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Use of Polymer Fiber to Improve Mechanical Properties of HMA Containing Recycled Asphalt Pavement (RAP)

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California State University Transportation Consortium

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16. Abstract
A great percentage of highways and roads in California are constructed with Hot Mix Asphalt (HMA), and, as California infrastructure ages, these highways and roads must be maintained and rehabilitated. Reclaimed Asphalt Pavement (RAP) is considered an excellent alternative to virgin (raw, unprocessed) materials because it reduces the use of virgin aggregate and binder. Also, the use of RAP decreases the amount of construction waste placed into landfills. This laboratory study investigated the effect of two different commercial polymer fibers on the mechanical properties of HMA with RAP. Three different HMA with RAP mixes were used in the study. One mix that is commonly utilized on the Central Coast contained 15% RAP while the second and third mixes contained 25% and 40% RAP, respectively. Three different fiber dosages (0.05%, 0.10%, and 0.15% of the total mix) were investigated. Specimens were prepared and tested for rutting and moisture sensitivity in a Hamburg Wheel Tracker (HWT) and for Cracking Tolerance Index (CTI). Test results showed that adding fibers improved resistance to rutting for mixes with RAP content higher than 25%. The use of fiber improved resistance to cracking at intermediate temperatures for all mixes with RAP contents. Also, adding fibers improved mixes' resistance to moisture damage. In addition, one of the two fibers used in the study outperformed the other. Overall, results indicate that adding polymer fibers to HMA mixes containing RAP has the potential to improve mixes' resistance to rutting, moisture damage and cracking, depending on fiber dosage and type. This study offers information valuable to the maintenance and rehabilitation of roads and highways in California and beyond.

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Executive Summary

A great percentage of highways and roads in California are constructed with Hot Mix Asphalt (HMA), and, as California's infrastructure ages, these highways and roads must be maintained and rehabilitated. Recycling of aggregates and other highway construction materials makes sound economic, environmental, and engineering sense. Reclaimed Asphalt Pavements, also known as Recycled Asphalt Pavement (RAP), is considered an excellent alternative to virgin materials. The use of RAP decreases the amount of construction waste placed into landfills and does not deplete non-renewable natural resources such as virgin aggregate. In addition, energy savings can be realized through the use of RAP in roadway construction by reducing the processing and hauling of virgin aggregate materials. However, the performance of HMA containing RAP depends on the percentage of RAP incorporated in the mix. This laboratory study was conducted to investigate the use of commercial polymer fiber in improving the mechanical properties of HMA with RAP percentages ranging between 15% and 40%.

Three Job Mix Formulas (JMF) were provided by two construction companies, namely CalPortland and Granit Construction. The first mix provided by CalPortland utilized 15% of RAP, and PG 64-10 binder grade is commonly used in projects on the Central Coast of California. The second and third mixes provided by Granite Construction utilized 25% and 40% RAP content, respectively and PG 58-22 binder grade and is commonly used for projects in the Bay Area.

Two polymer fibers that were recently used in a Caltrans maintenance project on State Route (SR) 1 were investigated in this study. These two fibers are named fiber A (wax-coated) and fiber B (not coated). Important properties and performance tests were conducted on the aggregate used in the asphalt mix design. The data provided by the two companies included tests performed on aggregate and asphalt binder. Tests on aggregate included bulk and apparent specific gravities as well as performance tests for durability, angularity, and clay content. The asphalt binder was tested in its virgin and aged states using the dynamic shear rheometer (DSR) test. This laboratory study tested the HMA mixes for maximum theoretical density, resistance to rutting and moisture damage using Hamburg Wheel Tracker (HWT), and the Cracking Tolerance Index (CTI).

Results from the HWT showed that the two fibers performed significantly differently. In general, fiber type B (treated with liquid emulsion) outperformed fiber type A (wax-coated) in enhancing HMA resistance to rutting. For mixes with 15% RAP, adding fibers (regardless of the type) did not seem to improve resistance to rutting as compared with the control mix. However, when increasing RAP content to 25% and 40%, fiber type B enhanced the mixture's resistance to rutting. For mixes with high RAP content (40%), fiber type B significantly improved the mixture's resistance to rutting. Both types of fibers (A and B) enhanced the mixtures' resistance to stripping, with the number of passes at the stripping inflection point higher than those for the control mix. For mixes with 15% RAP, the addition of fiber at high dosages (0.10% and 0.15%) improved the mixture's resistance to cracking compared to the control mix. The control mix with 25% RAP had the lowest CTindex, but fiber additions significantly improved performance, especially with fiber B

at 0.15%, indicating a strong response to both fiber type and dosage. For mixes with high RAP content (40%), resistance to cracking further improved with the addition of fiber B to the mix, particularly at 0.10% and 0.15% dosages.

1. Introduction

The use of Reclaimed Asphalt Pavement (RAP; also known as Recycled Asphalt Pavement) in Hot Mix Asphalt (HMA) is receiving growing interest from the public sector because of the environmental and economic benefits. This is due to the need to enhance the environmental friendliness and sustainability of road construction. In the following sections, a review of the literature concerning the history of RAP and its current practices in the United States (US), including the State of California, is discussed.

1.1 History of RAP in the US

The importance of the use of RAP dates to the 1970s when the Arab oil embargo caused a surge in crude oil prices. In response, the Federal Highway Administration (FHWA) partially funded Demonstration Project 39 to explore and document the use of RAP in pavements. Over the following two decades, the National Cooperative Highway Research Program (NCHRP) and FHWA released guidelines and recommendations to promote the effective use of RAP in asphalt pavements (Copeland, 2011). The guideline for the design of Superpave HMA containing RAP was developed in 1997 by the FHWA's RAP expert task group (FHWA, 2019). The NCHRP and state Departments of Transportation (DOTs) continued to fund research from the late 1990s through the early 2010s. This research enabled the industry to better understand how to effectively incorporate RAP into asphalt mixtures. The use of RAP is increasing drastically over the years. In 2021, the total estimated amount of RAP used in asphalt mixtures in the US reached 94.6 million tons, reflecting a 68.9 percent increase compared to 2009. Over this period, the overall tonnage of asphalt mixtures increased by only 20.6 percent (Williams et al., 2024).

It was reported that cost savings in 2017 totaled approximately $2.2 billion with RAP replacing virgin materials (NCHRP Report 927). However, the FHWA states three key conditions for the successful use of RAP: cost-effectiveness, environment friendliness, and performance.

1.2 History of RAP in California

Caltrans supports and encourages the use of recycled material RAP in its pavements to promote sustainability, save energy, and decrease greenhouse gas emissions. Starting in 2009, Caltrans allowed contractors to substitute RAP aggregate as part of the virgin aggregate in HMA in a quantity not exceeding 15 percent of the aggregate blend by weight. In 2012, the signed Assembly Bill 812 allowed Caltrans to establish specifications for the use of RAP of up to 40 percent for hot mix asphalt mixes. However, in 2014, the FHWA issued a memorandum noting an increasing number of state highway agencies (not including Caltrans) reporting premature cracking in relatively new asphalt pavements as a result of using a high content of recycled asphalt binder from RAP. The FHWA considers anything over 15 percent binder replacement as a high content of recycled asphalt binder. In 2013, Caltrans allowed up to 25 percent RAP aggregate in aggregate blends in HMA mixes, and, in 2018, Caltrans modified the current specification and implemented a non-standard Special Provision (nSSP) allowing up to 25 percent aggregate in the aggregate blend in HMA without the use of blending charts. In 2019, Caltrans formed a task force to revise Caltrans Standard Specification (Section 39) to allow up to 40% RAP in HMA. While standard specifications previously allowed up to 25% RAP, Caltrans has been developing and testing non-standard specifications and pilot projects to increase RAP usage to 40%.

1.3 Proportions of RAP in HMA in the US and CA

According to NCHRP Report 452, one of the main issues to be considered when using RAP is the variability of the material. Base, intermediate, and surface courses from the original pavement may all be combined in the RAP. It may include patches, chip seals, and other maintenance treatments that were used in the old pavement. Due to these variability issues, some states limit the amount of RAP that can be included in new mixtures. However, higher percentages of RAP are permitted in some states if the material is milled from the same project where the new mix will be applied (McDaniel et al., 2000). In 2019, the average RAP proportion in asphalt pavement in the US was about 21% (Williams et. al., 2020). Based on the responses received from producers in each state for the 12th Annual Asphalt Pavement Industry Survey, the estimated average percentage of RAP used in 2021 was between 20% and 29% in 28 states, between 15% and 19% in 13 states, and between 10% and 13% in 3 states. Notably, the number of states where producers reported average RAP percentages of 30% or greater included Florida, Georgia, North Carolina, and Virginia. In contrast, the average RAP content reported by agencies in California was 18% in 2017. This figure remained consistent at 16% for both 2018 and 2019, decreased to 15% in 2020, and then increased to 17% in 2021 (Williams et al., 2022).

1.4 Advantages and Disadvantages of RAP

The use of RAP in hot mix asphalt offers several benefits, such as the reduction of construction costs, the conservation of construction materials such as aggregate and binders, the preservation of existing pavement geometries, the reduction of the volume of waste material going into landfills, and the conservation of energy (Hossain et al., 2012). According to the 12th Annual Asphalt Pavement Industry Survey by National Asphalt Pavement Association (NAPA), net reduction of GHG emissions from use of RAP in new asphalt mixtures has increased from 1.5 Million Metric Tons of Carbon Dioxide Equivalent (MMT CO2e) in 2009 to 2.6 MMT CO2e in 2021—equivalent to the annual emissions from approximately 574,000 passenger vehicles (Williams et al., 2022).

Alongside environmental benefits, RAP also presents several drawbacks. High RAP content can stiffen the mix and make the mix brittle as it contains aged binder, potentially leading to low-temperature cracking. Pavements experiencing high deflections could be prone to premature cracking, affecting overall durability. Again, blending RAP with virgin binder can lead to concerns about the quality of the resulting binder. Especially in high RAP mixes with polymer-modified binders, there is a risk that the blended binder may not perform as expected. To determine the appropriate virgin binder grade for high RAP mixtures, blending charts are commonly used.

However, these charts require expensive and time-consuming binder extraction and recovery procedures, often involving hazardous solvents. Many contractors lack the equipment and expertise to perform binder extractions, recoveries, and subsequent tests. This limitation can hinder the widespread adoption of high RAP content in HMA (Copeland, 2011).

1.5 RAP Material Characterization

The quality of RAP materials depends on the milling machine used, including its speed and milling depth. Material from a single pavement layer tends to have homogeneous properties, including aggregate type, gradation, binder characteristics, and content. RAP contains fine particles that result from milling and crushing operations during pavement removal, which leads to RAP with a moisture content higher than virgin aggregates, impacting both production rates and drying costs. Also, key issues with RAP stockpiles include segregation, consolidation, and moisture retention. Therefore, proper stockpiling of RAP is crucial (Tarsi et al., 2020).

Sampling is an important step to characterize RAP aggregates. The specimens should be taken from each stockpile involved in the new asphalt mixture production. RAP materials undergo essential characterization to ensure their suitability for asphalt mix production. This process involves assessing three critical factors: aggregate gradation, binder content, and retained moisture (Tarsi et al., 2020). The bulk specific gravity of the RAP aggregate is another critical property for material characterization. For high RAP contents, RAP binder properties are also important to characterize. When considering the use of RAP in a surface mix for high-speed traffic, certain agencies may request additional tests. These tests aim to assess either the polishing characteristics or the mineralogical composition of the RAP aggregate. Two methods are suggested for determining RAP binder content and for recovering aggregates: the ignition method in accordance with AASHTO T 308 or ASTM D6307 and solvent extractions with trichloroethylene or other solvents (West, 2015).

1.6 Laboratory Preparation and Tests of HMA with RAP

One of the various proposed methods to increase the use of RAP is RAP fractionation, which screens a RAP stockpile into at least two sizes—fine and coarse—to improve the consistency of RAP particle sizes and binder content (Rizk et al. 2023). The RAP particle size can have a more significant impact on the mix performance than the RAP content (Saliani et al., 2019). In 2021, asphalt mixture producers from 31 states reported using fractionated RAP (Williams et al., 2022).

Selection of an appropriate binder grade for asphalt mixtures containing high RAP is another important factor. Typically, a softer virgin binder is supposed to balance the aged, stiffer binder in the RAP materials (Hossain et. al., 2012). When RAP content is less than 15%, the same binder grade is maintained. When RAP content is between 15% to 25%, both high- and low-temperature grades are to be reduced by one grade. When RAP content is greater than 25%, blending charts must be used (Willis et. al., 2013). The degree of blending between RAP and virgin binders can affect the overall properties of the asphalt mixture and long-term pavement service life.

Substantial studies have been dedicated to quantifying and qualifying the degree of blending. Bowers et al. (2014) proposed a new approach using Fourier Transform Infrared Spectroscopy (FTIR) to evaluate the blending efficiency of plant-produced recycled asphalt mixtures when virgin and RAP aggregates cannot be separated. Three mixes with 50% RAP content were used to validate this method: one warm mix and two hot mixes. One of the hot mixes included a rejuvenator. Results indicated that among the three mixtures, the warm mix exhibited the highest blending efficiency, while adding a rejuvenator had a limited effect. The proposed method was further verified using Gel Permeation Chromatography (GPC). Abdalfattah et al. (2021) used Titanium oxide (TiO2) nanoparticles as a virgin binder tracer and quantified the degree of blending using Energy Dispersive X-Ray Spectroscopy (EDX) analyses. Results showed a reduction in the average degree of blending with increasing RAP content and increasing RAP binder PG. Forty percent RAP content mixtures resulted in poor and nonhomogeneous blending compared to 15% and 25% RAP content. Moreover, the RAP binder with a lower PG showed an improved blending efficiency than one with a higher PG.

It is important to assess the performance of asphalt mixtures containing RAP, particularly those with high RAP content. Various performance tests are available for this purpose. These tests evaluate potential distress mechanisms such as permanent deformation (rutting), moisture sensitivity, fatigue resistance, and thermal cracking. Permanent deformation, or rutting, is evaluated using the Asphalt Pavement Analyzer or the Hamburg Wheel Tracking Device. The moisture sensitivity of mixtures is assessed through the Tensile Strength Ratio test and wet testing with the Hamburg Wheel Tracking Device. Fatigue resistance is determined using the Four-Point Bending Beam Fixture and dynamic modulus testing (Copeland, 2011). To evaluate cracking resistance, IDEAL CT, Overlay, or Semi-Circular Bending (SCB) tests are typically used. For index-based Performance Engineered Mixture Design (PEMD), which is similar to Balanced Mix Design (BMD), balancing asphalt pavement rutting resistance with durability and cracking resistance is needed to optimize the overall pavement performance (Hajj et al. 2019).

1.7 Performance of HMA Containing High RAP Content (Lab and Field Studies)

A RAP content of 25% or more is considered a high RAP mix, and designing HMA with high RAP content requires detailed evaluations (Saliani et al., 2019). High percentages of RAP may be suitable for areas with high temperatures, but it is not recommended in low temperatures due to the stiffening of the RAP binder (Pradhan et al., 2023). RAP can improve the rutting performance of the asphalt mixture but can reduce the cracking resistance (Saha et al., 2017). Pradhan et al. (2023) evaluated the mechanical properties of natural aggregate blended with 0%, 10%, 20%, and 30% RAP. The indirect tensile strength (ITS) for HMA gradually increased with an increase in RAP percentage due to the stiffness of the aged binder present in RAP. Twenty percent RAP exhibited the highest tensile strength ratio (TSR), although every mixture passed the minimum limiting TSR of 80%. The Marshall stability value increased up to the 20% RAP mix, and then it showed a decreasing trend.

Moreover, Abdalfattah et al. (2021) produced HMA with RAPs from three different sources and RAP contents of 15%, 25%, and 40% by weight of the mixture, totaling 9 different mixtures, and compared their performance with the control mix. The intermediate and low temperature cracking resistances of the mixtures were evaluated using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) and Thermal Stress Restrained Specimen Test (TSRST), respectively. Both cracking resistances gradually decreased with increasing RAP content, irrespective of the RAP source. Mogawer et al. (2012) reported that with increasing RAP content from 0% to 40%, the cracking resistance decreased; however, rutting and moisture damage resistance increased for plant-produced RAP mixtures.

RAP fractionation is recommended when using high RAP content. Rizk et al. (2023) compared the rutting and cracking resistance of HMA among three types of mixes: virgin mix, 10% unfractionated RAP mix, and 30% fractionated coarse RAP mix. The results showed that the inclusion of RAP can enhance the rutting resistance but reduce resistance to cracking. RAP fractionation demonstrated improvements in rutting resistance and enhanced mix ductility compared to the unfractionated RAP mix. Moreover, Saliani et al. (2019) compared the rutting resistance, fatigue cracking resistance, and low temperature cracking performance among three mixes: a control mix with no RAP, a 35% fine RAP mix (FRM), and a 54% coarse RAP mix (CRM). Both RAP-incorporated mixes demonstrated superior rutting resistance compared to the control mix. In terms of fatigue cracking, the CRM performed better than the FRM, though the control mix exhibited a longer fatigue life than both RAP mixes. The thermal stress restrained specimen testing (TSRST) results indicated that the control mix performed slightly better than the CRM. However, the CRM had a more desirable maximum tensile stress temperature compared to the FRM.

Aurangzeb et al. (2012) used two aggregate sources to develop eight asphalt mix designs: 0% (control), 30%, 40%, and 50% RAP for each material source. Different performance tests were conducted to evaluate the mixtures' moisture susceptibility, dynamic modulus, resistance to rutting, and fatigue resistance. The study concluded that samples including RAP could provide equal or better performance in resistance against moisture susceptibility, rutting, and fatigue failure. Harvey et al. (2023) investigated a pilot project that was built on State Route 49 in El Dorado County. The pilot project included one mix with 10 % RAP. The results showed that the mixes submitted for Job Mix Formula (JMF) verification and tested as part of QA all met the two performance-related specifications; the Hamburg Wheel Track test and the IDEAL-CT cracking resistance test.

1.8 Effects of Modifiers/Additives on the Performance of HMA with RAP

Aged binder in RAP increases the cracking susceptibility of the mixture at intermediate and low temperatures as it makes the mixture stiffer (Arafat et al., 2023). Aging affects the two major components of asphalt binder: asphaltenes and maltenes. Maltenes consist of saturates, aromatics, and resins. As aging occurs, the saturated content decreases due to oxidation, and the asphaltene and resin contents increase, impacting the maltene to asphaltene ratio. This results in a reduction of binder fluidity and higher viscosity, stiffness, and modulus, which negatively affect binder performance. Instead of using a softer virgin binder grade, rejuvenators (also called recycling agents) can also be used as modifiers during the production of asphalt mixtures containing RAP to restore the rheological and other properties of aged binders by improving the maltene to asphaltene ratio (Pradhan & Sahoo, 2019).

Different types of rejuvenators are available in the market. According to Martin et al. (2015), rejuvenators can be divided into five general categories: paraffinic oils, aromatic extracts, naphthenic oils, triglycerides & fatty acids, and tall oils. The conventional method of rejuvenator incorporation is to blend the rejuvenators with a virgin binder first and then to mix it with RAP (Ma et al., 2020). Elkashef et al. (2019) added a rejuvenator derived from soybean oil to an extracted RAP binder at 6% by weight of the binder, and then they obtained the performance grade of the control RAP and rejuvenated RAP binder by dynamic shear rheometer (DSR) and bending beam rheometer (BBR) measurements. The addition of the rejuvenator caused a drop in both the high and low temperature grades of control RAP binder with PG 88-16, resulting in a rejuvenated RAP binder with a PG 70-28. Arafat et al. (2023) reported that 15% bio-oil by weight of the binder was effective in lowering the high-temperature grade of RAP binder from PG 98 to PG 67. In contrast, achieving a similar effect required 35% aromatic oil. However, aromatic oil performed significantly better in cracking resistance than the bio-oil after long-term aging of high RAP mix, which was determined by semi-circular bending test performed at intermediate and low temperatures, as well as by overlay test. The results also showed rejuvenators can effectively restore cracking resistance in 15% RAP content mixes. However, for the mix with 30% RAP content, the cracking resistance cannot always be restored to the same level as the control mix. Again, rejuvenators can have an adverse effect on the rutting resistance of asphalt mix.

1.9 The Use of Fibers in HMA with RAP

Fiber modification can be a promising solution to mitigate the adverse effects of high RAP content on the performance of Hot Mix Asphalt (HMA). This topic holds significant importance for researchers aiming to enhance HMA performance. Riccardi et al. (2022) investigated the effect of using polyacrylonitrile (PAN) fibers on the mechanical properties of asphalt mixtures containing 50% RAP. The study found that fiber incorporation results in lower moisture resistance, likely due to the absorption of moisture by fiber, leading to binder stripping. In terms of stiffness, the addition of fibers resulted in softer, more elastic mixtures at low temperatures, as indicated by lower complex moduli and phase angles in fiber-modified mixtures compared to the control mix. Overall, the research confirms that adding fibers can improve fatigue and rutting resistance without compromising thermal cracking resistance.

Slebi-Acevedo et al. (2022) also investigated the effect of PAN fibers on the mixtures containing 50% artificial RAP with PAN fibers (PANRAP). Comparison between control PANRAP and fiber reinforced PANRAP showed that the fiber reinforcement increased the stiffness of the mixtures while keeping the same fatigue resistance and positively improved the permanent deformation of the mixture. Ramesh et al. (2022) developed a novel Warm Mix Asphalt (WMA) using a Sasobit warm mix additive, 70% RAP, and nano glass fibers (GF) in incremental proportions of 0.2% to 0.4%. The optimal mixture, containing 70% RAP and 0.3% GF, demonstrated significant improvements in terms of fracture properties through the SCB test: it sustained 3.3 times the peak load, exhibited 1.76 times the fracture energy, and achieved 1.8 times the critical strain energy release compared to the reference HMA mixture. Additionally, this mixture showed satisfactory performance in terms of TSR, resilient modulus, and rut resistance. Taziani et al. (2016) evaluated the effects of foamed bitumen mix containing 100% RAP and two types of polypropylene fiber, named F1 and F2, and Portland cement. Polypropylene fibers enhanced mechanical performance, with mixtures containing 0.075% F1 and 0.15% F2 showing 12% and 16% greater stiffness, respectively, and 0.15% of both fibers offering the best rutting resistance. Combining cement with fibers further increased tensile strength and stiffness. Overall, polypropylene fibers and cement significantly enhanced the properties of foamed bitumen recycled mixtures with 100% RAP. Ziari et al. (2021) compared the mechanical performance of WMA containing 0%, 50%, and 100% RAP content and the effect of using Para-fiber as an additive. The inclusion of RAP increased the resilient modulus and the mixtures' resistance to permanent deformation. However, the addition of RAP reduced the fatigue life of the mixtures, yet it was enhanced by the incorporation of Para-fiber. Due to the adverse effect on fatigue life, 50% RAP content was more practical than 100% RAP content. In mixtures with 50% RAP, adding 0.06% Para-fiber created optimal conditions for the TSR value, while 0.12% Para-fiber provided the minimum acceptable value.

In summary, a significant amount of RAP is produced annually in the US. There is growing interest in using higher proportions of RAP in asphalt pavement. However, extensive research is still required to effectively integrate high RAP content without compromising pavement performance. This research project investigated the use of commercially available polymer fiber in HMA containing RAP percentages up to 40%.

2. Experimental Work and Results

The goal of this study was to investigate the use of commercially available polymer fiber to improve the mechanical properties of Hot Mix Asphalt (HMA) containing different Reclaimed Asphalt Pavement (RAP) contents. The resistance to rutting and moisture damage was evaluated using the Hamburg Wheel Tracker (HWT) test in accordance with AASHTO 324-23. The resistance to cracking at intermediate temperatures was evaluated using the Cracking Tolerance Index (CTI) test in accordance with ASTM D8225-19. Two different types of aggregates and RAP materials normally used in HMA mixes on the Central Coast and in the Bay Area were supplied along with the Job Mix Formula (JMF) for each. This chapter presents the materials' physical properties, the JMF, and results from HWT and CTI tests.

2.1 Aggregate Properties

2.1.1 Mix with 15% RAP

Virgin and RAP aggregates used in HMA mixes commonly used in projects on the Central Coast of California were used with mixes containing 15% RAP and were supplied by CalPortland Construction from their HMA production plant located in Paso Robles, California. The aggregate properties were also provided and can be seen in Table 2.1.

Table 2.1. Properties of Aggregate Used for the 15% RAP Mix

Property	Test Method	Test Results	Specification[1]
Crushed coarse aggregate, One fractured face, %	AASHTO T 335	100	95
Crushed coarse aggregate, Two fractured faces, %	AASHTO T 335	100	90
Crushed fine aggregate, One fractured face, %	AASHTO T 335	99	40
Los Angeles abrasion, loss at 100 revolutions, %	AASHTO T 96	10	12
Los Angeles abrasion, loss at 500 revolutions, %	AASHTO T 96	39	40
Sand equivalent	AASHTO T 176	73	47
Flat and elongated particles (% by mass at 5:1)	ASTM D 4791	0	10
Bulk specific gravity of coarse aggregate	AASHTO T 85	2.56	NA[2]
Absorption of coarse aggregate	AASHTO T 85	1.4	NA
Bulk specific gravity (SSD) of fine aggregate	AASHTO T 84	2.56	NA
Bulk specific gravity of fine aggregate	AASHTO T 84	2.54	NA
Apparent specific gravity of fine aggregate	AASHTO T 84	2.61	NA
Apparent specific gravity of supplemental fines	AASHTO T 84	2.62	NA
Absorption of fine aggregate	AASHTO T 84	1.2	NA
Bulk specific gravity of aggregate blend	SP-2 Asphalt Mix	2.55	NA

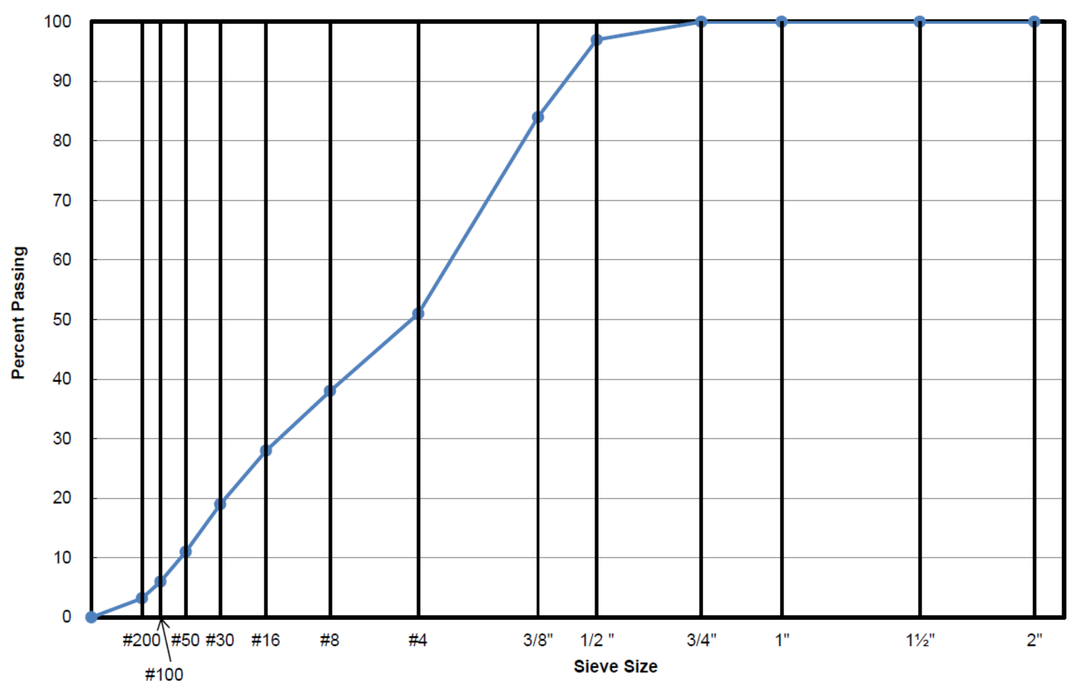
[1] Following Caltrans 2024 Standard Specifications; [2] NA = Not Available

Table 2.2 and Figure 2.1 present the gradation of individual aggregate fractions and the aggregate blend.

Table 2.2. Gradation of Individual Aggregate Fractions and Blend

Sieve Size	% in the mix						Specification
	Agg. #1	Agg. #2	Agg. #3	Bag house fine	RAP	Combined blend	
	20	28	36	1	15	100	
1”	100	100	100	100	100	100	100
¾”	100	100	100	100	100	100	92 - 100
½”	90	100	100	100	96	97	78 - 88
3/8”	30	98	100	100	87	83	46 - 56
#4	1	23	98	100	55	51	33 - 43
#8	1	1	85	100	42	38	-------
#16		1	60	100	32	27	14 - 22
#30			39	100	23	18	-------
#50			23	97	14	11	-------
#100			11	95	9	6	-------
#200			4.5	93	4.8	3.3	1 - 5

Figure 2.1. FHWA 0.45 Power Gradation Chart for 15% RAP Blend



2.1.2 Mix with 25% RAP

Virgin and RAP aggregates used in HMA mixes commonly used in projects in the Bay Area were used with mixes containing 25% RAP and were supplied by Granite Construction from their HMA production plant located in Salinas, California. Their different properties are presented in Table 2.3.

Table 2.3. Properties of Aggregate Used for the 25% RAP Mix

Property	**Test Method**	**Test Results**	**Specification**[1]
Crushed coarse aggregate, One fractured face, %	AASHTO T 335	99	95
Crushed coarse aggregate, Two fractured faces, %	AASHTO T 335	97	90
Crushed fine aggregate, One fractured face, %	AASHTO T 335	99	40
Los Angeles abrasion, loss at 100 revolutions, %	AASHTO T 96	5	12
Los Angeles abrasion, loss at 500 revolutions, %	AASHTO T 96	20	40
Sand equivalent	AASHTO T 176	76	47
Flat and elongated particles (% by mass at 5:1)	ASTM D 4791	0	10
Bulk specific gravity of coarse aggregate	AASHTO T 85	2.64	NA[2]
Absorption of coarse aggregate	AASHTO T 85	1.55	NA
Bulk specific gravity (SSD) of fine aggregate	AASHTO T 84	2.70	NA
Bulk specific gravity of fine aggregate	AASHTO T 84	2.66	NA
Apparent specific gravity of fine aggregate	AASHTO T 84	2.78	NA
Absorption of fine aggregate	AASHTO T 84	1.61	NA
Bulk specific gravity of aggregate blend	SP-2 Asphalt Mix	2.66	NA

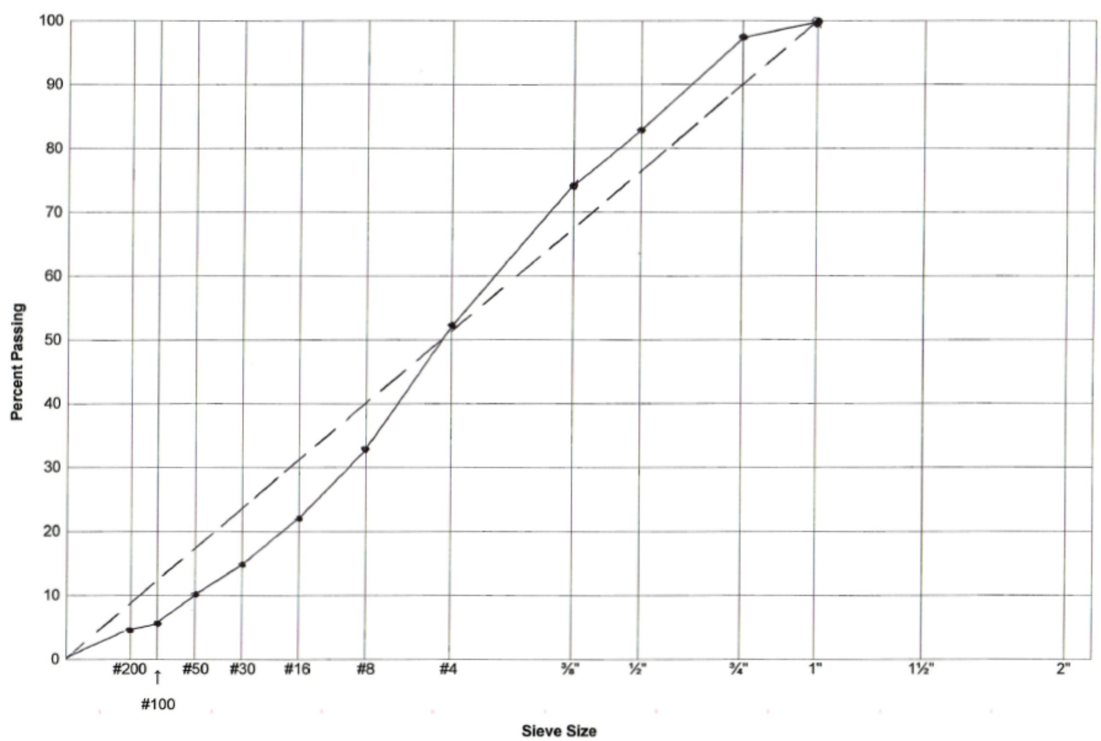
[1] Following Caltrans 2024 Standard Specifications; [2] Not Available

Table 2.4 and Figure 2.2 present the gradation of individual aggregate fractions and the aggregate blend.

Table 2.4. Gradation of Individual Aggregate Fractions and Blend

Sieve Size	% In the Mix							Specification
	Agg. #1	Agg. #2	Agg. #3	Agg. #4	Agg. #5	RAP	Combined blend	
	17	**10**	**18**	**6**	**24**	**25**	**100**	
1"	100	100	100	100	100	100	100	100
¾"	95	100	100	100	100	100	98	93 - 100
½"	14	79	100	100	100	96	83	77 – 89
3/8"	4	23	90	100	100	87	74	-------
#4	3	4	16	85	96	55	52	47 - 57
#8	2	3	6	4	70	42	33	28 - 38
#16	2	2	3	1	43	32	22	-------
#30	2	2	3	1	28	23	15	11 - 19
#50	1	2	2	1	16	14	10	-------
#100	1	1	2	0	8	9	6	-------
#200	0.6	0.7	0.9	0.3	4.1	4.8	4.3	2.3 – 6.3

Figure 2.2. FHWA 0.45 Power Gradation Chart for 25% RAP Blend



2.1.3 Mix with 40% RAP

Virgin and RAP Aggregates for HMA mixes containing 40% RAP were supplied by Granite Construction from their HMA production plant located in Salinas. Their different properties are presented in Table 2.5.

Table 2.5. Properties of Aggregate Used for the 40% RAP Mix

Property	**Test Method**	**Test Results**	**Specification**[1]
Crushed coarse aggregate, One fractured face, %	AASHTO T 335	100	95
Crushed coarse aggregate, Two fractured faces, %	AASHTO T 335	96	90
Crushed fine aggregate, One fractured face, %	AASHTO T 335	100	40
Los Angeles abrasion, loss at 100 revolutions, %	AASHTO T 96	5	12
Los Angeles abrasion, loss at 500 revolutions, %	AASHTO T 96	22	40
Sand equivalent	AASHTO T 176	78	47
Flat and elongated particles (% by mass at 5:1)	ASTM D 4791	1	10
Bulk specific gravity of coarse aggregate	AASHTO T 85	2.66	NA[2]
Absorption of coarse aggregate	AASHTO T 85	1.40	NA
Bulk specific gravity (SSD) of fine aggregate	AASHTO T 84	2.68	NA
Bulk specific gravity of fine aggregate	AASHTO T 84	2.63	NA
Apparent specific gravity of fine aggregate	AASHTO T 84	2.76	NA
Absorption of fine aggregate	AASHTO T 84	1.80	NA
Bulk specific gravity of aggregate blend	SP-2 Asphalt Mix	2.68	NA

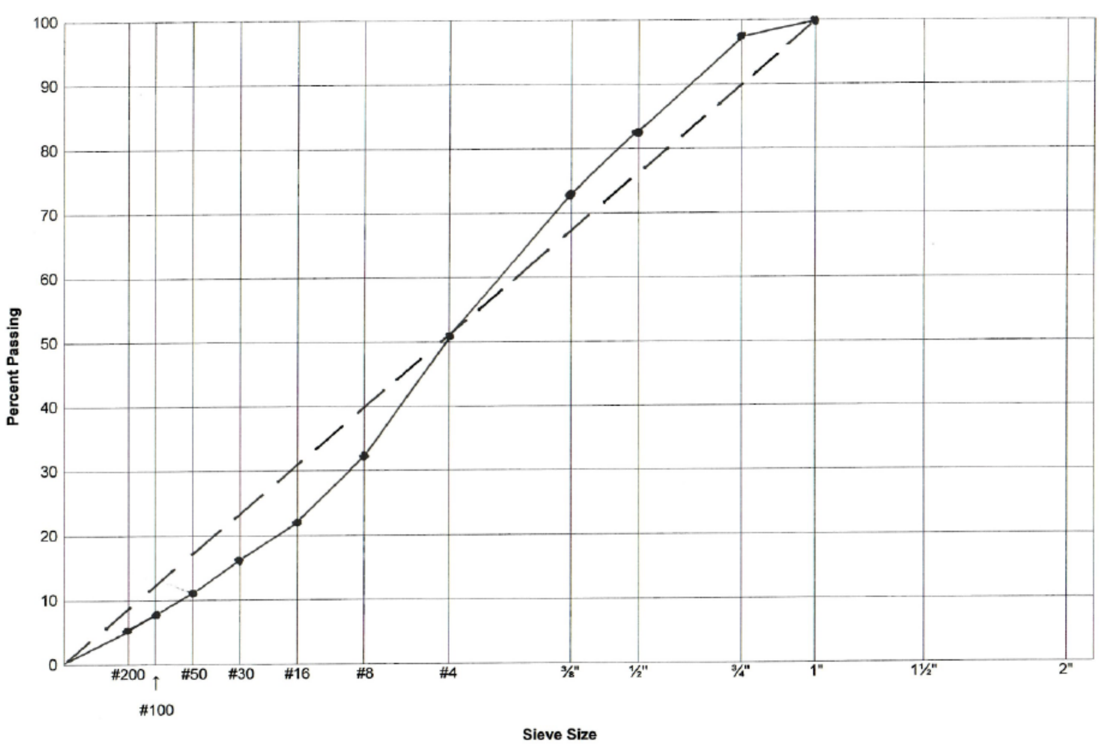
[1] Following Caltrans 2024 Standard Specifications; [2] Not Available

Table 2.6 and Figure 2.3 present the gradation of individual aggregate fractions and the aggregate blend.

Table 2.6. Gradation of Individual Aggregate Fractions and Blend

Sieve Size	% in the mix							Specification
	Agg. #1	Agg. #2	Agg. #3	Agg. #4	Agg. #5	RAP	Combined blend	
	18	10	16	6	10	40	100	
1"	100	100	100	100	100	100	100	100
¾"	95	100	100	100	100	100	98	93 - 100
½"	14	79	100	100	100	100	82	74 – 86
3/8"	4	23	90	100	100	87	73	--------
#4	3	4	16	85	96	83	51	50 - 60
#8	2	3	6	4	70	58	32	24 - 34
#16	2	2	3	1	43	42	22	--------
#30	2	2	3	1	28	31	16	12 - 20
#50	1	2	2	1	16	23	11	--------
#100	1	1	2	0	8	10	8	--------
#200	0.6	0.7	0.9	0.3	4.1	12.3	5.5	3.8 – 7.8

Figure 2.3. FHWA 0.45 Power Gradation Chart for 40% RAP Blend



2.2 Asphalt Binder Tests and Results

PG 64-10 asphalt binder that is commonly used on the Central Coast of California and supplied by CalPortland was used herein for HMA containing 15% RAP. However, the PG 58-22 asphalt binder supplied by Granite Construction was utilized for HMA containing 25% and 40% RAP. Table 2.7 presents the properties of PG 64-10 and PG 58-22 binder, respectively.

Table 2.7. Binder Properties

Property	Test Method	PG 64-10	PG 58-22
Specific Gravity	AASHTO T 228	1.026	1.026
Dynamic Shear (RFTO Residue)	AASHTO T 315	1.299 kPa @ 60°C	1.500 kPa @ 58°C

2.3 Polymer Fiber

Two polymer fibers that were recently used in one of Caltrans's maintenance projects on State Route 1 were investigated in this study. These two fibers are named fiber A (wax-coated) and fiber B (non-coated, treated with liquid emulsion). The properties of the two fiber types are presented in Table 2.8 and photos of the two fiber types are shown in Figures 2.4 and 2.5.

Figure 2.4. Aramid Fiber Type A

Figure 2.5. Aramid Fiber Type B

Table 2.8. Properties of Fiber Type A and Type B

Property	Fiber Type A	Fiber Type B
Material	Para-Aramid (min 63% by weight)	Para-Aramid (min 75% by weight)
Treatment	Wax (max 37% by weight)	Liquid emulsion binder (max 25% by weight)
Standard Dose	**2.1 oz per US ton of asphalt mix**	**2.1 oz per US ton of asphalt mix**
Decomposition Temp	>800°F / 425°C	>800°F / 425°C
Linear Density	>3200 dtex (ASTM D1907/1907M-12)	>3200 dtex (ASTM D1907-12, OPT6)
Length	**¾ in (19 mm) or 1.5 in (38 mm), ±10%**	**¾ in (19 mm) or 1.5 in (38 mm), ±10%**
Color	Yellow	Yellow
Tensile Strength	>2700 MPa (ASTM D2256, D7269)	>2700 MPa (ASTM D2256, D7269)
Young's Modulus	**>80 GPa (ASTM D2256, D7269)**	**>80 GPa (ASTM D2256, D7269)**

2.4 Uncompacted Asphalt Mix Tests

No specific mix design was conducted for the fiber-reinforced asphalt mixes. The two mixes, the original HMA, and the fiber-modified HMA, differed only in the addition of fibers, with no change in mixture volumetrics. The Job Mix Formulas for the HMA with the three RAP contents were made available by the construction companies that supplied the materials (CalPortland Inc. and Granite Construction). Table 2.11 presents the optimum binder contents for the HMA with different RAP contents. Three fiber dosages of 0.05, 0.10, and 0.15 percent of the HMA total weight were used in this study. All mixes used in this study utilized a liquid antistripping added to the mixes at a rate of 0.5% by weight of the asphalt binder. The optimum binder contents for the HMA mixes with 15%, 25%, and 40% RAP were 5.6%, 4.8%, and 5.2% of the total mix weight, respectively.

2.4.1 Theoretical Maximum Specific Gravity (AASHTO T 209)

The theoretical maximum specific gravity is an essential parameter for the overall mix design and in calculating the percent air voids in the compacted asphalt mixtures used for the subsequent tests in this study. For this test, asphalt mix specimens for each mix variation were prepared and cured for two hours. Mixes were then cooled in a loose, uncompacted state and placed in a vacuum container filled with water. A high vacuum pump, shown in Figure 2.6, was attached to the container and activated for at least 20 minutes to remove entrapped air. The container was also shaken to remove air bubbles. After vacuum saturation, the container was removed from the pump and filled to the calibrated level with water. Then the mass of the container, specimen, and water was determined. This value, along with the dry mass of the specimen and mass of the container filler with just water, was used to determine the theoretical maximum specific gravity by the following equation:

Theoretical Maximum Specific Gravity (TMSG) = A/(A+B-C)

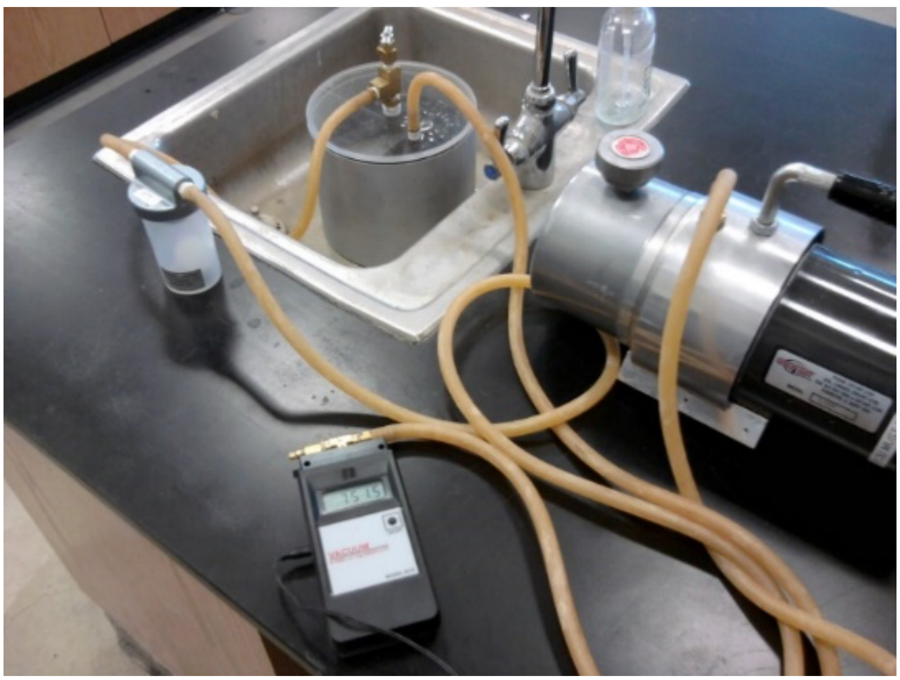
Where:

A = Mass of oven dry specimen (g);

B = Mass of container filled with water at 25 oC water (g); and

C = Mass of container filled with specimen and water (g).

Figure 2.6. Vacuum Saturating a Loose HMA Specimen for TMSG



The theoretical maximum specific gravities for each mix are presented in Table 2.10.

Table 2.9. MTSG for Different Mixes

% RAP[1]	Fiber Type	% Fiber[2]	Test Result, g/cm³ (lb/ft³)
15	Fiber A	0.00	2.403 (150.00)
		0.05	2.421 (151.13)
		0.10	
		0.15	
	Fiber B	0.00	2.403 (150.00)
		0.05	2.410 (149.33)
		0.10	
		0.15	
25	Fiber A	0.00	2.521 (157.40)
		0.05	2.500 (156.07)
		0.10	
		0.15	
	Fiber B	0.00	2.521 (157.40)
		0.05	2.515 (157.00)
		0.10	
		0.15	
40	Fiber A	0.00	2.506 (156.37)
		0.05	2.453 (153.05)
		0.10	
		0.15	
	Fiber B	0.00	2.506 (156.37)
		0.05	2.438 (152.14)
		0.10	
		0.15	

[1] of the total aggregate weight, [2] of the total mix weight

2.5 Preparation of Specimens for Hamburg Wheel Tracking (HWT) and Cracking Tolerance Index (CTI) Tests

Specimens were prepared using a Superpave Gyratory Compactor in accordance with AASHTO T 312. Specimens of 150 mm in diameter and thickness of 60 mm ± 1 mm for HWT and 62 mm ± 1 mm for CTI tests were compacted. The steps involved in preparing the specimens included drying aggregates to constant weight, batching aggregates, heating aggregates and binder to mixing temperature, mixing binder and aggregates, and conditioning (short-term aging) and compacting the specimen to appropriate percent air voids using the Superpave Gyratory Compactor:

1. All required aggregates were weighed in steel pans separately and combined to form a desired batch weight (see Figure 2.7). Typically, batches weighing approximately 5,250 grams of aggregate to produce two HWT specimens (150±2 mm in diameter and 60±1 mm in height) were prepared.

2. Batched aggregates including RAP and binder were heated in the oven to an appropriate mixing temperature based on the PG binder grade.

3. After aggregates and binder reached the mixing temperature, heated aggregates were introduced to a mechanical mixer and a crater was formed (Figure 2.8). The required amount of liquid antistripping agent was added to the binder. The binder and the fiber additives were added and mixing continued until every particle was uniformly coated with binder.

4. The weight of mixture needed to produce a specimen with specified air voids (7±0.5 % air voids for both HWT and CTI) was determined theoretically by the following equation:

   Weight of specimen 'W'= $\%G_{mm}$ @Nf $\times G_{mm}$ × volume of sample

where, $\%G_{mm}$ @ Nf = 0.93 (for HWT);

G_{mm}= theoretical maximum specific gravity of loose mixture; and

Volume= $\Pi d^2 h/4$; d=150 mm, h=60.2 mm for HWT specimens and 62 mm for CTI specimens.

After obtaining the theoretical weight (W) of the specimen, three trial specimens were prepared with the theoretical weight of specimen W, W+10 grams, and W-10 grams to calculate the exact weight of mixture needed to produce a compacted specimen with air voids in the desired range. The Superpave Gyratory Compactor (Figure 2.9) was used to compact the specimens to the desired height (Figure 2.10), and the air voids were calculated. Specimens used for HWT were saw cut, and the amount of material sawed from the cylindrical specimens were varied to achieve a gap between the molds of 4 mm ± 3 mm at the start of the test.

Figure 2.7. Aggregate Batches

Figure 2.8. Mechanical Mixer

Figure 2.9. Troxler SGC

Figure 2.10. HWT Specimen

2.6 Hamburg Wheel Tracker (HWT) Test (AASHTO T324)

The HWT used in this study was manufactured by James Cox & Sons, Inc. in Colfax, California, and the test procedure followed AASHTO T324. The laboratory-molded specimens were placed in a cutting template under the masonry saw to cut across the specimen (Figures 2.11 and 2.12) to fit into the HWT polyethylene molds. Specimens were then placed into the polyethylene mold and mounted into the tray and were placed into the HWT water bath (Figure 2.13). Water was then turned on, and once the water reached the designated temperature 122±2°F [50±1°C] for samples with PG 64-10 and 113±2°F [45±1°C] for samples with PG 58-22), the specimens were conditioned for an additional 30 minutes. After the conditioning period, the arms with wheels were lowered so they rested on the specimen and the test started. The testing device automatically stopped when either operator-specified maximum rut depth or the maximum number of wheel passes was reached, whichever occurred first. Linear variable differential transducers (LVDTs) connected to the machine on either side measured vertical deformation (rut depth), and rut depth was recorded using a computer-based automated data acquisition system connected to the HWT device.

Post compaction creep slope, stripping inflection point, and stripping slope were obtained from the plot of the number of wheel passes versus rut depth. Post-compaction consolidation is deformation (mm) at 1,000-wheel passes as it is assumed the wheel densifies the mixture within the first 1,000 passes and consequently is called post-compaction consolidation. Creep slope is the inverse of the rate of deformation in the linear region of plot between post compaction and stripping inflection point (if stripping occurs). Creep slope relates to rutting primarily due to plastic flow and is the number of wheel passes required to create 1 mm of rut depth. Stripping inflection point and stripping slope are related to moisture resistance of HMA. Stripping inflection point is the number of wheel passes at the intersection of creep slope and stripping slope. Stripping slope is the inverse rate of deformation after the stripping inflection point. It relates to rutting primarily due to moisture damage and is the number of wheel passes required to create 1 mm of rut depth after stripping inflection point (Yildirim et al. 2007). Figure 2.14 shows samples after being tested in HWT.

Results for the rut depth for all sample combinations are shown in Table 2.10, Table 2.11, and Table 2.12. Results for the stripping property in terms of the number of wheel paths at stripping inflection point are shown in Table 2.13, Table 2.14, and Table 2.15.

Figure 2.11. Saw-Cutting Specimen Along its Edge

Figure 2.12. HWT Specimen with Perpendicular Cut

Figure 2.13. Hamburg Wheel Tracker (HWT)

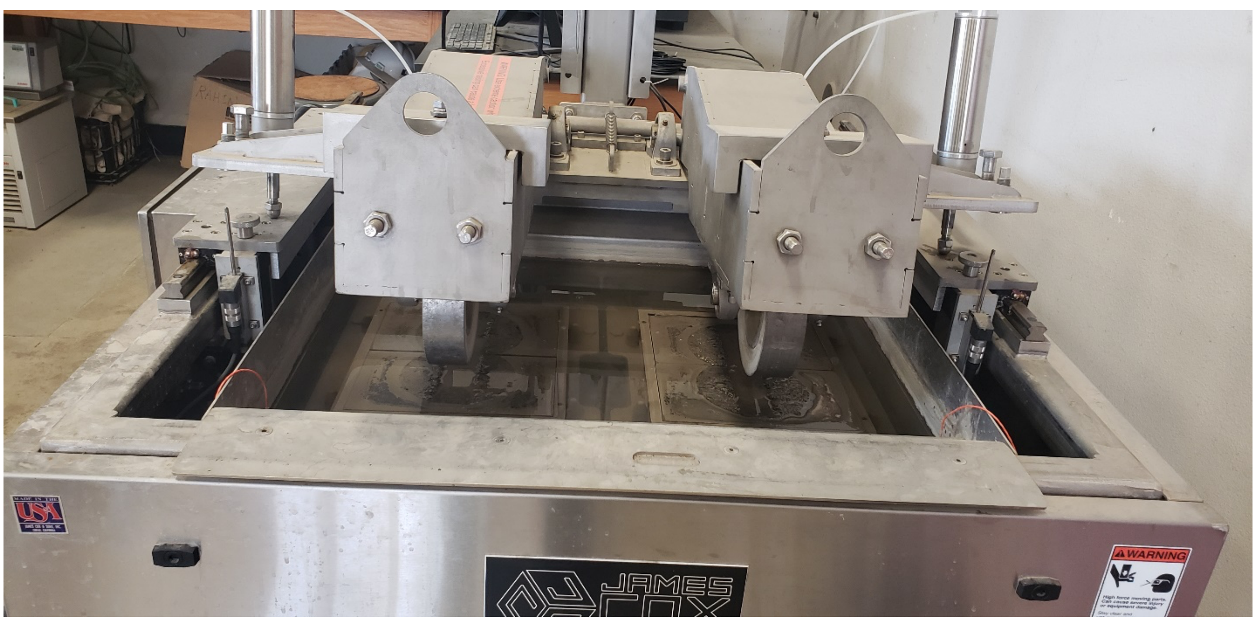


Figure 2.14. Specimens after HWT Test

Table 2.10. Rut Depth[1] for HMA with 15% RAP

Fiber Type	Fiber %	Left side (mm)	Right side (mm)	Average per set (mm)	Total average (mm)
Control	0	2.4	2.06	2.23	2.76
	0	3.73	2.82	3.28	
Type A	0.05	3.44	1.85	2.65	3.14
	0.05	3.48	3.77	3.63	
	0.10	4.85	3.12	3.99	4.10
	0.10	3.31	5.08	4.20	
	0.15	2.72	2.58	2.65	2.49
	0.15	2.52	2.11	2.32	
Type B	0.05	2.35	1.64	2.00	2.3
	0.05	2.58	2.62	2.60	
	0.10	1.85	2.91	2.38	2.94
	0.10	3.31	3.66	3.49	
	0.15	3.27	1.93	2.60	2.5
	0.15	2.58	2.22	2.40	

[1] Rut depth at 15,000-wheel passes

Table 2.11. Rut Depth[1] for HMA with 25% RAP

Fiber Type	Fiber %	Left side (mm)	Right side (mm)	Average per set (mm)	Total average (mm)
Control	0	6.08	3.86	4.97	4.18
	0	4.51	2.26	3.385	
Type A	0.05	7.50	6.30	6.9	5.534
	0.05	3.07	5.27	4.17	
	0.10	5.25	4.90	5.075	4.56
	0.10	5.06	3.03	4.045	
	0.15	3.65	3.22	3.435	4.06
	0.15	4.68	4.68	4.68	
Type B	0.05	7.33	3.65	5.49	4.68
	0.05	2.91	4.84	3.875	
	0.10	4.15	5.97	5.06	3.57
	0.10	2.61	1.55	2.08	
	0.15	4.03	2.66	3.345	2.67
	0.15	2.01	1.97	1.99	

[1] Rut depth at 15,000-wheel passes.

Table 2.12. Rut Depth[1] for HMA with 40% RAP

Fiber Type	Fiber %	Left side (mm)	Right side (mm)	Average per set (mm)	Total average (mm)
Control	0	5.4	7.18	6.29	6.05
	0	8.42	3.21	5.82	
Type B	0.05	4.23	3.02	3.625	3.35
	0.05	3.29	2.84	3.065	
	0.10	3.04	2.91	2.975	3.00
	0.10	2.87	3.19	3.03	
	0.15	4.52	3.48	4.00	3.61
	0.15	3.21	3.24	3.225	

[1] Rut depth at 15,000-wheel passes.

Table 2.13. Number of Wheel Passes at Inflection Point for HMA with 15% RAP

Fiber Type	Fiber %	Left side (mm)	Right side (mm)	Average per set (mm)	Total average (mm)
Control	0	13,617	NA[1]	13,617	13,617
	0	NA	NA	------	
Type A	0.05	12,862	16,202	14,532	16,120
	0.05	17,917	17,497	17,707	
	0.10	19,811	18,969	19,390	17,223
	0.10	15,914	14,198	15,056	
	0.15	17,563	17,552	17,558	17,755
	0.15	17,761	18,145	17,953	
Type B	0.05	14,110	12,905	13,508	14,693
	0.05	15,878	NA	15,878	
	0.10	18,091	16,259	17,175	16,879
	0.10	15,094	18,073	16,583	
	0.15	NA	NA	NA	19,251
	0.15	20,058	18,443	19,251	

[1] Data Not Available.

Table 2.14. Number of Wheel Passes at Inflection Point for HMA with 25% RAP

Fiber Type	Fiber %	Left side (# of passes)	Right side (# of passes)	Average per set (# of passes)	Total average # of passes
Control	0	11,427	NA[1]	11,427	11,916
	0	NA	12,404	12,404	
Type A	0.05	NA	17,480	17,480	17,542
	0.05	11,061	24,145	17,603	
	0.10	18,308	18,483	18,396	17,136
	0.10	17,469	14,284	15,877	
	0.15	17,701	18,066	17,884	17,882
	0.15	NA	NA	NA	
Type B	0.05	18,096	17,726	17,911	17,911
	0.05	NA	NA	NA	
	0.10	18,460	14000	16,230	16,360
	0.10	16,490	NA	16490	
	0.15	NA	17,520	17,520	16,825
	0.15	NA	16,129	16,129	

[1] Data Not Available.

Table 2.15. Number of Wheel Passes at Inflection Point for HMA with 40% RAP

Fiber Type	Fiber %	Left side (# of passes)	Right side (# of passes)	Average # of passes per set	Total average # of passes
Control	0	NA[1]	14,677	14,677	16,806
	0	17,897	17,845	17,871	
Type B	0.05	15,083	18,344	16,714	16,479
	0.05	18,025	14,464	16,245	
	0.10	19,197	NA	19,197	17,770
	0.10	15,569	18,543	17,056	
	0.15	4,031	3,128	3,580	3,772
	0.15	NA	4,158	4,158	

[1] Data Not Available.

2.7 Cracking Tolerance Index (CTI) Test (ASTM D8225)

The test procedure in the study followed ASTM D8225 to determine the cracking tolerance for each mixture. Pavetest's Dynamic Loading System (see Figure 15), a precision-controlled apparatus designed for dynamic modulus, fatigue, and performance evaluation of asphalt specimens under simulated traffic conditions, was used to conduct the test. It integrates a vertical axial loading mechanism equipped with loading plates, a sensitive load sensor, deformation measurement instrumentation, and guide rods for precise alignment, all housed within an environmentally regulated testing chamber. The system is also complemented by an advanced data acquisition and control module for monitoring and analyzing data.

Based on the standards, each specimen was compacted to a cylindrical shape with a diameter of 150 millimeters and a thickness of 62 millimeters using the Superpave Gyratory Compactor. The air voids of the samples were precisely controlled to meet air voids content of 7.0 +/- 0.5%. Specimens were conditioned in an environmental chamber prior to testing at an intermediate temperature of 31˚C for the mixtures with 15% Reclaimed Asphalt Pavement (RAP) and 22˚C for the mixtures containing 25% and 40% RAP for 120 +/- 10 minutes according to ASTM D8225-19. The target intermediate test temperature was determined using the following equation:

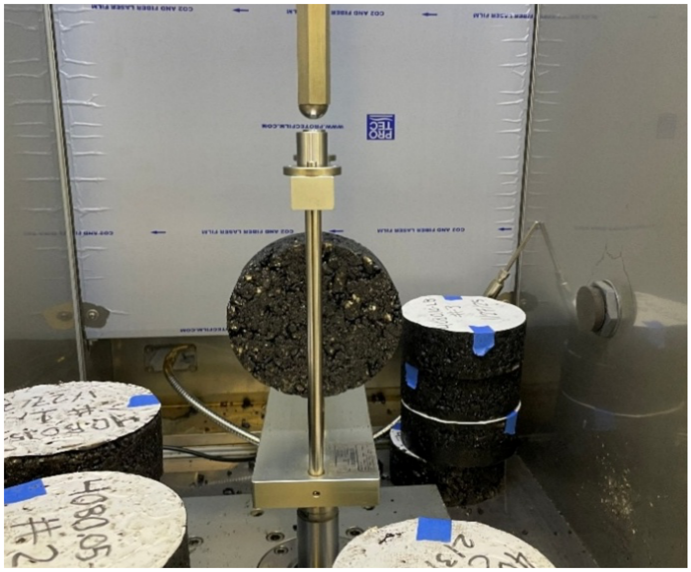
$$PG,IT = \frac{PG,HT + PG,LT}{2} + 4 \quad \text{(Eq-1)}$$

where PG, IT = intermediate performance grade temperature (˚C),

PG, HT = climatic high-performance grade temperature (˚C), and

PG, LT = climatic low-performance grade temperature (˚C).

Figure 2.15. IDEAL-CT Specimen Prepared for Testing



Immediately after conditioning, the specimens were transferred and placed in the indirect tensile testing fixture centrally as shown in Figure 15. At the midpoint of the specimens, a reference line was drawn across the diameter to ensure precise alignment of the specimens with respect to the center of the testing apparatus. Before testing, the loading plates and fixtures of the apparatus were thoroughly cleaned to remove any dust, debris, or residual asphalt binder to ensure accurate and consistent results. Immediately following conditioning of the specimens, they were transferred and centrally positioned in the cracking test fixture.

The fixture consisted of concave steel loading strips whose radius of curvature closely matched the specimen radius, ensuring uniform load distribution along the specimen edges. The indirect tensile cracking test was performed by applying an axial load at a constant Load-Line Displacement (LLD) rate of 50 mm/minute. The displacement measurements were captured by displacement measurement devices capable of resolving increments of at least 0.01 mm. Data were collected continuously through a high-frequency data acquisition system and software, recording at a minimum sampling rate of 40 data points per second to generate smooth and precise load-displacement curves.

The loading continued at the fixed displacement rate until the specimen experienced complete failure, defined explicitly as the point at which the measured load dropped below 100 N. The testing duration for each specimen was carefully monitored and maintained within 4 minutes from removal of the specimen from the conditioning chamber to completion of the test, minimizing temperature variations that might influence the measured parameters.

The software provided graphical representations and Excel spreadsheets containing displacement, load, and time data for each specimen which were subsequently analyzed to calculate the primary parameters relevant to cracking resistance. First, the work of failure (Wf, in Joules), representing the energy required to induce cracking, was computed as the area under the load-displacement curve using Equation 2:

$$W_f = \sum_{i=1}^{n-1}[(l_{i+1} - l_i)P_i + ½\,(l_{i+1} - l_i)(P_{i+1} - P_i)] \qquad \text{(Eq-2)}$$

where: W_f = work of failure (Joules),

Pi = applied load (kN) at the i-load step application,

Pi+1 = applied load (kN) at the i + 1 load step application,

li = LLD (mm) at the i step, and

li+1 = LLD (mm) at the i + 1 step.

The failure energy (G_f, Joules/m^2), which is required to evaluate the work energy that is required to initiate and propagate the cracks, was then calculated for each specimen. The following equation was used for the determination of failure energy:

$$G_f = \frac{W_f}{D * t} \times 10^6 \qquad \text{(Eq-3)}$$

where: G_f = failure energy (Joules/m^2),

W_f = work of failure (Joules),

D = specimen diameter (mm), and

t = specimen thickness (mm).

The major parameter associated with this test that represents the resistance of the asphalt mixture to fatigue cracking is the Cracking Tolerance Index (CT_{index}). Using the load displacement curve, the slope ($|m_{75}|$) of the straight line connecting 85% and 65% of the peak load was computed, which was then used in co-ordinance with the deformation (l_{75}) corresponding to 75% of the peak load and the dimensions of the specimen to calculate the CT_{index} value of the mixtures as shown in the following equation:

$$CTIndex = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \qquad \text{(Eq-4)}$$

where: CT_{Index} = cracking tolerance index,

Gf = failure energy (Joules/m2),

$|m_{75}|$ = absolute value of the post-peak slope m75 (N/m), and

l_{75} = displacement at 75 % the peak load after the peak (mm).

The Ideal-CT test was performed for all the specimens with varying amounts of Reclaimed Asphalt Content (RAP) and fiber. Consequently, the CT_{index} values and all the associated factors were evaluated and are included in Table 2.16 to Table 2.18.

Table 2.16. IDEAL-CT Test Results for 15% RAP Asphalt Mixtures Modified with Varying Fiber Types and Dosages

Sample Name	Sample	Air Voids (%)	Peak load, (kN)	I75, (mm)	|m75| (N/m)	Wf (Joules)	Gf (Joules/m2)	CTindex	CoV, (%)	*p*-value compared to the control
15-C[1]	1	7.4	15.21	5.32	3.24E+06	85.06	9,147	100.03	28.35	-
	3	7.3	17.91	4.84	5.58E+06	89.07	9,578	55.42		
	4	6.9	17.2	5.5	4.32E+06	94.31	10,141	86.17		
Average			16.77	5.22	4.38E+06	89.48	9,622	80.54		
15-A0.05[2]	2	6.6	18	4.98	5.13E+06	104.38	11,224	72.68	17.78	.9359
	3	7.1	17.92	5	5.48E+06	88.94	9,563	58.12		
	4	6.7	17.58	5.36	4.58E+06	99.4	10,688	83.42		
Average			17.83	5.11	5.06E+06	97.57	10,492	71.41		
15-A0.10[2]	1	7.2	15.1	5.33	2.57E+06	110.03	11,831	163.6	18.89	.0307
	2	6.8	15.58	5.53	3.26E+06	92.09	9,902	112.13		
	4	6.9	16.23	6.66	3.97E+06	111.74	12,015	134.27		
Average			15.64	5.84	3.27E+06	104.62	11,249	136.67		
15-A0.15[2]	1	7.2	17.55	5.14	3.28E+06	116.31	12,507	130.77	10.44	.178
	2	6.9	16.64	5.49	3.81E+06	104.75	11,264	108.14		
	4	7	18.6	5.48	4.09E+06	116.28	12,504	111.56		
Average			17.6	5.37	3.73E+06	112.45	12,091	116.82		
15-B0.05[3]	1	7.7	14.71	5.91	2.76E+06	100.51	10,808	154.27	17.02	.0255
	2	6.5	16.66	5.92	2.43E+06	112.43	12,089	196.46		
	3	7	17.59	5.79	3.40E+06	117.44	12,628	143.4		
Average			16.32	5.87	2.86E+06	110.13	11,841	164.71		
15-B0.10[3]	1	7.2	15.18	5.73	2.95E+06	100.72	10,830	140.46	18.63	.4589
	2	6.8	17.04	5.36	4.07E+06	106.8	11,483	100.82		
	3	6.9	20.58	5.54	4.97E+06	132.51	14,248	105.93		

Sample Name	Sample	Air Voids (%)	Peak load, (kN)	I75, (mm)	|m75| (N/m)	Wf (Joules)	Gf (Joules/m2)	CTindex	CoV, (%)	*p*-value compared to the control
Average			17.6	5.54	3.99E+06	113.34	12,187	115.74		
15-B0.15[3]	1	7.2	18.51	5.42	3.77E+06	136.69	14,698	140.89	33.72	.6128
	2	7.4	18.88	5.29	4.15E+06	128.81	13,850	117.89		
	3	6.9	22.26	4.68	6.00E+06	122.97	13,223	68.8		
Average			19.88	5.13	4.64E+06	129.49	13,924	109.19		

[1] Control Mix (No fiber), [2] Fiber type A (%), [3] Fiber type B (%)

Table 2.17. IDEAL-CT Test Results for 25% RAP Asphalt Mixtures Modified with Varying Fiber Types and Dosages

Sample name	Sample	Air Voids (%)	Peak load (KN)	I75, (mm)	|m75| (N/m)	Wf, (Joules)	Gf, (Joules/m2)	CTindex	CoV, (%)	*p*-value compared to the control
25-C[1]	1	6.9	19.46	4.89	1.10E+07	89.41	9,614	28.61	29.2	-
	2	7.2	19.11	5.52	8.05E+06	104.43	11,230	51.34		
	3	7.1	18.01	5.16	6.50E+06	86.7	9,322	49.31		
Average			18.86	5.19	8.50E+06	93.51	10,055	43.09		
25-A0.05[2]	1	6.9	16.6	4.18	6.50E+06	75.23	8,090	34.71	60.51	.9979
	2	6.4	17.5	5.91	5.25E+06	94.84	10,198	76.52		
	3	7.4	19	4.31	9.87E+06	79.26	8,522	24.82		
Average			17.7	4.8	7.21E+06	83.11	8,937	45.35		
25-A0.10[2]	1	8.1	14.63	6.33	4.24E+06	102	10,968	109.26	30.84	.002
	3	6.5	16.08	6.33	4.00E+06	113.67	12,223	124.59		
	5	6.7	18.95	6.26	4.48E+06	115.37	12,405	115.72		
Average			16.55	6.31	4.00E+06	110.35	11865.37	116.52		
25-A0.15[2]	1	7.2	17.45	4.36	5.75E+06	83.78	9,008	45.52	10.54	.9994
	2	7.4	18.44	3.52	4.67E+06	73.08	7,858	39.46		
	3	7.4	20.06	4.26	6.73E+06	107.32	11,540	48.7		
Average			18.65	4.05	5.72E+06	88.06	9,469	44.56		
25-B0.05[3]	1	7.5	14.27	5.67	6.27E+06	81.01	8,711	52.55	23.01	.81
	3	7.5	15.97	6.62	5.63E+06	98.32	10,572	82.91		
	4	6.9	15.9	5.38	4.27E+06	87.07	9,362	78.55		
Average			15.38	5.89	5.39E+06	88.8	9,548	71.33		
25-B0.10[3]	1	8.7	17.37	5.64	3.56E+06	122.81	13,205	139.5	52.71	.4322
	2	7.2	16.53	4.97	7.25E+06	84.56	9,093	41.56		
	3	7.3	16.72	5.47	4.44E+06	112.08	12,052	99.08		

Sample name	Sample	Air Voids (%)	Peak load (KN)	I75, (mm)	|m75| (N/m)	Wf, (Joules)	Gf, (Joules/m2)	CTindex	CoV, (%)	*p*-value compared to the control
Average			16.87	5.36	5.08E+06	106.48	11,450	93.38		
25-B0.15[3]	1	9.6	18.16	4.88	3.66E+06	137.14	14,747	130.84	32.82	.0177
	2	7.8	19.97	4.56	3.63E+06	136.77	14,707	123.36		
	4	7.1	18.08	8.27	3.79E+06	148.65	15,984	232.69		
	6	7.4	15.43	6.47	3.76E+06	112.32	12,078	138.54		
Average			17.91	6.05	3.71E+06	133.72	14,379	156.36		

[1] Control Mix (No fiber), [2] Fiber type A (%), [3] Fiber type B (%)

Table 2.18. IDEAL-CT Test Results for 40% RAP Asphalt Mixtures Modified with Varying Dosages

Sample name	Sample	Air Voids (%)	Peak load, (KN)	I75 (mm)	|m75| (N/m)	Wf (Joules)	Gf (Joules/m2)	CTindex	CoV (%)	*p*-value compared to the control
40-C[1]	1	6.2	16.09	7	3.49E+06	113.38	12,191	162.74	14.51	-
	2	7.3	18.48	5.85	3.85E+06	115.46	12,415	125.67		
	3	5.6	16.46	6.31	3.63E+06	104.51	11,237	130.1		
Average			17.01	6.39	3.66E+06	111.11	11,948	139.5		
40-B0.05[2]	1	7.5	18.7	5.47	4.29E+06	108.52	11,669	99.07	35.66	.928
	2	6.9	19.16	5.36	3.33E+06	118.1	12,699	136.33		
	3	7.6	19.02	5.29	5.82E+06	99.8	10,731	64.96		
Average			18.96	5.37	4.48E+06	108.81	11,700	100.12		
40-B0.10[2]	1	6.4	18.19	6.17	2.63E+06	138.18	14,858	232.19	49.84	.762
	2	6.6	17.98	4.87	3.74E+06	97.43	10,476	90.99		
	3	6.4	18.99	6.53	2.52E+06	155.11	16,679	287.97		
Average			18.38	5.86	2.96E+06	130.24	14,004	203.71		
40-B0.15[2]	2	7.8	17.7	6.51	2.48E+06	129.04	13,875	242.53	63.81	.9108
	3	8	12.66	6.79	1.86E+06	97.7	10,505	256		
	4	6.7	17.68	4.53	5.27E+06	78.22	8,410	48.18		
Average			16.02	5.94	3.20E+06	101.65	10,930	182.24		

[1] Control Mix (No fiber), [2] Fiber type A (%)

2.8 Summary

Section 2 discussed the materials and testing methods involved in this study. All materials used in this study, along with the Job Mix Formula (JMF) for each mix, were obtained from two pavement construction companies (CalPortland and Granite Construction). Theoretical maximum density for each mix was verified in the laboratory. Using the mix design provided, varying amounts of fiber additives were introduced to mixes containing 15%, 25%, and 40% RAP contents. Specimens were fabricated and tested for rutting and moisture sensitivity using Hamburg Wheel Tracker (HWT) tests and for resistance to cracking at intermediate temperature using the Cracking Tolerance Index (CTI) tests. Results were then organized and tabulated. Analyses of results are presented in the following section (Section 3).

3. Analysis and Discussion

3.1 Introduction

This section discusses the results of the Hamburg Wheel Tracker (HWT) and Cracking Tolerance Index (CTI) tests conducted in this study. Plots were created to graphically represent differences among the different additives, concentrations, and application methods.

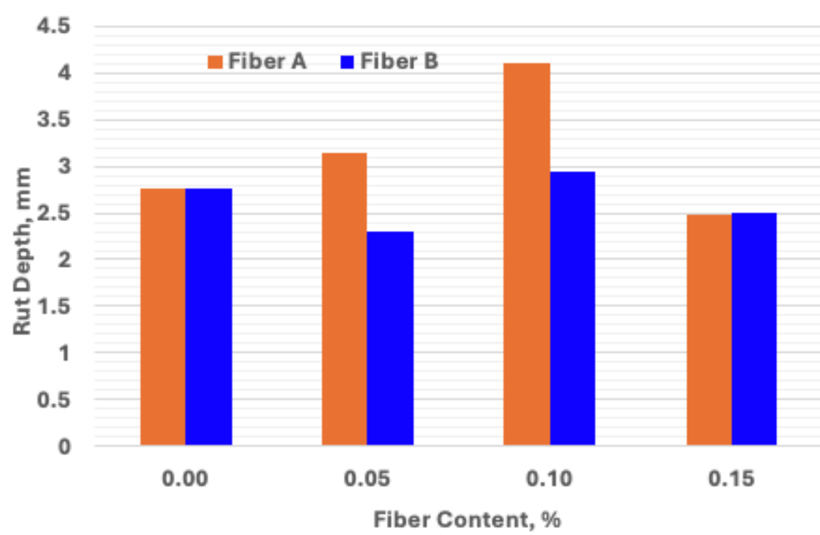
3.2 Hamburg Wheel Tracker Results

3.2.1 HMA with 15% RAP

Resistance to Rutting

Two fiber types (A and B) were added in three different percentages to HMA mix containing 15% RAP as discussed in Section 2. Figure 3.1 presents the average rut depth measured after 15,000 passes. Fiber B at 0.05% and 0.15% slightly improved resistance to rutting compared to the control mix. Also, rut depth for mixes with fiber B performed better than mixes with fiber A at fiber percentages lower than 0.15%. However, fiber A had a negative effect of rutting resistance for HMA with 15% RAP.

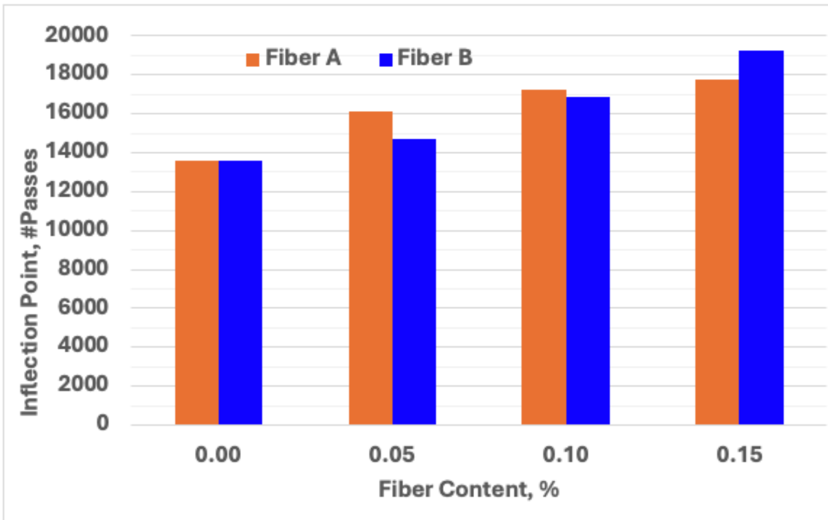
Figure 3.1. Effect of Fiber Type and Content on Rut Depth
for HMA with 15% RAP



Resistance to Stripping

Inflection points can be used to evaluate stripping potential. If the stripping inflection point occurs at a low number of load cycles (e.g., less than 10,000), the HMA mixture may be susceptible to stripping. Figure 3.2 presents the average number of passes at inflection point for HMA mix containing 15% RAP and different fiber types and contents. Results showed that adding both types of fibers resulted in an increase in the number of passes before reaching the inflection, an indication of improved resistance to stripping. All mixes, including the control mix, resulted in number of passes higher than the 10,000-threshold.

Figure 3.2. Effect of Fiber Type and Content on Inflection Point for Mixes with 15% RAP

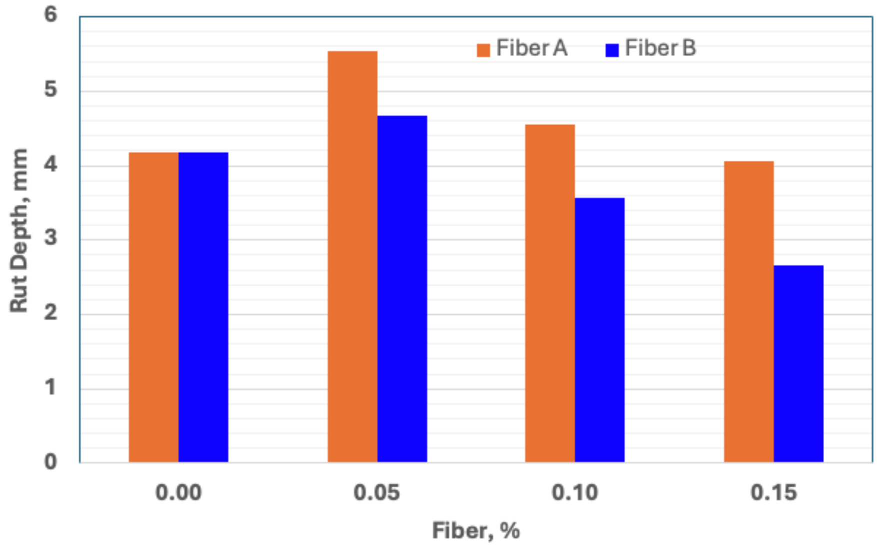


3.2.2 HMA with 25% RAP

Resistance to Rutting

Figure 3.3 presents the average rut depth measured after 15,000 passes. Fiber B at 0.10% and 0.15% slightly improved resistance to rutting. However, fiber A had a negative effect of rutting resistance for HMA with 25% RAP. Also, as was observed for HMA with 15% RAP, mixes containing fiber B outperformed those containing fiber A.

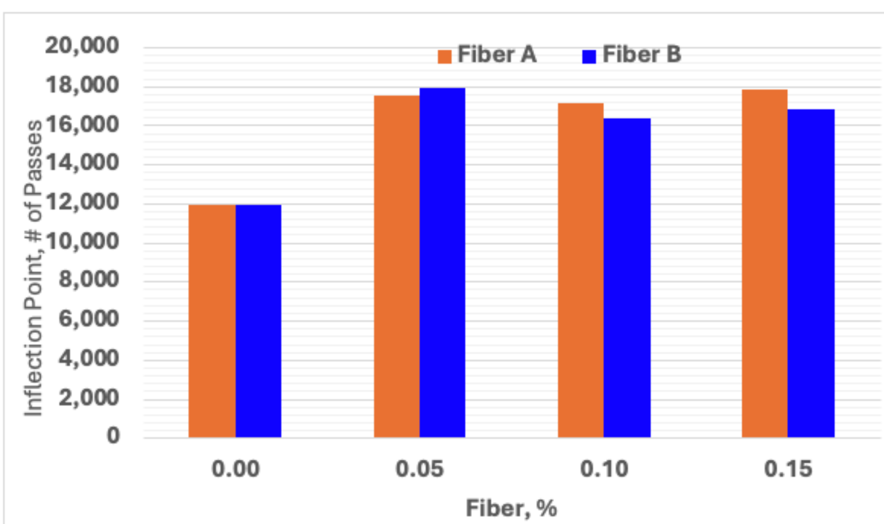
Figure 3.3. Effect of Fiber Type and Content on Rut Depth for HMA with 25% RAP



Resistance to Stripping

Figure 3.4 presents the average number of passes at the inflection point for HMA mix containing 25% RAP and different fiber types and contents. Results showed that adding both types of fibers resulted in an increase in the number of passes before reaching the inflection point, an indication of improved resistance to stripping. However, both fiber types performed almost equally for HMA with 25% RAP content. All mixes, including the control mix, resulted in number of passed higher than the 10,000-threshold.

Figure 3.4. Effect of Fiber Type and Content on Inflection Point for Mixes with 25% RAP



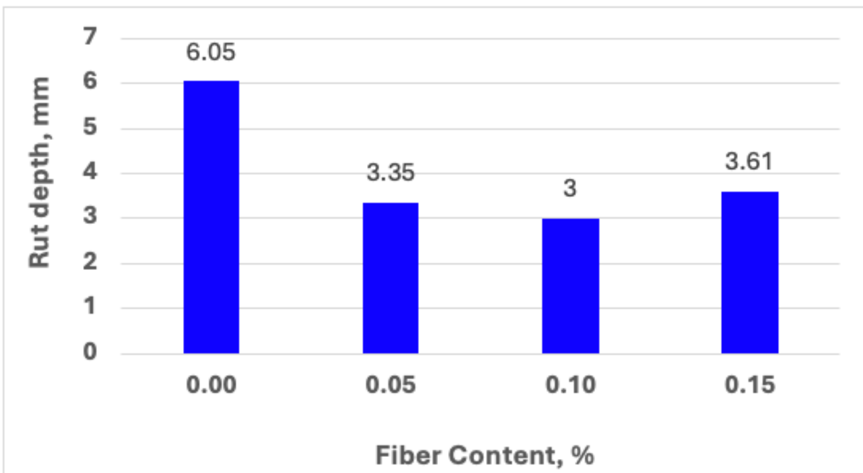
3.2.3 HMA with 40% RAP

As mentioned in Section 2, only fiber type B was used in HMA with high RAP percentage (40%). This decision was made after observing it outperforming fiber A for mixes with both 15% and 25% RAP.

Resistance to Rutting

Figure 3.5 presents the rut depth at 15,000 passes for HMA with 40% using fiber type B added at the same dosages previously used in (i) HMA with 15% and (ii) HMA with 25% RAP. Fiber type B significantly improved resistance to rutting in mix that contain high RAP content. The figure also shows that fiber content of 0.1% resulted in the best resistance to rutting.

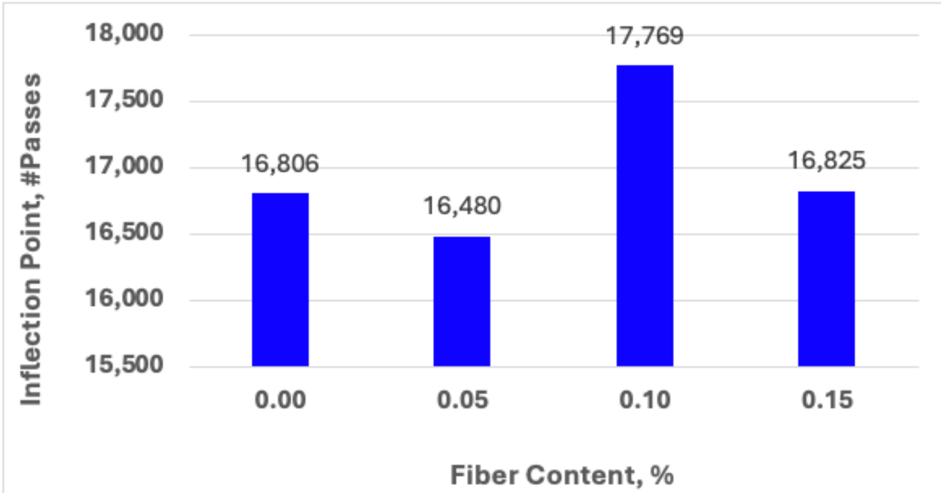
Figure 3.5. Effect of Fiber B on Rut Depth for Mixes with 40% RAP



Resistance to Stripping

Figure 3.6 presents the average number of passes at the inflection point for HMA mixes containing 40% RAP and different fiber types and contents. Results show that adding fiber B at 0.10% resulted in the highest number of passes at inflection point. However, fiber B contents of 0.05% and 0.15% resulted in approximately the same number of passes as the control mix. It is noteworthy to mention that all mixes resulted in numbers of passes significantly higher than the 10,000 passes threshold and higher than the 15% and 25% RAP mixes.

Figure 3.6. Effect of Fiber B on Inflection Point for Mixes with 40% RAP



3.2.4 Comparison of All Mixes

All combinations of mixes were grouped, and data were plotted on one graph (see Figures 3.7 and 3.8). Figure 3.7 presents the rut depth for mix groups. The control mix's resistance to rutting deteriorates as RAP content increases from 15 % to 25 % to 40%. In general, mixes with fiber type B outperformed those containing fiber type A. However, both types of fiber did not seem to improve resistance to rutting as compared with control mix, except for the mix with 25% RAP, where fiber type B at dosages higher than 0.05% exhibited slight improvement. For mixes with 40% RAP, adding fiber B significantly improved rutting resistance at all fiber contents. This is a promising result which could allow incorporating high RAP content in HMA mixes used as surface course (top pavement layer directly exposed to traffic) without compromising rutting resistance.

Figure 3.7. Average Rut Depth vs. Fiber Content for Mixes with Different RAP Contents

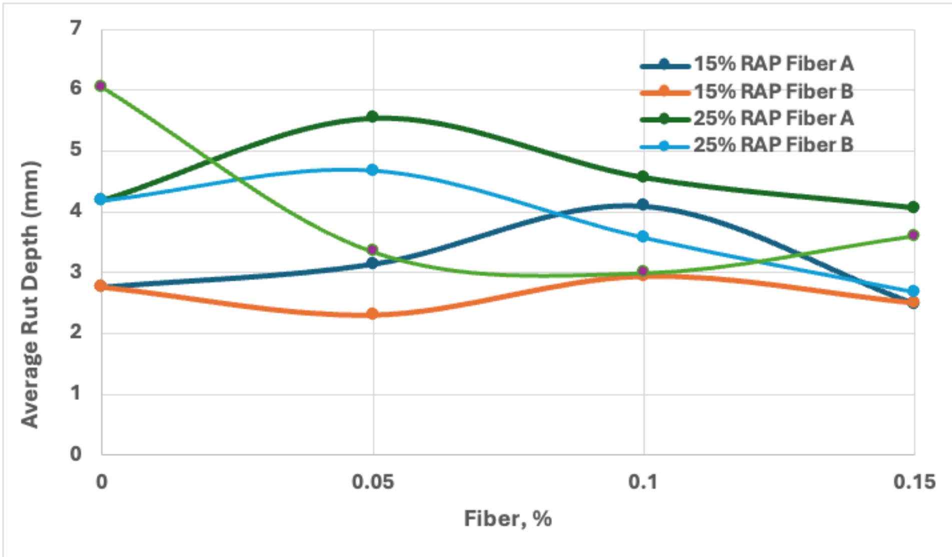
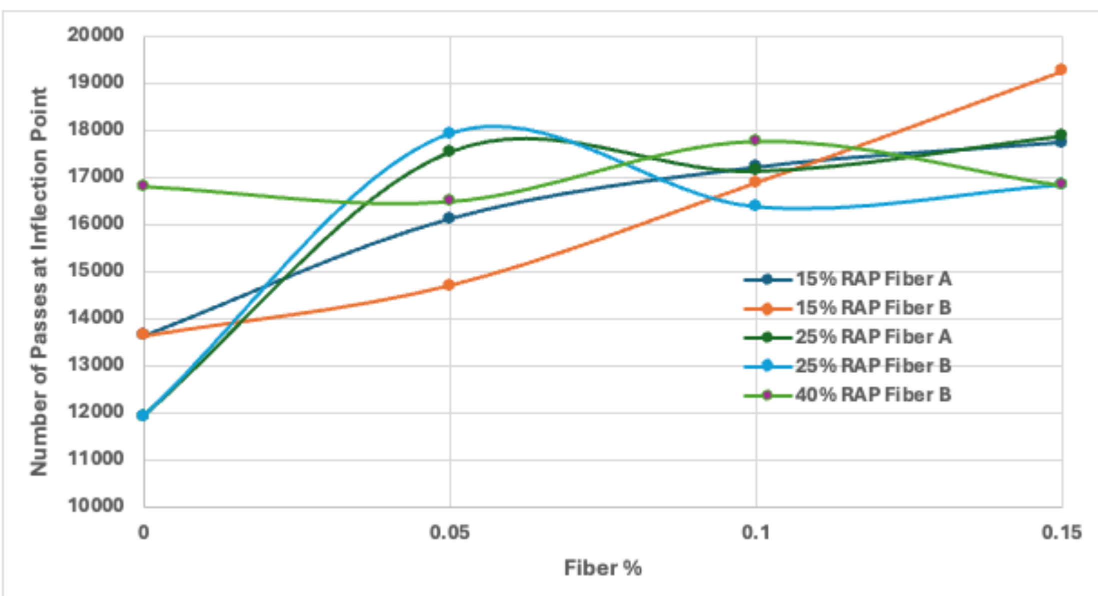


Figure 3.8 presents the relationship between the average number of passes at inflection point as a function of RAP and fiber contents for all mixes. Mixes with high RAP content (40%) exhibited the highest resistance to stripping. However, adding fiber to this mix did not show an impact on its resistance to stripping. Adding fiber to mixes with RAP contents of 15% and 25% improved their resistance to stripping, especially for mix with 15% RAP.

Figure 3.8. Average Number of Passes at Inflection Point vs. Fiber Content for Mixes with Different RAP Contents



3.2.5 ANOVA Analysis

An Analysis of Variance (ANOVA) was conducted using statistical analysis software Minitab. The response variables that were investigated were limited to rut depth at 15,000 passes and number of passes at the infection point.

Rut Depth for Fiber A vs Fiber B

To compare the performance of fiber A versus fiber B, the 15% and 25% RAP data were combined and sorted into two groups. Results from ANOVA analysis showed fiber B group had a lower mean rut depth at 15,000 passes than fiber A, as seen in Table 3.1. The difference between the means is statistically significant at the 95% confidence level (see Table 3.2).

Table 3.1. Mean Rut Depth at 15,000 Passes for the Fiber A and B Groups

Fiber Type	Mean Rut Depth at 15,000 Passes (mm)
A	3.98
B	3.10

Table 3.2. Differences in Mean Rut Depths at 15,000 Passes and Confidence Intervals for Fiber A and B Groups

Difference of Means (mm)	SE of Difference (mm)	*t*	Adjusted *p*-value
0.88	0.39	2.24	0.03

Inflection Point for Fiber A vs Fiber B

Fiber A had a greater mean number of passes at the inflection point than fiber B, as shown in Table 3.3. However, the results are not statistically significant at the 95% confidence level, as shown in Table 3.4. However, the results are statistically significant at a 90% confidence level.

Table 3.3. Mean Number of Passes at the Inflection Point for Fiber A and B Groups

Fiber Type	Mean Rut Depth at 15,000 Passes (mm)
A	16,815
B	14,788

Table 3.4. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for Fiber A and B Groups

Difference of Means (mm)	SE of Difference (mm)	*t*	Adjusted *p*-value
2,027	1,274	1.59	0.10

Mixes with 15% RAP

Within the 15% RAP group, there was no statistically significant difference between the performance of mixes with fibers A or B. Table 3.5 shows the mean rut depths at 15,000 passes for each group, and Table 3.6 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 15% RAP-fiber A group.

Table 3.5. Mean Rut Depth at 15,000 Passes for the 15% RAP-Fiber A Groups

Group	Mean Rut Depth at 15,000 passes (mm)
15% RAP Control	2.75
15% RAP with 0.05% Fiber A	3.14
15% RAP with 0.10% Fiber A	4.10
15% RAP with 0.15% Fiber A	2.48

Table 3.6. Differences in Mean Rut Depth at 15,000 Passes and Confidence Intervals for 15% RAP-Fiber A Groups

Group Comparison	Difference in Means (mm)	SE of Difference (mm)	*t*	Adjusted *p*-value	Significance at 95%	95% Confidence Intervals
0.05% A – Control	0.39	0.55	0.70	0.90	No	(-1.24, 2.00)
0.10% A – Control	1.35	0.55	2.45	0.12	No	(-0.28, 2.96)
0.15% A – Control	-0.27	0.55	-0.49	0.96	No	(-1.90, 1.35)

Table 3.7 shows the mean rut depths at 15,000 passes for each group, and Table 3.8 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 15% RAP-fiber B group.

Table 3.7. Mean Rut Depth at 15,000 Passes for the 15% RAP-Fiber B Groups

Group	Mean Rut Depth at 15,000 passes (mm)
15% RAP Control	2.75
15% RAP with 0.05% Fiber B	2.30
15% RAP with 0.10% Fiber B	2.93
15% RAP with 0.15% Fiber B	2.50

Table 3.8. Differences in Mean Rut Depth at 15,000 Passes and Confidence Intervals for 15% RAP-Fiber B Groups

Group Comparison	Difference in Means (mm)	SE of Difference (mm)	*t*	Adjusted *p*-value	Significance?	95% Confidence Intervals
0.05% B – Control	-0.45	0.46	-0.99	0.76	No	(-1.19, 0.91)
0.10% B – Control	0.18	0.46	0.35	0.98	No	(-1.18, 1.54)
0.15% B – Control	-0.25	0.46	-0.55	0.94	No	(-1.61, 1.11)

All three fiber A groups performed better than the control group with respect to the number of passes at the inflection point, but these results were not statistically significant as shown in Table 3.9 and Table 3.10.

Table 3.9. Mean Number of Passes at the Inflection Point for the 15% RAP-Fiber A Groups

Group	# of Passes at the Inflection Point
15% RAP Control	13,617
15% RAP with 0.05% Fiber A	16,120
15% RAP with 0.10% Fiber A	17,223
15% RAP with 0.15% Fiber A	17,755

Table 3.10. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for 15% RAP-Fiber A Groups

Group Comparison	Difference in Means (passes)	SE of Difference (passes)	*t*	Adjusted *p*-value	Significance?	95% Confidence Intervals
0.05% A – Control	2,503	2,254	1.11	0.69	No	(-4,543, 9,548)
0.10%$ A – Control	3,606	2,254	1.16	0.43	No	(-3,439, 10,651)
0.15% A – Control	4,138	2,254	1.84	0.32	No	(-2,907, 11,184)

For fiber B, the 0.05% fiber B performed worse, while the 0.10% fiber B and 0.15% fiber B mixes performed better than the control, as shown in Table 3.11. However, none of these results were statistically significant at the 95% confidence level, as shown in Table 3.12.

Table 3.11. Mean Number of Passes at the Inflection Point for the 15% RAP-Fiber B Groups

Group	# of Passes at the Inflection Point
15% RAP Control	13,617
15% RAP with 0.05% Fiber B	11,261
15% RAP with 0.10% Fiber B	16,879
15% RAP with 0.15% Fiber B	13,903

Table 3.12. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for 15% RAP-Fiber B Groups

Group Comparison	Difference in Means (passes)	SE of Difference (passes)	t	Adjusted p-value	Significance?	95% Confidence Intervals
0.05% B – Control	-2,356	5,819	-0.40	0.98	No	(-20,542, 15,830)
0.10% B – Control	3,262	5,819	0.56	0.94	No	(-14,924, 21,448)
0.15% B – Control	286	5,819	0.05	1	No	(-17,900, 18,472)

Mixes with 25% RAP

No statistically significant differences in average rut depth results were found for mixes with 25% RAP level. Table 3.13 shows the mean rut depths at 15,000 passes for each group, and Table 3.14 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 25% RAP-fiber A group.

Table 3.13. Mean Rut Depth at 15,000 Passes for the 25% RAP Fiber A Groups

Group	Mean Rut Depth at 15,000 Passes (mm)
25% RAP Control	4.18
25% RAP with 0.05% Fiber A	5.54
25% RAP with 0.10% Fiber A	4.56
25% RAP with 0.15% Fiber A	4.06

Table 3.14. Differences in Mean Rut Depth at 15,000 Passes and Confidence Intervals for 25% RAP-Fiber A Groups

Group Comparison	Difference in Means (passes)	SE of Difference (passes)	*t*	Adjusted *p*-value	Significance?	95% Confidence Interval
0.05% A – Control	1.36	0.98	1.39	0.53	No	(-1.55, 4.26)
0.10% A – Control	0.38	0.98	0.39	0.98	No	(-2.52, 3.29)
0.15% A – Control	-0.12	0.98	- 0.12	1	No	(-3.02, 2.78)

Table 3.15 shows the mean rut depths at 15,000 passes for each group, and Table 3.16 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 25% RAP-fiber B group.

Table 3.15. Mean Rut Depth at 15,000 Passes for the 25% RAP-Fiber B Groups

Group	Mean Rut Depth at 15,000 Passes (mm)
25% RAP Control	4.18
25% RAP with 0.05% Fiber B	4.68
25% RAP with 0.10% Fiber B	3.57
25% RAP with 0.15% Fiber B	2.67

Table 3.16. Differences in Mean Rut Depth at 15,000 Passes and Confidence Intervals for 25% RAP Fiber B Groups

Group Comparison	Difference in Means (passes)	SE of Difference (passes)	*t*	Adjusted *p*-value	Significance?	95% Confidence Interval
0.05% B – Control	0.50	1.17	0.43	0.97	No	(-2.96, 3.97)
0.10% B – Control	-0.61	1.17	- 0.52	0.95	No	(-4.07, 2.86)
0.15% B – Control	-1.51	1.17	- 1.30	0.58	No	(-4.97, 1.95)

Regarding the number of passes at the inflection point within the 25% RAP groups, all six groups performed better than the control group with a higher number of passes at the inflection point. However, none of these results were statistically significant at the 95% level. Table 3.17 shows the average number of passes at the inflection point, and Table 3.18 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 25% RAP-fiber A group.

Table 3.17. Mean Number of Passes at the Inflection Point for the 25% RAP-Fiber A Groups

Group	# of Passes at the Inflection Point
25% RAP Control	11,916
25% RAP with 0.05% Fiber A	17,562
25% RAP with 0.10% Fiber A	17,136
25% RAP with 0.15% Fiber A	17,884

Table 3.18. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for 25% RAP-Fiber A Groups

Group Comparison	Difference in Means (passes)	SE of Difference (passes)	*t*	Adjusted *p*-value	Significance?	95% Confidence Interval
0.05% A – Control	5,646	3,408	1.66	0.41	No	(-5633, 16926)
0.10% A – Control	5,220	3,233	1.61	0.43	No	(-5480, 15921)
0.15% A – Control	5,968	3,734	1.60	0.44	No	(-6388, 18324)

Table 3.19 shows the average number of passes at the inflection point, and Table 3.20 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 25% RAP-fiber B group.

Table 3.19. Mean Number of Passes at the Inflection Point for the 25% RAP-Fiber B Groups

Group	# of Passes at the Inflection Point
25% RAP Control	11,916
25% RAP with 0.05% Fiber B	17,432
25% RAP with 0.10% Fiber B	12,989
25% RAP with 0.15% Fiber B	16,825

Table 3.20. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for 25% RAP-Fiber B Groups

Group Comparison	Difference in Means (passes)	SE of Difference (passes)	*t*	Adjusted *p*-value	Significance?	95% Confidence Interval
0.05% B – Control	5,516	3,178	1.74	0.37	No	(-4665, 15697)
0.10% B – Control	1,073	3,178	0.34	0.99	No	(-9108, 11255)
0.15% B – Control	4,909	3,670	1.34	0.57	No	(-6847, 16665)

Mixes with 40% RAP

Within the 40% RAP group, there was a significant benefit to adding fiber B to the mix. Adding fiber B at 0.05%, 0.10%, and 0.15% had significantly lower mean rut depths than the control group at 15,000 passes. Table 3.21 shows the mean rut depths at 15,000 passes for each group, and Table 3.22 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 40% RAP group.

Table 3.21. Mean Rut Depth for the 40% RAP-Fiber B Groups

Group	Rut depth @ 15,000 passes
40% RAP Control	6.05
40% RAP with 0.05% Fiber B	3.61
40% RAP with 0.10% Fiber B	3.35
40% RAP with 0.15% Fiber B	3.00

Table 3.22. Differences in Mean Rut Depth and Confidence Intervals for 40% RAP-Fiber B Groups

Group Comparison	Difference in Means (mm)	SE of Difference (passes)	*t*	Adjusted *p*-value	Significance?	95% Confidence Interval
0.05% B – Control	-2.71	0.86	-3.15	0.04	Yes	(-5.26, -0.16)
0.10% B – Control	-3.05	0.86	-3.55	0.02	Yes	(-5.60, -0.50)
0.15% B – Control	-2.44	0.86	-2.84	0.05	Yes	(-5.00, -0.11)

The results were mixed for the effects of fiber on the mean number of passes at the inflection point for the 40% RAP group. The results show that 0.10% fiber B performed slightly better than the control group, while the 0.05% fiber B group performed slightly worse and the 0.15% fiber B group performed significantly worse than the control group. Therefore, there is 95% confidence that adding 0.15% fiber B to the mixture would result in a mean number of passes at the inflection point that is between 8,631 and 17,437 passes lower than the control group. Table 3.23 shows the mean number of passes at the inflection point for each group, and Table 3.24 shows the difference in means and confidence intervals between each fiber percentage and the control group within the 40% RAP group.

Table 3.23. Mean Number of Passes at the Inflection Point for the 40% RAP-Fiber B Groups

Group	**# of Passes at the Inflection Point**
40% RAP Control	16,806
40% RAP with 0.05% Fiber B	16,479
40% RAP with 0.10% Fiber B	17,770
40% RAP with 0.15% Fiber B	3,772

Table 3.24. Differences in Mean Number of Passes at the Inflection Point and Confidence Intervals for 40% RAP-Fiber B Groups

Group Comparison	**Difference in Means (passes)**	**SE of Difference (passes)**	***t***	**Adjusted *p*-value**	**Significance?**	**95% Confidence Interval**
0.05% B – Control	-327	1,318	-0.25	0.99	No	(-4446, 3791)
0.10% B – Control	964	1,409	0.68	0.90	No	(-3439, 5366)
0.15% B – Control	-13,034	1,409	-9.25	<0.01	Yes	(-17437, 8631)

3.3 Cracking Tolerance Index

3.3.1 Introduction

This section presents and interprets the results obtained from the Ideal CT tests conducted on the asphalt mixture samples with 15%, 25%, and 40% RAP. The study aimed to identify the effectiveness of fibers A and B on varying proportions of RAP in enhancing the cracking tolerance of the mixes. The higher the CT_{index}, the better the cracking resistance of the mixture.

3.3.2 Mixtures with 15% RAP

Figure 3.9 shows the CT_{index} values for the mixtures containing 15% RAP with varying fiber proportions, where 15-C represents the control mixture without any fiber, 15-A0.05 represents the asphalt mixture with 0.05% type A fiber, 15-B0.05 represents the asphalt mixture with 0.05% type B fiber, and so forth. The designation 15-C refers to the control mix without fibers, while mixtures such as 15-A0.05 and 15-B0.05 represent mixes with 0.05% type A and type B fibers, respectively, and so forth for other fiber contents and types.

Figure 3.9 presents the CT_{Index} values of different asphalt mixtures, with 15-C serving as the control mix. This control had a CT_{Index} of 80.5, which represents the baseline performance without any modification. Interestingly, one mix, 15-A0.05, performed even lower than the control, with a CT_{Index} of 71.4, indicating that this modification may have negatively affected cracking resistance. All other mixtures outperformed the control, suggesting that the introduction of certain additives or changes in mix design can lead to notable improvements in cracking performance.

Among the modified mixes, 15-B0.05 stands out with the highest CT_{Index} of 164.7—more than double the value of the control—indicating a significantly enhanced resistance to cracking. Meanwhile, 15-A0.10, 15-A0.15, 15-B0.10, and 15-B0.15 all exhibited CT Index values in the range of 109 to 137, clustering around the 100s. These mixtures show consistent improvement over control and suggest that moderate additive content provides effective crack resistance.

Figure 3.9. IDEAL-CT Test Results for 15% RAP Asphalt Mixtures Modified with Varying Fiber Types and Dosages

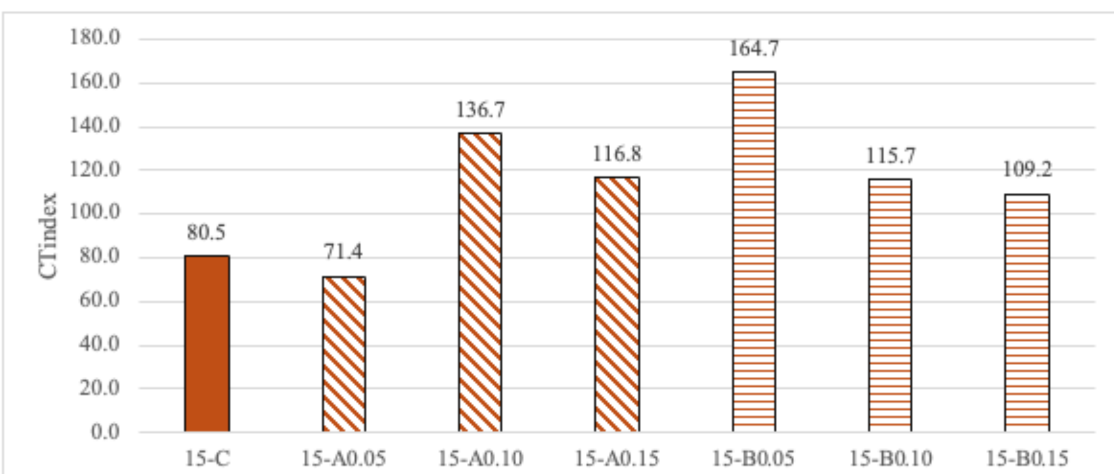


Figure 3.10 displays the load–deformation curves for 15% RAP mixtures containing fiber A. The control mix shows the sharpest post-peak drop, while all fiber-modified mixes exhibit extended deformation. The 0.05% fiber A mix reaches a slightly higher peak load but has limited post-peak improvement. The 0.10% fiber A mix shows both a higher peak and a more gradual decline, indicating increased energy absorption. The 0.15% fiber A mix maintains a similar peak to the

0.10% fiber A mix but demonstrates a steeper post-peak slope than 0.10% fiber A mix, with deformation ending earlier.

Figure 3.10. Comparison of 15% RAP Mixes Containing Fiber A with Control Mix

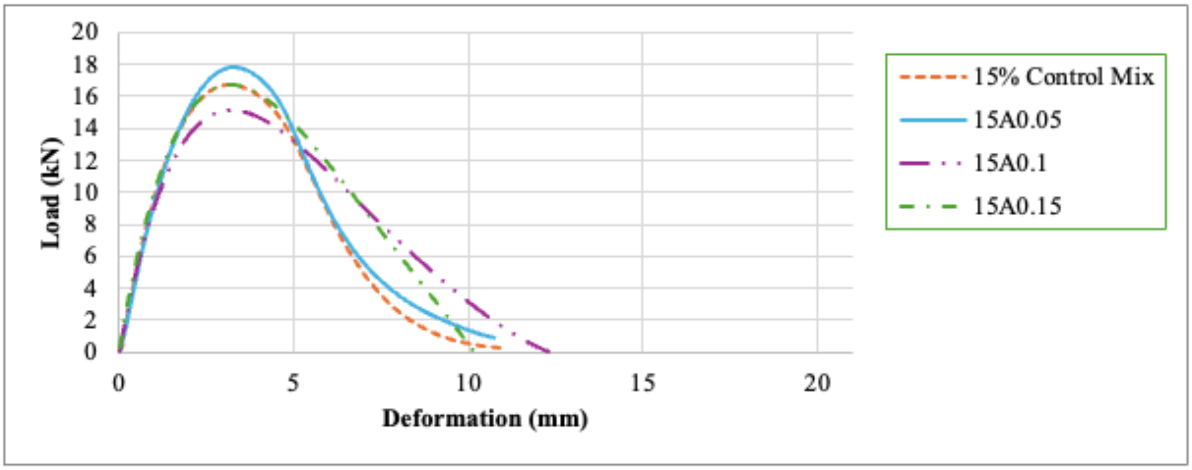
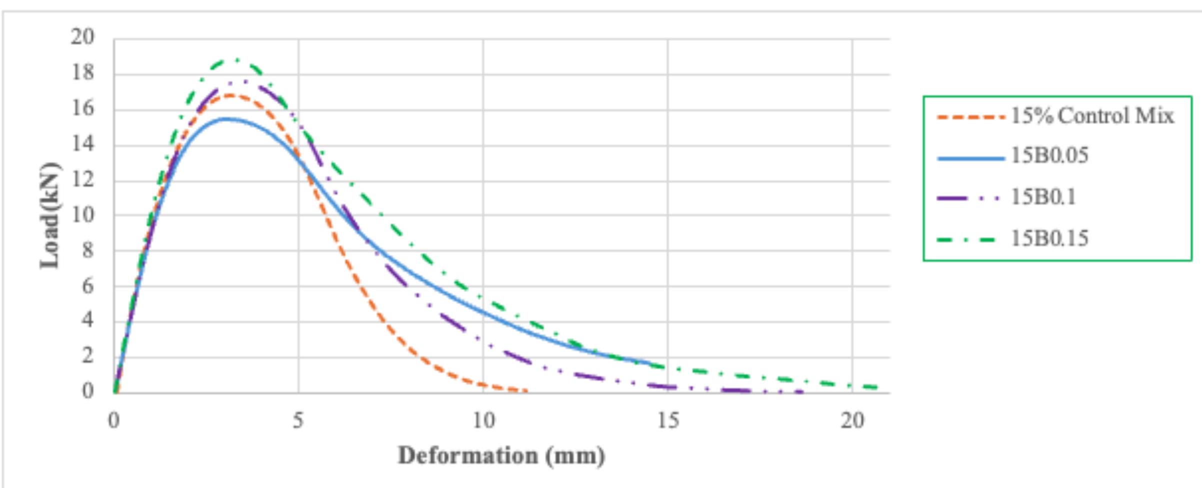


Figure 3.11 presents the performance of fiber B mixes compared to the control. All three fiber B mixes showed broader deformation ranges than the control. The 0.05% mix exhibited a relatively high peak and the most extended post-peak curve. The 0.10% and 0.15% fiber B mixes reached even higher peaks, but their post-peak slopes steepened earlier than the 0.05% mix. The 0.15% mix reached the highest peak compared to the other mixtures.

Figure 3.11. Comparison of 15% RAP Mixes Containing Fiber B with Control Mix



3.3.3 Mixtures with 25% RAP

The mixtures containing 25% RAP were prepared using both A-type and B-type fibers to evaluate their influence on cracking resistance. The control mix without any fiber is labeled 25-C, serving as the baseline for comparison. The A-type fiber-modified mixes are designated as 25-A0.05, 25-A0.10, and 25-A0.15, representing fiber contents of 0.05%, 0.10%, and 0.15%, respectively. Similarly, the B-type fiber-modified mixtures are labeled 25-B0.05, 25-B0.10, and 25-B0.15, corresponding to 0.05%, 0.10%, and 0.15% fiber content, respectively.

Figure 3.12 displays the CT_{Index} values for a different set of asphalt mixtures, with 25-C acting as the control sample. The control mixture had a relatively low CT_{Index} of 43.09, establishing a baseline for cracking resistance in this group. Mixtures 25-A0.05 and 25-A0.15 showed only slight improvements over the control, with CT_{Index} values of 45.35 and 44.56, respectively, indicating negligible gains in cracking resistance. In contrast, 25-A0.1 stands out among the fiber A mixes with a higher CT_{Index} of 95.56—more than double the control—suggesting that this dosage may be optimal within that group.

In the fiber B mixtures, there was a clear trend of increasing CT_{Index} with higher dosages. 25-B0.05 and 25-B0.1 demonstrated notable improvements, with CT_{Index} values of 71.33 and 93.38, respectively. However, 25-B0.15 stands out significantly with a CT_{Index} of 156.36, the highest among all samples. This value is more than three times the control and suggests exceptional cracking resistance. Like the results of 15% RAP mixtures, this dataset highlights one exceptionally high performer, a couple of low or near-control performers, and several mid-range mixes clustering around the 90–100 range, reinforcing RAP content couples with fiber content can interact to significantly impact cracking performance.

Figure 3.12. IDEAL-CT Test Results for 25% RAP Asphalt Mixtures Modified with Varying Fiber Types and Dosages

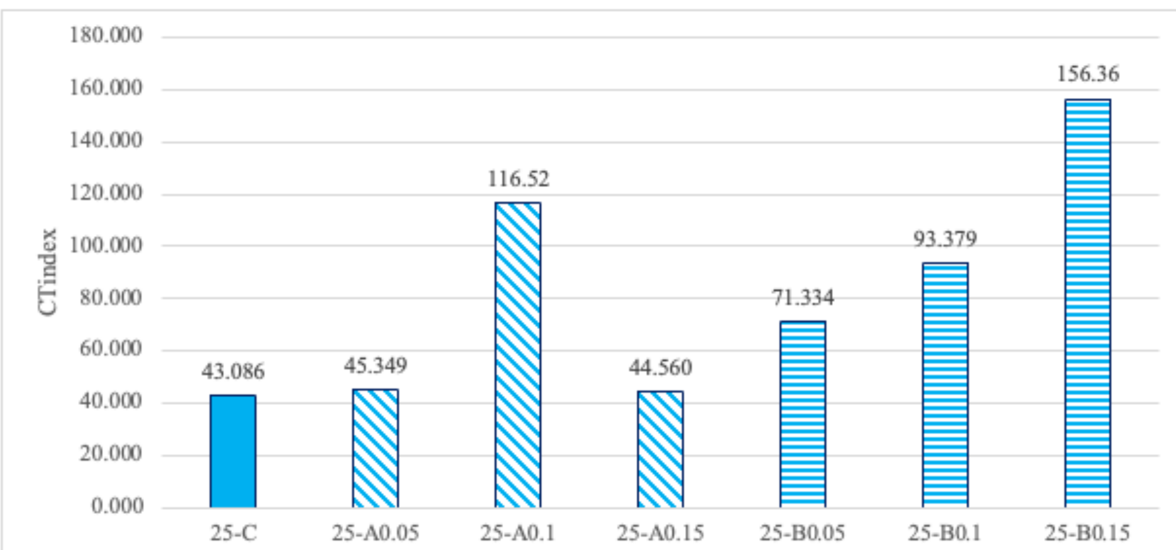


Figure 3.13 shows the Load vs. Deformation curves from the Ideal CT test for the control mix and A-fiber mixtures: 25-A0.05, 25-A0.1, and 25-A0.15. The control mix displays a smooth curve with moderate peak load and deformation, serving as the baseline for comparison. 25-A0.10

demonstrated the most favorable performance, maintaining a relatively high load over a broader deformation range, which indicates improved ductility and resistance to cracking. In contrast, 25-A0.05 and 25-A0.15 both reached higher peak loads than the control but exhibit sharper post-peak declines, suggesting a more brittle response. These trends support the CT Index results, where 25-A0.1 recorded the highest value among the fiber A mixtures, highlighting its balanced strength and fracture resistance.

Figure 3.13. Comparison of 25% RAP Mixes Containing Fiber A with Control Mix

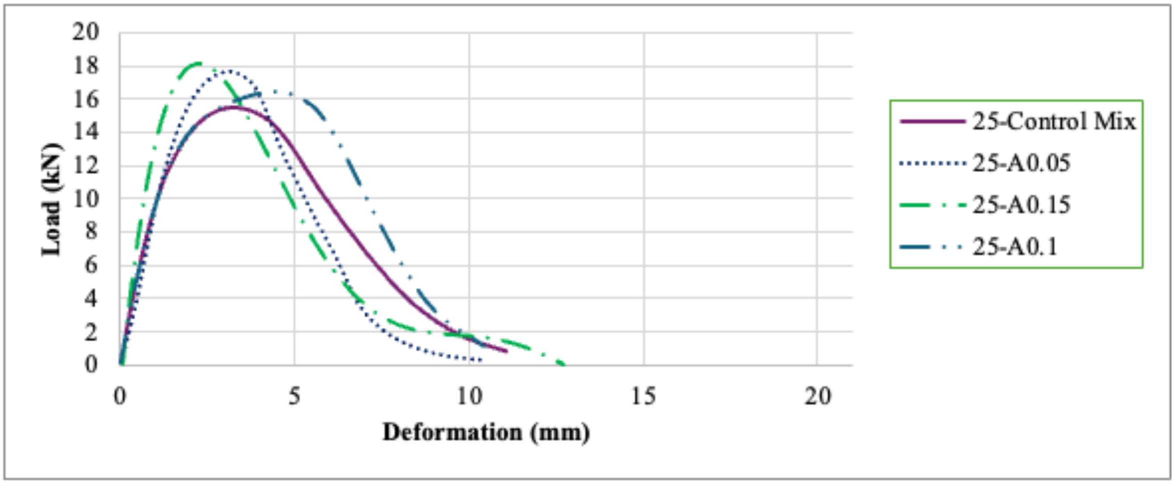
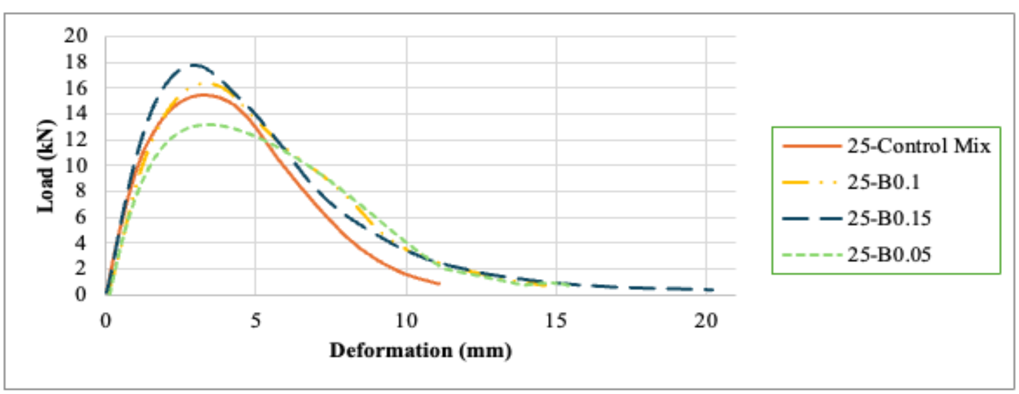


Figure 3.14 illustrates the Load vs. Deformation curves obtained from the Ideal CT test for the control mix and B-series mixtures: 25-B0.05, 25-B0.1, and 25-B0.15. Among these, 25-B0.15 exhibited the most favorable response, achieving the highest peak load and maintaining strength over the widest deformation range, indicating superior cracking resistance and toughness. 25-B0.05, on the other hand, showed a lower peak load and a sharp decline after reaching its maximum, suggesting a more brittle failure mode. The 25-B0.1 mixture and the control mix displayed intermediate behavior, with 25-B0.1 slightly outperforming the control in both peak strength and post-peak ductility. These observations are consistent with the CT Index results, where 25-B0.15 achieved the highest value, reinforcing its excellent cracking performance.

Figure 3.14. Comparison of 25% RAP Mixes Containing Fiber B with Control Mix



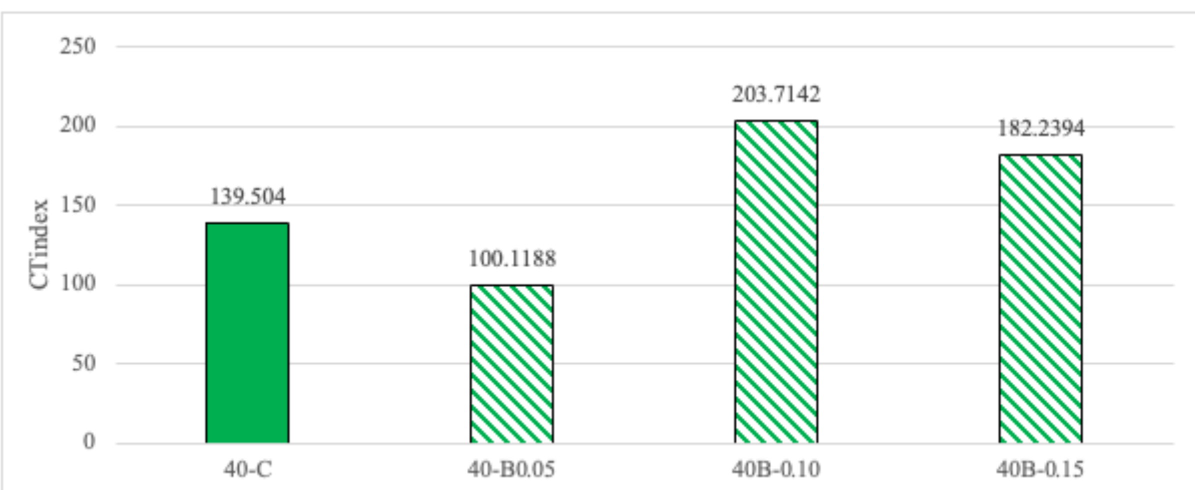
3.3.4 Mixtures with 40% RAP

As was discussed in Section 2, the mixtures containing 40% RAP were prepared using only B-type fibers, with no inclusion of A-type fibers in this series. The control mix without any fiber is labeled 40-C. The fiber-modified mixtures are designated 40-B0.05, 40-B0.10, and 40-B0.15, corresponding to 0.05%, 0.10%, and 0.15% fiber content, respectively. This grouping was designed to isolate and assess the effects of B-type fiber dosage on cracking resistance at elevated RAP levels.

The CTindex values in Figure 3.15 indicate a clear variation in cracking resistance among the 40% RAP mixtures modified with different dosages of B-type fiber. The control mix (40-C) exhibited a moderate CTindex of 139.50, which served as the benchmark for comparison. The 0.05% B-type fiber mix (40-B0.05) yielded the lowest performance, averaging a CTindex of 100.12, which is approximately 28% lower than the control. This reduction suggests that a low fiber dosage may not be sufficient to reinforce the cracking resistance of high-RAP content mixes.

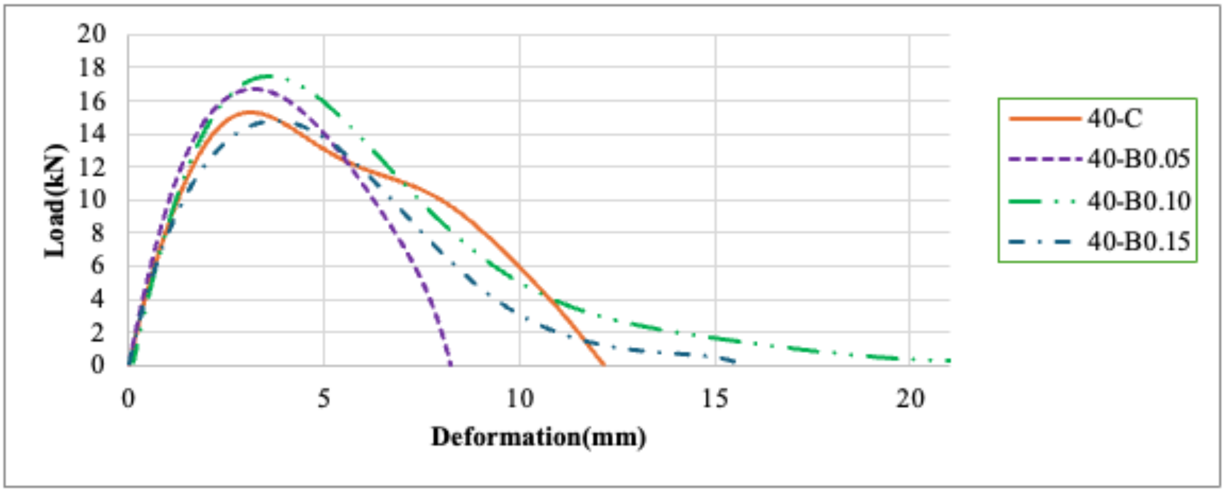
In contrast, both the 10% and 15% fiber mixes showed significant improvements. The 0.10% B-fiber mix (40-B0.10) achieved the highest CTindex, averaging 203.71, marking a 46% increase over the control. The 0.15% B-fiber mix (40-B0.15) also performed well with an average CTindex of 182.24, representing a 31% improvement over the control. These results indicate that moderate to high dosages of B-type fiber substantially enhance crack tolerance in 40% RAP mixtures, with 0.10% fiber content showing the most effective balance of energy absorption and post-cracking resistance. This observation supports the finding from the HWT test where mixes with 0.10% fiber B exhibited the highest resistance to rutting deformation.

Figure 3.15. IDEAL-CT Test Results for 40% RAP Asphalt Mixtures Modified with Varying Dosages



The load-displacement behavior of 40% RAP asphalt mixtures with different B-type fiber contents is depicted in Figure 3.16. Limited crack resistance is shown by the control mix (40-C), which exhibited a moderate peak load followed by a fast post-peak decrease. After breaking, the 40-B0.05 mix has a sharp decline in load, indicating little improvement in post-crack behavior, albeit reaching a slightly higher peak load. The 40-B0.10 mix, on the other hand, showed the longest post-peak curve and the highest peak load, suggesting much improved energy dissipation and fracture resistance. Although the 40-B0.15 mix's peak load was marginally lower than that of the mix with 0.10% fiber content, it also exhibited better post-crack performance.

Figure 3.16. Comparison of 40% RAP mixes containing Fiber B with Control Mix

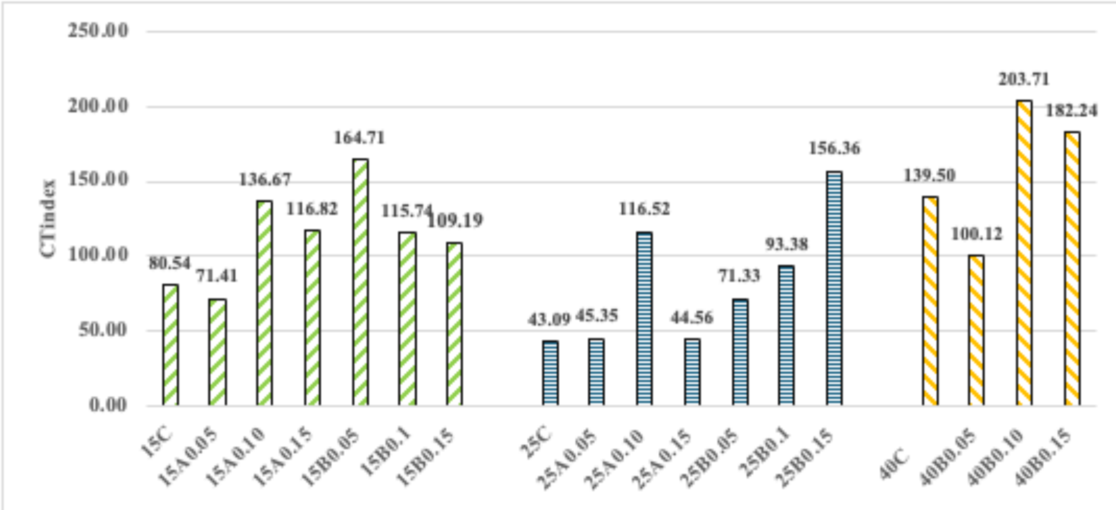


3.3.5 CTI Comparison for All Mix Combinations

Figure 3.17 presents the CT_{index} values of asphalt mixtures incorporating 15%, 25%, and 40% RAP, each modified with different fiber types and dosages. In the 15% RAP group, the control mixture (15C) showed moderate performance, while fiber modification led to varied improvements. Notably, the mix with fiber B at 0.05% dosage exhibited the highest enhancement, while fiber A showed better performance at 0.10% than at lower or higher dosages, suggesting an optimal point of effectiveness.

The control mix with 25% RAP group had the lowest CT_{index}, but fiber additions significantly improved performance, especially with fiber B at 0.15%, indicating a strong response to both fiber type and dosage. In the 40% RAP group, the unmodified mix already had a high CT_{index}, and performance further improved with the addition of fiber B to the mix, particularly at 0.10% and 0.15% dosages.

Figure 3.17. CTindex Values of Asphalt Mixtures with 15%, 25%, and 40% RAP Using Different Fibers and Dosages



A one-way ANOVA followed by Tukey's Honest Significant Difference (HSD) test were conducted to assess the effect of fiber content (0%, 5%, 10%, 15%) on mixture performance across asphalt mixes with different Reclaimed Asphalt Pavement (RAP) contents (15%, 25%, and 40%) and two fiber types (A and B). Each fiber percentage was compared to the control group (0%) to determine statistical significance at 95% confidence intervals. Results are presented in Table 3.25.

Table 3.25. Statistical Significance of Each Fiber Mix Compared to the Control Mix

RAP %	Fiber Type	Fiber Percentage	p-value	Significant at $p < .05$
15%	A	5%	.9359	No
15%	A	10%	.0307	Yes
15%	A	15%	.178	No
15%	B	5%	.0255	Yes
15%	B	10%	.4589	No
15%	B	15%	.6128	No
25%	A	5%	.9979	No
25%	A	10%	.002	Yes
25%	A	15%	.9994	No
25%	B	5%	.81	No
25%	B	10%	.4322	No
25%	B	15%	.0177	Yes
40%	B	5%	.928	No
40%	B	10%	.762	No
40%	B	15%	.9108	No

In the mix containing 15% RAP with fiber type A, the addition of 0.10% fiber resulted in a statistically significant improvement in performance ($p = 0.031$), while the 0.05% and 0.15% fiber contents did not show statistically significant differences compared to the control. For the corresponding mix with fiber type B, only 0.05% fiber content produced a significant enhancement ($p = 0.026$), highlighting the influence of fiber type on performance outcomes.

In the mixtures containing 25% RAP, fiber content played a more selective role. The use of 0.10% fiber yielded a statistically significant performance gain in the mix with fiber type A ($p = 0.002$), whereas 0.05% and 0.15% were not statistically different from the control. Conversely, in the mix with fiber type B, the 0.15% fiber content was the only dosage to produce a statistically significant improvement ($p = 0.018$), while lower percentages remained ineffective.

At a higher RAP level of 40%, no fiber dosage of fiber type B produced a statistically significant change in performance. This may indicate a threshold beyond which fiber reinforcement alone is insufficient to counteract the negative effects of high RAP content.

Overall, these results suggest that the effectiveness of fiber additives is highly dependent on both the RAP content and the fiber properties. Notably, mixes with intermediate RAP levels (15–25%) responded more favorably to fiber modification at specific percentages, underscoring the importance of optimizing fiber dosage and selection as part of a tailored mix design strategy.

3.4 Summary

Results from HWT showed the two fibers performed significantly different. In general, fiber type B outperformed fiber type A in enhancing HMA resistance to rutting. For mixes with 15% RAP adding fibers (regardless of the type) did not seem to improve resistance to rutting as compared with control mix. However, when increasing RAP content to 25 and 40%, fiber type B enhanced mixture's rutting resistance. For mixes with high RAP content (40%), fiber type B significantly improved mixture rutting resistance. Both types of fibers (A and B) enhanced a mixture's stripping resistance, with number of passes at stripping inflection point higher than those for the control mix. For mixes with 15% RAP, the addition of fiber at high dosages (0.10% and 0.15%), improved mixture's cracking resistance compared to the control mix. The control mix with 25% RAP group had the lowest CTindex, but fiber additions significantly improved performance, especially with fiber B at 0.15%, indicating a strong response to both fiber type and dosage. For mixes with high RAP content (40%), resistance to cracking further improved with the addition of fiber B to the mix, particularly at 0.10% and 0.15% dosages.

4. Summary and Conclusions

This study evaluated the use of two types of commercially available polymer fiber to improve the resistance of HMA that contains RAP at different percentages against rutting deformation and cracking at intermediate temperatures. Using three JMFs that were provided by two pavement construction companies, specimens were prepared for testing in the HWT and for CTI. Tables summarizing results from the different tests conducted in this study are presented in Section 2 and the analyses of these results using graphs and statistical analysis are presented in Section 3.

Based on the statistical and other analysis of results in this study, the following conclusions can be made:

4.1 Conclusions:

- In general, fiber type B (treated with liquid emulsion) outperformed fiber type A (wax coated) in enhancing HMA resistance to rutting.
- For mixes with 15% RAP adding fibers (regardless of the type) did not seem to improve resistance to rutting as compared with control mix. However, when increasing RAP content to 25% and 40%, fiber type B enhanced mixture's resistance to rutting.
- For mixes with high RAP content (40%), fiber type B significantly improved resistance to rutting and stripping.
- Both types of fibers (A and B) enhanced the mixture's resistance to stripping, yielding higher numbers of passes at the stripping inflection point than the control mix.
- For mixes with 15% RAP, the addition of fiber at high dosages (0.10% and 0.15%), improved resistance to cracking compared to the control mix.
- The control mix with 25% RAP group had the lowest CTindex, but fiber additions significantly improved performance, especially with fiber B at 0.15%, indicating a strong response to both fiber type and dosage.
- For mixes with high RAP content (40%), resistance to cracking further improved with the addition of fiber B to the mix, particularly at 0.10% and 0.15% dosages.

4.2 Recommendations:

- Agencies and contractors should consider field trials to validate these findings.
- Specs may be updated to allow limited use of such mixes, especially in high-stress zones.

- Cost-effectiveness of fiber use should be evaluated.

Future Research should:

- Test RAP contents above 50%.
- Validate performance through field studies.
- Explore fatigue life and aging behavior.

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