IMPACT OF CRUMB RUBBER MODIFIED BINDER PREPARATION PROCESS ON HOT MIX ASPHALT PERFORMANCE

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ABSTRACT

The technique used while adding Crumb Rubber (CR) into an asphalt mixture can significantly influence its long term performance. The purpose of this research was to investigate the effect of Crumb Rubber (CR) modified asphalt mixture preparation methods on Hot Mix Asphalt (HMA) performance through an extensive laboratory study. In this study, three different methods were utilized: Terminal Blend (CRTB), Wet (CRWet) and Dry (CRDry) processes. Specimens with CRTB binder were prepared by using a coarse dense graded Superpave mix design. Specimens with CRWet and CRDry process modified binders were manufactured with a gap-graded gradation. A control mix using dense gradation was prepared with virgin binder, and used as a benchmark in the analyses. The performances of CR modified mixes were compared to the control mix with respect to their permanent deformation (rutting) and fatigue cracking. These properties were investigated using Dynamic Modulus (|E|), Flow Number (FN) and Beam Fatigue (BF). It was observed that CRTB modified mixes showed better fatigue and permanent deformation characteristics than the other modified and control mixes. Although CRWet mixes performed well in fatigue, their rutting tolerance was relatively poor. Unlike CRWet, CRDry mixes performed well in rutting and poorly in fatigue cracking tests. Analyses showed that CR can successfully be added to asphalt mixtures to improve their overall performance; however, the CR addition technique should be carefully selected during mix design.*

Keywords: Crumb Rubber, Terminal Blend, Wet Process, Beam Fatigue, Flow Number

1. INTRODUCTION

Crumb rubber (CR) modified hot mix asphalt (HMA) pavements are formed by introducing crumbled scrap tire rubber into asphalt mixture using different methods [11]. The benefits of CR modified asphalt pavements have been acknowledged by numerous researchers [1, 2, 3]. Scrap tire rubber has been used in asphalt pavements since 1950s [4, 5, 6]. There are numerous laboratory and field studies that showed superior performance of CR modified asphalt pavements over traditional HMA. The CR modified asphalt is typically stiffer than conventional asphalt at high temperatures, which leads to improved rutting performance. In addition, at intermediate temperatures (15-25^{o}C), CR modified asphalt is more flexible (less brittle), reducing the fatigue cracking potential. This is partly because of their reduced aging (oxidation) potential due to the anti-oxidants that already exist in the scrap tire rubber. Another benefit of CR modified asphalt pavements is their surface characteristics such as improved skid resistance and decreased tire/pavement noise levels up to 6 decibels. Furthermore, CR modified asphalt pavements beneficially re-use 500-2000 scrap tires per lane per mile (based on the technology). For a four-lane roadway, this amounts to 2000 to 8000 tires [7, 8, 9, 10]. The initial cost difference between a conventional asphalt binder and CR modified asphalt binder is about $10 per ton of the mix [11]; however, when life cycle cost is considered, CR modified asphalt is much more economical than conventional asphalt binder. Hicks et al. studied the lifecycle cost of CR asphalt pavements [3]. They found that lifecycle cost savings for using CR asphalt when used in chip seal, thin asphalt overlay and structural overlay are $2.36/yd, $3.36/yd and $7.34/yd, respectively [11].

Currently, there are three major techniques to introduce CR into the asphalt pavements. These are Wet Process (CRWet), Dry Process (CRDry), and Terminal Blend (CRTB). In wet process, crumb rubber (CR) is added to liquid asphalt at temperatures around 325-400 °F (163-205 ºC) and about 15% - 22% by weight of the binder is utilized (1-1.5% by total weight of the mix) [12, 13]. It is known that wet process provides superior performance compared to many polymer modified asphalt pavement. CRTB is typically produced by mixing CR and a polymeric additive with asphalt binder. In CRTB, about 10%-12% CR by weight of the binder is utilized (0.6% by total weight of the mix). This additive is used to keep the CR particles suspend in the mixture and improve cohesive properties of the CR-binder mixture. One of the main advantages of CRTB method is that they can be hauled to long distances. Although it gives better performance, less crumb rubber is utilized (i.e., less sustainable as compared to CRWet) and it can be more costly. In dry process, CR is added as a replacement of fine aggregate up to 5% by total weight of the mixture. Even though anti-oxidants are not completely mixed with binder, dry process provides good skid resistance and deicing properties. More crumb rubber particles are utilized in this process. It should be also noted that Crumb Rubber Wet Process and Crumb Rubber Dry Process do not work well with the fine graded aggregate skeleton. Because of this reason, gap graded aggregate gradation is typically suggested [8]. Table 1 shows a summary of the different methods, their advantages and disadvantages.

Table 1: Summary of different crumb rubber modified asphalt pavement designs.

Technique	Description	Advantages	Disadvantages
Dry Process	Crumb rubber (CR) is added as a replacement of fine aggregate up to 5% by total weight of the mixture.	(i) Good skid resistance and de-icing properties. (ii) Less expensive (iii) More crumb rubber is utilized	(i) Anti-oxidants are not completely mixed with binder
Wet Process	CR is added to liquid asphalt at temperatures around 325-400^{o}F. About 15% by weight of the binder is utilized (1-1.5% by total weight of the mix)	(i) Well known to provide superior performance compared to many polymer modified asphalt pavements	(i) Possible segregation of CR grains if not mixed properly.
Terminally Blend	Similar to wet process, CR is added to liquid asphalt at temperatures around 375-400^{o}F. About 10 % by weight of the binder is utilized (0.6% by total weight of the mix). The main difference is in the additive used to keep the CR particles suspended in the mixture.	(i) Well known to provide superior performance compared to many polymer modified asphalt pavements (ii) no segregation of CR particles (iii) can be hauled for long distances.	(i) more costly than the other processes (ii) less crumb rubber is utilized

A premature failure of a CR modified asphalt pavement (CRDry process) in 1980s in Michigan lead to limitations of CR in asphalt pavements by the roadway agencies [7]. Since then, significant improvements in the method of application of CR into asphalt mixture have been developed. The purpose of this study was to evaluate different CR addition methods to (i) better understand the compatibility of the existing aggregate types in Michigan with the CR modified binders and (ii) investigate the resistance of different CR modified asphalt mixtures to the relatively harsh environmental conditions of Michigan. To accomplish this objective, three different methods listed in Table 1 were utilized to produce asphalt mixtures and their laboratory performance in terms of fatigue cracking and rutting was evaluated. The laboratory tests included Dynamic Modulus (|E*|), Four Point Bending Beam (FPBB), and Flow Number (FN). It is noted that the results presented in this paper are the first phase of the project funded by the Michigan

Department of Environmental Quality (MDEQ). The second phase includes construction of three test sections in Lansing, Michigan. The construction of the field test sections is scheduled to be completed on November 2011.

2. MATERIALS

2.1 Crumb Rubber Modification Methods

CR binder and mixture design is very crucial for the performance of HMA. As it was mentioned previously, four methods were evaluated in this study: CRTB, CRWet and CRDry. They were all made with a PG 64-22 base binder. CRTB was supplied from a local petroleum company and had a PG 76-22 grade and produced with fine crumb rubber particles, whose gradation is given in

Table 2. CRWet and CRDry were prepared in the laboratory. In the CRWet, CR acts as a binder modifier, while in the CRDry, CR is used as a replacement of the fine aggregate.

In CRWet process, CR was blended 12% by weight of binder. The base (Control) binder was heated up to 190˚C and mixed with CR particles with the aid of a mixer at a rate of 1000 rpm (rotation per minute) for 60 ± 5 minutes. CR was homogeneously distributed within the binder, with all CR clumps eliminated in the mixture. A digital dual-range mixer was used with a blade diameter of 1/3 of the of bucket size, which was 3.6 liters. Additionally, the binder temperature was kept constant during the mixing process by a bucket heater.

In CRDry process, dry CR was added to the HMA during mixing. The rubber particles, binder and aggregates were added to the mixing bucket at the same time. The percentage of CR was 2% by weight of the HMA mix. Both CRWet and CRDry were manufactured with fine size of the crumb rubber. The particle sizes were typically less than No.40 sieve size (0.420 mm) as shown in

Table 2.

Table 2: Crumb Rubber Gradation

Sieve No. (mm)	% Passing	
	CRTB Modified	CRWet / CRDry Modified
No. 16 (1.190)	100	100
No. 30 (0.590)	98	100
No. 40 (0.420)	72	94
No. 100 (0.149)	45	16
No. 200 (0.074)	9	2

The ASTM 6114, Standard Specification for Asphalt-Rubber Binder, specifies several binder tests for CRWet method. These include: Resilience (ASTM D5329-09), Ring and Ball Softening Point (ASTM D36-09), Penetration (ASTM D5-06) and Brookfield Viscosity (AASHTO T316-06) [14, 15]. The results of tests and ASTM 6114 limits are given in

Table 3 [15]. Some of the test results (e.g., viscosity) are outside the limits of ASTM 6114. This was because of the compaction problems that were experienced in gyratory compactor. Therefore, CRWet binder was designed such that it had low viscosity at the 177^{o}C. This ensured proper compaction in the gyratory compactor. The mixing and compaction temperatures of the CR modified HMA mixtures were determined based on the viscosities of 2.2 Pa.s and 3.0 Pa.s, respectively. These target viscosities were based on the CRTB manufacturer’s recommendation for workability.

Table 3: Properties of Crumb Rubber Modified Binders

Property	Value	

	CRTB	CRWet	ASTM D6114 limits (TYPE II)
Brookfield Viscosity (mPa.s) 177°C	1452	681	1500 – 5000
Softening Point (°C)	61	65	min. 54°C
Penetration (mm)	59	40	min. 25 & max. 75 (at 25°C, 100g, 5 s)
Resilience (%)	15	33	min. 20% (at 25 °C)
Base Binder PG	PG 64 -22	PG 64 -22	N/A

2.2 Asphalt Mixture Design

Mix designs for Control, CRTB, CRWet and CRDry HMA mixtures were based on Standard Practice for Superpave Volumetric Design for Hot-Mix Asphalt (AASHTO R35) and specifications of different States in USA [13, 14, 16, 17]. Figure 1 shows the aggregate gradations used in each method. The Control and CRTB samples were designed with coarse graded aggregate skeletons. On the other hand, CRWet and CRDry mixtures were produced with slightly different gap graded aggregate skeletons. Although Marshall Mix Design was the common method used for designing crumb rubber modified asphalt mixtures, Superpave Mix Design approach was followed with slight modifications. The limits for voids in the mineral aggregates (VMA), voids filled with asphalt (VFA) and percent of air voids at N_{design} were varied based on state experiences in USA [13,16]. The target air void at N_{design} for Control and CRTB was 4% as suggested in Superpave Mix Design. However, the air void at N_{design} for CRWet and CRDry were targeted as 5.5%. The mix design parameters of the mixtures are given in Table 4. As shown in Table 4, the binder content for CR modified binders were higher as compared to Control mix. The reason for the increase in amount of binder was the CR particles.

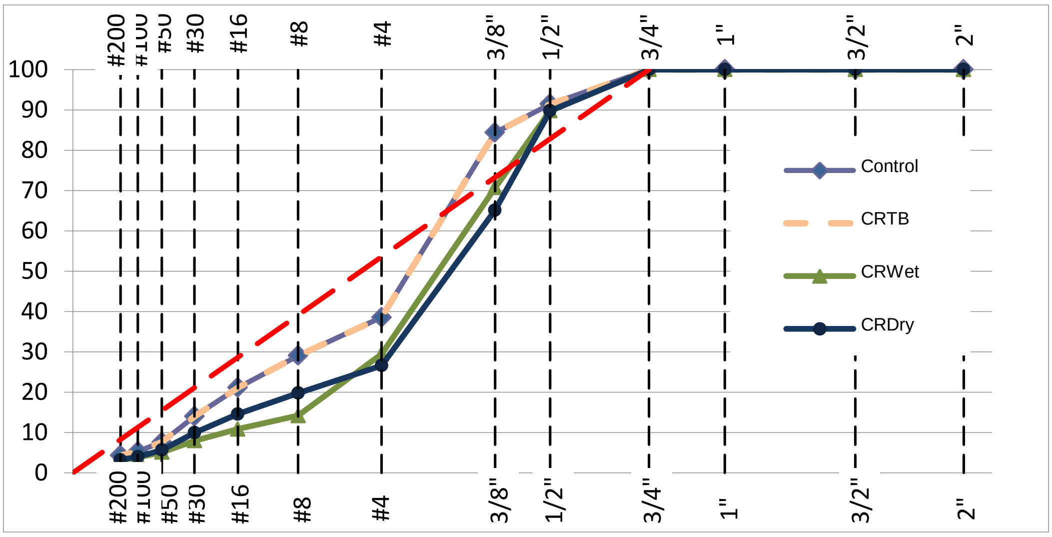

Figure 1: Aggregate gradations of different mix designs

Table 4: Superpave mix design parameters

Parameter	Control	CRTB Modified HMA	CRWET Modified HMA	CRDry Modified HMA
Target Air Void (%)	4	4	5.5	5.5
Binder Content, P_b (%)	4.53	5.3	7.5	5.03
Binder PG	PG 64 -22	Base Binder: PG 64 -22	Base Binder: PG 64 -22	Base Binder: PG 64 -22
VMA (%)	14.6	15.8	20.3	18.2
VFA (%)	73	72.5	73.5	69.8

3. MECHANICAL TESTING

The performances of mixes were evaluated based on their resistance to fatigue, rutting, and low temperature cracking. Four separate tests were conducted on the mixtures. First, Dynamic Modulus (|E*|) test was conducted and |E*| master curves were generated. While |E*| master curve represents the linear viscoelastic characteristics of asphalt mixtures it can also be a quick indicator of fatigue cracking and rutting. In order to accurately understand the rutting susceptibility of the mixtures, Flow Number (FN) tests were conducted. Fatigue cracking susceptibility was analyzed using Four Point Bending Beam (FPBB) fatigue test.

3.1 Dynamic Modulus (|E*|)

Dynamic Modulus (|E*|) is a major input to the Mechanistic Empirical Design Guide (ME-PDG) software and used for estimation of rutting and fatigue cracking of asphalt pavements at design stage. |E*| test is a non-destructive test to determine primary responses (i.e., undamaged, low-strain response) of asphalt mixtures in different temperatures and loading frequencies (AASHTO TP62) [14]. After determining dynamic modulus values at each temperature and frequency, |E*| master curves were generated (AASHTO TP62). |E*| master curve is useful for explaining the behavior of mixtures over a range of temperatures and rates of loading. Typically, mixtures with relatively low |E*| values at low temperatures/high frequencies are more flexible (and less brittle), therefore more resistant to fatigue cracking. On the other hand, mixtures with high |E*| at high temperatures/low frequencies are stiffer and are more resistant to rutting. Tests were conducted on two replicates from each mix type at temperatures of -10^{o}C, 4^{o}C, 21^{o}C, 37^{o}C and 54^{o}C at a range of frequencies between 0.1 and 25 Hz.

Figure 2 shows the |E*| master curves of all mixtures. At high frequencies/low temperatures, Control and CRDry mixtures are the stiffest (highest |E*| values). This might be an indicator of their potential brittleness and thus their susceptibility to fatigue cracking as compared to CRTB and CRWet mixtures. When low frequencies/high temperatures are considered, stiffest mixtures were CRTB and CRDry, which is an indication of their good potential to resist rutting. CRWet has much lower |E*| values at low frequency/high temperature region, therefore, this mixture may be more prone to rutting as compared to Control and the other mixtures.

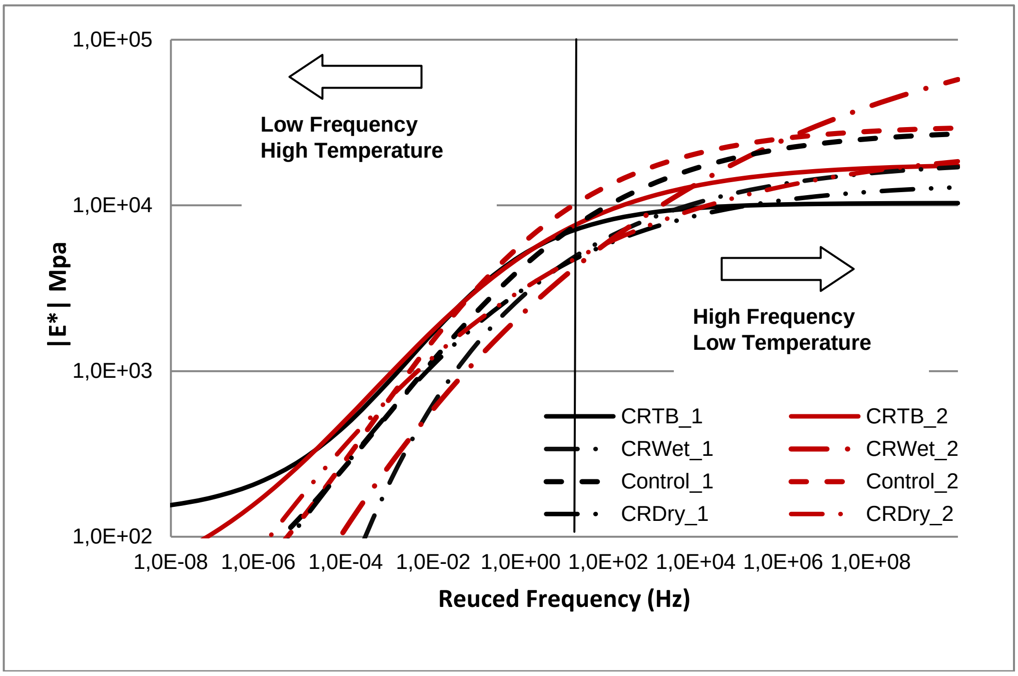

Figure 2: |E*| Master Curves for Control, CRTB, CRWet and CRDry specimens

3.2 Flow Number Test (FN)

Rutting, depression of pavement surface along the wheel path, is one of the major pavement distress types. One of the most reliable methods for evaluating rutting susceptibility of HMA mixtures is the Flow Number (FN) test. FN test is a repeated load test that is typically conducted at relatively high temperatures. In FN test, cylindrical HMA specimens with dimensions of 100 mm diameter and 150 mm tall are subjected to uniaxial pulse load. Each loading cycle includes a 0.1 second haversine loading followed by 0.9 second rest period. The test can be run in both in confined and unconfined conditions. Permanent (plastic) strain is recorded at the end of each loading cycle and the cycle that corresponds to the tertiary flow is called Flow Number [18].

In this study, FN tests were initially conducted at 64ºC with 30 psi deviatoric stress and 0 psi confining stress (unconfined) on CRWet, CRDry, CRTB and Control specimens. Two replicates from each type of mixtures were tested.

Plastic strain values for each cycle (N) were plotted as shown in Figure 3. As shown in Figure 3, CRWet samples performed the worst, because of largest permanent deformation at any cycle. Control mixtures performed better than CRWet and worse than CRDry and CRTB. CRDry and CRTB mixtures performed very well in rutting test when compared to CRWet and Control. These results agreed with the results of |E*| tests.

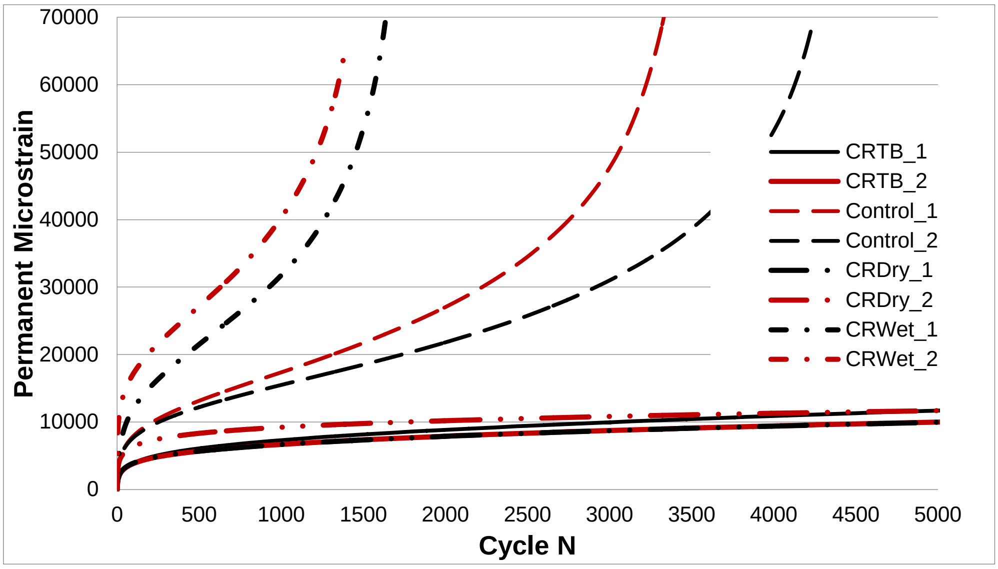

Figure 3: Permanent (plastic) strain with cycles obtained from FN tests: T=64°C, σ_d=30 psi, σ_c=0 psi

In order to further evaluate the relative performance of the mixtures under different temperatures, tests were repeated at 45°C with 70 psi deviatoric stress and 0 psi confinement. The tests were conducted on CRTB, Control and CRWet mixtures as shown in Figure 4. At this temperature and stress level, the ranking of the mixtures with respect to rut resistance did not change. The CRDry was not included in the further testing program because, at the time of the FN testing, CRDry mixture was eliminated from the field test matrix because of its poor performance in fatigue cracking tests, as described in the next section.

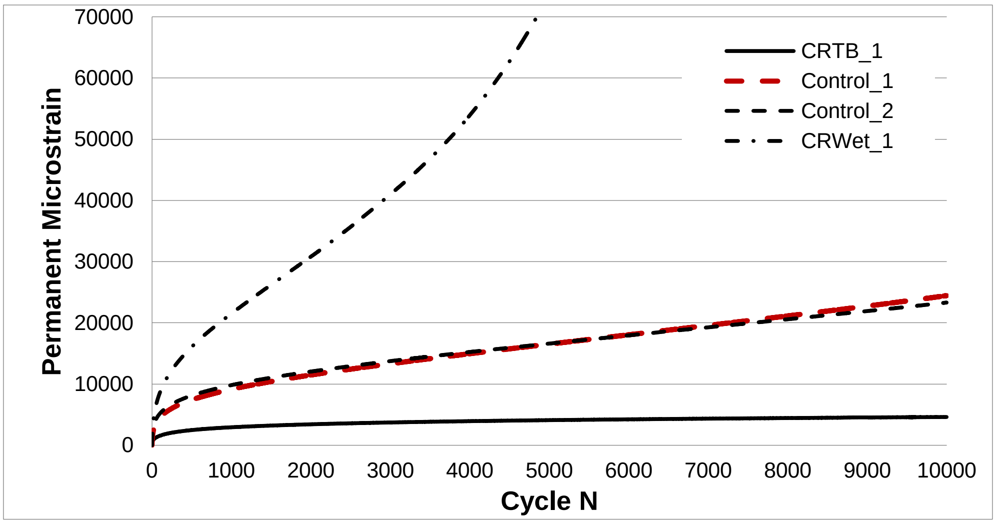

Figure 4: Permanent (plastic) strain with cycles obtained from FN tests: T=45°C, σ_d=70 psi, σ_c=0 psi

In order to evaluate the performance of the mixtures in confined conditions, further tests were conducted at 45°C with 70 psi deviatoric stress and 10 psi confinement. This was primarily to investigate if the gap-graded CRWet mixture would perform better in confined conditions. Two replicates from CRTB, Control and CRWet mixtures were tested as shown in Figure 5. In confined conditions, the ranking of the mixtures did not change. However, the resistance for all mixtures drastically increased because of the confinement.

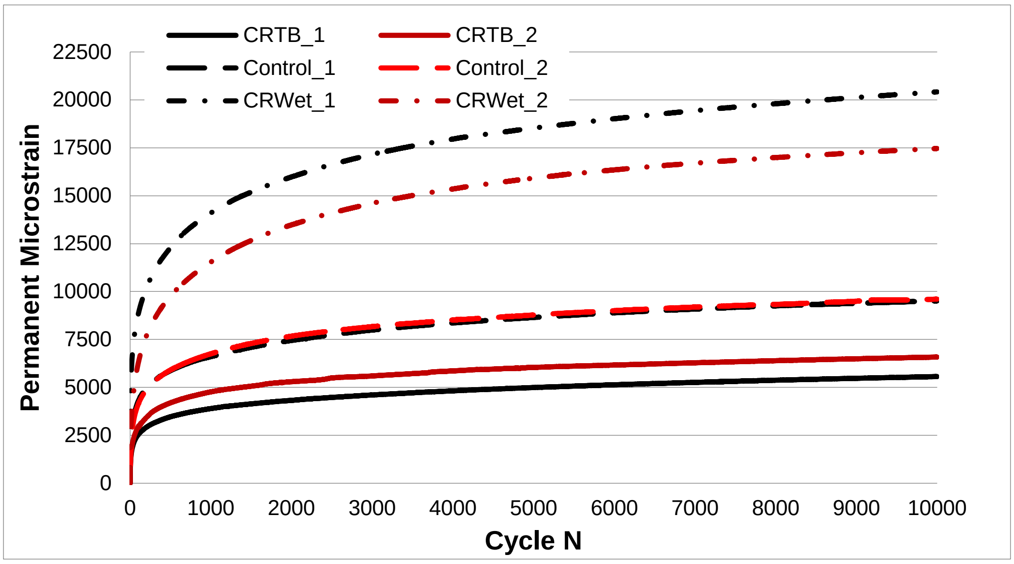

Figure 5: Permanent (plastic) strain with cycles obtained from FN tests: T=45˚C, σ_d=70 psi, σ_c=10 psi

3.3 Four Point Bending Beam (FPBB) Fatigue Tests

Four Point Bending Beam (FPBB) tests were conducted in accordance with AASHTP T321 [19]. The FPBB tests were conducted at the temperature of 18^{o}C and frequency of 10Hz. The actuator strain level was 500 microstrain (με) and on-specimen LVDT strain level ranged from 300 με to 500 με (increased during testing). Figure 6 shows the stiffness versus loading cycles of all the mixtures tested. One of the purposes of this test was to evaluate the CR modified mixture performances relative to the Control mixture. As shown the Control mixture failed at around 4000 cycles (as evidenced from the abrupt decrease in the stiffness). Two replicate CRTB mixtures failed at around 7000 and 10000 cycles. On the other hand, the CRWet did not exhibit an abrupt decrease in stiffness and lasted a lot longer than 12000 cycles shown in Figure 6.

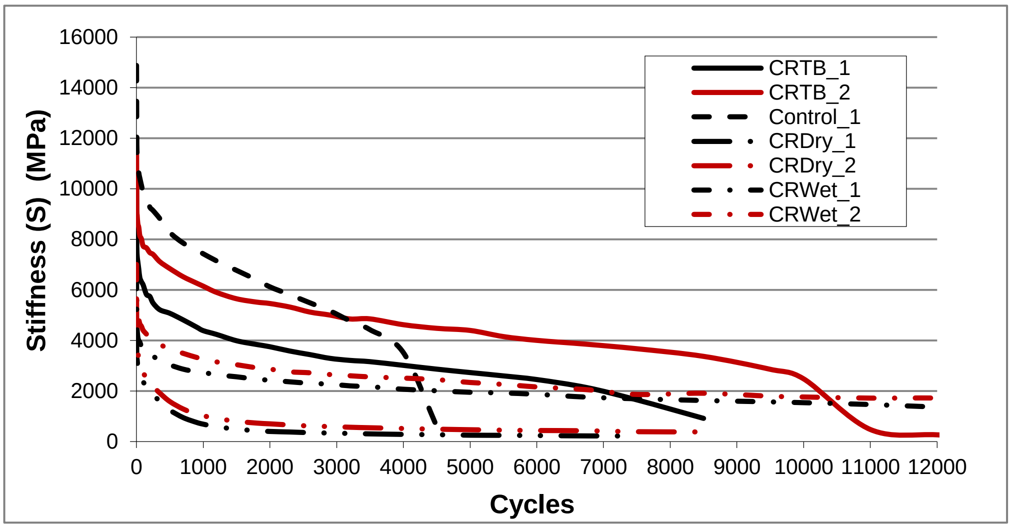

Figure 6: Reduction of stiffness (S) with loading cycles (N) in FPBB tests

CRDry showed very poor fatigue cracking behavior, where a quick drop in stiffness was observed in less than 1000 cycles. Because of the poor performance of the CRDry mixture, it was eliminated from the field test sections. This is mainly because fatigue cracking is a major concern in Michigan's climate.

4. CONCLUSIONS

This study investigated laboratory mechanical performance of different methods of Crumb Rubber modified HMA as well as a typical (unmodified) HMA mixture in Michigan. The specimens were evaluated with respect to fatigue and rutting in the laboratory. It was observed that:

a. CRTB performed better than Control in fatigue cracking, rutting tests.

b. CRWet performed well (better than the Control) in fatigue testing but poorly (worse than the Control in rutting.

c. CRDry performed poorly (worse than the Control) in fatigue testing but well in rutting (better than the Control).

It is noted that in Michigan's cold climate, fatigue cracking is a major concern and excessive rutting is typically not encountered. Although CRWet samples showed poor rutting, they exhibited excellent results in fatigue cracking. Therefore, in cold climates, CWet can be a good alternative to traditional HMA pavements. On the other hand, CRDry HMA mixture performed very well in rutting but very poorly in fatigue cracking. Based on the limited laboratory tests conducted in this study, CRDry mixture can be recommended in hot and tropical climates where rutting is a major concern.

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