# SELECTION OF A DURABLE, SUSTAINABLE AND COST-EFFECTIVE ASPHALT MIXTURE FOR PAVEMENTS IN OREGON

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## Technical Proposal

**SCHOOL OF CIVIL & CONSTRUCTION ENGINEERING**
**OREGON STATE UNIVERSITY**

# SELECTION OF A DURABLE, SUSTAINABLE AND COST-EFFECTIVE ASPHALT MIXTURE FOR PAVEMENTS IN OREGON

**TECHNICAL PROPOSAL**

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# 1.0 INTRODUCTION

Cracking is a common failure mechanism in asphalt concrete pavement structures. It is one of the main reasons for large road maintenance and rehabilitation expenditures, as well as reduced user comfort and increased fuel consumption due to high road roughness. The resistance of the pavement to this distress mechanism is dependent upon the ductility of the asphalt pavement mixture. The increased use of recycled asphalt materials with high binder replacement rates results in a significant reduction in ductility of the asphalt mixtures used in construction, which causes a significant reduction in the fatigue life of the pavement in many cases. In Oregon, asphalt cracking is the major distress mode, necessitating costly rehabilitation and maintenance at intervals of less than half of the intended design lives in some cases. For this reason, it is necessary to accurately quantify the impact of increasing the recycled asphalt content on the structural cracking and rutting resistance of the pavement through use of low-cost and efficient testing and design procedures that can easily be implemented.

Asphalt mixtures are designed to be used in pavements to withstand vehicular loads under different climatic conditions. The goal of asphalt mix design is to determine an economic blend of aggregates and binder such that the resultant mix provides sufficient stability to resist deformation under traffic loading, and flexibility to withstand cracking. The current asphalt mix design practice (Level 1-Volumetric only) involves proportioning of the aggregates and the asphalt binder based on empirical properties of aggregates and volumetric properties such as densities, air voids, voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA). However, most state DOTs and asphalt contractors do not think that commonly used asphalt mixture properties are directly reflecting the long-term performance of asphalt mixtures. For instance, although there are requirements for VMA set by almost all state DOTs, measurement of VMA relies on the accurate measurement of aggregate bulk specific gravity, while considerable issues were observed in terms of accuracy and variability during the measurement of this parameter (West et al. 2018). In addition, there are several new additives, polymers, rubbers, and high-quality binder types incorporated into asphalt mixtures today. Volumetric mixture design methods are not capable of capturing the benefits of using all these new technologies on asphalt mixture performance. Furthermore, the interaction of virgin binders with reclaimed asphalt pavement (RAP) mixtures with high binder replacement contents and the level of RAP binder blending into the asphalt mixture are still not well understood. Due to all these complications related to the more complex structure of asphalt mixtures, simple volumetric evaluations to determine the optimum binder content may not result in reliable asphalt mixture designs. Two volumetrically identical mixtures may provide completely different rutting and cracking performance according to laboratory tests (Coleri et al. 2017b).

For all these reasons, performance tests for rutting and cracking need to be incorporated into current asphalt mixture design methods to be able to validate or revise the optimum binder content determined by the volumetric mix design method. Numerous research studies were recently carried out and are currently being conducted to develop new mix design processes with performance verification (Epps et al. 2002; Zhou et al. 2006; Harvey et al. 2014; Cooper III et al. 2014; Williams et al. 2004; Bennert et al. 2014; Hughes and Maupin 2000; Dave and Koktan 2011; Kim et al. 2011; Zhou et al. 2014). However, this approach is not entirely new and draws upon the existing methods and procedures while the existing methods need to be revised and improved by incorporating findings from recent research studies.

Oregon Department of Transportation (ODOT) Research Projects SPR785, SPR797 (Coleri et al. 2017b; Coleri et al. 2017a; Sreedhar et al. 2018; Haddadi et al. 2019) constructed the beginnings of a performance-based balanced mix design method for Oregon. It was suggested that semi-circular bend (SCB) test is the most effective and practical cracking test that can effectively be used for balanced mix design. It was determined that the typical flexibility index (FI), an energy parameter calculated using SCB test results, values for production mixtures (plant-produced) with polymer-modified binder range from 9 to 14. However, more experiments need to be conducted to determine an exact threshold for FI that will provide acceptable long-term pavement cracking performance. In these two research projects, flow number (FN) test was used as the experiment for rutting performance evaluation. For highways with high traffic levels (ESALs > 30 million), an FN of 740 was suggested by AASHTO TP79-13 (2013) and used in SPR785 and SPR797 as the threshold value for rutting performance acceptance. However, FI and FN threshold numbers used in these two research projects were not validated using test results from actual asphalt production mixtures sampled from different construction projects. The effectiveness of the FN test and other potential laboratory test options, such as the Hamburg Wheel Tracking Test (HWTT), in predicting in-situ rutting performance was also not evaluated in those two ODOT research projects. In addition, the most effective asphalt mixture long-term aging protocols to achieve reliable semi-circular bend (SCB) test parameters that are correlated with in-situ cracking performance are needed to be developed. The developed aging protocol also needs to be integrated into the balanced mix design procedures that are developed for Oregon in this study.

A recently completed ODOT research project (SPR 801) suggested the adaptation of Hamburg Wheel Tracking Test (HWTT) and Semi-Circular Bend (SCB) tests for rutting and cracking performance quantification. This Balanced Mix Design (BMD) implementation study also developed rutting and cracking performance thresholds for high (Level 4) and medium (Level 3) Equivalent Single Axle Load (ESAL) roads. Based on the results of all analyses for cracking performance, a flexibility index (FI) threshold of 6 was recommended for Level 3 mixes while the threshold for Level 4 was selected as 8. For rutting performance, a HWTT rut depth threshold of 3mm was recommended for Level 3 mixes while the threshold for Level 4 was selected as 2.5mm. In this study, three asphalt mixtures with different recycled asphalt contents (RAP) and additives were evaluated in terms of cracking and rutting performance by using the thresholds for Level 4 asphalt mixtures. A balanced mix design process was followed to determine the required binder content for the three mixtures. Based on the life cycle cost and environmental impact analyses, the mixture with warm mix additive was selected as the most economically and environmentally viable asphalt mixture to be used for construction in Oregon.

# 2.0 PROBLEM STATEMENT AND KEY OBJECTIVES

In Oregon, fatigue cracking is the major distress mode for asphalt concrete pavement structures. It is one of the main reasons for large road maintenance and rehabilitation expenditures, as well as reduced user comfort and increased fuel consumption due to high road roughness. The resistance of the pavement to this distress mechanism is dependent upon the ductility of the asphalt pavement mixture. According to the literature, aging of asphalt binder associated with the oxidation of the binder is a major factor affecting the fatigue performance of asphalt mixtures. Increasing asphalt binder content, using elastomer-modified binders, and/or using softer binder grades were proved to improve fatigue cracking resistance (Coleri et al. 2017a, Coleri et al. 2017b). Coleri et al. (2017b) showed that binder content of the asphalt mixtures produced with the current volumetric design method can be increased without having rutting failures. The low binder content suggested by the current volumetric design methods results in early fatigue cracking and moisture damage. Increasing density (compactibility) and flexibility by using higher binder contents and/or different types of additives were also recommended to be viable options to improve longevity of Oregon roadway network. To address these issues, Coleri et al. (2020) developed a robust performance based asphalt mix design method to be able to recommend these strategies for performance improvement. In this study, balanced mix design procedures developed by Coleri et al. (2020) in the SPR801 ODOT research project were followed to design three asphalt mixtures for Oregon roads with high traffic levels (Level 4 mixtures).

The main objectives of this study are to:

- Design three trial asphalt mixtures for application on a four-lane divided highway (arterial collector) with a total 20 year design equivalent single axle load (ESAL) of 7,500,000. This ESAL level requires a Level 4 mixture design in Oregon;
- Evaluate the trial mixes for cracking and rutting performances;
- Determine design binder content range for each mix using the balanced asphalt mix design method developed for Oregon by incorporating performance tests for rutting and cracking into the current volumetric design process (Coleri et al. 2020);
- Determine the cost and environmental impact of all three mixtures by performing life cycle cost and environmental impact analysis; and
- Recommend the "best" asphalt mixture for the given conditions by considering the cost-effectiveness, sustainability and the long-term performance of the mixes.

# 3.0 BALANCED MIX DESIGN APPROACH

The Federal Highway Administration (FHWA) formed an Expert Task Group to develop a Balanced Mix Design (BMD) process (West et al. 2018). The group defines BMD as *"asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate and location within the pavement structure"*. Figure 3-1 illustrates the difference between conventional volumetric mix design and proposed balanced mix design process. In volumetric mix design, an optimum binder content required to achieve 4% air-void content by applying a predetermined compactive effort (number of gyrations in a Superpave Gyratory Compactor) is determined. However, performance properties of asphalt mixtures are not accounted for in the design process. On the other hand, in a balanced mix design process, performance properties of asphalt mixtures are evaluated in addition to volumetric properties. In the example presented in Figure 3-1, the binder content determined by the volumetric process is 5.7%. This binder percentage satisfies the rutting criteria for asphalt mixtures. However, this binder content does not satisfy the cracking performance requirements (flexibility index of 8 from the IFIT test). On the other hand, the balanced mix design approach yields a binder content ranging between 6.2% and 6.7%. Within this range, both cracking and rutting criteria are met.

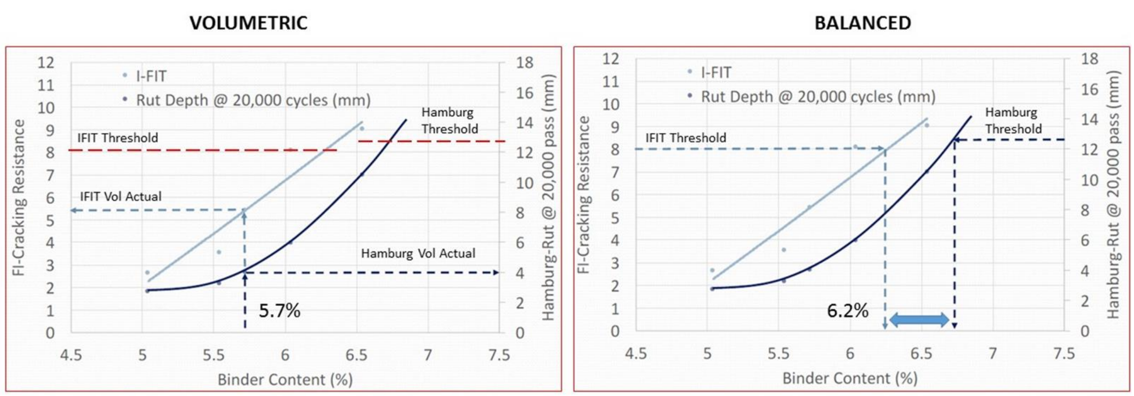



**Figure 3-1: Volumetric mix design vs balanced mix design example. (West et al. 2018)**

The FHWA group also determined three potential approaches to implement BMD (West et al. 2018), which are briefly described as follows:

**Approach 1: Volumetric Design with Performance Verification:** This is the most commonly used approach researched and employed by different agencies. In this approach, the mixture is designed based on Superpave specifications. Then, performance tests are conducted to validate whether the mix meets the performance requirements. The mixture should satisfy both volumetric and performance testing criteria. If the mixture does not meet the requirements, the entire mix design process is repeated. The adjustments to the mixture can be made through aggregate source, aggregate gradation, binder source, binder grade, and or additives. This approach is currently being implemented by state department of transportations (DOTs) in Illinois, Texas, Louisiana, New Jersey, and Wisconsin. The process is illustrated in Figure 3-2.

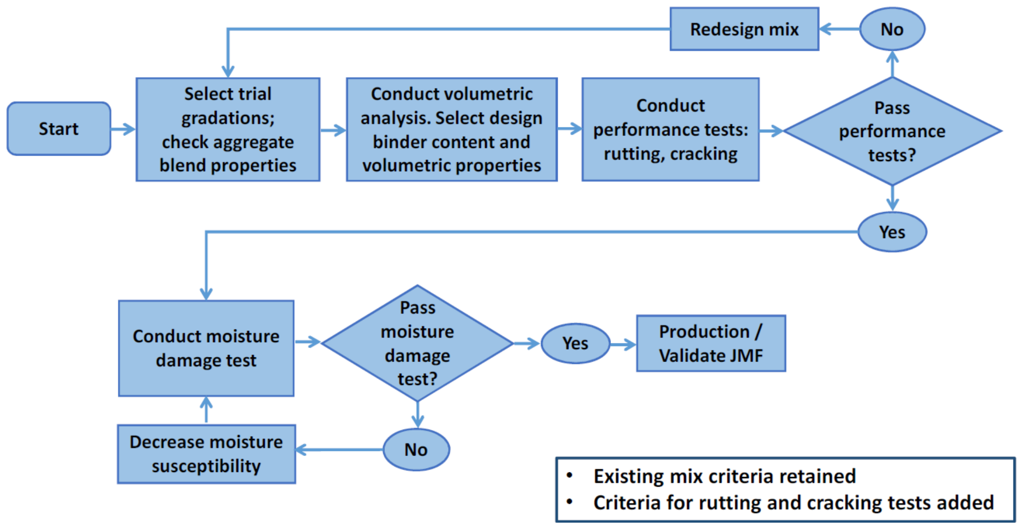



**Figure 3-2: Approach 1 - Volumetric design with performance verification. (West et al. 2018)**

## 3.1 BALANCED MIX DESIGN PROCESS IN OREGON – DESIGN APPROACH

The BMD approach proposed by Oregon State University (OSU) in the SPR 801 research project (Coleri et al. 2020) is using volumetric design plus performance testing. The motivation behind implementing this approach was to: i) address the performance issues related to the use of higher contents of RAP, ii) increasing binder contents to improve long-term cracking performance; and iii) quantifying the impact of using recently developed additive technologies (warm-mix, fibers, polymer modified binders, etc.) on long-term pavement performance. In the proposed process, binder content is determined using the Superpave volumetric mixture design process after selecting a suitable aggregate gradation and binder grade.

SCB tests were conducted at 25°C with a displacement rate of 0.5 mm/min (AASHTO TP 105-13; Coleri et al. 2017b). The Flexibility Index (FI) (Ozer et al. 2016) is used to evaluate the cracking performance after long-term conditioning (24 hours of loose mixture aging at 95 ± 2°C, based on the aging protocol that was also developed in the SPR 801 research project), while HWTT is used to evaluate the rutting resistance after only short-term conditioning (two hours of loose mix aging at 132 ± 3°C). HWTT was conducted at 50°C and the total rut depth (RD) accumulated after 20,000 repetitions was used for rutting performance evaluation. For balanced mix design in Oregon, Coleri et al. (2020) recommended an FI threshold of 6 for Level 3 (for medium ESAL roadway sections) mixes, while the threshold for Level 4 (for high ESAL roadway sections) mixes was selected as 8.

A HWTT RD threshold of 3mm was recommended for Level 3 mixes while the threshold for Level 4 was selected as 2.5mm. Since the designs in this proposal are for a roadway section with high ESAL levels (7.5 million), designed asphalt mixtures are required to be Level 4 mixes in Oregon (See ODOT 2019-Table 23). For this reason, an FI threshold of 8 and an RD threshold of 2.5mm were used for balanced mix design (Coleri et al. 2020). In the BMD approach suggested for Oregon in SPR 801, different requirements for binder content adjustments, change in binder source, or reduction in quantities of recycled materials are generally made to achieve the desired mixture performance.

# 4.0 ASPHALT MIX PROPETIES AND BALANCED MIX DESIGN

## 4.1 MATERIALS AND SAMPLE FABRICATION

This section provides information about the materials used in this study (including virgin binders, virgin aggregates and RAP materials). The materials were sampled from an asphalt plant located near Tigard, Oregon. In this study, laboratory mixed-laboratory compacted (LMLC) samples were used for testing and evaluation. LMLC is defined as follows:

- *Laboratory Mixed-Laboratory Compacted (LMLC) samples:* Aggregates, virgin binders and RAP material used to produce asphalt mixtures for field construction were sampled from asphalt plant. These materials were used to produce LMLC samples at the Asphalt Materials Performance Laboratory at Oregon State University.

Three different asphalt mixtures were used in this study: Mix1, Mix2, and Mix3. These trial mixes varied in gradation, amount of RAP content, and presence of additives. Mix1 was further divided into two mixes Mix1_AV5 and Mix1_AV7, differing by the compacted air void contents of the test samples (5% and 7%, respectively) to quantify the impact of density on performance. Mix 2 had 45% RAP content and Mix 3 was identical to Mix 1 except that in Mix3, Evotherm® was used as a warm-mix additive. Both Mix2 and Mix3 were compacted to 93 percent theoretical maximum density (±0.5%) in a gyratory compactor to produce test samples with conventional 7% air-void content. In this study, BMD samples were produced with 7% air-void content since 93% density during construction is the expected average density for contractors in Oregon. Figure 4-1 shows the gradation curves used for the production of the three mixtures. Once the target gradation was finalized, three trial binder contents were selected for mix design. For each binder content, $G_{mm}$ samples were mixed in triplicate according to AASHTO T 312-12 and their respective $G_{mm}$ values were determined as per AASHTO T 209-12 procedures. Subsequently, three replicate mix design samples were prepared for each binder content and compacted in the gyratory compactor by fixing the number of gyrations to 65 as required by the competition guideline. The air-void content for each sample was determined. The binder content corresponding to the target design air void was selected as the optimum binder content (OBC) for each mix. Moreover, mix design verification (MDV) was performed on the mixes with the OBC and the results were matched against the ODOT specifications and found to be within the tolerance limits (ODOT, 2018). The volumetrics and the other mix design variables of the three trial mixes considered in this study are summarized in Table 4-1.

**Table 4-1: Mix design and volumetric properties for the three trial mixes**

| ID [a] | Binder Grade | RAP [b] (%) | $AC_{RAP}$ (%) | AC [c] (%) | BR [d] (%) | $P_{be}$ [e] (%) | $P_{200}/P_{be}$ [f] Ratio | Addi.[g] | VMA[j]-VFA[k]% |
|---|---|---|---|---|---|---|---|---|---|
| Mix1_AV5 | PG 70-22ER | 30 | 5.02 | 5.6 | 26.9 | 4.63 | 1.4 | 1% Li[h] | 16.1-69 |
| Mix1_AV7 | | 30 | | 5.6 | 26.9 | 4.63 | 1.4 | 1% Li | 16.1-69 |
| Mix2 | | 45 | | 5.3 | 42.6 | 4.38 | 1.6 | 1% Li | 15.6-68 |
| Mix3 | | 30 | | 5.6 | 26.9 | 4.63 | 1.4 | 1% Li, 0.68% Evm[i] | 16.1-69 |

[a] All mixtures had dense gradation and aggregates with a nominal maximum aggregate size of 12.5mm;
[b] RAP = Reclaimed asphalt pavement added by weight;
[c] AC = Total asphalt content by weight from volumetric design for 65 gyrations;
[d] BR = Binder replacement;
[e] $P_{be}$ = Effective asphalt content present by weight in the total mix;
[f] $P_{200}/P_{be}$ = Dust to binder ratio in the mix;
[g] Addi. = Additive; [h] Li = Lime; [i] Evm = Evotherm warm mix additive; [j] VMA = Voids in mineral aggregate; [k] VFA = Voids filled with asphalt.

All the mixes exhibit high VMA values. However, it should be noted that all VMA values are within the 13.5-17.0 range required for 12.5mm nominal maximum aggregate size mixtures in Oregon according to the standard mix design verification process. All VFA values are also within the required range of 65 to 75 required for Level 4 asphalt mixtures in Oregon. Dust-to-binder ratios for all asphalt mixtures are also within the limits required by ODOT (0.8-1.6).

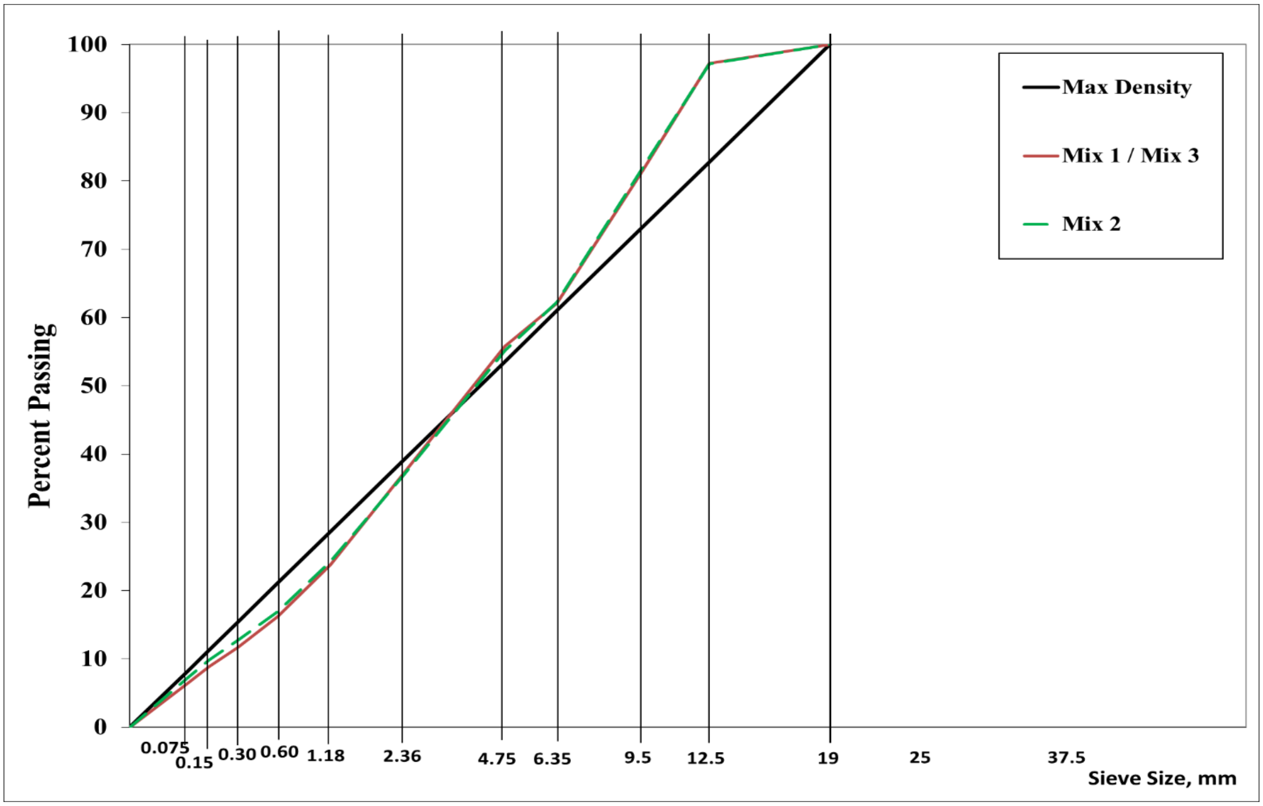



**Figure 4-1: Gradation curves for asphalt mixtures from all 3 mixes on a 0.45 power chart.**

### 4.1.1 Preparation of LMLC Specimens

For sample preparation, aggregates and RAP were batched to meet the final gradation and the 7% ± 1% air content for all the mixes (except Mix1_AV5 for which the target air content was 5%± 1% to determine the impact of density on performance). Then, batched samples were mixed and compacted by following the AASHTO T 312-12 (2012) specification. Before mixing, aggregates were kept in the oven at 10°C higher than the mixing temperature, RAP materials were kept at 110°C, and binder was kept at the mixing temperature for 2 hours. After mixing, the AASHTO R 30 (2010) recommends conditioning the prepared loose mixtures for 4 hours at 135°C to simulate short-term aging (STA). The goal of short-term aging is to simulate the aging and binder absorption that occurs during the production and silo storage phases. However, based on the suggestions from the NCHRP 815 (Newcomb et al. 2015), a short-term conditioning period of 2 hours at 135°C was adopted (which is also the short-term aging protocol suggested by Coleri et al (2020) for Oregon).

The long-term aging protocol developed for Oregon in SPR 801 research project was followed for conditioning asphalt mixtures for the SCB cracking tests. Based on the results and recommendations from SPR 801, short-term aged loose mixtures were further aged at 95°C for 24 hours to simulate long-term aging. The conditioning was carried out in a forced draft oven and mixtures were stirred at regular intervals to ensure uniform aging. After LTA conditioning, mixtures were further kept in the oven at compaction temperature for 2 more hours prior to compaction. The mixing and compaction temperatures were obtained from viscosity versus temperature plots for the binder provided by the plant. Cylindrical samples were compacted using a Superpave Gyratory Compactor (SGC) in accordance with the AASHTO T312-12 specification. Asphalt mixtures used for HWTT sample production were only short-term aged (no long-term aging) since rutting generally occurs early in the design life. Asphalt mixtures for only SCB samples were long-term aged to simulate the impact of aging (oxidation and volatilization of different components in the asphalt binder) on long-term cracking resistance.

For warm mix asphalt sample preparation, aggregates and RAP were batched following the same guidelines as the hot mix asphalt. Before mixing, binder and the warm mix additive Evotherm P25 were mixed using a counter top stationary mixer. Calculated Evotherm P25 dosages were 0.66%, 0.68%, and 0.71% by weight of total binder for asphalt mixtures with 6.1%, 5.6%, and 5.1% total binder contents, respectively. The chemical additive dosage was calculated according to Equation (4-1) considering the total binder in the mix (virgin binder and binder derived from RAP) and starting from a target Evotherm P25 dosage (in this case it was considered 0.5% by weight of total mix).

$$\%\,Adjusted\ Evotherm\ dosage = \frac{(\%\,Target\ Evotherm\ dosage) \times (\%\,Total\ binder)}{(\%\,Total\ binder\ -\ \%\,Binder\ from\ RAP)} \quad \text{(Ingevity,2019)} \quad \textbf{(4-1)}$$

For warm mix asphalt, the mixing temperature was 140°C. After mixing, the prepared loose mixtures were conditioned for 2 hours at 135°C. After STA conditioning, the loose mixtures prepared for SCB test sample production were conditioned for an additional 24 hours at 95°C to simulate long-term aging. After conditioning, mixtures were further kept in the oven at a compaction temperature of 126°C for 2 more hours prior to compaction.

## 4.2 TEST METHODS

### 4.2.1 Semi-Circular Bend (SCB) Test

In a previous research study performed at Oregon State University (Coleri et al. 2017b), semi-circular bend (SCB) test was selected as the most effective cracking experiment to characterize asphalt mixtures used in Oregon (Sreedhar et al. 2018). Therefore, SCB tests were conducted in this study to determine the cracking resistance of asphalt mixtures and to determine a suitable threshold for the test's output parameter (flexibility index) to be used as an acceptance criterion in the proposed balanced asphalt mixture design process. Test method for evaluating the cracking performance of asphalt concrete at intermediate temperatures developed by (Ozer et al. 2016) was followed with few modifications. A displacement rate of 0.5 mm/min was used instead of 50 mm/min (Sreedhar et al. 2018, Coleri et al. 2017b).

130 mm tall samples were compacted in the laboratory according to AASHTO T 312-12. Two samples with the thickness of 57 ± 2 mm were sawn from each gyratory compacted sample using a high-accuracy saw. Then, cylindrical samples (cores) were cut into two identical halves using a

special jig. Tests were conducted at 25$^{o}$C with a displacement rate of 0.5 mm/min. Samples were kept in the chamber at the testing temperature for conditioning the day before being tested. Flat side of the semi-circular samples was placed on two rollers. As a vertical load with constant displacement rate is applied to the samples, applied load is measured via a load cell. Test stops when the load drops below 0.5 kN. Flexibility index (FI) is the testing parameter obtained from this test and used for cracking resistance evaluation.

Flexibility Index (FI) is the ratio of the fracture energy ($G_f$) to the slope of the line (m) at the post-peak inflection point of the load-displacement curve (see Equation (4-2). FI correlates with ductility. Lower FI values show that the asphalt mixtures are more brittle with the higher crack growth rate.

$$FI = A \times \frac{G_f}{abs(m)} \tag{4-2}$$

Where, A is a unit conversion and scaling coefficient taken as 0.01.

### 4.2.2 Hamburg Wheel-Tracking Test (HWTT)

The Hamburg Wheel-Tracking Test (HWTT) system was developed to measure rutting and moisture damage (stripping) susceptibility of an asphalt concrete sample. The HWTT follows the AASHTO T 324 standard. According to the specification, either a slab or a cylindrical specimen can be tested. Tests are conducted by immersing the asphalt concrete sample in a hot water bath (at 40°C or 50°C) and rolling a steel wheel across the surface of the sample to simulate vehicular loading. Approximately 20,000 wheel passes are commonly used to evaluate the rutting and stripping resistance of a sample. The test provides information related to the total rut depth, post-compaction, creep slope, stripping inflection point and stripping slope of the asphalt concrete sample (Yildirim et al. 2007; Tsai et al. 2016). In this study, rut depth after 20,000 wheel passes is used for rutting performance evaluation. Cylindrical specimens were used for testing. In this study, selected test temperature for HWTT was 50°C.

## 4.3 EXPERIMENTAL DESIGN

This study was performed to evaluate three different mixes for their cracking and rutting performance and volumetrics. Hamburg Wheel-Tracking Tests (HWTT) was selected as the performance test for rutting. SCB test was used to quantify the cracking performance of the asphalt mixtures. General experimental plan followed in this study is given in Table 4-2. A total of 96 laboratory experiments were conducted for the balanced mix design portion of this study. Several additional samples were also prepared for the $G_{mm}$ measurement and volumetric design stages.

**Table 4-2: Experimental plan for balanced mix design.**

| Specimen Type [a] | Mix ID [b] | Test | Temperature (°C) | Asphalt Content (%) | Replicates | Total |
|---|---|---|---|---|---|---|
| LMLC | Mix1_AV5, Mix1_AV7, Mix3 | SCB | 25.0 | OBC [c], - 0.5%, + 0.5% | 4 | 36 |
| | | HWTT | 50.0 | | 4 | 36 |
| | Mix2 | SCB | 25.0 | OBC [c], + 0.5%, + 1% | 4 | 12 |
| | | HWTT | 50.0 | | 4 | 12 |

a LMLC = Laboratory mixed, and laboratory compacted;
b Mix1_AV5 – Mix3/ = LMLC samples from three trial mixes as described in Table 4-1.
c OBC = Optimum binder content obtained from volumetric mix design.

## 4.4 RESULTS AND ANALYSES

The three selected mixes (see Table 4-1) were mixed, and compacted to produce test specimens. Target test specimen air-void content was 7%. Binder contents from volumetric design are given in Table 4-1. For Mix1 and Mix3, three different asphalt contents (AC) were used for balanced mix design: $AC_{design}$ from volumetric mix design, $AC_{design}$-0.5%, $AC_{design}$+0.5%. For Mix2, $AC_{design}$-0.5% was too low and could result in a very dry mix (due to high RAP content) and hence the three asphalt contents considered were: $AC_{design}$ from volumetric mix design, $AC_{design}$+0.5%, and $AC_{design}$+1%. Hamburg Wheel-Tracking Tests (HWTT) were used to determine rutting performance of asphalt mixtures. SCB test was used to quantify the cracking performance of the asphalt mixtures. Four replicate tests were conducted for SCB tests while four replicate tests (four core samples with two rut depth measurements) were conducted for HWTT.

### 4.4.1 SCB Test Results

Figure 4-2 presents the results of tests for cracking (SCB) performance. FI was calculated and used to evaluate the cracking performance of all asphalt mixtures. The horizontal black line in Figure 4-2 is the FI thresholds selected in this study for Level 4 ($FI_{threshold}$=8) mixtures (determined by Coleri et al. (2020)).

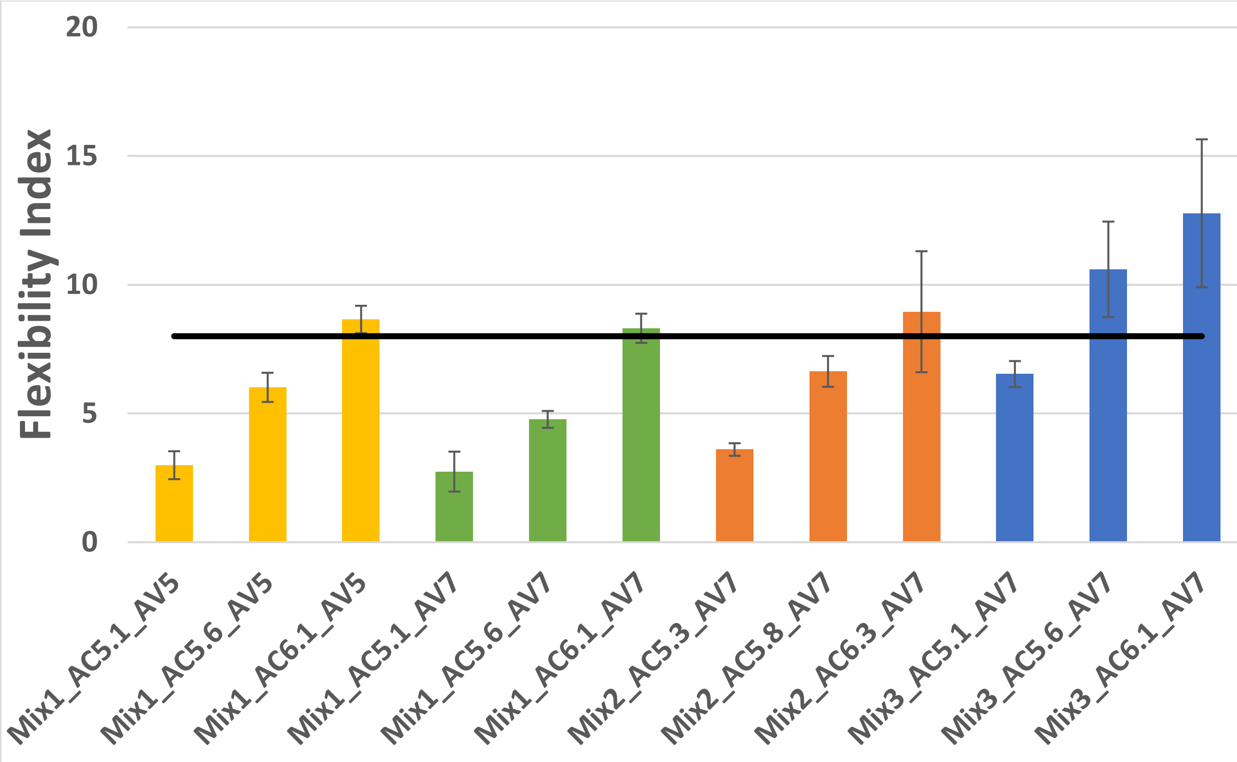



**Figure 4-2: FI test results for all mixtures (length of the error bar is equal to one standard deviation).**

It can be observed from Figure 4-2 that increasing binder content increases Flexibility Index (FI) for all cases, as expected. FI is able to capture the impact of increased binder content on cracking resistance. It should be noted that all the three mixes were Level 4 mixtures (designed with 65 gyrations).

From the figure it can be observed that the average FI values of Mix 3 were higher than that of the other mixes. In Figure 4-2, the first bar for Mix2 and the second bar of the other mixes show the FI value for the LMLC samples prepared at the volumetric design binder content. It can be observed that Mix3 has cracking resistances significantly higher than all other mixtures. Higher cracking resistance for the Mix3 is likely to be a result of the use of a warm mix additive. It is important to mention that the mixtures with warm mix additive are showing better cracking resistance than other corresponding mixes with same or higher binder contents. The FI value for Mix1 with 5% air-void was slightly higher than the same mix with 7% air void. Thus, density of the mix appears to have an effect on the cracking resistance. High RAP mix (Mix2) has better cracking resistance than the low RAP mix (Mix1) but this can be explained by the higher binder content of Mix2 specimens. BMD suggested optimum binder contents (calculated and presented in Section 4.4.3) for 30% and 45% RAP cases should be checked to determine the impact of increased RAP percentage on performance and design binder content.

### 4.4.2 HWTT Test Results

Figure 4-3 presents the results of HWTT tests conducted to determine the rutting performance of asphalt mixtures. Average surface rut depth after 20,000 wheel passes was used to evaluate the rutting performance of all asphalt mixtures. A mixture with higher rut depth is expected to show lower rutting resistance. The horizontal black line in Figure 4-3**Error! Reference source not found.** is the HWTT rut depth threshold used in this study for BMD ($RD_{threshold}$=2.5mm for Level 4 mixes determined by Coleri et al. (2020)).

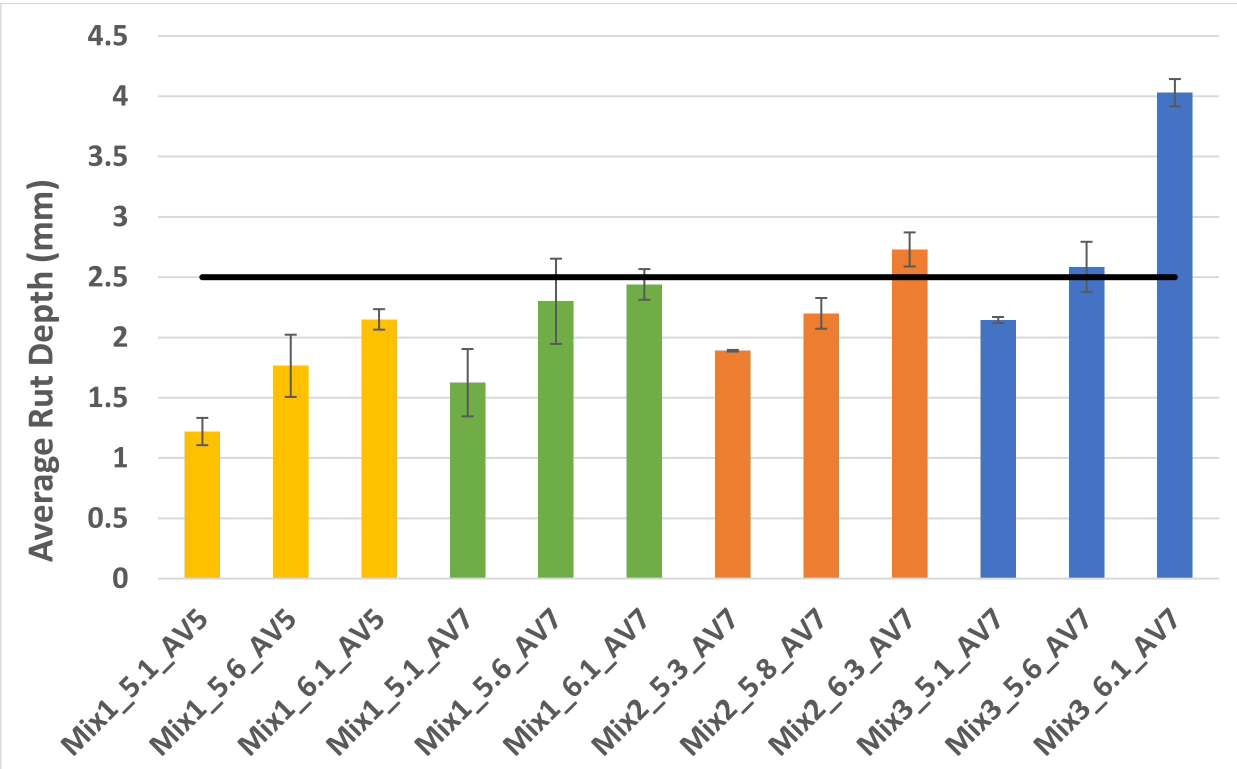



**Figure 4-3**: **HWTT test results for all mixtures (length of the error bar is equal to one standard deviation).**

It can be observed from Figure 4-3 that increasing binder content increases rut depth for all the cases, which is expected. In addition, it can be observed that Mix1_AV5 has the best rutting resistance among all the mixes. Samples for only this mixture were compacted at 5% air-void. Higher density (2% higher than 7% air-void samples) resulted in an improved rutting resistance. It is important to note that 2% increase in density resulted in significant improvements in rutting and cracking performance. Although not simulated in this study, increased density is also expected to reduce long-term aging and moisture susceptibility of the asphalt mixtures due to reduced permeability. It is possible that Mix3 with warm-mix additives can have better “compactibility” due to lower viscosity of the modified asphalt binder. Improved compactibility will result in higher density values with associated long-term performance benefits.

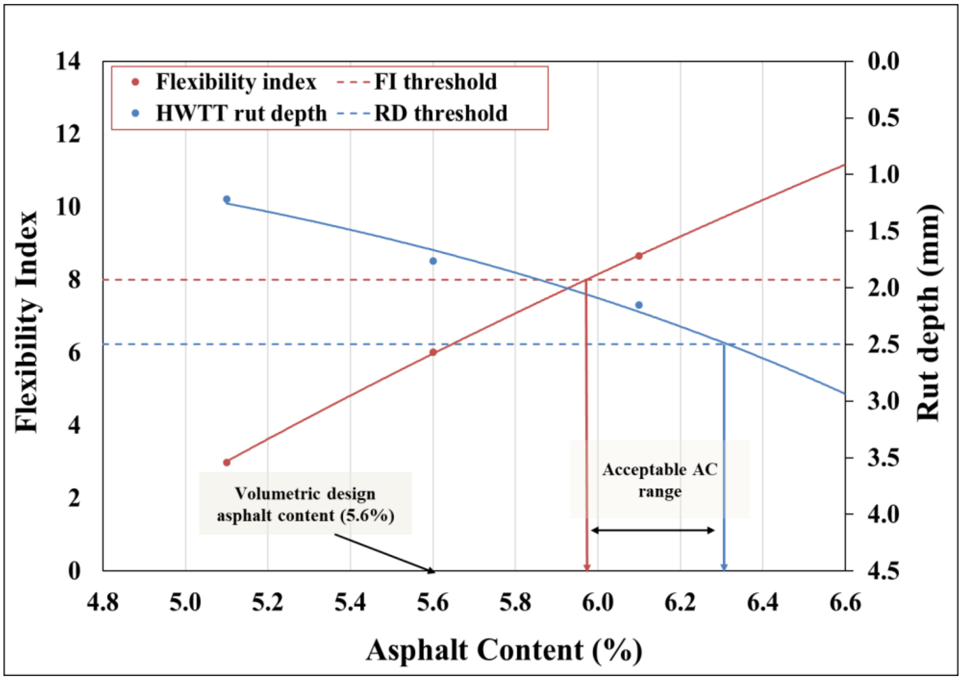
In this study, four replicate asphalt cores were produced for HWTT testing. Since two cores were attached edge-to-edge to run the experiment, a total of two rut depth values were collected from the test system for each case. Increasing replicate test results from two to three is recommended in this study to minimize the impact of high-test results' variability on average measured rut depth. In addition, since HWTT experiments were conducted under water, test results are also affected by the moisture susceptibility of the asphalt mixture in addition to rut resistance. Combined effect of moisture and rut resistance reflected in the test results might be increasing the variability of the test.

Mix3 is showing the highest rut-depth among all three mixes as the warm mix additive is making the mix softer. High RAP mix is showing higher rut depth than the low RAP mix (Mix1) but it should be noted that the high RAP mix also has higher binder content (0.2% more binder for every case).

### 4.4.3 Balanced Mix Design

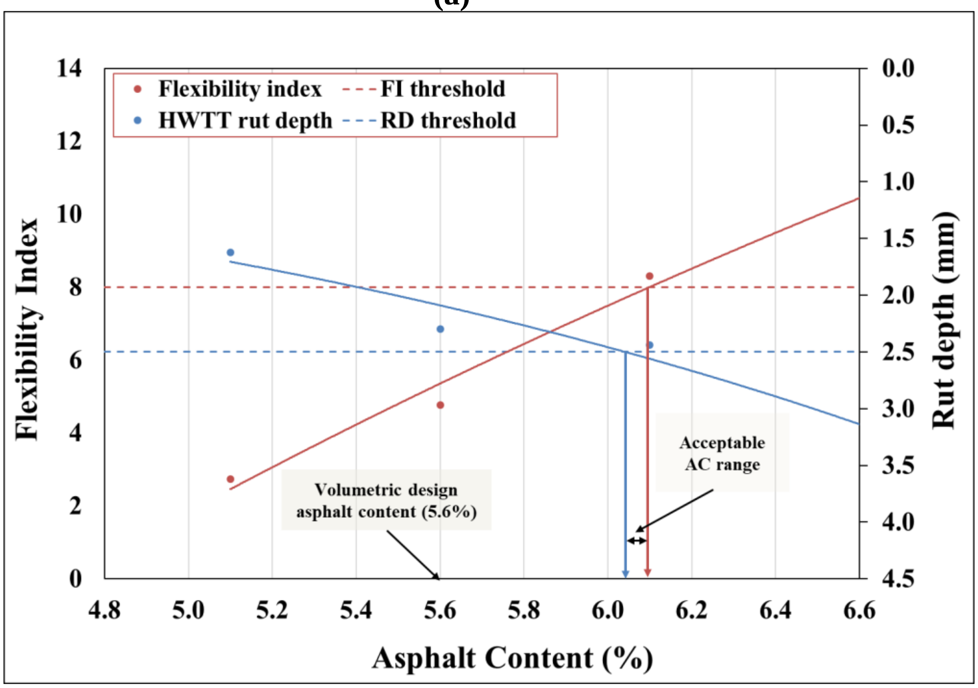
Balanced mix design approach helps in determining the binder content range that satisfies both cracking and rutting performance criteria. Minimum binder content is the lowest asphalt binder percentage allowed in the mix to satisfy the FI threshold of 8 for Level 4 mixtures and FI of 6 for Level 3 mixtures in Oregon. Maximum asphalt content is the highest percentage that satisfies the rutting criteria, rut depth of 2.5mm for Level 4 mixtures and 3mm for Level 3 mixtures in Oregon (Coleri et al. 2020). Figure 4-4(a)-(d) depict balanced mix design charts for all the mixes used in this study. Based on the volumetric mix design, Mix1 and Mix3 have an asphalt content of 5.6% and Mix2 has an asphalt content of 5.3%.

From Figure 4-4(a), it can be observed that Mix1 does not meet the cracking and rutting criteria at the design asphalt content. However, with the balanced mix design approach, the minimum asphalt binder content required is about 6% (see Figure 4-4(a)). This increased binder content is expected to significantly increase the cost of the Mix1_AV5 asphalt mixture while still keeping it in the acceptable region for rutting and cracking performance. However, to ensure a high long-term cracking performance, 6.3% asphalt binder content can also be used for production. However, it should be noted that using 6.3% design asphalt content creates a high risk for rutting since plant produced mixtures are allowed to have ±0.5% variability in production binder content in Oregon. ODOT is currently in the process of changing the binder content variability tolerance from ±0.5% to ±0.35%. This change is expected to reduce the risk of rutting or cracking failures due to production binder content variability. However, for practicality purposes and considering the mix costs, this study recommends to use the lower limit obtained from the balanced mix design approach. Similarly, based on the balanced mix design plots for other three mixes, the required asphalt content for Mix1_AV7, Mix2 and Mix3 are 6.05%, 6.10% and 5.30%, respectively. Although there is no binder content range for Mix 1_AV7 (See Figure 4-4b) that satisfies both the rutting and cracking requirements, the upper limit number that satisfies the rutting requirement is selected as the design binder content for balanced mix design.



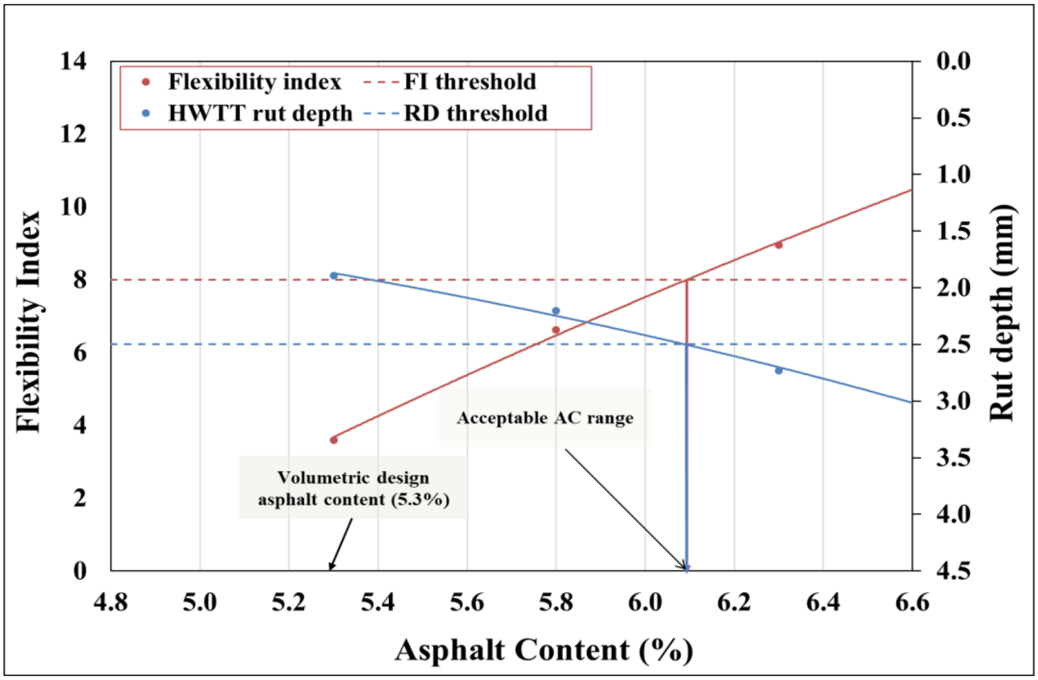
Flexibility index
FI threshold
HWTT rut depth
RD threshold
Flexibility Index
Rut depth (mm)
Asphalt Content (%)
Volumetric design asphalt content (5.6%)
Acceptable AC range
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
4.8
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
6.6


(a)

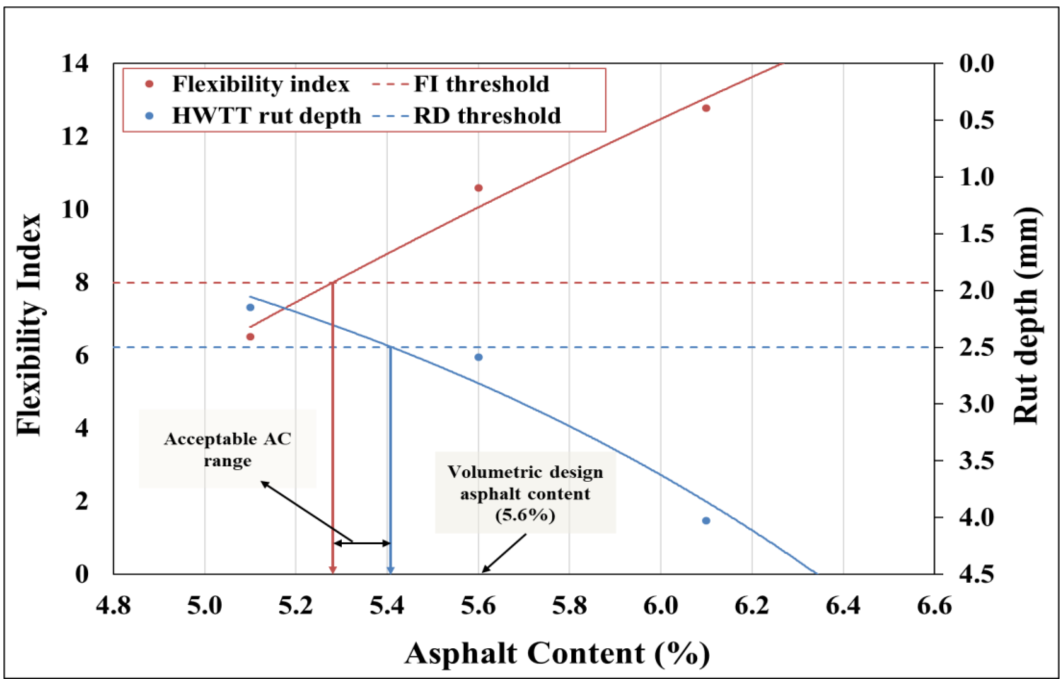


Flexibility index
FI threshold
HWTT rut depth
RD threshold
Flexibility Index
Rut depth (mm)
Asphalt Content (%)
Volumetric design asphalt content (5.6%)
Acceptable AC range
14
12
10
8
6
4
2
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
4.8
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
6.6


(b)




**(c)**




**(d)**

**Figure 4-4: Balanced mix design for (a) Mix1_AV5 (b) Mix1_AV7 (c) Mix2 and (d) Mix3.**

The asphalt content derived from the above balanced mix design plots and the results of the previously conducted $G_{mm}$ measurements were used to back calculate the volumetric properties of the mixes. Results are shown in Table 4-3. The mix design verification (MDV) performed with the mixes with balanced mix design binder contents revealed that the volumetric properties of the mixes were still meeting the ODOT specifications as discussed in Section 4.1.

**Table 4-3**: **Volumetric properties for the three mixes based on BMD design binder content**

| ID [a] | Binder Grade | RAP [b] (%) | $AC_{RAP}$ (%) | AC [c] (%) | BR [d] (%) | $P_{be}$ [e] (%) | $P_{200}/P_{be}$ [f] Ratio | Addi.[g] | VMA[j]-VFA[k]% |
|---|---|---|---|---|---|---|---|---|---|
| Mix1_AV5 | PG 70-22ER | 30 | 5.02 | 6.00 | 25.1 | 4.96 | 1.30 | 1% Li[h] | 16.2-69 |
| Mix1_AV7 | | 30 | | 6.05 | 24.9 | 4.99 | 1.28 | 1% Li | 16.2-69 |
| Mix2 | | 45 | | 6.10 | 37.0 | 5.04 | 1.27 | 1% Li | 15.4-68 |
| Mix3 | | 30 | | 5.30 | 28.4 | 4.37 | 1.46 | 1% Li, 0.68% Evm[i] | 16.4-70 |

[a] All mixtures had dense gradation and aggregates with a nominal maximum aggregate size of 12.5mm;
[b] RAP = Reclaimed asphalt pavement added by weight;
[c] AC = Design BMD asphalt content added by weight;
[d] BR = Binder replacement;
[e] $P_{be}$ = Effective asphalt content present by weight in the total mix;
[f] $P_{200}/P_{be}$ = Dust to binder ratio in the mix;
[g] Addi. = Additive; [h] Li = Lime; [i] Evm = Evotherm warm mix additive; [j] VMA = Voids in mineral aggregate; [k] VFA = Voids filled with asphalt.

### 4.4.4 Cost Calculation Tool

The use of RAP in Hot Mix Asphalt (HMA) paving is often considered a cost-saving measure. Although it can make the pavement more susceptible to cracking failure, it is considered a sustainable alternative to asphalt mixtures with all-virgin materials, both in terms of cost and environmental impacts. However, contractors and agencies who are not able to accurately quantify savings brought on by using RAP in HMA mix may be discouraged from using these materials due to their reduction in HMA cracking resistance. The culmination of these factors yields a necessity for a simple way to analyze different mix design options.

The use of Warm Mix Asphalt (WMA) is also seen as a method of decreasing costs. It is considered to be a sustainable alternative to HMA considering the cost (burner fuel reductions), environment (less CO2 emissions) and safety (improving the labor conditions for workers). The use of high RAP in WMA can be one of the best solutions for asphalt mixtures.

In this study, we used a tool created by Coleri et al. (2017a) that allows the users to compare mix design strategies against one another in order to calculate the potential savings they can realize by choosing mix designs with different RAP and RAS contents, as well as different binder types and binder contents. This tool is meant to increase incentive for users to use recycled materials in their HMA mixes, thereby increasing the sustainability and cost-effectiveness of asphalt pavement construction. Given the geometry of a pavement section and pertinent material cost data, the contractor and/or agency can evaluate the total estimated cost of implementing a particular mix design strategy for their project.

A screenshot of the tool's input tab is given in Figure 4-5 and Figure 4-6 presents the comparisons of all the mixes based on materials and plant burner fuel costs. In order to use the tool, the user must input data about their HMA and WMA mix design, such as target density, binder content and recycled materials content. Input data about the geometry of the pavement section, such as length, lane width, number of lanes and compacted layer thickness, should also be entered. The tool will automatically calculate the volume and weight of HMA material that is anticipated for the target density and pavement section geometry. The user must also input cost data for the materials. The user can input their unit costs for binder, aggregate and recycled materials (RAP). Input fields are shown in orange with blue text and calculated fields are shown in gray with orange text. The total mix cost for the pavement section is shown at the bottom of each mix design spreadsheet in dark gray text. It should be noted that calculated asphalt mixture costs are based on the cost calculations in the spreadsheet by using the raw material costs and do not include any plant operation costs or added profit for the plant. Since 45% RAP is not allowed in Oregon and warm-mix is not commonly used, it was not possible to get direct mixture costs for those alternatives.

The last step is calculating the production burner cost which was not included in the previous calculations. The burner fuel cost can be the key factor in determining whether the HMA or the WMA is the most cost-efficient asphalt mixture. In order to assess the contribution of the production costs, a fuel consumption of 2 gallons of diesel fuel per ton for HMA and 1 gallon of diesel fuel per ton for WMA with chemical additive Evotherm P25 (Sullivan and Moss, 2014) were considered, which means a reduction of 50% burner fuel. Also, a price of $3/gallon diesel fuel for Oregon was used (Statista, 2020). Table 4-4 shows the amount of burner fuel savings for WMA dependent on the additives used.

**Table 4-4: Amount of burner fuel savings for WMA (Sullivan and Moss, 2014)**

| Method | Example Product | Burner Fuel Savings |
|---|---|---|
| Chemical Additives | Advera® | 1.0 gal/ton (50%) |
| Organic Additives | Sasobit® | 0.7 gal/ton (35%) |
| Water-Based Foaming | Double-Barrel Green® | 0.4 gal/ton (20%) |

| | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| 1 | **RAP & RAS Cost Calculator** | | | | | |
| 2 | **Mix Design 4** | | | | | |
| 3 | **Inputs:** | | | | | |
| 4 | **Product** | **Cost** | **Unit** | **Source** | **Type** | |
| 5 | **Binder Type 4** | $ 490.00 | ton | ODOT | PG 70-22ER | |
| 6 | **RAP** | $ 20.00 | ton | | | |
| 7 | **RAS** | $ 40.00 | ton | | | |
| 8 | **Aggregate** | $ 13.00 | ton | | | |
| 9 | | | | | | |
| 10 | **Segment Property** | **Measure** | **Unit** | **Source** | | |
| 11 | **Geometry** | Straight | - | Assumption | | |
| 12 | **Length** | 1.0 | mi | Assumption | | |
| 13 | **Lane Width** | 12.0 | ft | Assumption | | |
| 14 | **Number of Lanes** | 1.0 | each | Assumption | | |
| 15 | **ɔmpacted Layer Thickness** | 2.0 | in | Assumption | | |
| 16 | | | | | | |
| 17 | **Mix Property** | **Measure** | **Unit** | **Source** | | |
| 18 | **Compacted Density** | 145.0 | lb/ft^3 | NAPA website | | |
| 19 | **Target Binder Content** | 6.0% | by weight | Estimate | | |
| 20 | **RAP Content** | 30.0% | by weight | Estimate | | |
| 21 | **RAS Content** | 0.0% | by weight | Estimate | | |
| 22 | **Aggregate Content** | **64%** | by weight | Calculation | | |
| 23 | **er Content (RAP material)** | 5.0% | by weight | Estimate | | |
| 24 | **er Content (RAS material)** | 0.0% | by weight | Estimate | | |
| 25 | **Virgin Binder Added** | **4.5%** | by weight | Calculation | | |
| 26 | | | | | | |
| 27 | **Outputs:** | **Measure** | **Unit** | | | |
| 28 | **Section Volume** | **10560** | ft^3 (all lanes) | | | |
| 29 | **Section Tonnage** | **765.6** | tons (all lanes) | | | |
| 30 | **Mix Cost** | **$ 27,822.36** | **segment** | | | |

Mix1_AV5 | Mix1_AV7 | Mix2_AV7 | Mix3_AV7 | Summary

**Figure 4-5: Cost calculation tool input tab**

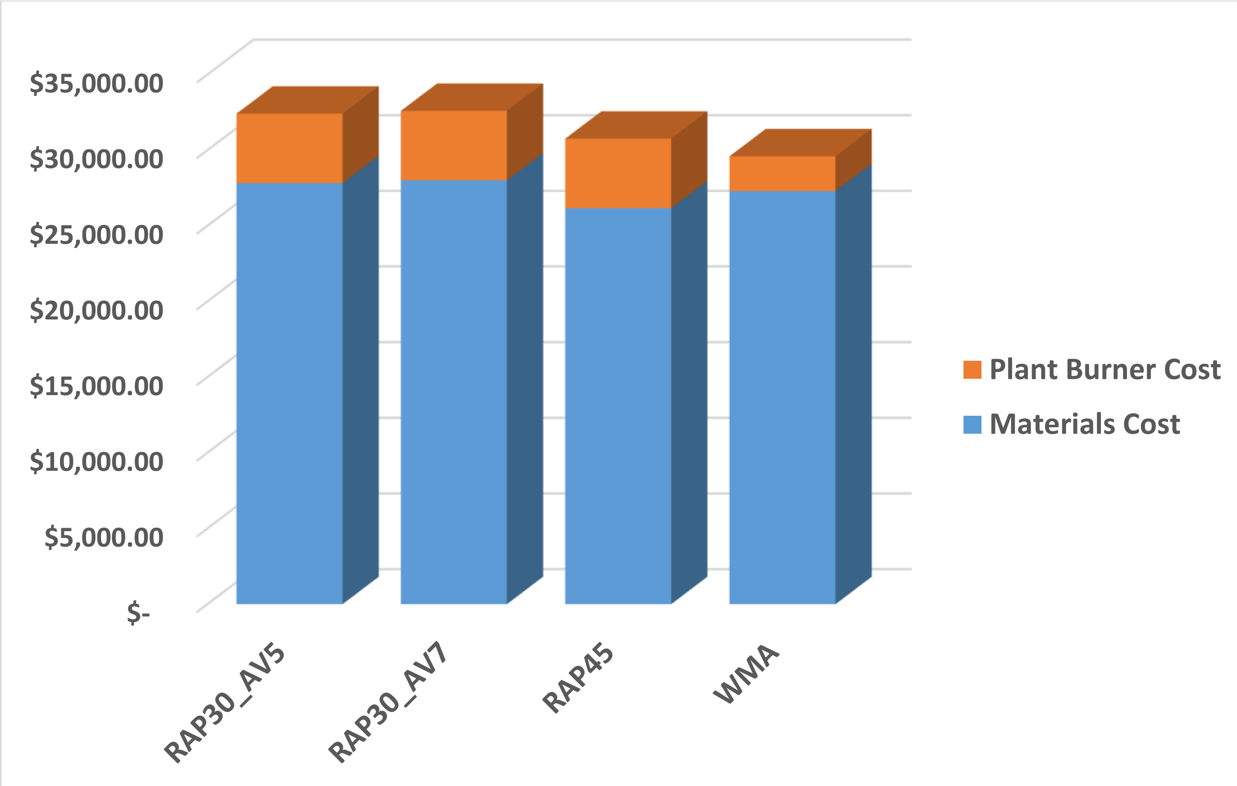



**Figure 4-6: Cost comparison for all the mixes based on materials and burner fuel cost**

The tool can compare up to four different mix strategies. This means the user can evaluate differences in total cost for up to four different binder types and/or RAP contents. A summary spreadsheet compares the various mix design options. This sheet shows the cost differences between each individual mix design, as well as maximum and minimum cost options. The lowest and highest cost options are indicated. Considering the production costs (burner fuel usage) the mixes total cost was also calculated (materials + production burner cost). A bar chart shows a side-by-side comparison of each mix design strategy in order to visualize the costs of each option and also it shows a comparison of total cost for all mixes.

In this study, the following costs were used to calculate the total material cost of asphalt mixtures. These are typical costs taking from previous years production:

- RAP: $20/ton
- Aggregate: $13/ton
- PG70-22ER binder: $490/ton
- Evotherm P25: $70/ton

### 4.4.5 Life-Cycle Cost Analysis (LCCA)

In this study, analyses were first performed by only considering material costs to be able to compare the impact of RAP content, binder content, and additives on life cycle costs. Then, a second set of LCCA was performed after including the plant burner costs to be able to determine the cost impact of using warm-mix.

In this study, each section was assumed to be a single-lane having a width of 12 ft (3.7 m) and a length of 1 mile and material costs were calculated for all mixes based on a 2inch (50.8mm) layer thickness. The cost calculation tool described in Section **Error! Reference source not found.**.4 was used to calculate the material costs.

Net present value (NPV) of agency costs were determined using a 4 percent interest rate for a 60 year analysis period by using Equation (4-3). Since all mix designs had a 20 year design period, it was assumed that same mixtures will be used every 20 years for the next 60 years. It should be noted that the purpose of LCCA is to be able to compare the cost effectiveness of all mixtures. Calculated NPV values can only be used for comparison and cannot be used for bidding or long-term cost predictions.

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad \textbf{(4-3)}$$

Where:

$C_t$ = estimated agency costs at year t,

r = interest rate, and

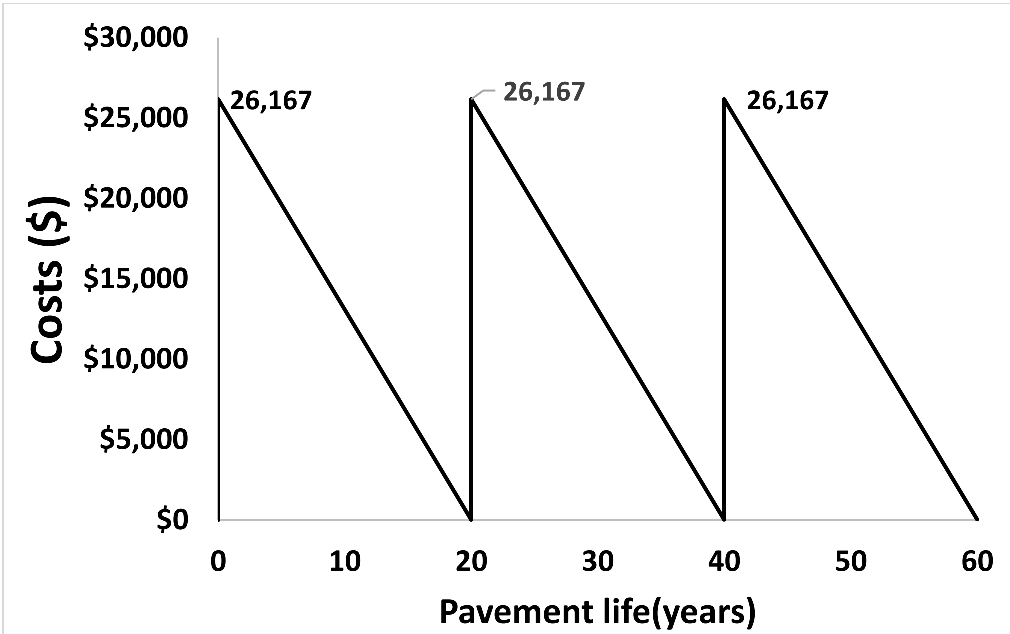
T = number of time periods.

In this study, the NPV was calculated for all the mixes and the equation below describe how the NPV for Mix1_AV5 was calculated.

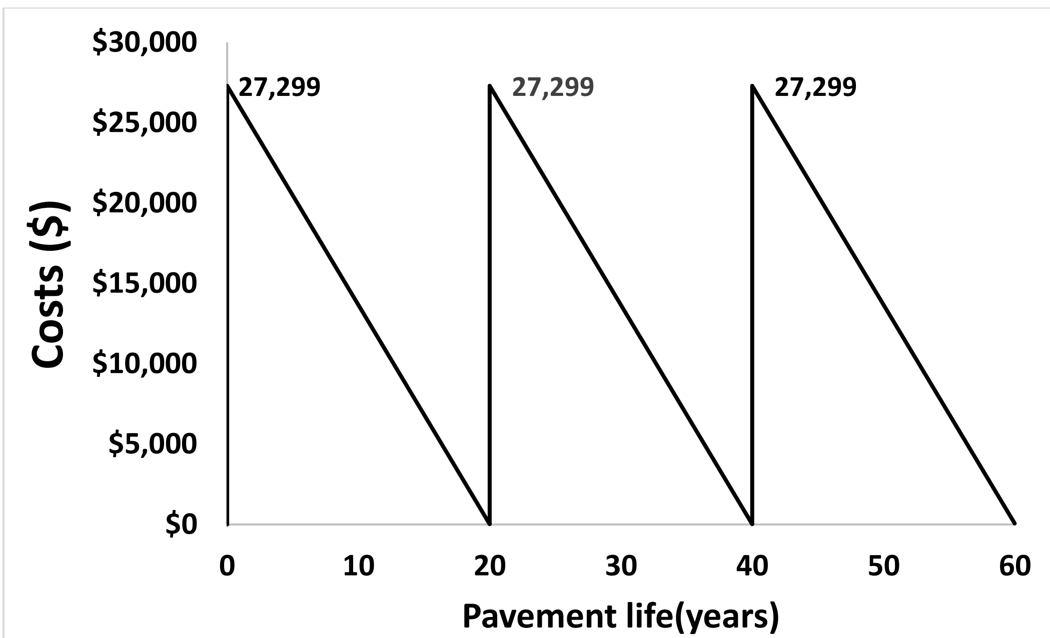
$$\mathrm{NPV}_{6\%BC}\mathrm{Mix1\_AV5} = \frac{\$27{,}823}{(1+0.04)^{0}} + \frac{\$27{,}823}{(1+0.04)^{20}} + \frac{\$27{,}823}{(1+0.04)^{40}} = \$46{,}316$$


$30,000
$25,000
$20,000
$15,000
$10,000
$5,000
$0
Costs ($)
27,823
27,823
27,823
0
10
20
30
40
50
60
Pavement life(years)
(a)


$30,000
$25,000
$20,000
$15,000
$10,000
$5,000
$0
Costs ($)
28,005
28,005
28,005
0
10
20
30
40
50
60
Pavement life(years)
(b)




(c)




(d)

**Figure 4-7: Diagrams used for LCCA (a) Mix1_AV5 (b) Mix1_AV7 (c) Mix2 and (d) Mix3.**

In Table 4-5, the NPVs without the burner fuel consumption costs (by just considering raw material costs) were summarized for all asphalt mixtures of this study.

**Table 4-5: NPVs for all the mixes – Without burner fuel consumption cost**

| S. No. | Mix ID | Initial cost ($) | NPV-1 ($) | NPV-2 ($) | NPV ($) |
|---|---|---|---|---|---|
| 1. | Mix1_AV5 | 27,823 | 12,698 | 5,795 | 46,316 |
| 2. | Mix1_AV7 | 28,005 | 12,781 | 5,833 | 46,619 |
| 3. | Mix2 | 26,167 | 11,942 | 5,450 | 43,560 |
| 4. | Mix3 | 27,299 | 12,459 | 5,686 | 45,444 |

It can be observed from Table 4-5 that the mix with 45% RAP content (Mix 2) has the lowest NPV over the course of 60 years analysis period followed by the warm mix asphalt (Mix 3) and the mix with 30% RAP (Mix 1) when only the raw material costs are considered. However, this ranking altered when the plant burner fuel consumption was incorporated into the life cycle cost analysis as can be seen in Table 4-6. **When the burner costs are included in the LCCA, the most cost-effective mix is the warm mix asphalt (Mix 3)** considering the reduced production (burner) temperature and consequently less fuel consumption during production.

**Table 4-6: NPVs for all the mixes – With burner fuel consumption cost**

| S. No. | Mix ID | Initial cost ($) | NPV-1 ($) | NPV-2 ($) | NPV ($) |
|---|---|---|---|---|---|
| 1. | Mix1_AV5 | 32,416 | 14,794 | 6,752 | 53,962 |
| 2. | Mix1_AV7 | 32,599 | 14,878 | 6,790 | 54,267 |
| 3. | Mix2 | 30,761 | 14,039 | 6,407 | 51,207 |
| 4. | Mix3 | 29,597 | 13,508 | 6,165 | 49,269 |

### 4.4.6 Environmental Impact

Athena Pavement LCA software was used to calculate the environmental impact of each pavement mixture. For a base case, a mixture of 6% binder content and 20% RAP content was selected (Mix F in the plots). This represents the most common pavement design in Oregon. The roadway geometry for all cases was defined to have three lifts of pavement with thicknesses of 2.5 inches, 5.5 inches, and 5.5 inches. The length of roadway was set to 0.62 mile (1 km), with three lanes of 12 feet each, a typical width for roadways in America.

In order to determine the differences in environmental performance, the primary characteristics for each pavement design were entered into the Pavement LCA software. Materials by percentage of total mixture weight were input (binder content, additives, RAP content, etc.) along with the asphalt type (HMA or WMA). All factors for which no data was available, or those factors which were not considered (such as hauling distance) were set to be default and equal between mixes so as not to affect the results. Pavement vehicle interaction (PVI), being a separate option in the software, was excluded entirely since all mixes were designed for 20 years and PVI related vehicle operating costs should be theoretically equal for all analyzed mixtures.

In order to accurately compare different pavement designs, each mixture was assumed to conform to a 60-year lifespan with rehabilitation occurring at every 20th year. For rehabilitation 2 inches of asphalt is milled and removed and then replaced (mill and fill process which is commonly used in Oregon for rehabilitation).

Results were exported from the software and plotted using excel. Results are given in Global Warming Potential (GWP), Acidification Potential (AP), and Eutrophication Potential (EP) for all three mixtures of this study. Mix 1 with 5% air void case was not evaluated since density does not directly change the environmental impact. Units do not represent the chemical composition of the pollution itself, but instead represent the amount of a standard normalizing factor representative of each pollution type (Myhre et al. 2013).

Figure 4-8 displays the results for global warming potential by mix type, in units of kilograms of carbon dioxide. Global warming potential acts as a useful parameter to assess the future impact of an emission on the atmosphere (Myhre et al. 2013).

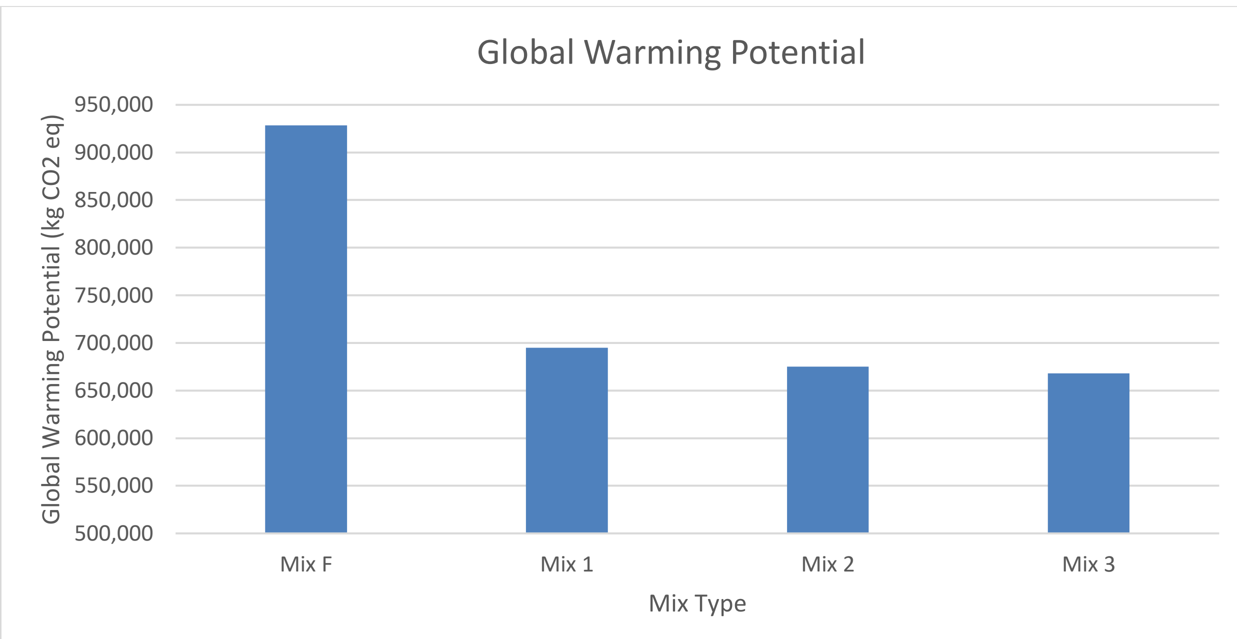



**Figure 4-8: Global Warming Potential (GWP) by mix type**

Mixtures 1, 2, and 3 each performed nearly equivalently, with mixture 1 exhibiting slightly worse performance and mixture 3 (warm-mix) being the best.  All mixtures had significantly lower impact when compared to the typical Oregon asphalt mixture with lower RAP content. This is likely caused by the difference in the production process between HMA and WMA and increased RAP content in the designed mixtures.

Figure 4-9 displays the acidification potential of each pavement mix. Acidification results from carbon dioxide released into the atmosphere dissolving into ocean waters which increases the concentration of carbonate ions and lowers ocean water pH (Feely et al. 2009).

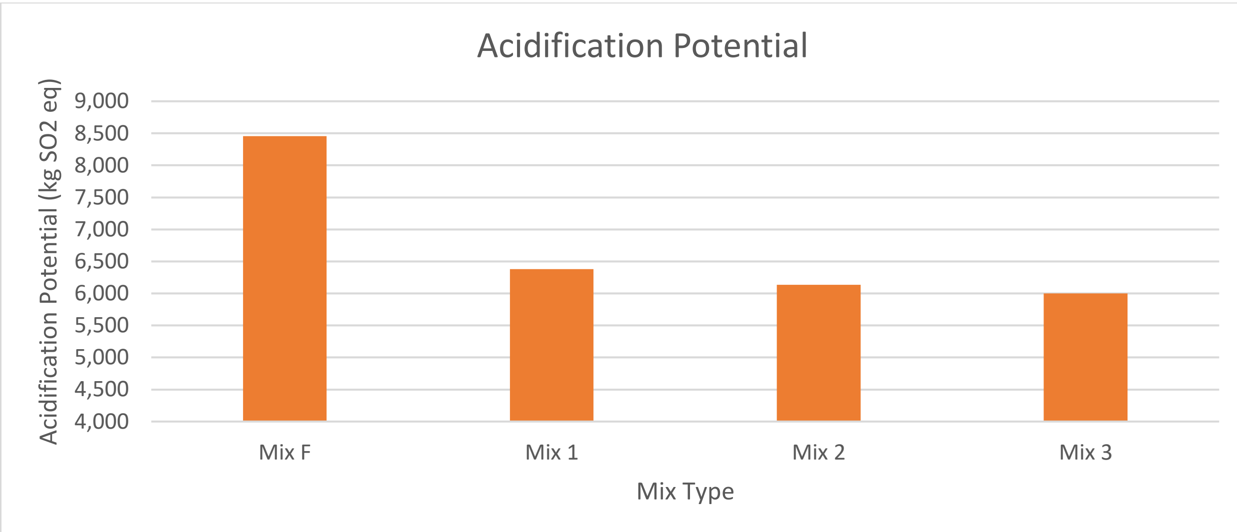



**Figure 4-9: Acidification Potential by Mix Type**

The results for acidification potential are similar to that of global warming potential. Mix F again performed poorly while mixes 1, 2, and 3 performed similarly. Mix 3 (warm-mix) again outperformed both Mixes 1 and 2. This is most likely a result of the WMA production process being significantly less energy intensive as well as the design allowing for a lower binder content and higher RAP.

Figure 4-10 displays the eutrophication potential generated by each mixture measured in kilograms of nitrogen. Eutrophication is a measure of the increased availability of normally population limiting factors for aquatic based photosynthetic organisms (Carpenter et al. 2015). Increased eutrophication can lead to the destabilization of ocean ecosystems.

The results indicate that mixtures 1, 2, and 3 again outperformed the typical pavement design. Mixture 3 (warm-mix) performed the highest of the three design mixtures. The differences between the three design mixtures and the typical mixture is likely explained by the increased RAP content in the three designs as well as the lower energy cost of WMA. Differences between the three designs is likely to be caused by the slight difference in binder content as well as RAP content.

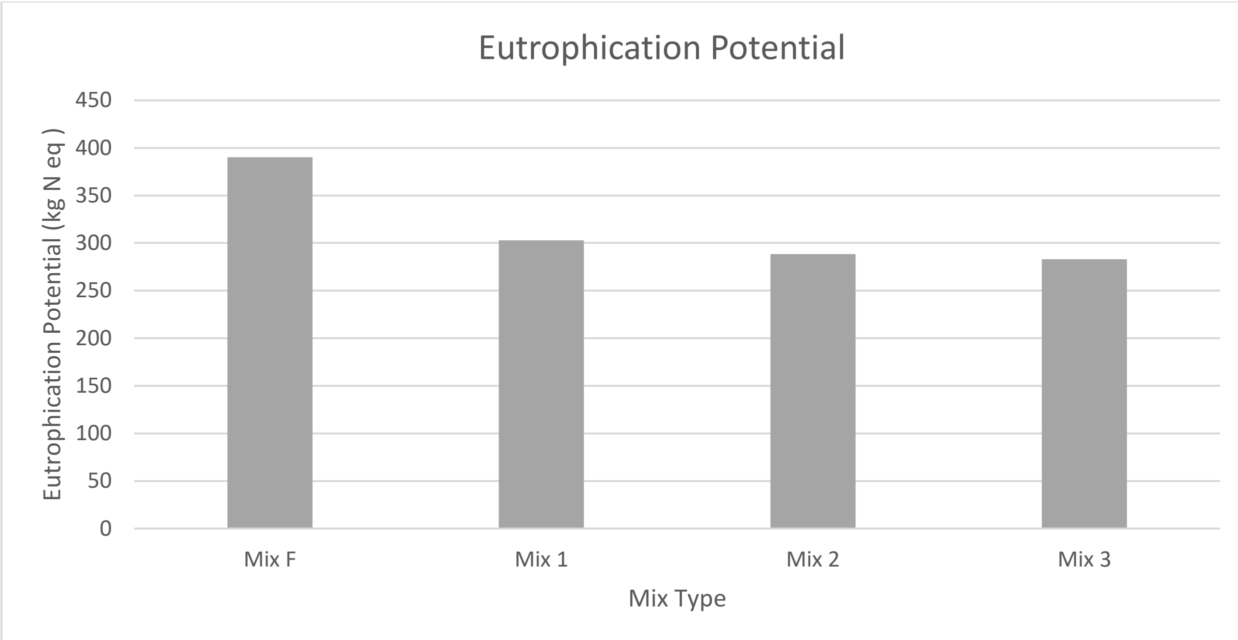



**Figure 4-10: Eutrophication Potential by Mix Type**

# 5.0 FINAL CONCLUSIONS AND RECOMMENDATIONS

In this study, volumetric and balanced mix designs were conducted to determine the optimum asphalt binder content for four different asphalt mixtures. Cost effectiveness and the environmental impact of those asphalt mixtures were also quantified and compared. Based on the quantified cost, performance, and environmental impact values, the mixture with warm-mix additives (Mix 3) is selected as the best asphalt mixture with lowest cost and lowest environmental impact. Other conclusions derived from this study are as follows:

1. According to volumetric mix design, all VMA values are within the 13.5-17.0 range required for 12.5mm nominal maximum aggregate size mixtures in Oregon according to the standard mix design verification process. All VFA values are also within the required range of 65 to 75 required for Level 4 asphalt mixtures in Oregon. Dust-to-binder ratios for all asphalt mixtures are also within the limits required by ODOT (0.8-1.6).
2. Mix3 has cracking resistances significantly higher than all other mixtures. Higher cracking resistance for the Mix3 is likely to be a result of the use of a warm mix additive. It is important to mention that the mixtures with warm mix additive are showing better cracking resistance than other corresponding mixes with same or higher binder contents.
3. The FI value for Mix1 with 5% air-void was slightly higher than the same mix with 7% air void. Thus, density of the mix appears to have an effect on the cracking resistance.

4. High RAP mix (Mix2) has better cracking resistance than the low RAP mix (Mix1) according to SCB test results but this is expected to be a result of the higher binder content of Mix2 specimens. The higher BMD binder content of Mix 2 (when compared to lower RAP mix-Mix 1) suggested that performance of high RAP mixture can be improved by slight increasing the binder content.
5. Although Mix 2 (45% RAP) had a higher BMD binder content than Mix 1 (30% RAP), it was still more cost effective due to the increased use of recycled asphalt material in the mix.
6. Mix1_AV5 has the best rutting resistance among all the mixes. Samples for only this mixture were compacted at 5% air-void. Higher density (2% higher than 7% air-void samples) resulted in an improved rutting resistance. It is important to note that 2% increase in density resulted in significant improvements in rutting and cracking performance. Although not simulated in this study, increased density is also expected to reduce long-term aging and moisture susceptibility of the asphalt mixtures due to reduced permeability.
7. It is possible that Mix 3 with warm-mix additives can have better "compactibility" due to lower viscosity of the modified asphalt binder. Improved compactibility will result in higher density values with associated long-term performance benefits.
8. Based on the balanced mix design plots for other three mixes, the required asphalt content for Mix1_AV7, Mix2 and Mix3 are 6.05%, 6.10% and 5.30%, respectively. The mix design verification (MDV) performed with the mixes with balanced mix design binder contents revealed that the volumetric properties of the mixes were still meeting the ODOT specifications.
9. The mix with 45% RAP content (Mix 2) has the lowest NPV over the course of 60 years analysis period followed by the warm mix asphalt (Mix 3) and the mix with 30% RAP (Mix 1) when only the raw material costs are considered. However, this ranking altered when the plant burner fuel consumption was incorporated into the life cycle cost analysis. When the burner costs are included in the LCCA, the most cost-effective mix is the warm mix asphalt (Mix 3) considering the reduced production (burner) temperature and consequently less fuel consumption during production.
10. Mix 3 (warm-mix) is also the most environmentally friendly mix with lower expected GWP, EP, and AP values for a 60 year analysis period.

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# APPENDIX A: GRADATION AND BINDER CONTENT OF RAP

This section represents the gradation, binder content and theoretical maximum specific gravity ($G_{mm}$) of RAP materials provided by Knife River.

**SAMPLE 1**

| Sieve Size | Mass Retained | % Retained | % Pass |
|---|---|---|---|
| 1" | 0.0 | 0.0 | 100.0 |
| 3/4" | 0.0 | 0.0 | 100.0 |
| 1/2" | 30.6 | 2.1 | 97.9 |
| 3/8" | 115.8 | 8.0 | 89.9 |
| 1/4" | 179.4 | 12.4 | 77.5 |
| #4 | 139.0 | 9.6 | 67.9 |
| #8 | 310.9 | 21.4 | 46.5 |
| #16 | 208.4 | 14.4 | 32.1 |
| #30 | 125.3 | 8.6 | 23.5 |
| #50 | 84.0 | 5.8 | 17.7 |
| #100 | 58.3 | 4.0 | 13.6 |
| #200 | 48.6 | 3.4 | 10.3 |
| Pan | 12.0 | | |

| | |
|---|---|
| Initial Dry Mass | 1449.5 |
| Dry Washed Mass | 1310.9 |
| Mass After Sieve | 1312.3 |
| Sieve Loss | -0.1 |

**SAMPLE 2**

| Sieve Size | Mass Retained | % Retained | % Pass |
|---|---|---|---|
| 1" | 0.0 | 0.0 | 100.0 |
| 3/4" | 0.0 | 0.0 | 100.0 |
| 1/2" | 39.0 | 2.4 | 97.6 |
| 3/8" | 111.6 | 6.9 | 90.7 |
| 1/4" | 201.0 | 12.4 | 78.3 |
| #4 | 149.1 | 9.2 | 69.1 |
| #8 | 358.1 | 22.1 | 46.9 |
| #16 | 232.6 | 14.4 | 32.6 |
| #30 | 144.2 | 8.9 | 23.7 |
| #50 | 97.8 | 6.0 | 17.6 |
| #100 | 66.2 | 4.1 | 13.5 |
| #200 | 52.7 | 3.3 | 10.3 |
| Pan | 20.8 | | |

| | |
|---|---|
| Initial Dry Mass | 1618.8 |
| Dry Washed Mass | 1473.9 |
| Mass After Sieve | 1473.1 |
| Sieve Loss | 0.1 |

**SAMPLE 3**

| Sieve Size | Mass Retained | % Retained | % Pass |
|---|---|---|---|
| 1" | 0.0 | 0.0 | 100.0 |
| 3/4" | 0.0 | 0.0 | 100.0 |
| 1/2" | 32.1 | 2.2 | 97.8 |
| 3/8" | 109.4 | 7.6 | 90.2 |
| 1/4" | 163.2 | 11.3 | 78.9 |
| #4 | 133.2 | 9.2 | 69.7 |
| #8 | 326.8 | 22.6 | 47.0 |
| #16 | 209.9 | 14.5 | 32.5 |
| #30 | 127.9 | 8.9 | 23.6 |
| #50 | 83.8 | 5.8 | 17.8 |
| #100 | 58.8 | 4.1 | 13.7 |
| #200 | 51.9 | 3.6 | 10.1 |
| Pan | 13.4 | | |

| | |
|---|---|
| Initial Dry Mass | 1443.3 |
| Dry Washed Mass | 1312.0 |
| Mass After Sieve | 1310.4 |
| Sieve Loss | 0.1 |

**SAMPLE 4**

| Sieve Size | Mass Retained | % Retained | % Pass |
|---|---|---|---|
| 1" | 0.0 | 0.0 | 100.0 |
| 3/4" | 0.0 | 0.0 | 100.0 |
| 1/2" | 26.3 | 1.8 | 98.2 |
| 3/8" | 104.8 | 7.1 | 91.1 |
| 1/4" | 188.2 | 12.8 | 78.2 |
| #4 | 131.6 | 9.0 | 69.2 |
| #8 | 325.9 | 22.2 | 47.0 |
| #16 | 211.6 | 14.4 | 32.6 |
| #30 | 131.2 | 8.9 | 23.6 |
| #50 | 89.6 | 6.1 | 17.5 |
| #100 | 60.7 | 4.1 | 13.4 |
| #200 | 47.2 | 3.2 | 10.2 |
| Pan | 16.8 | | |

| | |
|---|---|
| Initial Dry Mass | 1466.0 |
| Dry Washed Mass | 1332.9 |
| Mass After Sieve | 1333.9 |
| Sieve Loss | -0.1 |

**SAMPLE 5**

| Sieve Size | Mass Retained | % Retained | % Pass |
|---|---|---|---|
| 1" | 0.0 | 0.0 | 100.0 |
| 3/4" | 0.0 | 0.0 | 100.0 |
| 1/2" | 32.7 | 2.2 | 97.8 |
| 3/8" | 93.9 | 6.3 | 91.5 |
| 1/4" | 207.8 | 14.0 | 77.5 |
| #4 | 143.2 | 9.6 | 67.9 |
| #8 | 320.7 | 21.6 | 46.3 |
| #16 | 215.8 | 14.5 | 31.8 |
| #30 | 128.6 | 8.6 | 23.2 |
| #50 | 85.5 | 5.7 | 17.4 |
| #100 | 60.2 | 4.0 | 13.4 |
| #200 | 48.4 | 3.3 | 10.1 |
| Pan | 19.4 | | |

| | |
|---|---|
| Initial Dry Mass | 1487.2 |
| Dry Washed Mass | 1355.7 |
| Mass After Sieve | 1356.2 |
| Sieve Loss | 0.0 |

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**Average**

| Sieve Size | % Pass |
|---|---|
| 1" | 100.0 |
| 3/4" | 100.0 |
| 1/2" | 97.9 |
| 3/8" | 90.7 |
| 1/4" | 78.1 |
| #4 | 68.8 |
| #8 | 46.8 |
| #16 | 32.3 |
| #30 | 23.5 |
| #50 | 17.6 |
| #100 | 13.5 |
| #200 - 1% | 9.2 |
| Pan | |

**Figure A-1: RAP aggregate gradation**

**AASHTO T-209: Theoretical Maximum Specific Gravity**

| Sample | 1 | 2 | 3 | Average |
|---|---|---|---|---|
| Mass of Dry RAP ($R_{hot}$) | 1460.5 | 1459.4 | 1457.8 | |
| Mass of Added Binder ($Binder_{new}$) | 43.8 | 43.8 | 43.7 | |
| $P_{b\text{-new}}$, % | 2.912 | 2.914 | 2.910 | |
| Mass of Coated Sample (C) | 1504.3 | 1502.9 | 1501.8 | |
| Actual Dry Mass Uncoated Sample (A) | 1460.5 | 1459.1 | 1458.1 | |
| Actual Mass of Added Binder (C-A) | 43.8 | 43.8 | 43.7 | |
| Mass @ SSD | 1512.6 | 1510.4 | 1509.5 | |
| Pycnometer + Water | 7321.4 | 7321.4 | 7321.4 | |
| Pycnometer + Water + Mix | 8206.8 | 8205.8 | 8204.2 | |
| RAP $G_{mm}$ | 2.534 | 2.533 | 2.529 | 2.532 |
| RAP $G_{mm}$ SSD | 2.498 | 2.501 | 2.496 | 2.498 |

**Asphalt Content of RAP**

| Sample | 1 | 2 | 3 | 4 | 5 | Average |
|---|---|---|---|---|---|---|
| Basket Tare | 3025.2 | 3226.1 | 3086.4 | 3024.8 | 3085.4 | |
| Mass of Coated RAP + Basket | 4555.3 | 4935.9 | 4611.4 | 4573.1 | 4644.6 | |
| Mass of Agg and Basket | 4470.8 | 4841.2 | 4526.8 | 4487.4 | 4559.9 | |
| Mass of Cool Agg + Basket | 4474.7 | 4844.9 | 4529.7 | 4490.8 | 4572.6 | |
| Mass Initial, $M_i$ | 1530.1 | 1709.8 | 1525.0 | 1548.3 | 1559.2 | |
| Mass Final, $M_f$ | 1445.6 | 1615.1 | 1440.4 | 1462.6 | 1474.5 | |
| $\%I = \{[M_i - M_f]/[M_i]\}x100$ | 5.52 | 5.54 | 5.55 | 5.54 | 5.43 | |
| Corrected $P_b$, $C_f = 0.50$ | 5.02 | 5.04 | 5.05 | 5.04 | 4.93 | 5.02 |

RAP Gse 2.701

**AASHTO T-85: Specific Gravity and Absorption of Coarse Aggregate**

| Size | 1/2"-0 | | Average |
|---|---|---|---|
| Source | C. Lake RAP | | |
| A) Mass of Dry Sample | 2324.1 | 2124.5 | |
| B) Mass of SSD Sample | 2367.0 | 2165.3 | |
| C) Mass of Sample Immersed | 1498.3 | 1362.3 | |
| Bulk Specific Gravity ($G_{sb}$) | 2.675 | 2.646 | 2.661 |
| Bulk Specific Gravity (SSD) | 2.725 | 2.697 | 2.711 |
| Apparent Specific Gravity ($G_{sa}$) | 2.814 | 2.787 | 2.801 |
| Absorption (%) | 1.85 | 1.92 | 1.88 |

**Combined Specific Gravity**
T-84 & T-85

| Size | 1/2"-0 |
|---|---|
| Split Sieve | 4 |
| Percent Passing Split Sieve | 69.0% |
| Burnt Bulk Specific Gravity ($G_{sb}$) | 2.656 |
| Burnt Bulk Specific Gravity (SSD) | 2.710 |
| Burnt Apparent Specific Gravity | 2.807 |
| Absorption (%) | 2.0 |

**AASHTO T-84: Specific Gravity and Absorption of Fine Aggregate**

| Size | 1/2"-0 | | Average |
|---|---|---|---|
| Source | C. Lake RAP | | |
| S) Mass of SSD Sample | 497.5 | 496.1 | |
| B) Mass of Pyc. + Water | 661.2 | 657.8 | |
| C) Mass of Pyc.+H2O+Sample | 974.2 | 971.7 | |
| Mass of Dry Sample + Pan | 1163.1 | 1208.3 | |
| Mass of Pan | 677.2 | 720.9 | |
| A) Mass of Dry Sample | 485.9 | 487.4 | |
| Bulk Specific Gravity ($G_{sb}$) | 2.634 | 2.675 | 2.654 |
| Bulk Specific Gravity (SSD) | 2.696 | 2.723 | 2.710 |
| Apparent Specific Gravity ($G_{sa}$) | 2.810 | 2.809 | 2.810 |
| Absorption (%) | 2.39 | 1.78 | 2.09 |

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**Combined RAP Specific Gravity**
ODOT TM-319

| | |
|---|---|
| RAP $G_{sb}$ | 2.671 |
| RAP $G_{sa}$ | 2.815 |

**Figure A-2: Binder content and theoretical maximum specific gravity ($G_{mm}$) of RAP**

# APPENDIX B: TEMPERATURE CURVES AND PROPERTIES OF VIRGIN BINDER

The data below represents binder temperature curves used for this study. All temperature curves were provided by McCall Oil.

**Table B-1. Mixing and compaction temperatures of PG 70-22ER binder**

| Binder | **PG 70-22ER** |
|---|---|
| Temp (F) | Viscosity (cp) |
| **275** | **775** |
| **329** | **200** |

| | | | |
|---|---|---|---|
| Mixing Temperature Range, F | 331 | - | 343 |
| Compaction Temperature Range, F | 310 | - | 319 |

| | |
|---|---|
| Specific Gravity@ 60F | **1.0386** |

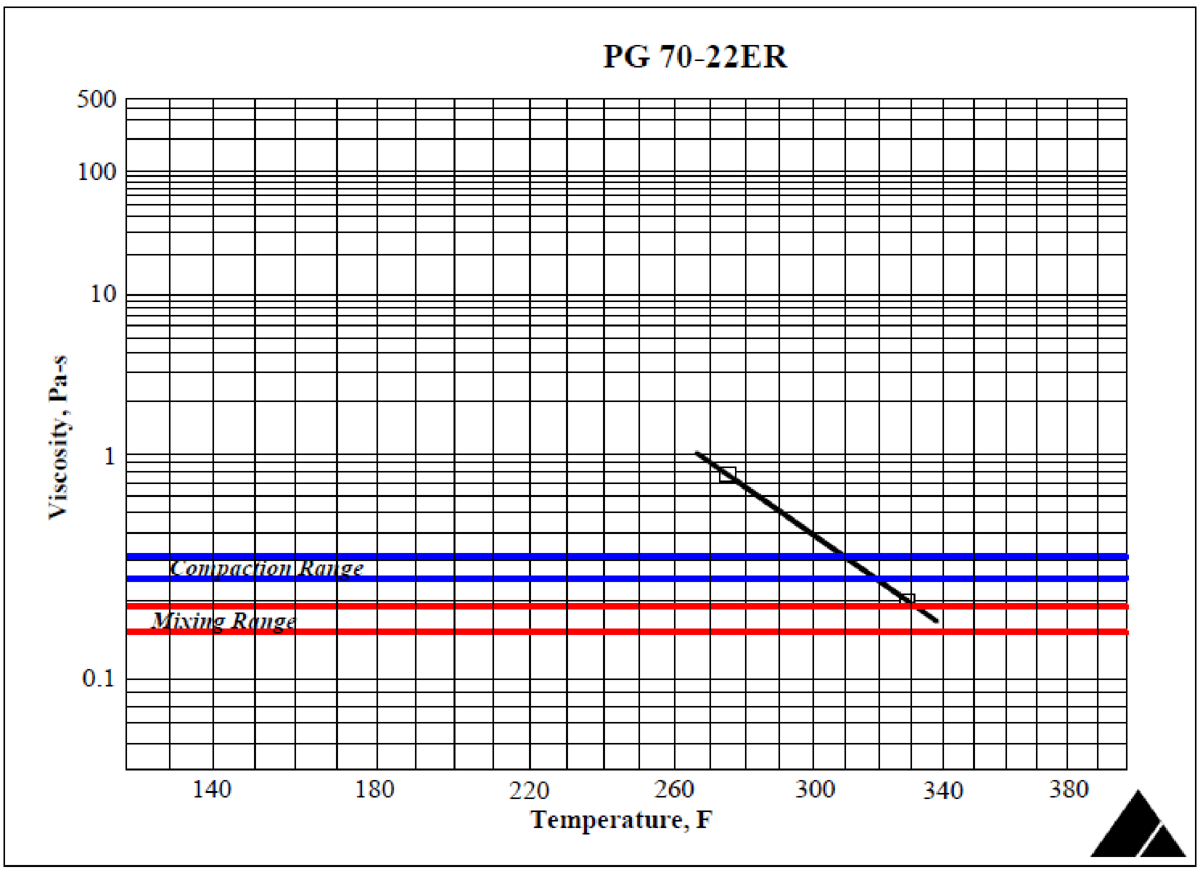


**Figure B-3: Temperature curve of PG 70-22ER binder**

# APPENDIX C: AN EXAMPLE FOR BATCHING SHEETS

The following example shows the procedure of calculating the quantity of materials for the mixture with 45% RAP, 5.3% binder content and binder grade of PG 70-22ER.

**Table C-1 Quantity of coarse, medium, and fine aggregates and RAP materials for the mixture with 45% RAP, 5.3% binder content and binder grade of PG 70-22ER**

| stockpile | coarse | medium | fine | RAP | Lime | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| stockpile percentage, Ps | 32 | 0 | 22 | 45 | 1 | Comparison: Combined vs. Target | | | | | |
| total percentage | 100 | | | | | combined aggregate | | | | | |
| sieve size | percentage passing | | | | | %retained | cum. Retained | %passing | target %pass | Diff | Diff^2 |
| 3/4" | 100.0 | 100.0 | 100.0 | 100.0 | 100 | 0.0 | 0.0 | 100.0 | 100 | 0.0 | 0.0 |
| 1/2" | 94.0 | 100.0 | 100.0 | 98.0 | 100 | 2.8 | 2.8 | 97.2 | 97 | -0.2 | 0.0 |
| 3/8" | 56.0 | 100.0 | 100.0 | 91.0 | 100 | 15.3 | 18.1 | 81.9 | 88 | 6.1 | 37.6 |
| 1/4" | 13.0 | 84.0 | 100.0 | 78.0 | 100 | 19.6 | 37.7 | 62.3 | 65 | 2.7 | 7.5 |
| #4 | 4.0 | 39.0 | 99.0 | 69.0 | 100 | 7.2 | 44.9 | 55.1 | 52 | -3.1 | 9.7 |
| #8 | 1.0 | 1.0 | 66.0 | 47.0 | 100 | 18.1 | 63.0 | 37.0 | 34 | -3.0 | 8.9 |
| #16 | 1.0 | 1.0 | 39.0 | 32.0 | 100 | 12.7 | 75.7 | 24.3 | 23 | -1.3 | 1.7 |
| #30 | 1.0 | 1.0 | 24.0 | 23.0 | 100 | 7.4 | 83.1 | 17.0 | 17 | 0.0 | 0.0 |
| #50 | 1.0 | 1.0 | 15.0 | 18.0 | 100 | 4.2 | 87.3 | 12.7 | 13 | 0.3 | 0.1 |
| #100 | 1.0 | 1.0 | 10.0 | 14.0 | 100 | 2.9 | 90.2 | 9.8 | 10 | 0.2 | 0.0 |
| #200 | 0.4 | 0.3 | 6.8 | 10.2 | 100 | 2.6 | 92.8 | 7.2 | 6.8 | -0.4 | 0.2 |
| pan | 0 | 0 | 0 | 0 | 0 | 7.2 | 100.0 | 0.0 | 0 | 0.0 | 0.0 |
| binder conent | --- | ---- | ---- | 5.02 | 0 | root mean square error | | | | | |
| | | | | | | | | | | Error | 65.7 |

| stockpile | coarse | medium | fine | RAP | Lime | coarse | medium | fine | RAP (agg) | Lime | RAP (total) | Lime(total) | Virgin Agg (g) | RAP Agg (g) | RAP + binder %remained |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| stockpile percentage, Ps | 32 | 0 | 22 | 45 | 1 | 32 | 0 | 22 | 45 | 1 | 45 | 1 | | | |
| total percentage | 100 | | | | | | | | | | | | | | |
| sieve size | percentage retained | | | | | batch mass, grams | | | | | | | | | |
| 3/4" | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 | **0.0** | **0.0** | 0.0 |
| 1/2" | 6.0 | 0.0 | 0.0 | 2.0 | 0.0 | 47.9 | 0.0 | 0.0 | 22.5 | 0 | 23.7 | 0.0 | **47.9** | **77.3** | 6.5 |
| 3/8" | 38.0 | 0.0 | 0.0 | 7.0 | 0.0 | 303.6 | 0.0 | 0.0 | 78.6 | 0 | 82.8 | 0.0 | **303.6** | **179.9** | 15.2 |
| 1/4" | 43.0 | 16.0 | 0.0 | 13.0 | 0.0 | 343.5 | 0.0 | 0.0 | 146.0 | 0 | 153.8 | 0.0 | **343.5** | **258.8** | 21.9 |
| #4 | 9.0 | 45.0 | 1.0 | 9.0 | 0.0 | 71.9 | 0.0 | 5.5 | 101.1 | 0 | 106.4 | 0.0 | **77.4** | **122.9** | 10.4 |
| #8 | 3.0 | 38.0 | 33.0 | 22.0 | 0.0 | 24.0 | 0.0 | 181.2 | 247.1 | 0 | 260.2 | 0.0 | **205.2** | **243.3** | 20.6 |
| #16 | 0.0 | 0.0 | 27.0 | 15.0 | 0.0 | 0.0 | 0.0 | 148.3 | 168.5 | 0 | 177.4 | 0.0 | **148.3** | **161.9** | 13.7 |
| #30 | 0.0 | 0.0 | 15.0 | 9.0 | 0.0 | 0.0 | 0.0 | 82.4 | 101.1 | 0 | 106.4 | 0.0 | **82.4** | **74.7** | 6.3 |
| #50 | 0.0 | 0.0 | 9.0 | 5.0 | 0.0 | 0.0 | 0.0 | 49.4 | 56.2 | 0 | 59.1 | 0.0 | **49.4** | **18.4** | 1.6 |
| #100 | 0.0 | 0.0 | 5.0 | 4.0 | 0.0 | 0.0 | 0.0 | 27.5 | 44.9 | 0 | 47.3 | 0.0 | **27.5** | **31.0** | 2.6 |
| #200 | 0.6 | 0.7 | 3.2 | 3.8 | 0.0 | 4.8 | 0.0 | 17.6 | 42.7 | 0 | 44.9 | 0.0 | **22.4** | **7.1** | 0.6 |
| pan | 0.4 | 0.3 | 6.8 | 10.2 | 100.0 | 3.2 | 0.0 | 37.3 | 114.6 | 24.96 | 120.6 | 25.0 | **40.5** | **7.6** | 0.6 |
| | | | | | | total weight | | | | | | | | | |
| | | | | | | 798.82 | 0.00 | 549.19 | 1123.34 | 24.96 | 1182.7 | 25.0 | 1348.0 | 1182.71 | |

**Table C-2 Quantity of binder, RAP materials, lime and total aggregates for the the mixture with 45% RAP, 5.3% binder content and binder grade of PG 70-22ER**

| | |
|---|---|
| target binder content % | 5.3 |
| aggregate mass, g | 2496.3 |
| mixture mass, g | 2636.0 |
| | |
| RAP binder (gr) | 59.37 |
| RAS binder (gr) | 0.0 |
| virgin binder (gr) | 80.3 |
| | |
| Gmm | 2.471 |
| Gmb | 2.298 |
| airvoid content (%) | 7 |
| gyratory height | 0.062 |
| mass of sample in GC (g) | 2510.5 |
| | |
| Lime Content (%) | 1 |
| Lime mass, g | 25.0 |