Recycled Crumb Rubber Turf Infill in Asphalt Concrete Mix Design

California Department of Resources Recycling and Recovery

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Contractor's Report
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Executive Summary

This report presents the development and evaluation of both dry and wet methods for incorporating crumb rubber turf infill (CRTI) into asphalt pavement using the Superpave mix design system. The mix design process, along with performance evaluations through laboratory tests such as the Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking Device (HWTD), and Indirect Tensile Asphalt Cracking Test (IDEAL-CT), were conducted to assess the properties and performance of asphalt mixtures containing CRTI. The following conclusions can be drawn from this project:

- In the dry method, all asphalt mixtures containing CRTI exhibit lower rutting resistance than conventional control hot-mix asphalt (HMA). While they meet moisture requirements, they fail the rutting criteria according to the APA test, except for the asphalt-turf mix with 3% Turf-AB.
- Similar to the dry method, the wet method using turf rubber infill SF1 mixtures demonstrates lower performance than traditional control HMA in terms of rutting resistance, according to the APA test. No moisture damage is observed during the testing.
- The binder test indicated that incorporating CRTI into asphalt using the wet method enhances its properties, especially at high temperatures and with aging. The higher complex shear modulus elastic portion, $G^*/\sin(\delta)$ values reflect improved durability and deformation resistance, making this rubber-modified asphalt suitable for hot climates.
- In contrast to the binder test, the high optimum binder content from the mix design of the wet method and the lack of fine aggregates in the Turf SF1 gradation may contribute to its poor rutting resistance through the APA test.
- The IDEAL-CT test indicates that the asphalt mixtures containing turf rubber infill in the wet method demonstrate excellent resistance to fatigue cracking.
- Asphalt mixtures containing turf rubber infill showed lower resistance to rutting when they had higher air void content than mixtures with lower air void content, regardless of whether dry or wet methods were used.
- The rutting resistance of the dry-method samples exceeds that of the SF1 sample produced using the wet method.
- Controlling air voids is essential for improving rutting resistance in asphalt-turf mixtures.
- Turf rubber asphalt mixtures are ideal for thin hot mix asphalt overlays less than 1.5 inches (37.5 mm) thick, as they can help reduce rutting, enhance cracking resistance, and improve pavement life.

This research demonstrates the feasibility of incorporating CRTI materials into asphalt mixtures using both dry and wet methods. However, further studies are needed to refine these findings. For the dry method, future work should explore different turf rubber proportions and material types, along with additional performance tests like the IDEAL-CT for testing cracking resistance. In the wet method, asphalt rubber binders should be developed by blending asphalt with crumb rubber turf infill in varying amounts, and different turf types should be tested. Additionally, improving the rutting resistance of asphalt-turf mixtures remains a key area for future research.

Introduction

Background

The Department of Resources Recycling and Recovery (CalRecycle) currently promotes the use of waste tires in various asphalt pavement applications to divert waste tires from landfills in California. Beyond waste reduction, incorporating tire-derived materials can enhance pavement performance. To improve these strategies, CalRecycle proposes to investigate the feasibility and benefits of using crumb rubber turf infill (CRTI) from synthetic turf athletic fields in asphalt pavement.

Figure 1 shows the components of synthetic turf fields. One of the most important elements is the infill layer, which enhances traction and provides shock absorption. Crumb rubber has long been the preferred choice for turf infill. An estimated 95% of existing fields in North America utilize recycled rubber infill, either exclusively or in combination with sand. Only 5% of fields are comprised solely of alternative infills (Thomas et al. 2019).

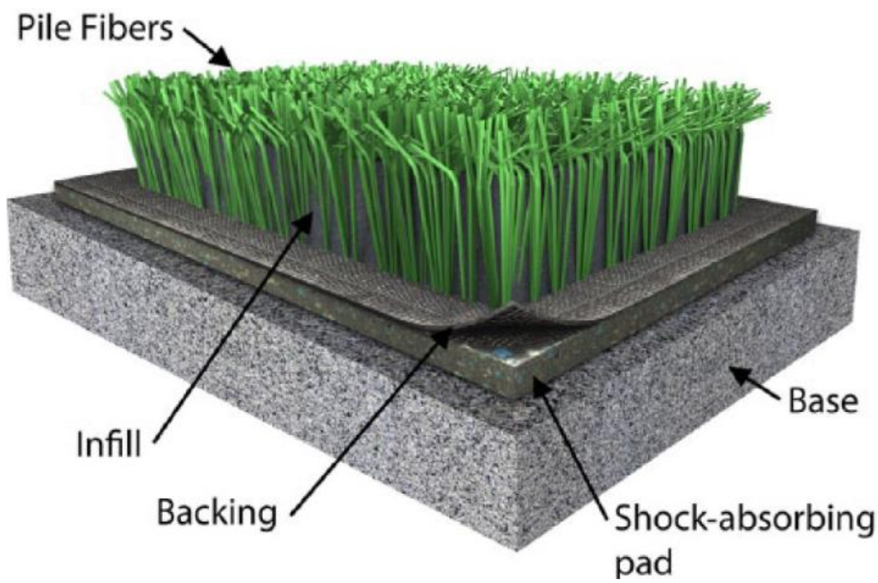


Figure 1. Components of Synthetic Turf, Including Crumb Rubber Infill (Jastifer Et Al. 2019)

Crumb rubber refers to any material made by reducing scrap tires or other rubber into uniform granules while removing all reinforcing materials (Fini 2016). It is produced by grinding used tires, during which steel and fiber tire components are removed, and the rubber pellets are sorted by size. Pellet sizes from one-sixteenth to one-quarter inch in diameter are utilized in synthetic turf (Information About Crumb-Rubber Infilled Synthetic Turf Athletic Fields 2018).

Crumb rubber is employed in various products, including playgrounds, sports surfacing, and rubber-modified asphalt. It is recognized for its use as a filler in synthetic turf fields, enhancing the texture and feel of the artificial grass blades and resulting in a more natural appearance (Information About Crumb-Rubber Infilled Synthetic Turf Athletic Fields 2018).

According to Synthetic Turf Council (STC), there are approximately 12,000 to 13,000 synthetic turf fields in the United States, with about 1,200 to 1,500 new installations annually (Benson, Kelsey, et al. 2019). The STC estimates that up to 1,000 fields may be removed each year nationally, with roughly 10% of those in California (Department of Toxic Substances Control Safer Consumer Products Program 2024). Since 2008, 4–6% of scrap tires in California have been utilized as turf infill (Crumb Rubber Manufacturers, n.d.).

Although there has been a general decline in the use of crumb rubber in turf infill since 2015, mainly due to the cautious stance of California feedstock suppliers and potential users awaiting the results of the Office of Environmental Health Hazard Assessment (OEHHA) study on potential health risks, the market has shown some resilience. In 2021, approximately 140–150 new synthetic turf fields were installed in California, consisting mostly of newly built fields along with some replacements for those that had reached the end of their service life (CalRecycle, 2021). In 2022 and 2023, California producers supplied 20 million pounds of crumb rubber for infill use in new and replacement fields, representing a slight increase compared to 2021, equivalent to 1,618 additional tons (CalRecycle 2022, CalRecycle 2023).

An average synthetic turf athletic field measuring 80,000 square feet typically contains around 200,000 to 225,000 pounds of crumb rubber (Louis Berger 2016). This crumb rubber often combined with sand, becomes difficult to separate and recycle. Consequently, the excavated material is typically sent to landfills and is unsuitable for reuse in conventional crumb rubber applications. This disposal method contributes substantially to greenhouse gas emissions. However, recycling CRTI can conserve significant amounts of energy and help lower these emissions (Crumb Rubber Manufacturers, n.d.). Given these challenges, integrating CRTI into asphalt pavement offers a promising and sustainable reuse option.

Project Objectives

The main objective of this study is to investigate various methods for incorporating CRTI into asphalt mixtures for pavement applications. Dry and wet methods were developed using the Superpave method for asphalt mix design. Performance tests, including the Asphalt Pavement Analyzer (APA), Hamburg Wheel Track Test, and Indirect Tensile Asphalt Cracking Test (IDEAL-CT), were conducted to evaluate the rutting, fatigue, and moisture damage properties of turf-infused asphalt mixtures. Several key questions must be addressed in this project:

- How does the performance of turf mixtures compare with conventional asphalt mixtures in terms of resistance to rutting, fatigue, and moisture damage under performance testing?
- Do different types of turf materials affect the performance of asphalt mixtures, and if so, in what ways?

- Which method of incorporating turf rubber infill yields better results: the dry method or the wet method?
- What lessons can be learned from the laboratory results, and how might they inform future implementation or research?

Literature Review

The dry and the wet processes have been recognized as the primary methods to incorporate crumb rubber into asphalt mixture. In the dry process, crumb rubber serves as a partial substitute for fine aggregates in the asphalt mixture. Meanwhile, the wet process involves blending crumb rubber with the binder, where it functions as an additive to improve the properties of the asphalt binder (Bressi et al. 2019).

The dry process exhibits several advantages, such as the potential to utilize a higher amount of crumb rubber, thereby saving energy and resources while addressing environmental concerns. This process also can be implemented with minimal modifications to existing asphalt plants (Guerrero-Bustamante et al. 2024). However, the main disadvantage of the dry process is that when large amounts of crumb rubber are used, insufficient cohesion between the crumb rubber and the asphalt binder can result in poor pavement performance (Riekstins and Barbars 2021). Additionally, the performance of crumb rubber pavements using the dry process has been observed to be inferior and less stable compared to those produced with the wet process (Bressi et al. 2019).

Rubberized asphalt produced via the wet process provides several benefits. The enhanced properties of the asphalt binder from the wet process improve the overall asphalt mixture characteristics, leading to better resistance against rutting, cracking, and moisture-related distress in asphalt mixtures (Riekstins and Barbars 2021, Poovaneshvaran et al. 2021). The main drawback is that this method demands significant adjustments to the facilities to achieve a homogeneous blend of crumb rubber in the asphalt binder. Moreover, incorporating crumb rubber in the wet process increases the viscosity of the binder, necessitating higher temperatures to ensure the required workability and fluidity during mixing (Guerrero-Bustamante et al. 2024).

According to the Environmental Protection Agency (EPA), state departments of transportation are using large quantities of asphalt rubber. States such as Arizona, California, Florida, Nebraska, and Texas are presently using large amounts of asphalt rubber. South Carolina, Georgia, Illinois, Massachusetts, Michigan, Missouri, New York, New Mexico, and Virginia have also been studying rubberized asphalt (Fini 2016; William G. Buttlar 2023).

In 1975, California started using asphalt rubber as chip seals in laboratory experiments and small test patches, and the results were promising. The first California dry process rubber-modified asphalt concrete pavement included 1% ground rubber by mass added to the aggregate. The wet process has been extensively used; it was first implemented on pavement in California in 1980. Caltrans has built 17 wet-process coat installations and reported that rubberized asphalt concrete (RAC) outperformed conventional thicker, dense-graded concrete by showing a lower extent of pavement distress (Fini 2016). Moreover, over the past two decades, 20% of cost savings were achieved for California road paving using rubberized asphalt (Crumb Rubber Manufacturers, n.d.).

Several studies have shown that rubberized asphalt offers enhanced resistance to rutting, with rutting resistance improving as the percentage of crumb rubber increases (Shatanawi and Amirkhanian 2008, Mashaan et al. 2014). Adding crumb rubber also reduces penetration, temperature susceptibility, and ductility while increasing the softening point, elastic recovery, and adhesion (Shen, Junan, et al. 2009). Furthermore, incorporating specific additives into crumb rubber further enhances its rheological properties (Fini 2016).

Studies also indicated that asphalt-rubber binders can significantly improve pavements' thermal cracking and high-temperature performance. Asphalt-rubber spray applications, such as chip seals, are particularly effective in mitigating reflective cracking in warmer climates (Fini 2016). Additionally, open-graded asphalt-rubber friction courses demonstrate superior durability in hotter regions compared to traditional friction courses (Fini 2016). Other research highlights that the primary benefit of adding rubber to asphalt is its increased elasticity to the binder, which enhances pavements' fatigue life and resistance to reflective cracking. This elasticity also improves flexibility and reduces susceptibility to low-temperature cracking (Davison, R. R. 2000; Mashaan et al. 2014, Nanjegowda, V. H. 2023).

The use of crumb rubber in asphalt reinforcement is widely regarded as a smart and sustainable solution, as it improves pavement performance and reuses waste materials. Crumb rubber modifier (CRM) has the potential to serve as an alternative polymer material, significantly improving the performance properties of hot-mix asphalt (Mashaan et al. 2014). Additionally, incorporating rubber into asphalt is environmentally beneficial, as it helps reduce solid waste while lowering traffic noise levels (Davison, R. R. 2000).

Although numerous applications and benefits of incorporating crumb rubber into asphalt pavement have been reported, there is a notable gap in research regarding the recycling and repurposing of materials from turf athletic fields, such as CRTI. Despite the growing interest in these sustainable practices, no comprehensive studies have been conducted to evaluate the use of CRTI in asphalt concrete pavements. As a result, the performance and viability of asphalt pavements containing CRTI remain uncertain.

To address this gap, this study investigated the feasibility of using CRTI in hot-mix asphalt. Two methods were developed: the dry method, in which the CRTI is added directly to the aggregate, and the wet method, in which it is blended with the asphalt binder to create asphalt rubber binder. The laboratory testing and evaluation components of this study aim to assess the viability and performance of these modified asphalt mixtures, providing valuable insights into potential recycling strategies for CRTI.

Develop a Dry Method using CRTI

In the dry method, a small portion of the fine aggregate (typically 1–3% by weight of the total aggregate in the mix) is replaced with granulated or ground rubber and/or crumb rubber. These rubber particles are blended with the aggregate before adding the asphalt cement (Chesner, W. H., 2002). The dry method for incorporating CRTI involves several steps*:

- Mix design: A conventional asphalt mixture (control mixture) is designed.
- Gradation analysis: Analyze the turf crumb rubber infill material gradation to determine compatibility with aggregates.
- Incorporation of CRTI: CRTI is incorporated into the approved aggregate gradation from the mix design by substituting a specific percentage of crushed dust in the aggregate. The combination of the aggregate and turf rubber infill is modified to meet gradation specification requirements.
- Specimen preparation: Specimens are prepared for performance evaluation using a Superpave gyratory compactor.
- Performance testing: Laboratory performance tests were conducted on both the control mixtures and asphalt mixtures containing turf rubber infill to evaluate their respective performance characteristics.

Detailed descriptions of each step are provided in the following sections.

Conduct Mix Design for the Control mixture

Asphalt Binder: Asphalt pavement design today primarily follows the Superpave system, as outlined by American Association of State Highway and Transportation Officials (AASHTO) standards and procedures. In the Superpave design method, the performance grade (PG) binder required for a project is determined based on factors such as environmental conditions, traffic levels, and traffic speeds. For this particular project, a PG 64-16 binder was selected.

A Dynamic Shear Rheometer (DSR) test was conducted to assess the behavior of the asphalt binder. To evaluate the binder’s short-term aging, the DSR test was conducted after aging the binder using the Rolling Thin Film Oven (RTFO) method. The original binder was tested at 64°C, with temperatures increasing in 6°C intervals until failure, using three samples for each testing temperature. In addition, DSR test was also conducted after short-term aging and 1-day ultraviolet (UV)-aging to investigate the effectiveness of short-term and UV-aging to the asphalt binder.

The DSR test results indicated that at 64°C, all three samples passed the test, with $G^*/\sin(\delta)$ values of 1.31, 1.32, and 1.35 for samples 1, 2, and 3, respectively. However, at 70°C, all samples failed the DSR test, with $G^*/\sin(\delta)$ values of 0.62, 0.63, and 0.63, all below the minimum required value of 1 kPa for $G^*/\sin(\delta)$ according to AASHTO T 315 “Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)”.

* The optimum binder content determined during the mix design is applied to the CRTI asphalt mixture.

The minimum required G*/sin(δ) value for short-term aging is 2.2 kPa (AASHTO T 315). The DSR test conducted after aging the binder using the RTFO method indicated that all three samples passed at 64°C, with G*/sin(δ) values of 3.67, 3.76, and 3.83. However, at a higher temperature, the samples failed, showing G*/sin(δ) values of 1.64, 1.67, and 1.69. In addition, the DSR test conducted on RTFO and UV samples reveal that G*/sin(δ) values significantly increase under these RTFO and UV conditions. The DSR test results were summarized in Table 1.

Table 1. DSR Test Results for PG 64-16 Asphalt Binder

Binder Condition	Test Temperature (°C)	Superpave Minimum G*/sin(δ) (kPa)	Sample 1	Sample 2	Sample 3	Pass/Fail
Original (Unaged)	64	≥ 1.00	1.31	1.32	1.35	Pass
Original (Unaged)	70	≥ 1.00	0.62	0.63	0.63	Fail
RTFO-Aged (Short-Term)	64	≥ 2.20	3.67	3.76	3.83	Pass
RTFO-Aged (Short-Term)	70	≥ 2.20	1.64	1.67	1.69	Fail
RTFO-Aged (Short-Term) + UV-Aged	64	≥ 2.20	20.8	25.8	23.3	Pass
RTFO-Aged (Short-Term) + UV-Aged	70	≥ 2.20	9.6	12.0	10.8	Pass
RTFO-Aged (Short-Term) + UV-Aged	76	≥ 2.20	4.7	5.6	5.00	Pass
RTFO-Aged (Short-Term) + UV-Aged	82	≥ 2.20	2.2	2.7	2.4	Pass
RTFO-Aged (Short-Term) + UV-Aged	88	≥ 2.20	1.1	1.4	1.2	Fail

Both non-aged and aged samples failed at 70°C for binder PG 64-16, yielding consistent results across all samples. Based on these findings, it can be concluded that the binder is unsuitable for use at very high temperatures. Figure 2 displays the DSR test results for both the original and short-term aged asphalt binder.

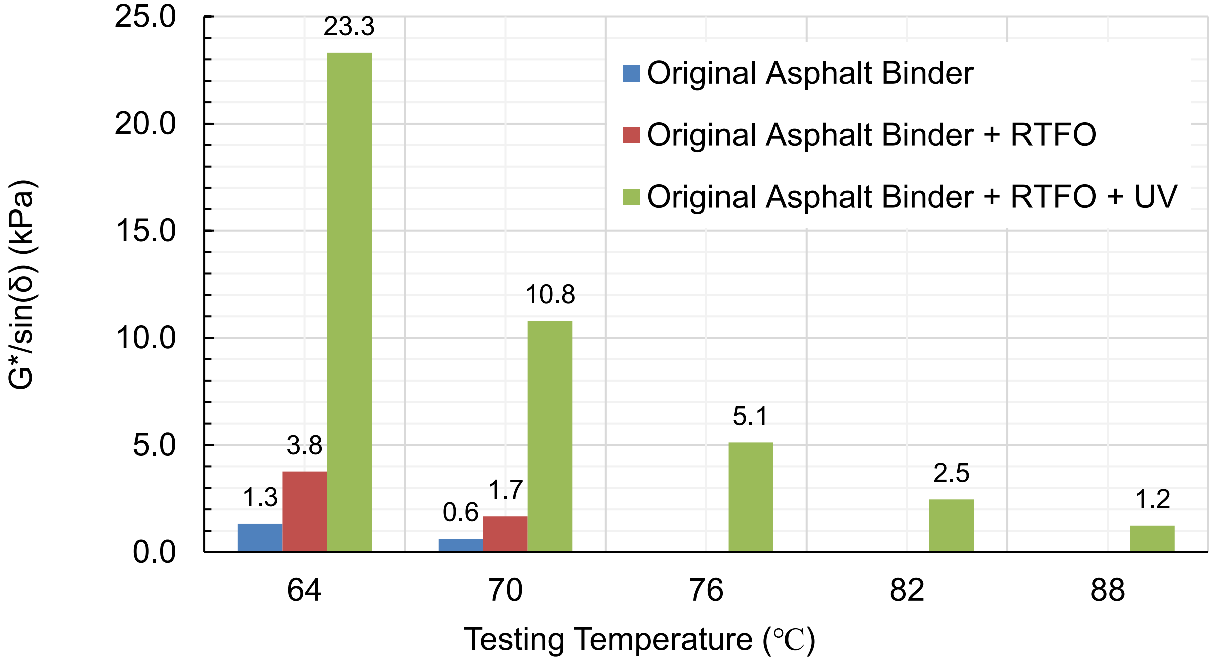


Figure 2. DSR Test Results: Superpave Rutting Parameter vs. Temperature

Figure 3 presents phase-angle results from DSR testing. The phase angle decreases under both short-term aging and UV-aging. On average, short-term aging reduces the phase angle by 4.5%, whereas the combination of short-term aging and UV-aging produces a larger reduction of 14.0%. These results indicate that UV-aging has a pronounced additional effect on the viscoelastic response (less viscous and more elastic behavior) of the original asphalt binder.

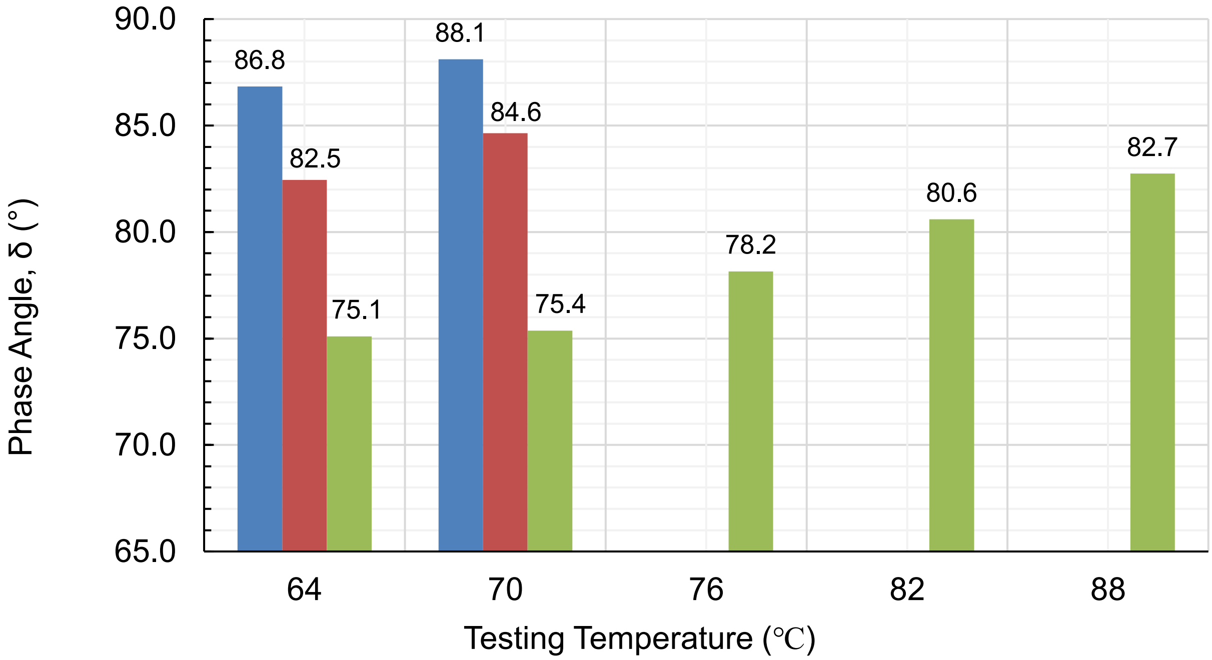


Figure 3. DSR Test Results: Phase Angle vs. Temperature

Aggregate: The aggregate was sourced from Knife River Construction (KRC) in Orland, CA, utilizing six stockpiles of materials: three coarse aggregates, two fine aggregates, and one reclaimed asphalt pavement (RAP), as detailed in Table 2. Materials from each bin were sieved to determine their gradation, as illustrated in Figure 4. The proportions of materials from each bin were then calculated using a trial method to create a blended aggregate that meets the specification limits for gradation. The resulting gradation of the blended aggregate, as shown in Figure 5, meets all specification limits, confirming the blend's suitability for use in asphalt mixture design.

Table 2. Aggregate Gradations from Different Stockpiles and Combined Gradation

Bin	**1**	**2**	**3**	**4**	**5**	**RAP**	**Combined Gradation**	**Specification Limits**
Material Size	**3/4"**	**1/2"**	**3/8"**	**Crushed Dust**	**Washed Dust**	**5/8"**		
Weight, g	234.0	561.5	351.0	280.8	561.5	351.0	2339.8	
Cumulative Weight, g	234.0	795.5	1146.5	1427.2	1988.8	2339.8		
Bin %	10	24	15	12	24	15	100	
Sieve Size	Percent Passing							
2"	100	100	100	100	100	100	100.0	
1 1/2"	100	100	100	100	100	100	100.0	
1"	100	100	100	100	100	100	100.0	
3/4"	88.6	100	100	100	100	100	98.9	93-100
1/2"	5.9	63.3	100	100	100	93.7	80.8	76-88
3/8"	1.7	12.8	91.5	100	100	83.8	65.5	
No. 4	0.8	1.3	10.8	96.6	96.8	58.5	45.6	42-52
No. 8	0.7	0.9	3.0	66.8	63.7	41.0	30.2	25-35
No. 16	0.6	0.8	1.9	48.6	41.4	29.6	20.7	
No. 30	0.6	0.6	1.3	36.5	26.8	21.6	14.5	10-18
No. 50	0.6	0.5	0.8	27.0	16.0	15.0	9.6	
No. 100	0.6	0.4	0.6	19.1	7.2	10.1	5.8	
No. 200	0.60	0.40	0.4	14.02	2.46	7.33	3.6	1.5-5.4

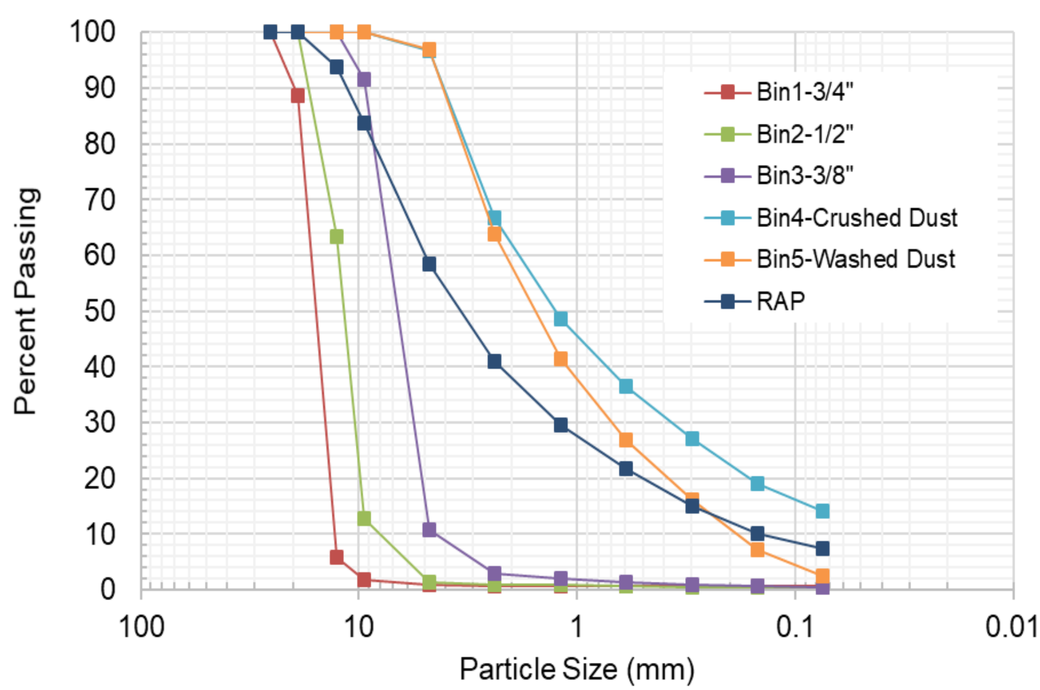


Figure 4. Gradation of Materials from Different Stockpiles

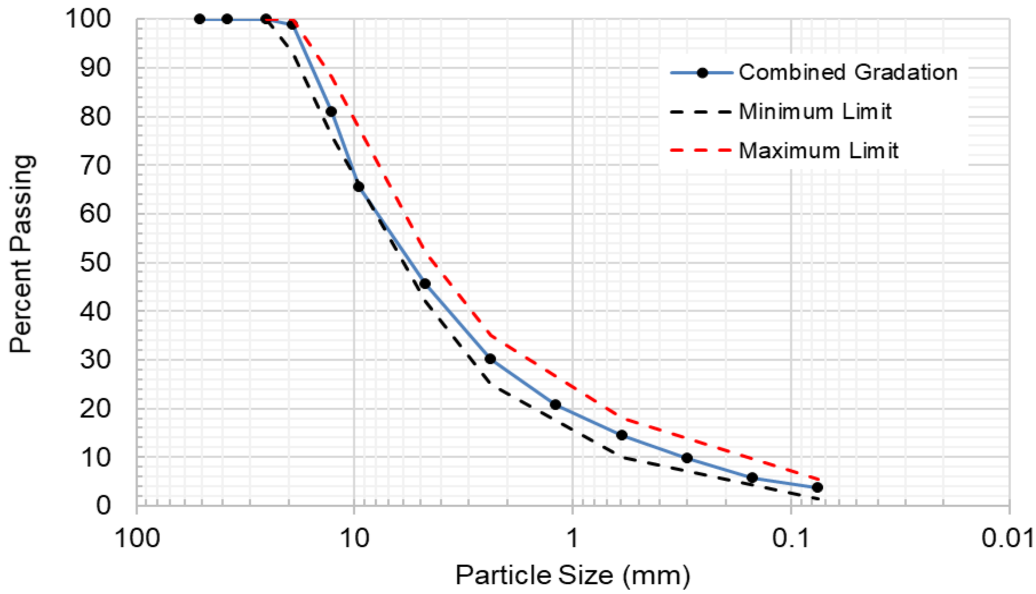


Figure 5. Gradation of the Combined Aggregate and Gradation Limits

In addition, a series of aggregate tests were conducted to ensure that the aggregates meet the necessary requirements for use in the asphalt mixture. Table 3 presents the details of these tests and their results. All tests were carried out by Knife River Construction, ensuring reliable and accurate results. The aggregate characteristics were thoroughly examined, and the results indicate that all tested aggregates satisfy the required specifications for use in asphalt mixtures.

Table 3. Aggregate Quality Tests

<table>
<tr><th colspan="6">AGGREGATE QUALITY*</th></tr>
<tr><th>Quality Characteristics/Property</th><th>Test Method</th><th colspan="4">Test Result</th></tr>
<tr><td>Crushed particles, coarse aggregate One fractured face (%)</td><td>AASHTO
T 335
Method 2</td><td colspan="4">99%</td></tr>
<tr><td>Crushed particles, coarse aggregate
Two fractured faces (%)</td><td>AASHTO
T 335
Method 2</td><td colspan="4">95%</td></tr>
<tr><td>Crushed particles, fine aggregate
(Passing No. 4 sieve and retained on No. 8 sieve)
One fractured face (%)</td><td>AASHTO
T 335
Method 2</td><td colspan="4">95%</td></tr>
<tr><td>Fine aggregate Durability Index</td><td>AASHTO
T 210</td><td colspan="4">65</td></tr>
<tr><td>Coarse aggregate Durability Index</td><td>AASHTO
T 210</td><td colspan="4">91</td></tr>
<tr><td rowspan="2">Sand equivalent</td><td rowspan="2">AASHTO
T 176</td><td>1</td><td>2</td><td>3</td><td>Average</td></tr>
<tr><td>72</td><td>69</td><td>69</td><td>70</td></tr>
<tr><td>Fine aggregate angularity (%)</td><td>AASHTO
T 304
Method A</td><td colspan="4">48.3%</td></tr>
<tr><td>Los Angeles Rattler, Loss at 100 Rev. (%)</td><td>AASHTO T 96</td><td colspan="4">4%</td></tr>
<tr><td>Los Angeles Rattler, Loss at 500 Rev. (%)</td><td>AASHTO T 96</td><td colspan="4">16%</td></tr>
<tr><td>Flat and elongated particles (% by mass at 5:1)</td><td>ASTM D 4791</td><td colspan="4">0</td></tr>
<tr><td>Plasticity Index</td><td>California Test 204</td><td colspan="4">NP</td></tr>
<tr><td>Bulk specific gravity (oven dry) of coarse aggregate</td><td>AASHTO T 85</td><td colspan="4">2.751</td></tr>
<tr><td>Absorption of coarse aggregate</td><td>AASHTO T 85</td><td colspan="4">1.4%</td></tr>
<tr><td>Bulk specific gravity (SSD) of fine aggregate</td><td>AASHTO T 84</td><td colspan="4">2.665</td></tr>
<tr><td>Bulk specific gravity of fine aggregate</td><td>AASHTO T 84</td><td colspan="4">2.611</td></tr>
<tr><td>Apparent specific gravity of fine aggregate</td><td>AASHTO T 84</td><td colspan="4">2.760</td></tr>
<tr><td>Apparent specific gravity of supplemental fines</td><td>AASHTO T 84</td><td colspan="4">N/A</td></tr>
<tr><td>Absorption of fine aggregate</td><td>AASHTO T 84</td><td colspan="4">2.1%</td></tr>
<tr><td>Bulk specific gravity of the aggregate blend</td><td>SP-2
Asphalt
Mixtures</td><td colspan="4">2.687</td></tr>
<tr><td>Bulk specific gravity of the virgin RAP aggregate blend</td><td>SP-2
Asphalt
Mixtures</td><td colspan="4">2.698</td></tr>
</table>

The mix design was done by KRC's laboratory. Specifically, after conducting asphalt binder and aggregate tests, asphalt mixtures with binder contents of 4.0%, 4.5%, 5.0%, and 5.5% were prepared for the mix design process. Specimens were then fabricated using the Superpave gyratory compactor, following the Superpave compaction criteria, which are based on three key stages of compaction: initial ($N_{initial}$), design (N_{design}), and maximum (N_{max}) numbers of gyrations. According to Caltrans standard specifications, $N_{initial}$, N_{design}, and N_{max} correspond to 8, 85, and 130 gyrations, respectively (California Department of Transportation, Standard Specifications. 2024).

The aggregate in the asphalt mixture is of the ¾" gradation, hot-mix in-place type. Caltrans specifies specific criteria for a ¾" gradation and this type of hot-mix asphalt:

- Air void (AV) content at N_{design} must range from 2.5% to 5.5%,
- Voids in mineral aggregate (VMA) must be between 12.5% and 15.5%, and
- Dust proportion should range from 0.6 to 1.3.

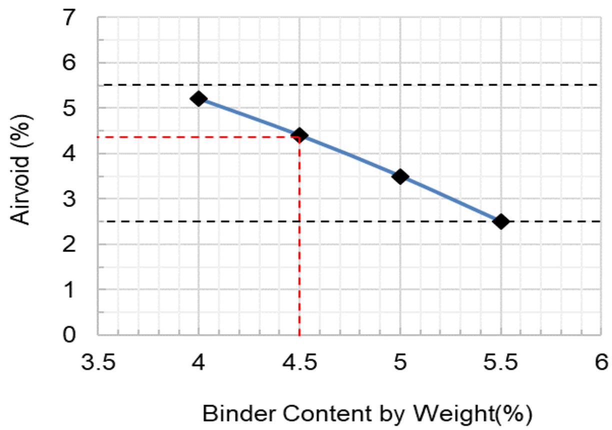
At a binder content of 4.5%, the mix achieved the corresponding values:

- AV: 4.3%,
- VMA: 12.5%,
- Voids filled with asphalt (VFA): 66%,
- Dust proportion: 1.32, and
- Unit weight: 153.9 lbs/ft³.

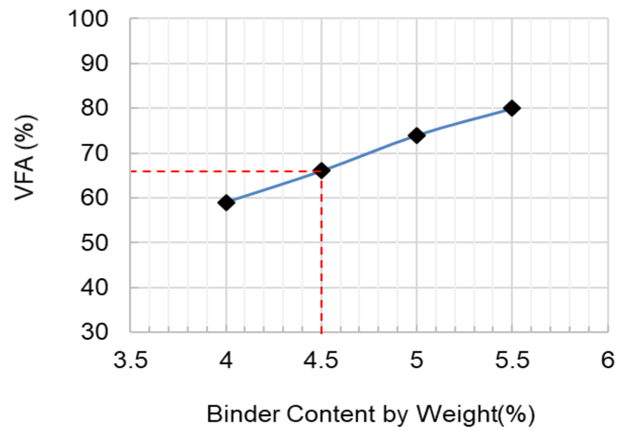
These values were obtained from the mix design process. Based on the results, all specified conditions were satisfied at this binder content, except for the dust proportion, which exceeded the upper limit of the Caltrans specification range by a small margin (1.32 compared to the upper limit of 1.30). However, this deviation was considered negligible and unlikely to significantly affect the mixture's performance. Consequently, a binder content of 4.5% was selected as the optimum binder content for the control mixture.

Figure 6 provides a comprehensive depiction of the relationships between binder content and critical parameters, including air void content, VMA, VFA, dust proportion, and unit weight. The red lines in the figure mark the optimum binder content and its corresponding parameter values, serving as a reference point for evaluating compliance with design requirements. The black lines represent the Caltrans specification limits, highlighting the acceptable range for each parameter.

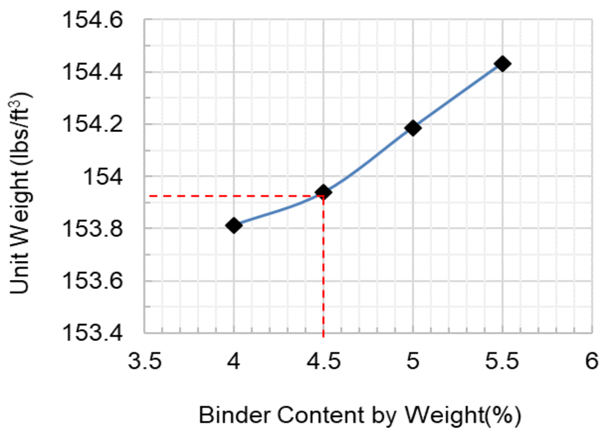
This graphical representation underscores how the selected binder content of 4.5% achieves a balance between multiple performance criteria, meeting design requirements while ensuring material compatibility. The slight exceedance in the dust proportion parameter is shown to have minimal impact when considering the overall performance of the mix, further supporting the decision to adopt this binder content for the control mixture.



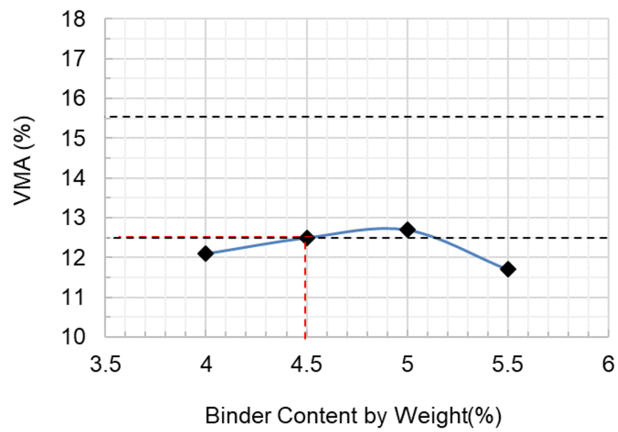
a) Binder Content vs. Air Void



b) Binder Content vs. VFA



c) Binder Content vs. Unit Weight



d) Binder Content vs. VMA

Figure 6. Mix Design Properties

Analyze the Gradation and Proportion of Crumb Rubber and Sand in CRTI

In this study, three turf infill materials, Turf 1, Turf 2, and Turf AB, were utilized to develop a dry method for incorporating turf rubber into asphalt. Figure 7a, b, and c show the visual characteristics of Turf 1, Turf 2, and Turf AB, respectively. From the images, Turf 1 contains visible traces of synthetic turf fibers which required removal before utilizing it in the asphalt mixture, while the crumb rubber particles exhibited a relatively uniform size. In contrast, Turf 2 and Turf AB were cleaner, with no visible turf fibers. However, these materials included aggregates of varying sizes along with the crumb rubber.

a) Turf 1

b) Turf 2

c) Turf AB

Figure 7. Photographs of Turf Infill Materials used: a) Turf-1, b) Turf-2, c) Turf-AB

Table 4 presents the gradation data for the three turf infill materials, while Figure 8 illustrates their respective gradation curves, highlighting distinct differences in particle size distribution. Turf AB contains a significantly higher proportion of fine materials compared to Turf 1 and Turf 2. In contrast, Turf 1 has the lowest fine material content, indicating it has the least dust among the three. Turf 1 has 28% of particles passing through No. 16 and 3% passing through No. 30. Dust content increases progressively in Turf 2 and Turf AB. Turf 2 shows 58% passing through No. 16, 18% through No. 30, 4% through No. 50, and 1% through No. 100. Turf AB has 79% of particles passing through No. 16, 22% passing through No. 30, and 1% passing through No. 50. Specifically, particles from all three turfs pass through the No. 8 sieve. The distribution of aggregate sizes for the turf materials primarily falls between sieve #50 and sieve #16.

Table 4. Sieve Analysis of Turf Infill Materials

Sieve Size	Turf 1	Turf 2	Turf AB
	Percent Passing		
#4	100	100	100
#8	100	100	100
#16	28	58	79
#30	3	18	22
#50	0	4	1
#100	0	1	0
#200	0	0	0

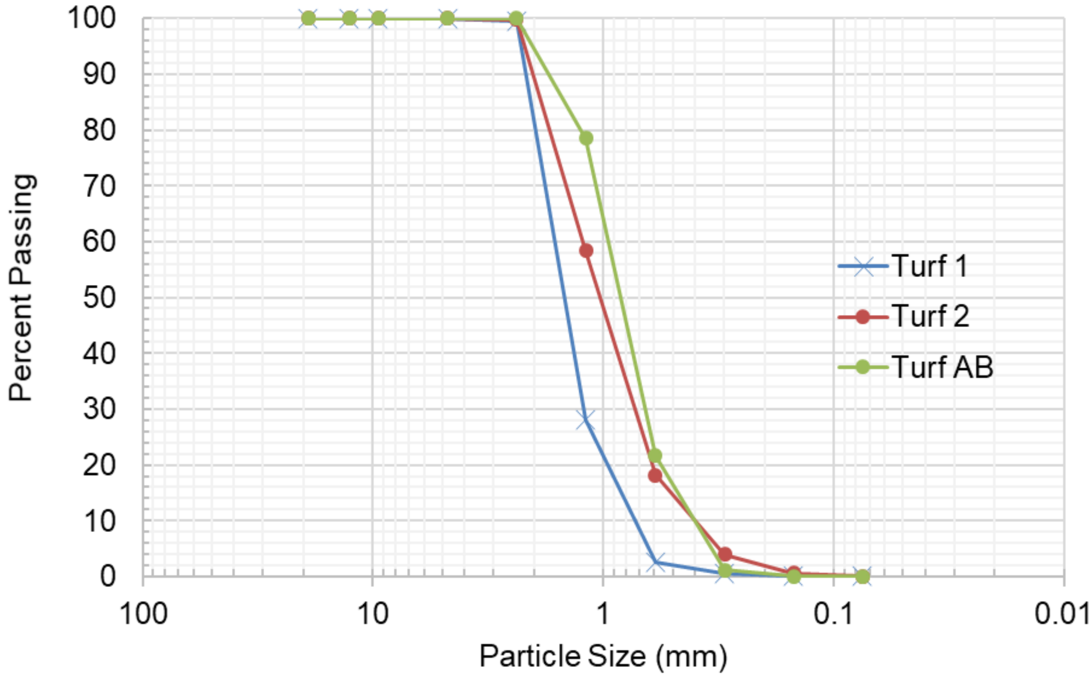


Figure 8. Gradation of Turf Infill Materials

Replace sand portion of Caltrans-approved mix design with recycled crumb rubber and sand infill

In the dry method, approximately 1 to 3% by weight of the total aggregate in the mix is commonly substituted with crumb rubber. These rubber particles are thoroughly blended with the aggregate prior to the incorporation of asphalt binder (Chesner, W. H., 2002). In the dry method of this research, 2-3% of crumb rubber infill materials were added to the aggregate. The crushed dust portion of the approved gradation from the mix design of the control mixture was replaced with 3% by weight for Turf 1 and Turf 2 and 2% and 3% for Turf AB using the dry method.

To ensure consistency and compliance with performance standards, the gradations of the blended aggregates, which included the turf rubber infill, were carefully analyzed.

Table 5, Table 6, Table 7, and Table 8 present the gradations for the blended aggregates containing the three turf materials: 3% Turf 1, 3% Turf 2, 2% Turf AB, and 3% Turf AB, respectively. It can be observed that all combined gradations, after blending the crumb rubber infill into the aggregate, meet the specification limits, demonstrating the viability of using turf crumb rubber-infill aggregates in asphalt mixtures.

Table 5. Gradation of Rubber Infill Mixtures With 3% Turf 1

Bin	1	2	3	4	5	6	RAP	Combined Gradation	Specification Limits
Material Size	3/4"	1/2"	3/8"	Crushed Dust	Washed Dust	Rubber Infill	5/8"		
Weight, g	234.0	561.5	351.0	210.6	561.5	70.2	351.0		
Cumulative Weight, g	234.0	795.5	1146.5	1357.1	1918.6	1988.8	2339.8		
Bin %	10	24	15	9	24	3	15	100	
Sieve Size	Percent Passing								
2"	100	100	100	100	100	100	100	100	
1 1/2"	100	100	100	100	100	100	100	100	
1"	100	100	100	100	100	100	100	100	
3/4"	88.6	100	100	100	100	100	100	99	93-100
1/2"	5.9	63.3	100	100	100	100	93.7	81	76-88
3/8"	1.7	12.8	91.5	100	100	100	83.8	66	
No. 4	0.8	1.3	10.8	96.6	96.8	100	58.5	46	42-52
No. 8	0.7	0.9	3.0	66.8	63.7	100	41.0	31	25-35
No. 16	0.6	0.8	1.9	48.6	41.4	28	29.6	20	
No. 30	0.6	0.6	1.3	36.5	26.8	3	21.6	13	10-18
No. 50	0.6	0.5	0.8	27.0	16.0	0	15.0	9	
No. 100	0.6	0.4	0.6	19.1	7.2	0	10.1	5	
No. 200	0.60	0.40	0.4	14.02	2.46	0	7.33	3	1.5-5.4

Table 6. Gradation of Rubber Infill Mixtures With 3% Turf 2

Bin	1	2	3	4	5	6	RAP	Combined Gradation	Specification Limits
Material Size	3/4"	1/2"	3/8"	Crushed Dust	Washed Dust	Rubber Infill	5/8"		
Weight, g	234.0	561.5	351.0	210.6	561.5	70.2	351.0		
Cumulative Weight, g	234.0	795.5	1146.5	1357.1	1918.6	1988.8	2339.8		
Bin %	10	24	15	9	24	3	15	100	
Sieve Size	Percent Passing								
2"	100	100	100	100	100	100	100	100	
1 1/2"	100	100	100	100	100	100	100	100	
1"	100	100	100	100	100	100	100	100	
3/4"	88.6	100	100	100	100	100	100	99	93-100
1/2"	5.9	63.3	100	100	100	100	93.7	81	76-88
3/8"	1.7	12.8	91.5	100	100	100	83.8	66	
No. 4	0.8	1.3	10.8	96.6	96.8	100	58.5	46	42-52
No. 8	0.7	0.9	3.0	66.8	63.7	100	41.0	31	25-35
No. 16	0.6	0.8	1.9	48.6	41.4	58	29.6	21	
No. 30	0.6	0.6	1.3	36.5	26.8	18	21.6	14	10-18
No. 50	0.6	0.5	0.8	27.0	16.0	4	15.0	9	
No. 100	0.6	0.4	0.6	19.1	7.2	1	10.1	5	
No. 200	0.60	0.40	0.4	14.02	2.46	0	7.33	3	1.5-5.4

Table 7. Gradation of Rubber Infill Mixtures With 2% Turf AB

Bin	1	2	3	4	5	6	RAP	Combined Gradation	Specification Limits
Material Size	3/4"	1/2"	3/8"	Crushed Dust	Washed Dust	Rubber Infill	5/8"		
Weight, g	234.0	561.5	351.0	234.0	561.5	46.8	351.0		
Cumulative Weight, g	234.0	795.5	1146.5	1380.5	1942.0	1988.8	2339.8		
Bin %	10	24	15	10	24	2	15	100	
Sieve Size	Percent Passing								
2"	100	100	100	100	100	100	100	100	
1 1/2"	100	100	100	100	100	100	100	100	
1"	100	100	100	100	100	100	100	100	
3/4"	88.6	100	100	100	100	100	100	99	93-100
1/2"	5.9	63.3	100	100	100	100	93.7	81	76-88
3/8"	1.7	12.8	91.5	100	100	100	83.8	66	
No. 4	0.8	1.3	10.8	96.6	96.8	100	58.5	46	42-52
No. 8	0.7	0.9	3.0	66.8	63.7	100	41.0	31	25-35
No. 16	0.6	0.8	1.9	48.6	41.4	79	29.6	21	
No. 30	0.6	0.6	1.3	36.5	26.8	22	21.6	14	10-18
No. 50	0.6	0.5	0.8	27.0	16.0	1	15.0	9	
No. 100	0.6	0.4	0.6	19.1	7.2	0	10.1	5	
No. 200	0.60	0.40	0.4	14.02	2.46	0	7.33	3	1.5-5.4

Table 8. Gradation of Rubber Infill Mixtures With 3% Turf AB

Bin	1	2	3	4	5	6	RAP	Combined Gradation	Specification Limits
Material Size	3/4"	1/2"	3/8"	Crushed Dust	Washed Dust	Rubber Infill	5/8"		
Weight, g	234.0	561.5	351.0	210.6	561.5	70.2	351.0		
Cumulative Weight, g	234.0	795.5	1146.5	1357.1	1918.6	1988.8	2339.8		
Bin %	10	24	15	9	24	3	15	100	
Sieve Size	Percent Passing								
2"	100	100	100	100	100	100	100	100	
1 1/2"	100	100	100	100	100	100	100	100	
1"	100	100	100	100	100	100	100	100	
3/4"	88.6	100	100	100	100	100	100	99	93-100
1/2"	5.9	63.3	100	100	100	100	93.7	81	76-88
3/8"	1.7	12.8	91.5	100	100	100	83.8	66	
No. 4	0.8	1.3	10.8	96.6	96.8	100	58.5	46	42-52
No. 8	0.7	0.9	3.0	66.8	63.7	100	41.0	31	25-35
No. 16	0.6	0.8	1.9	48.6	41.4	79	29.6	22	
No. 30	0.6	0.6	1.3	36.5	26.8	22	21.6	14	10-18
No. 50	0.6	0.5	0.8	27.0	16.0	1	15.0	9	
No. 100	0.6	0.4	0.6	19.1	7.2	0	10.1	5	
No. 200	0.60	0.40	0.4	14.02	2.46	0	7.33	3	1.5-5.4

Develop a Wet Method Using CRTI

Create Asphalt Rubber Binders by Blending Neat Asphalt Binder with Recycled Crumb Rubber

The wet method for incorporating crumb rubber infill involves blending the crumb rubber directly into the asphalt binder. In field applications, this blending occurs at temperatures ranging from 175°C to 200°C for 45 to 60 minutes. Typically, crumb rubber is added at a proportion of 15% to 22% by weight of the asphalt and rubber blend (Chesner, Warren H., et al. 2002; Kocak, S., & Kutay, M. E. 2017).

Only the rubber particles in the turf infill are blended with the asphalt binder in the wet process. Generally, turf materials contain not only rubber but also other substances such as sand, dust, and synthetic fibers. Figure 9 illustrates the Turf SF1 used to develop a wet method for applying crumb rubber infill.

To isolate the crumb rubber from the other materials, a gravity separation method was used. This technique utilizes the differences in specific gravity between rubber and sand: crumb rubber particles have a lower specific gravity than water and tend to float, while sand particles are heavier than water and settle at the bottom. This process involved submerging the turf material in water and agitating it thoroughly to physically separate the sand and crumb rubber particles. Once the separation is complete, a filter is used to collect the crumb rubber. Finally, the sand and crumb rubber are retrieved and dried separately for further use. Figure 10 shows the gradation of Turf SF1 rubber and sand gradation after the separation process.

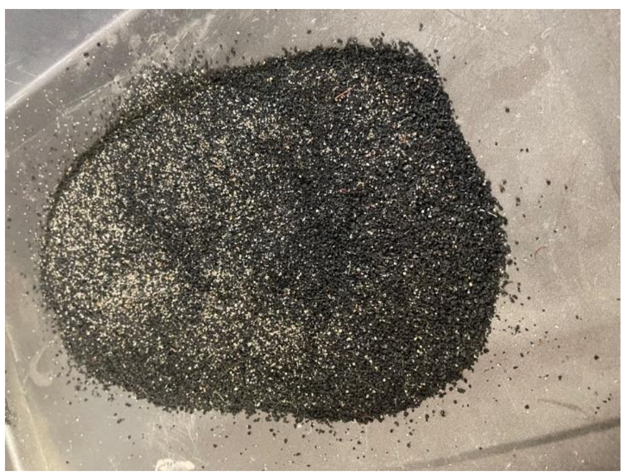


Figure 9. Turf SF1 Used to Develop a Wet Method

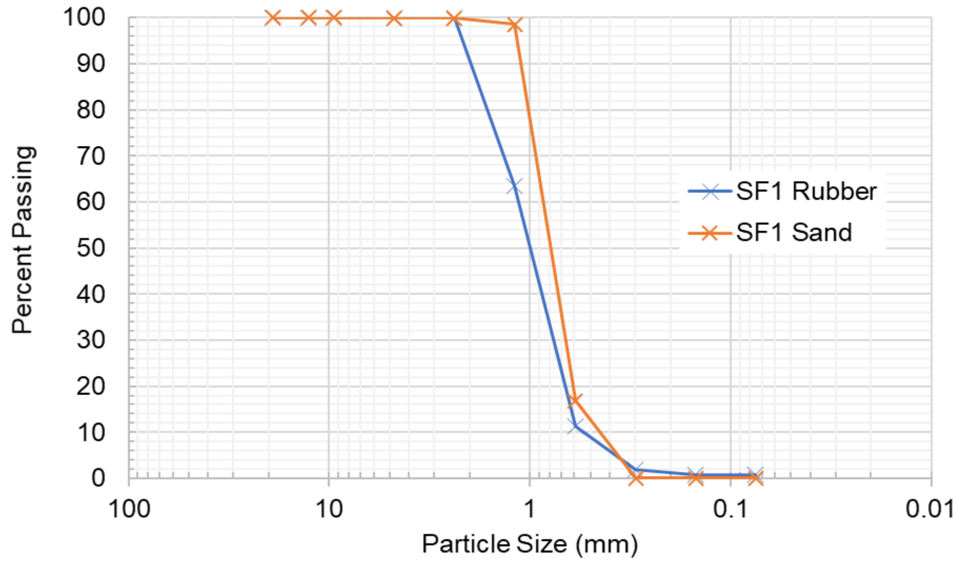


Figure 10. Gradation of Turf SF1 Rubber and Sand

After the separation and drying process, the recovered crumb rubber particles are used to create asphalt rubber binder by blending with neat asphalt binder. The process of mixing crumb rubber with the asphalt binder can be carried out using the following procedure†:

1. Rubber Proportioning:
    - Calculate the amount of crumb rubber as 15% of the total weight.
2. Preheat Binder:
    - Heat the PG 64-16 binder to 190℃ and maintain this temperature for approximately 60 minutes (± 10 minutes). Set the thermometer to monitor temperatures in the 190-200℃ range.
3. Oven Preparation:
    - Set the blending oven to a target temperature of 195℃.
4. Initial Blending Setup:
    - Turn on the blender and set it to 800 rpm.
    - Add the crumb rubber into the preheated binder.
    - Insert a thermometer into the binder to continuously monitor temperature.
5. Temperature Management During Blending:
    - While blending the rubber and binder, allow the mixture to rise to a temperature of 174℃, then turn off the heat source.
    - The temperature of the mixture will continue to increase to over 200℃ (it will take 20 minutes to decrease to 193℃).

---

† Note: The rubber-modified binder should be blended for 2 minutes prior to preparing HMA samples.

- Once the binder temperature reaches 190℃, increase the mixing speed to 1500 rpm and start the 45-minute blending timer.

6. Maintaining Temperature Range (190-200℃):
    - Turn on the heater to 193℃.
    - Once the binder returns to 193℃, turn off the heater.
    - Repeat this process for 45 minutes of blending time. The goal is to maintain temperatures between 190℃ and 200℃ during the blending process.
7. Post-Blending Procedure:
    - Once mixing is complete, remove the blender head.
    - Turn off all equipment.
    - Clean all tools and surfaces used during the process.

Asphalt Binder: The same binder tests conducted in the dry method were also used to characterize the behavior of the modified asphalt binder. In the DSR test, the crumb rubber-modified asphalt binder was evaluated similarly to a conventional binder, starting at 64°C and increasing in 6°C intervals until failure. For short-term aging, the binder was aged in the Rolling Thin Film Oven (RTFO) prior to the DSR test to assess its performance. In addition, DSR test was conducted after RTFO and 1 day under UV test in order to study the performance of the modified binder under shorten-aging and UV aging condition.

Figure 11 presents the DSR test results for the crumb rubber-modified asphalt binder. The findings demonstrate that the modified binder significantly outperforms the original asphalt binder, exhibiting a much higher G*/sin(δ) value. The DSR test for the modified binder reached its failure point at 94°C, indicating superior performance under high-temperature conditions. Similarly, the DSR results for the crumb rubber-modified binder after short-term aging also failed at 94°C. Figure 12 displays the DSR test results for the short-term aging and UV aging of crumb rubber-modified asphalt binder.

These results demonstrate that incorporating CRTI into the asphalt binder enhances its properties, particularly under high temperatures and aging conditions. The improved G*/sin(δ) values and consistent performance, even after short-term aging and UV aging, emphasize the potential of crumb rubber-modified binders for improved durability and resistance to deformation. Khalili, Mehdi, et al. 2019 also concluded that rubber is used as a modifier to increase the asphalt's elasticity, flexibility, and durability against aging. Therefore, the test results of the modified asphalt binder are consistent with the findings of Khalili et al. (2019), further supporting the use of crumb rubber as a beneficial additive for improving asphalt binder properties.

Figure 13 illustrates the effect of different aging conditions on the phase angle of the modified binder. The results show that DSR testing after short-term and UV aging leads to a reduction in phase angle, indicating increased stiffness (i.e., reduced viscous behavior) of the binder under aging conditions. Specifically, the phase angle of the modified binder decreased by 13.6% after short-term aging, while the combination of short-term aging and UV aging resulted in a larger reduction of 18.2%. The effect of UV aging alone contributed to a 4.6% decrease in the phase angle, which is not considered significant.

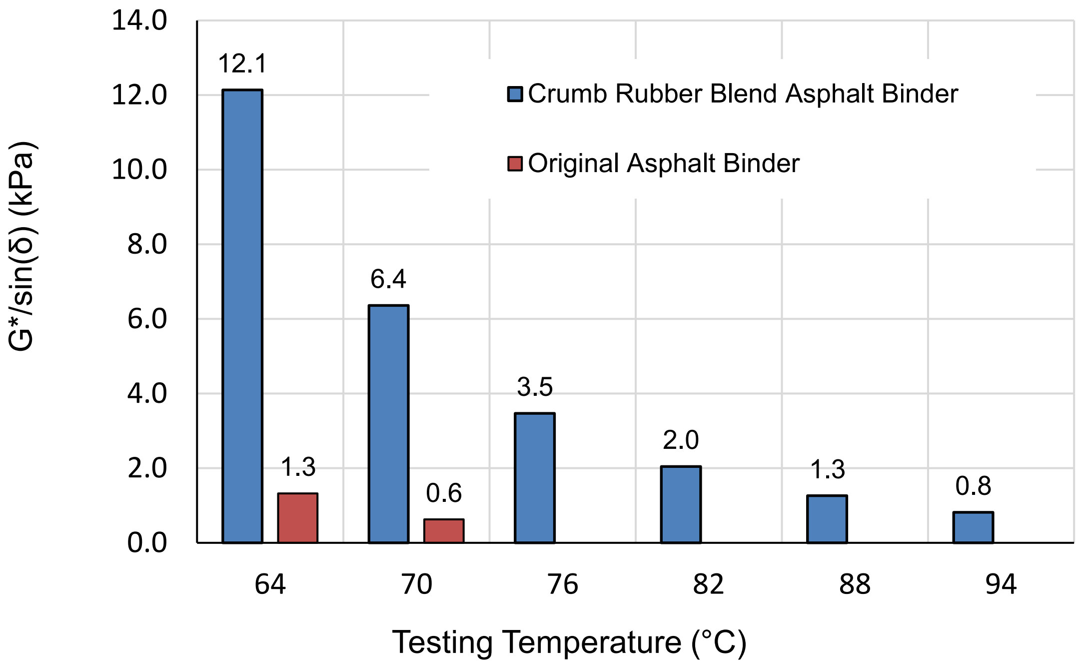


Figure 11. DSR Test Result for Crumb Rubber Blend with Asphalt Binder

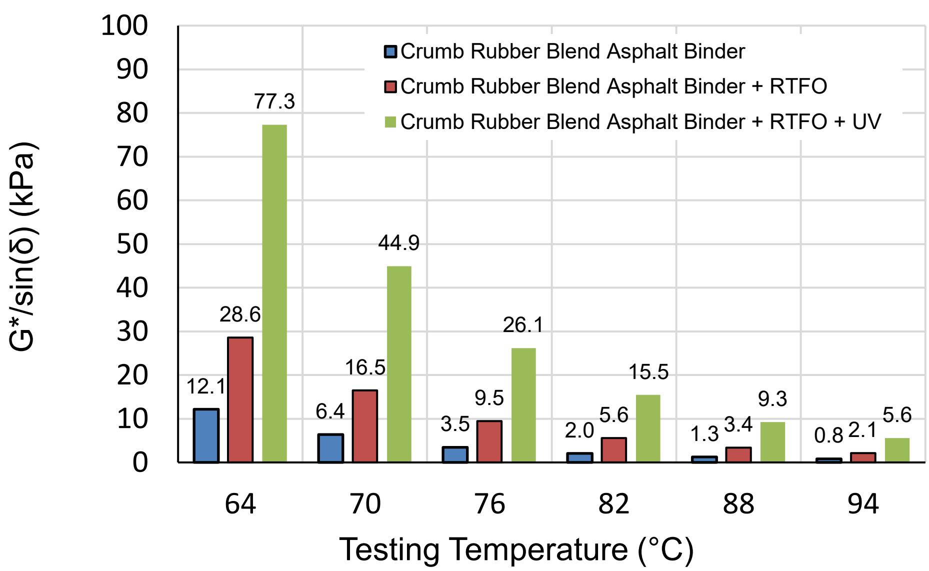


Figure 12. DSR Test Result for Crumb Rubber Blend with Asphalt Binder

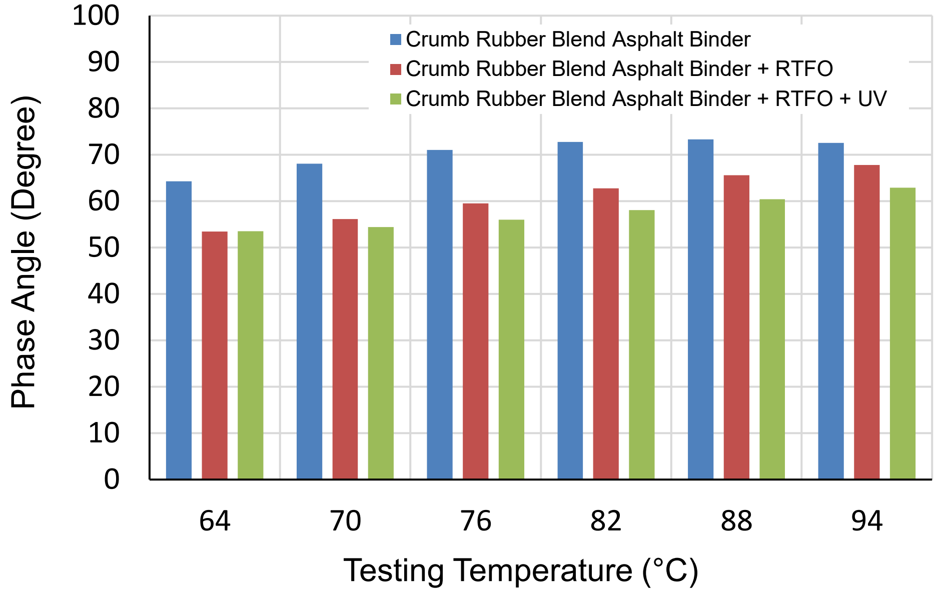


Figure 13. Phase Angles from DSR Test Result for Crumb Rubber Blend With Asphalt Binder

Aggregate: The same aggregate utilized in the dry method was also employed in the wet method, as shown in Table 9. The proportions of materials from each bin were carefully calculated to produce a blended aggregate. However, the gradation of the resulting blended aggregate, as illustrated in Figure 14, falls outside the specified limits in order to provide space to incorporate crumb rubber modified binder.

Table 9. Aggregate Gradations from Different Stockpiles and Combined Gradation

Bin	**1**	**2**	**3**	**4**	**5**	**6**	**RAP**	**Combined Gradation**	**Specification Limits**
Material Size	**3/4"**	**1/2"**	**3/8"**	**Crushed Dust**	**Washed Dust**	**Sand Infill**	**5/8"**		
Weight, g	218.3	698.5	589.4	174.6	482.5	19.5	0.0		
Cumulative Weight, g	218.3	916.8	1506.2	1680.8	2163.3	2182.9	2182.9		
Bin %	10	32	27	8	22	0.90	0	100	
Sieve Size	**Percent Passing**								
2"	100	100	100	100	100	100	100	100	
1 1/2"	100	100	100	100	100	100	100	100	
1"	100	100	100	100	100	100	100	100	
3/4"	88.6	100	100	100	100	100	100	99	93-100
1/2"	5.9	63.3	100	100	100	100	93.7	79	76-88
3/8"	1.7	12.8	91.5	100	100	100	83.8	60	
No. 4	0.8	1.3	10.8	96.6	96.8	100	58.5	33	42-52
No. 8	0.7	0.9	3.0	66.8	63.7	100	41.0	21	25-35
No. 16	0.6	0.8	1.9	48.6	41.4	99	29.6	15	
No. 30	0.6	0.6	1.3	36.5	26.8	18	21.6	10	10-18
No. 50	0.6	0.5	0.8	27.0	16.0	0	15.0	6	
No. 100	0.6	0.4	0.6	19.1	7.2	0	10.1	3	
No. 200	0.60	0.40	0.4	14.02	2.46	0	7.33	2	1.5-5.4

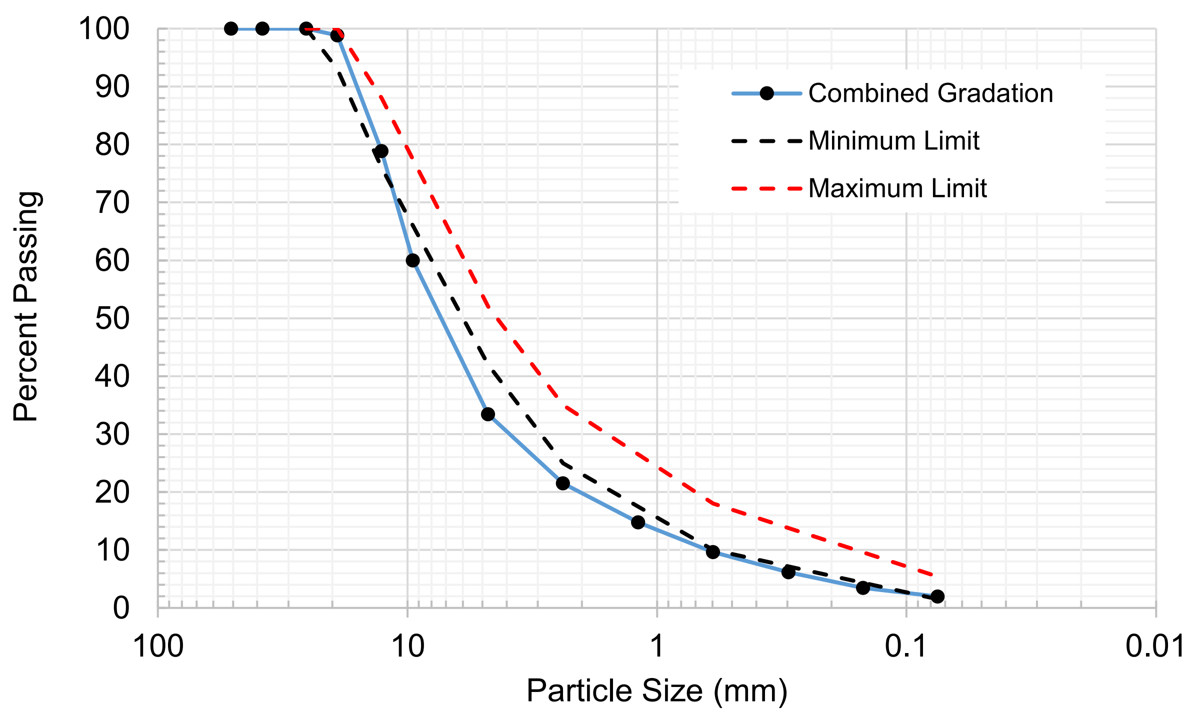


Figure 14. Gradation of the Combined Aggregate and Gradation Limits

Conduct Mix Design

Similar to the dry method, the Superpave system was employed for the mix design in this study. Binder contents of 6.5%, 7.0%, 7.5%, and 8.0% were used for the mix design. Unlike the control mixture, where the mix design was conducted in place, the mix design for the wet process was carried out in the California Pavement Preservation (CP^2) Center. The aggregate in the asphalt mixture is of the 3/4" gradation, hot-mix. Caltrans specifies specific criteria for a 3/4" gradation and this type of hot-mix asphalt:

- Air void (AV) content at N_{design} is 4.0%
- Voids in mineral aggregate (VMA) must be between 13.5% and 16.5%, and
- Dust proportion should range from 0.6 to 1.3.

At a binder content of 7.7%, the mix achieved the corresponding values:

- AV: 4.0%,
- VMA: 16.5%,
- Voids filled with asphalt (VFA): 76%,
- Dust proportion: 0.54, and
- G_{mm}: 2.452
- G_{mb}: 2.355
- Unit weight: 153.9 lbs/ft³.

These values were obtained from the mix design process. Based on the results, all specified conditions were satisfied at the binder content of 7.7% according to the Caltrans specification. As a result, a binder content of 7.7% was selected as the optimum binder content for SF1 asphalt mixture.

Figure 15 provides a comprehensive depiction of the relationships between binder content and critical parameters, including air void content, VMA, VFA, dust proportion, G_{mm} and G_{mb}. The red lines in the figure mark the optimum binder content and its corresponding parameter values, serving as a reference point for evaluating compliance with design requirements.

This graphical representation underscores how the selected binder content of 7.7% achieves a balance between multiple performance criteria, meeting design requirements while ensuring material compatibility.

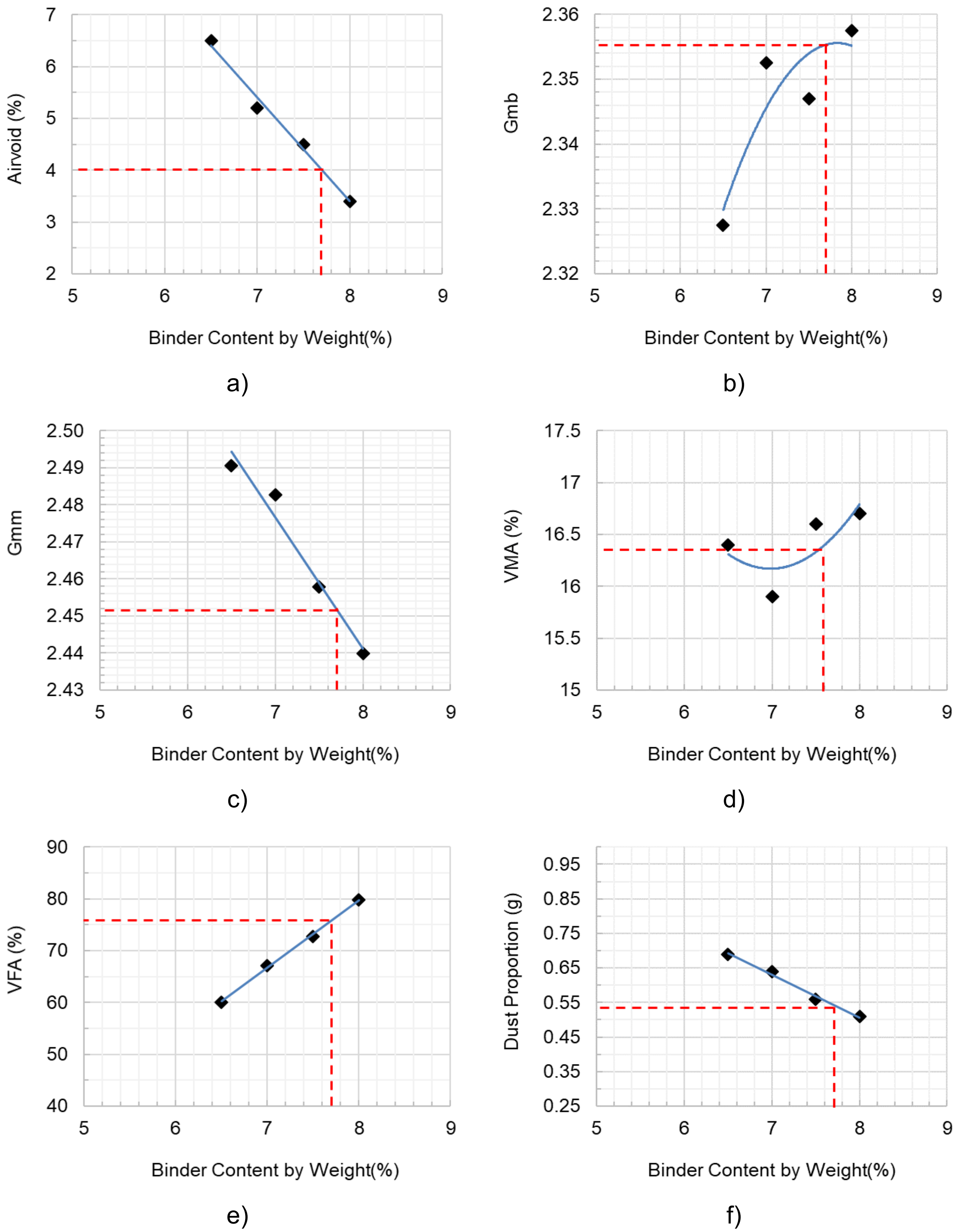


Figure 15. Relationship Between Binder and Other Parametric a) Air Void, b) Gmb, c) Gmm, d) VMA, e) VFA, and f) Dust Proportion

Performance Evaluations

Rutting Test

Rutting resistance and moisture susceptibility assessments were carried out using the Hamburg Wheel Tracker Device (HWTD) and the Asphalt Pavement Analyzer (APA). While KRC evaluated the rutting resistance of the control mixtures using the HWTD, the APA at the CP^2 Center was used to assess the rutting resistance of crumb rubber turf infill mixtures. The HWTD features two wheels, whereas the APA machine, equipped with three wheels, can test up to six briquettes at the same time.

In both test devices, the briquettes must be 60 mm thick, with 7 ± 0.5% air voids, and cut to fit the molds properly. Each mold holds two briquettes, and 7–8 mm of clearance is required between the molds to ensure a proper fit. This dimension should be considered when cutting the briquettes to size. Both the HWTD and the APA are not only effective for rutting measurement but also useful for evaluating compacted asphalt mixtures underwater. This capability provides valuable insights into the material's moisture susceptibility and indicates its durability and resistance to damage in wet environments. Figure 16 illustrates the arrangement of the briquettes in the mold prior to testing.

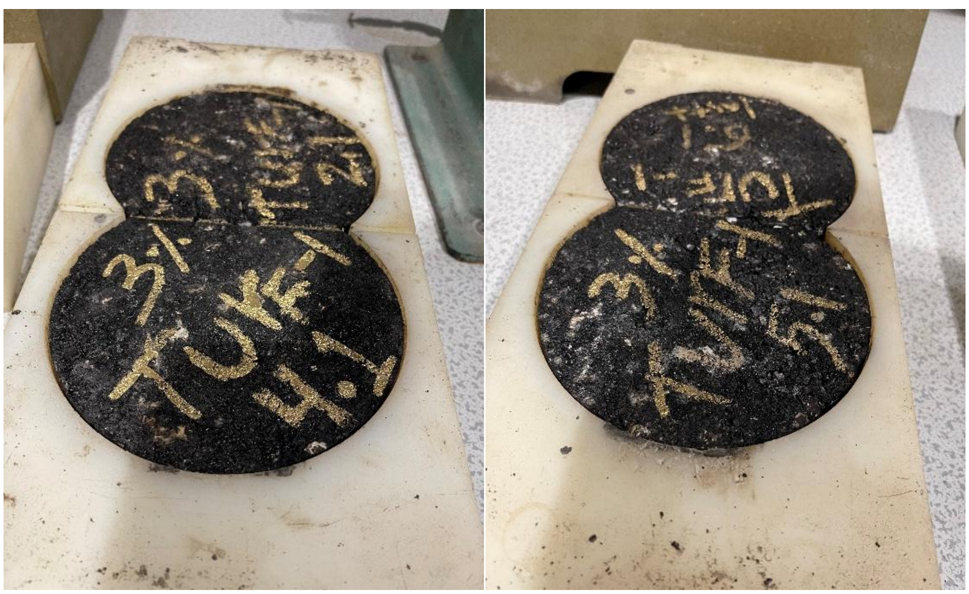


Figure 16. Samples for Rutting Test

Once the molds are placed in the machine, one under each wheel, the samples are submerged in water at a temperature of 50℃ and are subjected to repetitive wheel loads for a maximum of 20,000 passes or until a maximum rut depth of 20 mm is reached, whichever occurs first. The Hamburg test results provide the rut depth at each wheel pass which help to determine the creep slope and number of passes at failure (1/2 in or 12.7 mm rut depth).

Table 10 presents the properties of various mixtures developed by the dry method, including air void content and bulk specific gravity, used for the APA test. For consistency, mixtures with similar air void levels were used for each mold. Consequently, six molds were tested:

- Turf-1 (3%) samples 2 and 4 (Turf-1-3%-2&4)
- Turf-1 (3%) samples 5 and 6 (Turf-1-3%-5&6)
- Turf-2 (3%) samples 1 and 4 (Turf-2-3%-1&4)
- Turf-2 (3%) samples 2 and 7 (Turf-2-3%-2&7)
- Turf-AB (3%) samples 3 and 9 (Turf-AB-3%-3&9)
- Turf-AB (2%) samples 1 and 8 (Turf-AB-2%-1&8)

Table 10. Mixtures Properties Used for APA Test in the Dry Method

Mold Name	Mixtures	Air Voids, %	Specimen Bulk Specific Gravity
Turf-1-3%-2&4	Briquette Turf-1 (2) 3%	6.09	2.31
	Briquette Turf-1 (4) 3%	6.03	2.32
Turf-1-3%-5&6	Briquette Turf-1 (5) 3%	7.15	2.29
	Briquette Turf-1 (6) 3%	6.83	2.30
Turf-2-3%-1&4	Briquette Turf-2 (1) 3%	6.20	2.32
	Briquette Turf-2 (4) 3%	6.61	2.31
Turf-2-3%-2&7	Briquette Turf-2 (2) 3%	6.90	2.30
	Briquette Turf-2 (7) 3%	7.61	2.29
Turf-AB-3%-3&9	Briquette Turf-AB (3) 3%	6.15	2.32
	Briquette Turf-AB (9) 3%	6.82	2.30
Turf-AB-2%-3&9	Briquette Turf-AB (1) 2%	7.04	2.30
	Briquette Turf-AB (8) 2%	7.78	2.28

Table 11 presents the properties of various mixtures developed by the wet method, including air void content used for the APA test. Two molds were used for the APA tests:

- Turf-SF1-3&4 samples 3 and 4
- Turf-SF1-6&8 samples 6 and 8

The briquettes in Turf-SF1-6&8 exhibited slightly higher air void content compared to those in Turf-SF1-3&4.

Table 11. Mixtures Properties Used for APA Test in the Wet Method

Mold Name	Mixtures	Air Voids, %	Average Air Void, %
Turf-SF1-3&4	Briquette Turf-SF1 (3)	6.62	6.60
	Briquette Turf-SF1 (4)	6.57	
Turf-SF1-6&8	Briquette Turf-SF1 (6)	6.57	6.69
	Briquette Turf-SF1 (8)	6.80	

Cracking Resistance Test

Indirect Tensile Asphalt Cracking Test (IDEAL-CT) is an indirect tension test that can be used to evaluate the cracking potential of asphalt mixtures with a fracture mechanistic parameter: cracking tolerance index (CT_{index}). The specimens are fabricated to 150 mm in diameter and 62 mm in height with 7.0 ± 0.5% air void, shown in Figure 17. The test is run at room temperature (25℃) and similar to the indirect tensile (IDT) strength test with a monotonic loading rate of 50 mm/min. The CT_{index} can be determined by using the following equations:

$$CT_{index} = \frac{G_f}{|m_{75}|} \times \frac{l_{75}}{D} \quad (1)$$

$$|m_{75}| = \left|\frac{P_{85} - P_{65}}{l_{85} - l_{65}}\right| \quad (2)$$

Where:

G_f is the fracture energy, or the work of facture (the area of the load versus vertical displacement curve) divided by area of cracking face,

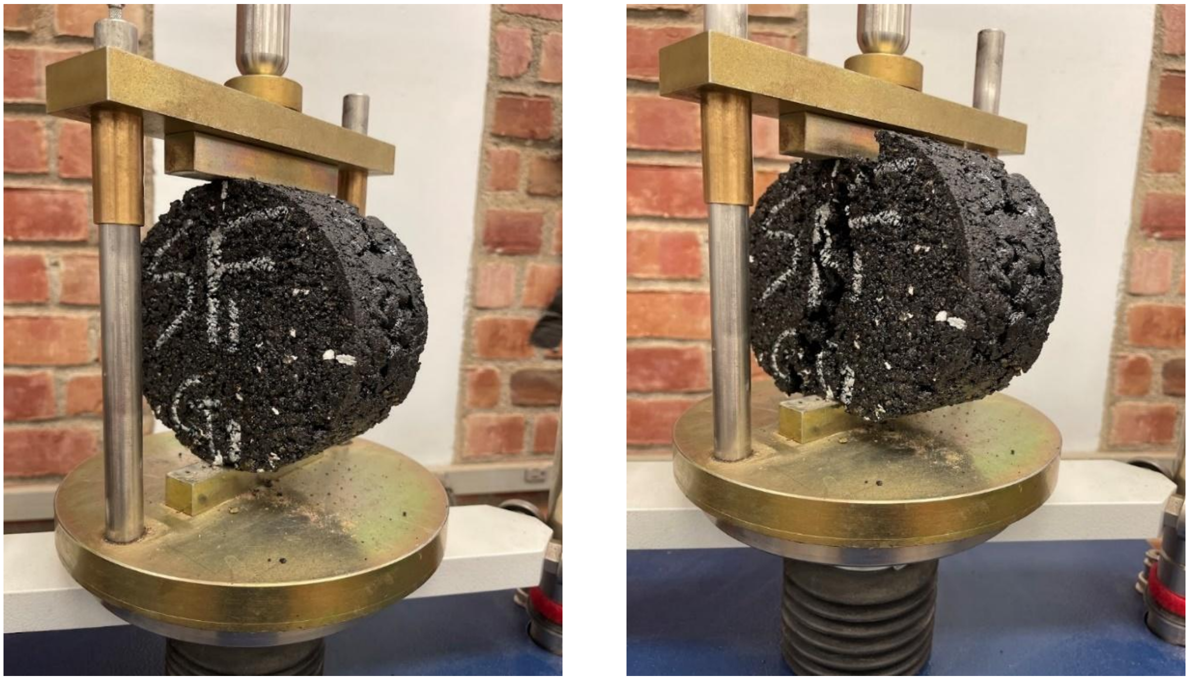
$|m_{75}|$ is the absolute value of the slope of the load-displacement curve at 75% drop peak load,

l_{75} is the displacement at 75% drop peak load,

D is the specimen diameter, and

l_{75}/D is a strain tolerance parameter (or the deformation tolerance under a load).

Figure 18 illustrates the parameters used in the IDEAL-CT test.



a) Sample before IDEAL-CT Test b) Sample after IDEAL-CT Test

Figure 17. Samples before and after IDEAL-CT Test

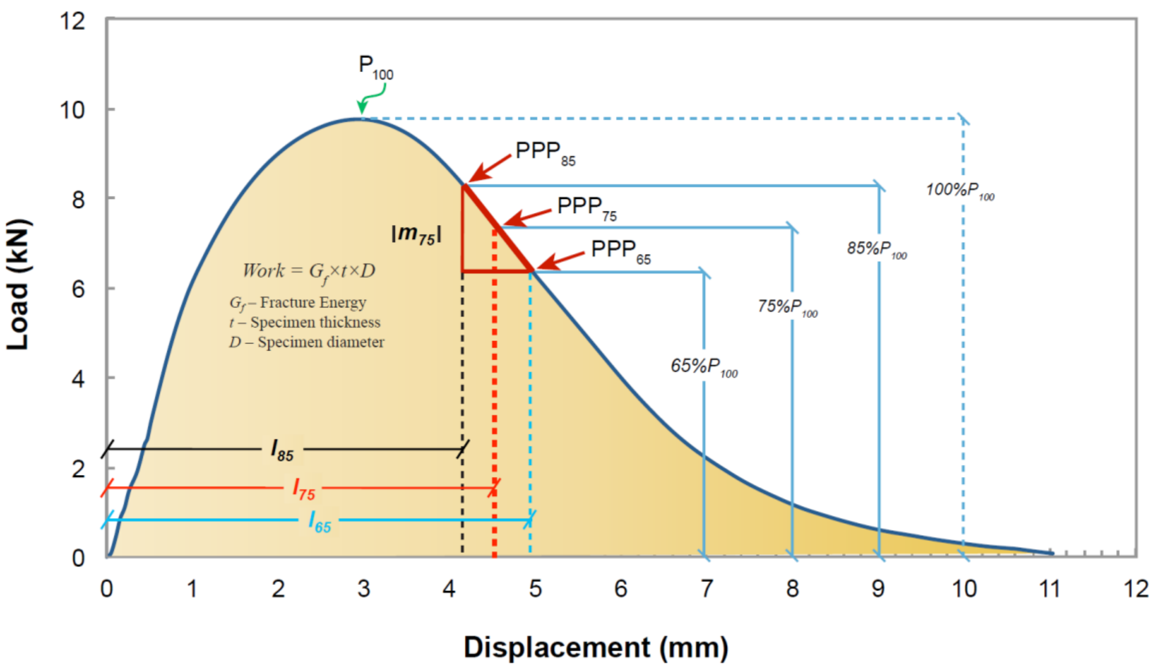
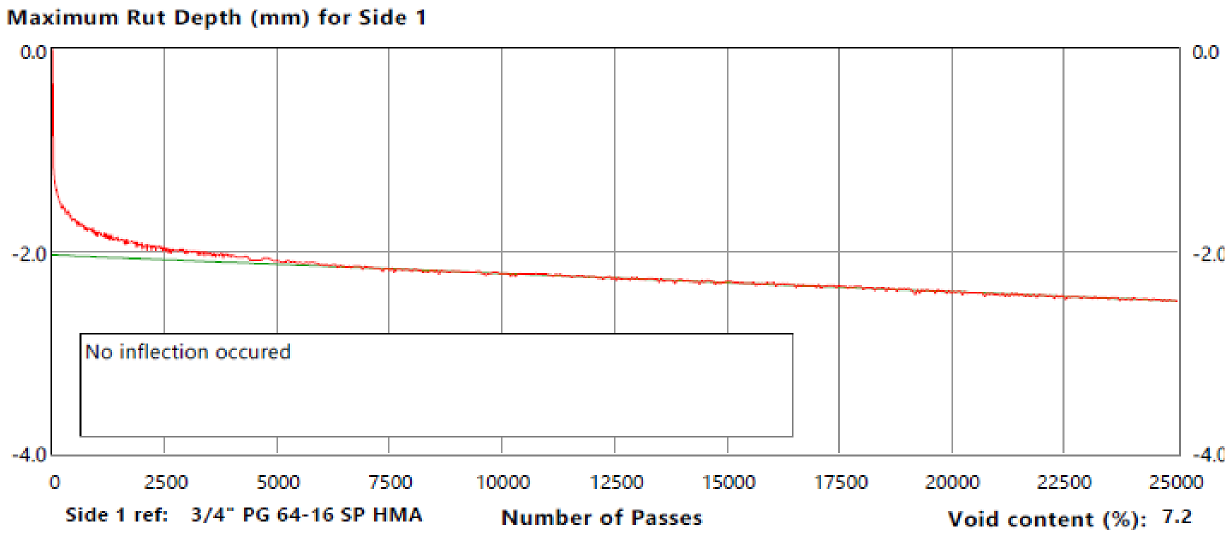


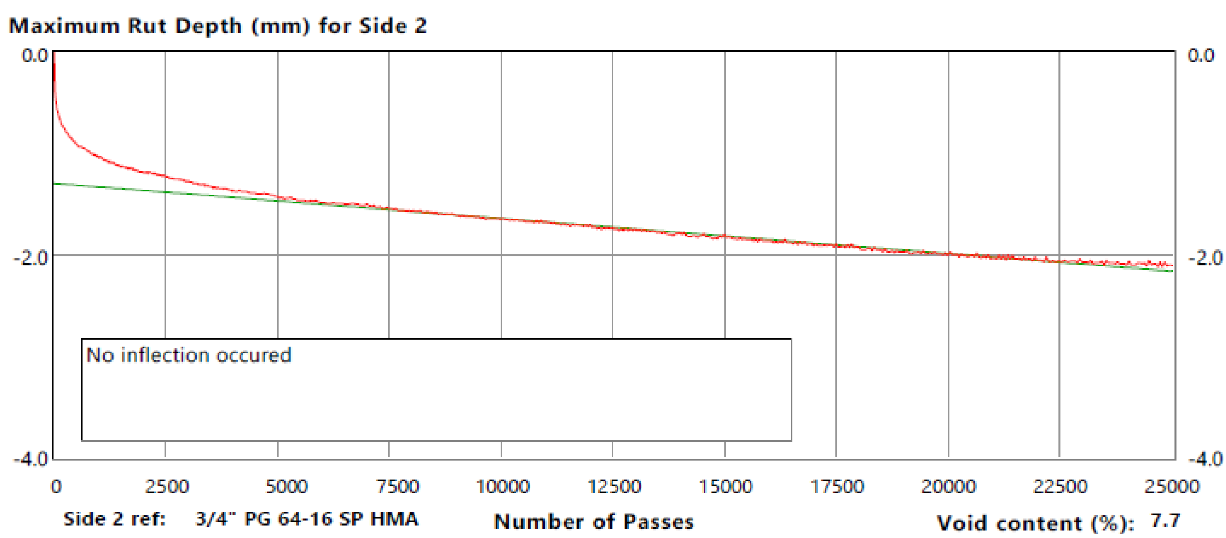
Figure 18. Illustration of the Parameters In IDEAL-CT Test (Zhou, F. 2019)

Test Results

Figure 19 shows the HWTD test results. The results indicated that the mix design for the control mixture satisfies the HWTD test according to the California specification (California Department of Transportation, Standard Specifications, 2024) with a maximum rut depth on both sides well below the 0.5-inch threshold after 15,000 cycles, and no inflection occurred during the test. It can be concluded that the control mixture passed the rutting resistance test.



a) HWTD Test on Control Mixtures Side 1



b) HWTD Test on Control Mixtures Side 2

Figure 19. HWTD Test Results for the Control Mixtures

Figure 20, Figure 21, Figure 22, Figure 23, Figure 24, Figure 25, and Figure 26 illustrate the APA test results alongside images of various asphalt mixtures incorporating different Turf types in the dry and wet method. The analysis reveals a clear trend: mixtures with higher air void content and lower bulk specific gravity are more prone to rutting. This behavior is consistently observed across all mixtures, irrespective of the turf type: Turf-1, Turf-2, Turf-AB, or Turf-SF1.

Asphalt-turf mixtures with 3% Turf-1, 3% Turf-2 and 2% Turf-AB, and Turf-SF1 failed the rutting resistance via APA test, with total rut depths reaching ½ inch after fewer than 15,000 passes, as specified for binder grade PG 64 (California Department of Transportation, Standard Specifications, 2015). In contrast, the asphalt-turf mixture with 3% Turf-AB passed the rutting resistance test, showing a maximum rut depth of less than ½ inch after 15,000 cycles. Notably, none of the samples exhibited signs of moisture damage during testing, underscoring the durability under wet conditions across all asphalt-turf mixtures.

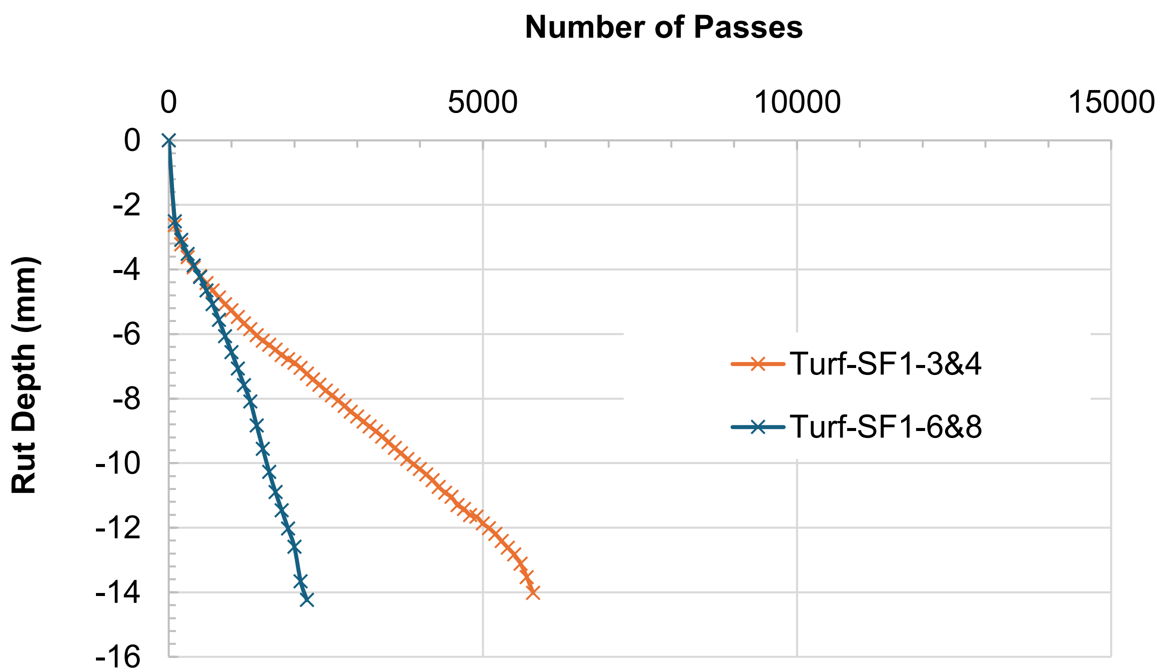


Figure 20. APA Results for Mixture with Turf SF1

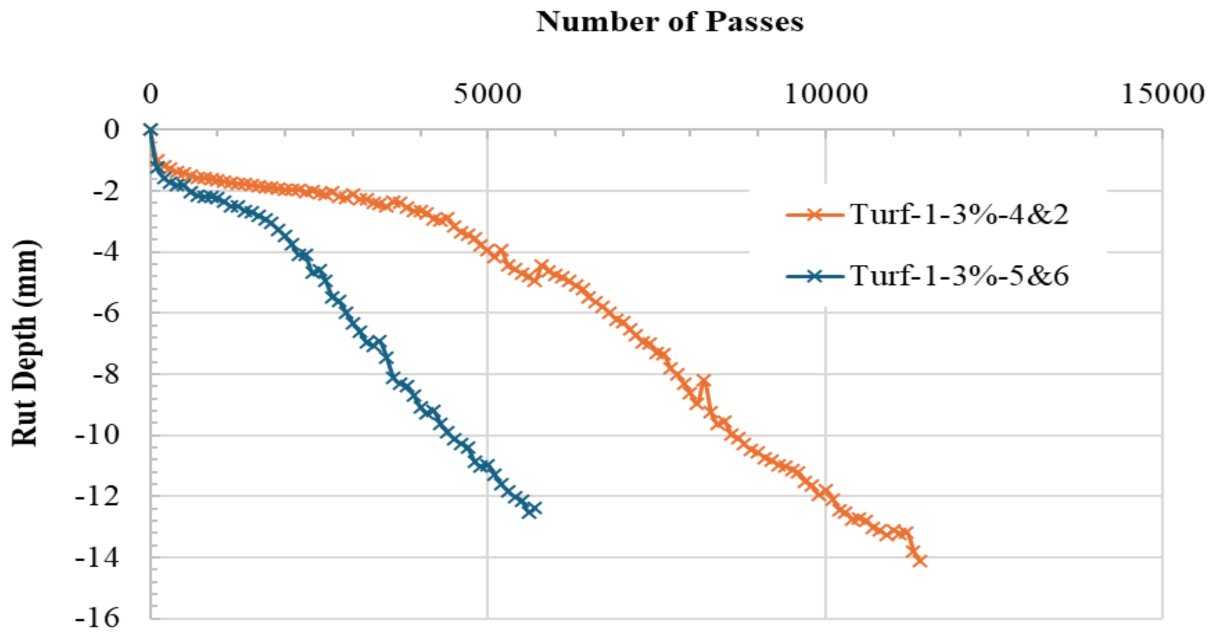


Figure 21. APA Results for Mixtures With Turf 1

a) Turf-1 3% S4&S2

b) Turf-1 3% S5&S6

Figure 22. Turf-1 Mixtures After APA Test

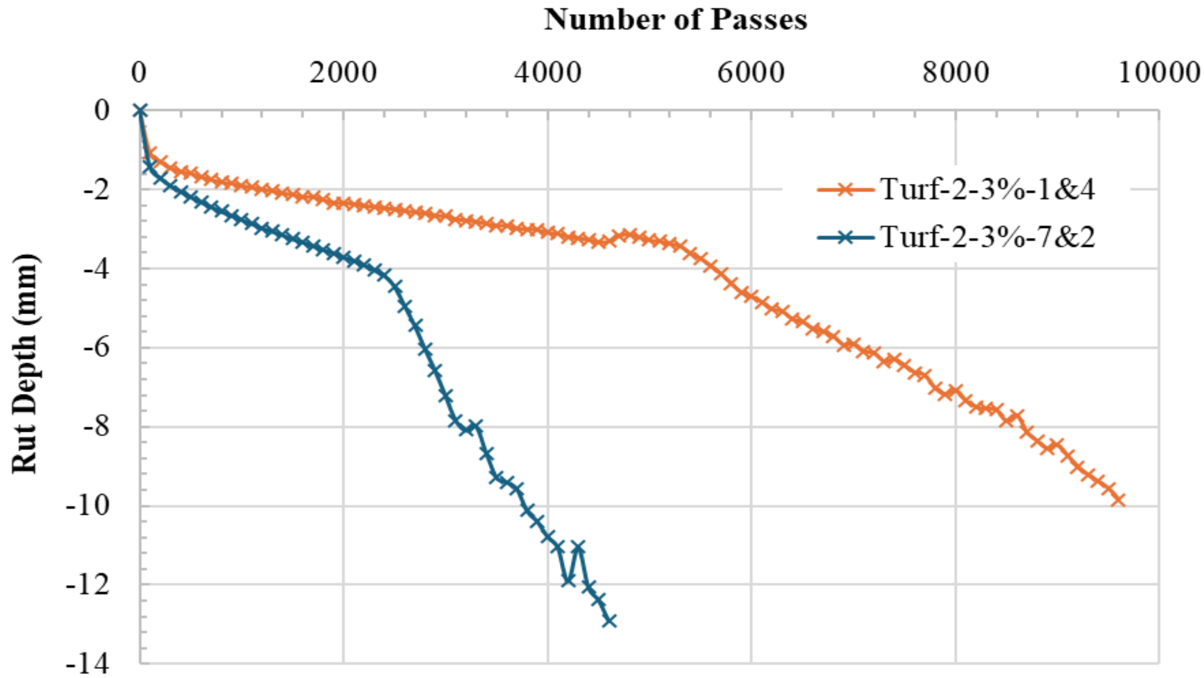


Figure 23. APA Results for Mixtures With Turf 2

a) Turf-2 3% S1&S4 **b) Turf-2 3% S7&S2**

Figure 24. Turf-2 Mixtures After APA Test

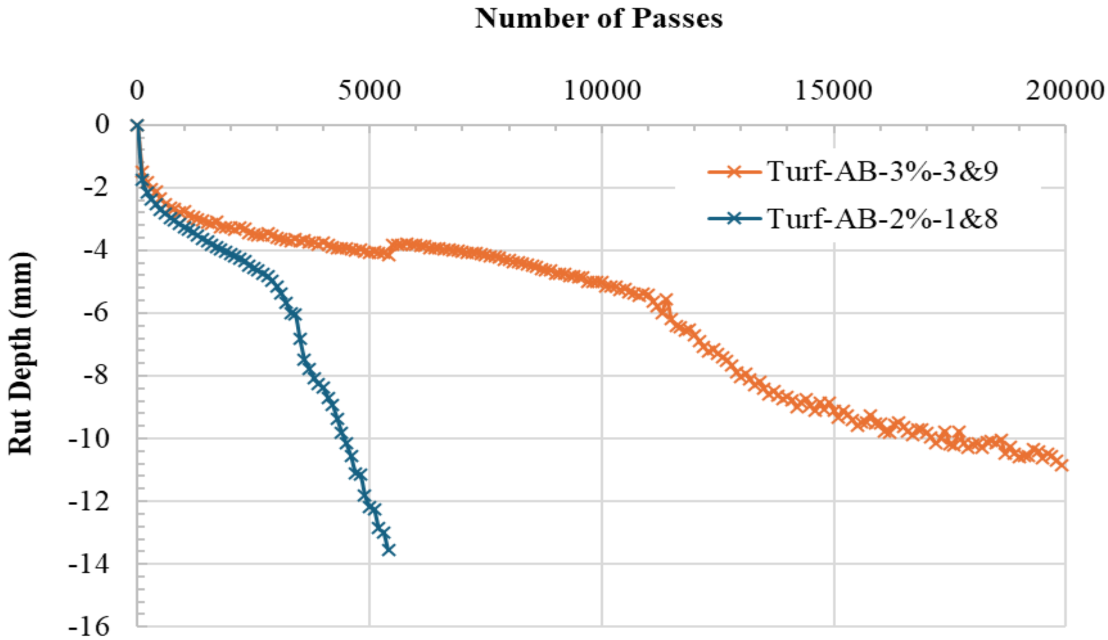


Figure 25. APA Results for Mixture with Turf AB

a) Turf-AB 3% S3&S9

b) Turf-AB 2% S1&S8

Figure 26. Turf-AB Mixtures After APA Test

To accurately compare the rutting resistance of different turf mixtures from the rutting test, the mixtures were grouped based on similarities in air void content and bulk-specific gravity. Two categories were established: a low air void group and a high air void group.

The low air void group included the following mixtures:

- Turf-1-3% samples 4 and 2 (6.06% AV)
- Turf-2-3% samples 1 and 4 (6.41% AV)
- Turf-AB 3% samples 3 and 9 (6.49% AV)
- Turf-SF1 samples 3 and 4 (6.60% AV)
- Control mixture 7.2% AV

The high air void group comprised of:

- Turf-1-3% samples 5 and 6 (6.99% AV)
- Turf-2-3% samples 7 and 2 (7.26% AV)
- Turf-AB 2% samples 1 and 8 (7.41% AV)
- Turf-SF1 samples 6 and 8 (6.69% AV)
- Control mixture 7.7% AV

Figure 27 and Figure 28 present the rutting resistance comparisons for the low and high air void groups, respectively. As shown in Figure 27, all turf mixtures in the low air void group had lower rutting resistance compared to the control mixture. The following key findings are summarized in Table 12:

- Turf-AB (3%) exhibited the highest resistance to rutting, never reaching its failure point and achieving a maximum rut depth of approximately 9 mm at 20,000 cycles, thereby passing the rutting test.
- Turf-2 (3%) demonstrated better performance with a maximum impression of around 10 mm at nearly 10,000 cycles.
- Turf-1 (3%) reached a maximum impression of approximately 14 mm after 11,000 cycles.
- Turf SF1 had the worst rutting resistance with rutting more than 14 mm at nearly 6,000 cycles.

Table 12. Summary of Rutting Resistance by Mixture Type for Low Air Void Group

Mixture	Air Voids (%)	Max Rut Depth (mm)	Cycle to Max Rut	Pass/Fail
Turf-1-3%-2&4	6.06	~14.0	~11,000	Fail
Turf-2-3%-1&4	6.41	~10.0	~10,000	Fail
Turf-AB-3%-3&9	6.49	~9.0	20,000	Pass
Turf-SF1-3&4	6.60	>14.0	~6,000	Fail
Control	7.2	<<12.7 (1/2 inch)	>15,000	Pass

Similar to the low air void group, all turf mixtures in the high air void group exhibited lower rutting resistance compared to the control mixture. Figure 28 illustrates that the rutting resistance performance of the various turf mixtures within the high air void group follows a comparable trend, with similar total rut depths except Turf SF1. The following key observations were found and are summarized in Table 13:

- Turf-1 (3%) demonstrated a total rut depth of 12.58 mm at around 5,000 cycles.
- Turf-2 (3%) reached 13.35 mm at around 5,000 cycles.
- Turf-AB (2%) showed 12.50 mm after less than 6,000 cycles.
- Turf SF1 had a total rut depth of more than 14 mm after only 2,000 cycles.

Table 13. Summary of Rutting Resistance by Mixture Type for High Air Void Group

Mixture	Air Voids (%)	Max Rut Depth (mm)	Cycle to Max Rut	Pass/Fail
Turf-1-3%-5&6	6.99	~12.6	~5,000	Fail
Turf-2-3%-2&3	7.26	~13.4	~5,000	Fail
Turf-AB-2%-1&8	7.41	~12.5	<6,000	Fail
Turf-SF1-6&8	6.69	>14.0	~2,000	Fail
Control	7.7	<<12.7 (1/2 inch)	>15,000	Pass

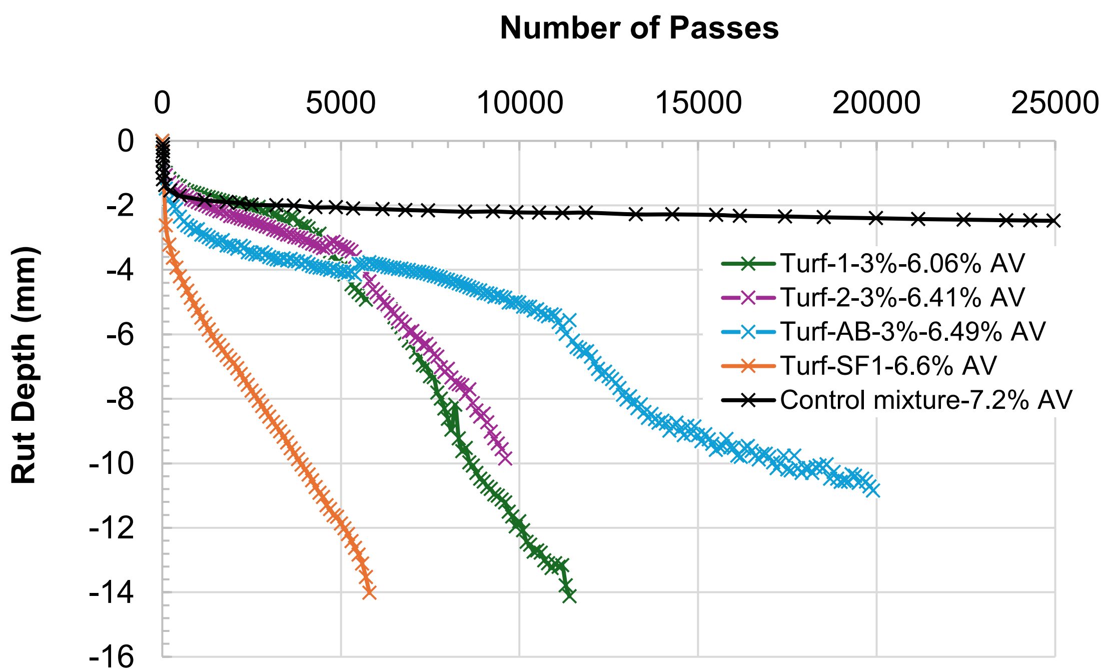


Figure 27. Comparison of Rutting Resistance for Mixtures in Low Air Void Group

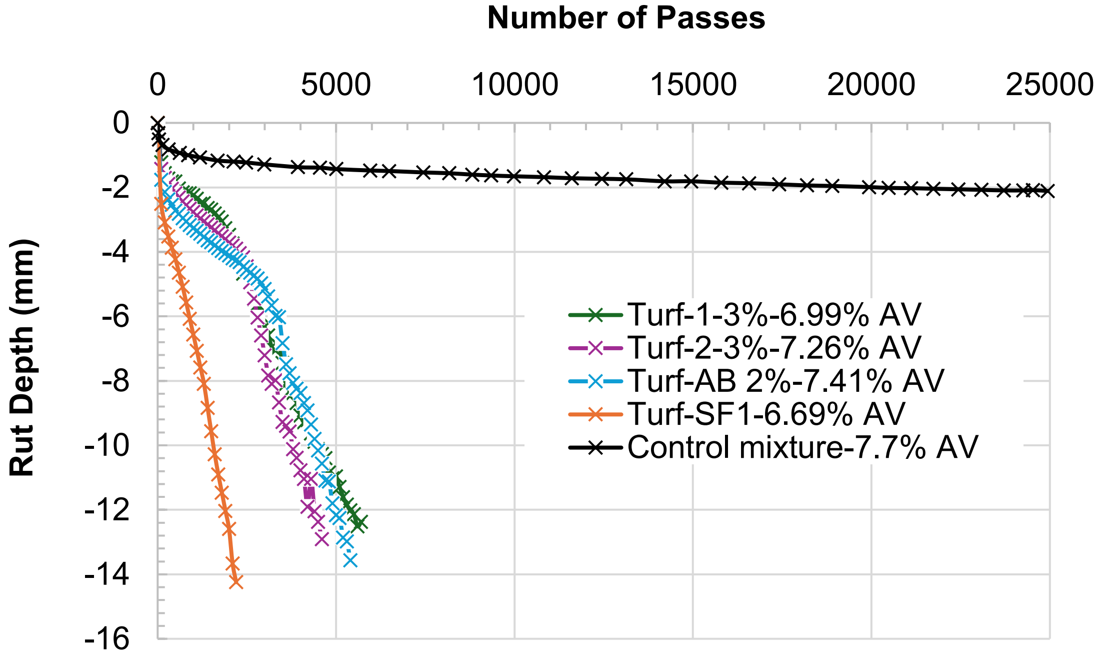


Figure 28. Comparison of Rutting Resistance for Mixtures in High Air Void Group

Based on the analysis of both groups, it can be concluded that the samples containing 3% Turf AB exhibit superior rutting resistance compared to other samples. While the samples with 3% Turf AB successfully passed the rutting test, the other turf samples did not. Furthermore, no moisture damage was observed in any of the samples during testing, indicating that the turf mixtures maintain good workability under moist conditions.

Although the modified binder with crumb rubber significantly improves the binder properties compared to the original asphalt binder, the Turf-SF1 samples with the modified binder still exhibited higher rutting than the control mixture and other turf mixtures developed in the dry method. This could be due to the high percentage of optimum binder, which may have contributed to increased rutting in the Turf-SF1 samples. The lower percentage of fine aggregate passing through the No. 4 and No. 8 sieves, which falls outside the specification limits, could be another contributing factor to the high rutting observed in the Turf-SF1 samples.

Along with the rutting test, IDEAL-CT was used to evaluate the cracking potential of asphalt mixtures. In this study, the IDEAL-CT test was conducted on the Turf-SF1 samples from the wet method. Table 14 summarizes the parameters obtained from the IDEAL-CT test, while Figure 29 illustrates the relationship between force and displacement during the test. The results of the IDEAL-CT test reveal an average CT_{Index} of 657.93, a standard deviation of 249.63, and a coefficient of variation (COV) of 37.94% across three Turf-SF1 samples. According to several studies such as Newcomb, D., & Zhou, F. (2018), Jiao (2023), a minimum CT_{Index} value of 80 is necessary to prevent premature fatigue cracking.

These results indicate that the SF1 samples significantly exceed the specified requirement, with an average CT_{Index} more than eight times higher than the minimum threshold. Although the relatively high COV (37.94%) suggests some variability among the samples, the minimum performance criteria for fatigue cracking resistance are easily met.

The superior fatigue cracking resistance of the SF1 samples can be attributed to the enhanced performance of the modified binder, which results from the blend of crumb rubber and asphalt binder produced through the wet process. This innovative modification likely contributed to the mixture's excellent durability and resistance to cracking.

Table 14. Parameters from IDEAL-CT Test for SF1 Samples

Specimen ID	Air Voids (%)	Tensile Strength (kPa)	Disp. mm	CT-index			
				CT-index	Avg.	Std.	COV
#1 SF1-CT1	7.45	597.7	10.4	703.57	657.93	249.63	37.94
#2 SF1-CT2	7.09	604.5	8.5	881.60			
#3 SF1-CT3	6.56	708.4	8.7	388.64			

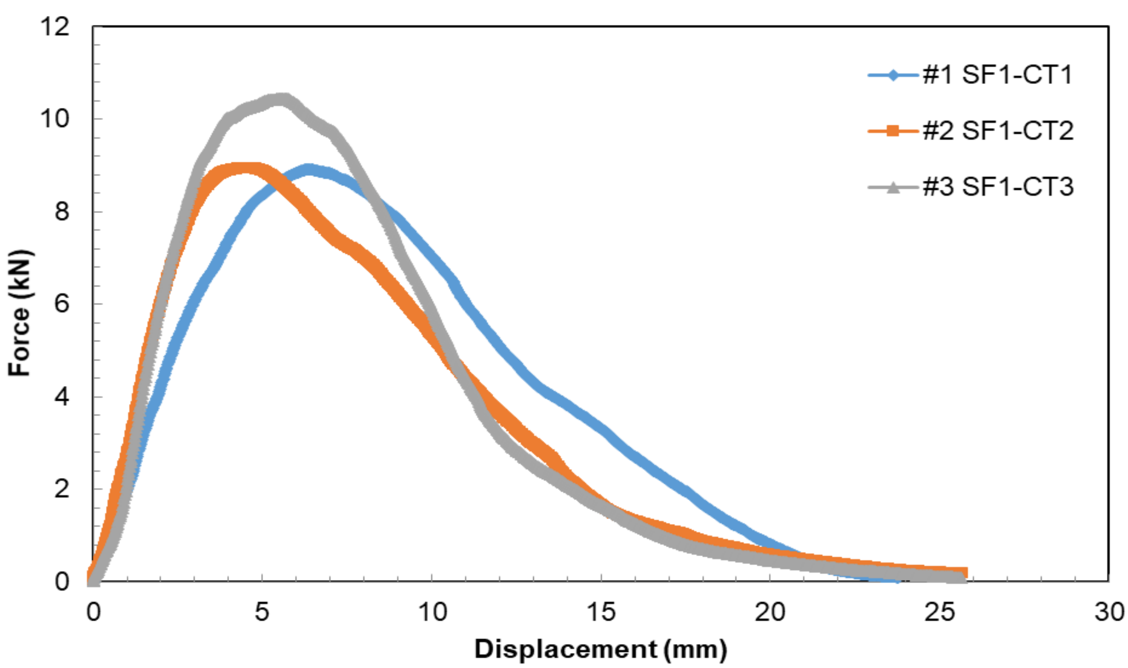


Figure 29. IDEAL-CT Test Results for SF1 Samples

Findings

This study conducted Superpave mix designs and laboratory performance tests on different asphalt mixtures containing crumb rubber turf infill (CRTI) using both dry and wet methods. Based on the results obtained, several key findings can be drawn from this study as follows:

- In the dry method, all asphalt containing turf rubber material mixtures have lower rutting resistance compared with the conventional control asphalt mixtures. While they meet moisture requirements, they fail the rutting criteria as per the APA test except the asphalt turf mixture with 3% Turf-AB.
- Rutting was higher in mixtures with high air void content than mixtures with lower air void content for all samples in both dry and wet methods.
- The binder test demonstrated that incorporating crumb turf rubber into asphalt using the wet method significantly enhances its properties, especially under high temperatures and aging conditions. The substantial increase in G*/sin(δ) values highlights a marked improvement in durability and resistance to deformation at elevated temperatures. As a result, the rubber-modified asphalt mixture produced through the wet process is an ideal solution for regions with hot climates.
- Turf SF1 was utilized in the wet process, and the results show that SF1 mixtures slightly exceeded the rutting test limits according to the APA test. However, Turf SF1 demonstrated excellent performance in cracking resistance, with a CT_{index} value surpassing the recommended minimum threshold by over eight times, as shown by the IDEAL-CT test.
- The high binder content and the lack of fine aggregates in Turf SF1 may contribute to reduced rutting resistance in the asphalt-turf mixture when using the wet method.
- The rutting resistance of the dry-method samples outperforms that of the SF1 sample developed by the wet method.
- Based on the research conducted in this study, it is feasible to incorporate CRTI materials into asphalt mixtures using both dry and wet methods.
- Controlling air voids content is crucial for enhancing the rutting resistance of the asphalt-turf mixture.
- The use of turf rubber asphalt mixtures appears to be well-suited for thin hot mix asphalt overlays with less than 1.5 inches (37.5mm) according to Caltrans (Caltrans Division of Maintenance). Although turf rubber asphalt mixtures were tested for their inadequate resistance to rutting, applying it in thinner layers can mitigate rutting issues, enhance surface cracking resistance, and contribute to a longer pavement service life.

Recommendations

- In the dry method, it is essential to investigate various proportions of turf rubber in the asphalt mixture and test different types of turf. Additionally, more performance tests, like the IDEAL-CT and TSR, should be conducted to thoroughly assess the performance of turf mixtures. The optimal proportion of turf materials in the asphalt mixture should also be investigated.
- In the wet method, asphalt-rubber binders should be created by blending the original asphalt binder with recycled turf rubber in varying amounts (5%, 10%, 15%, and 20% by weight of the asphalt binder) to find the optimum proportions of turf rubber infill materials used. Furthermore, other turf types should be assessed to evaluate their performance in the mixture.
- Future research should focus on improving the rutting resistance of turf rubber asphalt mixtures to promote broader use of turf rubber infill in pavement applications.

Abbreviations and Acronyms

AASHTO	American Association of State Highway and Transportation Officials
APA	Asphalt Pavement Analyzer
ASTM	American Society for Testing and Materials
AV	Air Voids
CalRecycle	The Department of Resources Recycling and Recovery
Caltrans	California Department of Transportations
CP^2	California Pavement Preservation Center
CRTI	Crumb Rubber Turf Infill
DSR	Dynamic Shear Rheometer
Gmm	Maximum specific gravity
Gmb	Bulk specific gravity
HMA	Hot-Mix Asphalt
HWTD	Hamburg wheel tracker device
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
KRC	Knife River Construction
PG	Performance Grade
RAP	Reclaimed asphalt pavement
RTFO	Rolling Thin Film Oven
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate

Glossary of Terms

Asphalt Mixture – A composite material that is a combination of aggregate, filler, and asphalt binder, used in the construction and maintenance of pavements, with the possibility of including additives for enhanced performance.

Air Voids – Small airspaces or pockets of air that occur between the coated aggregate particles in the final compacted mix.

Asphalt Binder – A dark brown to black cementitious material in which the predominant constituents are bitumen, which occur in nature or are obtained in petroleum processing

Crumb Rubber – Finely ground recycled rubber produced from scrap tires after removal of fabric and steel belts.

Mix Design – The process to determine the appropriate proportions of aggregate and asphalt binder for use in hot mix asphalt mixture

Superpave Mix Design – A mix design system that combines material selection (asphalt and aggregate) with volumetric proportioning, based on the specific climate and traffic conditions of the project.

Optimum Binder Content – The amount of asphalt binder that balances different desirable mixture properties for each combination of aggregate type and aggregate gradation.

Dry Method – The process of incorporating crumb rubber into the asphalt mixture as a small part of the aggregate or filler rather than blending the rubber with liquid asphalt binder.

Wet Method – The process of incorporating crumb rubber into the asphalt binder and blending them to create modified asphalt binder before mixing the modified asphalt binder with aggregate.

Thin Overlay – Thin asphalt overlay treatments less than 1.5 inches (37.5 mm) in thickness.

Appendix 1 – Binder Test

Data Table for Figure 2, Figure 3, and Figure 11. DSR Test on Original Binder.

Sample ID	S1	S2	S3	S1	S2	S3
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	64	64	64	70	70	70
G*/sin(d) kPa	1.31	1.32	1.35	0.62	0.63	0.63
Pass the test	Yes			No		
G*/sin(delta)(Pa)	1.31E+03	1.32E+03	1.35E+03	6.15E+02	6.27E+02	631.2
G*/sin(delta)(Pa)	1.31E+03	1.32E+03	1.35E+03	6.14E+02	6.26E+02	630.6
Shear Viscosity (complex component) (Pa s)	1.31E+02	132.2	134.7	6.15E+01	6.27E+01	63.09
Angular Frequency (rad/s)	10					
Shear Modulus (complex component) (Pa)	1.31E+03	1.32E+03	1.35E+03	6.15E+02	6.27E+02	630.9
Phase Angle (◦)	86.9	86.77	86.82	88.18	88.04	88.11
Complex Shear Strain (%)	11.9993	11.9974	12.0001	11.9996	11.9999	11.9988
Complex Shear Stress (Pa)	1.57E+02	158.6	161.6	7.38E+01	7.52E+01	75.7
Gap (mm)	1					
Torque (N m)	4.81E-04	4.87E-04	4.96E-04	2.26E-04	2.31E-04	2.32E-04
Angular Displacement (rad)	9.60E-03	9.60E-03	9.60E-03	9.60E-03	9.60E-03	9.60E-03
Time (sample)(s)	2.24E+03	6.88E+03	2.61E+03	3.55E+03	8.13E+03	3.93E+03
Time (sequence)(s)	2.17E+03	2.09E+03	2.43E+03	3.48E+03	3.34E+03	3.75E+03
Plate Diameter	25					
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 2 and Figure 3. DSR Test after RTFO on Original Binder.

Sample ID	S1	S2	S3	S1	S2	S3
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	64	64	64	70	70	70
G*/sin(d) kPa	3.67	3.76	3.83	1.64	1.67	1.69
Pass the test	Yes			No	No	No
G*/sin(delta)(Pa)	3.67E+03	3.76E+03	3.83E+03	1.64E+03	1.67E+03	1.69E+03
G*/sin(delta)(Pa)	3.60E+03	3.70E+03	3.76E+03	1.62E+03	1.65E+03	1.68E+03
Shear Viscosity (complex component) (Pa s)	363.6	372.9	379.3	162.9	165.8	168.5
Angular Frequency (rad/s)	10			10	10	10
Shear Modulus (complex component) (Pa)	3.64E+03	3.73E+03	3.79E+03	1.63E+03	1.66E+03	1.69E+03
Phase Angle (◦)	82.48	82.48	82.4	84.65	84.64	84.62
Complex Shear Strain (%)	10.01	10.01	10.01	10.00	9.99	9.99
Complex Shear Stress (Pa)	363.9	373.3	379.8	162.9	165.8	168.5
Gap (mm)	1			1	1	1
Torque (N m)	1.12E-03	1.15E-03	1.17E-03	5.00E-04	5.09E-04	5.17E-04
Angular Displacement (rad)	8.01E-03	8.01E-03	8.01E-03	8.00E-03	8.00E-03	8.00E-03
Time (sample)(s)	2.71E+03	8.70E+03	1.26E+04	3.99E+03	9.89E+03	1.40E+04
Time (sequence)(s)	2.56E+03	2.04E+03	2.10E+03	3.84E+03	3.23E+03	3.44E+03
Plate Diameter	25	25	25	25	25	25
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test on Rubberized Binder at 64℃ and 70℃.

Sample ID	S1	S2	S3	S1	S2	S3
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	64	64	64	70	70	70
G*/sin(d) (kPa)	11.49	12.69	12.23	5.93	6.78	6.37
G*/sin(delta)(Pa)	11500	12700	12200	5930	6780	6380
G*sin(delta)(Pa)	9550	10200	9790	5250	5740	5420
Shear Viscosity (complex component) (Pa s)	1050	1140	1090	558.1	623.7	588
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	10500	11400	10900	5580	6240	5880
Phase Angle (◦)	65.73	63.75	63.46	70.2	66.87	67.27
Complex Shear Strain (%)	12.0241	12.0243	12.0248	12.0149	12.0198	12.0169
Complex Shear Stress (Pa)	1260	1370	1320	670.5	749.7	706.5
Gap (mm)	2	2	2	2	2	2
Torque (N m)	0.00387	0.0042	0.00404	0.00206	0.0023	0.00217
Angular Displacement (rad)	0.01924	0.01924	0.01924	0.01922	0.01923	0.01923
Time (sample)(s)	2870	7200	2590	4340	8450	3940
Time (sequence)(s)	1930	2260	2440	3390	3510	3800
Plate Diameter	25	25	25	25	25	25
Notes						
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test on Rubberized Binder at 76℃ and 82℃.

Sample ID	S1	S2	S3	S1	S2	S3
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	76	76	76	82	82	82
G*/sin(d) (kPa)	3.17	3.78	3.46	1.8	2.3	2.04
G*/sin(delta)(Pa)	3170	3780	3460	1800	2300	2040
G*sin(delta)(Pa)	2930	3300	3070	1710	2020	1840
Shear Viscosity (complex component) (Pa s)	304.3	353.2	325.8	175	215.7	193.7
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	3040	3530	3260	1750	2160	1940
Phase Angle (◦)	73.96	69.07	70.18	77.04	69.48	71.85
Complex Shear Strain (%)	12.0004	12.0051	12.0031	11.9985	11.9979	11.9991
Complex Shear Stress (Pa)	365.2	424	391.1	210	258.8	232.4
Gap (mm)	2	2	2	2	2	2
Torque (N m)	0.00112	0.0013	0.0012	0.000644	0.000794	0.000713
Angular Displacement (rad)	0.0192	0.01921	0.0192	0.0192	0.0192	0.0192
Time (sample)(s)	5560	9650	5210	6810	10900	6510
Time (sequence)(s)	4610	4720	5070	5860	5990	6370
Plate Diameter	25	25	25	25	25	25
Notes						
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test on Rubberized Binder at 88℃ and 94℃.

Sample ID	S1	S2	S3	S1	S2	S3
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	88	88	88	94	94	94
G*/sin(d) (kPa)	1.08	1.47	1.23	0.68	0.99	0.78
G*/sin(delta)(Pa)	1.08E+03	1.47E+03	1.23E+03	6.82E+02	987.2	776.2
G*sin(delta)(Pa)	1.04E+03	1.27E+03	1.12E+03	6.63E+02	815.3	702.9
Shear Viscosity (complex component) (Pa s)	1.06E+02	136.4	117.4	6.72E+01	89.72	73.87
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	1.06E+03	1.36E+03	1.17E+03	6.72E+02	897.2	738.7
Phase Angle (◦)	79.03	68.25	72.67	80.29	65.33	72.11
Complex Shear Strain (%)	11.9991	11.9988	11.9979	11.9988	11.9997	11.9986
Complex Shear Stress (Pa)	1.27E+02	163.6	140.8	8.07E+01	107.7	88.63
Gap (mm)	2	2	2	2	2	2
Torque (N m)	3.91E-04	5.02E-04	4.32E-04	2.48E-04	3.30E-04	2.72E-04
Angular Displacement (rad)	1.92E-02	0.0192	0.0192	1.92E-02	0.0192	0.0192
Time (sample)(s)	8.12E+03	1.23E+04	7.95E+03	9.42E+03	1.35E+04	9.25E+03
Time (sequence)(s)	7.17E+03	7.32E+03	7.80E+03	8.47E+03	8.59E+03	9.10E+03
Plate Diameter	25	25	25	25	25	25
Notes						
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test after RTFO on Rubberized Binder at 64℃, 70℃, and 76℃.

Sample ID	S1	S2	S1	S2	S1	S2
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	64	64	70	70	76	76
G*/sin(d) (kPa)	27.96	29.22	16.08	16.85	9.17	9.8
G*/sin(delta)(Pa)	2.80E+04	2.92E+04	1.61E+04	1.69E+04	9.17E+03	9.80E+03
G*sin(delta)(Pa)	1.82E+04	1.87E+04	1.12E+04	1.15E+04	6.94E+03	7.14E+03
Shear Viscosity (complex component) (Pa s)	2.26E+03	2.34E+03	1.34E+03	1.39E+03	797.8	836.7
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	2.26E+04	2.34E+04	1.34E+04	1.39E+04	7.98E+03	8.37E+03
Phase Angle (◦)	53.78	53.2	56.71	55.63	60.44	58.63
Complex Shear Strain (%)	10.0002	9.99797	10.0057	10.0046	10.0104	10.0103
Complex Shear Stress (Pa)	2.26E+03	2.34E+03	1.35E+03	1.39E+03	798.6	837.6
Gap (mm)	2	2	2	2	2	2
Torque (N m)	6.92E-03	7.18E-03	4.13E-03	4.27E-03	2.45E-03	2.57E-03
Angular Displacement (rad)	0.016	0.016	0.01601	0.01601	0.01602	0.01602
Time (sample)(s)	1.45E+04	3.99E+03	1.58E+04	5.26E+03	1.73E+04	6.47E+03
Time (sequence)(s)	4.39E+03	2.34E+03	5.69E+03	3.61E+03	7.16E+03	4.82E+03
Plate Diameter	25	25	25	25	25	25
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test after RTFO on Rubberized Binder at 82℃, 88℃, and 94℃.

Sample ID	S1	S2	S1	S2	S1	S2
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	82	82	88	88	94	94
G*/sin(d) (kPa)	5.36	5.86	3.25	3.57	2	2.22
G*/sin(delta)(Pa)	5.36E+03	5.86E+03	3.25E+03	3.58E+03	2.00E+03	2.22E+03
G*sin(delta)(Pa)	4.33E+03	4.54E+03	2.75E+03	2.90E+03	1.75E+03	1.86E+03
Shear Viscosity (complex component) (Pa s)	481.5	516	298.7	322.2	187.1	203.5
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	4.82E+03	5.16E+03	2.99E+03	3.22E+03	1.87E+03	2.04E+03
Phase Angle (◦)	63.93	61.67	66.82	64.33	69.41	66.26
Complex Shear Strain (%)	10.0077	10.008	10.0025	10.0041	9.99997	10.0018
Complex Shear Stress (Pa)	481.9	516.4	298.8	322.3	187.1	203.6
Gap (mm)	2	2	2	2	2	2
Torque (N m)	1.48E-03	1.58E-03	9.17E-04	9.89E-04	5.74E-04	6.25E-04
Angular Displacement (rad)	0.01601	0.01601	0.016	0.01601	0.016	0.016
Time (sample)(s)	1.86E+04	7.70E+03	2.00E+04	9.02E+03	2.13E+04	1.04E+04
Time (sequence)(s)	8.45E+03	6.05E+03	9.84E+03	7.37E+03	1.11E+04	8.70E+03
Plate Diameter	25	25	25	25	25	25
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test after RTFO and UV on Original Binder at 64℃, 70℃, 76℃.

Sample ID	S1	S2	S3	S1	S2	S3
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	64	64	64	70	70	70
G*/sin(d) kPa	20.79	25.83	23.3	9.6	12.02	10.76
Pass the test	Yes	Yes	Yes	Yes	Yes	Yes
G*/sin(delta)(Pa)	2.22E+03	2.58E+04	2.33E+04	9.61E+03	1.20E+04	1.08E+04
G*/sin(delta)(Pa)	2.17E+03	2.33E+04	2.12E+04	9.07E+03	1.12E+04	1.01E+04
Shear Viscosity (complex component) (Pa s)	219.3	2.45E+03	2.22E+03	933.3	1.16E+03	1.04E+03
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	2.19E+03	2.45E+04	2.22E+04	9.33E+03	1.16E+04	1.04E+04
Phase Angle (◦)	81.29	71.72	72.31	76.34	74.52	75.26
Complex Shear Strain (%)	9.99971	10.0084	9.98618	10.0043	10.0065	10.0025
Complex Shear Stress (Pa)	219.3	2.46E+03	2.22E+03	933.7	1.16E+03	1.04E+03
Gap (mm)	1	1	1	1	1	1
Torque (N m)	6.73E-04	7.53E-03	6.80E-03	2.87E-03	3.56E-03	3.19E-03
Angular Displacement (rad)	8.00E-03	8.01E-03	7.99E-03	8.00E-03	8.01E-03	8.00E-03
Time (sample)(s)	2.06E+04	2.33E+03	1.13E+04	1.82E+04	3.59E+03	1.25E+04
Time (sequence)(s)	5.19E+03	2.24E+03	1.99E+03	2.77E+03	3.51E+03	3.21E+03
Plate Diameter	25	25	25	25	25	25
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test after RTFO and UV on Original Binder at 76℃, 82℃.

Sample ID	S1	S2	S3	S1	S2	S3
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	76	76	76	82	82	82
G*/sin(d) kPa	4.72	5.62	4.99	2.22	2.71	2.43
Pass the test	Yes	Yes	Yes	Yes	Yes	Yes
G*/sin(delta)(Pa)	4.52E+03	5.62E+03	4.99E+03	2.22E+03	2.71E+03	2.43E+03
G*/sin(delta)(Pa)	4.36E+03	5.35E+03	4.78E+03	2.17E+03	2.63E+03	2.37E+03
Shear Viscosity (complex component) (Pa s)	443.7	548.4	488.7	219.3	266.6	240.1
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	4.44E+03	5.48E+03	4.89E+03	2.19E+03	2.67E+03	2.40E+03
Phase Angle (◦)	78.99	77.36	78.12	81.29	79.94	80.56
Complex Shear Strain (%)	10.0041	10.0017	10.0011	9.99971	10.0013	9.99932
Complex Shear Stress (Pa)	443.9	548.5	488.8	219.3	266.7	240
Gap (mm)	1	1	1	1	1	1
Torque (N m)	1.36E-03	1.68E-03	1.50E-03	6.73E-04	8.18E-04	7.36E-04
Angular Displacement (rad)	8.00E-03	8.00E-03	8.00E-03	8.00E-03	8.00E-03	8.00E-03
Time (sample)(s)	1.93E+04	4.77E+03	1.37E+04	2.06E+04	6.05E+03	1.50E+04
Time (sequence)(s)	3.95E+03	4.69E+03	4.39E+03	5.19E+03	5.97E+03	5.62E+03
Plate Diameter	25	25	25	25	25	25
Temperature Control Method	Peltier Dry Chamber					

Data Table for Figure 12 and Figure 13. DSR Test after RTFO and UV on Original Binder at 88℃.

Sample ID	S1	S2	S3
Parameter	n/a	n/a	n/a
Temperature (℃)	88	88	88
G*/sin(d) kPa	1.11	1.36	1.23
Pass the test	Fail	Fail	Fail
G*/sin(delta)(Pa)	1.11E+03	1.36E+03	1.23E+03
G*/sin(delta)(Pa)	1.09E+03	1.33E+03	1.21E+03
Shear Viscosity (complex component) (Pa s)	109.9	134.7	121.7
Angular Frequency (rad/s)	10	10	10
Shear Modulus (complex component) (Pa)	1.10E+03	1.35E+03	1.22E+03
Phase Angle (◦)	83.39	82.12	82.71
Complex Shear Strain (%)	10.0001	9.9985	9.99991
Complex Shear Stress (Pa)	109.9	134.7	121.7
Gap (mm)	1	1	1
Torque (N m)	3.37E-04	4.13E-04	3.73E-04
Angular Displacement (rad)	8.00E-03	8.00E-03	8.00E-03
Time (sample)(s)	2.19E+04	7.46E+03	1.64E+04
Time (sequence)(s)	6.56E+03	7.37E+03	7.02E+03
Plate Diameter	25	25	25
Temperature Control Method	Peltier Dry Chamber		

Data Table for Figure 12 and Figure 13. DSR Test after RTFO and UV on Rubberized Binder.

Sample ID	S1	S1	S1	S1	S1	S1
Parameter	n/a	n/a	n/a	n/a	n/a	n/a
Temperature (℃)	64	70	76	82	88	94
G*/sin(d) kPa	77.28	44.91	26.13	15.45	9.26	5.57
Pass the test	Yes	Yes	Yes	Yes	Yes	Yes
G*/sin(delta)(Pa)	7.73E+04	4.49E+04	2.61E+04	1.55E+04	9.26E+03	5.57E+03
G*/sin(delta)(Pa)	5.00E+04	2.97E+04	1.80E+04	1.11E+04	7.01E+03	4.41E+03
Shear Viscosity (complex component) (Pa s)	6.21E+03	3.65E+03	2.17E+03	1.31E+03	805.6	495.6
Angular Frequency (rad/s)	10	10	10	10	10	10
Shear Modulus (complex component) (Pa)	6.21E+04	3.65E+04	2.17E+04	1.31E+04	8.06E+03	4.96E+03
Phase Angle (◦)	53.51	54.46	56.03	58.07	60.43	62.93
Complex Shear Strain (%)	10.0966	10.0223	10.0173	10.0194	10.0149	10.0062
Complex Shear Stress (Pa)	6.27E+03	3.66E+03	2.17E+03	1.31E+03	806.8	495.9
Gap (mm)	2	2	2	2	2	2
Torque (N m)	0.01924	0.01124	6.66E-03	4.03E-03	2.48E-03	1.52E-03
Angular Displacement (rad)	0.01615	0.01604	0.01603	0.01603	0.01602	0.01601
Time (sample)(s)	4.53E+03	5.83E+03	7.05E+03	8.32E+03	9.60E+03	1.09E+04
Time (sequence)(s)	2.38E+03	3.68E+03	4.90E+03	6.16E+03	7.45E+03	8.76E+03
Plate Diameter	25	25	25	25	25	25
Temperature Control Method	Peltier Dry Chamber					

Appendix 1 – Mix Design

Data Table for Figure 6. Mix Design of the Control Mix in the Dry Method.

Binder content (%)	Air Voids (%)	VFA (%)	VMA (%)	Unit Weight (lbs./ft³)
4.0	5.2	59	12.1	153.8
4.5	4.4	66	12.5	153.9
5.0	3.5	74	12.7	154.2
5.5	2.5	80	11.7	154.4

Data Table for Figure 15. Mix Design of the SF1 Mix in the Wet Method.

Binder content (%)	G_{mm}	G_{mb}	Air Voids (%)	VMA (%)	VFA (%)	Dust Proportion
6.5	2.491	2.328	6.5	16.4	60.1	0.69
7.0	2.483	2.353	5.2	15.9	67.1	0.64
7.5	2.458	2.347	4.5	16.6	72.8	0.56
8.0	2.440	2.358	3.4	16.7%	79.8	0.51

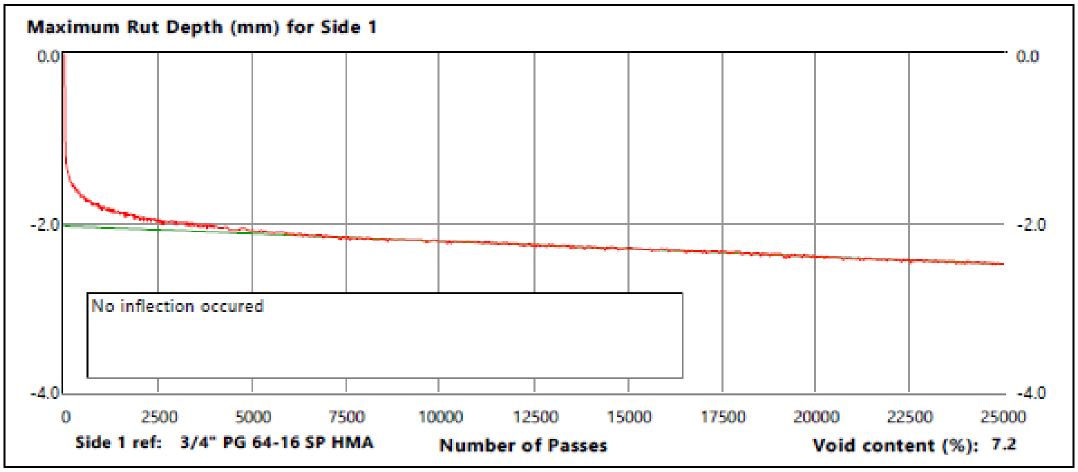
Appendix 2 – RUTTING Test

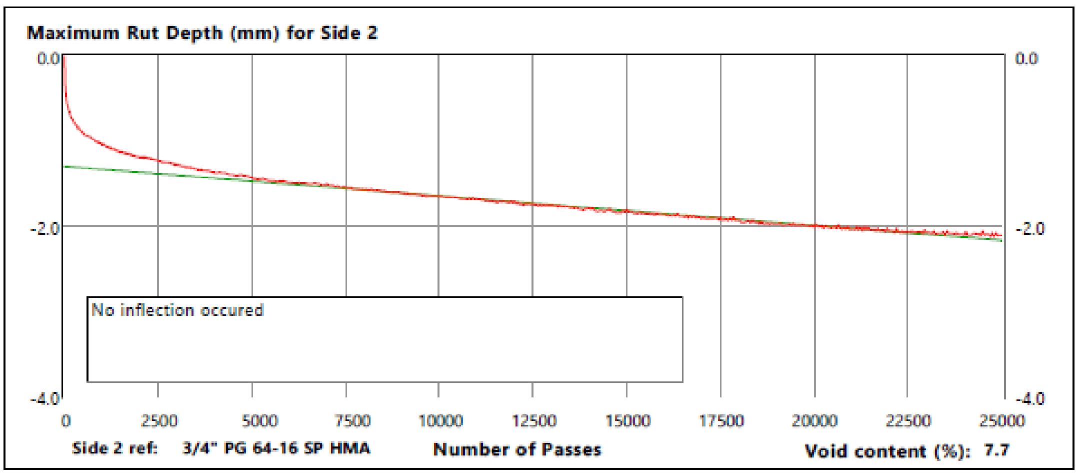
Data for Figure 19, Figure 27, Figure 28. Hamburg Test Result on Control Mixtures.

Hamburg Wheel-Tracker Test Results

AASHTO 324 (Modified)
Date/time of test: 12/10/2020 10:55 AM
Lab. No.: KRC-Chico
Project name: JMF Verification - Curb Ramp, SW, and Driveways, Route 32/I-5 SB On-Ramp (Orland) Glenn Co.

Date sampled: 12/07/20
Job No.: California Highway Construction Group (Outside Sales)
Project No.: 03-4F8104
Project Engineer.: Ryan Johnson - Caltrans
Submitted by: Zack Mason





Max Rut Depths (mm)

Pass No.	Side 1	Side 2
5000	-2.09	-1.42
10000	-2.22	-1.65
15000	-2.30	-1.80
20000	-2.42	-2.01
25000	-2.49	-2.10

Mix type: 3/4" SP HMA with 15% RAP
Asphalt grade: PG 64-16 Valero
Mix source: KRC Orland Plant
Test temperature (°C): 50.0
Mix depth (mm): 60.0

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AN MDU RESOURCES COMPANY

Data Table for Figure 20, Figure 27, Figure 28. APA Test Result on SF1 Mixtures.

Number of Passes	Left Wheel (mm)	Right Wheel (mm)
0	0.00	0.00
200	-3.22	-3.09
400	-3.94	-3.88
600	-4.43	-4.65
800	-4.87	-5.57
1000	-5.27	-6.57
1200	-5.67	-7.59
1400	-6.05	-8.84
1600	-6.34	-10.28
1800	-6.65	-11.47
2000	-6.89	-12.60
2200	-7.23	-14.24
2400	-7.58	
2600	-7.90	
2800	-8.23	
3000	-8.56	
3200	-8.87	
3400	-9.18	
3600	-9.54	
3800	-9.88	
4000	-10.19	
4200	-10.53	
4400	-10.92	
4600	-11.30	
4800	-11.62	
5000	-11.87	
5200	-12.19	
5400	-12.63	
5600	-13.12	
5800	-14.02	

Data Table for Figure 21, Figure 27, Figure 28. APA Test Result on Turf 1 Mixtures.

Number of Passes	Left Wheel (mm)	Right Wheel (mm)
0	0	0
200	-1.56	-1.17
400	-1.81	-1.38
600	-2.04	-1.51
800	-2.18	-1.59
1000	-2.24	-1.65
1200	-2.51	-1.74
1400	-2.64	-1.78
1600	-2.81	-1.84
1800	-3.06	-1.90
2000	-3.48	-1.94
2200	-4.10	-1.96
2400	-4.68	-1.99
2600	-4.95	-2.12
2800	-5.62	-2.18
3000	-6.33	-2.11
3200	-6.95	-2.29
3400	-6.92	-2.43
3600	-8.10	-2.36
3800	-8.38	-2.55
4000	-9.08	-2.64
4200	-9.21	-2.91
4400	-9.89	-2.88
4600	-10.27	-3.34
4800	-10.85	-3.55
5000	-10.96	-3.95
5200	-11.60	-3.95
5400	-12.02	-4.57
5600	-12.51	-4.79
5800		-4.42
6000		-4.73
6200		-4.96
6400		-5.22
6600		-5.64
6800		-5.98
7000		-6.28
7200		-6.72
7400		-6.99

Number of Passes	Left Wheel (mm)	Right Wheel (mm)
7600		-7.33
7800		-8.00
8000		-8.62
8200		-8.19
8400		-9.63
8600		-9.97
8800		-10.30
9000		-10.57
9200		-10.80
9400		-11.01
9600		-11.22
9800		-11.65
10000		-11.80
10200		-12.44
10400		-12.75
10600		-12.78
10800		-13.10
11000		-13.10
11200		-13.16
11400		-14.13

Data Table for Figure 23, Figure 27, Figure 28. APA Test Result on Turf 2 Mixtures.

Number of Passes	Left Wheel (mm)	Right Wheel (mm)
0	0.00	0.00
200	-1.29	-1.71
400	-1.55	-2.05
600	-1.68	-2.32
800	-1.81	-2.55
1000	-1.90	-2.76
1200	-1.99	-2.97
1400	-2.09	-3.15
1600	-2.18	-3.32
1800	-2.26	-3.52
2000	-2.33	-3.71
2200	-2.41	-3.90
2400	-2.47	-4.17
2600	-2.54	-4.94

Number of Passes	Left Wheel (mm)	Right Wheel (mm)
2800	-2.60	-6.04
3000	-2.67	-7.21
3200	-2.78	-8.09
3400	-2.87	-8.67
3600	-2.91	-9.39
3800	-3.00	-10.12
4000	-3.09	-10.77
4200	-3.19	-11.90
4400	-3.27	-12.05
4600	-3.31	-12.91
4800	-3.13	
5000	-3.28	
5200	-3.37	
5400	-3.61	
5600	-3.92	
5800	-4.37	
6000	-4.71	
6200	-5.02	
6400	-5.27	
6600	-5.51	
6800	-5.71	
7000	-5.90	
7200	-6.14	
7400	-6.30	
7600	-6.63	
7800	-7.03	
8000	-7.07	
8200	-7.50	
8400	-7.58	
8600	-7.71	
8800	-8.36	
9000	-8.47	
9200	-9.02	
9400	-9.39	
9600	-9.85	

Data Table for Figure 25, Figure 27, Figure 28. APA Test Result on Turf AB Mixtures.

Number of Passes	Left Wheel (mm)	Right Wheel (mm)
0	0.00	0.00
200	-2.14	-1.83
400	-2.54	-2.12
600	-2.82	-2.51
800	-3.06	-2.69
1000	-3.27	-2.75
1200	-3.43	-2.92
1400	-3.64	-3.06
1600	-3.80	-3.15
1800	-3.97	-3.25
2000	-4.11	-3.28
2200	-4.26	-3.26
2400	-4.47	-3.46
2600	-4.65	-3.52
2800	-4.83	-3.46
3000	-5.15	-3.61
3200	-5.66	-3.68
3400	-6.03	-3.65
3600	-7.49	-3.67
3800	-8.07	-3.74
4000	-8.38	-3.75
4200	-8.91	-3.89
4400	-9.80	-3.93
4600	-10.56	-3.96
4800	-11.13	-3.96
5000	-12.17	-4.07
5200	-12.86	-4.10
5400	-13.56	-4.16
5600		-3.83
5800		-3.77
6000		-3.83
6200		-3.87
6400		-3.93
6600		-3.98
6800		-4.01
7000		-4.05
7200		-4.07

Number of Passes	**Left Wheel (mm)**	**Right Wheel (mm)**
7400		-4.11
7600		-4.18
7800		-4.23
8000		-4.32
8200		-4.38
8400		-4.47
8600		-4.54
8800		-4.63
9000		-4.73
9200		-4.76
9400		-4.81
9600		-4.87
9800		-5.02
10000		-5.02
10200		-5.15
10400		-5.27
10600		-5.33
10800		-5.45
11000		-5.42
11200		-5.79
11400		-5.57
11600		-6.40
11800		-6.54
12000		-6.69
12200		-7.08
12400		-7.17
12600		-7.39
12800		-7.67
13000		-8.03
13200		-8.12
13400		-8.18
13600		-8.59
13800		-8.64
14000		-8.68
14200		-8.99
14400		-8.74
14600		-9.13
14800		-9.08
15000		-9.13

Number of Passes	Left Wheel (mm)	Right Wheel (mm)
15200		-9.10
15400		-9.39
15600		-9.50
15800		-9.25
16000		-9.53
16200		-9.81
16400		-9.47
16600		-9.78
16800		-9.72
17000		-9.81
17200		-10.15
17400		-9.76
17600		-10.22
17800		-10.15
18000		-10.17
18200		-10.30
18400		-10.08
18600		-10.03
18800		-10.27
19000		-10.58
19200		-10.57
19400		-10.39
19600		-10.48
19800		-10.71

Appendix 3 – IDEAL-CT Test

Data Table for Figure 29. IDEAL-CT Test Results on Turf SF1, Sample 1.

Time (sec)	Load (kN)	Displacement (mm)
0	0.00	0.00
1	1.16	0.64
2	3.02	1.42
3	4.77	2.24
4	6.24	3.10
5	7.31	3.95
6	8.23	4.77
7	8.68	5.57

Time (sec)	Load (kN)	Displacement (mm)
8	8.91	6.35
9	8.78	7.18
10	8.41	8.05
11	7.90	8.93
12	7.21	9.79
13	6.49	10.63
14	5.64	11.41
15	4.94	12.18
16	4.33	13.00
17	3.89	13.87
18	3.44	14.76
19	2.92	15.63
20	2.46	16.47
21	2.06	17.28
22	1.65	18.05
23	1.27	18.86
24	0.91	19.72
25	0.61	20.61
26	0.34	21.50
27	0.21	22.34
28	0.13	23.16

Data Table for Figure 29. IDEAL-CT Test Results on Turf SF1, Sample 2.

Time (sec)	Load (kN)	Displacement (mm)
0	0.00	0.00
1	1.84	0.69
2	4.66	1.54
3	7.07	2.42
4	8.48	3.29
5	8.91	4.11
6	8.92	4.89
7	8.53	5.67
8	7.89	6.52
9	7.31	7.39
10	6.86	8.25
11	6.16	9.08

Time (sec)	Load (kN)	Displacement (mm)
12	5.45	9.91
13	4.69	10.68
14	4.06	11.46
15	3.46	12.29
16	2.90	13.16
17	2.24	14.02
18	1.73	14.86
19	1.38	15.70
20	1.20	16.52
21	1.06	17.30
22	0.86	18.11
23	0.73	18.98
24	0.60	19.85
25	0.51	20.73
26	0.43	21.55
27	0.36	22.38
28	0.29	23.17

Data Table for Figure 29. IDEAL-CT Test Results on Turf SF1, Sample 3.

Time (sec)	Load (kN)	Displacement (mm)
0	0.00	0.00
1	1.27	0.72
2	4.61	1.59
3	7.47	2.48
4	9.30	3.35
5	10.09	4.17
6	10.35	4.95
7	10.44	5.74
8	9.94	6.59
9	9.41	7.46
10	8.35	8.31
11	7.09	9.14
12	6.00	9.95
13	4.81	10.71
14	3.78	11.47
15	3.00	12.29

Time (sec)	Load (kN)	Displacement (mm)
16	2.48	13.16
17	2.08	14.03
18	1.69	14.89
19	1.36	15.73
20	1.07	16.53
21	0.85	17.31
22	0.69	18.11
23	0.58	18.99
24	0.48	19.86
25	0.40	20.73
26	0.33	21.56
27	0.26	22.38
28	0.22	23.15

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