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FINAL REPORT ~ FHWA-OK-19-01

IMPLEMENT BALANCED ASPHALT MIX DESIGN IN OKLAHOMA

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Oklahoma Department of Transportation

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16. ABSTRACT

The objective of this study was to evaluate selected ODOT mixtures to assist with determining test procedures, specifications and special provisions for evaluation and eventual adaptation of a BMD procedure for ODOT. The test plan was developed by ODOT and consisted of evaluating I-FIT test results from 31 existing mixes and I-FIT and Ideal CT Index tests from nine mixes from three ODOT projects. The nine mixes consisted of three control mixes and six BMD mixes. Testing was performed by ODOT and a consultant laboratory on plant produced field sampled materials.

There were inconsistent results from the testing within and between the data sets. BMD mixes differed from control mixes by the addition of RAP, increased VMA and increased asphalt content. Many of these high VMA BMD mixes collapsed in the field resulting in void properties below specification limits. It is recommended that ODOT consider adopting the Ideal CT test due to ease of testing and perform this testing on all mix designs submitted for use on ODOT projects. The data should be analyzed to determine what mix factors impact test results and to determine where ODOT mixes fall on the scale of CT_{Index} results.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1 INTRODUCTION

1.1 Introduction

As stated in the RFP, Oklahoma Department of Transportation (ODOT) uses a volumetric asphalt mix design method based on AASHTO R 35. Like many agencies, ODOT uses the Hamburg Wheel Test (HWT) to screen mixtures for rutting potential; however, they have no current test for evaluating fatigue resistance.

There is a national effort to move toward a balanced mix design (BMD) approach for design of asphalt mixtures. BMDs incorporate two or more mechanical tests such as a rutting test and a cracking test to assess how well the mixture will resist common forms of distress. The mechanical tests selected for a BMD and the accompanying specifications should account for mixture aging, traffic, climate and location within the pavement structure (1).

Based on a previous ODOT funded research project (2), the researchers recommended ODOT use a Semi-Circular Bend (SCB) test in conjunction with the HWT to better evaluate asphalt mixtures. The research project only evaluated one of the two current SCB tests, the Louisiana procedure or ASTM D8044. The second SCB test is the Illinois procedure, or I-FIT test (AASHTO TP 124). Adopting a BMD design approach in Oklahoma should lead toward a less prescriptive approach to mix design and longer lasting, better performing asphalt pavements.

1.2 Objectives

The objectives of this study were to review the available literature and select the best SCB test for use in a BMD for Oklahoma and to evaluate selected ODOT mixtures to assist with determining test procedures, specifications and special provisions for evaluation and eventual adaptation in a BMD procedure for ODOT.

1.3 Work Plan

The proposed work plan has been designed to meet the objectives of the RFP and this proposal. A literature review will be performed to assist with the selection of the most appropriate SCB test for ODOT and Oklahoma contractors and testing laboratories. In addition, the literature will be consulted to determine if any modifications to the current SCB test standards are needed, including investigating mixture and/or sample aging procedures as preliminary reviews have indicated this may impact the ability of the two SCB tests to identify the effects of high RAP and RAS contents. Once a test has been identified, mix design samples, plant produced samples or both will be selected, after consultation with ODOT, for evaluation using the SCB. It is proposed to use existing mix design HWT data from ODOT.

To accomplish the objectives of this study, the following tasks, listed below, will be performed.

Task 1 Literature Review (Tasks 1 & 2 from RFP). A review of available literature will be made concentrating on the use of the two SCB tests for BMD since ODOT has decided to go in this direction. The literature review will concentrate on what other agencies are doing, test procedures followed, specification limits and aging protocols. The literature will be reviewed to help decide if SCB testing will be performed during the mix design on laboratory mixed samples or on field produced samples as a QC test or a combination of both. It should be anticipated that laboratory and plant mixed samples will have different SCB test results.

Task 2 Progress meeting with ODOT (Task 3 from RFP). At the conclusion of Task 1 a meeting will be held with ODOT to review the findings and determine the direction of the study. Specifically, the SCB test to use (ASTM D8044 or AASHTO TP 124) will be decided at this meeting. A decision on using laboratory mixed samples as a part of the mix design process, plant produced mixes for QC testing or a combination of both will be decided. The need to evaluate different aging protocols for SCB testing and a draft BMD procedure for evaluation will be decided (Task 4 from RFP). Completion of Tasks 5 and 6 from the RFP should be delayed until completion of mixture evaluation performed in Task 4.

Task 3 Additional Progress Meeting (Tasks 6 & 7 from RFP). Shortly after completion of Task 2, a second meeting will be held with ODOT. The purpose of this meeting will be to develop and approve the test plan and test protocols selected in Task 2. These would include the SCB test to use, if there are any deviations from the standard test methods, if an additional aging protocol should be evaluated and whether laboratory or plant mixed samples, or a combination of both, will be used.

Task 4 Project Selection & SCB Testing (Task 8, 9 & 10 from RFP). With assistance from ODOT and OAPA, mixtures will be selected for SCB testing. HWT results will be obtained from the submitted mix designs. Most contractors use the same aggregate sources and similar percentages for mixtures with and without RAP.

Therefore, it is recommended that either S-3 or S-4 mixtures be selected for evaluation. An S-3 or S-4 mix with and without RAP should be selected from each contractor.

Aggregates and RAP will be sampled by the contractors and supplied to OSU at the time of original mix design. The building housing the bituminous laboratories at OSU is currently being demolished and a replacement facility has not been identified at this time; therefore, testing will be outsourced to a private testing laboratory. Testing will be performed by Thunderhead Testing, an ODOT and ARML certified testing laboratory with experience in research grade work and SCB testing. SCB tests will be performed at the specified aging protocol in the appropriate test method. A second aging protocol could be evaluated if recommended from Tasks 2 & 3. If desired for QC control, plant mixed samples could be obtained of the same mixtures for SCB testing.

From the RFP, the total number of SCB tests will be limited to 30. The exact number of mixtures sampled and tested will depend on the use of plant mixed samples and if a second aging protocol is selected.

Task 5 Reports and Meetings (Task 11 & 12 from RFP). Monthly progress reports will be supplied to ODOT summarizing progress to date. The PI will attend the meetings described in Tasks 2 and 3 as well as any other meetings deemed necessary by either ODOT or the PI to keep the project on track. A final report will be prepared for ODOT that will provide recommendations for development of a specification and special provision for implementation of balanced mix designs.

1.4 Anticipated Benefits

Development of draft specifications for a balanced mix design procedure for ODOT will move ODOT away from a voids based mix design procedure, allowing more innovative design concepts and producing longer lasting more durable and rut resistant pavements.

1.5 Implementation

At the completion of the study ODOT will have a draft specification for implementation of BMD on a trial basis in Oklahoma. Mixtures evaluated in this study should be monitored for several years to validate any proposed specification limits.

CHAPTER 2 LITERATURE REVIEW

Asphalt mixtures for ODOT projects are designed using the Superpave system, which was developed to address an observed increase in rutting seen in the late 1980s and early 1990s. The Superpave system relies on empirical aggregate quality characteristics and mixture volumetrics. Many agencies were not comfortable with the procedure without some type of mixture stability test and the Asphalt Pavement Analyzer and HWT tests were adopted by most agencies. These tests evaluated mixture stability, many times at the expense of mixture durability. ODOT uses the HWT and has recently raised the minimum asphalt content and VMA requirements in an effort to improve mixture durability. The move toward BMD is a logical next step.

According to the Asphalt Institute (3), the concept of BMD is not new but is seeing renewed interest. An accepted definition of BMD is "an asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure (3)."

Most agencies test mixture stability using either the HWT or the APA. Oklahoma uses the HWT. The question is what durability test should an agency use. The answer to that question depends on what distress the agency wants to address as a part of a BMD. Table 2.1 lists the following tests currently available for durability testing, depending on the mode of distress (1).

Table 2.1 Test Procedures Available for Durability Testing in a BMD

Laboratory Test	Test Standard	Bottom Up Fatigue Cracking	Top Down Fatigue Cracking	Thermal Cracking	Reflective Cracking
Bending Beam Fatigue Test	AASHTO T 321	X			
Texas Overlay Test	TxDOT Tex-248-F	X	X		X
SCB	ASTM D8044	X	X		
SCB I-FIT	AASHTO TP 124	X	X		X
Direct Tension Cyclic Fatigue	AASHTO TP 107	X			
Ideal CT	N/A	X	X		X
IDT Creep Compliance	N/A			X	
TSRST	BS EN12697			X	
SCB at Low Temperature	ASTM D8044			X	
Disk Shaped Compact Tension	ASTM D7313			X	X

BMDs generally rely on performance space diagrams to chart the results of multiple performance tests. Figure 2.1 shows a performance space diagrams using DCT test results but one would look similar using SCB test results for the DCT. Performance applicability zones are identified for rutting and cracking resistance and mixtures can be optimized, depending on where the mix is located in the pavement structure and the need for stability or durability.

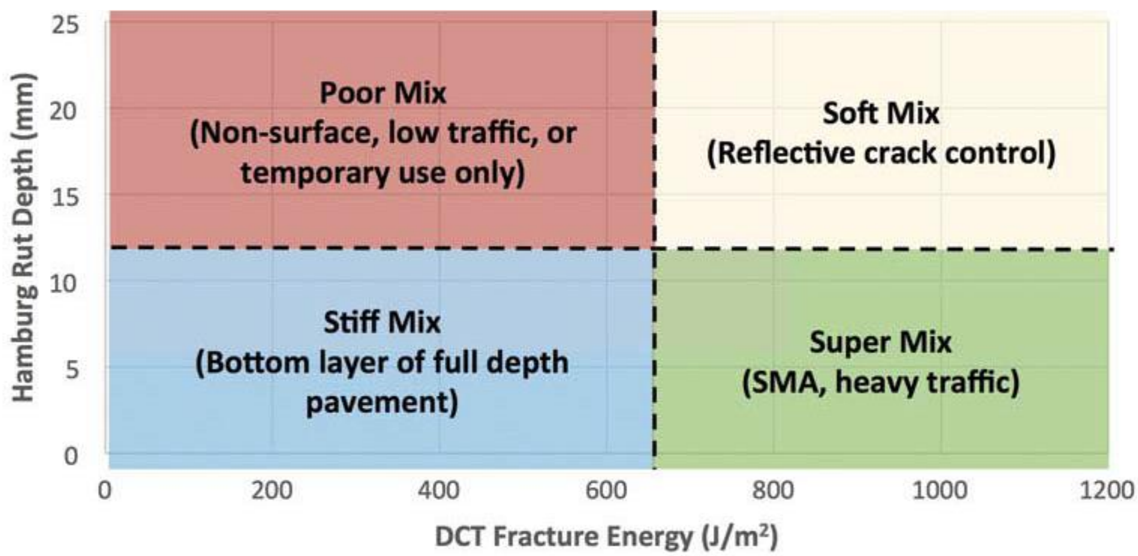

Figure 2.1 Example Performance Space Diagram

As previously stated, ODOT sponsored a research project that evaluated mixture fatigue tests and recommended the Louisiana SCB test (2). They did not evaluate the I-FIT procedure, which was not as far along in development at the time of the study. The two SCB tests are both standardized, the Louisiana SCB procedure by ASTM (ASTM D8044) and the Illinois or I-FIT procedure as a provisional procedure by AASHTO (AASHTO TP 124). The I-FIT test is performed at a faster loading rate and uses one notch depth compared to three for the Louisiana procedure. The test heads are slightly different as well. The Louisiana procedure looks at the first half of the load displacement curve where the I-FIT test also looks at the back half of the curve. According to NCAT (4), both work reasonably well and both have shortcomings. By only looking at the first half of the cure stiff mixes can occasionally show better cracking resistance in the Louisiana procedure whereas mixture density can influence I-FIT results (4).

Another factor that should come into play when deciding which SCB test to use is the ease of testing and cost of the equipment. NCAT (5) reviewed several cracking tests that have been proposed for use in a BMD. They rated each procedure based on performance at the cracking sections at the NCAT Test Track and on their ease of use. There were eight cracking sections evaluated after one loading cycle. NCAT reported little to no cracking on most sections and that additional load applications would be necessary to definitively evaluate the test procedures. However, NCAT did rank the test procedures on equipment cost, testing time and complexity (5). Complexity was rated on a scale of 1 to 5 with 1 being the least complex. The results are shown in Table 2.2.

Table 2.2 NCAT Evaluation of Cracking Tests

Cracking Test	Approximate Equipment Cost (Thousand $)	Sample Preparation, Testing and Analysis Time	Number of Specimens per Test	Complexity
Texas Overlay Tester	55-85	3-4 Days	4	2.2
NCAT Overlay Tester	55-85	3-4 Days	4	2.4
SCB ASTM D8044	10-30	2-3 Days	12	3.4
I-FIT AASHTO T 124	10-20	2-3 Days	6	2.4
Ideal CT Test	10-20	1-2 Days	3	1.2

InstroTek has developed a “SMART-JIG” for use with an existing universal testing such as used for AASHTO T 283 testing. This should further reduce the above stated cost of the Ideal CT test.

Adoption of BMD will require purchase of the selected SCB equipment and software. InstroTek (6) reported that the AMPT can be used to perform SCB testing, as performed on a previous ODOT project (2), but they do not recommend using it due to ruggedness issues with the AMPT. The Louisiana procedure (ASTM D8044) calls for the use of an environmental chamber, which would add to the cost. Due to the slower loading rate and multiple notch depths of ASTM D8044, the I-FIT procedure is a shorter test and preliminary inquiries indicated it was preferred by many contractors (7,8,9).

Prior to the selection of contractors to produce BMD mixes it was decided by ODOT to use the I-FIT procedure (AASHTO TP 124). The Ideal CT test was added after mixes were designed but prior to field sampling and testing. Therefore, an extensive literature was not performed. TRID is an integrated database that combines the records from TRB’s Transportation Research Information Services (TRIS) Database and the OECD’s Joint Transport Research Centre’s International Transport Research Documentation (ITRD) Database. A quick search of TRID returned 246 records for SCB and 148 records for SCB testing, 104 records for BMD, 24 records for I-FIT and 7 records for Ideal CT. There is extensive literature on balanced mix designs.

Researchers at the University of Illinois developed the I-FIT procedure and have published numerous papers on the topic (10-14). The procedure has been standardized by AASHTO as TP 124. Illinois has set a minimum Flexibility Index (FI) of 8 for their mixes (15) and this is the most common reported minimum FI value (16). The basic drawback to the procedure is the requirement for two saws to prepare a sample for testing, one to cut the test specimens from a larger sample and a second to cut the notch.

The shape of the load displacement curve for the I-FIT and Louisiana SCB test are similar. In fact, the curve has the same basic shape as any indirect tensile strength test, such as for AASHTO T 283. Researchers at Texas A&M noticed this and developed the Ideal CT test (17,18). A detailed test procedure is in the appendix to their study (18). The Ideal CT test uses a cylindrical specimen without any saw cuts. The specimen is tested similar to the I-FIT test. The only difference is in the calculations. The CT test calculates the slope of the post-peak curve where the load is reduced to 75% of its peak value rather than the inflection point (5). Buchanan (16) reported that most assume the CT_{index} will be 10 times larger than an equivalent FI; therefore, if an agency used a minimum FI of 8 then an equivalent CT_{index} would be 80. Buchanan (16) pointed out that there is little verification of what FI or CT_{index} would be required to limit cracking for individual states.

CHAPTER 3 REVIEW OF EXISTING ODOT TEST DATA

3.1 Existing ODOT Mix Data

ODOT had extra samples from 31 different mixes of various ages available for I-FIT and Hamburg rut testing. Testing was performed by ODOT and the data provided to the PI for analysis. The number of replicate test samples for each mix varied from 1 to 4, based on available material. Therefore, only the average values are reported and the analysis was performed on the computed averages due to the highly unbalanced data. The average test results from the data provided by ODOT are shown in Table 3.1. Binder source information is available from the PI and ODOT. Hamburg rut depths are maximum rut depths at 10,000 cycles for PG 64-22 mixes, 15,000 cycles for PG 70-28 mixes and 20,000 cycles for PG 76-28 mixes.

3.2 Analysis of Existing Data

The number or replicate test samples for each mix varied from 1 to 4; therefore, only the average values are reported and the analysis was performed on the computed averages due to the highly unbalanced data. The exact age of the samples at the time of testing was unknown and sample age can affect mixture hardness or brittleness. ODOT reported that the mixes were one to four months old at the time of sample fabrication. Due to the unknown age of the samples and the effect on mixture aging, care should be exercised on drawing definite conclusions from this data.

Table 3.1 Average I-FIT and Hamburg Rut Depth Results from Existing ODOT Mixtures

Mix	Binder Grade	Binder Source	% RAP	Average FI Value	Hamburg Rut Depth (mm)
S3	PG 64-22	3	25	0.69	1.63
S3	PG 64-22	5	0	4.53	3.72
S3	PG 64-22	5	25	4.17	6.19
S3	PG 64-22	4	25	0.06	2.49
S3	PG 64-22	1	25	0.56	3.58
S3	PG 64-22	2	25	1.49	3.95
S3	PG 64-22	2	0	2.10	3.38
S3	PG 64-22	2	25	0.44	0.82
S3	PG 70-28	2	0	0.55	1.90
S3	PG 70-28	1	0	0.56	12.08
S3	PG 64-22	2	15	1.50	0.71
S3	PG 76-28	1	15	0.40	1.84
S3	PG 76-28	2	0	5.01	2.15
S4	PG 64-22	3	0	4.13	4.91
S4	PG 64-22	3	15	1.06	2.94
S4	PG 64-22	4	0	7.07	1.56
S4	PG 64-22	4	0	0.68	7.13
S4	PG 64-22	1	25	1.20	1.59
S4	PG 64-22	1	0	7.67	1.89
S4	PG 64-22	2	0	6.68	4.00
S4	PG 64-22	2	25	1.39	4.49
S4	PG 70-28	4	0	4.81	2.08
S4	PG 70-28	4	0	1.65	9.99
S4	PG 70-28	1	0	5.46	8.98
S4	PG 76-28	4	0	1.48	1.84
S4	PG 76-28	1	0	1.69	1.74
S4	PG 76-28	2	0	5.47	6.61
S4	PG 76-28	2	0	5.88	0.26
S4	PG 76-28	2	0	4.78	2.14
S4	PG 76-28	2	0	3.23	9.25
S5	PG 70-28	1	0	12.9	11.18

Of the 31 mixtures, none failed the ODOT requirements for rut depth using the HWT device. Only one of the 31 mixes had a FI above 8, a typical threshold value for the I-FIT test (16). There was no good relationship between HWT rut depth and FI, as shown in figure 3.1, as indicated by an R^2 of 0.05.

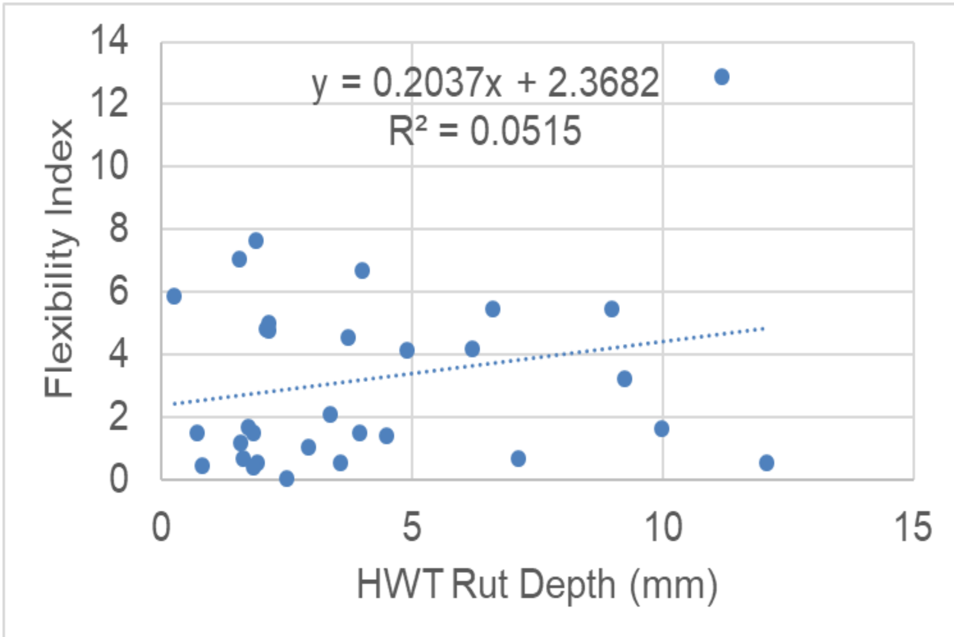

Figure 3.1 Relationship Between Hamburg Rut Depth and FI

Figure 3.2 shows an interaction plot for the same data for FI and HWT rut depth. Only one mix falls in the acceptable range with the other 30 mixes falling in the stiff and brittle quadrant. No mixes fell in the right two quadrants, soft & flexible or soft & unstable. Again, the effects of the unknown sample age on the test results is not known but is assumed to increase mixture brittleness slightly.

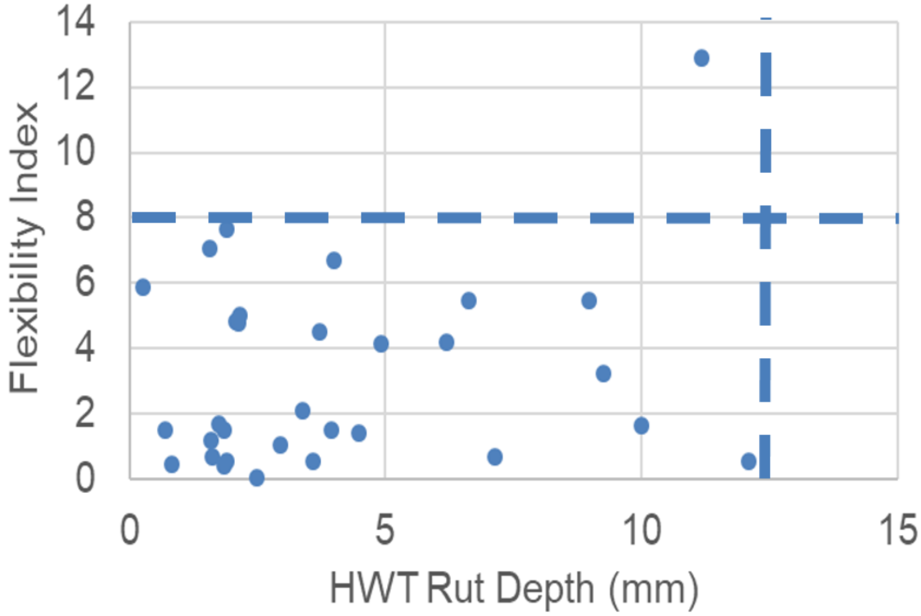

Figure 3.2 Interaction Plot for FI and Hamburg Rut Depth

Figure 3.3 shows the effect mix type and percent RAP had on FI. The data was analyzed by mix type as a whole, and with and without RAP in the mix. There were 17 S4 mixtures, three with RAP, and 13 S3 mixtures, eight with RAP. When the RAP mixes were included in the analysis the S4 mixtures had a higher average FI than the S3 mixes. This held true when the mixtures with RAP were removed from the analysis. There was no difference in FI between the S4 and S3 mixtures for the mixtures with RAP.

To show the effect of PG binder grade on FI the mixtures with RAP need to be removed from the data set. This left eight PG 64-22 mixes, five PG 70-28 mixes and seven PG 76-28 mixes. It is expected that mixes with lower dynamic modulus values at intermediate temperatures would have higher FI. The effect of PG binder grade on FI is shown in figure 3.4.

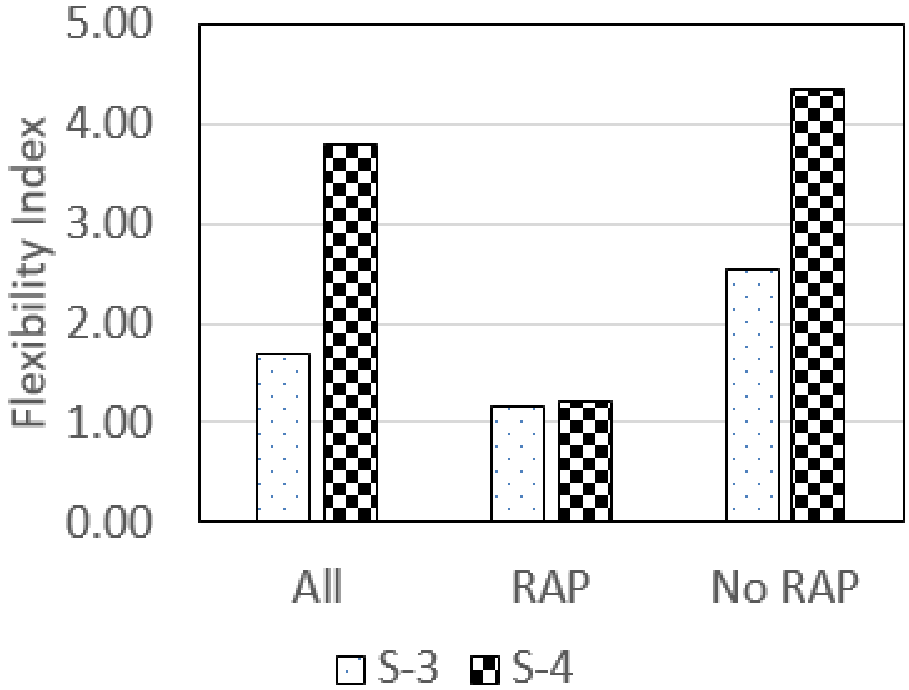

Figure 3.3 Flexibility Index by Mix Type

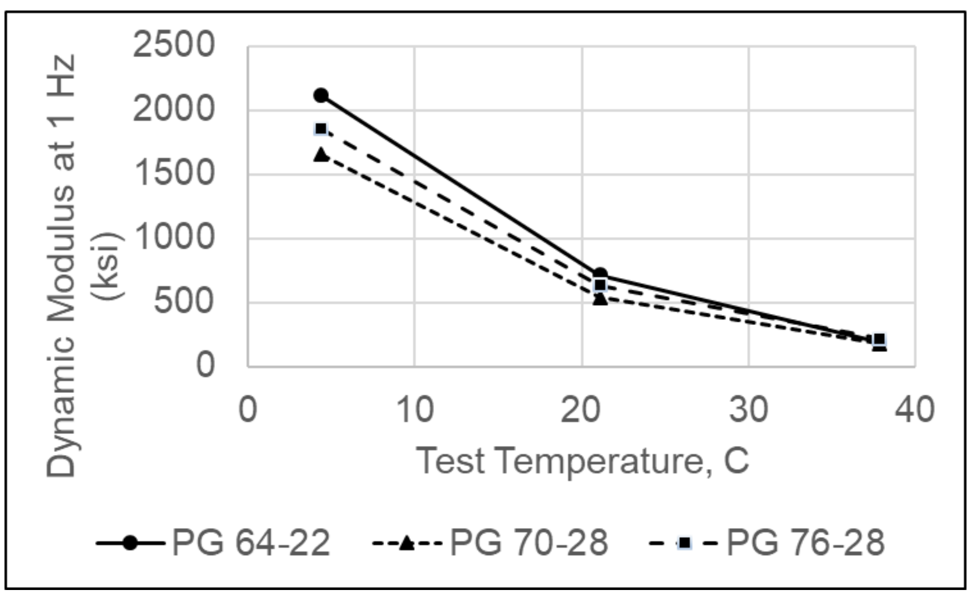

Figure 3.4 Dynamic Modulus for Typical Mixes, by PG Binder Grade

At intermediate temperatures and a 1 Hz loading frequency, a PG 70-28 would be expected to have the lowest dynamic modulus followed by a PG 76-28 binder with the PG 64-22 expected to have the highest dynamic modulus. These values are from a report by the PI (19). The expected difference in dynamic modulus between a PG 70-28 and a PG 76-28 binder is larger than the difference between a PG 64-22 and a PG 76-28.

The effect of binder PG grade on FI is shown in figure 3.5. The results from the ODOT data follow the expected trend with the PG 70-28 mixes have the highest FI, followed by the PG 64-22 mixes and the PG 76-28 mixes. The FI numbers are all low and it is doubtful there is any real difference in FI between the mixes.

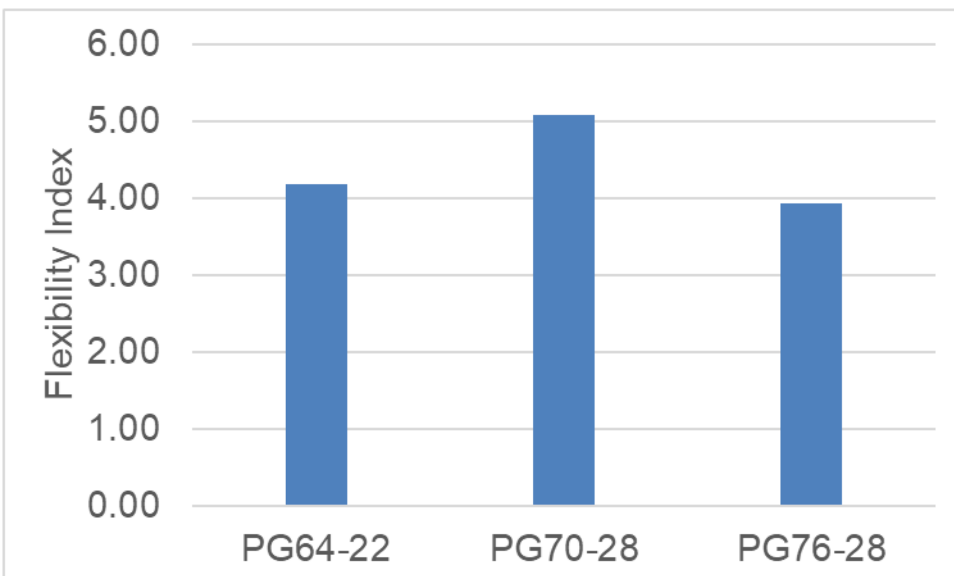

Figure 3.5 Flexibility Index by Mixture PG Binder Grade.

Crude source/supplier could have an effect on binder stiffness and therefore, FI. However, the presence of RAP in the mix would have an effect as well. Therefore, only mixes without RAP were analyzed. The results of FI by binder source are shown in figure 3.6. Suppliers 4-6 only had one mix each with no RAP.

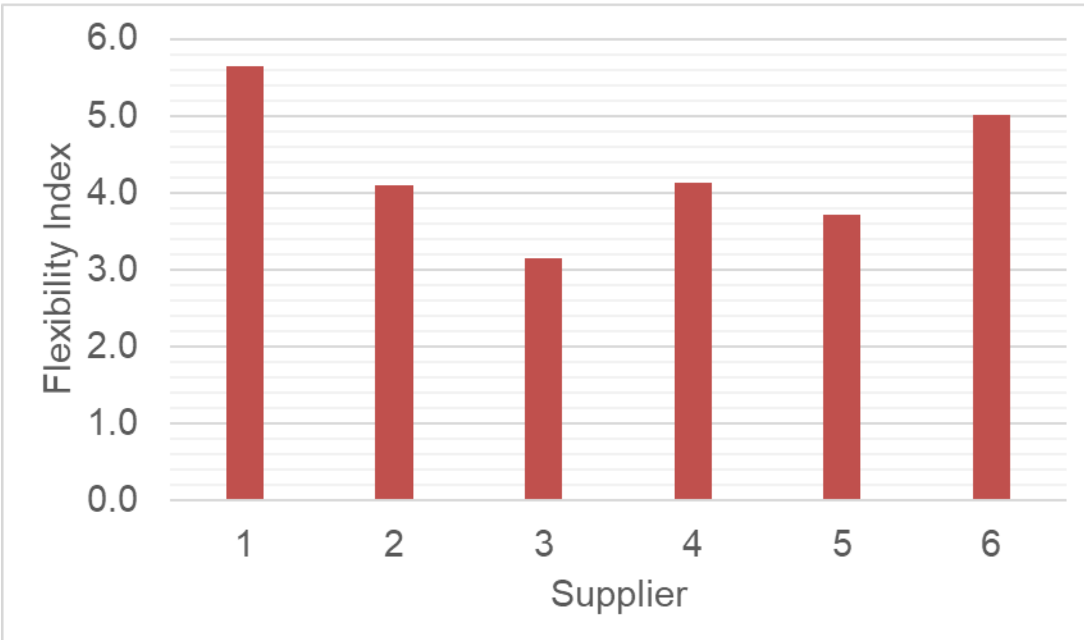

Figure 3.6 Flexibility Index by Binder Supplier

There is a slight difference in FI based on supplier. Although crude sources change, there could be value in evaluating delta Tc for each major supplier of binders in Oklahoma. Neet binders with high delta Tc values might be difficult to use in a balanced mix design, especially with high amounts of RAP. Rejuvenators might be required or application of a surface treatment immediately after placement might be beneficial to prevent rapid oxidation of surface mixes (20).

3.3 Summary

Although the age of the samples tested is unknown, a few general trends were noted.

- There was not a good correlation between HWT rut depth and FI.
- Only one mix met the requirement for a BMD mix with an FI $\geq$ 8.
- The presence of RAP lowered the FI.
- The softer the PG grade of the binder at low and intermediate temperatures the higher the FI.
- The source of the binder had an effect on FI.
- All of these trends are as expected from the review of the literature.

CHAPTER 4 ANALYSIS OF FIELD TEST SECTION DATA

4.1 Test Plan

The final test plan for this study was developed by ODOT. The intent of the study was to document the results of contractor's attempts to develop and place a balanced mix design using the I-FIT test and the Hamburg Wheel Tracking Test as the BMD parameters. The Ideal CT test was added after the study began and was not a part of the mix designs. Three contractors agreed to participate on ODOT projects on SH 20, I-35 and SH 156. Testing was performed on field sampled plant produced material.

For each project at least one BMD mix was placed on one lot with the remainder of the project receiving the control or normal mix. Testing was performed on plant produced materials obtained from one lot of each BMD mix and one lot of the control mix. Contractor quality control (QC) data from the respective lots were used for maximum specific gravity, gradations and lab molded mix properties. Mix design information was obtained from either ODOT mix design records or from the QC sheets for each lot.

Mixes were sampled by either ODOT or the contractors. Half of the material was provided to a consultant retained by OSU for testing with ODOT retaining the remainder of the materials for testing. I-FIT testing was performed in accordance with AASHTO TP 124-18 and Ideal CT testing was performed in accordance with the procedures described in SHRP-2 report (18). The materials were plant produced so there was no oven aging of the samples. For the I-FIT test, a test is the average from three or four test specimens cut from one sample. For the Ideal CT test, a test is the average of tests results from three molded specimens. The consultant performed replicate tests whereas ODOT used extra materials for additional testing.

There was one control mix and one BMD mix placed on SH 20 and I-35. There was one control mix and four BMD mixes placed on SH 156. All of the BMD mixes contained RAP. None of the control mixes contained RAP. There were two S4 control mixes and one S5 control mix. There were four S4 BMD mixes and three S5 control mixes. Table 4.1 shows the mixes evaluated.

Table 4.1 Mixes Evaluated in the Study

Route	Mix Type	ODOT Mix Designation	Binder Grade	% RAP
SH 20	Control	S4	PG 64-22	0
SH 20	BMD	S4	PG 64-22	12
I-35	Control	S5	PG 70-28	0
I-35	BMD	S5	PG 70-28	15
SH 156	Control	S4	PG 64-22	0
SH 156	BMD	S4	PG 64-22	11
SH 156	BMD	S4	PG 58-28	11
SH 156	BMD	S5	PG 64-22	11
SH 156	BMD	S5	PG 58-28	11

4.2 Test Results

Tables 4.2 – 4.5 show the results from the QC testing for each mix placed along with the available mix design data. Table 4.6 shows the average FI results from the I-FIT testing and Table 4.7 shows the average CT_{Index} results from the Ideal CT testing.

Table 4.2 Mix Design and QC Test Results for SH 20 Control and BMD Mixes

Mix Parameter	JMF Control	JMF BMD	QC Control	QC BMD
3/4 inch Sieve	100	10	100	100
1/2 inch Sieve	93	94	91	95
3/8 inch Sieve	85	88	86	90
No. 4 Sieve	64	63	63	65
No. 8 Sieve	38	37	39	37
No. 16 Sieve	24	24	25	24
No. 30 Sieve	14	17	17	16
No. 50 Sieve	9	10	11	11
No. 100 Sieve	5	5	6	6
No. 200 Sieve	3.9	4.5	4.9	5.4
Asphalt Content (%)	5.3	5.8	5.3	5.8
Air Void Content (%)	4.0	3.4	4.10	3.2
VMA (%)	15.07	16.20	15.2	16.0
% RAP	0	12	0	12

Table 4.3 Mix Design and QC Test Results for I-35 Control and BMD Mixes

Mix Parameter	JMF Control	JMF BMD	QC Control	QC BMD
3/4 inch Sieve	100	100	100	100
1/2 inch Sieve	100	100	100	100
3/8 inch Sieve	98	97	97	95
No. 4 Sieve	80	77	76	74
No. 8 Sieve	54	50	51	51
No. 16 Sieve	38	34	35	36
No. 30 Sieve	29	25	26	27
No. 50 Sieve	20	18	18	19
No. 100 Sieve	9	10	10	9
No. 200 Sieve	5.8	6.5	5.7	4.7
Asphalt Content (%)	5.5	5.6	5.3	5.0
Air Void Content (%)	4.0	4.0	2.9	4.5
VMA (%)	15.5	15.6	14.0	14.5
% RAP	0	15	0	15
I-FIT	9.0	9.6	See Table 4.6	See Table 4.6

Table 4.4 Mix Design and QC Test Results for SH 156 Control and BMD Mixes

Mix Parameter	S4 JMF Control	S4 PG 64 BMD JMF	S4 PG 64 BMD JMF	S4 QC PG64 BMD	S4 QC PG 58 BMD
3/4 inch Sieve	100	100	100	100	100
1/2 inch Sieve	94	94	94	94	90
3/8 inch Sieve	84	84	84	84	80
No. 4 Sieve	61	61	61	62	57
No. 8 Sieve	44	44	44	47	43
No. 16 Sieve	30	30	30	32	30
No. 30 Sieve	21	21	21	22	22
No. 50 Sieve	13	13	13	15	14
No. 100 Sieve	8	8	8	9	9
No. 200 Sieve	5.8	5.8	5.8	7.2	6.5
Asphalt Content (%)	5.3	5.3	5.3	5.4	5.0
Air Void Content (%)	4.0	4.0	4.0	2.0	2.8
VMA (%)	14.76	14.5	14.1	12.9	12.3
% RAP	0	11	11	11	11

Table 4.5 Mix Design and QC Test Results for SH 156 S5 BMD Mixes

Mix Parameter	S5 PG 64 JMF BMD	S5 PG 58 JMF BMD	S5 QC PG64 BMD	S5 QC PG 58 BMD
3/4 inch Sieve	100	100	100	100
1/2 inch Sieve	100	100	100	100
3/8 inch Sieve	98	98	98	98
No. 4 Sieve	69	69	68	65
No. 8 Sieve	43	43	43	42
No. 16 Sieve	29	29	28	28
No. 30 Sieve	20	20	20	20
No. 50 Sieve	13	13	13	14
No. 100 Sieve	8	8	9	9
No. 200 Sieve	5.8	5.8	7.2	7.3
Asphalt Content (%)	6.1	6.1	6.1	6.2
Air Void Content (%)	4.0	4.0	3.0	2.6
VMA (%)	16.9	16.9	16.1	15.9
% RAP	11	11	11	11

Table 4.6 Average Flexibility Index Values

Route	Mix Type	ODOT Mix Designation	Binder Grade	Consultant Average FI	ODOT Average FI
SH 20	Control	S4	PG 64-22	9.7	3.2
SH 20	BMD	S4	PG 64-22	13.8	16.9
I-35	Control	S5	PG 70-28	4.3	4.1
I-35	BMD	S5	PG 70-28	7.3	2.2
SH 156	Control	S4	PG 64-22	11.3	7.4
SH 156	BMD	S4	PG 64-22	27.1	3.2
SH 156	BMD	S4	PG 58-28	14.5	8.8
SH 156	BMD	S5	PG 64-22	18.0	7.0
SH 156	BMD	S5	PG 58-28	14.1	17.1

Table 4.7 Average Ideal-CT Values

Route	Mix Type	ODOT Mix Designation	Binder Grade	Consultant Average CT_{Index}	ODOT Average CT_{Index}
SH 20	Control	S4	PG 64-22	91.2	37.0
SH 20	BMD	S4	PG 64-22	188.8	170.5
I-35	Control	S5	PG 70-28	62.6	42.1
I-35	BMD	S5	PG 70-28	85.9	33.2
SH 156	Control	S4	PG 64-22	247.4	109.3
SH 156	BMD	S4	PG 64-22	271.0	125.3
SH 156	BMD	S4	PG 58-28	155.6	52.0
SH 156	BMD	S5	PG 64-22	268.6	169.5
SH 156	BMD	S5	PG 58-28	243.4	165.3

4.3 Comparisons of Test Data

4.3.1 SH 20

The mix parameters for the SH 20 project were shown in Table 4.2. The control mix was an ODOT S4 mix with no RAP and PG 64-22 binder. To produce a BMD mix, the mix was modified to include 11% RAP. The VMA was increased 15.1

to 16.2% and the binder content increased from 5.3 to 5.8%. The BMD mix was also designed at 3.4% air voids rather than the specified 4.0% air voids.

The QC data indicates that the BMD mix had a VMA of 16.0% and the control mix 15.2%. The mixes were designed at 16.2 and 15.1%, respectively. ODOT requires S4 mixes be designed at a minimum of 14.5% VMA and have a minimum VMA of 14.0% in the field. There is a danger that mixes designed with high VMA will collapse in the field. The BMD mix was designed approximately 2% above the typical minimum of 14.0% and the original trial of this mix collapsed in the field, resulting in lab molded void properties below the minimum specified values.

The mix design FI value of the SH 20 mixes is unknown but it is assumed that the BMD mix had an FI of 8 or more, the prescribed minimum value for a BMD mix. Ideal CT testing was not performed during the mix design phase but was performed on field produced samples. The results of the FI and CT_{Index} values for the SH 20 mixes are shown in Tables 4.6 and 4.7 and shown graphically in figures 4.1 and 4.2, respectively. The consultant test results indicate both the control and BMD mix exceeded the typical minimum FI and CT_{Index} values for a BMD. ODOT test results indicate the BMD mix exceeded the typical minimum FI and CT_{Index} values for a BMD but the control mix did not.

4.3.2 I-35

The mix parameters and QC data for the I-35 project were shown in Table 4.3. The control mix was an ODOT S5 mix with no RAP and PG 70-28 binder. This mix, as originally designed, met the requirements for a BMD mix with a FI of 9.0 and a passing Hamburg rut depth. The contractor modified the control mix to produce a

BMD mix by adding 15% RAP. The addition of the RAP increased the VMA from15.5 to 15.6% and the binder content increased from 5.5 to 5.6%. The mix design FI of the BMD mix was reported as 9.6.

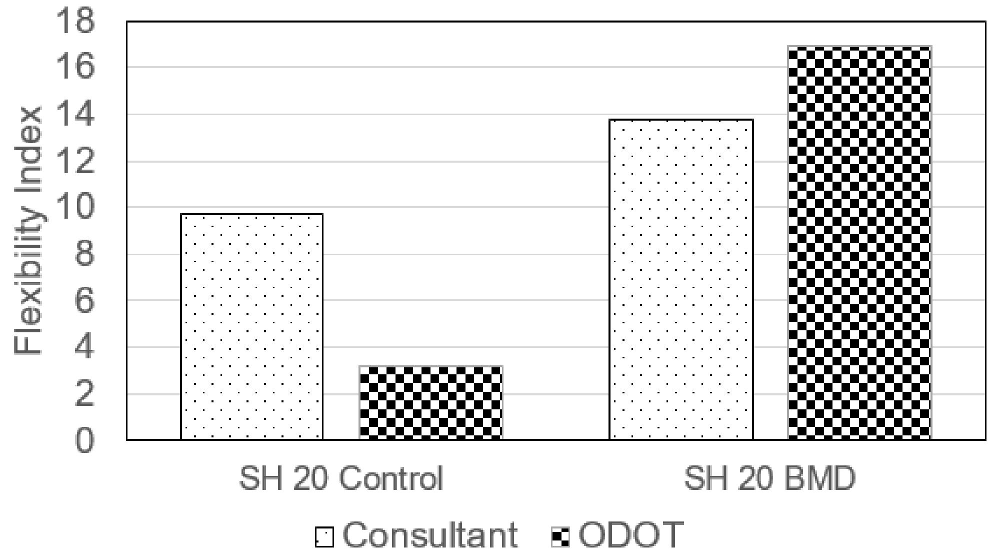

Figure 4.1 SH 20 Average FI

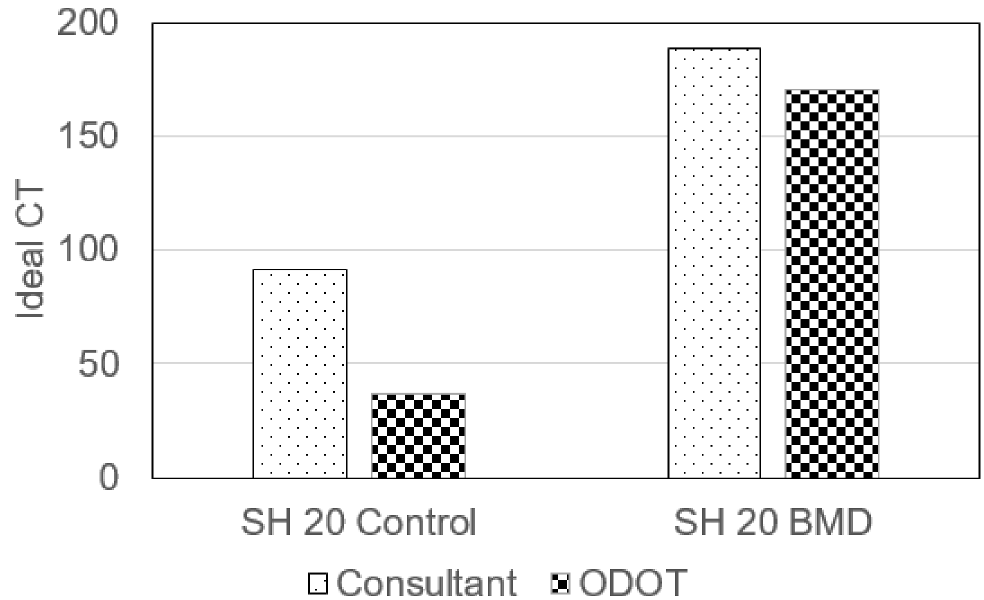

Figure 4.2 SH 20 Average CT_{Index}

The QC data indicates that the BMD mix had a VMA of 14.5% and the control mix 14.0%, below the ODOT requirement of 15.0% for an S5 mix. The mixes were designed at 15.6 and 15.5%, respectively. The gradation and asphalt content of the control mix was close to the mix design values. The gradation of the BMD mix was slightly coarser and the asphalt content was 0.6% less than the mix design. The lab molded air void content of the control mix was 2.9% and 4.5% for the BMD mix.

The results of the I-FIT and Ideal CT testing on the I-35 mixes were shown in Tables 4.6 and 4.7 and shown graphically in figures 4.3 and 4.4, respectively. The field produced control mix, for both the consultant and ODOT test results, did not exceed the typical minimum FI and CT_{Index} values for a BMD even though the mix design did. For the BMD mix the ODOT test results showed the mix to be below the typical minimum FI and CT_{Index} values for a BMD mix. The consultant data showed the BMD mix exceeded the minimum CT_{Index} value and was just under the minimum FI value of 8.0, with an FI of 7.3.

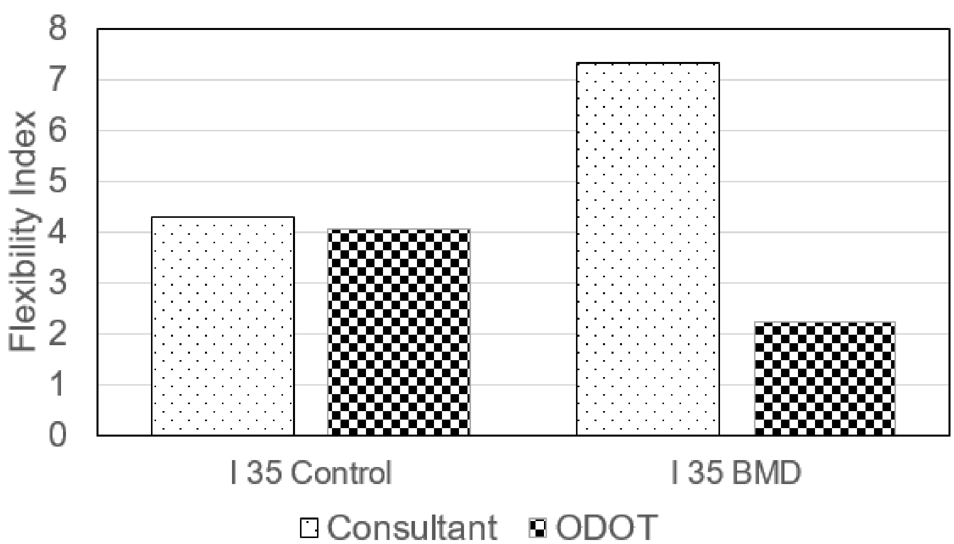

Figure 4.3 I-35 Average FI

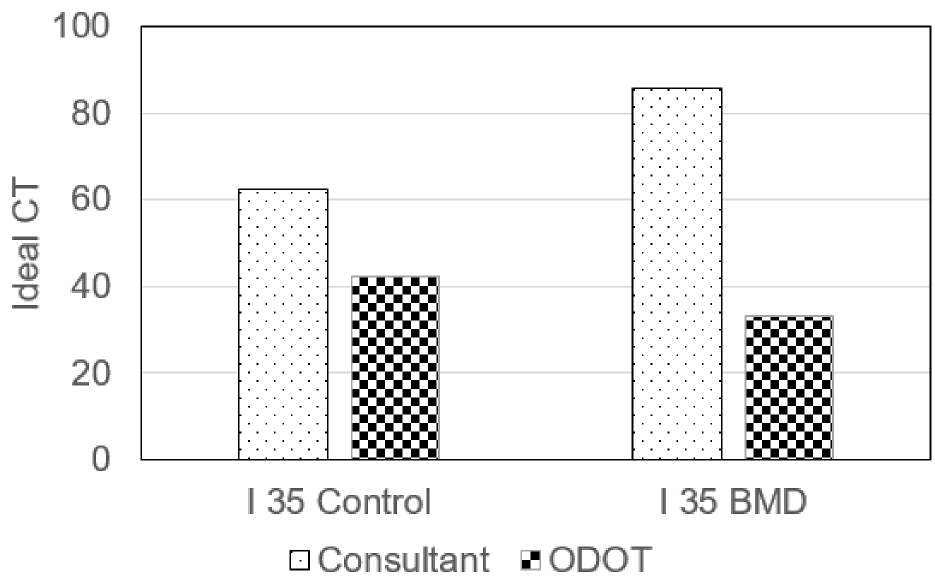

Figure 4.4 I-35 Average CT_{Index}

4.3.3 SH 156

The SH 156 project consisted of five mixes, a control mix and four BMD mixes. The four BMD mixes consisted of two S4 mixes and two S5 mixes, each made with PG 64-22 and PG 58-28 binder. Table 4.8 shows the key used to identify the mixes in the following figures.

Table 4.8 Mix ID for SH 156 Mixes

Mix Type	ODOT Mix Designation	Binder Grade	Mix ID
Control	S4	PG 64-22	1
BMD	S4	PG 64-22	2
BMD	S4	PG 58-28	3
BMD	S5	PG 64-22	4
BMD	S5	PG 58-28	5

The mix parameters and QC data for the SH 156 S4 mixes were shown in Table 4.4. The control mix was produced with no RAP and PG 64-22 binder. To produce the two S4 BMD mixes, Mix 2 & 3, the control mix (Mix 1) was modified to include 11% RAP and a PG 58-28 binder was used in Mix 3. Design gradations and binder contents of the three mixes were reported as the same but the design VMAs were reported as 14.8, 14.5 and 14.1% for Mix 1, Mix 2 and Mix 3, respectively. Design binder contents were reported as 5.3% for all three mixes.

QC data was not available for the control mix. The reported QC gradation and binder content of Mix 2 was similar to the mix design. Mix 3's gradation was slightly finer on the coarse end than the mix design and the binder content was 0.3% lower than the mix design. Both of the BMD mixes (Mix 2 & 3) had an increase in the percent passing the No. 200 sieve from the mix design percent of 0.7 to 1.4%, and significant reduction in VMA, to less than 13%. Lab molded air voids were below 3%.

The mix parameters and QC data for the SH 156 S5 mixes were shown in Table 4.5. There was not a control S5 mix. The two S5 BMD mixes were produced with 11% RAP and a PG 64-22 (Mix 4) and PG 58-28 binder (Mix 5). The mix design gradations appear similar to the S4 control mix (mix 1) with the 1/2-inch material removed. Design gradations, binder contents and VMA of the two S5 BMD mixes were reported as the same, with binder contents of 6.1% and VMA of 16.9%.

The reported QC gradations and binder contents of Mix 4 & 5 were similar to the mix designs. Both Mix 4 & 5 had an increase in the percent passing the No. 200 sieve from the design percent of 1.4 and 1.5%, respectively. Both mixes had a reduction in VMA, from 16.9% to 16.1 and 15.9%. Lab molded air voids were at or below 3%.

The design FI value of the SH 156 mixes is unknown but it is assumed that the BMD mixes had an FI of 8 or more, the prescribed minimum value for a BMD mix. CT_{Index} values were not performed during the mix design phase but were performed on field produced samples. The results of the I-FIT and Ideal CT testing on the SH 156 S4 mixes are shown in Tables 4.6 and 4.7 and shown graphically in figures 4.5 and 4.6, respectively. The consultant test results indicate that all five mixes exceeded the typical minimum FI and CT_{Index} values for a BMD. The only ODOT tested BMD mix to fall below the typical minimum CT_{Index} value was Mix 3. For ODOT FI test results, three of the mixes fell below the typical minimum FI value; however, two of these mixes, Mix 1 and 4, had FI values over 7.

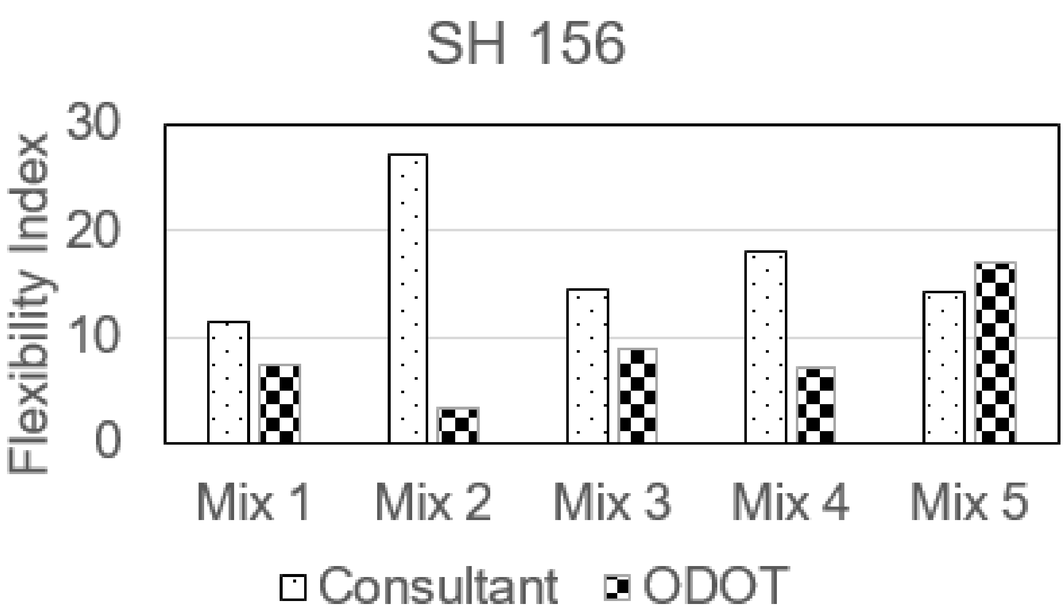

Figure 4.5 SH 156 Average FI

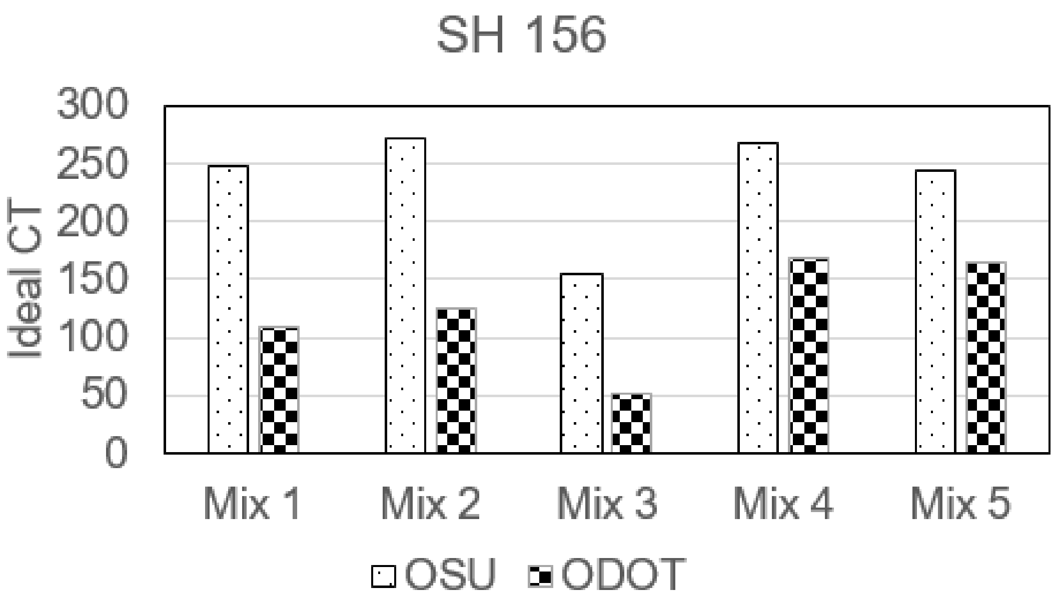

Figure 4.6 SH 156 Average CT_{Index}

4.4 Summary

There were three control mixes and 6 BMD mixes. However, the I-35 control mix as designed met the requirements for a BMD mix making two mixes that were not designed as BMD mixes and seven BMD mixes.

- Both of the non BMD mixes met the QC requirements for lab molded VMA and air voids.
- Only three of the seven BMD mixes met the QC requirements for lab molded VMA and air voids.
- For the consultant and ODOT data sets, both non BMD mixes exceeded the typical minimum FI and CT_{Index} requirements for a BMD mix.

- For the ODOT data, both non BMD mixes failed to meet the typical minimum FI requirement for a BMD mix but one non BMD mix passed the typical minimum CT_{Index} requirement.
- Only three of the seven BMD mixes met the QC requirements for lab molded VMA and air voids.
- For the consultant data, six of the seven BMD mixes met the typical minimum FI and CT_{Index} requirement for a BMD mix.
- For the ODOT data, three BMD met the typical minimum FI requirement for a BMD mix and four BMD mixes met the typical minimum CT_{Index} requirement.

CHAPTER 5 STATISTICAL ANALYSIS OF I-FIT AND IDEAL CT DATA

5.1 Mann-Whitney Statistical Analysis

To test the statistical significance of two data sets, t-test and analysis of variance (ANOVA) are among the two most popular approaches. The common assumptions for these tests include those regarding the scale of measurement, random sampling, normality of data distribution, and adequacy of sample size. However, in this study, the size of available data sets is small and the distribution of the data is unknown.

The Mann–Whitney U test is the nonparametric counterpart of the t-test and gives the estimates of significance, especially when sample sizes are small and/or when the data do not approximate a normal distribution. The U test is therefore used in this study for statistical analysis. In statistics, the null hypothesis of the U test is that the two populations have the same central tendency, or mean value, while the alternative hypothesis is the central tendencies are not the same. The test statistic for the Mann Whitney U Test is denoted U as below:

$$\mathrm{U_i} = \mathrm{n_1 n_2} + \frac{\mathrm{n_2(n_2+1)}}{2} - \mathrm{R_i} \qquad [5.1]$$

Where: n_1 and n_2 are the sample sizes for data sets 1 and 2, R_i is the sum rank of the sample.

If the numbers of observations n_1 and n_2 are larger than eight, a normal approximation, as shown by Mann and Whitney (1947), can be used with the following sampling properties (mean and standard deviation):

$$E(U) = \frac{n_1 n_2}{2} \qquad [5.2]$$

$$\sigma(U) = \sqrt{\frac{n_1 n_2 (n_1 + n_2 + 1)}{12}} \qquad [5.3]$$

Subsequently the value of the test statistics is obtained as:

$$z^* = \frac{U - E(U)}{\sigma(U)} \qquad [5.4]$$

At the 0.05 level of significance, the critical z value of a normal distribution is 1.645. If z* is greater than the critical value (1.645), the null hypothesis is rejected, indicating that the two samples are statistically not the same, or statistically different. Otherwise, the two samples are considered to be the same.

Two data sources were used: ODOT and the Consultant data bases. The statistical significant results for both FI and CT_{Index} are summarized in Tables 5.1 to 5.4. Table 5.5 is a key for the mix IDs for the comparisons for the SH 156 mixes. It should be noted that some of the analyses have data sample sizes smaller than 8, as recommended in the U test. In that case, the statistical results may not be as robust. The SH 156 project has one control mix and four BMD mixes where the SH 20 and I-35 mixes consisted of a single control and BMD mix each. The SH 156 mixes will be discusses later in this chapter.

Tables 5.1 and 5.2 show the results of the Mann-Whitney comparisons of Control and BMD mixes performed by the Consultant and by ODOT based on FI. There is not complete agreement between the Consultant's and ODOT's data sets.

Tables 5.3 and 5.4 show the results of the Mann-Whitney comparisons of Control and BMD mixes performed by the consultant for OSU and by ODOT based on CT_{Index}. As with the FI data, there is not complete agreement between the Consultant and ODOT data sets.

Table 5.1 Mann–Whitney U Test Results: Comparisons of Control and BMD Mixes, Consultant FI Data Sets

Route	# Control	Avg. Control	Std. Dev. Control	# BMD	Avg. BMD	Std. Dev. BMD	Z*	Significantly Different
All	24	9.12	3.23	48	15.88	7.72	3.81	Yes
SH 20	8	9.71	2.08	8	13.76	4.61	1.89	Yes
I-35	8	4.31	0.59	8	7.34	1.85	1.58	No
SH 156	8	11.30	2.86	32	18.43	7.75	2.44	Yes

Table 5.2 Mann–Whitney U Test Results: Comparisons of Control and BMD Mixes, ODOT FI Data Sets

Route	# Control	Avg. Control	Std. Dev. Control	# BMD	Avg. BMD	Std. Dev. BMD	Z*	Significantly Different
All	12	4.88	1.98	24	9.18	6.42	0.69	No
SH 20	4	3.15	0.13	4	16.88	4.50	2.31	Yes
I-35	4	4.08	0.22	4	2.23	0.63	-2.31	Yes
SH 156	4	7.43	0.92	16	8.99	5.51	0.38	No

Table 5.3 Mann–Whitney U Test Results: Comparisons of Control and BMD Mixes, Consultant CT_{Index} Data Sets

Route	# Control	Avg. Control	Std. Dev. Control	# BMD	Avg. BMD	Std. Dev. BMD	Z*	Significantly Different
All	18	133.7	91.5	36	202.2	75.6	2.83	Yes
SH 20	6	91.2	23.9	6	188.8	28.6	2.88	Yes
I-35	6	62.6	11.5	6	85.9	10.3	2.72	Yes
SH 156	6	247.4	63.5	24	234.7	61.8	-0.42	No

Table 5.4 Mann–Whitney U Test Results: Comparisons of Control and BMD Mixes based ODOT CT_{Index} Data Sets

Route	# Control	Avg. Control	Std. Dev. Control	# BMD	Avg. BMD	Std. Dev. BMD	Z*	Significantly Different
All	12	62.8	35.7	24	119.3	66.9	2.45	Yes
SH 20	4	37.0	7.6	4	170.5	27.2	2.31	Yes
I-35	4	42.1	16.5	4	33.2	20.4	-0.87	No
SH 156	4	109.3	1.3	16	127.9	62.2	0.76	No

The SH 156 project consisted of five mixes, a control mix and four BMD mixes. Table 5.5 shows the key used to identify the mixes in the following tables and figures.

Table 5.5 Mix ID for SH 156 Mixes

Mix Type	ODOT Mix Designation	Binder Grade	Mix ID
Control	S4	PG 64-22	1
BMD	S4	PG 64-22	2
BMD	S4	PG 58-28	3
BMD	S5	PG 64-22	4
BMD	S5	PG 58-28	5

Tables 5.6 and 5.7 show the results of the Mann-Whitney comparisons of Control and BMD mixes performed by the consultant for OSU and by ODOT based on FI. As with the other two projects, there is not complete agreement between the Consultant and ODOT data sets.

Table 5.6 Mann–Whitney U Test Results: Comparisons of SH 156 Mixes, Consultant FI Data Sets

Mix	# 1st Mix	Avg. 1st Mix	Std. Dev. 1st Mix	# 2nd Mix	Avg. 2nd Mix	Std. Dev. 2nd Mix	Z*	Significantly Different
1 vs. 2	8	11.30	2.86	8	27.11	4.41	-3.36	Yes
1 vs. 3	8	11.30	2.86	8	14.54	3.73	1.68	Yes
1 vs. 4	8	11.30	2.86	8	17.99	6.70	-2.42	Yes
1 vs. 5	8	11.30	2.86	8	14.06	7.89	0.11	No
2 vs. 3	8	27.11	4.41	8	14.54	3.73	-3.36	Yes
2 vs. 4	8	27.11	4.41	8	17.99	6.70	2.52	Yes
2 vs. 5	8	27.11	4.41	8	14.06	7.89	7.14	Yes
3 vs. 4	8	14.54	3.73	8	17.99	6.70	0.95	No
3 vs. 5	8	14.54	3.73	8	14.06	7.89	-0.84	No
4 vs. 5	8	17.99	6.70	8	14.06	7.89	-1.47	No

Table 5.7 Mann–Whitney U Test Results: Comparisons of SH 156 Mixes, ODOT FI Data Sets

Mix	# 1st Mix	Avg. 1st Mix	Std. Dev. 1st Mix	# 2nd Mix	Avg. 2nd Mix	Std. Dev. 2nd Mix	Z*	Significantly Different
1 vs. 2	4	7.43	0.92	4	3.15	0.84	-2.31	Yes
1 vs. 3	4	7.43	0.92	4	8.80	1.51	1.44	No
1 vs. 4	4	7.43	0.92	4	6.98	1.74	-0.29	No
1 vs. 5	4	7.43	0.92	4	17.05	2.83	2.31	Yes
2 vs. 3	4	3.15	0.84	4	8.80	1.51	2.31	Yes

Mix	# 1st Mix	Avg. 1st Mix	Std. Dev. 1st Mix	# 2nd Mix	Avg. 2nd Mix	Std. Dev. 2nd Mix	Z*	Significantly Different
2 vs. 4	4	3.15	0.84	4	6.98	1.74	2.31	Yes
2 vs. 5	4	3.15	0.84	4	17.05	2.83	2.31	Yes
3 vs. 4	4	8.80	1.51	4	6.98	1.74	-1.30	No
3 vs. 5	4	8.80	1.51	4	17.05	2.83	2.31	Yes
4 vs. 5	4	6.98	1.74	4	17.05	2.83	2.31	Yes

Table 5.8 Mann–Whitney U Test Results: Comparisons of SH 156 Mixes, Consultant CT_{Index} Data Sets

Mix	1st Mix	Avg. 1st Mix	Std. Dev. 1st Mix	# 2nd Mix	Avg. 2nd Mix	Std. Dev. 2nd Mix	Z	Significantly Different
1 vs. 2	6	247.4	63.5	6	271.0	41.5	0.48	No
1 vs. 3	6	247.4	63.5	6	155.6	42.7	-2.24	Yes
1 vs. 4	6	247.4	63.5	6	268.6	53.2	0.64	No
1 vs. 5	6	247.4	63.5	6	243.4	25.6	-0.16	No
2 vs. 3	6	271.0	41.5	6	155.6	42.7	-2.72	Yes
2 vs. 4	6	271.0	41.5	6	268.6	53.2	-0.32	No
2 vs. 5	6	271.0	41.5	6	243.4	25.6	-1.12	No
3 vs. 4	6	155.6	42.7	6	268.6	53.2	2.56	Yes
3 vs. 5	6	155.6	42.7	6	243.4	25.6	2.72	Yes
4 vs. 5	6	268.6	53.2	6	243.4	25.6	-0.80	No

Table 5.9 Mann–Whitney U Test Results: Comparisons of SH 156 Mixes, ODOT CT_{Index} Data Sets

Mix	# 1st Mix	Avg. 1st Mix	Std. Dev. 1st Mix	# 2nd Mix	Avg. 2nd Mix	Std. Dev. 2nd Mix	Z*	Significantly Different
1 vs. 2	4	109.3	1.3	4	125.3	26.6	1.16	No
1 vs. 3	4	109.3	1.3	4	52.0	9.7	-2.31	Yes

Mix	# 1st Mix	Avg. 1st Mix	Std. Dev. 1st Mix	# 2nd Mix	Avg. 2nd Mix	Std. Dev. 2nd Mix	Z*	Significantly Different
1 vs. 4	4	109.3	1.3	4	169.5	56.6	1.16	No
1 vs. 5	4	109.3	1.3	4	165.0	59.2	2.31	Yes
2 vs. 3	4	125.3	26.6	4	52.0	9.7	-2.31	Yes
2 vs. 4	4	125.3	26.6	4	169.5	56.6	1.16	No
2 vs. 5	4	125.3	26.6	4	165.0	59.2	0.58	No
3 vs. 4	4	52.0	9.7	4	169.5	56.6	2.31	Yes
3 vs. 5	4	52.0	9.7	4	165.0	59.2	2.31	Yes
4 vs. 5	4	169.5	56.6	4	165.0	59.2	0.00	No

5.2 Correlation Analysis

Many agencies are looking to replace the Flexibility Index test with the Ideal CT test due to ease of testing. However, a threshold value for a minimum CT_{Index} has not been determined. Buchanan (16) suggested that most agencies assume the CT_{Index} would be ten time larger than the equivalent FI. This works out to the a minimum CT_{Index} of 80.

There are two data sets where the relationship between FI and CT_{Index} can be evaluated, the ODOT data and the Consultant data. Figures 5.1 and 5.2 show the relationships between FI and CT_{Index} for each data set, respectively.

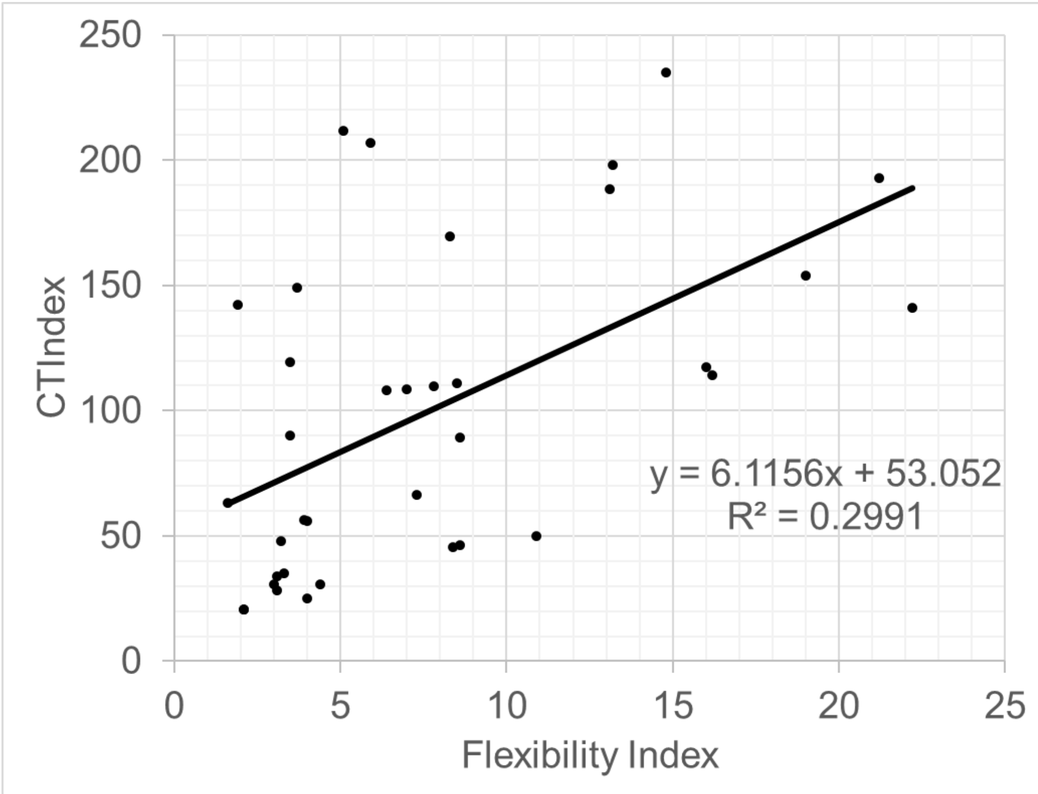

Figure 5.1 FI vs. CT_{Index}, ODOT Data

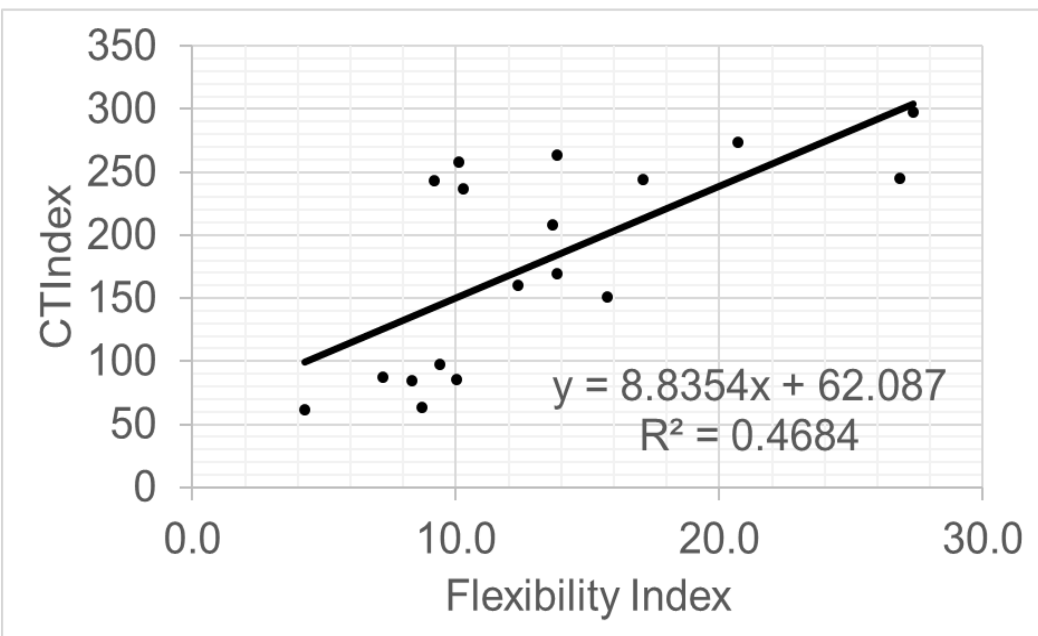

Figure 5.2 FI vs. CT_{Index}, Consultant Data

As shown in figures 5.1 and 5.2, there is a slightly stronger relationship between FI and CT_{Index} for the Consultant data set than the ODOT data set with R^2 values of 0.30 and 0.47, respectively. Solving the best fit equation for a FI of 8 results in a CT_{Index} of 102.0 for the ODOT data and 132.8 for the Consultant data, both considerably larger than the value of 80 typically reported. It is interesting to note that if you reverse the axes and solve for FI using a CT_{Index} of 80 you get FI values of 6.7 for the ODOT data and 8.0 for the Consultant data. This lack of agreement is another indication of the poor correlation of the data.

5.3 Summary

There were six BMD mixes and three control mixes of which one met the requirements for a BMD mix. The mixes were placed on three projects by three different contractors. Due to the limited data set care should be exercised in drawing any definitive conclusions from the data analysis

- There was a significant difference between the Consultant and ODOT data sets.
- There was little agreement between the data sets.
- There was not a strong correlation between FI and CT_{Index}.
- Form this data set, an equivalent CT_{Index} to a FI of 8 could be larger than 100, compared to the typical reported value of 80.

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This was a limited study to determine if BMD principals could be easily adopted into ODOT mix designs. The BMD mixes generally differed from their control mixes by the addition of RAP, increased VMA and increased asphalt content. Many of these higher VMA mixes collapsed in the field resulting in VMA below specified limits. There was little agreement between the two data sets or between the I-FIT and Ideal CT test results. These data sets were based on plant produced materials and the time between mixture sampling, sample fabrication and sample testing was reported as inconsistent.

6.2 Recommendations

If ODOT decides to move forward with implementation of balanced mix designs the following recommendations are made.

- The Ideal CT Index test does not require as much sample preparation nor as expensive equipment as the Flexibility Index Test. Due to this fact, and the high variability of the data, if ODOT decides to move forward with BMD it is recommended that they concentrate on the Ideal CT test.
- ODOT should investigate using 95 mm diameter specimens, especially during mixture design. This will allow the use of AASHTO T 283 dry or

unconditioned samples, saving time, materials and money. However, current ODOT AASHTO T 283 sample aging procedures differ from AASHTO R 30 procedures for performance testing. This will need to be reconciled.

- Sample aging has an impact on CT_{Index} results. ODOT will need to decide what short-term oven-aging procedure to follow.
- If plant produced mixes will be evaluated then requirements for time limits between sampling, fabrication and testing will need to be established.

To move forward, it is recommended that ODOT require Ideal CT Index testing be performed as a part of ODOT mix designs. This would allow ODOT to better determine where their mixes fall on the CT_{Index} scale and determine if there are mix properties that are impacting test results.

- Dry AASHTO T 283 samples could be used and compared to 62 mm samples if desired.
- There could be some value in evaluating delta Tc of unmodified binders supplied to Oklahoma. However, due to the difficulty of extracting and recovering asphalt from RAP, and the variability of RAP itself, it is not recommended that actual blends be tested. It may be difficult to make BMD mixes with some binder sources and it has been suggested that surface mixes with these binders could benefit from application of a surface treatment shortly after placement. Montana and South Dakota

have reported excellent results applying surface treatments shortly after placement of surface mixes.

- The above recommendations could be carried out through ODOT’s SPR program with cooperation from ODOT contractors.
- If the above analysis indicates mixes without RAP are having difficulty exceeding a CT_{Index} of 80 then consideration should be given to dropping the PG 76-28 binder grade and adding a PG 64-28 binder grade.

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