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Performance Testing of Hot Mix Asphalt Containing Biochar

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CSUTC California State University Transportation Consortium

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PERFORMANCE TESTING OF HOT MIX ASPHALT CONTAINING BIOCHAR

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16. Abstract
In recent years, researchers have been able to identify asphalt binder additives, such as polymers and bio-binder, that can enhance the rheological and mechanical properties of asphalt binders. Earlier studies show that utilizing bio-binder as a partial replacement for asphalt binder has shown promising results in both mechanical and sustainability aspects. Biochar additions improved binder viscosity and low-temperature characteristics. Biochar, which is a byproduct of producing bio-binder, has shown enhanced rheological and mechanical properties when used as an additive to the asphalt binder. In this study, the mechanical properties of asphalt mixtures containing Biochar were investigated. In addition, its color degradation was investigated. The Semi-Circular Bending (SCB) test proved to be a suitable test method to analyze the fracture properties of asphalt mixtures. Similarly, the Hamburg Wheel Tracking (HWT) test is efficient in testing for and analyzing the rutting and moisture susceptibility of asphalt mixtures. This study used the SCB and HWT tests to investigate the mechanical properties of asphalt mixtures containing Biochar. The study incorporated conventional (virgin) and rubberized mixtures and investigated the effect of aging as well. The SCB results suggest that adding Biochar helped attain higher strain energy values for virgin and rubberized mixtures after aging. The HWT results showed that the addition of Biochar helped achieve lower rut depth for non-aged mixtures. After aging, and since Biochar reduces the effect of aging, aged Biochar mixtures achieved higher rut depth (less hardening) compared to virgin aged mixtures. As for color degradation, the addition of Biochar helped to decrease the color degradation of the asphalt mixture compared to the control mixture.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Roads were not projected to carry the heavy traffic volumes currently travelling across the USA. Limitations on existing natural material and the increasing need to produce more environmentally friendly materials are the main drive for national and state agencies to push researchers to explore better alternatives. Biochar is a bio-modified binder that could be used as an asphalt additive in the hot mix asphalt (HMA) and rubberized hot mix asphalt (RHMA). Semi-Circular Bend (SCB) and Hamburg Wheel Tracking (HWT) tests were used to investigate the mechanical properties of asphalt mixtures and Xenon Arc Light test according to ASTM G155 was used for color degradation.

In this study, the PG 64-10 asphalt binder was used. Asphalt binder was mixed with crumb rubber to produce rubberized asphalt binder. The process for mixing was carried out by combining 18% rubber and 82% binder. For the asphalt mixtures, Biochar was added at five percentage by the weight of binder. The Biochar HMA samples were compared to no Biochar samples.

HMA mixtures were aged before the start of the compaction. Aging was done over two stages: short-term aging and long-term aging. All samples were subjected to short-term aging according to the AASHTO R-30 test method, the samples were heated at 135°C for four hours and were cooled to room temperature to start the compaction. Long-term aging was done for half of the samples to simulate the properties' change after 16 years; long-term aging was conducted based on the method by NCHRP project 09-54, 2018. Only long-term aged HMA mixture was called as aged HMA mixture.

The SCB results suggest that adding Biochar helped attain higher strain energy values for virgin and rubberized mixtures after aging. The HWT results showed that the addition of Biochar helped achieve lower rut depth for non-aged mixtures. After aging, and since Biochar reduces the effect of aging, aged Biochar mixtures achieved higher rut depth (less hardening) compared to virgin aged mixtures. As for color degradation, the addition of Biochar seems to have helped to decrease the color degradation of the asphalt mixture compared to the control mixture.

These results showed that Biochar can improve the performance and durability of HMA mix over time.

I. INTRODUCTION

The United States is undergoing an increase in population and traffic volume. Advancements in truck and tire manufacturing have produced vehicles that can carry higher loads and cause significant savings in freight cost. However, these very loads were not accounted for at the time the roads were designed and constructed. Pavements are deteriorating at ages less than their projected life. Increasing demand on pavement material is anticipated to grow to meet the increase demand on transportation. Limitations on existing natural material and the increasing need to produce more environmentally friendly materials are the main drive for national and state agencies to push researchers to explore better alternatives. In recent years, researchers have been able to identify asphalt binder additives that can enhance the performance of asphalt mixtures. Polymers are considered the most common additive that would enhance the performance of asphalt binders.

Rubberized Hot Mix Asphalt (RHMA) is an asphalt mixture wherein crumb rubber is mixed with the binder to enhance the properties of the asphalt mixture. Furthermore, carbonaceous materials have also been used as additives because they are inherently compatible with asphalt binders due to the carbon in their chemical structure. Increasing carbon content in asphalt binders is believed to increase tensile strength, which in turn will enhance the cracking resistance of asphalt pavements. Modified binders also helped address the increasing concerns about service life, as oxidation is known to be one of the main causes of pavement failure.

In the pursuit of more sustainable and environmentally friendly alternatives and in response to the ever-diminishing supplies of fossil fuels, the application of bio-modified binders and its effects on Hot Mixture Asphalt (HMA) have been studied. This research included the production of bio-binder, a material produced from swine manure that has undergone the pyrolysis process: a thermochemical conversion process that transforms biomass into bio-oil, followed by distillation and filtration.[1] Bio-binder produced from biomass is a promising partial replacement for asphalt binder that has been shown to improve the mechanical properties of the original binder. Biochar is the waste product of the thermochemical process of converting swine manure into bio-oil. Biochar is retracted using a vacuum pump and a simple filtration process. Biochar is an additive that has been shown to enhance the performance of asphalt binder when added.[2]

Rutting and cracking are two major distresses occurring to flexible pavements. Researchers and practitioners have employed different test methods to characterize the fracture resistance of HMA. In this study, the effects of adding Biochar to different oil-based binders will be investigated, as well as changes in HMA's crack and rutting resistance. Two tests are primarily used: 1) the Semi-Circular Bending (SCB) test to analyze crack resistance, and 2) the Hamburg Wheel Tracking (HWT) test, commonly known as the Hamburg Wheel test, to analyze the rutting resistance.

Oxidation and many other factors such as weather conditions, water flow, and constant exposure to radiation have been proven to affect the physical properties of asphalt concrete and HMA and causing it to age.[3] In order to study the ability of Biochar to resist color deterioration, the researchers used the test referred to as the ASTM G155 Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials. This practice covers the basic principles and operating procedures for using xenon arc light and water apparatus intended to reproduce the weathering effects that occur when materials are exposed to sunlight (either direct or through window glass) and moisture (as rain or dew) in actual use. This procedure was followed, and a report was produced showing the quantified color changes in the sample.

Aging increases the viscosity of the asphalt binder, causing it to become stiffer. Hence, to facilitate a better understanding of the effect of Biochar, aged and non-aged HMA samples with and without Biochar were included in the factorial.

II. LITERATURE REVIEW

The transportation industry's shift towards greater sustainability paved the way to further investigate and analyze biofuels. In material design, more sustainable innovations, such as Bio-binder, have been studied and used in mix designs as viable alternatives to their fossil fuel counterparts. Bio-binder has been shown to improve asphalt's rheological and chemical properties.[4] Bio-binder is produced using a thermochemical conversion process of swine manure to bio-oil followed by distillation and filtration.[5] According to the USDA, more than 335 million tons of manure are produced annually in the U.S. with 40.2 million tons being from swine. This has significantly harmed the environment with respect to surface water, ground water and air quality. Spillage of untreated manure into nearby waterways and groundwater in North Carolina has been linked to the outbreaks of dinoflagellates that resulted in the death of more than four millions fish in the Neuse River in 2003.[6] The gaseous emissions have contributed greatly to the effects of global warming. Finding a way to utilize biological waste in the Transportation industry would thus benefit both the environment and the industry itself. The goal of this study is to analyze the possibility of utilizing the by-products of swine manure, mainly Biochar, and its effect on asphalt mixtures.

The hydrothermal liquefaction (HTL) process known as Pyrolysis utilizes this manure and thus helps mitigate some of its impacts on the environment. In this method, animal waste is charges in a high-pressure batch reactor. The working pressure of 34.4 MPa and a working temperature of 500°C were maintained in that reactor. Nitrogen gas is used as a processing gas to purge the residual air in the reactor three times. The reactor is heated up to the setting temperature, which is maintained at a constant level for a specific time. After the reaction is completed, the reactor is rapidly cooled down to room temperature by using a recycled ice-water cooling coil. The gas is then released from the autoclave, reducing the pressure in the autoclave to atmospheric pressure. The sticky residue is then separated from the aqueous solutions by filtration under vacuum to acquire bio-binder for further testing and characterization. The oil is later processed by the production plant using vacuum distillation and filtration.[7] Essentially, HTL consists of the rapid decomposition of materials in a vacuum space to convert the biomass into liquid bio oil and some byproducts.[8] One of the byproducts of pyrolysis is Biochar, a carbonaceous solid waste matter that is a viable option to add to an asphalt binder due to its carbon morphology.

Biochar is comprised of irregular fiber-shaped particles with a porous structure, the complexity of the surface structure relating directly to the high or low-heating rate during manufacturing of the Biochar. The fibrous structure of the Biochar may prove to be very helpful in building a stronger carbon-binder matrix that would enhance the performance and properties of the modified binder.[9]

The rheological properties of asphalt binder are common in HMA-related studies. It has been shown that the rheological properties of the bitumen affect the pavement performance. The viscosity of any modified binder was significantly increased under selected high service temperatures. This may be attributed to the volume filling and the physiochemical reinforcement of the particles added into the binder.[10] It has also been shown that only the modifier content and the modifier type seem to affect the binder's viscosity to a noticeable level. The higher the modifier content, the higher the stiffness of the mixture—mainly due to the particle interaction reinforcement mentioned earlier.

In 2018, Sirin et al. did a comprehensive study on the effects of aging on the HMA mixtures, reviewing over 30 previous studies. In their study, researchers reviewed the results of both types of aging (short-term and long-term) as well as the contributing factors leading to failures of designs such as air voids and moisture content. In addition, they reviewed the latest studies and streamlined suggestions for long-term aging process. The purpose of their research was to suggest a new long-term aging method, as currently there is no standardized method. They were also interested in testing the effects of anti-oxidation additives on the asphalt binder resistance for aging. Among their conclusions, they found that anti-oxidation additives help in reducing the damage caused by aging on the asphalt binder and the HMA mixture, and that their aging method is not encouraged in other environments and requires further study.[11] Further tests conducted on the effects of Biochar on HMA's rheological characteristics showed that adding Biochar to asphalt binder decreases the viscosity while increasing the shear rate. It was also shown that increasing Biochar percentages from 2% to 5% leads to a 5.4% increase in rotational viscosity. The analysis concluded that the addition of Biochar to the control binder improved temperature performance and aging resistance.[12]

Kim et al. did a similar study with the focus being on the development of a new standard for long-term aging. Their study was more focused on the relationship of long-term aging in pavement with heat distribution analysis and the heat environment in the United States. According to their research, long-term aging duration can vary depending on the location in which the pavement will be installed, and the Enhanced Integrated Climatic Model (EICM) gives a better understanding and comprehensive analysis for long-term aging. According to Kim's research, a standardized test method was provided to determine the appropriate procedure to follow when conducting long-term aging testing.[13] In this study, the long-term aging method provided by Kim et al. will be followed.

Few studies have been conducted on the deformation of biomodified HMA. The two most important characteristics for this study are rutting resistance and cracking performance. Previous tests conducted have utilized the same test machines intended for use during this research: the DTS-30 for the Semi-Circular Bend test and the Hamburg wheel for the Hamburg Wheel Test. Huang et al. conducted the SCB test on specimens with different notch depths at 25°C at a constant rate of 0.5 mm/min. The J-integral value was obtained and used as an indicator of fracture resistance in asphalt mixtures. J-integral has been successfully used to characterize the fracture resistance in asphalt mixtures. The SCB test confirmed what other tests, such as the Superpave IDT test, have concluded and validated their results, further indicating the effectiveness of Biochar as an asphalt modifier. Both the DCSE results from the Superpave IDT tests and the J-Integral results from the SCB notched fracture test suggested that Biochar might increase the cracking resistance of HMA.[14] The Biochar role in enhancing cracking resistance was further proved by testing done to measure the cracking temperature. Results showed that cracking temperature decreases as the amount of Biochar increases, which reduces low-temperature cracking. It was then deduced that bio-modified binder from swine waste can serve as a modifier in HMA and that increasing the percentage of this biomaterial can produce asphalt pavements with better low-temperature performance.

In 2013, Huang et al. did a study to verify whether the SCB test characterizes the fracture resistance in HMA mixtures. Their study focused on utilizing the Finite Element Method (FEM) to analyze the results of the SCB test and compare them to the fracture results. Their study demonstrated that there is a good the correlation between the SCB test results and the fracture resistance analysis, and that SCB is a good indicator for fracture resistance. In addition, additives that changed the properties of the asphalt binder will also change the fracture resistance of the HMA mixture.[15]

In 2017, Chaturabong and Bahia did an evaluation study on the moisture relative effect in the HWT test. Their study conducted the HWT test in both wet and dry conditions to test the comparative change in results. The results of their research showed that conducting the HWT test according to AASHTO 324 is considered as a good substitute to the dry HWT creep stage test.[16]

With millions of dollars allocated annually for pavement rehabilitation and construction, the physical appearance should not be overlooked. Over a design life of 20 years, the constant exposure to radiation is bound to affect the color and appearance of hot mix asphalt. In 2004, Lin et al. analyzed the fading and color changes in colored asphalt by using A QUV test, a test performed in the ultraviolet light accelerated weathering tester. The test was conducted in Q-Panel Lab, a third-party lab. Lin found that ultraviolet light affects the colors and is dependent on the time in the QUV machine. However, for this research paper, a different test was performed. The same lab was contracted to conduct the ASTM G155 test, Standard Practice for Operating Xenon Arc Light Apparatus for Exposure of Non-Metallic Materials. Instead of testing for the effects of colored paint, the test aims to analyze the fading and degradation of the HMA samples' colors from their initial black.[17]

This study will focus on the effect of adding Biochar to two types of asphalt mixtures and the effect of aging them and, furthermore, the color degradation caused by the environmental aging simulation.

III. OBJECTIVES

Adding Biochar to HMA mixtures has been previously shown to improve asphalt binder rheological behavior by increasing its viscosity and reducing temperature susceptibility.[18] However, this study is solely focused on the mechanical properties of the asphalt mixture containing Biochar. The objective of this research is to analyze the effect of adding Biochar to HMA and RHMA mixtures, using both SCB and the HWT. The SCB test will be used to measure the fatigue resistance, while the HWT test will be used to investigate the rutting resistance and moisture susceptibility of asphalt mixtures according to the following factorial in Table 1.

Table 1. Testing Factorial

No Biochar	Biochar 5%
Virgin No Biochar (VN)	Virgin Biochar (VB)
Aged Virgin No Biochar (AVN)	Aged Virgin Biochar (AVB)
Rubber No Biochar (RN)	Rubber Biochar (RB)
Aged Rubber No Biochar (ARN)	Aged Rubber Biochar (ARB)

IV. MATERIALS

Asphalt mixtures generally consist of three components: aggregates, asphalt binder, and air. Aggregates form the largest mass and volume, as they represent 90–95% of the total mass of the HMA mixture and are the main source of strength in HMA mixtures. Asphalt binder acts as both a glue for the aggregates and a viscous material to absorb the load impact from the traffic. Air voids are air volume entrapped within the HMA mixture after compaction.

AGGREGATES

Aggregates include sand, gravel, slag, and crushed stones. Because of the wide range of sources and types, aggregates have many characteristics, i.e. gradation, cleanness, fractured faces, absorption, and specific gravity (G_s). Each of these characteristics helps in understanding whether this aggregate is suited for the mixture or not. Table (2) shows the aggregates characteristics used in this study.

Table 2. Aggregates Characteristics for Both Mixtures

Property	Design		Specifications	
	RHMA	Virgin	RHMA	Virgin
FAA, Um	45	43.8	≥45	
LA Abrasion	10	5		
LA Abrasion	13	22		
FM	5.55	4.859		
SE	61	77	≥47	≥47
Elongated	0	0	(5:1)	
Flat	0	0	(5:1)	
Flat/Elongated	11		(3:1)	
Flat/Elongated	3	0	(5:1)	
Fractured Faces (>1)	100	100		≥95
Fractured Faces (>2)	100	100	≥90	≥90
Absorption	0.3	1.4		
Absorption (Fine)	1.8	1		
Total Moisture	0.86	22.22		
SPGR (Dry, Gsb)	2.978	2.597		
SPGR (SSD)	2.889	2.643		
SPGR (Apparent, Gsa)	2.91	2.693		
SPGR Fine (Dry, Gsb)	2.749	2.698		
Unit Wt (Loose)	85	82		
Unit Wt (Rodded)	94	92		

GRADATION

Table 3 and Figure 1 show the gradations used in this study.

Table 3. Aggregates Gradations both RHMA and Virgin HMA

Sieve	% Passing		Specifications	
	RHMA	Virgin	RHMA	Virgin
1” (25mm)	100	100	100–100	100–100
3/4” (19mm)	97.9	97.9	93–100	93–100
1/2” (12.5mm)	83.9	86.3	77–89	80–92
3/8” (9.5mm)	72.2	78.1	67–77	
#4 (4.75mm)	36.3	52.5	30–42	49–59
#8 (2.36mm)	18.8	38.1	14–24	33–43
#16 (1.18mm)	12.7	27		
#30 (0.6mm)	9	18.5		13–21
#50 (0.3mm)	6.1	11		
#100 (0.15mm)	4.2	6.4		
#200 (75μm)	3.01	4.45	0.6–4.6	2.5–6.5
Pan	0	0		

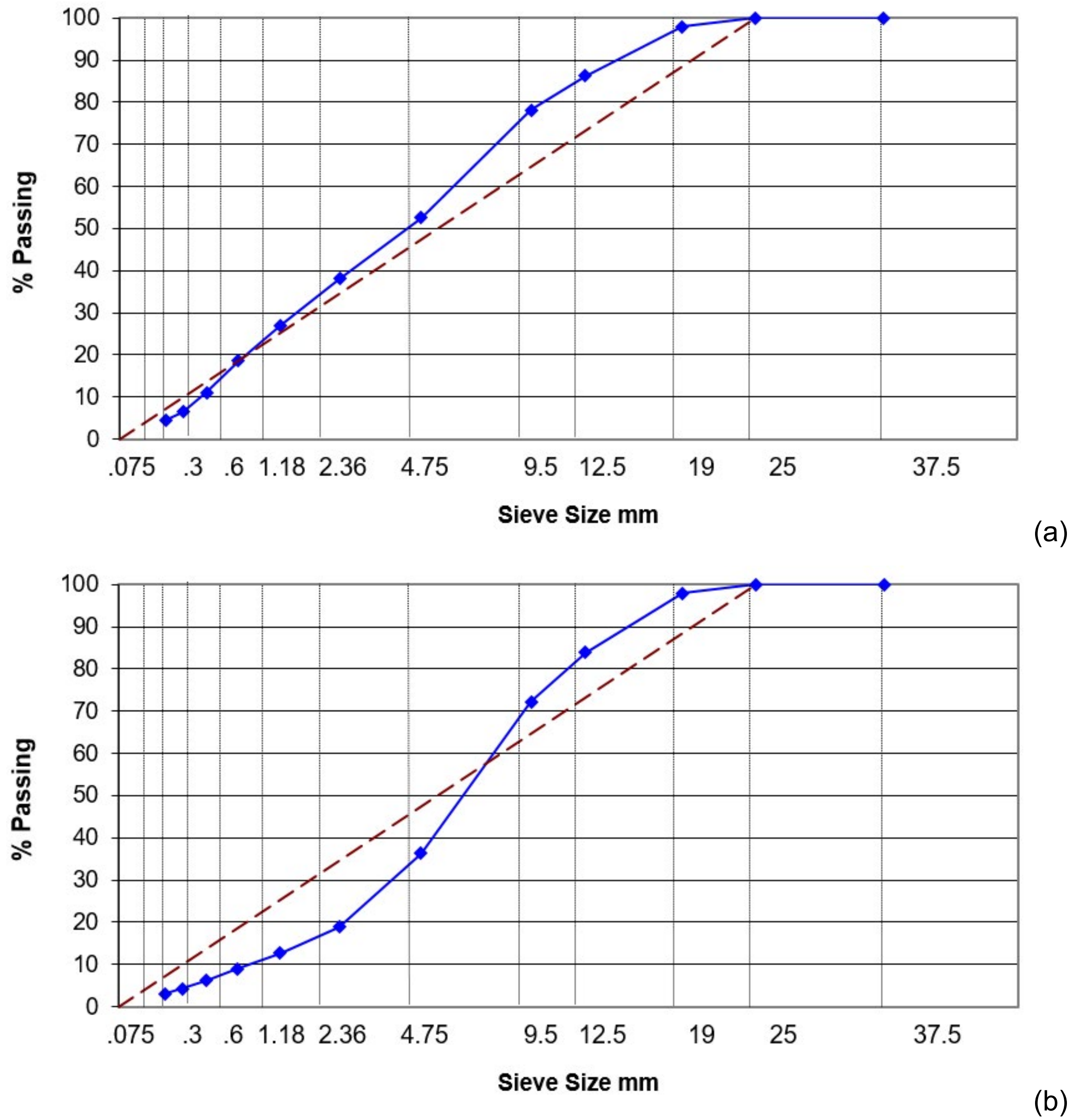


Figure 1. Graphs Representation for Aggregate Gradation: (a) Dense Graded Mix; (b) Gap Graded Mix

ASPHALT BINDER

Asphalt binder mixes with fines (passing #200 aggregates) to form mastic, which is the glue binding aggregates with each other. Asphalt binder is a by-product of refining crude oil into its primary components. Superpave performance grading (PG) is used to determine properties: in this study PG 64-10 was used in the HMA mixtures. The properties of the asphalt binder are presented in Table 4.

Table 4. Asphalt Binder Properties

Property	Test Method	Result HMA	Result RHMA	Specification
Original Binder				
Rotational Viscosity, Pa·s, (135°C)	AASHTO T316	0.402	0.398	3.0 maximum
Flash, COC, °C	AASHTO T48	302	300	230 minimum
Solubility in TCE, %	AASHTO T44	100	99.9	99.0 minimum
Dynamic Shear,				
Test Temperature, °C	AASHTO T315	64	64	
G*/sin(delta), kPa		1.173	1.192	1.00 minimum
G*, kPa		1.172	1.191	
Phase Angle, °		87.35	87.39	
RTFO Test Aged Binder				
Dynamic Shear,				
Test Temperature, °C	AASHTO T315	64	64	
G*/sin(delta), kPa		3.631	3.684	2.20 minimum
G*, kPa		3.603	3.655	
Phase Angle		82.82	82.76	
Mass Change, %	AASHTO T240	-0.128	-0.129	1.00 maximum
Ductility, cm		100	100	
RTFO Test and PAV Aged Binder				
PAV Aging Temperature, °C	AASHTO R28	100	100	
Dynamic Shear,				
Test Temperature, °C	AASHTO T315	31	28	
G*sin(delta), kPa		1182	2285	5000 maximum
G*, kPa		1492	2977	
Phase Angle		52.41	50.15	
Bending Beam Rheometer				
Test Temperature,° C	AASHTO T313	0	-6	
S-value, MPa		28	68	300 maximum
M-value		0.468	0.414	0.300 minimum

Asphalt binder was combined with crumb rubber to produce rubberized asphalt binder. The process for the mixing was carried out by combining 18% rubber and 82% binder. Table 5 shows the gradation of the crumb rubber mixed with the asphalt binder.

Table 5. Crumb Rubber Gradation

CA LP-10 Sieve Size	Scrap Tire % passing	Scrap Tire Specification	High Nat % passing	High Nat Specification
No.8	100	100	100	100
No.10	100	98–100	100	100
No.16	48	45–75	100	95–100
No.30	10	2–20	72	35–85
No.50	3	0–6	24	10–30
No.100	1	0–2	4	0–4
No.200	0	0	1	0–1

BIOCHAR

Biochar is an organic compound high in carbon and a byproduct of the pyrolysis process. Pyrolysis is the process of thermal decomposition in an inert atmosphere with the absence of oxygen to prevent combustion. Biochar is produced when biomass, most commonly swine manure, is converted into a bio-oil using a hydrothermal liquefaction process (HTL). HTL turns the swine manure into bio-oil, a liquid product as well as other by-products including Biochar, syngas and other hydrocarbon gases. Among them, Biochar is the only solid waste product of the HTL process. Properties of Biochar may differ depending on the pyrolysis process. Fast pyrolysis would lead to different physical and chemical functionality of the Biochar compared to slower pyrolysis rates. Bio-oil may be considered a good resource as a binder due to the chemical and rheological similarities it possesses with the asphalt binder. Bio-oil may be used to produce the bio-binder that can be utilized as an additive to asphalt pavement to improve the asphalt's properties. Utilizing bio-binder from swine manure as a partial replacement for asphalt binder was shown to be promising in both mechanical and sustainability aspects.[19]

HTL usually takes place between 200 and 374°C and from 4 to 20 MPa.[20] To produce bio-binder, the operating temperature of HTL at a laboratory scale is in the range of 200–400°C, and the time required for the process (residence time) is less than two hours. HTL is followed by filtration under vacuum and vacuum distillation to obtain bio-binder. During vacuum distillation, the pressure above the liquid mixture is reduced to less than its vapor pressure, which causes the most volatile liquids to evaporate.[21]

Biochar was added as an additive to the asphalt binder in order to enhance its properties. Adding 5% Biochar to the asphalt binder increases its rheological properties as well as reducing the temperature susceptibility of the asphalt binder. It was also shown that Biochar may enhance the performance of the mixture: for instance by improving rutting resistance and decreasing moisture susceptibility. Preliminary tests also suggest that Biochar might increase the cracking resistance of HMA.[22]

V. METHODOLOGY

HMA mixtures require preparation before the testing is conducted, including mixing of the material, aging the samples, and compaction and fabrication of the samples.

MIXING

HMA was prepared for mixing by batching the aggregates to the required gradation for that mix and then adding the asphalt binder to the aggregate batch and mixing it to obtain a homogeneous HMA mixture. The HMA mix that was used in this project has a Nominal Maximum Aggregate Size (NMAS) of 3/4”. The asphalt binder that was used had a grade of PG 64-10, and the binder content for that mix was 4.8% of total weight.

Aggregates, Biochar, and mixing buckets were heated to 163°C (325°F) prior to mixing for about two hours; asphalt binder was heated to 177°C (325°F) for three hours to reach a homogeneous liquid phase. Later, aggregates were poured into the mixing bucket as shown in Figure 2-a, aggregates in the bucket were weighted on the scale, and the asphalt binder was added to the mix and weighted as seen in the Figure 2-b. The binder and the aggregate in the bucket were placed in the mixer, where the aggregate started to be coated: see Figure 2-c. After the aggregates were completely covered, the aggregates were placed in a tray to prepare them for compaction: see Figure 2-d. Biochar was mixed with the asphalt binder prior to its addition to the mixing bucket using a shear mixer. The mixing speed was 1100–1500 RPM for five minutes. Figure 3 shows the shear mixer used. The Biochar binder was placed back in the oven for two hours before mixing.

(a) (b)

(c) (d)

Figure 2. (a) Aggregate Batch Poured into the Mixing Bucket; (b) Asphalt Binder Added to the Mixing Bucket; (c) Mixture Before the Aggregates are Fully Covered; (d) Mixture After Fully Covered

(a) (b)

Figure 3. (a) Shear Mixer used to Blend Biochar; (b) Shear Mixer during Mixing

AGING

HMA mixtures were aged before the start of the compaction. Aging is a laboratory procedure used to simulate the effects of HMA initial aging and binder absorption that occurs during the pre-compaction phase of mass production plant mixing. Aging for the Virgin Mix was held at 122°C, while aging for the rubber batches was held at 132°C. Aging took two hours and started immediately after the samples had reached the target temperature for aging. The aging process was performed according to the Mixture Conditioning for Volumetric Mixture Design portion of the AASHTO R-30 test.

Aging was done over two stages: short-term aging and long-term aging. All samples were subjected to short-term aging according to the AASHTO R-30 test method, the samples were heated at 135°C for four hours and were cooled to room temperature to start the compaction.

Long-term aging was done for half of the samples to simulate the properties' change after 16 years; long-term aging was conducted based on the method provided by Kim et al. in NCHRP project 09-54, 2018[23]. Since the purpose of long-term aging in this study is to measure the Biochar's durability compared to the control mix, the aging was assumed to be for 16 years and for a layer at a depth of 20 mm in Los Angeles, CA; based on that assumption, long-term aging was done for 5 days at 95°C. After the mixture was produced, it was boxed into small cardboard boxes and stored away from humidity and other weather conditions until needed. Samples were mixed and moved every hour to ensure a continuous and homogeneous heat distribution.

COMPACTION AND FABRICATION OF SPECIMENS

The specimens needed for this study were developed based on the testing factorial in Table 1 included above. A total of 56 specimens was needed: 28 for Virgin HMA and 28 for Rubber HMA. The SCB compacted specimens were 120 mm high, and the HWT specimens were 60 mm high. The specimens created in the lab using aggregates were taken from a quarry. The binder used was obtained from a local oil refinery. Fabricating the specimens took place over a series of steps. The initial part was conducted in the lab according to AASHTO specifications and consisted of various lab experiments explained below. The second part dealt with cutting the compacted specimens produced in the first step into appropriate specimens to be used for testing.

After aging performed for the required time, the sample was reduced into smaller applicable testing sizes. Reducing the sample was done according to AASHTO R47, the standard practice for reducing samples of Hot Mix Asphalt to testing size. Variability of aggregates constitutes a major portion of the overall mixture performance; thus, this reduction helps ensure homogeneity is well maintained within the mixture. The two types and methods of splitters outlined in the standard were used for testing. The types of the mechanical splitter used are based on the total amount of amount of material split. The Type A splitter was used for the larger masses, about or larger than 5000 g. Type B was used for smaller samples, usually less than 5000 g. Both splitters are shown in Figure 5. Precautions were taken to ensure minimal aggregate loss, including the use of an oil-based releasing agent, as well as preheating the splitters before the splitting of the HMA mixtures.

(a) (b)

Figure 4. (a) Quartermaster Splitter; (b) Riffle Splitter

After the samples were reduced in size and appropriated into pans and weighed, the material was ready for volumetric property testing. Four main tests were conducted. The standard tests used were:

- AASHTO T 209: Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm})
- AASHTO T 312: Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor
- AASHTO T 166: Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Hot Mix Asphalt using the Saturated Surface-Dry Method
- AASHTO T 269: Standard Method of Test for Percent Air Voids in Compacted Dense and Open Asphalt Mixtures

The initial test conducted was the AASHTO T-209 to determine the specific gravity (G_{mm}) of the loose sample. After the sample was aged, it was taken out of the oven and set outside to cool to room temperature. The most crucial part of the test is to make sure the sample being tested is completely loose and without voids. This is done by spreading the material apart and making sure no aggregates are sticking to each other, specifically any fine aggregates. After the aggregates reached room temperature, they were transferred into an empty pycnometer where the mass of the dry sample was recorded. The minimum mass of aggregates used was 2500 g per the test's specification. The sample was then submerged in water with the water level being at least an inch higher than the sample surface. The sample was then put under vacuum for 15 minutes while applying sufficient vacuum pressure of 27.5 ± 2.5 mmHg. After completion, the pressure was released, and the pycnometer filled up with water up to the very edge. Standardization of the pycnometer was performed per testing specification. The mass of the pycnometer, sample, and water is then measured. The last measurement needed is the mass of the pycnometer filled with water. After these three readings were recorded, the appropriate equations per specification were used to calculate the G_{mm} of the sample. After the G_{mm} was calculated, the following equation was used to calculate the trial mass of sample needed to achieve a testing specimen with the required air voids.

$$GSM_{Trial} = [(1\text{-Air Voids})/100] \times G_{mm} \times 176.71 \times \text{height of specimen}$$

The previous equation is used on a trial and error basis, and multiple trials were needed at times to achieve the proper specifications of the gyratory compacted sample. The trial sample mass is directly affected by the theoretical maximum specific gravity (G_{mm}) of the sample.

The mass calculated was the mass input into the compaction mold. The compaction process followed the AASHTO T-312 specifications. Compaction was performed using a Pine Gyratory Compactor. Compacted specimens were needed for both tests: the SCB and the HWT. The SCB compacted specimens were 120 mm high and Hamburg Wheel specimens were designed to be 60 mm high.

COMPACTION

Samples were ready for compaction after the splitting was completed and the G_{mm} was obtained. HMA material was placed in the oven until it reached the compaction temperature: for virgin mixtures compaction temperature of 122°C was used and for the rubber mixtures the temperature was 151°C. After HMA mixtures reached the compaction temperature, they were filled into the compaction mold and compacted per AASHTO T 312. The mixtures were subjected to different pressures: virgin mixtures and rubber mixtures were subjected to 600 kPa and 825 kPa, respectively. Asphalt binder is a viscous material and part of it is elastic; the elastic characteristic makes the material rebound after compaction, and that would make for an error in either the height of the samples or the air void percentage calculations. Samples were subjected to a squaring time wherein the sample stayed in its place until the rebound period was over, for the virgin mixtures, 3 minutes was sufficient to prevent the rebound, but for the rubber mixtures squaring was done for 45 minutes.

After compacting and squaring the samples were completed, the compacted specimen was extruded and left to cool down to room temperature. Once the specimen cooled down, its bulk specific gravity (G_{mb}) was determined. AASHTO T-166 was followed, and Method A was used to determine the bulk volume of the compacted HMA mix. The mass of the dry sample was taken, as well as its mass underwater after being suspended for 4 minutes. The final measurement needed for this test was the Saturated Surface Dry (SSD) mass. This was determined by removing the specimen from the water bath and damp drying the specimen by blotting it with a damp towel. It is critical to accurately achieve the SSD condition in order to correctly account for the surface voids of the compacted HMA specimen. The equations provided in the specification were then used to determine the $G_{mb.}$

Finally, once the G_{mm} and the G_{mb} were found, the AASHTO T-269 test method was used to calculate the air voids in the compacted HMA samples. A simple equation was used to calculate the percent air voids in the asphalt mixture:

$$V_a = 100*(1- (\frac{Gmb}{Gmm}))$$

The target air voids for the specimens was 7% ± 0.5%. All samples tested and compacted adhered to that restriction. Specimens with air voids above or below the allowed limit were discarded.

FABRICATION

After verifying the air void percentage in the compacted samples and ensuring everything is just as it is required by the specification, samples were ready to be cut for the HWT and SCB tests. Cutting the specimens was done in professional third-party labs meeting all required specifications. In total, 24 cylinders were compacted for the SCB test with each measuring 150 mm in diameter and 120 mm in height. Cylinders were cut in half for the SCB samples with each half measuring 57±1 mm. Subsequently, each half was then cut again into a half-circle shape, making sure each half was within 1 mm of the other. After the specimen was cut into the appropriate size and shape, it was prepared for notching. The notching was done by table saw. The test mandates three notches be used for the study: a 25mm, 32mm, and 38mm notch. Notch widths averaged a measurement of 2mm, while making sure none exceeded the 3.5mm maximum allowed width per the ASTM D8044-16 standard. After the notching was completed, the samples were transported back to the testing laboratory where they were stored away from moisture, humidity, and direct sunlight until testing time. HWT samples were cut as seen in Figure 5, and the samples were combined to make the shape shown in Figure 5-d.

(a)

(b)

(c)

(d)

Figure 5. (a) Marking the Line of Cut using the Mold for Hamburg Wheel Test; (b) Aligning the Saw with the Line Prior to Cutting; (c) Post-cutting Shape; (d) HWT Samples Before Running the Test

VI. TESTING

This study focused on the cracking strength and rutting resistance of modified HMA. The main testing procedures used for studying the cracking and rutting properties of the samples were ASTM D8044-16: Standard Test Method for Evaluation of Asphalt Mixture Cracking Resistance using the Semi-Circular Bend Test (SCB) at intermediate Temperatures and AASHTO T 324-17: Standard Test Method for Hamburg Wheel-Track Testing of Compacted Asphalt Mixtures.

SEMI-CIRCULAR BEND TEST

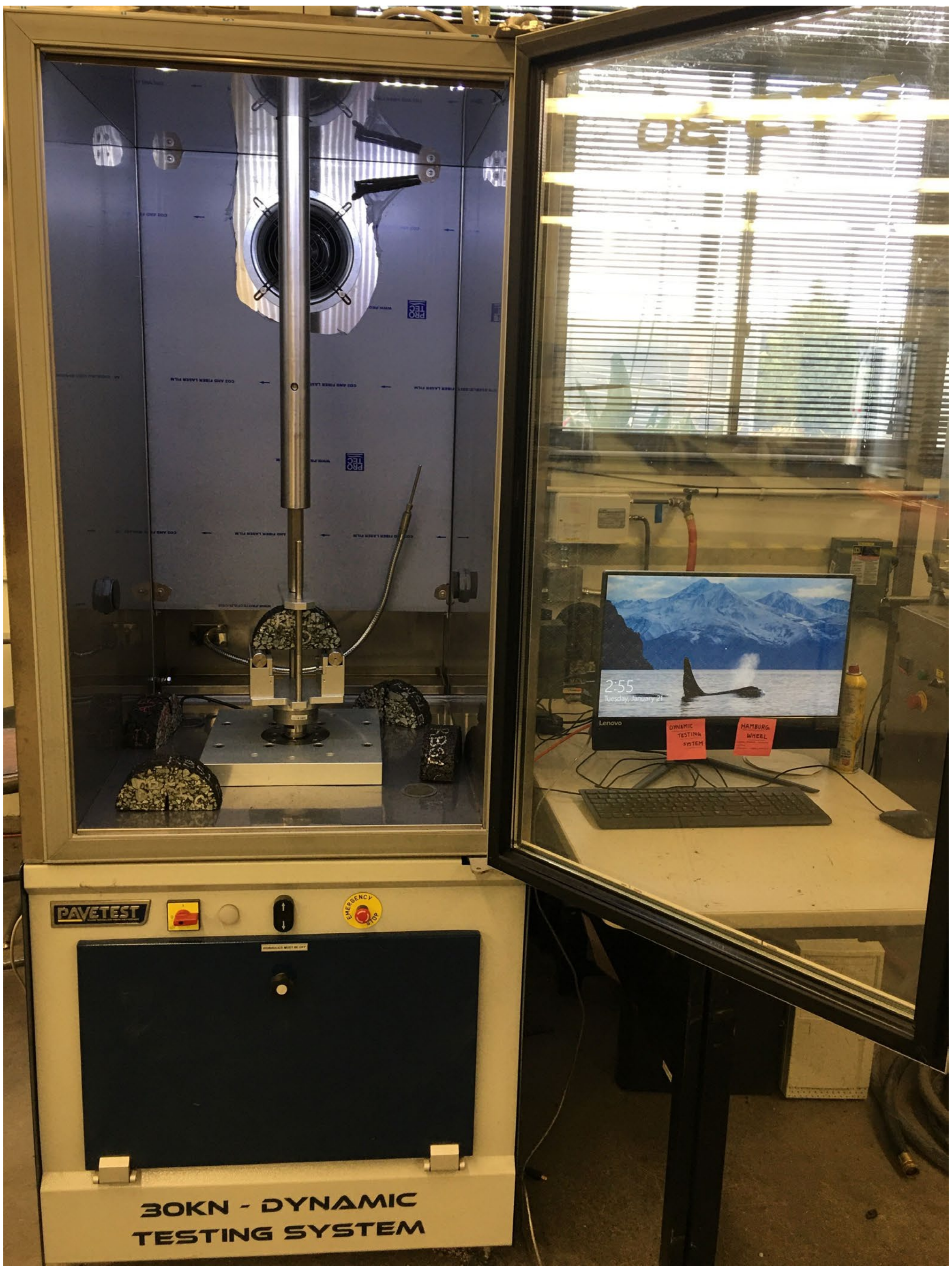


Figure 6. SCB Testing Machine

The ASTM D8044: SCB Test was conducted first. The test is conducted by loading a semi-circular specimen, prepared according to the standard described previously, monotonically until fracture failure occurs. The apparatus consisted of a load test system, axial loading device, environmentally controlled chambers and a data control and acquisitions system. All of the above were found in the testing machine used, the DTS-30, as seen in Figure 6. The test also required a minimum of four semi-circular specimens to be tested at each of the notches. This test is used to determine the critical strain energy release rate J_c. The critical strain energy release rate, J_c, is used to compare the cracking resistance of asphalt mixtures prepared with different binders and aggregate types. An important factor in the SCB testing is temperature control and managing the temperature inside the chamber. Setting the temperature of the chamber and allowing it to stabilize to test temperature is one of the first steps to take. The test temperature is selected based on the climate intermediate temperature performance grade temperature as defined in Specifications D6373, AASHTO M320, or M332. According to the specimens and binder used, a temperature of 31°C was used for virgin hot mix asphalt mixtures and a temperature of 28°C was used for rubber hot mix asphalt mixtures. The specimens are then placed in the environmental chamber for a minimum of two hours to reach the required temperature equilibrium. Once all preliminary steps have been taken and the specimen is ready to be tested, it is loaded onto the fixture making sure it is centered and making direct contact with the fixture: see Figure 7. All contact surfaces were cleaned in advance and it was ensured that they had no debris. In addition, PTFE (Polytetrafluoroethylene) strips were used to reduce the friction between the specimen and the support rollers of the loading fixture.

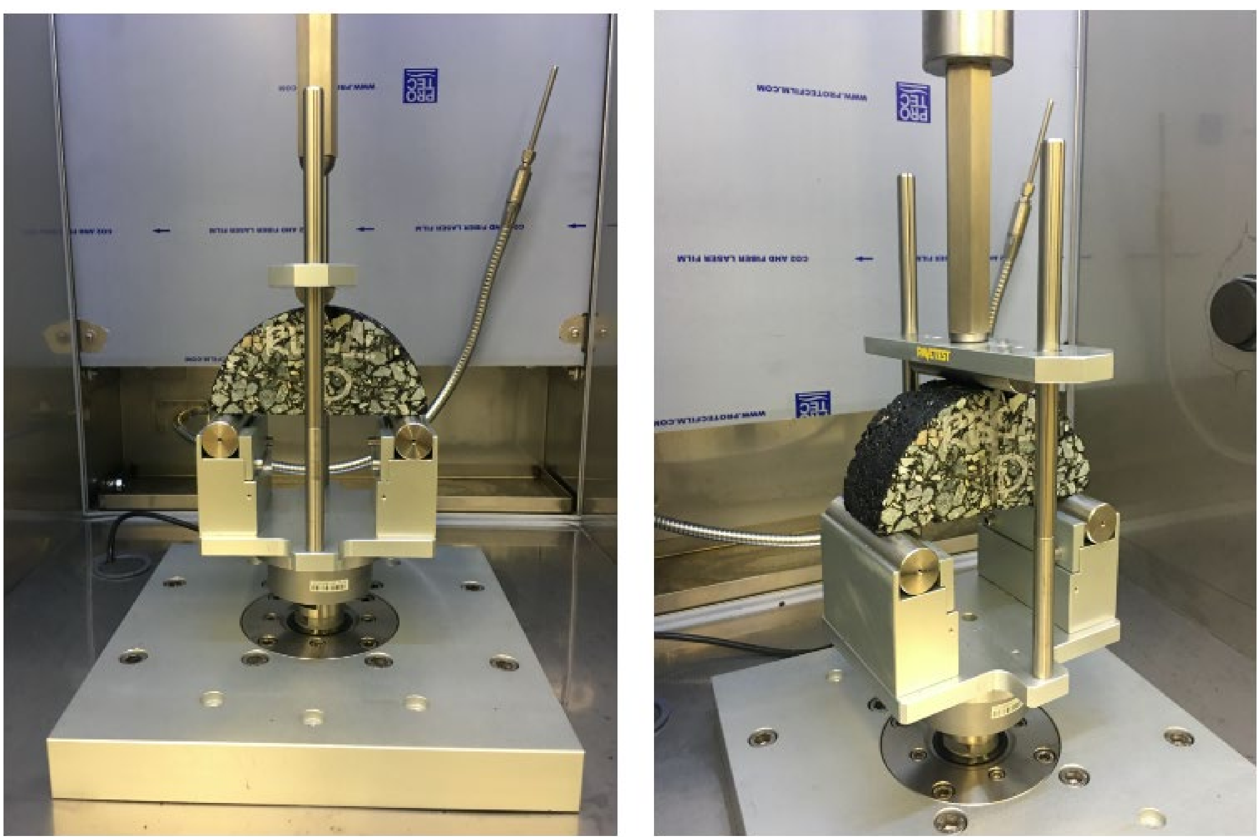


Figure 7. SCB Sample During Testing

Once the test starts, the sample being tested is loaded using the axial loading device found in the SCB machine. After temperature equilibrium is reached, a preload of 45 N is applied to make sure the sample is seated properly. The load was applied at a rate of 0.5 mm/min, ensuring all parameters were being recorded and measured by the appropriate sensors and devices. The load and the deformation are continuously recorded for the duration of the test and used to construct a table with both readings. Once the testing has been completed, the values are tabulated and then exported into an appropriate software for analysis.

One of the main unknowns for this test is the strain energy to failure, *U*. Strain energy is the area under the loading portion of the load versus deformation graph plotted, up to the maximum load measured for each notch depth, the peak load. According to the ASTM standard method, there are two methods for calculating the strain energy value: using the quadrangle rule or fitting the load vs. displacement curve for each notch depth with a sixth order polynomial and integrating from the origin to the displacement that corresponds to the maximum load.

Once the strain energy was calculated, some preliminary statistical operations must take place, such as identifying and removing outliers per Practice E178. All observations for *U* were then plotted versus the notch depth and modeled with a linear regression line. The slope of the line represents the change of strain energy with notch depth (d*U*/da).

After strain energy for each individual material sample was calculated, the data were plotted, and a linear best-fit line was constructed for them. The slope of this line (d*U*/da) represents the change in strain energy with the notch depth (kJ/m). This value is crucial in calculating the critical strain energy for the sample. After the d*U*/da value was calculated, the average sample thickness of the tested material (b) was measured, and the researchers used the following equation to calculate J_c:

$$J_c = \frac{-1}{\mathrm{b}}\left(\frac{\mathrm{d}U}{\mathrm{da}}\right)$$

J_c = critical strain energy release rate (kJ/m^2)

b = sample thickness (m)

a = notch depth (m)

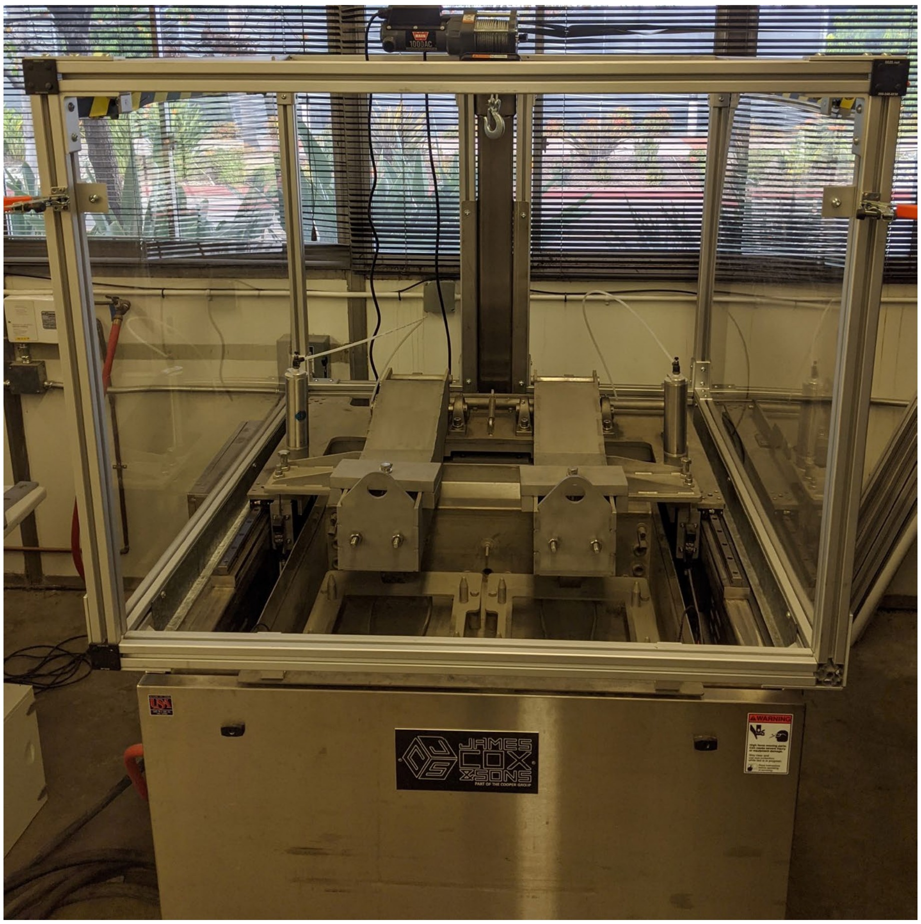
U = Strain Energy to failure (kJ)

d*U*/da = change of strain energy with notch depth (kJ/m)

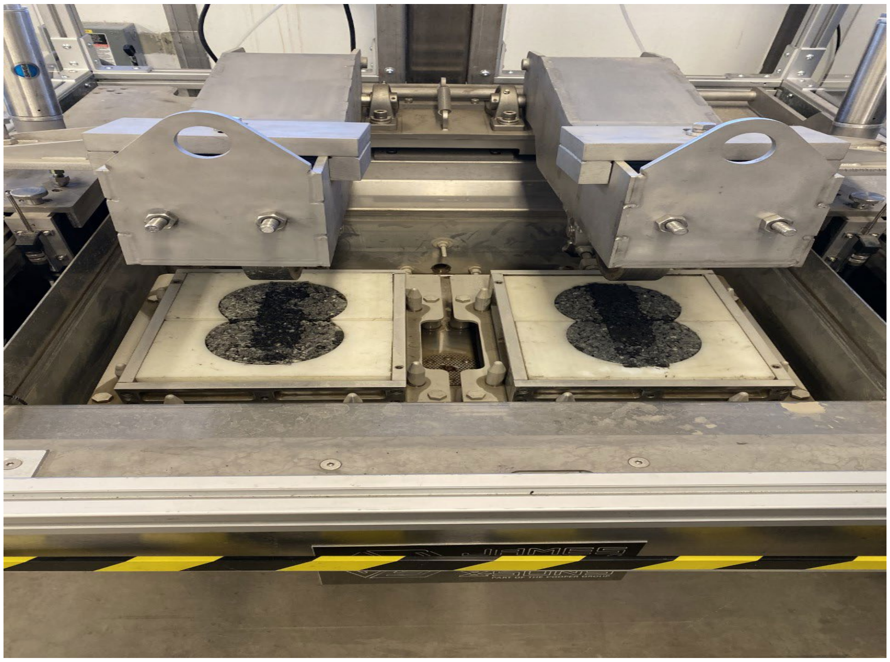
After the critical strain energy release rate (J_c) value was calculated, it was tabulated and prepared for statistical analysis. Sample calculations are included in the analysis portion of this report.

HAMBURG WHEEL TEST

The second test conducted was the AASHTO T 324: Hamburg Test. The method outlines the testing of submerged compacted asphalt mixtures in a continuous rolling-wheel device. Sensors connected to the machine continuously monitor and record data, providing the rate of deformation from a moving concentrated load. The test also measures the potential for moisture damage effects since the specimens are submerged under water for the complete duration of the test. This test method measures the rut depth and number of passes to failure.



(a)



(b)

Figure 8. (a) Hamburg Wheel Machine; (b) Samples after Testing

The apparatus for the tests includes a Hamburg Wheel-Tracking Device—an electrically powered machine capable of moving a steel wheel over the center of the test specimen. The wheel is 1.85” thick with a diameter of 8”. The load on the wheel is 705 N ± 4.5 N. A temperature control system and measurement systems are required as well. The specimens are held down using specialized mounting systems such as the one in Figure 8.

To begin the test, the testing device and the software used were turned on. The tank was then filled with water at 50°C or other test temperature required based on applicable specifications. After the required water temperature was reached, the compacted cylinders were rigidly mounted using the mounting trays and were secured in. Once everything was in place, the maximum allowable rut depth and number of passes were selected on the software based on the applicable specifications. This research selected a maximum allowable rut depth of 12.5 mm and a number of passes of 20,000 based on Caltrans specifications. According to the standard, the testing specimen required 45 minutes of conditioning time—time to allow the internal temperature of the specimen to reach a certain temperature in the water before the start of the test. After the specimen reached the conditioning temperature, the test was ready to start. A hydraulic mechanism was used to lower the wheels onto the edge of the testing specimen and the test is started by pressing the ‘Start’ button. The test continued until it reached the predetermined number of passes or the allowable rut depth; samples were considered failed if they exceeded the maximum allowable rut depth. After that, the wheels were raised, and the specimen were removed from the mounting tray. The valves were then opened beneath the tank to drain the water bath.

The software plots the rut depth versus the number of passes for each test. A typical output would include a stripping inflection point (SIP), number of passes to failure, and number of passes to Stripping Inflection Point (SIP). The slopes before and after the SIP are to be calculated. Mixtures in this research had very high rut resistance; therefore, they did not show any clear SIP.

VII. RESULTS AND ANALYSIS

SEMI-CIRCULAR BEND TEST

In this study, a graphical interpretation analysis method was utilized. The test tabulated values were exported into Microsoft Excel. Once the tables were in appropriate formats, they were used to construct a graph. A scatter diagram was constructed with an appropriate polynomial trend line of the sixth degree. The trend line represented the best equation fitting the graph given by test data. With the use of calculations described in the following paragraph, the value for the critical strain energy release rate, J_c, was computed.

Once the graph was constructed and the polynomial equation is determined, Simple differentiation was performed to calculate the local maximum for the graph produced; the local maximum represents the highest load before fracture (peak load). Figure 9 pertains to ARBS1. The local maximum by definition also has a derivative of zero, and hence deriving the equation and solving it for zero provides the x-coordinate value (deformation) at the maximum peak load in the graph. Integration is then performed for the area under the graph, starting from zero to the upper limit of integration, which was determined to be the value of the maximum deformation under the peak load (U). The integration process computes the strain energy to failure (U) needed for every subsample at the three different notch depths. The strain energy for each sample tested, as well as the peak load and displacement at peak load values, are shown in Tables 6, 7, and 8.

Table 6. Semi-Circular Bend (SCB) Test Results across Samples with Low Notch Depth

	Low Notch (25 mm)			
Sample	**Subsample**	**Peak Load (kN)**	**Displacement (mm)**	**Strain Energy U (J)**
		VNS1		
Virgin No Biochar (VNS)	VNS1-A	0.802	1.290	0.695
	VNS1-B	0.706	0.856	0.432
	VNS1-C	0.868	1.030	0.627
	VNS1-D	0.792	1.150	0.678
		AVNS1		
Aged Virgin No Biochar (AVNS)	AVNS1-A	0.256	0.997	0.200
	AVNS1-B	0.180	1.200	0.161
	AVNS1-C	0.275	1.170	0.225
	AVNS1-D	0.286	1.360	1.360
		VBS1		
Virgin Biochar (VBS)	VBS1-A	0.630	1.190	0.491
	VBS1-B	0.374	0.572	0.159
	VBS1-C	0.634	1.160	0.480
	VBS1-D	0.637	1.170	0.467
		AVBS1		
Aged Virgin Biochar (AVBS)	AVBS1-A	0.518	0.819	0.316
	AVBS1-B	0.624	0.962	0.425
	AVBS1-C	0.466	1.000	0.319
	AVBS1-D	0.615	1.260	0.472
		RNS1		
Rubber No Biochar (RNS)	RNS1-A	0.905	1.140	0.650
	RNS1-B	0.829	0.846	0.504
	RNS1-C	0.865	0.998	0.623
	RNS1-D	0.892	0.823	0.516
		ARNS1		
Aged Rubber No Biochar (ARNS)	ARNS1-A	0.909	0.594	0.363
	ARNS1-B	0.767	0.532	0.277
	ARNS1-C	0.897	0.703	0.423
	ARNS1-D	0.810	0.602	0.305
		RBS1		
Rubber Biochar (RBS)	RBS1-A	1.010	0.747	0.494
	RBS1-B	1.180	0.692	0.521
	RBS1-C	1.060	0.791	0.501
	RBS1-D	0.048	0.822	0.179

Low Notch (25 mm)				
Sample	**Subsample**	**Peak Load (kN)**	**Displacement (mm)**	**Strain Energy U (J)**
		ARBS1		
Aged Rubber Biochar (ARBS)	ARBS1-A	0.762	0.767	0.398
	ARBS1-B	0.969	0.951	0.605
	ARBS1-C	0.779	0.670	0.349
	ARBS1-D	0.906	0.890	0.536

Subsamples highlighted in red represent strain energy readings that have been identified as outliers per Practice E178 and have been removed from the data set and not included in any analysis from this point forward.

Table 7. Semi-Circular Bend (SCB) Test Results for Samples with Medium Notch Depth

Medium Notch (32 mm)				
Sample	**Subsample**	**Peak Load (kN)**	**Displacement (mm)**	**Strain Energy U (J)**
		VNS2		
Virgin No Biochar (VNS)	VNS2-A	0.396	0.959	0.273
	VNS2-B	0.509	1.070	0.395
	VNS2-C	0.437	0.956	0.285
	VNS2-D	0.436	1.270	0.425
		AVNS2		
Aged Virgin No Biochar (AVNS)	AVNS2-A	0.176	1.430	0.210
	AVNS2-B	0.197	1.130	0.156
	AVNS2-C	0.116	1.450	0.136
	AVNS2-D	0.153	0.905	0.115
		VBS2		
Virgin Biochar (VBS)	VBS2-A	0.444	0.853	0.240
	VBS2-B	0.370	0.802	0.207
	VBS2-C	0.406	0.802	0.207
	VBS2-D	0.377	0.815	0.214
		AVBS2		
Aged Virgin Biochar (AVBS)	AVBS2-A	0.543	0.888	0.327
	AVBS2-B	0.366	0.646	0.184
	AVBS2-C	0.428	0.662	0.202
	AVBS2-D	0.557	1.040	0.395
		RNS2		
Rubber No Biochar (RNS)	RNS2-A	0.506	0.928	0.353
	RNS2-B	0.596	0.951	0.412
	RNS2-C	0.595	0.740	0.315
	RNS2-D	0.538	0.673	0.257

Medium Notch (32 mm)				
Sample	**Subsample**	**Peak Load (kN)**	**Displacement (mm)**	**Strain Energy U (J)**
		ARNS2		
Aged Rubber No Biochar (ARNS)	ARNS2-A	0.643	0.521	0.221
	ARNS2-B	0.587	0.506	0.206
	ARNS2-C	0.550	0.585	0.231
	ARNS2-D	0.613	0.548	0.234
		RBS2		
Rubber Biochar (RBS)	RBS2-A	0.630	0.855	0.367
	RBS2-B	0.463	0.570	0.179
	RBS2-C	0.567	0.788	0.313
	RBS2-D	0.484	0.783	0.270
		ARBS2		
Aged Rubber Biochar (ARBS)	ARBS2-A	0.482	0.770	0.277
	ARBS2-B	0.561	0.694	0.273
	ARBS2-C	0.642	0.904	0.413
	ARBS2-D	0.596	0.811	0.330

Subsamples highlighted in red represent strain energy readings that have been identified as outliers per Practice E178 and have been removed from the data set and not included in any analysis from this point forward.

Table 8. Semi-Circular Bend (SCB) Test Results across Samples with High Notch Depth

High Notch (38 mm)				
Sample	**Subsample**	**Peak Load (kN)**	**Displacement (mm)**	**Strain Energy U (J)**
		VNS3		
Virgin No Biochar (VNS)	VNS3-A	0.345	0.876	0.228
	VNS3-B	0.309	0.898	0.209
	VNS3-C	0.350	0.863	0.226
	VNS3-D	0.327	0.966	0.246
		AVNS3		
Aged Virgin No Biochar (AVNS)	AVNS3-A	0.137	0.700	0.079
	AVNS3-B	0.094	0.518	0.043
	AVNS3-C	0.070	0.345	0.022
	AVNS3-D	0.090	0.556	0.045
		VBS3		
Virgin Biochar (VBS)	VBS3-A	0.196	0.769	0.107
	VBS3-B	0.189	0.627	0.088
	VBS3-C	0.257	0.864	0.156
	VBS3-D	0.185	1.060	0.137
		AVBS3		
Aged Virgin Biochar (AVBS)	AVBS3-A	0.416	1.090	0.315
	AVBS3-B	0.366	0.947	0.251
	AVBS3-C	0.328	0.822	0.192
	AVBS3-D	0.250	0.681	0.126

High Notch (38 mm)				
Sample	**Subsample**	**Peak Load (kN)**	**Displacement (mm)**	**Strain Energy U (J)**
			RNS3	
Rubber No Biochar (RNS)	RNS3-A	0.542	0.851	0.348
	RNS3-B	0.437	0.544	0.171
	RNS3-C	0.546	0.626	0.244
	RNS3-D	0.623	0.753	0.336
			ARNS3	
Aged Rubber No Biochar (ARNS)	ARNS3-A	0.399	0.443	0.113
	ARNS3-B	0.418	0.576	0.173
	ARNS3-C	0.376	0.576	0.155
	ARNS3-D	0.640	0.618	0.259
			RBS3	
Rubber Biochar (RBS)	RBS3-A	0.498	0.687	0.232
	RBS3-B	0.517	0.836	0.294
	RBS3-C	0.443	0.726	0.241
	RBS3-D	0.440	0.565	0.181
			ARBS3	
Aged Rubber Biochar (ARBS)	ARBS3-A	0.454	0.635	0.218
	ARBS3-B	0.406	0.567	0.175
	ARBS3-C	0.539	0.678	0.268
	ARBS3-D	0.539	0.727	0.286

Note: Adding H or S after the mixture's name will refer to the test conducted on it: HWT or SCB respectively. For example, VNS refers to Virgin No Biochar used in Semi Circular Bending.

After calculating the strain energy (U) for all the samples, U was then plotted on a graph versus the notch depths. The standard calls for a total of four samples per notch depth to be tested and analyzed, bringing up the total of subsamples to 12 per material type. Hence, 12 specimens were analyzed and the strain energy (U) results calculated and plotted versus the notch depth.

A linear regression best-fit line was produced: see Figure 10. The slope of the linear line was determined and used to calculate the critical strain energy release rate (J_c) by dividing it by the average width of the sample thickness. The values for the average thickness and calculated J_c are shown in Table 9.

Table 9. Average Thickness and J_c Values for SCB Test Samples

Sample	Average Thickness (b)	Critical Strain Energy (kJ/)
VNS	57.48	0.582
AVNS	57.55	0.224
VBS	57.51	0.477
AVBS	57.51	0.217
RNS	57.57	0.407
ARNS	57.5	0.227
RBS	57.58	0.352
ARBS	57.41	0.317

Note: Adding S after the mixture's name will refers to the samples tested using the Semi-Circular Bend test.

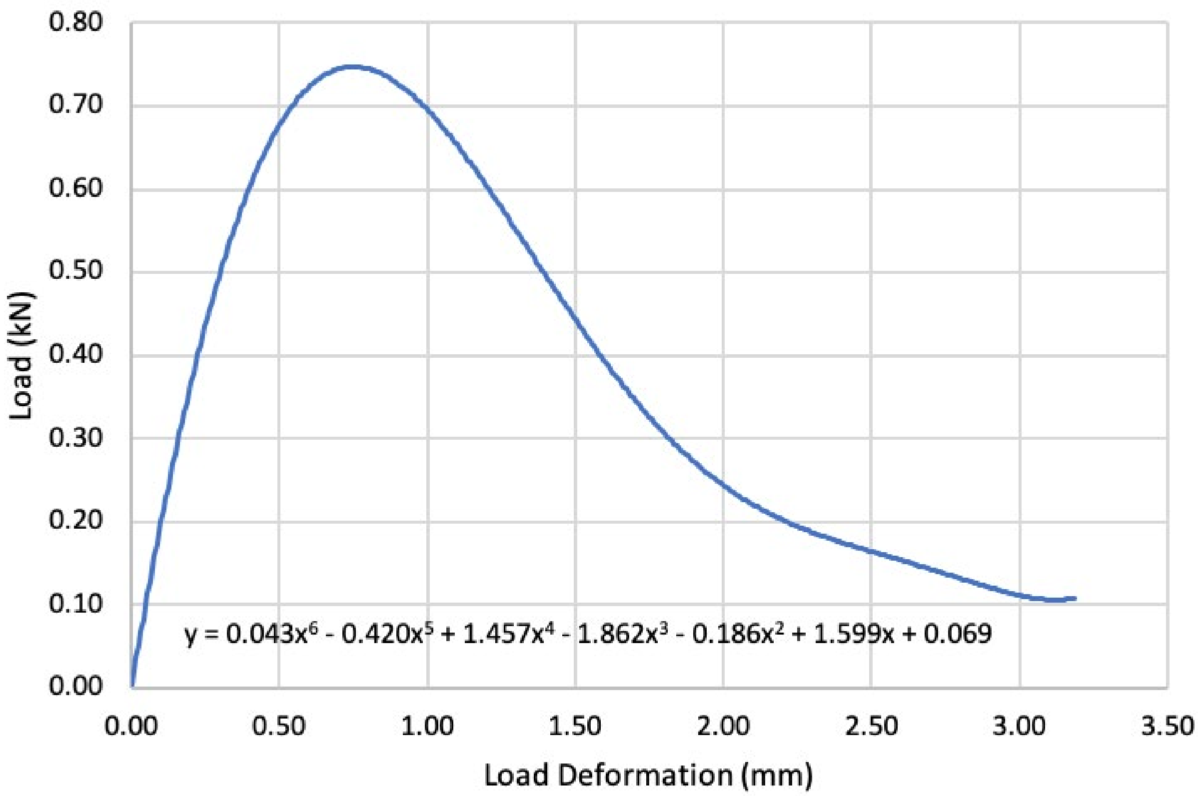


Figure 9. Load vs. Displacement Curve for ARBS1

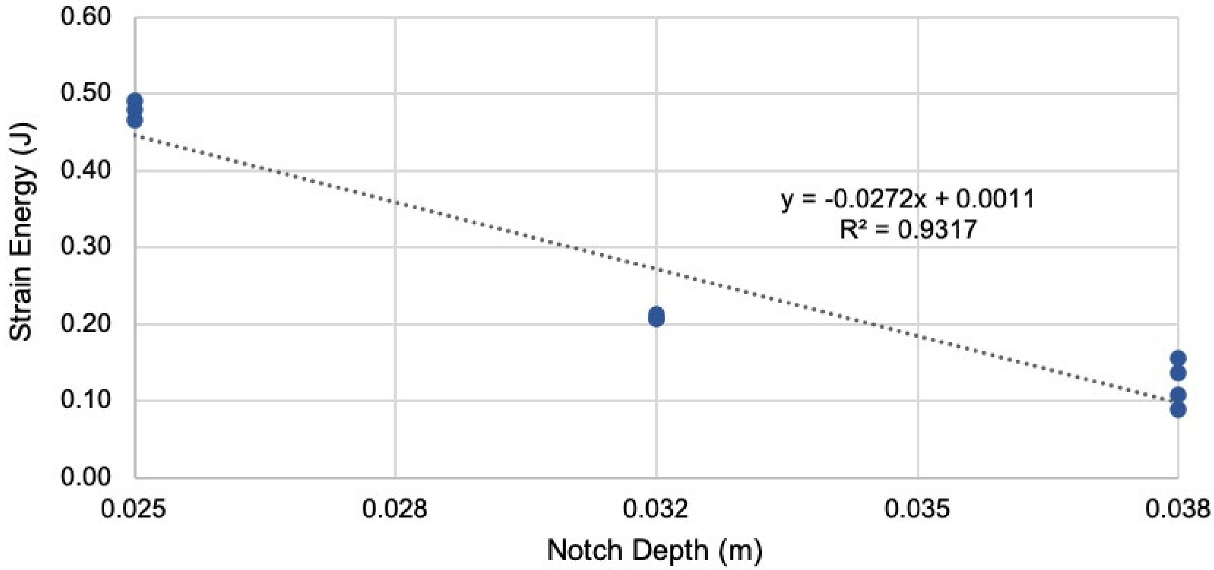


Figure 10. Stain Energy (U) (kJ) vs. Notch Depth for VBS Mix

STATISTICAL ANALYSIS FOR SCB SAMPLES

The strain energy data were inputted into Minitab to perform the statistical analysis. The analysis was conducted on each mixture and compared with the other mixtures that correlate with it using a t-test (for example, comparing the VNS mixture with the VBS mixture, since both are virgin and not aged with Biochar being added to VBS samples). Table 10 shows the P-value for the analysis results.

Table 10. Significant Levels Between Mixtures

Comparison	Low Notch	Med Notch	High Notch	Low Notch	Med Notch	High Notch	Mix 1	Mix 2
Mix_1 vs Mix_2	p-Value	p-Value	p-Value	U_1 vs U_2	U_1 vs U_2	U_1 vs U_2	J_{c1}	J_{c2}
					(J)		(kJ/m^2)	
VNS vs VBS	0.000	0.015	0.000	0.666 vs 0.479	0.345 vs 0.209	0.227 vs 0.122	0.582	0.478
AVBS vs AVNS	0.006	0.032	0.003	0.383 vs 0.216	0.277 vs 0.154	0.221 vs 0.047	0.217	0.224
RNS vs RBS	0.093	0.174	0.228	0.573 vs 0.505	0.334 vs 0.282	0.275 vs 0.237	0.408	0.353
ARBS vs ARNS	0.051	0.012	0.084	0.472 vs 0.342	0.323 vs 0.223	0.237 vs 0.175	0.317	0.228
VNS vs AVNS	0.000	0.002	0.000	0.666 vs 0.216	0.345 vs 0.154	0.227 vs 0.047	0.582	0.224
VBS vs AVBS	0.047	0.846	0.969	0.479 vs 0.383	0.209 vs 0.277	0.122 vs 0.221	0.478	0.217
RNS vs ARNS	0.002	0.008	0.051	0.573 vs 0.342	0.334 vs 0.223	0.275 vs 0.175	0.408	0.228
RBS vs ARBS	0.329	0.774	0.499	0.505 vs 0.472	0.282 vs 0.323	0.237 vs 0.237	0.353	0.318

Note: Adding S after the mixture's name will refers to the samples tested using the Semi-Circular Bend test. For example, VNS refers to Virgin No Biochar samples used in Semi Circular Bending.

The Effect of Biochar and Virgin Mix

When comparing VNS with VBS strain energy (*U*) in Figure 11, the VBS mixture had significantly lower *U* than the virgin mixture (VNS). However, after aging, the AVBS mixture had significantly higher *U* than AVNS mixture as seen in Table 10. Also, it was noticed that the reduction in *U* for the Biochar mixtures due to aging was not significant (VBS vs. AVBS) while the virgin mixture had a significant reduction after aging (VNS vs. AVNS). Adding Biochar evidently helped attain higher strain energy values after aging. In addition, the critical strain energy J_c was higher for VNS compared to VBS, but J_c was almost similar for AVBS compared to AVNS.

The Effect of Biochar and Rubber Mix

When comparing RNS and RBS mixtures in Figure 12 and Table 10, the RNS mixture had higher and insignificant *U* compared to the RBS mixture. However, after aging, the ARBS mixture had higher *U* compared to the ARNS mixture. Once again, the effect of adding Biochar helped attain higher strain energy values after aging for rubberized mixtures as well. In addition, the critical strain energy J_c was higher for RNS compared to RBS, but J_c was higher for ARBS compared to ARNS.

The Effect of Aging

When studying the effect of aging on the same mixture, comparing VNS to AVNS, VBS to AVBS, RNS to ARNS, and RBS to ARBS, all non-aged mixtures achieved higher critical strain energy J_c compared to aged mixtures. See Table 10. It can be observed, though, that for RBS compared to ARBS, the drop in J_c due to aging was smaller compared to other mixtures. It can be observed that after aging the rubberized mixtures had higher (in the case of Biochar) or similar (in the case of no Biochar) J_c compared to virgin mixtures. This finding might suggest that the addition of Biochar either helped or had no effect on the overall performance of rubberized mixtures.

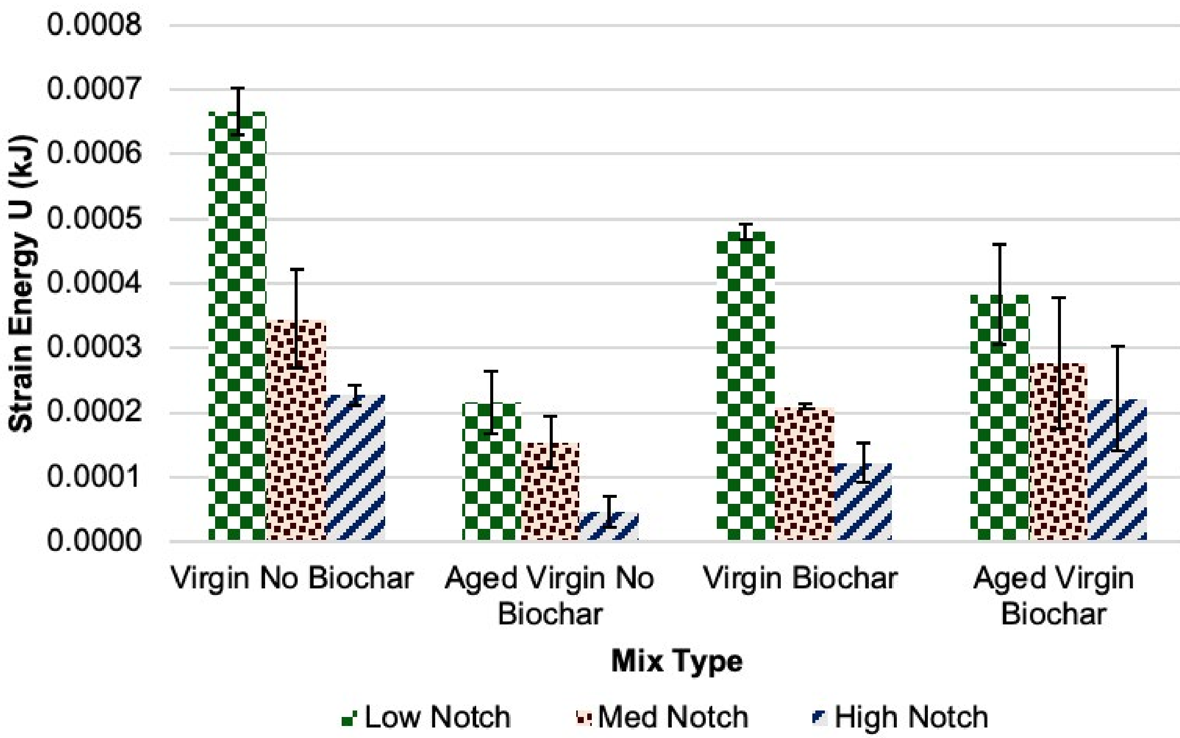


Figure 11. Strain Energy (U) across Virgin HMA Samples

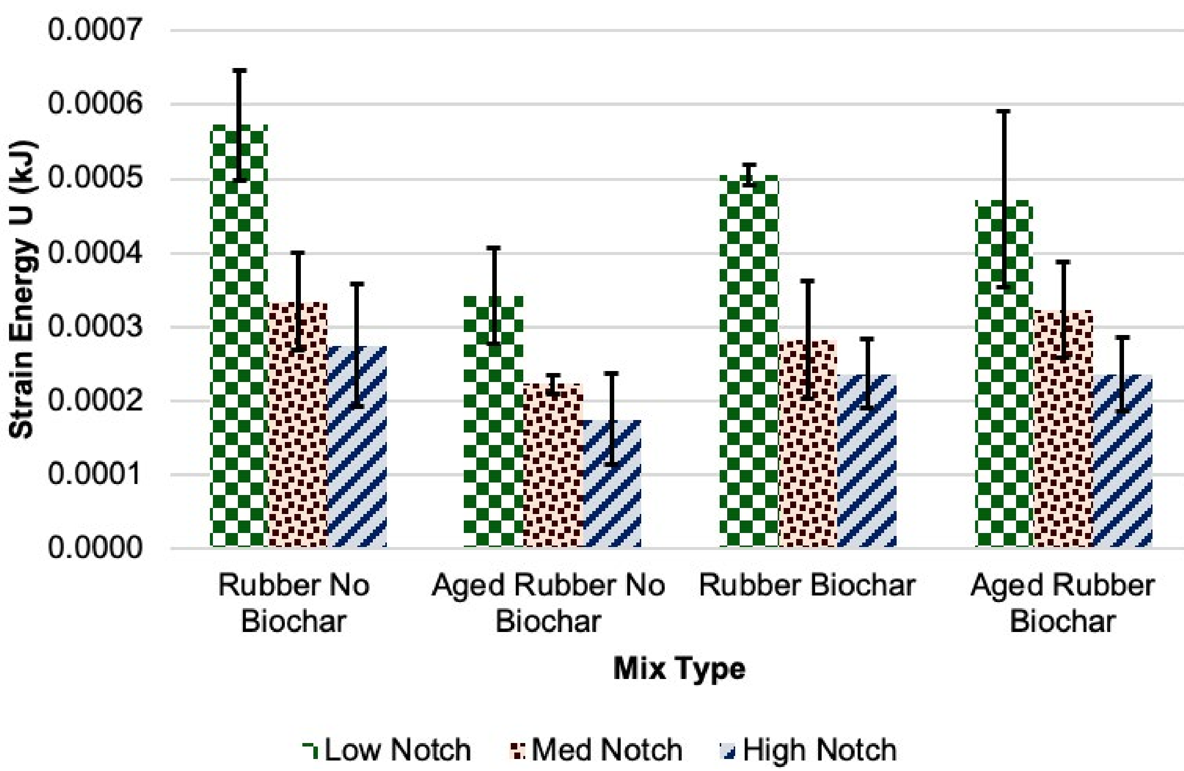


Figure 12. Strain Energy (U) across Rubber HMA Samples

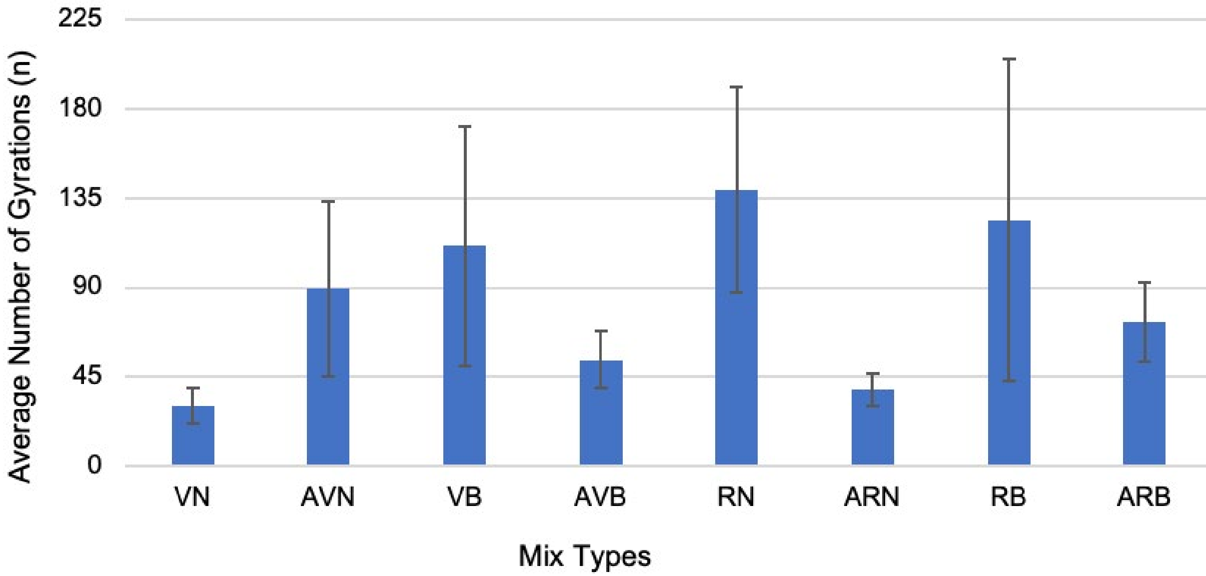


Figure 13. Average Number of Gyrations across Different Mix Designs

In order to study the effect of different parameters on workability, the number of gyrations required to achieve the same height was recorded as seen in Figure 13. The mixes that require a high number of gyrations have a lower workability score compared to the mixes that have lower numbers of gyrations. It can be noticed that all aged mixtures had lower number of gyrations compared to non-aged mixtures, except for AVN which was higher than VN. For the Biochar effect, VB had a higher number of gyrations compared to VN, but AVB had a lower number of gyrations compared to AVN. In addition, RB had a lower number of gyrations compared to RN; however, ARB had a higher number of gyrations compared to ARN. Thus, in this study, there was no specific trend that can be named based on the addition of Biochar on workability.

HAMBURG WHEEL ANALYSIS

The Hamburg Wheel Tracking test was conducted for two wheels; the data for the samples were recorded by the sensors installed in the HWT machine for the duration of each test. The data were extracted and the average rut depth at 20,000 passes measured; average rut depth is provided in Table 11.

Table 11. Hamburg Wheel Rut Depth Results

Mixture Type	VNH	VBH	AVNH	AVBH	RNH	RBH	ARNH	ARBH
				Rut depth, mm				
Left	-3.117	-2.931	-2.020	-2.856	-0.830	-1.254	-1.128	-1.482
Right	-2.394	-1.998	-2.076	-1.888	-1.937	-0.871	-0.939	-1.223
Average	**-2.756**	**-2.465**	**-2.048**	**-2.372**	**-1.384**	**-1.062**	**-1.034**	**-1.353**

Note: Adding H after the mixture's name will refer to the samples tested using HWT. For example, VNH refers to Virgin No Biochar samples used in Hamburg Wheel Tracking (HWT).

According to Caltrans standards, HWT samples would fail if they achieved a rut depth of 12.5 mm or more during 20,000 passes. In the results found here, none of the samples exceeded a four mm rut depth, and therefore the comparison will be conducted on the rut depth achieved at 20,000 passes rather than the number of passes required to achieve failure.

When comparing the virgin mixtures as seen in Figure 14, it was noticed that VBH samples had lower rut depth when compared with VNH, whereas after aging AVBH had higher rut depth than AVNH. It was also noticed that VBH had similar rut depth to AVBH, but VNH had higher rut depth compared to AVNH. The results suggest that the addition of Biochar reduced the rutting/moisture susceptibility of the virgin mix.

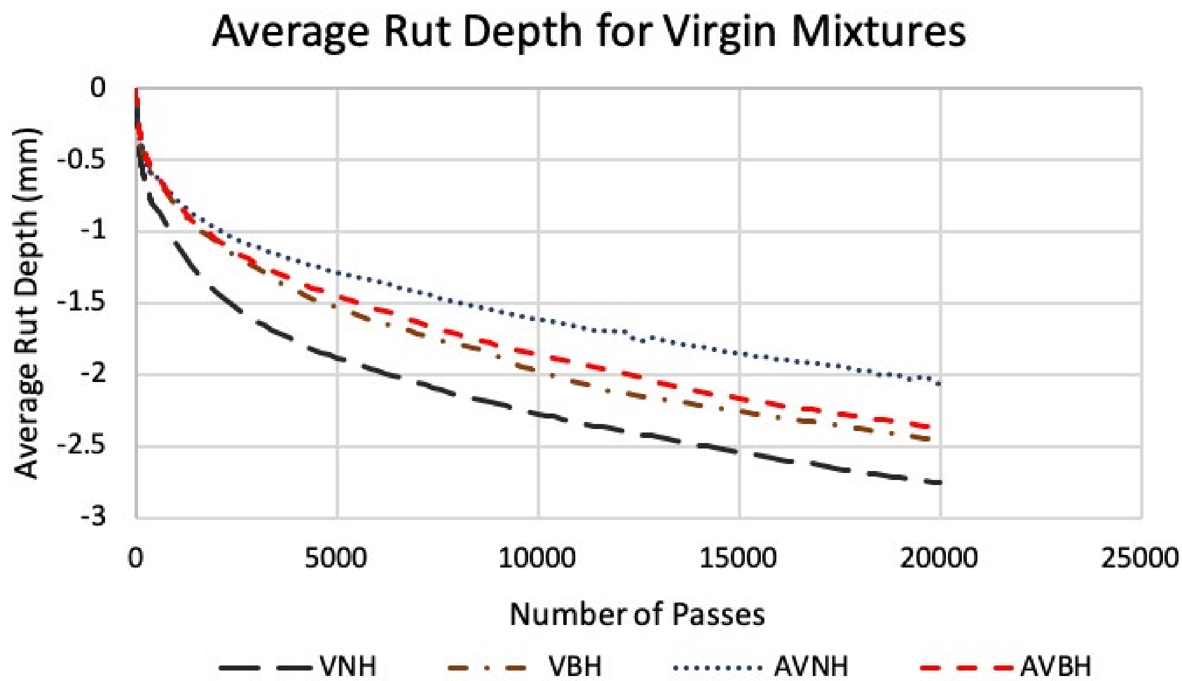


Figure 14. Average Rut Depth for Virgin Mixtures

Another comparison conducted within rubber mixtures (Figure 15) showed that RBH had lower rut depth than RNH before aging. However, ARNH had lower rut depth compared to ARBH after aging.

When comparing non-aged mixtures (Figure 16), it was noticed that RBH had the lowest rut depth while VNH had the highest rut depth. Also, mixtures that had Biochar (VBH and RBH) had lower rut depth compared to their equivalents that did not have Biochar (VNH and RNH). It can be seen that the addition of Biochar helped achieve lower rut depth for mixtures before aging.

Finally, when comparing aged mixtures (Figure 17), it was noticed that AVBH had the highest rut depth, while ARNH had the lowest rut depth. Additionally, it was noticed that both aged mixtures lacking Biochar (AVNH and ARNH) had lower rut depth than their equivalents that had Biochar (AVBH and ARBH). This observation suggests that the Biochar effect reduced the effect of aging (hardening), resulting in a higher rut depth compared to aged non-Biochar aged mixtures.

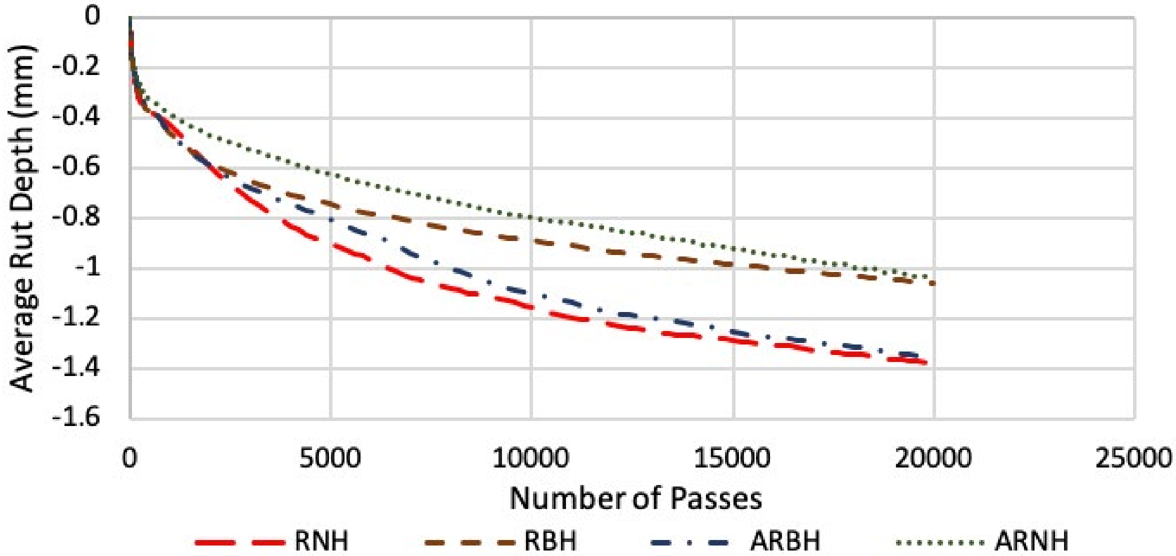


Figure 15. Average Rut Depth for Rubber Mixtures

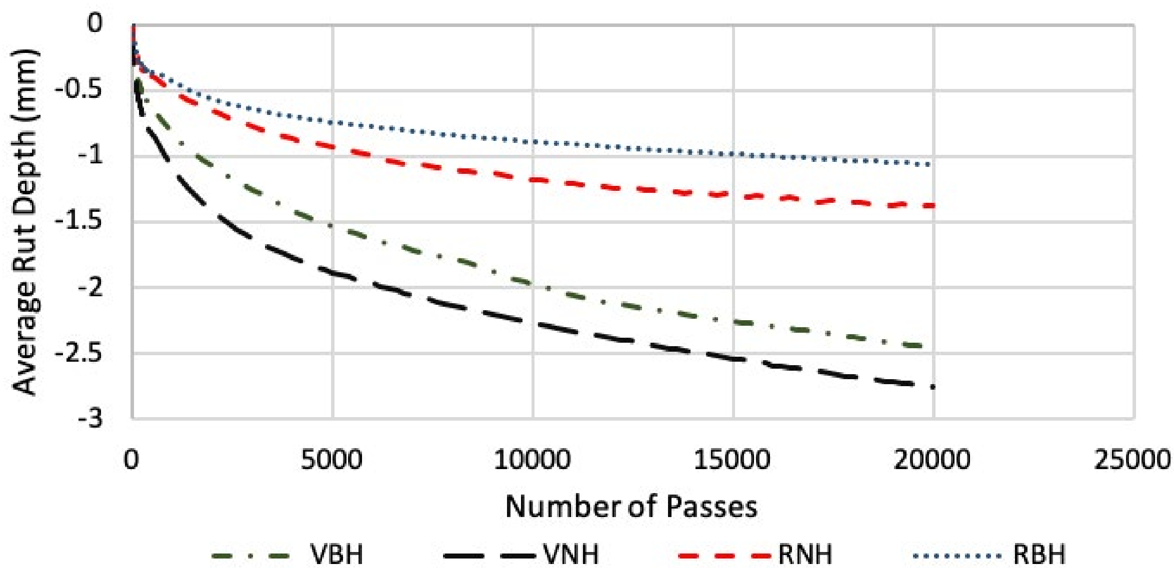


Figure 16. Average Rut Depth for Non-Aged Mixtures

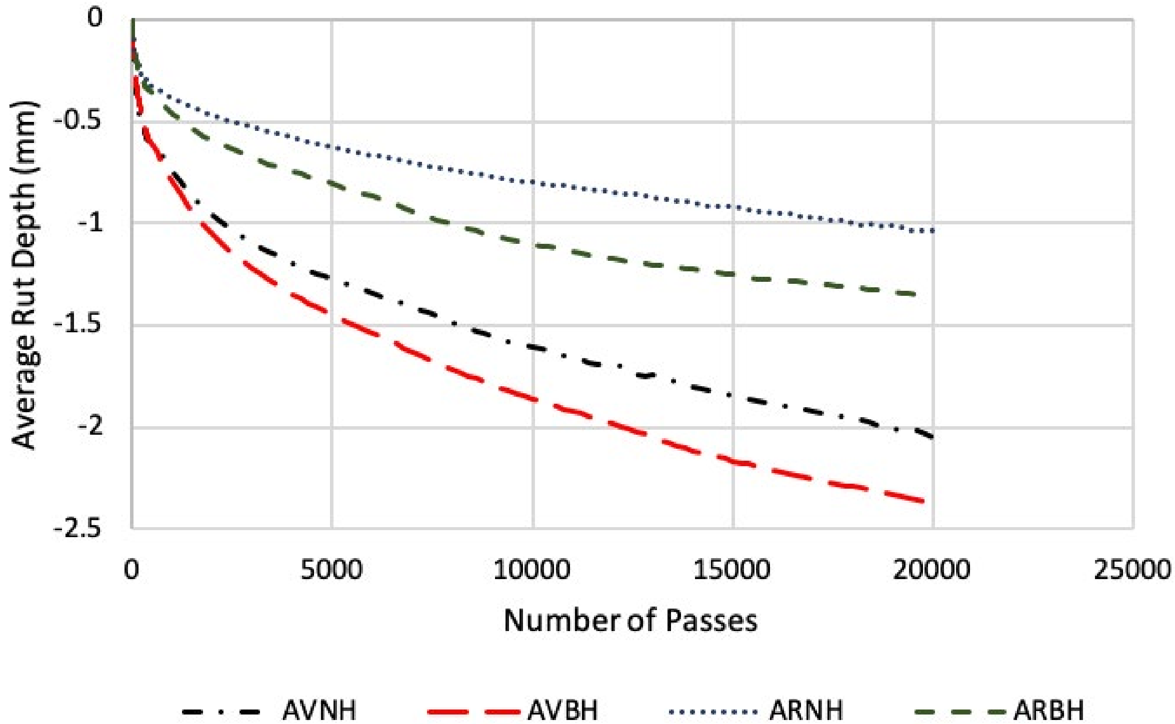


Figure 17. Average Rut Depth for Aged Mixtures

COLOR DEGRADATION

Color analysis was performed at a third-party testing lab, Q-Lab, for weathering research services. The test performed measured instrumental color measurements following standard ASTM G155. This practice covers the basic principles and operating procedures for using xenon arc light and water apparatus intended to reproduce the weathering effects that occur when materials are exposed to sunlight (either direct or through window glass) and moisture (as rain or dew) in actual use. This practice is limited to the procedures for obtaining, measuring, and controlling conditions of exposure.

Specimens are exposed to repetitive cycles of light and moisture under controlled environmental conditions. The use of this apparatus is intended to induce property changes associated with the end use conditions, including the effects of sunlight, moisture, and heat. These exposures may include a means to introduce moisture to the test specimen. Exposures are not intended to simulate the deterioration caused by localized weather phenomena, such as atmospheric pollution, biological attack, and saltwater exposure. Alternatively, the exposure may simulate the effects of sunlight through window glass. Typically, these exposures would include moisture in the form of humidity.

Instrumental color is considered the most complicated of all electro-optical measurements. Color measurements are made by shining a light on the specimen and collecting the light that is reflected from the specimen. The reflected light's wavelength is measured and used to calculate numbers that are then used as a shorthand to describe the color of the measured object. This instrumental color reading uses the L*, a*, and b* color calculation model to define the color. In this system, three numbers are used to describe a color. Each of the three numbers refers to one of the three color coordinates. The three numbers represent three factors: lightness factor (L*), Red/Green factor (a*), and Blue/Yellow factor (b*).

L* measures the lightness or darkness of the specimen with 0, 50, and 100 meaning black, gray, and white, respectively. The red/green waves are measured by ‘a*’: a positive a*-value represents a redder object, whereas a negative number represents a greener object. An a*-value of zero represents samples in the middle. The b*-value represents the object’s yellowness or blueness. The more positive a number, the yellower it is, while a more negative value indicates a bluer sample. A value of zero indicates it would be intermediate between yellow or blue.

Color change is calculated as the difference in the L*, a*, and b* values before and after exposure. The larger the value, the larger the color change.

Table 12. Xenon Arc Aging Color Changes Data

Hours	0	500	1000	0	500	1000	0	500	1000
		L*			a*			b*	
Control Mixture	22.83	20.3	23.62	0.73	0.25	-0.18	1.69	1.15	1.94
Biochar Mixture	23.51	20.67	21.94	0.51	0.48	-0.37	0.7	1.01	0.67

Samples were subjected to 1000 hours of weathering simulation using the Xenon Arc test.

Figure 18 present the change in L* for the control and Biochar mixtures. It can be seen that L* decreased at 500 hours and then increased at 1000 hours for both mixtures. However, for the Biochar mixture, the L* was less than the initial value at 0 hours. This finding indicated a darker Biochar mixture after exposure compared to the control mixture.

Figure 19 presents the change in a* for the control and Biochar mixtures. Both mixtures had lower a* with exposure (greener or less red).

Figure 20 presents the change in b* for the control and Biochar mixtures. It can be seen that control mixture had increased b* (more yellow) while the Biochar mixture had similar or slightly decreased b* (more blue) after 1000 hours of exposure.

Overall, the addition of Biochar seems to have helped decrease the color degradation of the asphalt mixture compared to the control mixture.

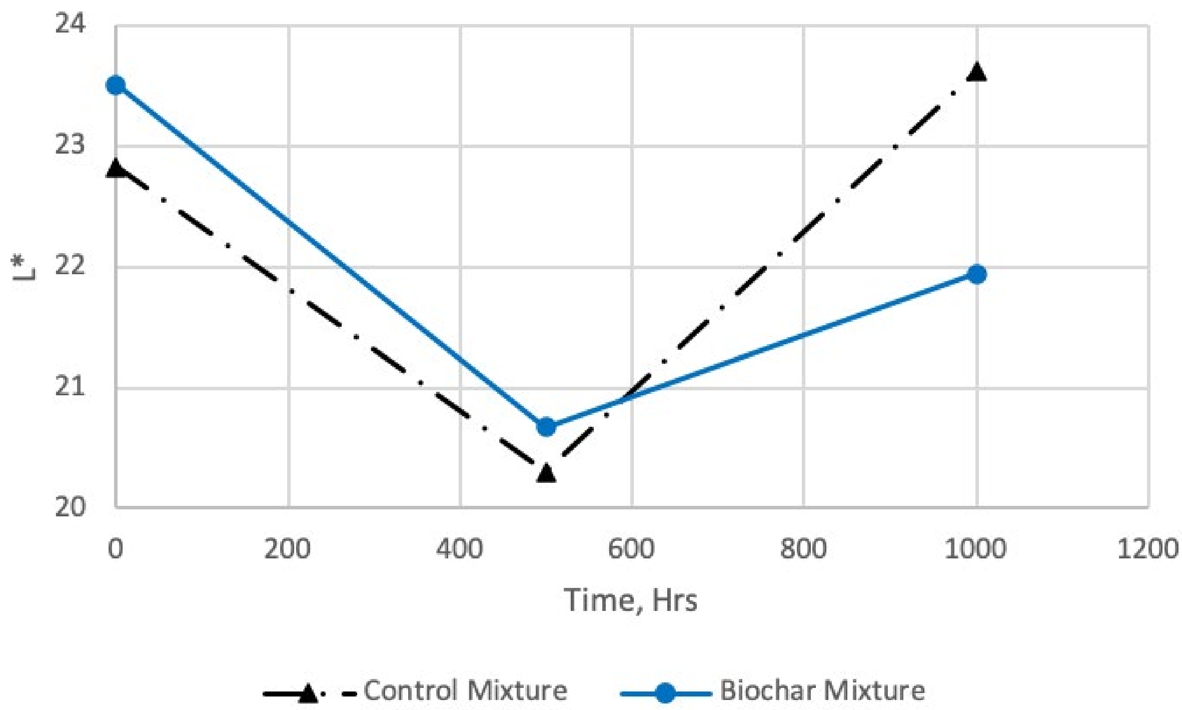


Figure 18. Change in L* During the Test Time

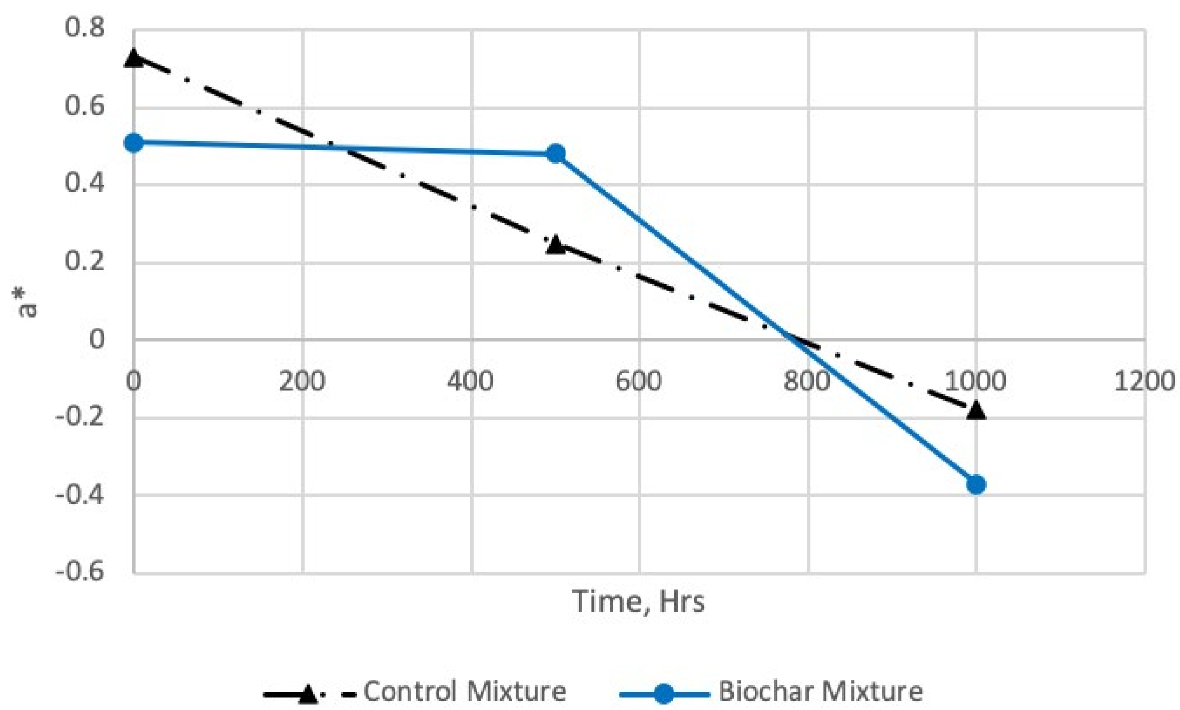


Figure 19. Change in a* During the Test Time

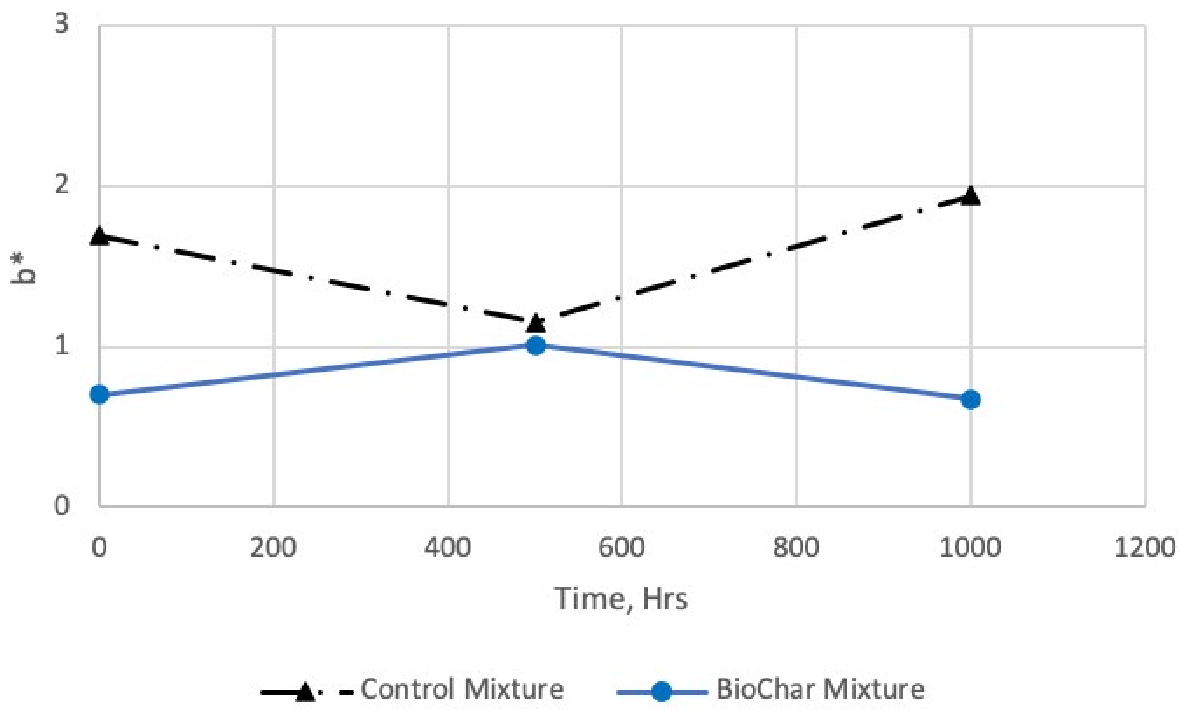


Figure 20. Change in b* During the Test Time

VIII. CONCLUSION

In this study, the mechanical properties of asphalt mixtures containing Biochar were investigated. In addition, the color degradation was also investigated. The Semi-Circular Bending (SCB) test proved to be a suitable test method to analyze the fracture properties of asphalt mixtures. Similarly, the Hamburg Wheel Test (HWT) has been proven efficient in testing and analyzing the rutting and moisture susceptibility of asphalt mixtures. This study used the SCB and HWT tests to investigate the mechanical properties of asphalt mixtures containing Biochar. The study incorporated conventional (virgin) and rubberized mixtures and investigated the effect of aging as well.

For virgin mixtures, the effect of adding Biochar evidently helped attain higher strain energy values after aging. In addition, the critical strain energy J_c was higher for Virgin No Biochar SCB sample (VNS) compared to Virgin Biochar SCB samples (VBS). However, J_c was almost similar for Aged Virgin Biochar SCB samples (AVBS) compared to Aged Virgin No Biochar SCB samples (AVNS). Indicating that for the virgin HMA mixes, Biochar decreased the fracture resistance of the mixture but helped maintain the fracture resistance after aging.

For rubberized mixtures, the effect of adding Biochar evidently helped attain higher strain energy values after aging. In addition, the critical strain energy J_c, was higher for (Rubber No Biochar SCB samples) RNS compared to (Rubber Biochar SCB samples) RBS, but J_c was higher for ARBS compared to ARNS.Indicating that for RHMA mixes, Biochar decreased the fracture resistance of the mixtures but had higher fracture resistance after aging.

All non-aged mixtures achieved higher critical strain energy J_c compared to aged mixtures

Mixtures with Biochar before aging had higher rut resistance compared to no-Biochar mixtures. However, after aging, non-Biochar mixtures had higher rut resistance compared to Biochar mixtures. This change indicates that Biochar increased the asphalt binder resistance to aging (less hardening).

When subjected to UV aging overall, the addition of Biochar was found to decrease the color degradation of the asphalt mixture compared to control mixture.

IX. LIMITATIONS AND FUTURE WORK

The results of this study are limited to the materials tested. The authors acknowledge that more extensive testing is required to draw more conclusive results.

The following suggestions can be tested:

Introducing different percentages of Biochar may have different effects on the mechanical and rheological properties of HMA. The results from experimenting with different percentage of Biochar might help in exploring new information about the optimum percentage of Biochar in HMA.

It could provide new information if the Biochar is mixed with different grade and types of binders in HMA samples. The test results from those samples could be compared to the results given by this research which may leads to new findings.

ABBREVIATIONS AND ACRONYMS

ARBH	Aged Rubber Biochar HWT Sample
ARNH	Aged Rubber No Biochar HWT Sample
AVBH	Aged Virgin Biochar HWT Sample
AVNH	Aged Virgin No Biochar HWT Sample
ARBS	Aged Rubber Biochar SCB Sample
ARNS	Aged Rubber No Biochar SCB Sample
AVBS	Aged Virgin Biochar SCB Sample
AVNS	Aged Virgin No Biochar SCB Sample
BC	Biochar
FEM	Finite Element Method
HMA	Hot Mix Asphalt
HTL	Hydrothermal liquefaction
HWT	Hamburg Wheel Test
J_c	Critical Strain Value
NMAS	Nominal Maximum Aggregate Size
PG	Performance Grade
RBS	Rubber Biochar SCB Sample
RBH	Rubber Biochar HWT Sample
RHMA	Rubberized Hot Mix Asphalt
RNS	Rubber No Biochar SCB Sample
HWT	Rubber No Biochar HWT Sample
SCB	Semi Circular Bend
SIP	Stripping Inflection Point
USDA	United States Department of Agriculture
UV	Ultraviolet
VBS	Virgin Biochar SCB Sample
VBH	Virgin Biochar HWT Sample
VNS	Virgin No Biochar SCB Sample
VNH	Virgin No Biochar HWT Sample
WMA	Warm Mix Asphalt

ENDNOTES

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PEER REVIEW

San José State University, of the California State University system, and the Mineta Transportation Institute (MTI) Board of Trustees have agreed upon a peer review process required for all research published by MTI. The purpose of the review process is to ensure that the results presented are based upon a professionally acceptable research protocol.