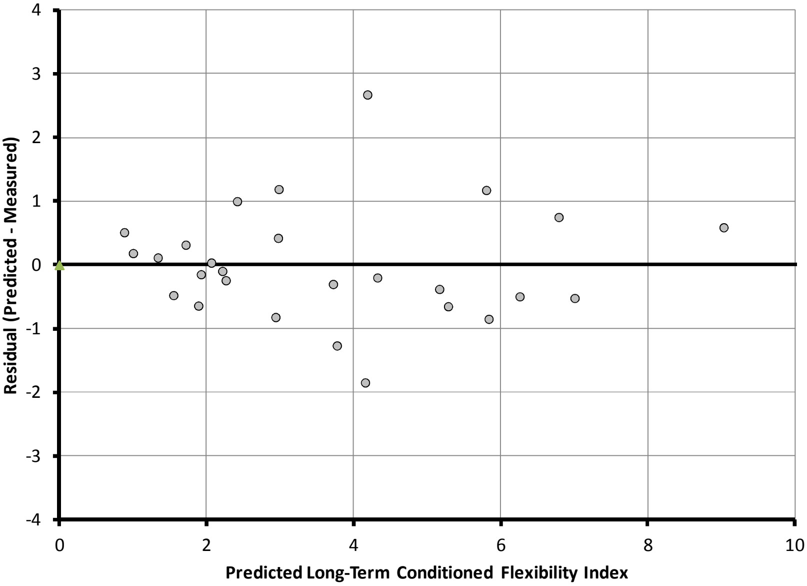

Figure 11. *Plot of residuals versus predicted long-term oven aged flexibility index.*

A couple of comments on Equation 3 are in order. First, for short-term oven aged flexibility index values less than 1.07, Equation 3 produces negative estimated values of the long-term oven aged flexibility index, which is not possible. As discussed in the previous section, low short-term oven aged flexibility index values are not important to this research to evaluate methods to improve cracking resistance. Second, the negative constant term in Equation 3 becomes increasingly important as the short-term oven aged flexibility index decreases. As the short-term oven aged flexibility index decreases, the ratio of the long-term to short-term oven aged flexibility index also decreases as shown in Table 11. The important take away from this discussion is that methods that improve the short-term oven aged flexibility index will also improve the long-term oven aged flexibility index. Therefore, for materials with normal aging characteristics, it is reasonable to base decisions on how to improve mixture load associated cracking resistance on the estimated short-term flexibility index.

Table 11. *Ratio of* FI_{LTOA} *to* FI_{STOA} *from Equation 3.*

$\mathbf{FI_{STOA}}$	$\mathbf{FI_{LTOA}}$	$\mathbf{FI_{LTOA}/FI_{STOA}}$
14.00	8.47	0.60
12.00	7.16	0.60
10.00	5.85	0.58
8.00	4.54	0.57
6.00	3.23	0.54
4.00	1.92	0.48
2.00	0.61	0.30

4.0 Plant Mix Verification Experiment

4.1 Experimental Design

A verification experiment was conducted using plant mixtures that were not included in the laboratory prepared mixtures experiment. The objective of the plant mix verification experiment was to compare estimates of cracking resistance obtained from Equation 1, which was developed from the laboratory prepared mixtures experiment, with values measured on plant produced mixtures that were not included in the laboratory prepared mixtures experiment. The verification experiment did not include a statistical design. Mixtures were sampled based on availability during the 2015 construction season. Table 12 shows: (1) the 81 cells considered in the experimental design of the laboratory prepared mixtures experiment, (2) the 25 cells that were tested in the laboratory prepared mixtures experiment, and (3) the 16 plant mixtures included in the plant mix verification study. The shaded cells identify the cells that were tested in the laboratory prepared mixtures experiment, and the "V" numbers identify the plant mixtures included in the verification experiment. The verification experiment included eight cells not tested during the laboratory prepared mixtures experiment and five cells that were tested. The verification experiment also included replicate mixtures in two of the cells.

Table 12. *Matrix showing laboratory prepared mixtures experiment and plant verification experiment.*

Recycle Content	**NMAS, mm**	**PG 52 or 58-34**			**PG 58-28**			**PG 64-22**		
		S	**H**	**V**	**S**	**H**	**V**	**S**	**H**	**V**
Virgin	19.0					▨				
Virgin	12.5		▨		▨		▨		▨	
Virgin	9.5					▨	V1			
RAP	19.0		▨		▨		▨		▨	
RAP	12.5	▨ V2, V3		▨	V4, V5	▨ V6	V7	▨ V8		▨
RAP	9.5	V9	▨		▨ V10		▨	V11	▨	
RAP+RAS	19.0			V12	V13	▨				
RAP+RAS	12.5		▨		▨ V14		▨		▨	
RAP+RAS	9.5				V15	▨		V16		

[1] *Shaded cells were tested in the laboratory prepared mixtures experiment.*
[2] *"V" numbered mixtures represent plant mixtures.*

4.1.2 Test Procedures

A reduced amount of testing was performed on the plant mixtures from the verification experiment. Since the FI was the response that was modeled from the laboratory prepared mixtures experiment, only the SCB tests at 15°C, 0.5 mm/min loading rate, and 25 mm notch depth were conducted. Replicate gyratory specimens were prepared to an air void content of 7.0 ±0.5% to produce four SCB specimens. The plant mix samples were reheated for 2 hours at 135°C prior to compaction. The volumetric properties and binder properties used in the flexibility index regression models developed from the laboratory prepared mixtures experiment were obtained from mixture design data submitted by the suppliers.

4.1.3 Results and Analysis

Table 13 summarizes estimated and measured flexibility indices from the plant mix verification experiment. These data are compared in Figure 12 which clearly shows that Equation 1 from the laboratory prepared mixtures experiment underestimates the measured flexibility index by a factor of approximately two. There is, however, a good relationship between the measured and estimated values as shown by the regression equation in Figure 12.

Table 13. *Estimated and measured flexibility indices from the plant mix verification experiment.*

Mix	Virgin Binder Grade	NMAS, mm	V_{be}, Vol %	RAP Binder Ratio	RAS Binder Ratio	Estimated FI	Measured FI
V1	58-28 S	9.5	11.0	0.000	0.000	6.7	13.6
V2	52-34 S	12.5	11.1	0.123	0.000	7.5	18.1
V3	52-34 S	12.5	11.2	0.226	0.000	8.5	25.0
V4	58-28 S	12.5	11.6	0.137	0.000	7.2	15.5
V5	58-28 S	12.5	10.8	0.173	0.000	4.5	10.7
V6	58-28 H	12.5	11.2	0.123	0.000	6.7	14.5
V7	58-28 V	12.5	9.8	0.140	0.000	5.0	9.6
V8	64-22 S	12.5	11.9	0.226	0.000	3.8	7.7
V9	52-34 S	9.5	12.3	0.098	0.000	10.4	26.3
V10	58-28 S	9.5	11.9	0.172	0.000	6.6	12.7
V11	64-22 S	9.5	12.6	0.203	0.000	6.5	11.9
V12	52-34 V	19	10.1	0.219	0.107	4.3	8.1
V13	58-28 S	19	9.7	0.210	0.121	3.8	4.7
V14	58-28 S	12.5	10.8	0.109	0.117	5.2	9.8
V15	58-28 S	9.5	12.6	0.129	0.102	6.8	15.5
V16	64-22 S	9.5	12.2	0.133	0.107	1.7	4.5

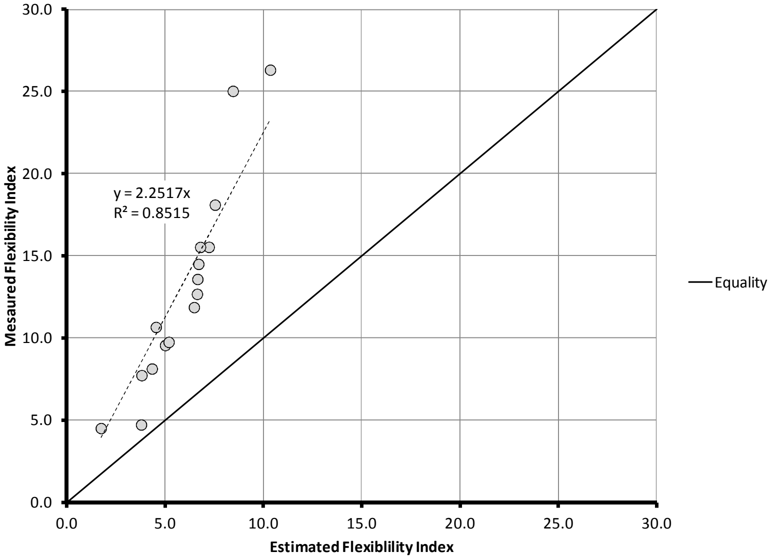

Figure 12. *Comparison of measured flexibility indices to Equation 1 estimated flexibility indices for the verification mixtures.*

The likely reason for the difference between the measured and estimated flexibility indices is differences in aging for the mixtures. The mixtures for the laboratory prepared mixtures experiment were aged for 4 hours at 135 °C, while the mixtures from the plant mix verification experiment were reheated for 2 hours in an oven set at 135 °C. This difference resulted in less aging of the binder for the plant mix verification mixtures. To account for the differences in aging, Figure 13 was constructed which compares the ranking of the mixtures based on Equation 1 and the measured flexibility indices. In this figure, the mixture with the rank of 1 has the highest resistance to load associated cracking while the mixture with a rank of 16 has the lowest resistance. The agreement in ranking is reasonable with no mixtures differing by more than three rank positions. The best ranked mixtures (V9, V2, and V3), were 9.5 or 12.5 mm mixtures produced with -34 binder and low to moderate recycle contents. The poorest ranked mixtures (V13, V16, and V8) were 9.5 or 12.5 mm mixtures produces with -22 binder and moderate to high recycle contents and a 19.0 mm mixture produced with -28 binder and a high recycle content.

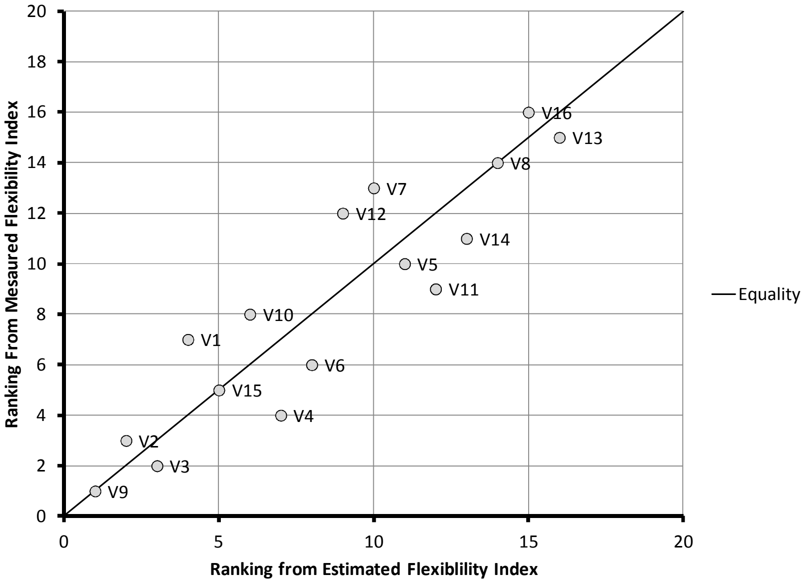

Figure 13. *Comparison of ranking based on Equation 1 and measured flexibility indices for the verification mixtures.*

5.0 Application to Mix Design Specifications

The objective of the research described here was to make recommendations on changes to mixture composition to improve load associated cracking resistance and reduce age hardening. The scope of the mixtures included in the study is summarized in Table 14. This scope covers the range of mixtures typically used in surface and lower layers in Wisconsin. The regression equations developed in this study should not be applied to mixtures outside of the ranges in Table 14.

Within the scope of the mixtures tested for this project, the laboratory study found no major differences in the aging characteristics of the mixtures. This finding appears to contradict an earlier National Center for Asphalt Technology (NCAT) study that showed a significant reduction in aging with increased film thickness (Kandhal and Chakraborty, 1996). The range of V_{be} considered in the NCAT study was from approximately 5 to 15%. However, over the range of V_{be} of 8.8 to 12.3% which is typical of Wisconsin mixtures, the 25°C modulus ratio (ratio of long-term oven aged modulus to short-term oven aged modulus) reported in the NCAT study only varied from 1.33 to 1.17, which is similar in magnitude to the aging ratios for the stiffness index measured in this study.

Table 14. *Summary of the scope of mixtures used in the laboratory experiments.*

Property	Range			
Effective Volume of Binder, %	8.8 to 12.3			
Nominal Maximum Aggregate Size	9.5 to 19.0			
Gradation	Fine			
RAP Binder ratio	0 to 0.26			
RAP Continuous Grade, AASHTO M 323 Appendix, °C	High	Intermediate	Low	ΔTc
	82.1 to 89.1	25.5 to 27.1	-19.7 to -23.3	-1.9 to -4.0
RAS Binder ratio	0 to 0.18			
Extrapolated RAS Continuous Grade, WHRP Project 0092-10-06 Procedure, °C	High	Intermediate	Low	ΔTc
	108.2 to 112.2	29.2 to 30.9	-12.9 to -19.3	-10.4 to -14.8
Effective RAP Binder ratio	0 to 0.41			
Virgin Binder Continuous Grade, °C	High	Intermediate	Low	ΔTc
	54.2 to 80.6	11.9 to 23.7	-36.4 to -24.2	1.6 to -0.7
Polymer Modification, AASHTO M 332	S, V, and E			
% Recovery, AASHTO T 350	0 to 86			

Within the scope of mixture tested, the laboratory experiments confirmed that the load associated cracking resistance of Wisconsin mixtures is affected by the following properties that can be specified, and controlled through the quality control testing:

- **Volume of Effective Binder (V_{be}).** The load associated cracking resistance of asphalt concrete mixtures improves with increasing V_{be}.
- **Low Temperature Grade of the Virgin Binder.** The load associated cracking resistance of asphalt concrete mixtures improves as the low temperature grade of the binder decreases.
- **Recycle Content.** The load associated cracking resistance of asphalt mixtures reduces as the recycle content of the mixture increases. The effect for RAS is greater than that for RAP, but the two can be combined by using an effective RAP binder ratio that accounts for the greater stiffening effect of RAS compared to RAP.
- **Polymer Content.** The load associated cracking resistance of asphalt mixtures improves with increasing percent recovery as measured in AASHTO T 350.

Equation 1 was used to develop a mix design specification for 12.5 mm surface course mixtures that provides equivalent or improved load associated cracking resistance. Since data relating the flexibility index to actual cracking in pavements is limited, the specification is based on providing mixtures with flexibility indices equal to or greater than that obtained from AASHTO M 323 for a virgin mixture produced with the appropriate grade of binder based on environmental considerations. WisDOT has divided Wisconsin into two zones for binder grade selection: (1) Southern Asphalt Zone, where PG 58-28 S is specified, and (2) Northern Asphalt Zone, where PG 58-34 S is specified. Table 15 presents the specification for 12.5 mm nominal maximum aggregate size mixtures in the Southern Asphalt Zone. The following assumptions were made in constructing Table 15:

- PG 58-28 binders have a low temperature continuous grade of -30°C.
- PG 58-34 binders have a low temperature continuous grade of -35°C.
- Percent recovery for S grade binders is 0
- Percent recovery for H grade binders is 30%.
- Percent recovery for V grade binders is 55%.
- Percent recovery for E grade binders is 75%.

The assumed low temperature continuous grades are based on typical grading data. The percent recovery values are the minimum percent recoveries specified in the Combined State Binder Group 2016 Method of Acceptance for Asphalt Binders (Combined State Binder Group, 2016). Table 15 gives the minimum design V_{be} for 12.5 mm mixtures for various recycled binder contents, and various grades of virgin binder. This approach provides producers the flexibility to select the most economical combination of virgin binder grade, level of modification, recycle content, and effective binder content to meet the specified load associated cracking resistance. Cells with the minimum design V_{be} of 10.0, shown in bold, would have improved load associated cracking resistance compared to a virgin 12.5-mm mixture and would not likely be supplied without an incentive. From an earlier study, the maximum effective RAP binder ratio for the standard temperature grade of -28 is

0.30 based on thermal cracking considerations (Bonaquist, 2011b). For effective RAP binder ratios above this level, the low temperature grade of the binder must be reduced to reduce the potential for low temperature cracking.

Table 15. *Example minimum design V_{be} specification for12.5 mm mixtures in the Southern Asphalt Zone.*

Effective RAP Binder Ratio	**Minimum Design V_{be}, vol %**							
	58-28 S	**58-28 H**	**58-28 V**	**58-38 E**	**58-34 S**	**58-34 H**	**58-34 V**	**58-34 E**
0.00	10.0	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**
>0.00 ≤0.05	10.4	10.2	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**
>0.05 ≤0.10	10.7	10.5	10.1	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**
>0.10 ≤0.15	11.1	10.9	10.4	**10.0**	**10.0**	**10.0**	**10.0**	**10.0**
>0.15 ≤0.20	11.5	11.3	10.8	10.2	10.1	**10.0**	**10.0**	**10.0**
>0.20 ≤0.25	11.9	11.7	11.2	10.6	10.4	10.2	**10.0**	**10.0**
>0.25 ≤0.30	12.2	12.0	11.5	11.0	10.8	10.6	10.1	**10.0**
>0.30 ≤0.35	Low Temperature Grade Controls				11.2	11.0	10.5	**10.0**
>0.35 ≤0.40					11.5	11.3	10.9	10.3
>0.40 ≤0.45					11.9	11.7	11.2	10.6
>0.45 ≤0.50					12.3	12.1	11.6	11.0

Table 16 shows a similar specification for 12.5 mm mixtures in the Northern Asphalt Zone. Since a binder softer than -34 is not readily available and there is concern over effectiveness of softening agents, the specification for the Northern Asphalt Zone is somewhat more restrictive. It limits the effective RAP binder ratio to 0.30 based on low temperature cracking and includes only one low temperature grade of binder. Table 16 is based on Equation 1 and the same assumptions for binder properties listed above.

Table 16. *Example minimum design V_{be} specification for12.5 mm mixtures in the Northern Asphalt Zone.*

Effective RAP Binder Ratio	**Minimum Design V_{be}, vol %**			
	58-34 S	**58-34 H**	**58-34 V**	**58-34 E**
0.00	10.0	**10.0**	**10.0**	**10.0**
>0.00 to ≤0.05	10.4	10.2	**10.0**	**10.0**
>0.05 to ≤0.10	10.7	10.5	10.1	**10.0**
>0.10 to ≤0.15	11.1	10.9	10.4	**10.0**
>0.15 to ≤0.20	11.5	11.3	10.8	10.2
>0.20 to ≤0.25	11.9	11.7	11.2	10.6
>0.25 to ≤0.30	12.2	12.0	11.5	11.0

Please note that Table 15 and Table 16 were developed based on the assumption that the load associated cracking resistance of a properly designed and constructed 12.5 mm virgin mixtures in Wisconsin is acceptable. If improved load associated cracking resistance is desired, then the baseline V_{be} for virgin mixtures should be increased, for example by 1.0% as recommended in the new National Cooperative Highway Program Mix Design Manual (Advanced Asphalt Technologies, 2011). The relative changes in the minimum design V_{be} shown in Table 15 and Table 16 for increasing effective RAP binder ratio, decreasing low temperature grade, and increasing modification would be the same. Thus an effective method of improving the cracking resistance of mixtures in Wisconsin is to specify 9.5 mm mixtures using tables similar to Table 15 and Table 16 with all of the design V_{be} values increased by 1%. This approach is particularly useful in the Northern Asphalt Zone where a softer binder is not readily available.

6.0 Conclusions

This paper describes the development and practical application of regression equations to estimate the relative load associated cracking resistance of asphalt mixtures from properties that are included in specifications and controlled through current quality control and acceptance procedures. The regression equations were developed from a laboratory prepared mixtures experiment that included a wide range of binders and mixtures, and used two levels of oven aging to simulate short- and long-term aging. The regression equation for load associated cracking resistance based on SCB flexibility index values measured for short-term oven aging was verified using plant mixtures that were not part of the laboratory prepared mixtures experiment. The equation was then used to specify design volumetric properties that provide mixtures with similar cracking resistance for Wisconsin conditions over a wide range of recycled binder contents. The major conclusions drawn from this work are:

1. The flexibility index from SCB tests is sensitive to the primary factors that were evaluated: (1) effective volume of binder, (2) low temperature grade of the virgin binder, (3) recycled binder content, (4) polymer modification, and (5) aging. The aging effect is quite large. Flexibility index values for reheated plant mixed samples were a factor of two higher than those for laboratory mixtures aged 4 hours at 135 °C, which were a factor of two higher than laboratory mixtures that were short-term aged and then long-term aged an additional 120 hours at 85 °C.
2. Resistance to load associated cracking as measured by the flexibility index from SCB tests: (1) decreases with aging, (2) increases with increasing effective volume of binder, (3) increases with decreasing low temperature grade of the virgin binder, (4) decreases with increasing amount of recycled binder, and (5) increases with increasing levels of polymer modification. Two regression equations quantifying these effects were developed.
3. The flexibility index for long-term aged mixtures is highly correlated to the flexibility index for short-term aged mixtures indicating that factors that improve the short-term aged flexibility index will also improve the long-term aged flexibility index. Therefore, for materials with normal aging characteristics, it is reasonable to base decisions on how to improve load associated cracking resistance on the estimated short-term flexibility index.
4. The regression equation for the short-term aged flexibility index was used to develop model mix design specification tables for Wisconsin conditions. These design tables show that the negative effect of recycled binder on load associated cracking resistance can be offset by increasing the effective volume of binder, decreasing the low temperature grade of the binder, or using polymer modified binders allowing moderate levels of recycled binder to be used without sacrificing resistance to cracking. Tables of this type provide producers the flexibility to use various materials and optimize based on cost for a specified level of performance while providing agencies a level of assurance that the mixtures will meet minimum levels of cracking resistance.

7.0 Recommendations

The development of relationships between properties that can be specified and controlled and performance related properties of asphalt mixtures similar to Equation 1 are critical to effective implementation of balanced mix design concepts. Such relationships provide agencies and producers the knowledge needed to specify, design, and control mixtures with improved performance. Additional research using a wider range of mixtures should be conducted to confirm the relationships presented here and expand them to a wider range of mixtures.

The flexibility index developed at the University of Illinois appears to be a test that can likely be implemented in a balanced mixture design system. The test is: (1)

sensitive to changes in mixture composition that affect load associated cracking resistance, (2) relatively simple to perform, and (3) repeatable. Additional research is needed to relate the flexibility index to pavement performance and develop criteria for cracking performance that can be used in specifications and asphalt mixture design. Further improvement and standardization of the test and analysis procedure are also needed.

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