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Evaluating Testing, Protocols, and Limits for Asphalt Rejuvenating Agents in PA

FINAL REPORT

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16. Abstract

The objective of this research project was to establish the testing, protocols, and specification limits for the use of rejuvenators, also known as recycling agents (RA), in asphalt paving materials used in Pennsylvania, and to provide a guide protocol for usage. A laboratory experiment was designed to achieve this objective. Five sources of rejuvenator were considered for the research. Selection of the sources was in consultation with the project technical advisor. Rejuvenators were used in asphalt mixes containing RAP, RAS, or both. One RAP source and one RAS source were included in the study. Control mixes without any rejuvenating agents were included for each group of mixtures under this research. All materials were procured from sources within the Commonwealth of Pennsylvania. The experiment included testing of the RA-modified asphalt concrete specimens as well as characterization testing of the binder. Rejuvenators were incorporated into both the binders and the asphalt mixtures. Extensive rheological testing was conditioned on RAP binders modified with rejuvenating agents. Asphalt concrete specimens were subjected to wheel tracking to capture the rutting and stripping potential, and to indirect tensile cracking testing to assess the mix flexibility and the cracking potential. After completion of performance testing, several asphalt mixtures were processed for binder extraction and recovery. The recovered binders were exposed to performance grading and determination of rheological properties. The study also included comparison of cracking performance of long-term and short-term conditioned asphalt mixtures. This research showed that when rejuvenators are added to mixtures with a high RAP content or mixtures containing a combination of RAP and RAS, the mix performance is improved when it comes to low-temperature cracking and fatigue cracking. However, extension of this work to field pilot projects is essential to ensure effective application of the rejuvenating products.

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Disclaimer

CHAPTER 1

Introduction

BACKGROUND

Recycled materials such as reclaimed asphalt pavement (RAP) have been utilized in asphalt mixtures for decades, but their application has significantly increased with time, since such application is believed to reduce the cost of asphalt mixtures, conserves energy, and protects the environment. Similarly, the use of recycled asphalt shingles (RAS) has attracted considerable attention lately and their use in asphalt mixtures is currently pursued by several state highway agencies. However, unless necessary measures are taken, as the amount of RAP and RAS increases in the asphalt mixture, the mix tends to become more brittle, increasing the risk of cracking and raveling of the asphalt pavement. The mix will also be less workable and difficult to compact in the field, again increasing the potential for premature field failure. Among ways of allowing more RAP and RAS in the asphalt mixtures is the use of special recycling agents (RAs), sometimes referred to as rejuvenating agents or simply rejuvenators. The term "rejuvenator" may not be a suitable term, as this modifier rebalances the proportions of the binder composition rather than breaking the oxidation within the binder, but it is a common term used by many in the asphalt industry. Aging of the asphalt mixture during construction and during the long-term service of asphalt pavements results in oxidation of the mix and loss of a large portion of the maltenes in the binder composition. Maltenes provide the softening effect in the binder, and these recycling agents, when properly used, are expected to reduce the stiffness of asphalt mixtures that contain oxidized brittle RAP and RAS. Typically, rejuvenators include a high proportion of maltene constituents or similar material that help rebalance the composition of the aged binders.

The working mechanism (or diffusion process) of a rejuvenator includes the following steps (Behnood, 2019).

- A low-viscosity layer is formed by the rejuvenator, enclosing the asphalt-coated aggregate of the RAP.
- The rejuvenator starts to penetrate and soften the aged binder layer.
- As the rejuvenator continues penetrating the binder, the viscosity of the inner layer is reduced while the viscosity of the outer layer is increased. This trend is the result of the fact that with

penetration of the rejuvenator, the amount of rejuvenator coating the aged asphalt is gradually decreased until no more of the raw rejuvenator becomes available.

- After a certain time, equilibrium is approached over most of the recycled binder film.

There are two general classes of rejuvenators: petroleum driven and agricultural/plant driven. The petroleum-based rejuvenators are mainly promoted as additives capable of enriching the maltene concentration in the aged asphalt and breaking asphaltene clusters, creating a compatible colloidal system. Examples of petroleum-based rejuvenators include paraffinic oil and aromatic extracts, or engine oil. The plant-derived additives are promoted to enhance performance based on their viscosity-reduction capabilities and composition and are derived from vegetables and plants. Examples include vegetable oil (glyceride and fatty acid), modified vegetable oil, and tall oil, a byproduct of the paper manufacturing process from pine trees (Epps et al., 2020).

There are many commercially available products promoted as rejuvenators. Guidance is needed on how to decide on the suitability of these products for asphalt mix applications and the optimum dosage rates.

OBJECTIVE AND SCOPE OF WORK

The objective of this research project was to establish the testing, protocols, and specification limits for the use of rejuvenators in asphalt paving materials used in Pennsylvania, and to provide a guide protocol for usage. A laboratory experiment was designed to achieve this objective. Five sources of rejuvenator were considered for the research. Selection of the sources was in consultation with the project technical advisor. Rejuvenators were used in asphalt mixes containing RAP, RAS, or both. One RAP source and one RAS source were included in the study. Control mixes without any rejuvenating agents were included for each group of mixtures under this research. All materials were procured from sources within the Commonwealth of Pennsylvania. The experiment included testing of the RA-modified asphalt concrete specimens as well as characterization testing of the binder. Rejuvenators were incorporated into both the binders and the asphalt mixtures. Extensive rheological testing was conditioned on RAP binders modified with rejuvenating agents. Asphalt concrete specimens were subjected to wheel tracking to capture the rutting and stripping potential, and to indirect tensile cracking testing to assess the mix flexibility and the cracking potential. After completion of performance testing, several asphalt mixtures were processed for binder extraction and recovery. The recovered binders were exposed to performance grading and determination of rheological properties. The study also included comparison of cracking performance of long-term and short-term conditioned asphalt mixtures.

DELIVERABLES AND REPORT ORGANIZATION

This report is organized into six chapters, with the intent to present the research activities and findings in an organized sequence. Chapter 2 is allocated to the findings from the literature review, which was covered under Task 1 of the research project. The experimental program of the research, which was developed under Task 2, is covered in Chapter 3. The research on binder modification and mixture performance is covered in Chapters 4 and 5, respectively. These two chapters cover presentation and analysis of an extensive amount of data generated under Tasks 3 and 4, which were the largest portion of the research and required the longest time to execute. Finally, conclusions, recommendations, and a rejuvenator usage guide protocol are presented in Chapter 6. Task 5 of the research was associated with development of the draft final report and a PowerPoint presentation. The final report of the project, executed under Task 6 and presented in this document, is a comprehensive presentation of the completed work, data analysis, and research findings. This report also includes six appendices. Appendix A is allocated to *A Guide to the Use of Recycling Agents in Asphalt Paving Mixtures*, and it can be used as a stand-alone document. Appendix B covers a summary of results from testing the binders recovered from asphalt mixtures. Appendices C and D present results from Hamburg wheel tracking and, finally, Appendices E and F are allocated to the test results from IDEAL-CT index tests.

CHAPTER 2

Review of Literature

APPROACH IN LITERATURE REVIEW

The literature review was conducted in a way to produce information and data that could be useful to the goal of this project. With the project goal in mind, it was important to investigate past work on several matters related to the rejuvenators. It was the intention to find the answers to the following questions from the literature review:

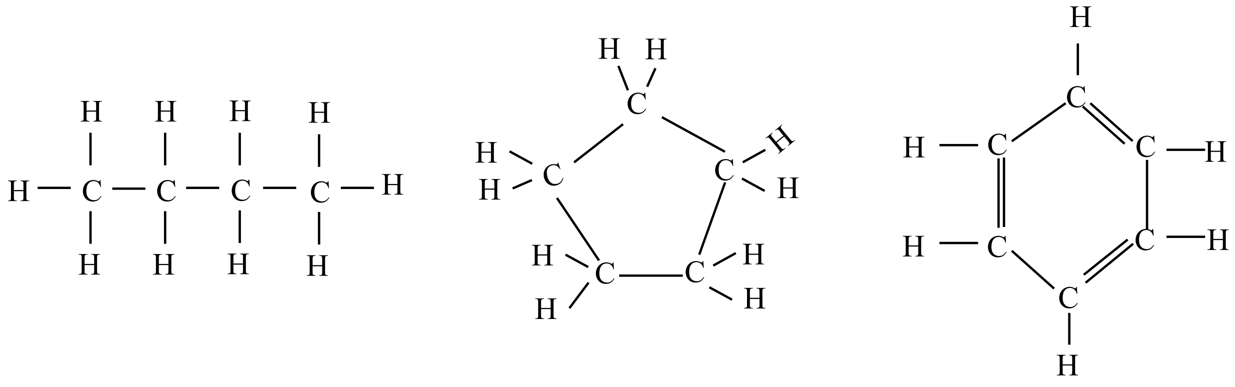
- Have rejuvenators, in general, been effective in enhancing the mix performance?
- How do they impact the binder properties?
- Are there differences among the rejuvenators, and how would one distinguish among them?
- What are the limits in using rejuvenators in asphalt mixes, and what level of usage is desirable?
- What is the long-term impact of rejuvenators? Do they remain effective with aging?
- Have there been field trials, and how have they performed?

The documents reviewed included those coming from national research agencies such as the National Cooperative Highway Research Program (NCHRP) and National Asphalt Pavement Association (NAPA), as well as those from research funded by state highway agencies.

LITERATURE REVIEW SUMMARY

Crude Oil Composition

To understand the impact of rejuvenators on asphalt properties, it will be beneficial to review the basics of asphalt composition and its production. Asphalt is a byproduct of crude oil refining through the distillation process. It is a mixture of hydrocarbons, which also includes other compounds such as sulfur, nitrogen, oxygen, and trace metals. Composition of the asphalt is heavily influenced by the composition of the crude oil and the refining process. There are three major types of hydrocarbons in crude oil affecting asphalt composition (Khalaf, 2008): paraffins, naphthenes, and aromatics. The paraffin, with general formula C_nH_{2n+2}, is characterized by a single bond connection between carbon atoms in a straight chain structure (Figure 1.a). All other bonds are saturated with hydrogen atoms. In naphthenes, with general formula C_nH_{2n}, carbon atoms are also connected with a single bond but make a ring structure (Figure 1.b). All other available bonds of the carbon atoms are saturated with hydrogen. Finally, there are aromatics in which the hydrocarbons make a cyclic structure with single bonds and double bonds alternating between atoms (Figure 1.c). Aromatics, with general formula C_nH_{2n-6}, contain unsaturated benzene rings, and while stable, their stability does not match that of paraffins. Beyond these three types of hydrocarbons, a fourth type, named olefins, is generated during the refining process as a result of dehydrogenation of paraffins and naphthenes (Khalaf, 2008). Only aromatic/naphthenic or mixed base crude oils can be processed, while the use of paraffinic crude oils has not proven successful.



(a) (b) (c)

Figure 1. Molecular structure of hydrocarbons in crude oil.

Basics of Asphalt Composition

Asphalt is a black viscous thermoplastic material, and highly temperature susceptible. It can be in solid, semisolid, or liquid phase, depending on the temperature. Its characteristics are heavily influenced by the fraction of the different hydrocarbon structure it is made of and the corresponding molecular structure. The constituent components of asphalt are asphaltenes and maltenes. The asphaltene with high molecular weight is insoluble in n-pentane (an alkane with five carbon atoms), whereas maltene with lower molecular weight is soluble. Asphaltenes are dispersed in maltenes in the colloidal form, and while they have different molecular weights and hydrocarbon structure, they form a single colloidal form called asphalt. Maltene is further classified into resins, aromatics, and saturates. Table 1 presents the fractional composition of asphalt based on the information presented and discussed by Paliukaite et al. (2014).

Table 1. Fractional composition of asphalt based on information presented by Paliukaite et al. (2014).

Asphalt Fractional Composition	% In Composition	Range of Molecular Weight (g/mol)	Solubility Parameter, $MPa^{0.5}$	Density (g/cm^3)	Description
Asphaltene	5 – 25	800 – 3,500	17.6 – 21.7	1.15	n-heptane insoluble black or brown amorphous solids
Resins	30 – 45	300 – 2,000	18.5 – 20.0	1.07	Transition from oil to asphaltene, semisolid or solid at room temperature, fluid when heated, brittle when cold
Aromatics	30 – 45	800 (average)	17.0 – 18.5	1.0	Black highly viscous liquid
Saturates	5 – 15	600 (average)	15.0 – 17.0	0.9	Clear liquid of medium viscosity, aliphatic

Asphaltenes tend to have high polarity, while saturates have low polarity. Polarity is generated as a result of polar bonds in an unsymmetrical arrangement, and the polar bond is the result of uneven partial charge distribution between atoms of the compound. Paraffin-rich crude oil is generally considered not quite suitable for bitumen production, while lack of asphaltene-rich crude oils may demand the use of paraffin naphthenic crude oils as base material for production of bitumen.

Effect of Wax on Asphalt

Since some rejuvenators are paraffinic based, a brief discussion of the effect of wax on asphalt properties will be useful to this project with respect to selection of the appropriate rejuvenators. Waxes in asphalt reduce the stiffness if they remain part of the liquid fraction but stiffen the asphalt if they separate into solid wax. However, wax in bitumen could disturb the colloidal structure (orientation of polar groups), stability, and homogeneity of the binder. Additionally, waxy bitumen may harden with time (physical hardening), especially at lower temperatures, possibly initiating cracks in asphalt pavements.

N-alkane-rich crystallizing wax in bitumen, as a rule, gives a sudden softening effect at higher temperatures and a stiffening effect at lower temperatures. Crystallizing wax, with no or very low n-alkane content, affects the bitumen to a lesser extent and, above all, gives a certain stiffening effect below the melting point of the wax. The sudden decrease in viscosity when wax is present is due to the melting of crystallized wax (Edwards, 2009). Such a decrease can be favorable if the intention is to ensure flow or compaction of asphalt. This property of wax is a reason for commercially available waxy additives as viscosity reducers for use in asphalt. However, it could also be a reason for concern in case of viscosity reduction within a temperature range that could reduce the mix's ability to resist permanent deformation of the asphalt pavement. Edwards (2009) indicates that the wax content of asphalt could also result in brittleness, physical hardening, poor ductility, and poor adhesion. However, the authors also note that the observed negative effects of wax in bitumen are based mainly on laboratory studies, and not on field studies. Similarly, Soenen et al. (2004) state that large effects on binders due to wax content does not necessarily mean a large influence on asphalt concrete mixture properties.

Typical viscosity-lowering additives used for bitumen are FT-paraffin, mainly wax-based products, oxidized polyethylene wax, thermoplastic resins, and fatty acid amide. Note should be made that the molecular weight distributions of such products differ a lot. Long chain paraffins contained in the paraffinic crude oils deliver asphalt that can cause cracking at low temperatures and permanent deformation at high temperatures and thus reduce the durability of the asphalt mix (Lenk and Loibel, 2000).

Rejuvenator versus Softener

It is important to distinguish between the additives promoted as rejuvenators and the additives that are simply softening agents. First, it should be realized that rejuvenators do not reverse the oxidative aging of the binder and do not reduce the high asphaltene content, which is the major contributor to binder brittleness. This is simply a myth. Rather, an effective rejuvenator increases the binder ductility through enriching the maltene content, peptizing and polarizing asphaltenes, and rebalancing the ratio of asphaltenes to maltenes. Recycling agents with strongly polar compounds capable of polarizing asphaltene clusters and compatibilizing them with maltenes are referred to as rejuvenators (Epps et al., 2020). Rejuvenators often contain a high proportion of maltene constituents such as naphthalic or polar aromatic fractions, a high proportion of aromatics, and low content of saturates (Dunning and Mendenhall, 1978 and Tran et al., 2012). Rejuvenators are also capable of maintaining their effectiveness through years after the asphalt pavement has been exposed to long-term aging.

Those agents lacking characteristics necessary to act as rejuvenators are simply known as softeners. The softening agents reduce the binder viscosity and stiffness not because of enriching maltene content, breaking asphaltene clusters, or creating a compatible system, rather just by increasing the proportion of the light components (light oil) compared with the heavy asphaltene portion of the aged asphalt binder. An example of softeners are some of the paraffinic oils that are non-polar and not compatible with the aromatic asphaltenes in asphalt. Other examples include refined engine oil bottom (REOB), flux oils, slurry oils, and many of the agriculture-based recycling products. Some subscribe to the belief that petroleum-driven agents are true rejuvenators, as maltene is absent from agricultural-based products (Durant, 2019).

Types of Rejuvenators

The asphalt paving industry has been exposed to numerous brands of rejuvenators within the last three decades. These rejuvenators can, in general, be classified into two groups: petroleum driven or agricultural/plant driven. The petroleum-based rejuvenators are mainly promoted as additives capable of enriching the maltene concentration in the aged asphalt and breaking asphaltene clusters, creating a compatible colloidal system. Examples of petroleum-based rejuvenators include paraffinic oil and aromatic extracts, engine oil or re-refined engine oil bottom (REOB). In regard to petroleum-based rejuvenators, the use of those with high paraffin content (saturated compounds) is discouraged, while the use of those with high aromatic extracts (unsaturated hydrocarbons) is promoted. Past research indicates that asphalts with higher content of polar compounds and reactive aromatics and lower amounts of paraffins are more stable (White et al., 1970).

The plant-derived additives, also known as bio-based additives, are promoted to enhance performance based on their viscosity reduction capabilities and composition. The plant-derived rejuvenators include those produced from vegetables and plants. Examples include vegetable oil (glyceride and fatty acid), modified vegetable oil, and tall oil, a byproduct of the paper manufacturing process from pine trees (Epps et al., 2020). To this list, one could add waste vegetable oil and reacted bio-based oils. The reacted bio-based oils are engineered to reduce oxidative aging of the binder.

Effect of Rejuvenators on Binder and Mix Performance, Laboratory Studies

Review of the literature indicates a large number of studies allocated to investigation of binder and mixture performance when rejuvenators are incorporated into the binder or mixture. These studies are, in general, showing the softening effect of rejuvenators and enhanced binder performance. They also indicate that there is a difference in rejuvenators in terms of the impact on binder rheology and performance. While the results of these studies are consistent with respect to binder performance, the results on mixture performance vary. In general, based on mixture test results, the rejuvenators do not exhibit the same level of improvement observed in the binders.

The following is a summary of some of the past research studies focused on the performance of binders and asphalt mixtures in light of rejuvenators.

Source of Study: Epps et al. (2020)

- **Rejuvenators:** Vegetable oil, tall oil, aromatic extracts (10 different recycling agents).
- **Mix Type:** Four mixes from TX, IN, NV, and VI, mix type not specified but five aggregate types were used in the study.
- **Recycled Materials:** RAP at 15%, 16%, 31%, 27%, 33%, 36%, 40%, and 58% levels; RAP/RAS at 10%/5%, 16%/8%, 20%/4%, 28%/2%, 29%/4%, 43%/4%, and 40%/4% levels. Six RAP sources were used. Percentages are for different RAP sources.
- **Optimum Asphalt Content:** 4.6%, 5.0%, 5.4%, and 5.8%.
- **Rejuvenator Dosage Rates and Application Technique:** 2%, 2.7%, 3.5%, 5.5%, 6.0%, 8%, and 9.5% for tall oil; 2%, 5.5%, and 6.5% for aromatic extracts; 1.2%, 5.5%, and 9.0% for vegetable oil. All incorporated into the base binder through hand-stirring.
- **Binder Tests:** DSR, BBR, Colloidal Instability Index (CII), Total Precondensed Aromatics (TPA), Modulated Differential Scanning Calorimeter (MDSC), FTIR.
- **Mix Tests:** Indirect Tension Resilient Modulus, HWT, SCB, Uniaxial Thermal Stress and Strain Test (UTSST), Asphalt Pavement Analyzer (APA).
- **Results:** The researchers developed a recycling dose selection method and materials proportioning. They also developed component material selection guidelines as well as binder and mixture evaluation tools. The authors used the research results to develop an AASHTO draft specification, presented as an appendix in their report. Direct conclusions from the research are not clearly explained in their concluding chapter. However, the following are some of the general statements provided in the summary chapter of the report:
    - Rejuvenation is more effective for less aged, recycled materials.
    - Rejuvenator mechanisms differ by recycling agent type.
    - Some high RBR mixtures with recycling agents may be more susceptible.
    - Reheating to produce plant mix laboratory-compacted specimens is detrimental to high-RBR mixtures with recycling agents.

Source of Study: Soohyok et al. (2014)

Source of Study: Elkashef and Williams (2017)

- **Rejuvenators:** Soybean-derived rejuvenator.
- **Recycled Materials:** RAP to max size of 12.5 mm, dried at 110 °C, RAP binder 5.1%.
- **Rejuvenator Dosage Rates and Application Technique:** Added to PG 58-28 at 6% and 12% levels by weight of binder. Add this to extracted RAP binder at a ratio of 1 to 5. So, rejuvenator dosage rate 1% (for 6%) and 2% (for 12%) total weight of RAP binder.
- **Binder Tests:** Dynamic Shear Rheometer on RTFO and PAV aged binders, Linear Amplitude Sweep Test (LAS).
- **Mix Tests:** DM, Disk-Compact Tension Test (DCT).
- **Results:** Binder: Both intermediate- and low-temperature cracking resistance improved based on DSR testing of PAV-aged binders with the use of rejuvenators. ΔT_c improved with use of rejuvenator (Figure 2); ΔT_c is a measure of binder brittleness and its capacity to resist non-load thermal cracking. It is calculated as the difference between the continuous grade temperatures when binder stiffness is 300 MPa, and the relaxation parameter (m-value) is 0.3 (based on criteria developed for the bending beam rheometer (BBR)). The authors showed that the number of load cycles to fatigue failure in LAS increased for the binders with rejuvenator, and this improvement was more pronounced at higher strain rates. While the researchers' results from the binder study were compelling with respect to the improvements gained, their results from testing asphalt mixture did not deliver clear conclusions.

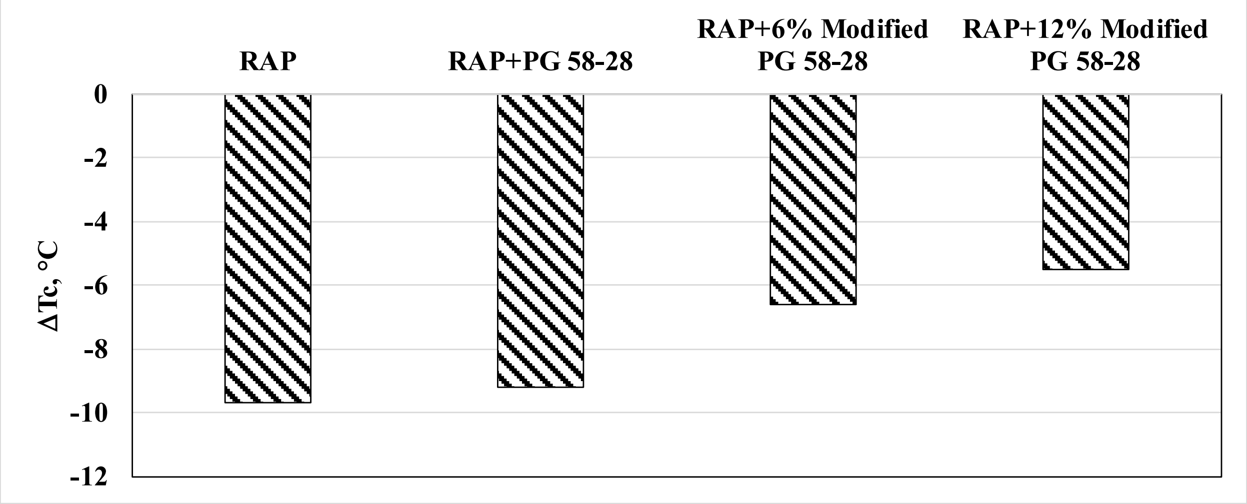


Figure 2. Effect of rejuvenator on ΔT_c [plot generated from data reported by Elkashef and Williams (2017)].

Source of Study: Booshehrian et al. (2013)

- **Rejuvenators:** 3 different rejuvenators, one of them with paraffinic wax.
- **Mix Type:** 9.5-mm specimen mix, mix temp 150 °C, comp temp 137 °C.
- **Recycled Materials:** 40% RAP, 5% RAS, 35% RAP/5% RAS.
- **Optimum Asphalt Content:** 6%.
- **Rejuvenator Dosage Rates and Application Technique:**
    - 40% RAP: added at 0.5% by weight of RAP, 9.3% by weight of RAP binder.
    - 5% RAS: added at 1.64% by weight of RAS, 9.3% by weight of RAS binder.
    - 35% RAP/5% RAS: added at 0.64% by weight of RAP/RAS, 9.3% by weight of RAP/RAS binder.
- **Results:** Clearly see the reduction in stiffness and viscosity by rejuvenators, and dropping of the continuous grade temperature at high, intermediate, and low levels. Their MSCR test shows increase of creep compliance, an indication of higher rutting potential. Their LAS test shows significant increase in the number of cycles to fatigue failure. The authors also conducted several tests on mixes prepared with recycled materials with and without rejuvenators. The HWT at 145 °C showed that the mixes with recycled material without rejuvenator performed better than those with rejuvenator. This performance difference was seen in stripping inflection point, rut depth at 10,000 passes, and rut depth at 20,000 passes. The results from the overlay tester showed, with no exception, that once rejuvenator was added to the asphalt mix with recycled materials (RAP, RAS, or a combination of both), the number of cycles to failure increased even though there was a difference in the level of effectiveness from different rejuvenators. Finally, improvement was observed, to various degrees, in cracking temperature based on the results of the Thermal Stress Restrained Specimen Test (TSRST).

Source of Study: Haghshenas et al. (2015)

- **Rejuvenators:** 3 rejuvenators (petroleum based, green based, and agriculture-based soybean).
- **Mix Type:** 12.5-mm Superpave mix; mixing temperature of 160±3 °C for hot mix and 138±3 °C for warm mix; compaction temperature of 138±3 °C for hot mix and 127±3 °C for warm mix.
- **Recycled Materials:** 65% RAP, RAP binder content 5.4%.
- **Optimum Asphalt Content:** 5.0–5.1%.
- **Rejuvenator Dosage Rates and Application Technique:**
    - Petroleum based at 6.2% of total binder (9% of RAP binder), added to the virgin binder.
    - Green based at 8.2% of total binder (0.65% of RAP material) added to the hot mix batch.
    - Soybean at 1.6% of total binder (5% of virgin binder), added to the virgin binder.

- **Binder Tests:** DSR, Atomic Force Microscopy (AFM), Fourier Transform Infra-Red (FTIR), and SARA analysis.
- **Mix Tests:** Torsion and Multiple Stress Creep Recovery (MSCR) on fine aggregate matrix (FAM), and Semicircular Bend Test (SCB), DM, Dynamic Creep Tests on asphalt concrete.
- **Results:** Rejuvenators softened the high RAP content mix and increased rutting potential. The petroleum-based rejuvenator had the most significant softening effect, while the agriculture-based had the lowest effect. While not reported by the authors, the observed difference may be the result of the soybean being at a low dosage rate compared to the other two. All rejuvenators increased cracking resistance. Resistance to moisture damage was sacrificed with all rejuvenators, with the green-based rejuvenator having the worst impact. Petroleum-based and agriculture-based rejuvenators decreased carbonyl, sulfoxide, and aromatics, and increased aliphatic index, with the final effect of restoring the chemical composition of aged binder. Green-based rejuvenator had an opposite effect.

Source of Study: Bennert et al. (2015)

- **Rejuvenators:** 5 rejuvenators (three petroleum-based and two plant-based: one vegetable oil and one tall oil).
- **Recycled Materials:** 25% and 45% RAP.
- **Rejuvenator Dosage Rates and Application Technique:**
  - preblend each with PG 76-22 at 330 °F, apply high shear for 1 hr.
- **Results:** after blending with PG 7-22, the binder grade changed, and the change was affected by the rejuvenator type and the dosage rate. For 45% RAP, the blend of 76-22 and rejuvenators delivered a PG 64-28 binder grade, except one of the petroleum-based rejuvenators, which resulted in a 58-34 grade. For 25% RAP, the blend yielded a PG 70-22, except one case of PG 70-28. The binder results did not correlate with the mixture results, possibly due to poor blending in the mix. Their general conclusion was that two of the petroleum-based rejuvenators were the best (dewaxed paraffinic oil and aromatic oil).

Source of Study: Majidfard et al. (2015)

- **Rejuvenators:** Waste cooking oil (mostly fatty acids).
- **Mix Type:** PG 58-22 (continuous grade 61.1-25.5 °C).
- **Recycled Materials:** 60% and 100% RAP (continuous grade 82.3-10.3 °C) and 12% crumb rubber (CRM), by weight of virgin binder. Incorporation of CRM at 160 °C for 2 hours and 5,000 RPM.
- **Optimum Asphalt Content:** 5.9% with no RAP mix, 7.3% for 60% RAP/Rejuvenator mix, 7.7% for 60% RAP/CRM/Rejuvenator mix, and 7.6% for 100% RAP/rejuvenator mix.

- **Rejuvenator Dosage Rates and Application Technique:** 10%, 16%, and 20% by weight of RAP binder in the blend.
- **Binder Tests:** DSR, Bending Beam Rheometer (BBR).
- **Mix Tests:** Indirect Tensile Strength.
- **Results:** Waste cooking oil improved workability and low-temperature grade of the binder. It reduced resistance to moisture damage and rutting. The blended binder with high oil content and high RAP content satisfied the high-temperature performance grade and delivered an improved low-temperature performance grade. As the oil content increased, both the low-temperature performance grade and the high-temperature performance grade of the binder decreased, an indication of improvement in resistance to fatigue cracking but increase in rutting potential.

Field Applications

While there is an abundance of studies on laboratory performance of asphalt mixes with rejuvenators, the number of field trials is limited. The following presents a few field studies on the use of rejuvenators with recycled asphalt pavements.

Xie et al. (2017) report on field trials with 25% RAP and 5% RAS mixes and the inclusion of two rejuvenators. The mixes were prepared in a drum plant. The warm mix additive was incorporated into the rejuvenators. Target production temperatures were 149 °C (300 °F) and 129 °C (265 °F) for the control mix and experimental mixes, respectively. The control mix had 20% RAP with no rejuvenator. All mixes were made with the 12.5-mm nominal maximum aggregate size and PG 76-22 binder. Experimental section 1 included 7.8% of rejuvenator 1 and section 2 included 13.8% of rejuvenator 2. The researchers do not identify the source and type of the rejuvenators. The mixes were placed on U.S. 31 in Alabama in 2014. A distress survey was conducted approximately 24 months after construction. While IRI and rutting were similar for all sections, the experimental sections exhibited significantly more cracking than the control section, both in terms of quantity and severity. The researchers' conclusion was that the rejuvenators were not effective for the mixes placed.

Epps et al. (2020) report on several field projects as part of their research, including one in Texas. The authors state that for this mix, the use of 2.7% recycling agent (tall oil) did not facilitate incorporating RAP and RAS. In general, the mix with rejuvenating agent exhibited a higher level of transverse and longitudinal cracking compared with the control mix, at an RBR level of 0.28. RBR refers to the recycled binder ratio, which is the ratio of the RAP/RAS binder to the total binder available to the mix. The researchers' argument is that the 2.7% field dosage level was not sufficient to restore the binder blend to be similar to the base binder from a rheological point of view. They state that the use of 0.5% WMA additive and lower temperature was more effective than the use of a recycling agent (Epps et al., 2019). Similar results were observed with the mix placed in Indiana, where transverse cracking, longitudinal cracking and alligator cracking were higher than what was observed in the control mix. The Indiana mix had 3% tall oil. These results were reported based on a distress survey 2 years after construction, for both TX and IN projects. Note should be taken that for the control mix RBR was 0.32, whereas for the experimental section with recycling agent it was 0.42. This significantly higher RBR has most probably played a role in observing the higher distress levels in spite of the use of rejuvenators.

Aging Effect

Through the aging of asphalt, some of the maltene changes into asphaltene. This transition has two adverse effects: (1) generating a higher concentration of asphaltene and (2) reducing the maltene. Increase in asphaltene tends to make the binder more viscous and more brittle. At the same time, reduction in maltene, which is the important dispersing medium for asphaltene, makes is easier for the asphaltene micelles to coalesce. These two simultaneous actions make the asphalt more brittle and more susceptible to cracking. It was previously stated that a simple compositional definition of maltene is that it is made of resins, aromatics, and resins. In general, as the ratio of aromatics to saturates decreases and the ratio of resin to asphaltene decreases, the result will be partial loss of stability of asphalt micelles (Demirbas, 2002). This solvency power of maltene and the preceding ratios are very important in how the binder behaves when exposed to long-term oxidation. Therefore, it may be conceivable that an asphalt with a high ratio of aromatics to asphaltenes be exposed to considerable oxidation but not exhibit signs of significant aging. In contrast, an asphalt with a low ratio of aromatics to asphaltenes may age fast even when exposed to lower oxidation levels (Dunning and Mendenhall, 1978).

Cavalli et al. (2018) discussed the impact of three different rejuvenators on binder characteristics when exposed to long-term aging. Three rejuvenators and one RAP source were used for this purpose. The RAP had a binder content of 5.6%. Stiffness of the RAP and the virgin binder was reported based on penetration grading. The RAP was graded as Penn 22 (i.e., 2.2 mm of needle penetration at 25 °C) and the virgin binder graded as Penn 62. The softening points were reported as 65.7 °C and 49 °C for RAP binder and virgin binder, respectively. The rejuvenators were all bio-based: seed oil, cashew nutshell oil, and tall oil. The dosage rate was established as 5% by mass of the RAP binder or based on a targeted final grade. Before blending in the rejuvenator, the RAP binder was heated at 110 °C for 20 minutes. Blending occurred using a shear blender at room temperature for 1 minute. The modified binder was then subjected to short-term (rolling thin film oven, RTFO) and long-term (pressure aging vessel, PAV) aging. Finally, the binders were tested in 3-point bending to measure fracture toughness and in dynamic shear rheometer to measure rheological characteristics. The chemical characteristics were measured using ATR-FTIR.

An interesting task undertaken by the authors was to check the chemical stability of the rejuvenators. Pure rejuvenator was placed in the oven at 160 °C for 3 hours. It was reported that no change was observed in the chemical composition as a result of this severe high-temperature heating. The authors concluded that the addition of rejuvenator could soften the RAP binder, but they did not see that rejuvenator effective in breaking functional groups (carbonyls and sulfoxides) that were caused by oxidation. In the authors' opinion, this lack of effectiveness in breaking the aforementioned functional groups might have been due to the fact that the tall oil and seed oil themselves contain carboxylic (C=O) groups. The increase in carbonyl and sulfoxide groups was the result of aging of the RAP binder. Their test results indicate that rejuvenators decrease fracture toughness of the unaged binder and aged binder. Work of fracture was higher for the rejuvenator-modified RAP binder before and after aging. The rejuvenators reduced the modulus and increased the phase angle, both resulting in increased resistance against cracking.

In a study by Majidifard et al. (2018), the effect of waste cooking oil on long-term aging of binder was also investigated. The virgin binder was PG 58-22 (noted in their work as FB: Fresh Binder). The long-term aging was conducted using two cycles of pressure aging vessel (noted in their work as FBP2) to deliver an artificially aged binder to simulate the RAP binder. The continuous grade of the virgin binder was -25.5 °C and 61.1 °C at the low and high ends, respectively. The grade of the aged binder was -10.3 °C and 82.3 °C, respectively. Part of the study also included evaluating the effect of rejuvenator when 12% crumb rubber modifier (by the weight of virgin binder) was added to the blend. The addition of crumb rubber modifier (CRM) was conducted at 160 °C for 2 hours and at shear blending rate of 5,000 rpm.

The researchers found that recycled binders aged at a faster rate compared with virgin binder (Figure 3). This observation indicates the importance of considering aging susceptibility of rejuvenators when used to improve the binder cracking resistance characteristics.

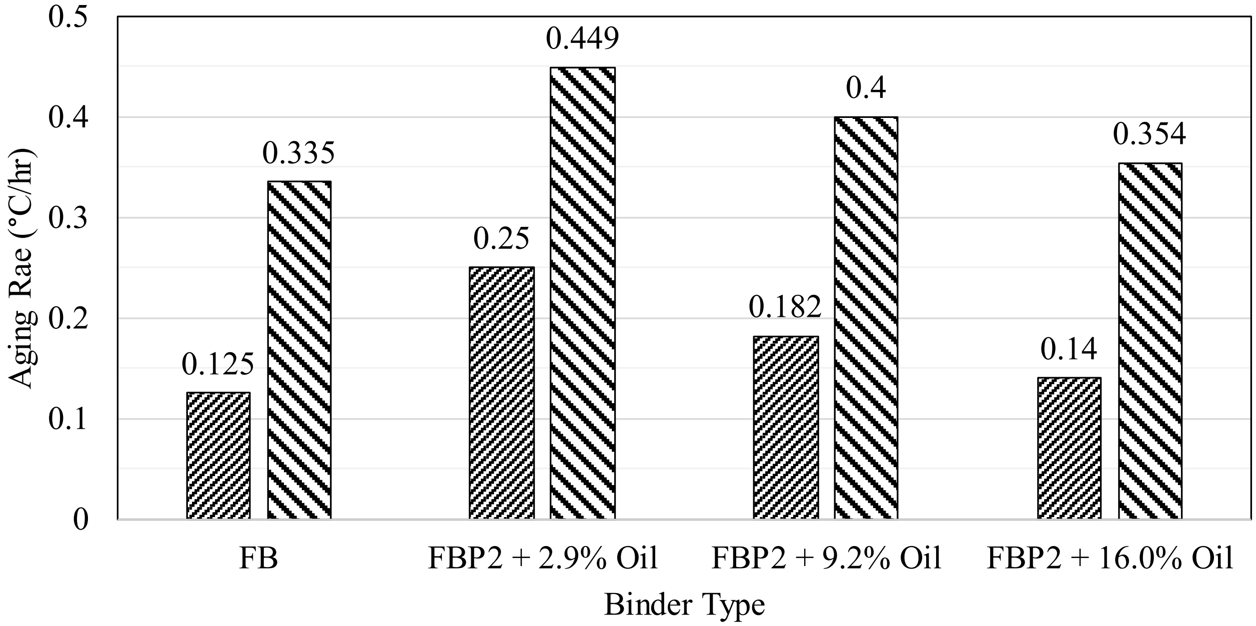


Figure 3. Aging rate of fresh and recycled binders based on low-temperature and high-temperature performance grade (after Majidfard et al., 2018).

Tabatabaee and Kurth (2017) report that the Colloidal Instability Index is shown to be a useful parameter for monitoring the effect of aging on the rejuvenated bitumen. This index is expressed as the ratio of the sum of asphaltenes and saturates to the sum of aromatics and resins in a crude oil. The rejuvenator tested in their study showed good aging stability, as indicated by the relatively limited increase in CII due to aging. In general, it is believed that if CII>2 for the blend of two oils, the blend tends to lose stability and present an incompatible system (Asomaning and Watkinson, 2000).

Mohammadafzali et al. (2015) studied the effect of four different rejuvenators on long-term aging. The rejuvenators included an emulsion (with residue 60%), heavy paraffinic distilled solvent extract with high aromatic content, 50/50 aromatic/naphthenic extract, and vegetable-based fatty acids. The authors indicate that the rejuvenators were manually blended into the aged asphalt at 140 to 160 °C. Dosage rate was established in a way to deliver the original grade (continuous grade of 68.4+/-1 °C for binder 1 and 71.6+/-1 °C for binder 2). The rejuvenator content varied in the range of 20–33% for binder 1 and 13–30% for binder 2.

An interesting observation from their long-term aging (PAV) was that the rate of aging was different among the binders depending on the type of rejuvenator, even though before the beginning of aging they were all at the same grade. The emulsion and the heavy paraffinic showed a slower rate of aging compared to the control binder (without modification with rejuvenator), while the 50/50 aromatic/naphthelic and vegetable-based rejuvenators showed a faster rate of aging (Figure 4). However, while the authors did not discuss the reason for such, it seems that the rejuvenator content must have played a role in addition to the influence of the rejuvenator type. The 50/50 aromatic/naphthelic and vegetable-based rejuvenators were incorporated at a significantly lower dosage to deliver the same grade compared with the heavy paraffinic oil and emulsion.

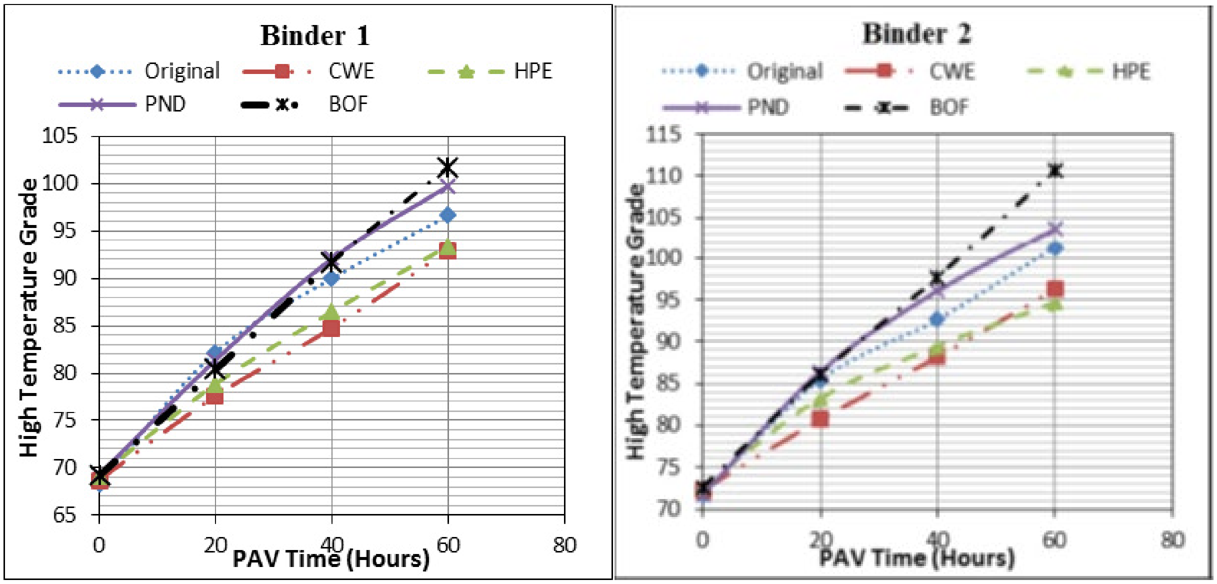


Figure 4. Binder continuous grade after PAV for binders modified with different rejuvenators (after Mohammadafzali et al., 2015).

The authors also found that the low-temperature grade after PAV was clearly improved (was lower) for all modified binders compared with the original binder based on the stiffness criterion. The improvement was not so pronounced based on the m-value (relaxation parameter), and in a few cases no change was observed.

CHAPTER 3

Experimental Program

EXPERIMENT PLAN FOR THE BINDER STUDY

There were two sections to the comprehensive experiment: (1) testing asphalt binders with and without rejuvenating agents and analysis of the corresponding results, and (2) testing asphalt concrete compacted mixtures with and without rejuvenating agents and analysis of the corresponding results. This section deals with the experimental plan for binder evaluation. It was discussed in Chapter 2 (the literature review) that in some cases the laboratory test results from binder testing do not correlate well with the results from testing the asphalt mix when rejuvenators are used with high RAP mixes. The most probable cause of this discrepancy is that when asphalt binder is mixed with the rejuvenator, it is possible to obtain an almost full homogenous blend, and hence it is easier to capture the effect of the rejuvenating agent on the binder properties. However, in case of the mixes, it is not possible to know exactly how the rejuvenator-modified virgin binder interacts with the RAP/RAS binder. Even if the rejuvenating agent is pre-blended with the RAP or RAS, it is highly unlikely that the final blend of the RAP/RAS binder and the virgin binder will be homogenous and uniform. In spite of these shortcomings, binder testing provides the benchmark data and a reference on how the binder properties change with the addition of rejuvenators, and how effective the rejuvenators are in maintaining long-term performance.

The experimental plan included a limited number of binder/rejuvenator combinations. Originally, the binder tests were to be conducted for only two rejuvenators (one petroleum based and one plant/vegetable based) and for only one dosage level. As this work was undertaken and information from the rejuvenator manufacturers was gathered, it was found that expansion of binder testing was needed, and a new testing matrix was developed. The plan was expanded to include all five rejuvenators for Section 1 of the study. Three of these rejuvenators were incorporated into the RAP binder at two dosage rates. Testing was also conducted on the blend of RAP and virgin binder. Rheological testing was conducted at both high and low temperatures on the prepared binders.

Selection of Rejuvenators

Rejuvenators were received from five different sources, as presented in Table 2. Attempts were made to include both plant/vegetable-based and petroleum-based rejuvenators. In addition, communication was made with the manufacturers regarding any special instructions regarding the use of rejuvenators.

Table 2. Rejuvenators used in this research.

Company	Product	Description	Abbreviation Used in this Study
Holly Frontier	Hydrolene H90T	Extracts (petroleum), heavy paraffinic distillate solvent	HT
Cargill	ANOVA 1815	Biobased additive	AN
Ingevity	Evoflex CA-7	Engineered additive designed to work with Evotherm®, production temperatures lower than 135 ºC	IN
Green Asphalt Tech	Hydrogreen S	100% natural mixtures of plant extracts, rosins, rosin esters, fatty acids, and vegetable oils	HG
Krayton	Sylvaroad RP1000	Crude tall oil (CTO), a renewable raw material that is a by-product of the paper industry	SR

Selection of Virgin Binder

Two different performance-grade binders from an approved source in Pennsylvania (PennDOT Publication 35, Bulletin 15) were included in the study: One was a standard PG 64S-22 binder and the other a standard PG 58S-28, both meeting requirements of AASHTO M 332.

Selection of RAP

Material from a single RAP source was used in the study. The RAP was delivered to the research team by the project technical liaison on March 11, 2020. The RAP was from Alleghany County, and in total, 20 medium-sized bags of RAP were received. Each bag weighed approximately 50 lb. The RAP was processed to ensure uniformity with a reduced level of moisture content.

Selection of Binder Tests

The binder tests selected for this research were those to provide the binder grading when rejuvenators are used and the effect of aging and conditioning on short-term and long-term performance of the binder (Table 3).

Table 3 Binder tests executed for this research.

Binder Test	AASHTO Standard	Response	Purpose
Dynamic Shear Rheometer at high and intermediate temperatures	T 315	Modulus and phase angle	Performance grade based on AASHTO M 320
Bending Beam Rheometer at low temperature	T 313	Binder stiffness and relaxation value (m-value)	Critical cracking temperature and ΔT_c
Multiple Stress Creep and Recovery	T 350	Creep compliance and percent recovery	Potential for rutting and elastic recovery, Performance Grade based on AASHTO M 332
Short-Term Conditioning (Aging)	T 240	To deliver short-term oxidized aged material for testing and evaluation	Evaluate effect of rejuvenator on short-term aged binder
Long-Term Conditioning (Aging)	R 28	To deliver long-term oxidized aged material for testing and evaluation	Evaluate effect of rejuvenator on long-term aged binder

Matrix of Testing

Careful consideration was given to planning the testing program. The program was designed to capture the effect of different rejuvenators, the aging and conditioning effect, and the effect of dosage rate. For this purpose, several different combinations of virgin binder, RAP binder, rejuvenator type, and dosage rate were included, as presented in Table 4. Dynamic shear rheometer (DSR) was used to capture rheological properties (complex modulus and phase angle) at high and intermediate temperature according to requirements of AASHTO T 315. Multiple Stress Creep Recovery (MSCR) tests were also conducted to capture creep compliance at 64 °C according to AASHTO T 350. Finally, the low-temperature rheological properties (stiffness and relaxation index) were measured according to AAHTO T 313. The neat binder, RAP binder, and rejuvenator-modified binders were tested without any conditioning wherever needed and possible. For many of the cases, the binders were subjected to short-term conditioning and long-term conditioning before rheological testing. Short-term aging was accomplished using RTFO according to AASHTO T 240, and long-term conditioning was achieved using PAV according to AASHTO R 28. Table 4 presents all the binders and the tests that were conducted for this phase of research. A considerable amount of RAP binder was recovered through solvent extraction and binder recovery. This process had to be repeated many times to procure enough RAP binder for testing, an extremely labor-intensive and time-consuming process.

Table 4. Matrix of testing for materials of this research.

PG of Virgin Binder	Rej. Type	% Rej.	RBR	High Temp. with DSR		Interm. Temp. with DSR	MSCR with DSR at 64 °C	Low Temp. with BBR		
				Unaged	RTFO	PAV	RTFO	Unaged	RTFO	PAV
58-28	▨	0	0.00					▨	▨	
64-22	▨	0	0.00					▨	▨	
64-22	AN	3	0.00					▨	▨	
64-22	IN	3/0.4*	0.00					▨	▨	
64-22	HT	3	0.00					▨	▨	
64-22	HG	3	0.00					▨	▨	
64-22	SR	3	0.00					▨	▨	
58-28	IN	2/0.4	0.35			▨		▨		▨
58-28	HT	2	0.35			▨		▨		▨
▨	▨	0	1.00			▨				▨
▨	AN	5	1.00			▨				▨
▨	IN	5/0.4	1.00							
▨	HT	5	1.00							
▨	AN	10	1.00			▨				▨
▨	IN	10/0.4*	1.00			▨		▨		▨
▨	HT	10	1.00			▨				▨

Establishing the Range for Rejuvenator Content

It is obvious that the rejuvenator content not only depends on the type of rejuvenator but also on several other factors, including the properties and amount of the virgin binder, the RAP, and the RAS, as well as the target binder grade and the design binder content. The actual rates to be considered for each rejuvenator were later established during the work with asphalt mixes, as discussed in the next chapter. However, even for this phase of study, which is focused on the rejuvenator-binder interaction, the amount of rejuvenator to be used must be within a realistic range. Table 5 is provided as an example of the amount of required rejuvenator needed for different RAP/RAS content scenarios. The amount of rejuvenator is determined based on virgin and target binder grades. This is an acceptable approach in practice, but the true acceptability of the rejuvenator content must come through the asphalt mix performance testing, as will be shown later in studying the effect of rejuvenator on asphalt mixes. The following assumptions are made in producing Table 5.

- Virgin Binder Grade: PG 58-28 (True Grade: PG 60-29)
- Target Binder Grade: PG 70-27
- Design Binder Content: 5.4%
- RAS Binder Content: 23%
- RAP Binder Content: 5.9%
- RAP Binder Grade: PG 89-14
- RAS Binder Grade: PG 137+2 (+2 is the low-temperature grade)

Table 5. An example scenario for rejuvenator content to achieve a target binder grade.

					Amount of Rejuvenator Needed %				
% RAP in Mix	% RAS in Mix	RAP RBR	RAS RBR	Target Temperature	% of Total Binder	% of Virgin Binder	% of Recycled Binder	% of Mix	Final PG, °C
35	0.00	0.38	0.0	Target Low Temp	1.83	3.06	4.79	0.10	67.5–27.0
				Target High Temp	0.56	0.91	1.46	0.03	70.0–24.4
45	0.00	0.49	0.0	Target Low Temp	2.63	5.47	5.36	0.14	69.1–27.0
				Target High Temp	2.18	4.49	4.44	0.12	70.0–26.1
0	5	0.0	0.21	Target Low Temp	2.26	2.95	10.59	0.12	72.0–27.0
				Target High Temp	3.28	4.35	15.41	0.18	70.0–29.1
0	8	0.00	0.34	Target Low Temp	4.20	6.8	12.32	.23	78.1–27.0
				Target High Temp	8.33	14.46	24.44	0.45	70.0–35.4
15	5	0.16	0.21	Target Low Temp	3.46	5.88	9.18	0.19	74.4–27.0
				Target High Temp	5.72	10.10	15.17	0.31	70.0–31.6

It can be seen from Table 5 that for the example shown, depending on the RAP/RAS content, the rejuvenator content varies in a range of roughly 0.6–8% when calculated with respect to total binder content of the mix. It is also very important to recognize that for a specific target grade, the dosage rate varies depending on whether the high-temperature grade is targeted or the low-temperature grade. For example, for the case of 15% RAP and 5% RAS (with total RBR of 0.37), a dosage rate of 3.5% based on the total binder mass yields PG 74.4-27, matching the desired low-temperature grade (recall from the assumptions that the target grade is PG 70-27). However, to match the high-temperature grade, a dosage rate of 5.7 is needed. For a case like this, obviously, any dosage rate between these two numbers will be acceptable, as both high and low ends of the temperature grade will be satisfied. However, in cases where a higher rate is needed to satisfy the low end of the temperature grade compared to the dosage rate needed to satisfy the high end, only one end can be satisfied. For example, in the case of 35% RAP (with RBR of 0.38), the dosage rates based on total binder are 1.8% and 0.6%, respectively. At 1.8% rejuvenator content, the target high-temperature grade is not satisfied. As we tend to decrease the amount of rejuvenator to satisfy the high-temperature grade, the low-temperature grade gets compromised. Therefore, only one end can be satisfied at a time. In a case like this, if the intent becomes to truly satisfy both ends, there will be a need for further adjustments to the mix. However, it is mostly the low temperature which is of great concern due to the mix cracking potential, and typically the rejuvenator dosage rate is determined to ensure that the modified binder performance grade satisfies the low-temperature requirements. Using Table 6 as a guide, for the binder study discussed in this report, the dosage rates shown in Table 6 were used to prepare the rejuvenator-binder blends.

Table 6. Selection of rejuvenator content for binder study.

Type of Blend	Rejuvenator Content as Percent of Total Binder
Rejuvenator + Virgin Binder	3
Rejuvenator + RAP Binder	5 and 10
Rejuvenator + Virgin Binder + RAP Binder	2

EXPERIMENT PLAN FOR THE MIXTURE STUDY

The experimental program for the mixture study included plans for the selection and procurement of materials, preparation of specimens, selection of mixture performance tests, and finally, execution of the testing plan and data analysis.

Materials

Rejuvenators

From the list of rejuvenators selected for the binder study, four were chosen to be included in the mixture study. Three of the plant/vegetable-based rejuvenators along with the only available petroleum-based rejuvenator were included in this part of the research. The rejuvenator from Holly Frontier, as discussed previously, constituted aromatic oils and paraffinic oils. The other three were Evoflex CA-7 from Ingevity, Anova from Cargill, and Hydrogreen S from Asphalt Green Tech.

Virgin Binder Sources

The asphalt binder PG 58S-28, previously discussed, was used to prepare all the mixtures with RAP/RAS and rejuvenators.

Aggregate Sources

One type of virgin aggregate was included in the study. It was a limestone aggregate from an approved quarry source in Pennsylvania.

RAP

Material from a single RAP source was used for the mixture study, as was discussed previously in this chapter.

RAS

Post-consumer recycled asphalt shingles (PCRAS) were procured from one source for this work through coordination with the PennDOT technical liaison of the project. The RAS source is located in Pennsylvania. Deleterious material such as nails, felt, wood, and plastic were removed from the PCRAS.

Antistripping Agent

The liquid antistripping agent used in this work was from Ingevity, promoted under the term P25.

Basic Material Characterization

The RAP and RAS were characterized for gradation and binder content in a previous study (Solaimanian et al., 2021). Basic material characterization included determination of RAS/RAP gradation before and after binder ignition and RAS/RAP binder content (Table 7 and 8). Gradation of the RAS/RAP was needed for establishing the mix designs. The RAS/RAP was fractionated on #100 sieve for better control of the fines in the mix. The performance grade of the RAS/RAP binder was also determined. The gradation of the RAP and RAS before and after extraction are presented in Tables 7 and 8, respectively.

Table 7. Gradation and binder content of the RAS source.

Sieve Size		RAS		
US (inches)	**SI (mm)**	**Air Dried**	**After Solvent Extraction**	**After Ignition Burn**
1	25	100.0	100.0	100.0
3/4	19	100.0	100.0	100.0
1/2	12.5	100.0	100.0	100.0
3/8	9.5	100.0	100.0	100.0
#4	4.75	100.0	100.0	100.0
#8	2.36	99.9	99.8	100.0
#16	1.18	97.3	98.1	98.2
#30	0.6	79.5	86.3	86.1
#50	0.3	49.3	72.5	72.7
#100	0.15	21.0	56.5	57.1
#200	0.075	6.1	36.5	38.5
pan	0	0.1	0.2	0.1
Binder Content based on Solvent Extraction		22.7%		

Table 8. Gradation and binder content of the RAP source.

Sieve Size		RAP		
US (inches)	**SI (mm)**	**Air Dried**	**After Solvent Extraction**	**After Ignition Burn**
1	25	100.0	100.0	100.0
3/4	19	100.0	100.0	100.0
1/2	12.5	99.9	100.0	100.0
3/8	9.5	94.4	95.9	95.9
#4	4.75	61.9	71.9	70.8
#8	2.36	38.2	53.8	52.3
#16	1.18	22.4	41.1	39.5
#30	0.6	13.9	33.2	31.9
#50	0.3	7.4	25.6	24.0
#100	0.15	3.7	20.0	18.1
#200	0.075	1.7	16.3	14.4
pan	0	0.0	0.0	0.0
Binder Content from T308, %		6.1%		

Mix Design

A time-consuming part of this work was designing the asphalt mixes according to specifications before they could be processed for preparation of performance index testing. Numerous mix designs were needed because of versatility in the number of rejuvenators, RAP/RAS combinations, and different rejuvenator contents. Each required preparation of design specimens and checking the volumetrics. In several cases, gradations had to be adjusted to deliver a suitable design. In general, three types of mixes were included in this work: Type 1 included the mixes with 15% RAP and 5% RAS. Type 2 was allocated to the mixtures with 35% RAP and no RAS, and finally, Type 3 mixes were those with 5% RAS but no RAP content. **For the sake of brevity, in many parts of this report, these three mixtures are referred to as 15/5, 35/0, and 0/5 mixtures, respectively, with the first number referring to the percent of the RAP content based on the mass of the mixture, and the second number referring to the percent of the RAS content based on the mass of the mixture.** All three types had control mixes, i.e., the mixes with the RAP and/or RAS without any rejuvenators. For type 1 and 2 mixes, all four rejuvenators were used in the experiment, but for type 3 only two of the four rejuvenators were studied. Table 9 shows the type of mixes used in the research. For design verification, all mixes were prepared at 75 gyrations with PG 58-28 and limestone aggregate with nominal aggregate size of 9.5 mm. Volumetric specimens were conditioned 2 hours at 150 ºC (302 °F) and compacted at 150 ºC, IDEAL and HWT were conditioned 4 hours at 135 ºC (275 °F), 1 hour at 150 ºC, and compacted at 150 ºC, maintaining the temperature within the range for different binder grades, as established in Table A of Section 413 of PennDOT Publication 408.

Table 9. Types of asphalt concrete mixes used in this research.

Mix Type	%RAP	%RAS	Control Mix (No Rejuvenator)?	Mixes Designed with Rejuvenators			
1	15	5	Yes	IN	AN	HT	HG
2	35	0	Yes	IN	AN	HT	HG
3	0	5	Yes	IN	AN		

For most of the cases, the design was simply verification through checking the mix volumetric parameters at one or two different asphalt contents. Some of the mixes were intentionally kept similar with the change of one parameter so that meaningful comparison could be made. For example, mix #4 with 5% RAS and 15% RAP (as a percent of mix mass) was designed at 3.2% virgin binder. Mix

#5 is similar to mix #4 with just increase of virgin binder content from 3.2% to 4.2% to evaluate the effect of higher binder content on the performance index test results. Some mixes were processed for long-term aging before performance testing so that comparison could be made between the long-term and short-term conditioned cases. Out of all the mixes prepared during the course of this research, a select group, as presented in Table 9, were processed for performance testing. The binder replacement ratio (RBR) varied among the mixes depending on the binder content, RAP/RAS content, and rejuvenator content.

Determination of Rejuvenator Content in the Asphalt Mixtures

An important step during the design of the mixtures was determination of the amount of the rejuvenating agent to be used for each mix type; for example, the asphalt mixture containing 35% RAP, or the mixture containing 15% RAP and 5% RAS. For two of these rejuvenators (namely, CA-7 from Ingevity and Anova from Cargill), the characteristics of mixture components were provided to the manufacturers and they provided the research team with their recommended dosage rates. For example, for the mixtures with 15% RAP and 5% RAS, the information provided in Table 10 was provided to the manufacturer of the rejuvenator so that they could determine the dosage rate. For the other two rejuvenators, the recommended dosage rates were more generic; for example, for the Hydrogreen agent, the dosage rate was 0.75% by total weight of RAP/RAS material as percent of the mix, and in the case of only using RAS, it was 1.5% of the total weight of the RAS as percent of the mix. For Hydrolene agent, dosage rate was 9% of the RAP/RAS binder content and reported as percent of the total mix mass. Table 11 presents a comprehensive list of the mixes used in this research. For each mixture, the table shows various important parameters such as the virgin and total binder content, RBR from RAP or RAS as well as total RBR, and the type and amount of each rejuvenator.

Table 10. Mix components used to determine the rejuvenator content.

Component	% In the Mix	Binder Grade (RTFO Aged	Binder Content, %
Virgin Binder		59.0-29.5	
RAP	15	89.0-13.0	5.3
RAS	5	143.0-11.9	22.7
Total Binder in the Mix	5.5, 6.0, 6.5		

Table 11. Mixes used in this research and the corresponding parameters.

Mix Information										
MIX ID	Virgin AC, %	Total AC, %	RAP %	RAS %	Rejuv. Type	Rej. % of Total binder	Rej. % of Virgin binder	RBR from RAP	RBR from RAS	Total RBR
Specimens are short-term aged at 135C for 4 hours, followed by conditioning at 150C for 1 hour before compaction.										
Experimental Mixes (i.e., mixes with the recycling agents)										
#4	3.2	4.7	12.0	4.0	CA-7	2.38	3.54	0.13	0.19	0.33
#5	4.2	5.7	12.0	4.0	CA-7	2.58	3.54	0.11	0.16	0.27
#18	3.8	5.7	15.0	5.0	CA-7	2.35	3.54	0.14	0.20	0.34
#20	3.8	5.7	15.0	5.0	CA-7	2.35	3.54	0.14	0.20	0.34
#21	3.8	5.7	15.0	5.0	CA-7	4.70	7.08	0.14	0.20	0.34
#23	3.8	5.7	15.0	5.0	CA-7	5.30	7.99	0.14	0.20	0.34
#38	3.7	5.6	35.0	0.0	CA-7	3.20	4.80	0.33	0.00	0.33
#24	4.1	6.0	15.0	5.0	Anova	1.30	1.91	0.13	0.19	0.32
#39	3.7	5.6	35.0	0.0	HT	2.88	4.32	0.33	0.00	0.33
#40	3.7	5.6	35.0	0.0	HG	2.50	3.75	0.33	0.00	0.33
#42	3.7	5.6	35.0	0.0	Anova	1.10	1.65	0.33	0.00	0.33
#35	4.6	5.7	0.0	5.0	CA-7	1.90	2.37	0.00	0.20	0.20
#36	4.6	5.7	0.0	5.0	Anova	0.80	1.00	0.00	0.20	0.20
#25	4.1	6.0	15.0	5.0	HT	2.88	4.24	0.13	0.19	0.32
#26	4.1	6.0	15.0	5.0	HG	2.50	3.68	0.13	0.19	0.32
Specimens are long-term aged at 135C for 8 hours, followed by conditioning at 150C for 2 hours before compaction.										
Experimental Mixes (i.e., mixes with the recycling agents)										
#24	4.1	6.0	15.0	5.0	Anova	1.30	1.91	0.13	0.19	0.32
#33	3.8	5.7	35.0	0.0	None	0.00	0.00	0.33	0.00	0.33
#39	3.7	5.6	35.0	0.0	HT	2.88	4.32	0.33	0.00	0.33
#23	3.8	5.7	15.0	5.0	CA-7	5.30	7.99	0.14	0.20	0.34
#38	3.7	5.6	35.0	0.0	CA-7	3.20	4.80	0.33	0.00	0.33
Specimens are short-term aged at 135C for 4 hours, followed by conditioning at 150C for 1 hour before compaction.										
Control Mixes (i.e., mixes without recycling agents)										
#19	3.8	5.7	15.0	5.0	None	0.00	0.00	0.14	0.20	0.34
#33	3.8	5.7	35.0	0.0	None	0.00	0.00	0.33	0.00	0.33
#37	4.6	5.7	0.0	5.0	None	0.00	0.00	0.00	0.20	0.20

Study of the Blending Techniques

There are two ways of incorporating the rejuvenator into the asphalt mixtures: one is adding it directly to the virgin asphalt binder, and the other is incorporating it into the mixture. In the latter case, it is best to add the rejuvenator to the RAP or RAS or the blend of the two to allow some interaction between the recycling agent and the RAP and RAS binder before mixing with the aggregate and adding the virgin binder. These two approaches are respectively referred to as Method 1 and Method 2 in this study. To assess how these two different blending methods affect the results, for one of the mixtures containing RAS and RAP, both techniques were applied. For all other mixes, only method 2 was applied.

Method 1

With this method, the rejuvenator and anti-strip additive were added directly to the virgin binder. The rejuvenator was added based on a percentage of total weight of the binder, and the anti-strip additive was added at 0.25% by total weight of the binder. Each one of the rejuvenators had a different dosage rate based on the recommended dosage rate of the manufacturers. Each can of virgin binder had enough binder for a complete set of four test specimens. The percentage of rejuvenator was calculated for the asphalt mixtures that were tested using this blending technique and added to the heated binder and stirred by hand for 60 seconds to make sure it was properly blended. The can of binder and rejuvenator was then placed into the oven at 150 °C to bring it to the mixing temperature before preparing the compacted asphalt mixtures.

Method 2

The blending technique that was used for all of the specimens was adding the rejuvenator directly to the RAP at room temperature. With this method, the rejuvenator was added directly to the RAP by a percentage of total weight of binder (i.e., total of virgin binder, RAP binder, and RAS binder). The anti-strip additive was added to the virgin binder at 0.25% by total weight of binder. Each of the rejuvenators had a different dosage rate based on laboratory testing with virgin and recovered recycled binders and also by the recommended dosage rate of the manufacturers.

The rejuvenator was added to the RAP and maintained at room temperature for 30 minutes, followed by stirring for 60 seconds. Afterward, the RAP and rejuvenator blends were placed into an oven at 110 °C for 30 minutes prior to mixing with the virgin aggregate and or virgin aggregate and RAS material. With mixtures that contained 15% RAP and 5% RAS, the RAS was blended with the heated virgin aggregate 5 minutes prior to mixing, and then placed into the oven at 160 ℃ to help soften the RAS binder.

Preparation of Specimens for Performance Testing

For mixing and compaction of all laboratory specimens, the binders were heated in an oven at 150 ℃ and the virgin aggregates were heated in an oven at 160 ℃ before mixing. For verification specimens, the asphalt mixtures were cured in an oven for 2 hours at 150 ℃ before compaction. For IDEAL-CT and Hamburg test specimens, the asphalt mixtures were cured in an oven for 4 hours at 135 ℃, then heated to 150 ℃ for 1 hour before compaction.

All specimens were cylindrical and compacted using a Superpave gyratory compactor (SGC). The performance test specimens were prepared in the disk-shaped geometry, 150 mm in diameter and 60±2 mm thick. The specimens were prepared with the constituents presented in Table 11. For Hamburg wheel tracking specimens, the target air void was 7.0±0.5%. For IDEAL-CT index test, the target air void was 5.5±0.5%.

Description of Performance Tests

After completion of mix design verification, specimens were prepared using the Superpave gyratory compactor to conduct performance tests. These tests included the Hamburg wheel tracking (HWT) test and indirect tensile asphalt cracking test (IDEAL-CT), which yields the cracking tolerance index (CT_{index}).

HWT

AASHTO T 324 was followed for testing the specimens' resistance to moisture damage and rutting under wheel tracking. Testing was conducted on specimens when submerged in water at 50 °C and subjected to 20,000 wheel passes. Replicate specimens were prepared using the gyratory compactor. The specimens were trimmed at the sides and were paired to deliver the required track. Two tracks were generated out of four compacted specimens.

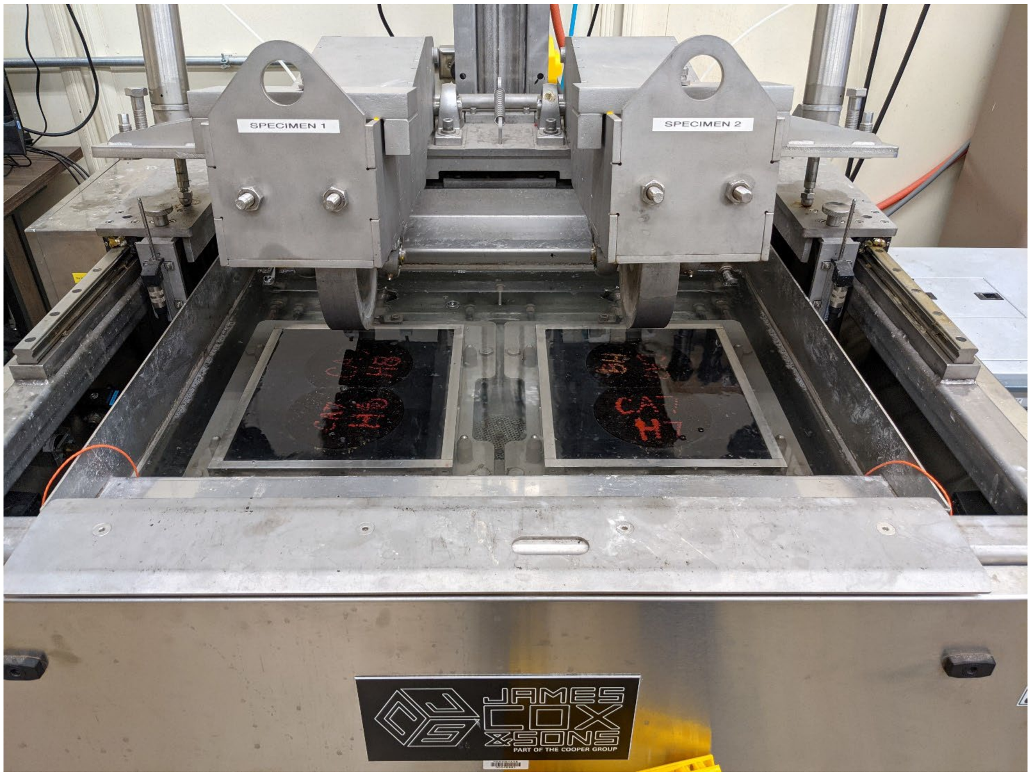


Figure 5. Setup for Hamburg wheel tracking.

The graph of a typical deformation-time curve delivers three segments: initial (primary) creep, secondary creep, and tertiary creep (Figure 6). The initial creep defines the early stage of deformation, which typically occurs within a limited number of cycles. The secondary creep is a more stable part of deformation, which defines the progress of rutting with increasing number of passes linearly and typically carries a significantly larger number of cycles compared with the initial creep. Finally, the tertiary creep begins when the mix has become unstable as moisture damage takes effect and shows a significant rate of deformation as time progresses. In this report, the point of intersection of the slopes from secondary and tertiary creeps is defined as the inflection point for tertiary creep, or the stripping inflection point (SIP). There are several distinguishing parameters that can be derived from the HWT test and used in this research: maximum rut depth (i.e., rut depth at the highest number of wheel passes), SIP, ratio of stripping slope (or tertiary creep slope) to secondary creep slope, number of wheel passes to reach 12.5 mm of rut depth, rut depth after completion of 10,000 wheel passes, and finally the stripping slope in terms of rut depth for 1,000 wheel passes. All of these parameters have been extracted from the test results and are presented in this report.

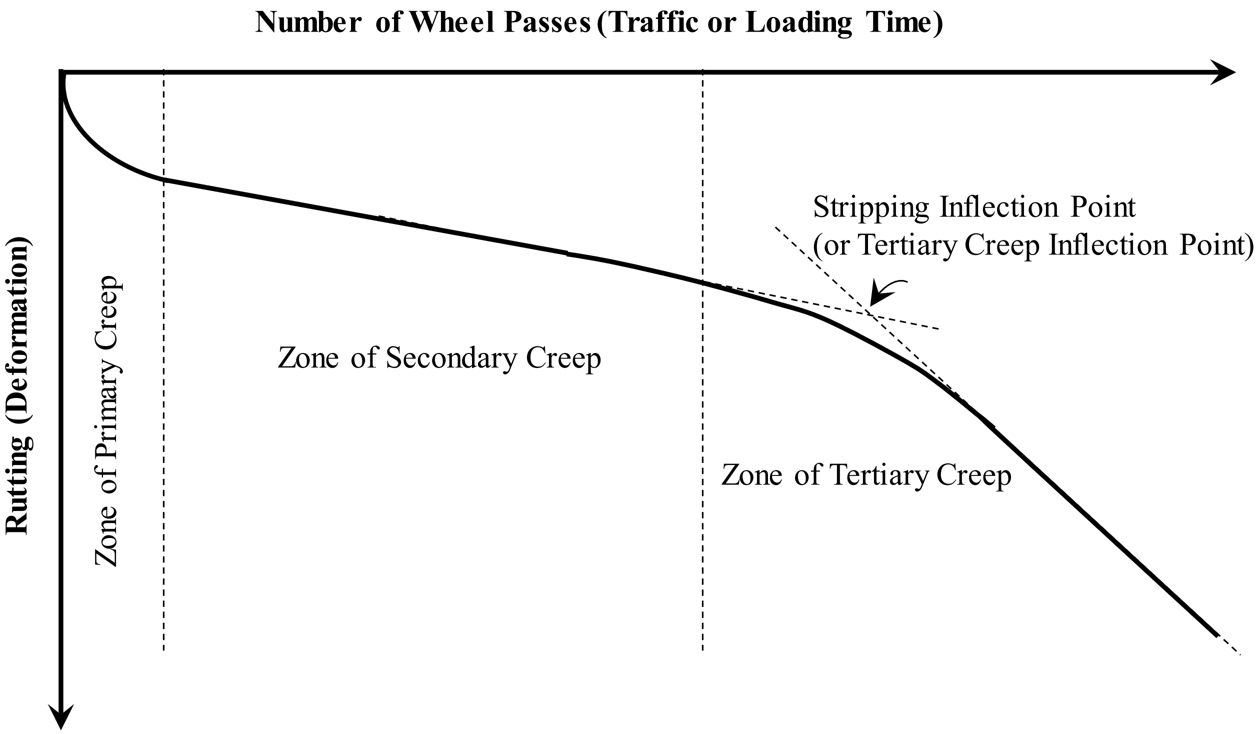


Figure 6. Different creep zones for a typical load-deformation test.

IDEAL-CT

This cracking test was conducted according to ASTM D8225-19, using a displacement rate of 50 mm/min and a 25 °C test temperature. The test setup and the corresponding response are presented in Figures 7 and 8, respectively. Based on the load-displacement curve, several engineering parameters are derived, including the pre-peak and post-peak modulus, fracture energy, and peak load. The work of fracture divided by the slope of the post-peak curve at 75% of the peak load and multiplied by the extension at 75% of peak load gives the cracking index (Equations 1 and 2).

$$CT_{Index} = \frac{G_f}{\frac{P}{l}} \times \left(\frac{l_{75}}{D}\right) \tag{1}$$

$$\frac{P}{l} = |m_{75}| = \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \tag{2}$$

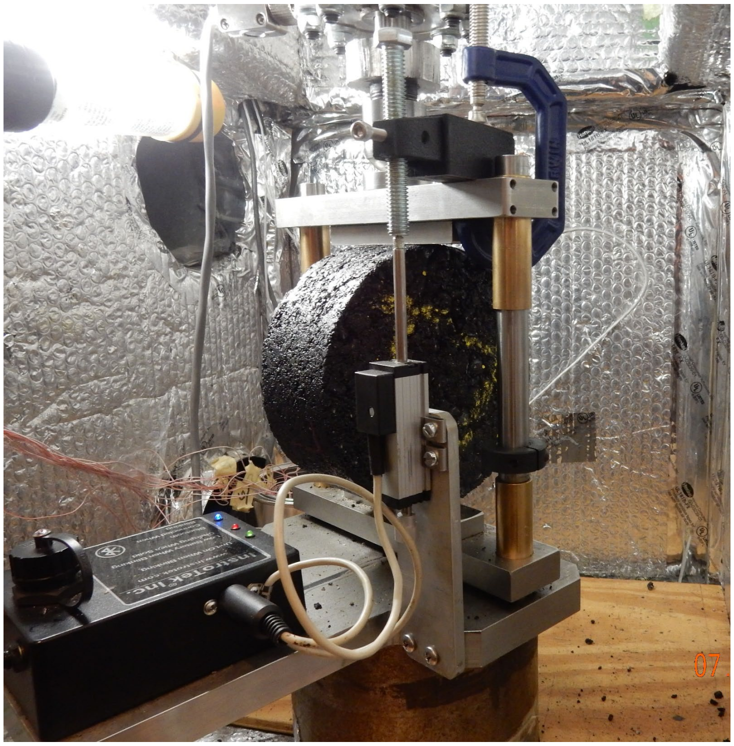


Figure 7. A picture of the IDEAL-CT test setup.

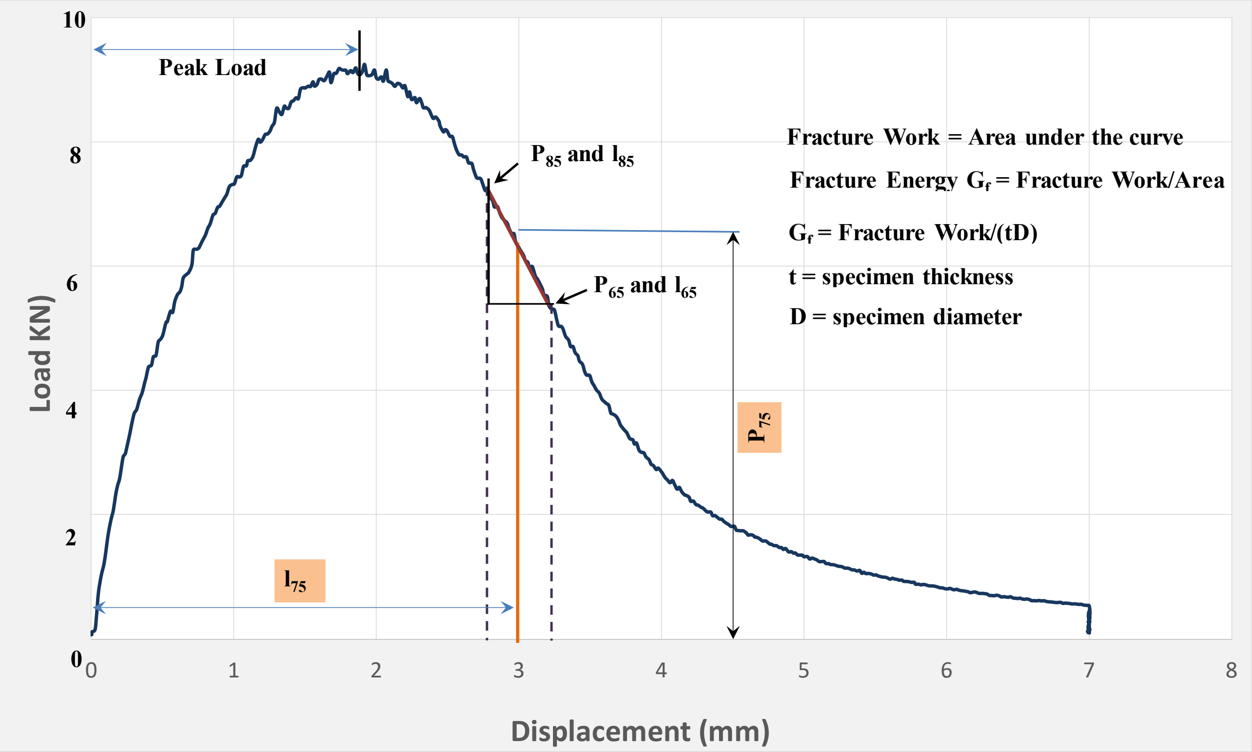


Figure 8. Load-displacement curve from a typical IDEAL-CT test.

Binder Extraction and Recovery and Corresponding Rheological Tests

It was discussed previously that the research included direct incorporation of the rejuvenating agents into the RAP binders for determination of the impact of these agents on performance grading and characteristics of the binder. However, for the purpose of this study, it was equally important, or perhaps more important, to determine the characteristics of the modified binder after it has been incorporated into the asphalt mixtures. Such characterization is important to determine if adding the rejuvenator directly to the RAP binder produces results similar to the case of adding the rejuvenator to the RAP itself in the asphalt mixture. Therefore, for a selected number of mixtures, extraction and recovery of the binder was conducted. The solvent extraction was conducted for quantitative determination of the binder content and providing the solution of dissolved binder for recovery. A rotavapor was used for binder recovery (Figure 9). Binder recovery was conducted according to ASTM 5404, Standard Practice for Recovery of Asphalt Binder from Solution Using the Rotary Evaporator. The recovered binder was subjected to various aging levels, as required by specifications, and subsequently tested for performance grade and characteristics.

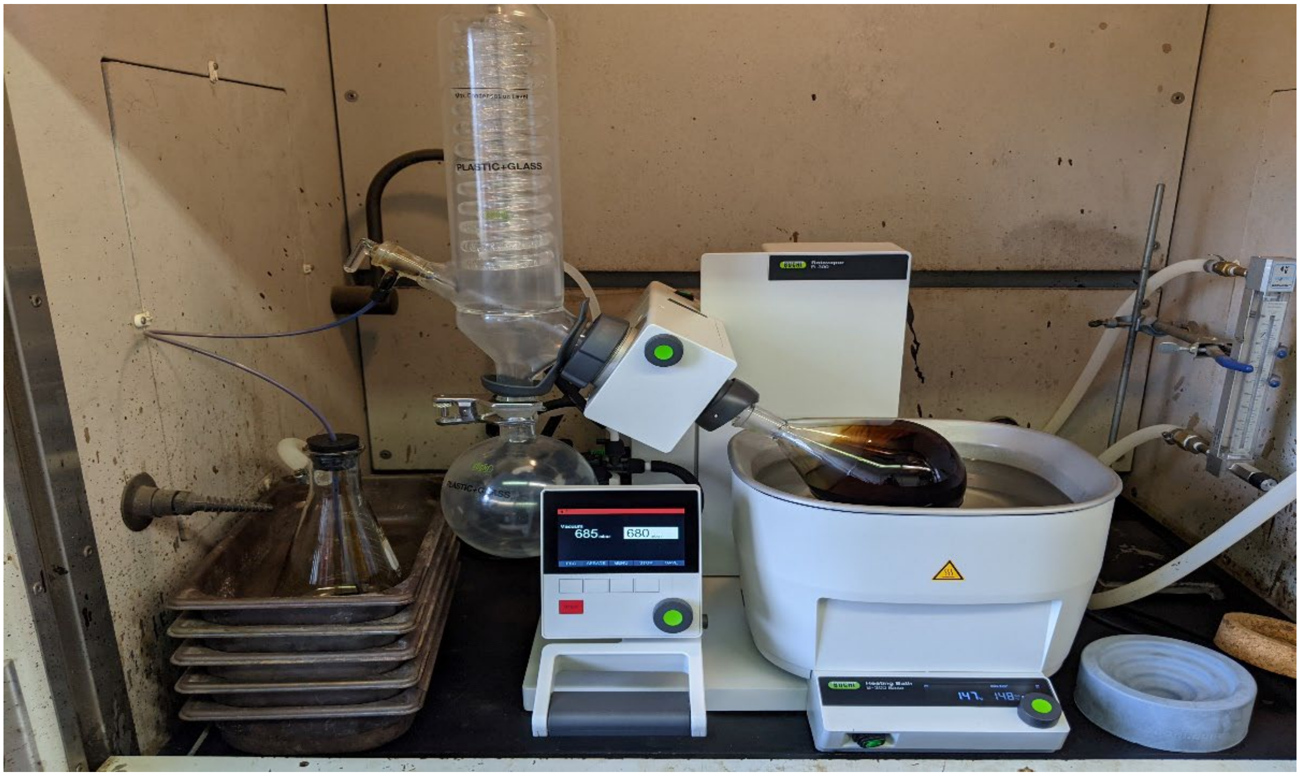


Figure 9. Setup for Rotavapor.

CHAPTER 4

Analysis of Binder Characteristics

Studying Rejuvenator Durability Using Virgin Binder

Effect on High and Intermediate Temperature Grades

An important consideration in selection of a rejuvenator is its long-term effectiveness after the asphalt mix has been exposed to aging and years of service. In the laboratory environment, the pressure aging vessel is utilized for long-term conditioning of the binder to simulate its field behavior. The five rejuvenators selected for this research were added to a PG 64-22 virgin binder at a ratio of 0.03 to 1 (i.e., 3%). The exception was Ingevity CA-7; based on the manufacturer's recommendation, their liquid antistrip (P25) was also included at a dosage rate of 0.4%, in addition to 3% rejuvenator. The results are shown in Table 12.

Table 12. Effect of binder aging on effectiveness of rejuvenators (high & intermediate temperature).

			Unaged		RTFO Aged		PAV Aged		
PG of Virgin Binder	Rej. Source	% Rej	True Grade °C	% Change from Virgin Binder	True Grade °C	% Change from Virgin Binder	True Grade °C	% Change from Virgin Binder	Change from PG 58-28 °C
58-28			61.1		61.1		18.9		
64-22			69.0		71.8		24.5		
64-22	IN	3	61.7	10.6	61.9	13.8	20.4	16.7	0.8
64-22	AN	3	63.8	7.5	64.4	10.3	20.6	15.9	3.3
64-22	HG	3	63.3	8.3	63.8	11.1	22.1	9.8	2.7
64-22	SR	3	63.3	8.3	63.8	11.1	20.3	17.1	2.7
64-22	HT	3	64.6	6.4	64.8	9.7	22.7	7.3	3.7

It can be clearly seen that, as compared with the virgin binder, after short-term conditioning (RTFO-aged) and long-term conditioning (PAV-aged), the reduction in binder stiffness holds. In other words, the long-term aging process has not deteriorated the effectiveness of any of the tested rejuvenators. However, it appears that some of the rejuvenators indicate more effectiveness in reducing the binder stiffness compared to some others. It should also be noted that the results for PG 58-28 binder are reported in Table 12 for reference. The results indicate that the 3% rejuvenator content, regardless of the rejuvenator chosen, when added to the PG 64-22 used in this research, did not soften the binder to a level matching that of the PG 58-28. However, it can be seen from Table 12 that the obtained grade is about 2.7–3.7 °C higher than that of the PG 58-28 for the high-temperature grade. The exception is the Ingevity CA-7, for which the difference is only 0.8 °C. As a reminder, this rejuvenator was accompanied by 0.4% antistripping agent P25, which might have also contributed to a further softening effect.

Effect on Low-Temperature Grade

A similar exercise can be conducted to evaluate the effect of rejuvenators on the low-temperature grade of the binder. For comparison, all binders were tested in the bending beam rheometer at -12 °C according to AASHTO T 313. Table 13 presents the results from this exercise. Two parameters were obtained from this test: the binder stiffness (reported after 60 seconds of loading) and the relaxation parameter *m* (an indicator of the binder ability to shed stresses with time).

Table 13. The effect of rejuvenator on the stiffness of virgin binder at low temperature.

			PAV Aged, BBR at -12 °C				
PG of Virgin Binder	**Rej. Source**	**Rej. Content**	**Stiffness MPa**	**% Change from Virgin Binder**	**% Change from PG 58-28**	**m-value**	**% Change from Virgin Binder**
58-28			125			0.379	
64-22			214			0.324	
64-22	IN	3	133	-37.9	6.4	0.363	12.0
64-22	AN	3	125	-41.6	0.0	0.36	11.1
64-22	HG	3	162	-24.3	29.6	0.358	10.5
64-22	SR	3	121	-43.5	-3.2	0.364	12.3
64-22	HT	3	191	-10.7	52.8	0.336	3.7

It can be seen from Table 13 that the rejuvenators result in reduction of stiffness in the range of almost 10–40% compared with the virgin binder (PG 64-22), with the smallest reduction belonging to the HT rejuvenator. The increase in relaxation index *m* varies in the range of almost 4–12%. Comparing the stiffness with that of PG 58-28, it can be seen that for three of the rejuvenators, the stiffness values are comparable and for two of the rejuvenators, the modified PG 64-22 binder is still significantly stiffer than the PG 58-22 binder.

The Effect of Rejuvenator on RAP Binder at High Temperature

The next step in the process of investigating the rejuvenator/binder blends was to establish rheological properties of different blends when the rejuvenator is added to the RAP binder at different dosage rates. Three of the rejuvenators were selected for this purpose and were blended with the recovered RAP binder, or combination of recovered RAP binder and virgin binder, at the dosage rates presented in Table 14. A summary of the results is presented in Table 14. The results for the two virgin binders are also presented in Table 14 for comparison. Several findings can be reported based on the data presented in Table 14. One is that the blend of PG 58-28 with the RAP binder provides a similar grade to that of a PG 64-22. The other is that for pure RAP binder, at least 10% rejuvenator is needed to bring the high-temperature grade of RAP close to that of PG 64-22. Obviously, targeting PG 58-28 will require an even higher dosage. It can be seen that the 65/35 blend with 2% rejuvenator is still stiffer than the PG 58-28 used in this study.

Table 14. Results from rheological tests with DSR at different aging levels.

				True Grade, °C		
Rej. Source	**%Virgin Binder**	**%RAP Binder**	**% Rej.**	**Unaged**	**RTFO**	**PAV**
	100 PG 58-28	0	0	61.1	61.1	18.9
	100 PG 64-22	0	0	69.0	71.8	24.5
	0	100	0.0	89.7	89.1	
	65	35	0.0	70.2		
IN	0	100	5/0.40	78.0	77.6	25.0
AN	0	100	5.0	81.8	80.1	
HT	0	100	5.0	83.4	83.1	28.9
IN	0	100	10/0.40	68.5	68.2	
AN	0	100	10.0	73.9	72.2	
HT	0	100	10.0	77.9	77.3	
IN	65	35	0.4/2.0	64.8	65.3	
HT	65	35	2.0	67.1	68.2	

The results for the unaged binders are presented in graphical form in Figure 10. One can see the difference between the rejuvenators in terms of the dosage rate needed to deliver the same final grade of the binder.

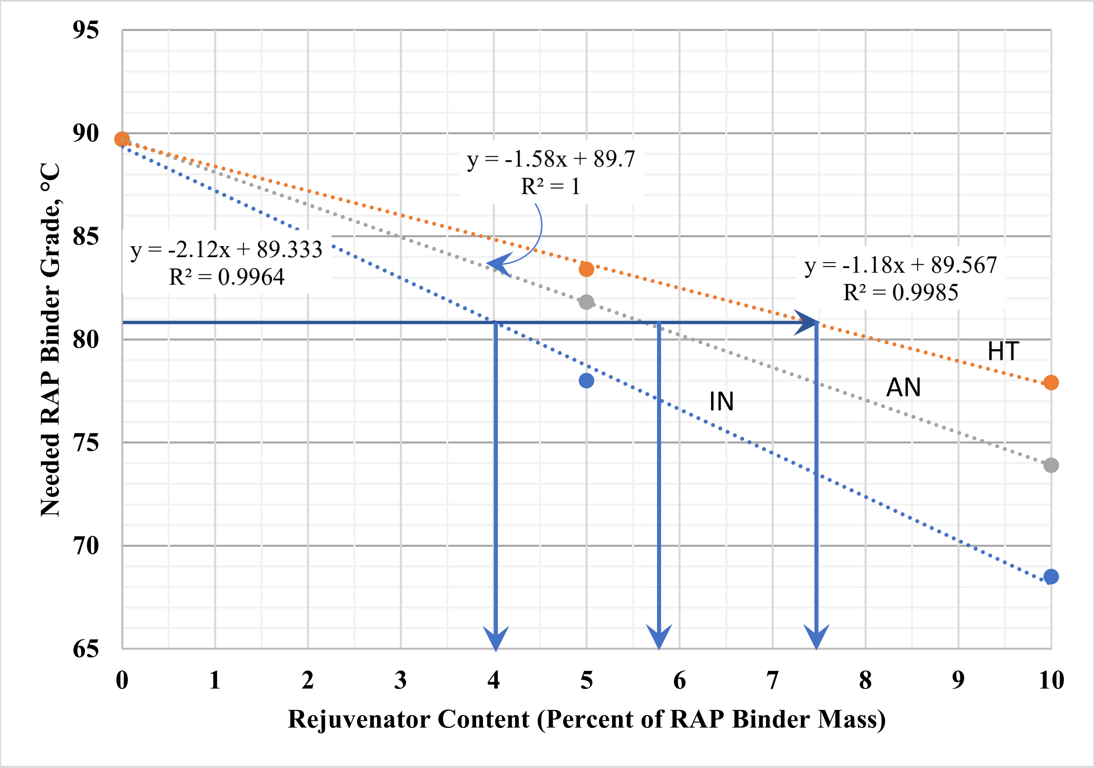


Figure 10. Determination of rejuvenator content for given conditions (high temperature).

Dosage Rate Determination based on High-Temperature Grade

To determine the required dosage level of rejuvenator, one needs to know the high-temperature grade of the virgin binder, the high-temperature grade of the target binder, and the percent and grade of the RAP binder in the blend. Using the known values, one can use Equation 3 to determine the performance grade of the RAP binder that will be needed to deliver the desired final grade.

$$T_{RAP\ (needed)} = \frac{T_{T} - T_{V} \times P_{V}}{P_{RAP}} \tag{3}$$

Where $T_{RAP\ (\text{needed})}$ = Needed Grade for the RAP (after rejuvenation) - unknown

P_{RAP} = Proportion of RAP binder in the blend
P_V = Proportion of virgin binder in the blend
T_V = Performance grade of virgin binder
T_T = Target (desired) grade of blend

Once the required RAP binder grade is determined from Equation 3, it will be used in Figure 10 to establish the dosage rate of the rejuvenator. To understand this process clearly, an example is provided. It is assumed that the following data are available.

P_{RAP} = Proportion of RAP binder in the blend = 0.45 (RBR)
P_V = Proportion of virgin binder in the blend = 0.55
T_V = True performance grade of virgin binder = 61.1 °C
T_T = Target (desired) grade of blend = 70 °C
$TRAP$ = 89.7 °C (current grade of RAP binder) – shown in Figure 10.

Using these values in Equation 3 yields the needed performance grade of the RAP binder as 80.9 °C. Using this value in Figure 10 gives the rejuvenator dosage rate. It can be seen from this graph that values of 4.0%, 5.8%, and 7.5% are found depending on the rejuvenator type. This exercise was conducted using unaged binders. A similar approach can be taken for short-term or long-term aged binders.

The Effect of Rejuvenator on RAP Binder at Low Temperature

Low-Temperature Binder Grade

The low-temperature rheological properties from testing with the bending beam rheometer are presented in Table 15. Some of the binders were too soft to mold or to test in BBR. Those included the unaged binders made with RBR of 0.35 and 2% rejuvenator as well as the unaged binder made with 10% Ingevity CA-7 and 0.4% P25 antistripping agent. Also, the BBR testing on PAV-aged specimens was limited to only the neat binders and the RAP binders modified with 5% Hydrolene and 5% CA-7 with 0.4% P25 antistripping agent.

Table 15. BBR test results for rejuvenated binders at different aging levels.

Rej	% Virgin Binder	%RAP Binder	%Rej	Aging	Test Temp, °C	S, MPa (2 Tests)		m-value (2 Tests)		Avg. S, MPa	Avg. m Value
None	0	100	0	Unaged	-6	119	121	0.352	0.348	120	0.350
					-18	478	483	0.248	0.249	481	0.249
				RTFO	-6	170	173	0.315	0.316	172	0.316
					-12	322	317	0.268	0.264	320	0.266
HT	0	100	5	Unaged	-12	145	146	0.351	0.348	146	0.350
					-18	312	286	0.297	0.296	299	0.297
				RTFO	-12	234	231	0.308	0.304	233	0.306
					-18	442	447	0.250	0.252	445	0.251
				PAV	-6	136	131	0.321	0.321	134	0.321
					-12	246	252	0.273	0.268	249	0.271
					-18	475	495	0.230	0.232	485	0.231
HT	0	100	10	Unaged	-12	88	92	0.395	0.388	90	0.392
					-18	226	210	0.332	0.327	218	0.330
				RTFO	-12	150	153	0.342	0.339	152	0.341
					-18	348	349	0.289	0.287	349	0.288
IN	0	100	5	Unaged	-12	84	81	0.418	0.417	83	0.418
					-18	208	212	0.335	0.335	210	0.335
				RTFO	-12	140	147	0.365	0.36	144	0.363
					-18	308	311	0.291	0.287	310	0.289
				PAV	-12	178	169	0.321	0.312	174	0.317
					-18	368	389	0.259	0.259	379	0.259
IN	0	100	10	RTFO	-12	48	50	0.463	0.46	49	0.4615
					-18	139	140	0.382	0.385	140	0.3835
AN	0	100	5	Unaged	-12	88	93	0.381	0.384	91	0.383
					-18	202	197	0.329	0.324	200	0.327
				RTFO	-12	121	123	0.355	0.350	122	0.353
					-18	272	266	0.297	0.294	269	0.296
AN	0	100	10	Unaged	-12	32	33	0.451	0.448	33	0.450
					-18	91	91	0.382	0.379	91	0.381
				RTFO	-12	38	41	0.438	0.431	40	0.435
					-18	102	101	0.374	0.373	102	0.374
IN	65	35	2	RTFO	-12	77	*	0.445	*	77	0.445
					-18	199	208	0.364	0.361	204	0.363
HT	65	35	2	RTFO	-12	100	98	0.412	0.409	99	0.411
					-18	269	*	0.339	*	269	0.339
None	100	0	0	PAV	-12	116	115	0.380	0.377	116	0.379
					-18	232	236	0.318	0.322	234	0.320
None	100	0	0	PAV	-12	216	212	0.327	0.321	214	0.324
					-18	475	470	0.244	0.255	473	0.250

* The specimen broke during the test.

Low-Temperature Binder Grade and ΔT_c

Delta T_c (ΔT_c) is a binder parameter related to durability and cracking potential of asphalt mixture. It is defined as the difference between two critical cracking temperatures, one associated with threshold criterion on the binder stiffness (S=300 MPa) and the other with creep rate (relaxation parameter) *m* (*m*=0.3). These temperatures define the low-temperature grade of the binder as required by governing specifications (for example, AASHTO M 320). To establish critical temperatures for limiting values of stiffness and creep rate, the bending beam rheometer test (AASHTO T 313) must be conducted at at least two temperatures. Ideally, these two temperatures bracket the threshold value of 300 MPa for S and 0.3 for *m* so that the critical temperatures are calculated through interpolation. However, in a few cases in this research, the two temperatures ended up on one side and extrapolation was used to establish the critical temperatures. The extended level of testing required precluded the research team from continuing BBR testing at bracketing temperatures for all of the tested blends. Once the critical temperatures are established, ΔT_c is calculated using Equation 4.

$$\Delta T_c = T_{c,S} - T_{c,m} \tag{4}$$

Where

$T_{c,S}$ = critical cracking temperature to satisfy stiffness threshold value of 300 MPa
$T_{c,m}$= critical cracking temperature to satisfy stiffness creep rate value of 0.3

The low-temperature performance grade of the binder is decided by the larger number between $T_{c,S}$ and $T_{c,m}$. For example, if $T_{c,S}$ = -26.2 °C and $T_{c,m}$ = -23.7 °C, then the binder grade is established as -23.7 °C. Positive values of ΔT_c indicate that the binder cracking potential is governed by creep stiffness, while negative values indicate that the binder cracking potential is governed by the creep rate. In general, as ΔT_c becomes more negative, the binder is perceived to be more prone to cracking. Most of the states that have adopted ΔT_c as a specification parameter have set the threshold value at -5 °C (i.e., ΔT_c must not drop below -5 °C).

The significance of the data presented in Table 15 is in calculation of critical cracking temperatures that are provided in Table 16. A highly important note is to be made regarding the association between the reported critical temperatures in Table 16 and the aging level. For the purpose of binder grading, the critical temperatures are determined after long-term aging of the material through the PAV. However, it is common practice to use short-term aged (RTFO-aged) binder in BBR to determine the RAP binder grade. As a result, it is the authors' opinion that there is a mismatch, in common practice, in determining the grade of the binder when the virgin binder is blended with the RAP binder, as the low-temperature grade of the former is determined based on PAV-aged binder and the latter based on RTFO-aged binder. In the authors' opinion, all binders need to be long-term aged for determination of the grade according to the specifications. Nonetheless, as this study is focused on the highly stiff RAP binder grade and the effect of rejuvenators, BBR testing was conducted on unaged and RTFO-aged binders wherever possible and whenever the binder was not too soft to test. Therefore, extreme care should be taken in interpretation of data, and attention must be given to the aging level of the binder.

Table 16. Low-temperature true grade (critical temperature) for different binders.

Rej	%Virgin Binder	%RAP Binder	%Rej	Aging	$T_{c,\,s}$	$T_{c,\,m}$	ΔT_c
None	0	100	0	Unaged	-23.9	-21.9	-2.0
				RTFO	-21.4	-17.9	-3.5
HT	0	100	5	Unaged	-28.0	-27.6	-0.4
				RTFO	-24.4	-22.7	-1.7
				PAV	-23.7	-17.5	-6.2
HT	0	100	10	Unaged	-30.2	-30.9	0.7
				RTFO	-26.9	-26.6	-0.3
IN	0	100	5	Unaged	-30.3	-30.5	0.3
				RTFO	-27.8	-27.1	-0.7
				PAV	-26.2	-23.7	-2.5
IN	0	100	10	RTFO	-32.4	-34.4	2.0
AN	0	100	5	Unaged	-31.1	-30.8	-0.3
				RTFO	-28.8	-27.5	-1.3
AN	0	100	10	Unaged	-35.0	-35.0	0.0
				RTFO	-34.9	-35.2	0.3
IN	65	35	2	RTFO	-30.4	-32.5	2.1
HT	65	35	2	RTFO	-28.7	-31.3	2.6
None	100 PG 58-28	0	0	PAV	-30.1	-30.3	0.2
None	100 PG 64-22	0	0	PAV	-24.6	-23.8	-0.8

The results in Table 16 indicate that, as expected, the rejuvenator reduces the critical cracking temperature, and as the binder ages, the corresponding ΔT_c becomes more negative. One can see that, based on the results from the RTFO-aged binder, 5% rejuvenator reduces the critical cracking temperature of the RAP binder by 5–10 °C depending on the rejuvenator. In the case of using 10% rejuvenator, the impact is more significant, resulting in an 8–18 °C drop in temperature. Based on the PAV-aged binder test results, it can be seen that using a dosage rate of 5% with the RAP binder brings it close to the low-temperature grade of the PG 64-22 binder. If the intention is to rejuvenate the RAP binder to the extent that it matches a PG 58-28, a higher dosage rate than 5% is needed, as shown by the data. It seems that depending on the rejuvenator, this dosage rate will vary in the range of about 8–12% by the mass of the RAP binder to result in a low-temperature grade similar to that of a PG 58-28. An interesting observation from the data of Table 16 is that the 65/35 blend (i.e., 65% PG 58-28 and 35% RAP binder) with 2% dosage rate comes close to the low-temperature grade of the PG 58-28 used in this study.

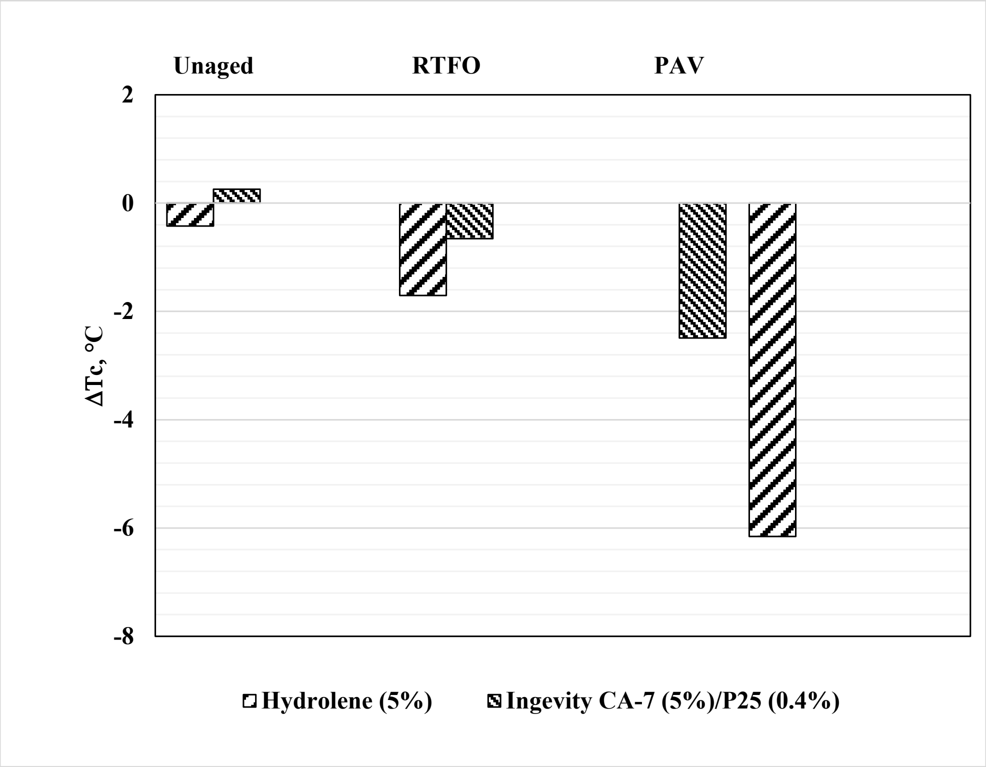


Figure 11. Aging effect on ΔT_c for rejuvenated RAP binder.

An example of this behavior is shown in Figure 11. Again, caution should be exercised in interpreting these data, as the actual ΔT_c is measured on long-term aged binder only. One can also see that the rejuvenators do not have the same effect on ΔT_c, as for PAV aged, rejuvenated RAP binder at 5% dosage rate, one of the rejuvenators delivers ΔT_c of roughly -6.2 °C, while the other yields a value of -2.5 °C. Finally, the data indicate that as the rejuvenator content goes higher, ΔT_c is reduced, helping with better crack resistance.

Dosage Rate Determination based on Low-Temperature Grade

The preceding approach discussed for high-temperature dosage rate can also be utilized to investigate the amount of rejuvenator needed to satisfy the low-temperature performance grade. For example, the following conditions are considered.

P_{RAP} = Proportion of RAP binder in the blend = 0.45 (RBR)
P_V = Proportion of virgin binder in the blend = 0.55
T_V = True performance grade of virgin binder = -30.3 °C
T_T = Target (desired) grade of blend = -28°C
TRAP = -18.0 °C (current grade of RAP binder) – shown in Figure 12.

Figure 12 is plotted using the RTFO-aged temperature grades for two types of binders: the RAP binder with no treatment, and the RAP binder with 5% rejuvenator. It is reasonably assumed that the low-temperature grade decreases linearly as the amount of rejuvenator in the binder increases. Similar to the procedure followed for high temperature, with the given data one can establish that the RAP binder must have a low-temperature grade of at least -25.2 °C (RTFO aged) to deliver a target grade of -28 °C (RTFO aged) for the blended binder. Using this value in the graph yields values in the range of 3.1–5.7% depending on the rejuvenator type. It must be noted that this example was presented based on the results from RTFO-aged binder, and the attempt was to satisfy the grade for this level of aging. If the binder grade after PAV aging is desired, a similar procedure is followed using the results from the PAV-aged binder.

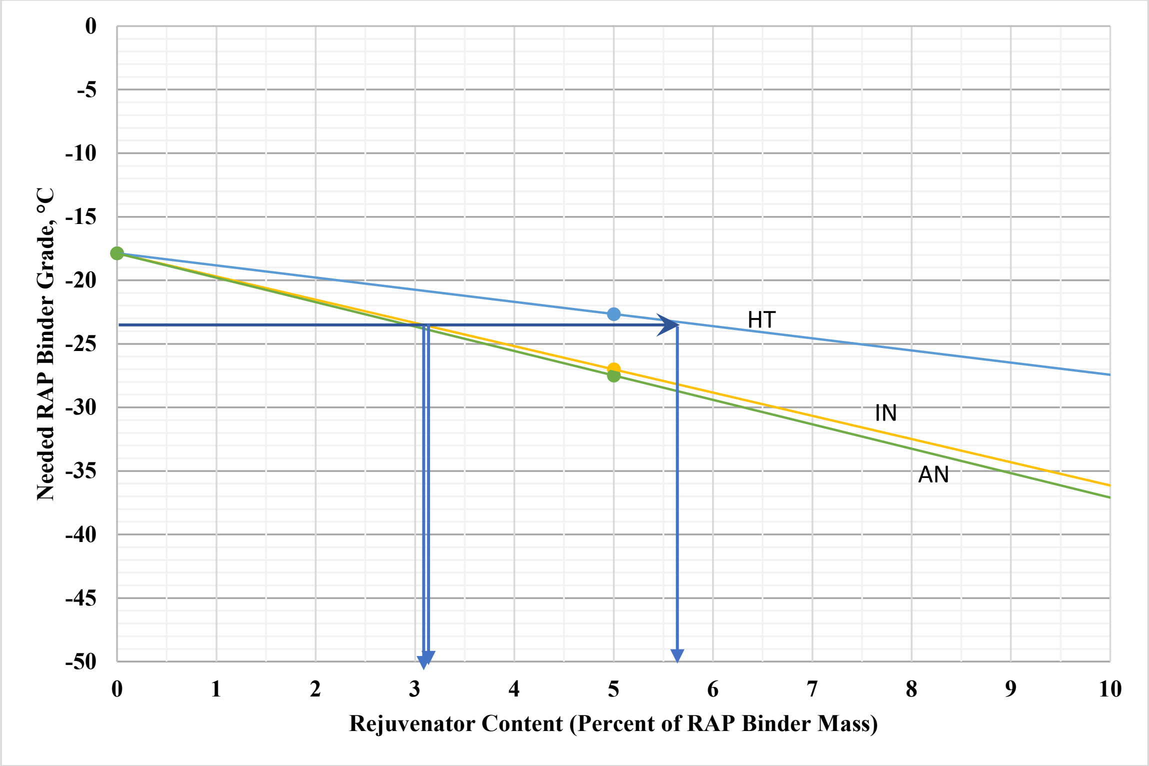


Figure 12. Determination of rejuvenator content for given conditions (low temperature).

Binder Performance Grade based on AASHTO M 332 Criteria

Multiple Stress Creep Recovery (MSCR) tests were also conducted on different blends according to the AASHTO T 350 test method. All testing was conducted at 64 °C, and the performance grading reported in this report is based on this temperature. Typical results from testing at two different load levels (0.1 KPa and 3.2 KPa) are presented in Tables 17 and 18. Definitions of the terms shown in Tables 17 and 18 are as follows.

γ_0	Initial strain value, reported in %, at the beginning of creep portion
γ_c	Strain, reported in %, at the end of the creep portion (i.e., after 1 s)
γ_1	Adjusted (net) strain, reported in %, at the end of creep portion of loading (i.e., after 1 s) = $\gamma_c - \gamma_0$
γ_r	Strain, reported in %, at the end of the recovery portion (i.e., after 10 s)
$\gamma_{10} = \gamma_{nr}$	Adjusted (net) strain, reported in %, at the end of the recovery creep (i.e., after 10 s) = $\gamma_r - \gamma_0$
γ_{nr}	Non-recoverable shear strain, reported in %
J_{nr}	Non-recoverable creep compliance, 1/KPa

Table 17. MSCR strain levels and unrecoverable creep compliance for the RAP binder at 0.1 KPa.

	Load	0.1	KPa				
Load Cycle	**g_0, %**	**g_c, %**	**g_1, %**	**g_r, %**	**g_{nr}, %**	**%Rec**	**J_{nr}, 1/KPa**
1	7.90	9.17	1.26	8.67	0.77	39.14	0.0768
2	8.67	9.94	1.27	9.44	0.77	39.41	0.0768
3	9.44	10.71	1.27	10.21	0.77	39.11	0.0770
4	10.21	11.47	1.26	10.98	0.77	39.33	0.0766
5	10.98	12.24	1.27	11.74	0.77	39.45	0.0767
6	11.74	13.01	1.26	12.51	0.77	39.34	0.0766
7	12.51	13.77	1.26	13.27	0.76	39.74	0.0762
8	13.27	14.54	1.27	14.04	0.77	39.50	0.0768
9	14.04	15.30	1.26	14.80	0.76	39.58	0.0761
10	14.80	16.07	1.27	15.56	0.76	39.87	0.0761
					Average	**39.45**	**0.0766**

Table 18. MSCR strain levels and unrecoverable creep compliance for the RAP binder at 3.2 KPa.

	Load	3.2	KPa				
Load Cycle	**g_0, %**	**g_c, %**	**g_1, %**	**g_r, %**	**g_{nr}, %**	**%Rec**	**J_{nr}, 1/KPa**
1	15.56	56.30	40.74	43.02	27.46	32.60	0.0858
2	43.02	83.55	40.53	69.59	26.58	34.44	0.0830
3	69.59	110.04	40.45	95.88	26.28	35.02	0.0821
4	95.88	136.26	40.39	122.02	26.14	35.27	0.0817
5	122.02	162.36	40.34	148.11	26.09	35.31	0.0815
6	148.11	188.43	40.31	174.18	26.07	35.34	0.0815
7	174.18	214.44	40.26	200.23	26.05	35.29	0.0814
8	200.23	240.44	40.21	226.27	26.04	35.24	0.0814
9	226.27	266.44	40.17	252.28	26.01	35.24	0.0813
10	252.28	292.44	40.16	278.31	26.03	35.19	0.0813
					Average	**34.89**	**0.0821**

As an example, Figures 13 through 16 show the strain response of the RAP binder before and after blending with the Anova rejuvenator.

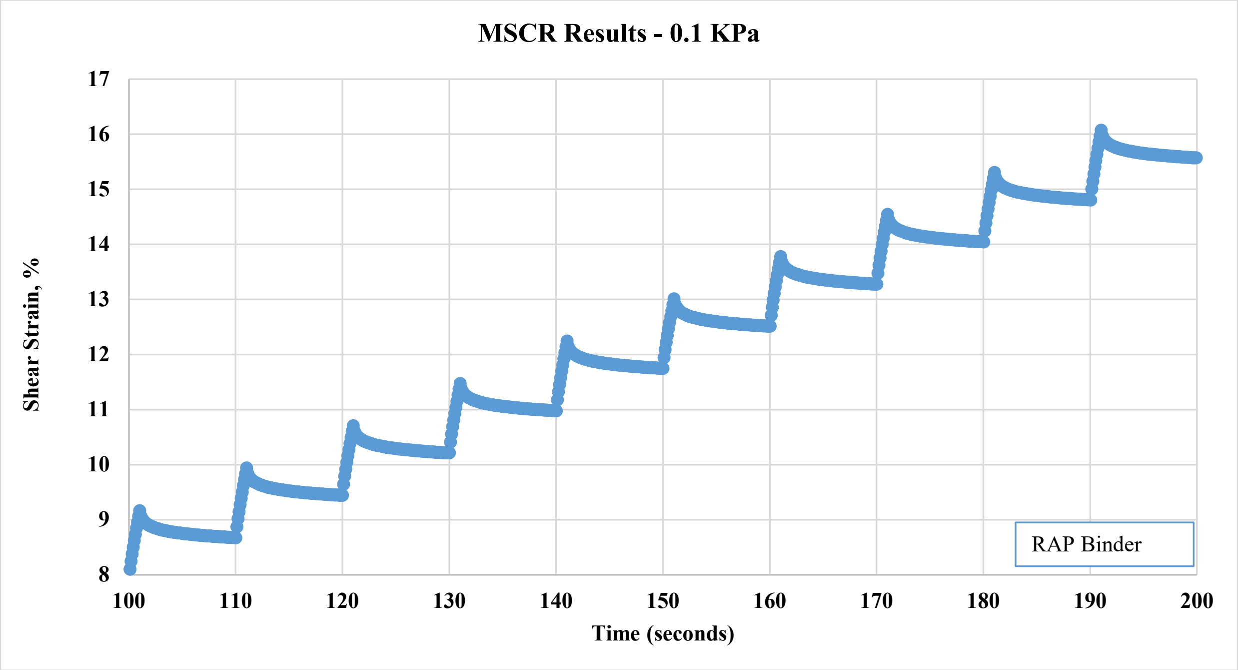


Figure 13. MSCR strain development in the RAP binder as a function of time under 0.1 KPa load.

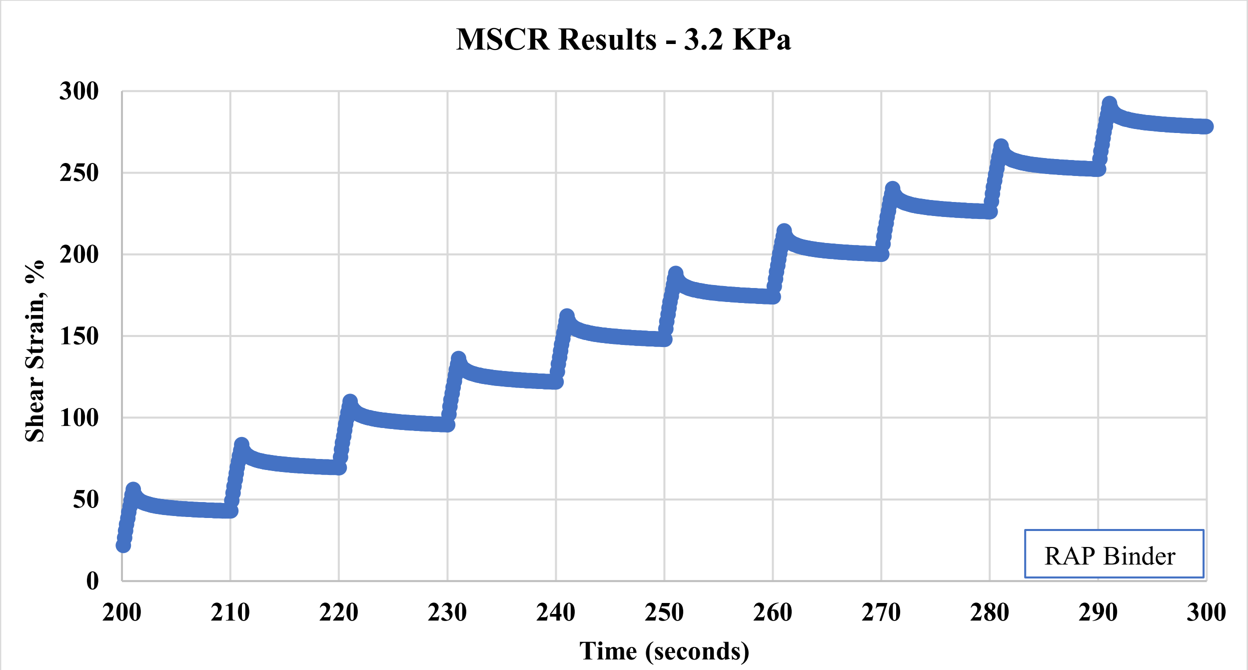


Figure 14. MSCR strain development in the RAP binder as a function of time under 3.2 KPa load.

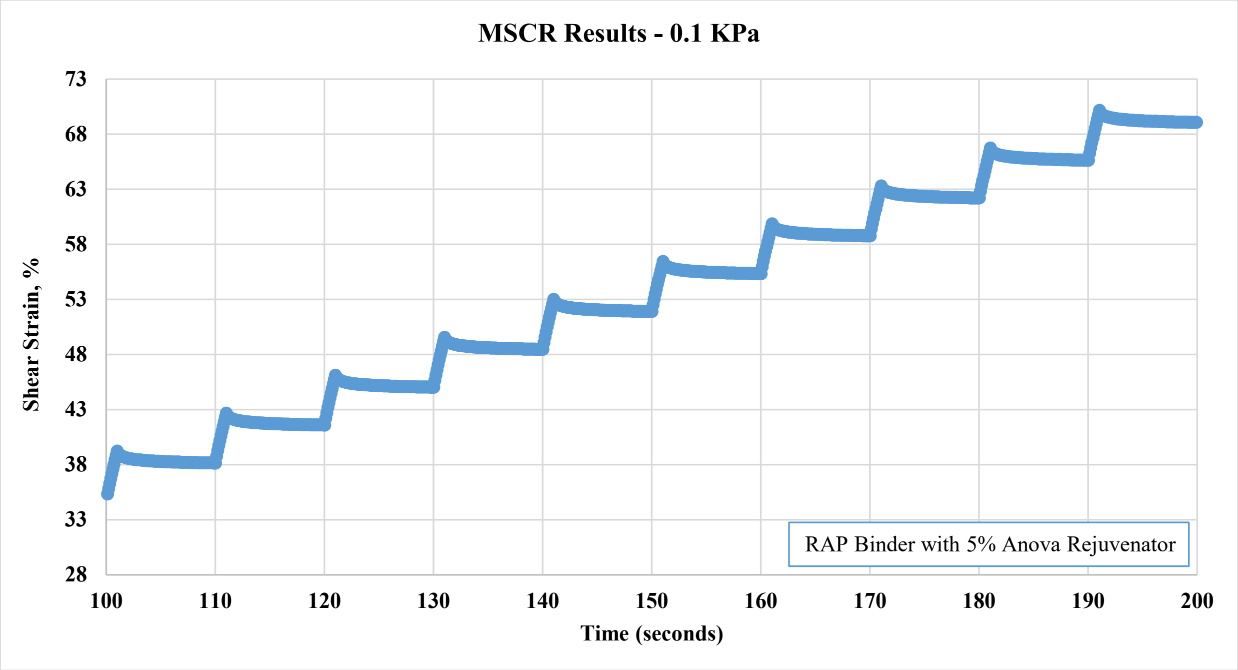


Figure 15. MSCR strain development in the modified binder as a function of time under 0.1 KPa load.

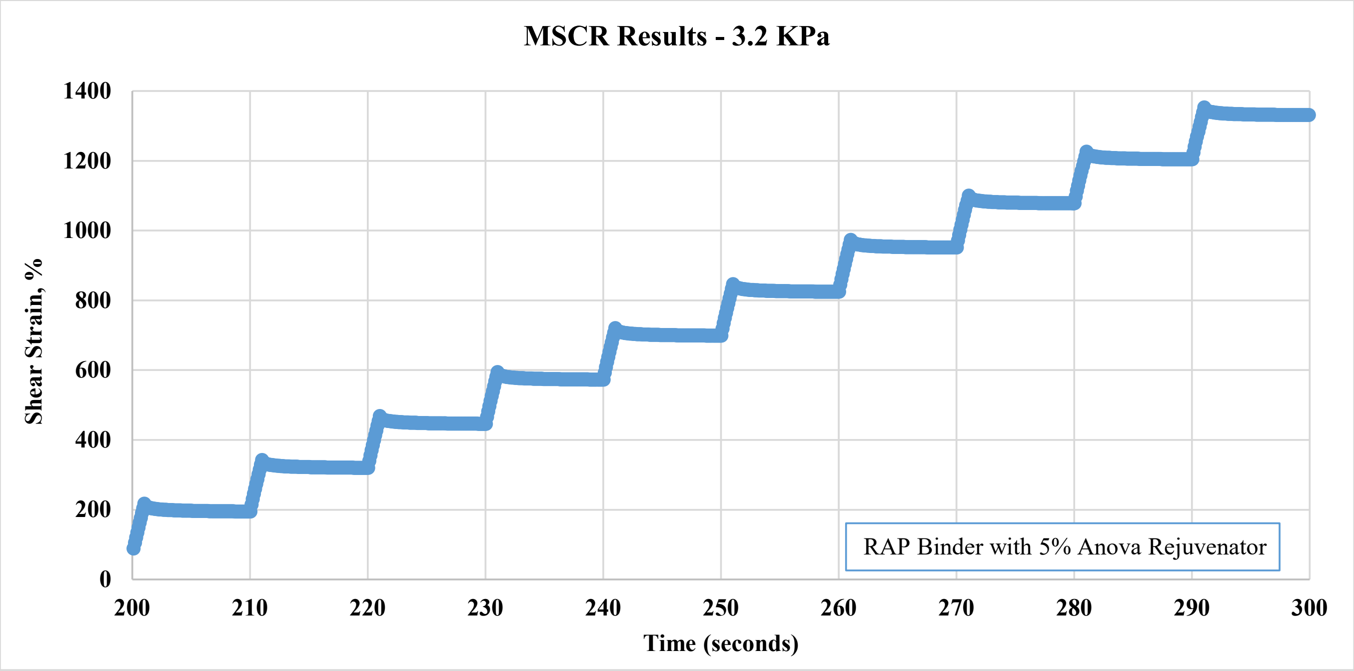


Figure 16. MSCR strain development in the modified binder as a function of time under 3.2 KPa load.

Based on the MSCR test results, high-temperature performance of the binder is given in Table 19. Designations S, H, V, and E, shown in the performance grade of the binder (for example, 64S-22), refer to standard, heavy, very heavy, and extreme traffic levels, respectively. It must be noted that the designations S, H, V, and E reported in Table 19 are valid for testing at 64 °C. Once temperatures change, these designations will change as well. For example, a binder graded as 64V-22 may grade at 70H-22 or 76S-22 if tested at 70 °C or 76 °C, respectively. It can be seen that application of 3% rejuvenator softens the PG 64H-22 binder to the point that in most cases the binder grades as PG 64S-22, and for two of the cases the grade remains as PG 64H-22. In the case of the RAP binder, which grades as 70E-22, the addition of 5% or 10% rejuvenator brings the grade down to PG 64S-22 through PG 64E-22, depending on the amount and type of rejuvenator.

Table 19. MSCR creep compliance and associated grading.

PG of Virgin Binder	Rej. Type	%	RBR	% Recovery			Creep Compliance, 1/KPa			PG
		Rej.		Load Level			Load Level			
				0.1 KPa	3.2 KPa	Change, %	0.1 KPa	3.2 KPa	Change. %	
58-28		0	0.00	0.00	0.00	0.00	6.51	7.18	10.29	58S-28
64-22		0	0.00	6.16	1.78	71.10	1.39	1.56	12.23	64H-22
64-22	AN	3	0.00	1.42	0.00	100.00	4.07	4.53	11.30	64S-22
64-22	IN	3/0.4	0.00	0.00	0.00	0.00	5.64	6.14	8.87	64S-22
64-22	HT	3	0.00	1.29	0.00	100.00	3.82	4.22	10.47	64H-22
64-22	HG	3	0.00	2.61	0.00	100.00	4.32	4.88	12.96	64S-22
64-22	SR	3	0.00	1.08	0.00	100.00	4.40	4.88	10.91	64S-22
58-28	IN	2/0.4	0.35	2.65	0.00	100.00	3.57	4.08	14.29	64H-22
58-28	HT	2	0.35	5.94	0.42	92.93	2.22	2.62	18.02	64H-22
		0	1.00	39.45	34.89	11.56	0.08	0.08	7.18	70E-22
	AN	5	1.00	24.31	14.84	38.96	0.34	0.39	14.71	64E-22
	IN	5/0.4	1.00	16.00	7.43	53.56	0.58	0.66	15.31	64V-22
	HT	5	1.00	28.66	21.55	24.81	0.21	0.24	12.15	64E-22
	AN	10	1.00	14.52	3.26	77.55	1.19	1.50	26.05	64H-22
	IN	10/0.4	1.00	6.95	0.44	93.67	2.25	2.76	22.67	64S-22
	HT	10	1.00	19.58	9.04	53.83	0.55	0.65	18.80	64V-22

Results from Testing the Binders Recovered from the Asphalt Mixtures

It was discussed in the previous chapter that part of the study required testing the modified binders from asphalt mixtures containing various types of rejuvenators and different amounts of RAP/RAS in the mix. It was also mentioned previously that this testing was undertaken because it is believed that the effect of rejuvenator, when directly incorporated into the virgin binder or the RAP binder and grading them directly, may not be the same as the case where it is added to the virgin binder or the RAP in the mixture. The binders recovered from the asphalt mixtures were tested for rheological properties in the unaged condition, RTFO-aged condition, and PAV-aged condition. Detailed results are presented in Appendix A.

Effect of Rejuvenator on the High-Temperature Grade of the Recovered Binder

Two examples of the RA impact on high-temperature grade, based on testing the recovered binder, are shown in Figures 17 and 18 for one of the rejuvenators. One can clearly see that for both unaged and RTFO-aged conditions of the recovered binder, RA has reduced the high-temperature grade of the binder. This is true for all three types of mixtures (15/5, 35/0, and 0/5). One can also notice that, in spite of the softening effect of RA, with the dosage rates shown, the high-temperature grade still exceeds 80 °C, except for the 35/0 mixture under the unaged condition.

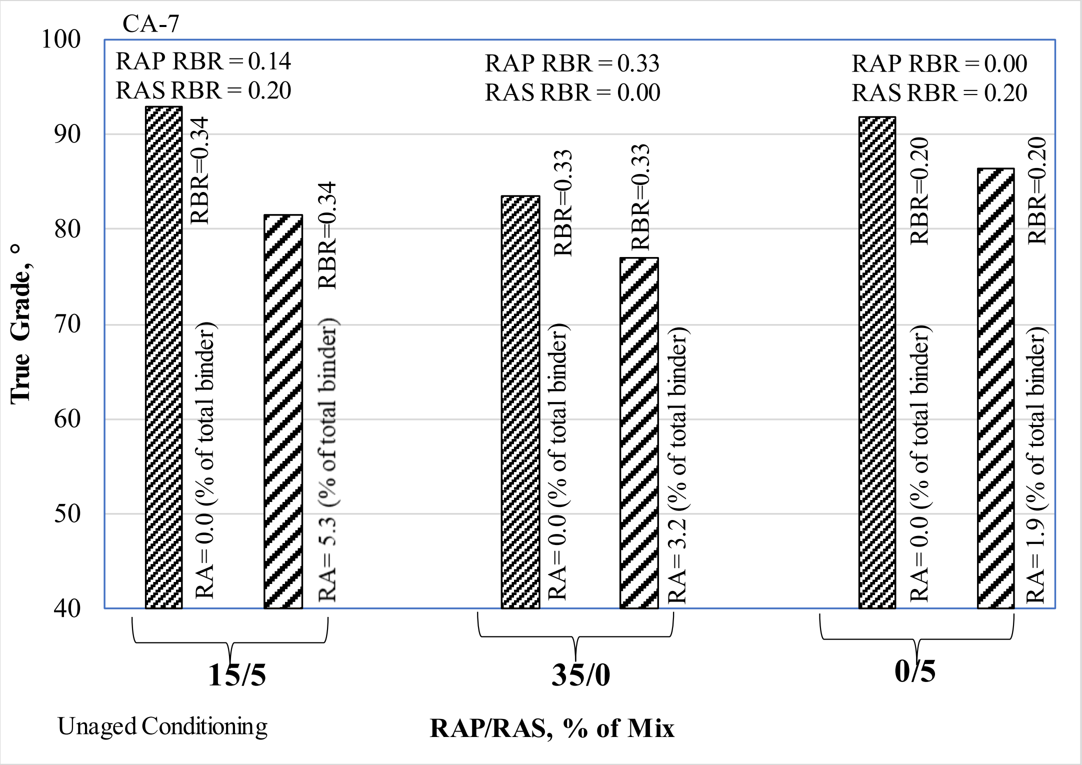


Figure 17. Grading of the recovered binder at high temperature for different mixtures (unaged).

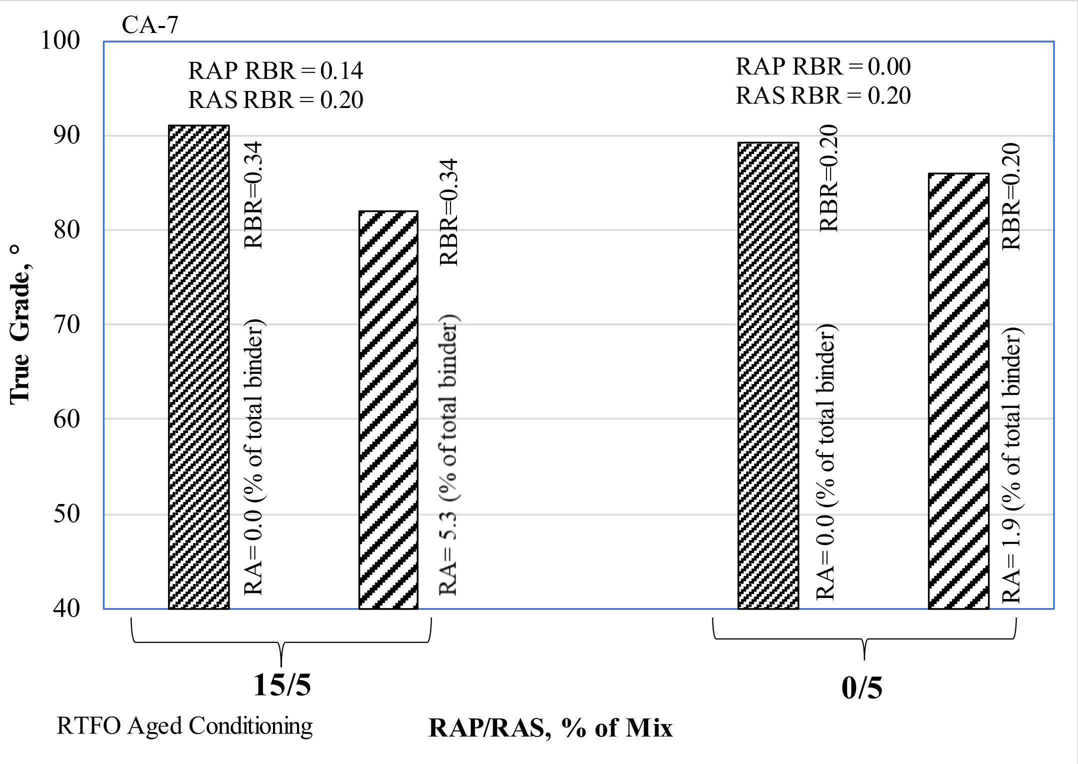


Figure 18. Grading of the recovered binder at high temperature for different mixtures (RTFO aged).

Effect of Rejuvenator on the Low-Temperature Grade of the Recovered Binder

When rejuvenators are used with RAS and high RAP mixtures at recommended and typical dosage rates, the softening at high temperature is not of concern. The main concern is the efficiency of the rejuvenator in reducing the cracking potential at low and intermediate temperatures. Two examples of the RA impact on low-temperature stiffness of the binder are presented in Figures 19 and 20 for the 15/5 mixtures using two of the rejuvenators. These figures provide a comparison of low-temperature grade of the recovered binders containing RA with the low-temperature grade of the binders recovered from the mixtures without RA. The figures clearly show the benefit of the rejuvenator in lowering the stiffness, hence reducing the low-temperature cracking potential. The mix without RA is graded as -22 °C based on stiffness, whereas the mix with RA is graded as -28 °C. This grade improvement is significant. It should be noted that this grading is based on testing of RTFO-aged binders, not PAV-aged binders. Similarly, one can see the significant benefit of using the rejuvenator in reducing ΔT_c, as presented in Figure 21. The significance of controlling this parameter was discussed earlier in this chapter. It should again be noted that this graph is based on short-term aging of the recovered binder.

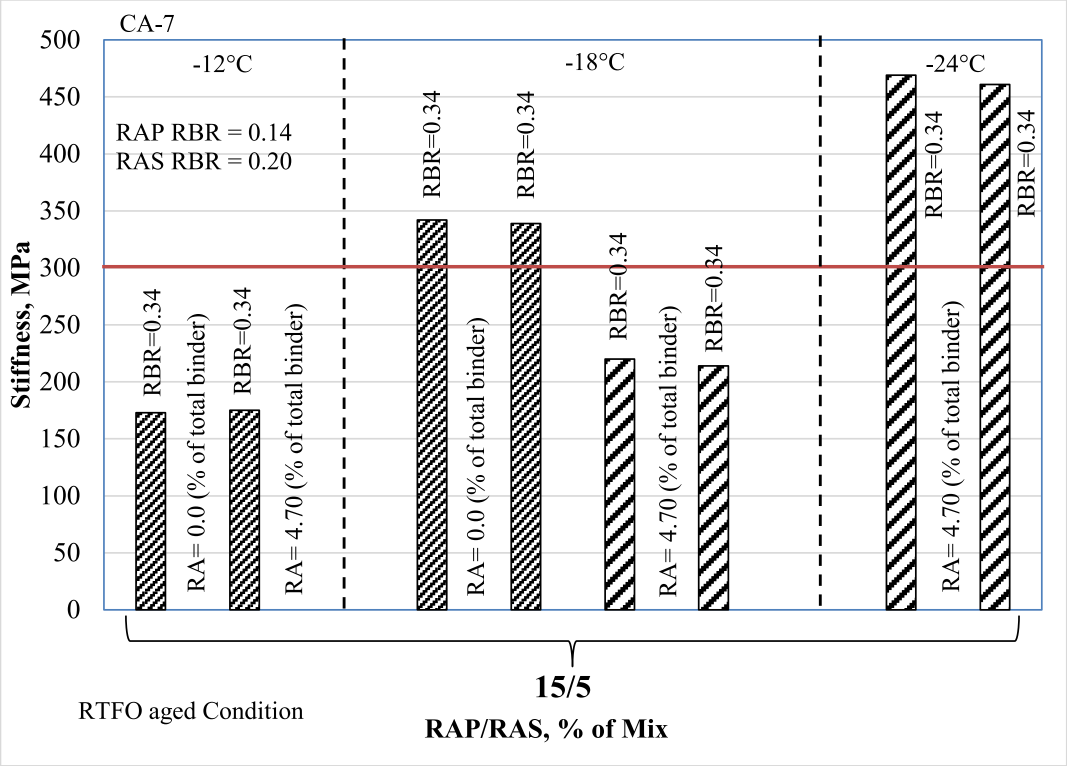


Figure 19. Stiffness of the recovered binder at low temperature for different mixtures (RTFO aged).

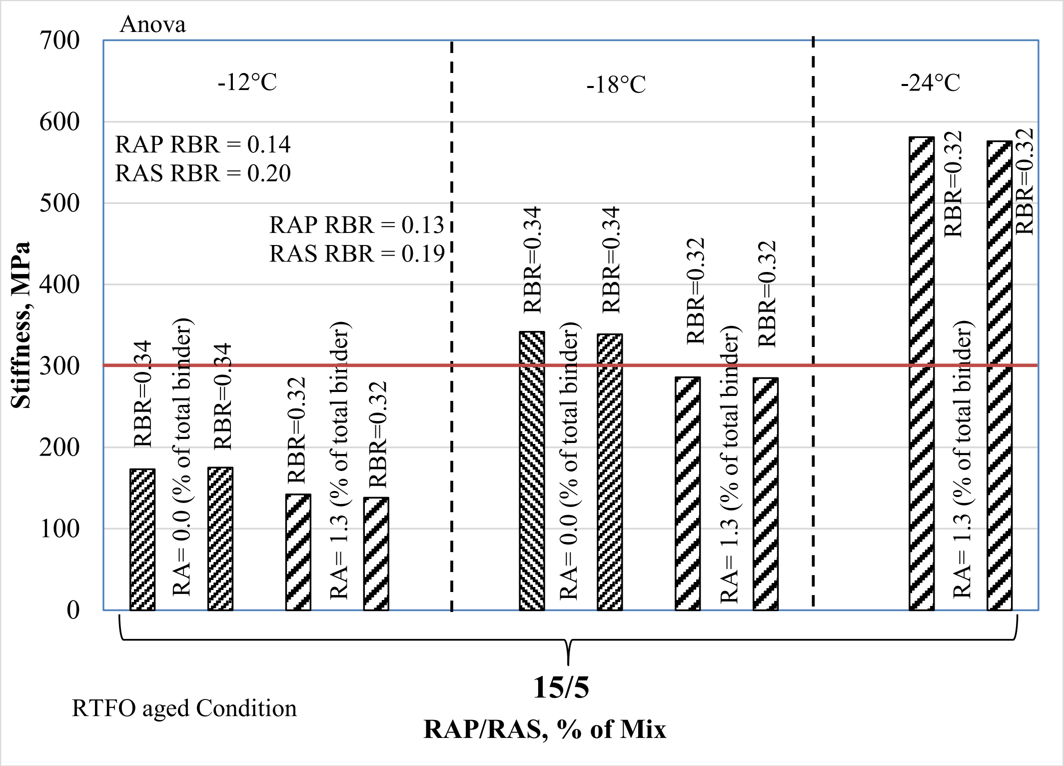


Figure 20. Stiffness of the recovered binder at low temperature for different mixtures (RTFO aged).

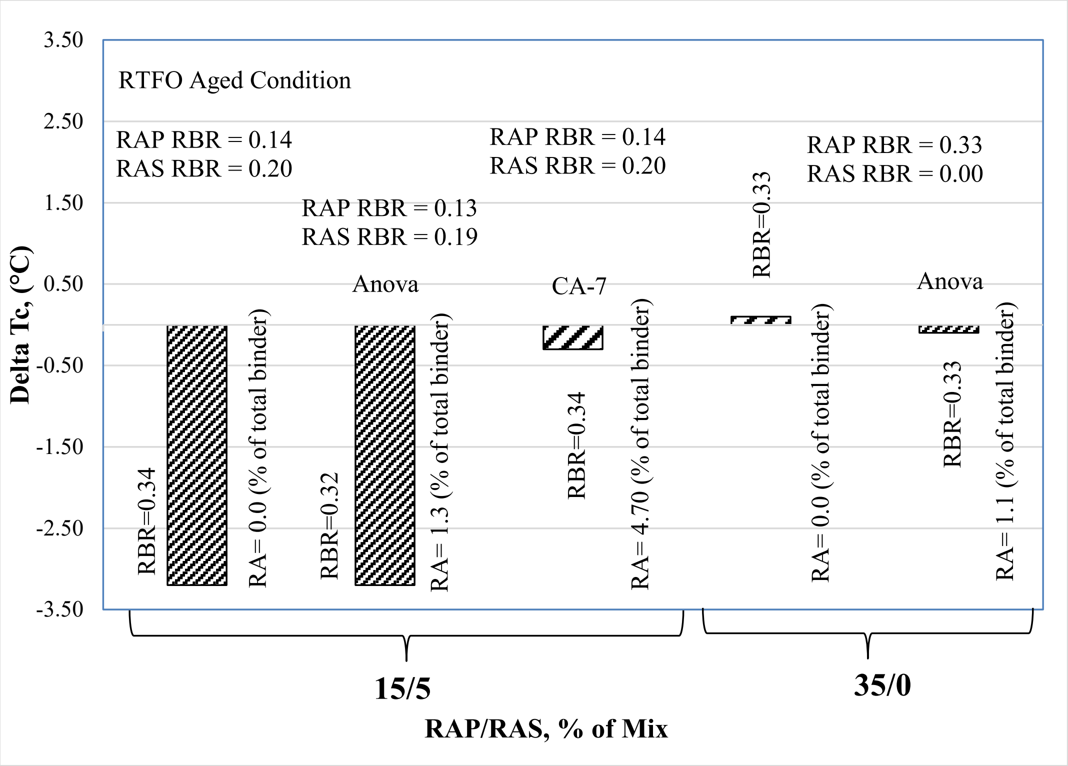


Figure 21. Effect of rejuvenators on ΔTc.

<u>ΔT_c of Recovered Binder after 40-hr PAV Aging</u>

In the NCHRP Research Report 967 (Bonaquist et al., 2021), it is mentioned that there is a growing interest in using ΔT_c as a specification criterion when determined from testing 40-hr PAV-aged binder residue. The authors of that report recommend that one should use either 12.5 g, 20-hr, 2.1 MPa PAV conditioning or 50.0 g, 40-hr, 2.1 MPa conditioning.

The binders recovered from six of the mixtures used in this research were therefore subjected to 40-hr PAV conditioning and subsequently tested in BBR for determination of ΔT_c. The results are presented in Figure 22. Two of the mixtures shown in the figure are control mixtures with no recycling agent incorporated: (1) the mixture with 15% RAP/5% RAS and (2) the mixture with only 5% RAS. Other mixtures shown contain either Ingevity CA-7 or Cargill Anova. It can be seen that the addition of RA consistently resulted in improvement of ΔT_c, which is a positive outcome. However, one can also see that for the dosage rates used and for all cases except one (35% RAP mix with CA-7), ΔT_c significantly exceeds the limiting criterion of -5 °C. It appears that, even though rejuvenators improve ΔT_c, the 40-hr conditioning imposes such a severe aging level in the binder that even the rejuvenators have not been able to increase ΔT_c to the -5 °C limit.

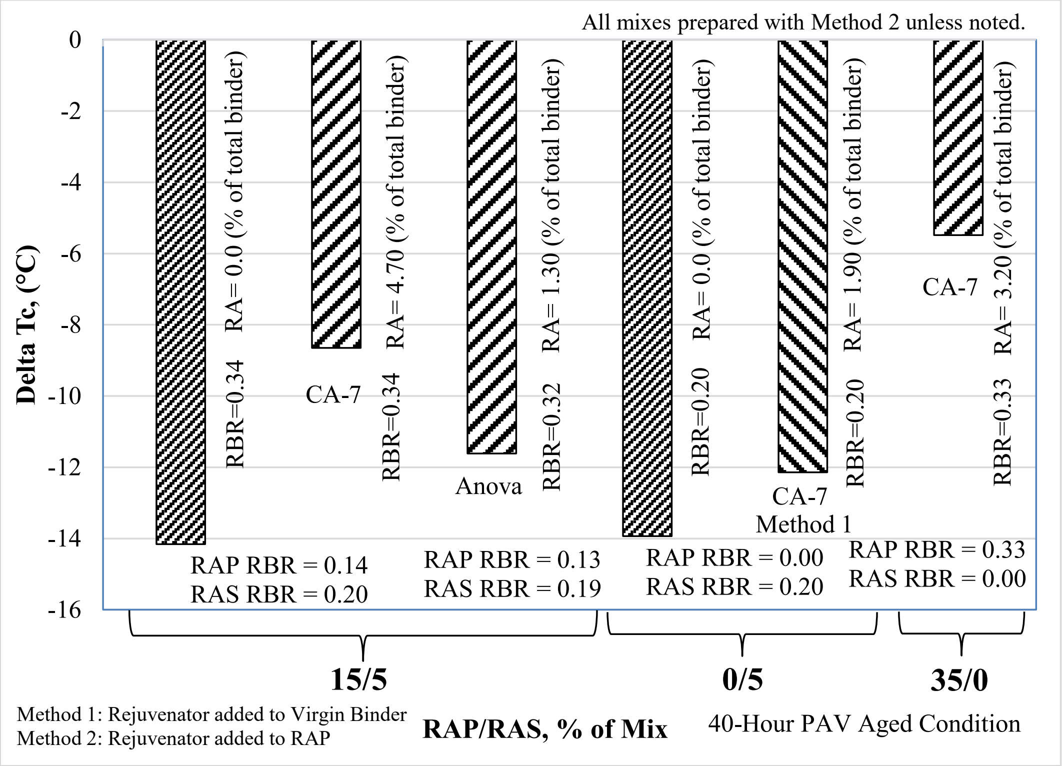


Figure 22. ΔT_c of recovered binders after 40-hr PAV aging.

Effect of Rejuvenator on the Intermediate Temperature Grade of the Recovered Binder

The benefit of the rejuvenator is not only in improving the asphalt mixture crack resistance at low temperatures, but is also giving the mixture better resistance to cracking at intermediate temperatures. This is evident from the results shown in Figure 23. It can be seen that for both RTFO- and PAV-aged recovered binders, the binder containing RA delivers a lower true grade at intermediate temperature compared with the mix with no RA. The true grade here is defined as the temperature at which the binder stiffness times the phase angle (i.e., G*.sinδ) is equal to 5,000 KPa. The benefit of rejuvenator is that the recovered binder containing the rejuvenator requires a lower temperature to achieve 5,000 KPa for this parameter compared with the binder without RA. In other words, the RA has resulted in a softer binder at the intermediate temperature at which fatigue cracking is of concern. A softer binder at intermediate temperature is believed to do a better job in resisting fatigue cracking.

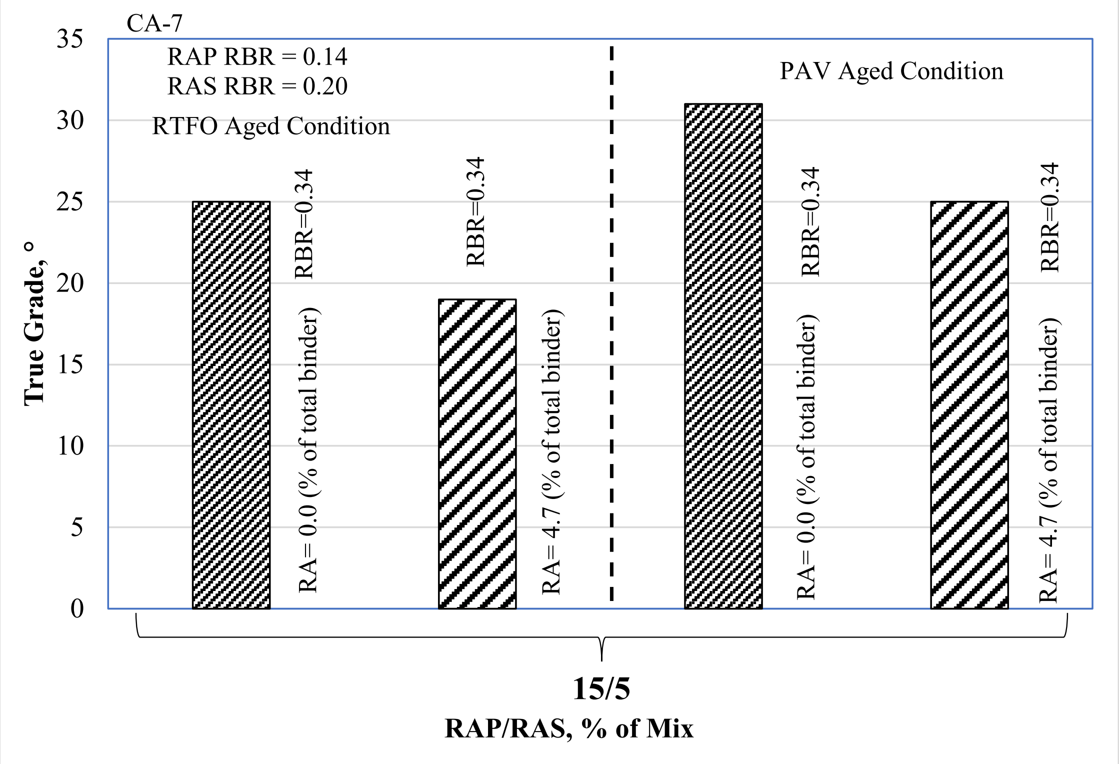


Figure 23. Positive effect of rejuvenators on intermediate temperature grade.

CHAPTER 5

Analysis of Mixture Characteristics

The focus of this chapter will be on discussion and analysis of data generated from mixture performance tests. These include mainly the results from Hamburg wheel tracking and indirect tensile asphalt cracking test.

Hamburg Wheel Tracking (HWT) Test Results

Before discussing the results, it must be noted that two of the rejuvenators (CA-7 and Anova) were applied to all three types of mixtures used in this study (i.e., mixtures with 15% RAP/5% RAS, 35% RAP, and 5% RAS). The other two rejuvenators were only applied to the mixtures containing 35% RAP based on the total mass of the mixture. The reason for using the first two rejuvenators for all the mixtures was because determination of dosage rate for these two was based on the performance grade of the RAP and RAS binders, whereas for the other two, the dosage rate was decided more generically.

Detailed results for each track of the HWT test and for each individual mix are provided in Appendices B and C. A summary of all results is presented in Table 20. The general conclusion is that at the recommended dosage rates, all mixes performed good to excellent in HWT. Examples of excellent and good performance of theses mixes are evident from the graphs shown in Figures 24 and 25, respectively. It must be mentioned that for most of the mixtures, both tracks provided similar results, as evidenced from the results in Table 20.

The maximum rut depth of 2–6 mm after 20,000 passes places these mixes in the category of good to excellent performers (Figures 26 and 27). A similar conclusion can be drawn based on the rut level at 10,000 passes, number of passes to 12.5-mm rut depth, stripping inflection point, stripping slope, and the ratio of stripping slope to creep slope (Appendices B and C). These are very good to excellent results in light of the fact that HWT is generally considered a severe test, sometimes referred to as a torture test, as it generates harsh conditions for the mix.

As presented in Table 20, for none of the mixtures did the maximum rut depth after 20,000 wheel passes exceed 6 mm. For most of the mixtures, no stripping inflection point was reached within the 20,000 wheel passes applied to the specimen. For those few mixes for which an SIP was reached within the 20,000 passes of the wheel tracking, the SIP varied between roughly 14,500 and 17,500 passes, an indication of good to excellent performance. In all cases except one, the ratio of stripping slope to creep slope is significantly below 2.0, a threshold used by some agencies for acceptance/rejection based on ratio of slopes. It is noteworthy that the ratio of 1.0, as shown in Table 20, indicates that no SIP was reached.

Table 20. Summary of results from Hamburg wheel tracking.

Mix	Hamburg Wheel Tracking Test Results						
MIX ID	**Max. Rut Depth(mm)**	**SIP**	**Strip/ Creep Ratio**	**# of Passes to 10 mm rut depth**	**# of Passes to 12.5 mm rut depth**	**Creep Slope (mm/1,000 passes)**	**Stripping Slope (mm/1,000 passes)**
#4	-2.21	NR	1.00	213,116	275,474	0.04	NA
	-2.56	NR	1.00	180,709	235,255	0.05	NA
#5	-3.45	NR	1.00	124,846	164,819	0.06	NA
	-4.48	15,715	2.61	39,708	48,582	0.11	0.28
#18	-2.61	NR	1.00	137,286	177,056	0.06	NA
	-2.42	NR	1.00	213,150	276,925	0.04	NA
#19	-2.21	NR	1.00	266,390	345,452	0.03	NA
	-1.96	NR	1.00	342,472	442,713	0.02	NA
#20	-2.34	NR	1.00	221,496	287,506	0.04	NA
	-2.25	NR	1.00	267,619	347,598	0.03	NA
#21	-3.73	15,520	1.23	75,834	97,960	0.09	0.11
	-4.66	16,198	1.35	49,981	63,956	0.13	0.18
#23	-5.68	15,199	1.61	35,719	44,754	0.17	0.28
	-3.76	NR	1.00	83,466	108,993	0.10	NA
#24	-2.36	NR	1.00	197,198	255,219	0.04	NA
	-2.14	NR	1.00	286,703	371,434	0.03	NA
#33	-3.24	NR	1.00	140,188	184,745	0.06	NA
	-2.76	NR	1.00	176,605	230,803	0.05	NA
#35	-3.91	16,374	1.41	63,514	81,371	0.10	0.14
	-3.74	15,816	1.34	72,220	93,054	0.09	0.12
#36	-2.88	NR	1.00	146,252	190,772	0.06	NA
	-3.36	NR	1.00	119,108	156,494	0.07	NA
#37	-3.08	NR	1.00	201,021	266,433	0.04	NA
	-2.93	NR	1.00	238,643	315,976	0.03	NA
#38	-4.26	NR	1.00	77,859	103,150	0.10	NA
	-5.19	17,517	1.25	45,604	58,839	0.15	0.19
#39	-3.39	NR	1.00	111,464	146,099	0.07	NA
	-3.17	NR	1.00	132,727	173,985	0.06	NA
#40	-3.45	NR	1.00	135,269	179,259	0.06	NA
	-4.73	14,456	1.35	53,228	68,973	0.12	0.16
#42	-3.39	NR	1.00	110,363	144,499	0.07	NA
	-3.87	17,299	1.41	62,742	80,169	0.10	0.14

NR=not reached.

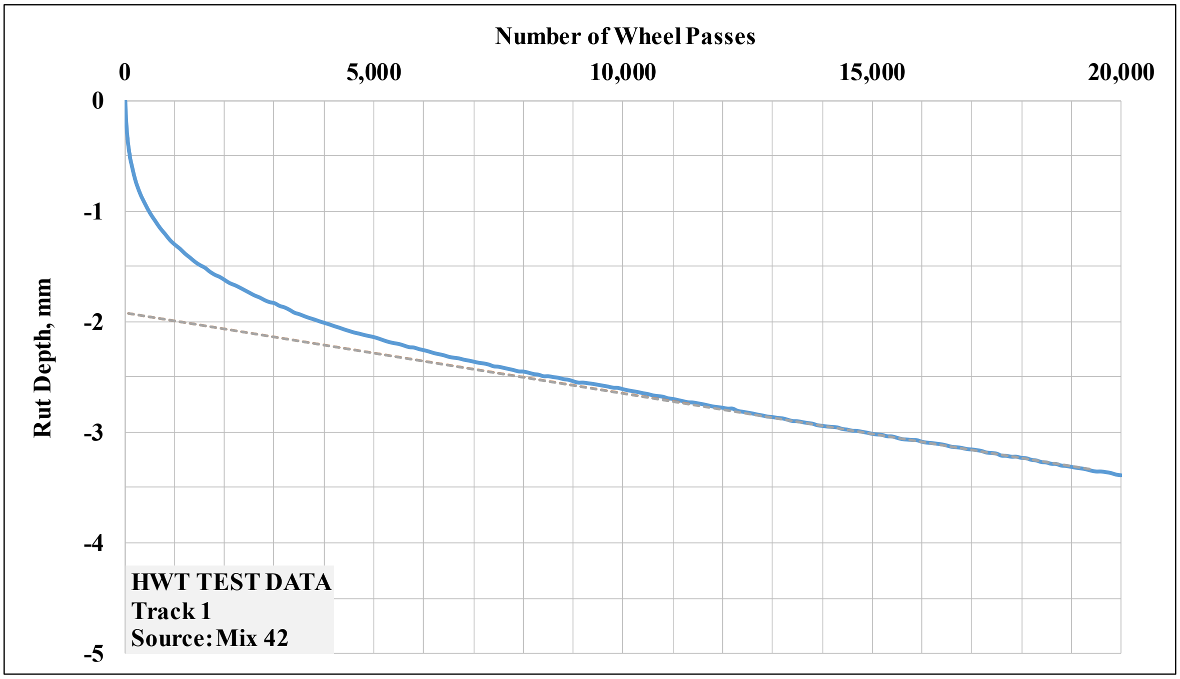


Figure 24. Behavior of excellent performing mix in the Hamburg wheel tracking device.

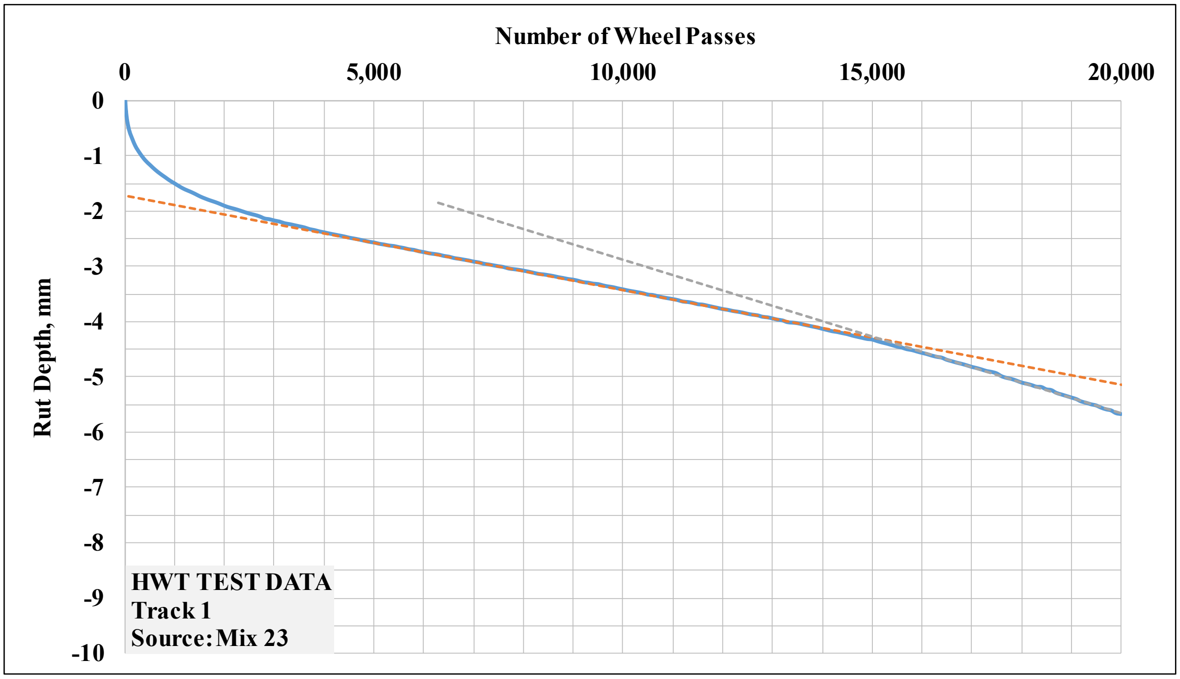


Figure 25. Behavior of a good performing mix in the Hamburg wheel tracking device.

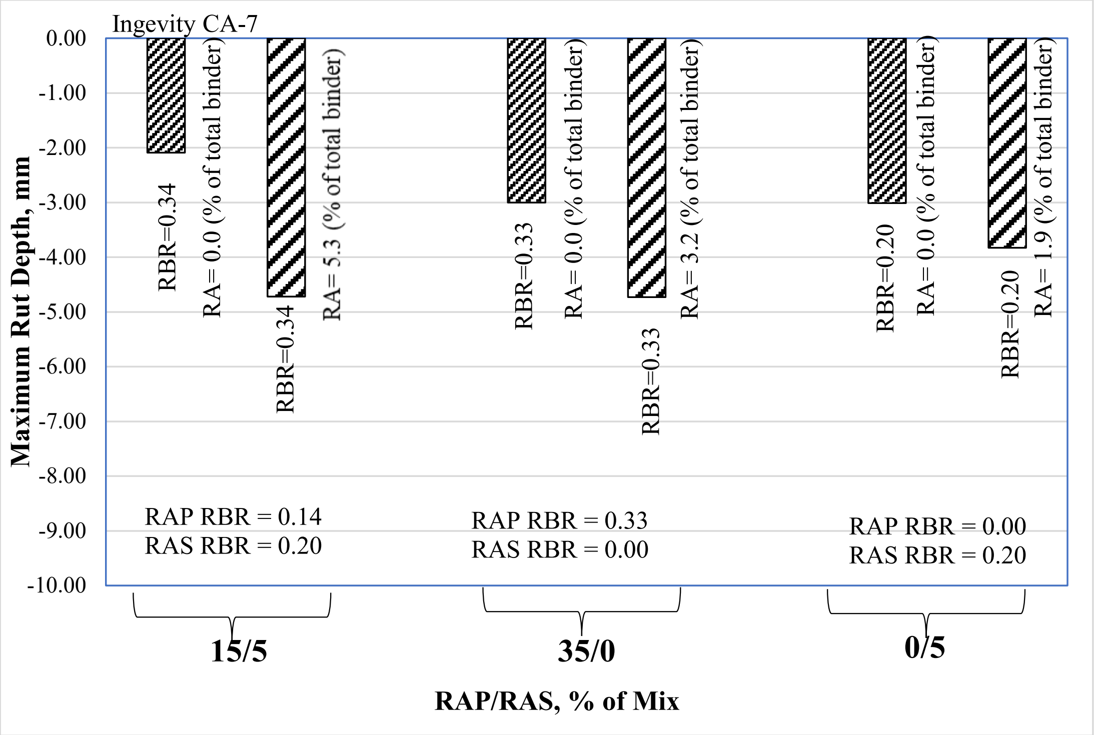


Figure 26. Maximum rut depth in HWT for different mixtures containing RA CA-7.

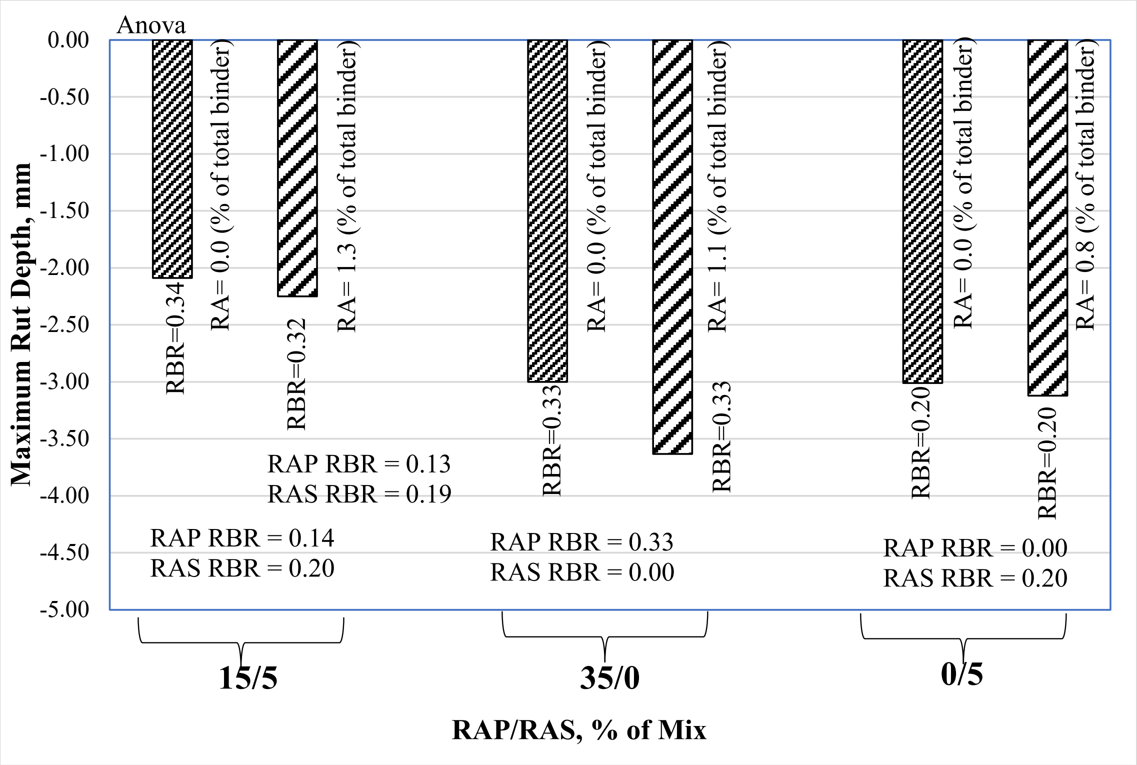


Figure 27. Maximum rut depth in HWT for different mixtures containing RA Anova.

For the Hydrolene H90T RA, there was little or no change in HWT test results with the addition of RA. For example, Figure 28 shows the maximum rut depth was almost the same for the 35/0 mixture containing this RA. Finally, for the 35/0 mixture, there was a significant increase in the rut depth when the Hydrogreen S RA was incorporated compared with the case of no RA (Figure 29). The HWT test results for stripping inflection point, rut depth at 10,000 passes, number of passes to 12.5-mm rut depth, and stripping/creep ratio are presented in Appendix C for all four rejuvenating agents and all mixtures.

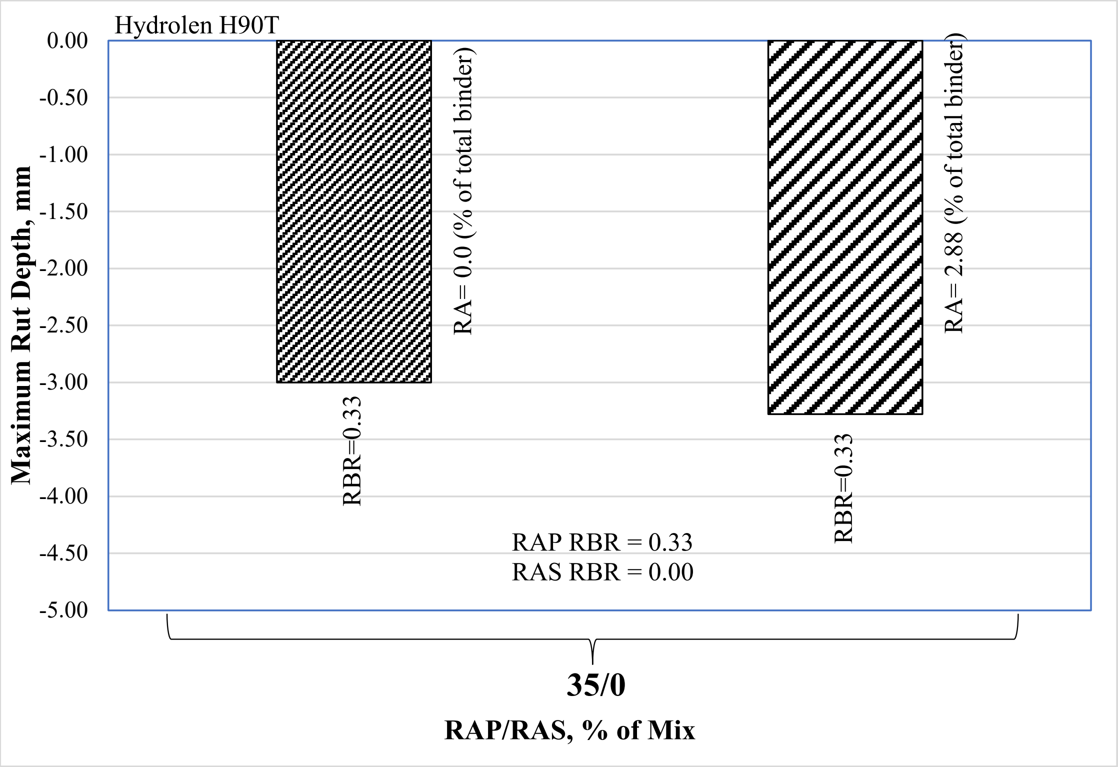


Figure 28. Maximum rut depth in HWT for different mixtures containing RA Hydrolene H90T.

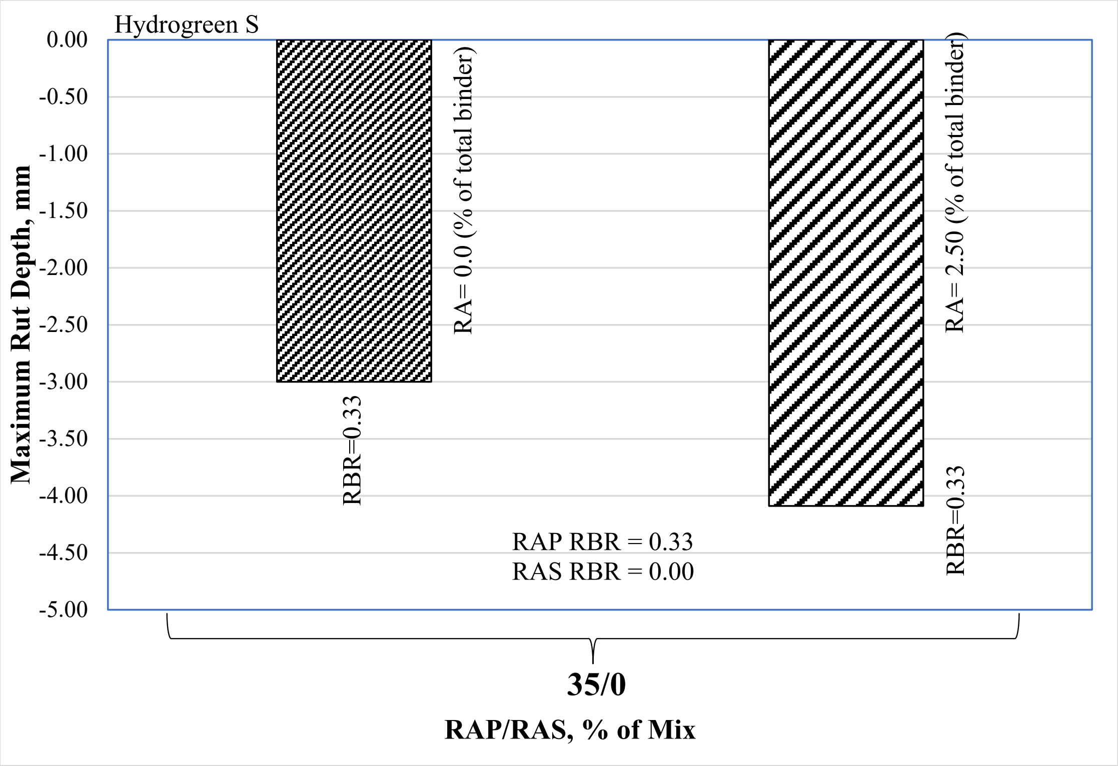


Figure 29. Maximum rut depth in HWT for different mixtures containing RA Hydrogreen S.

IDEAL Test Results

It was shown that adding the rejuvenating agents at the recommended dosage rates, in general, increased the rut depth for the mixtures containing RAS or high RAP content or both. However, the increase still maintained the final rut depth in good to excellent levels of performance. The main reason for adding RA to the mixtures containing RAP and RAS is to increase their flexibility in terms of resistance to low-temperature cracking or intermediate-temperature fatigue cracking, without compromising rutting resistance. Hence, testing of all mixtures in the IDEAL-CT test was conducted to assess the impact of RA on the RAP/RAS flexibility.

Two examples of the load-displacement curves are presented in Figures 30 and 31. Each graph shows the results for four replicates of the same mixture. These graphs indicate a high quality of mixture production and testing, as the replicates deliver a very low coefficient of variability. Detailed results along with the corresponding graphs for all the mixtures are presented in Appendix D, and comparison graphs from IDEAL-CT tests are presented in Appendix E. Table 21 provides a summary of IDEAL-CT test results for all the mixtures tested in this study. As a reminder, all the mixtures reported in Table 21 were made with 9.5-mm NMAS aggregated and with PG 58S-28 binder. In general, all data indicate that adding the recycling agent to the asphalt mixture, as expected, results in an increase in the IDEAL-CT index.

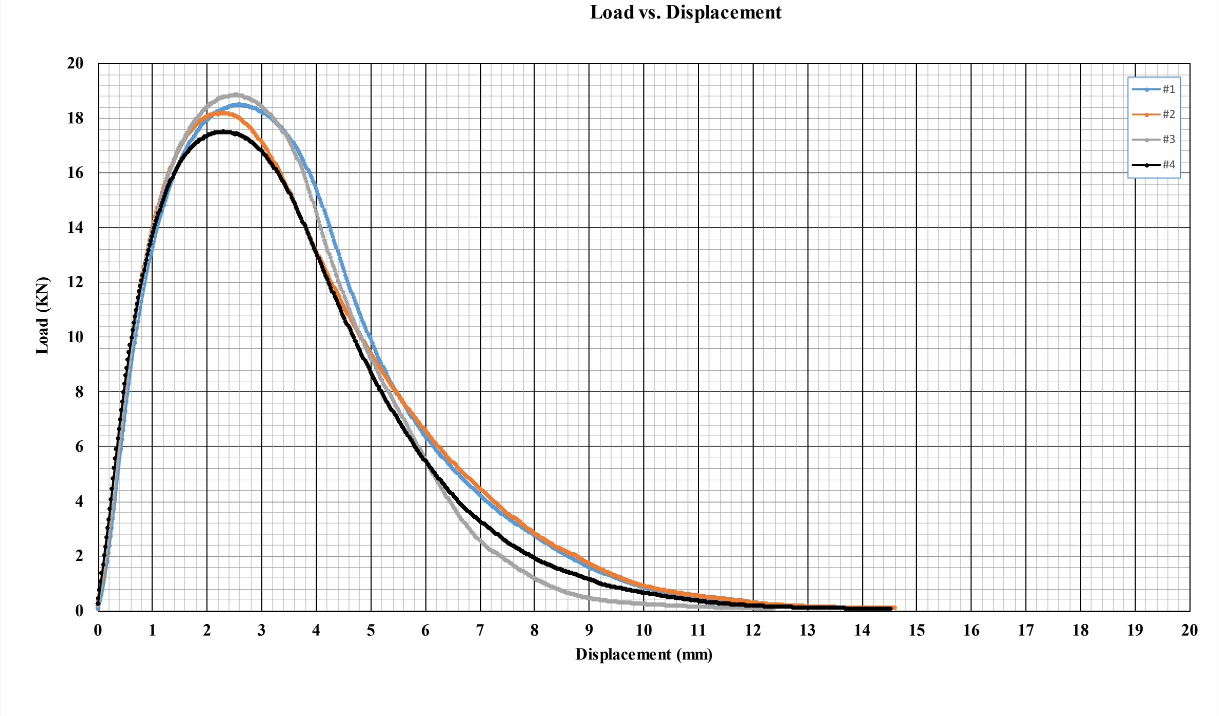


Figure 30. Load-displacement curve from IDEAL-CT test mix 19.

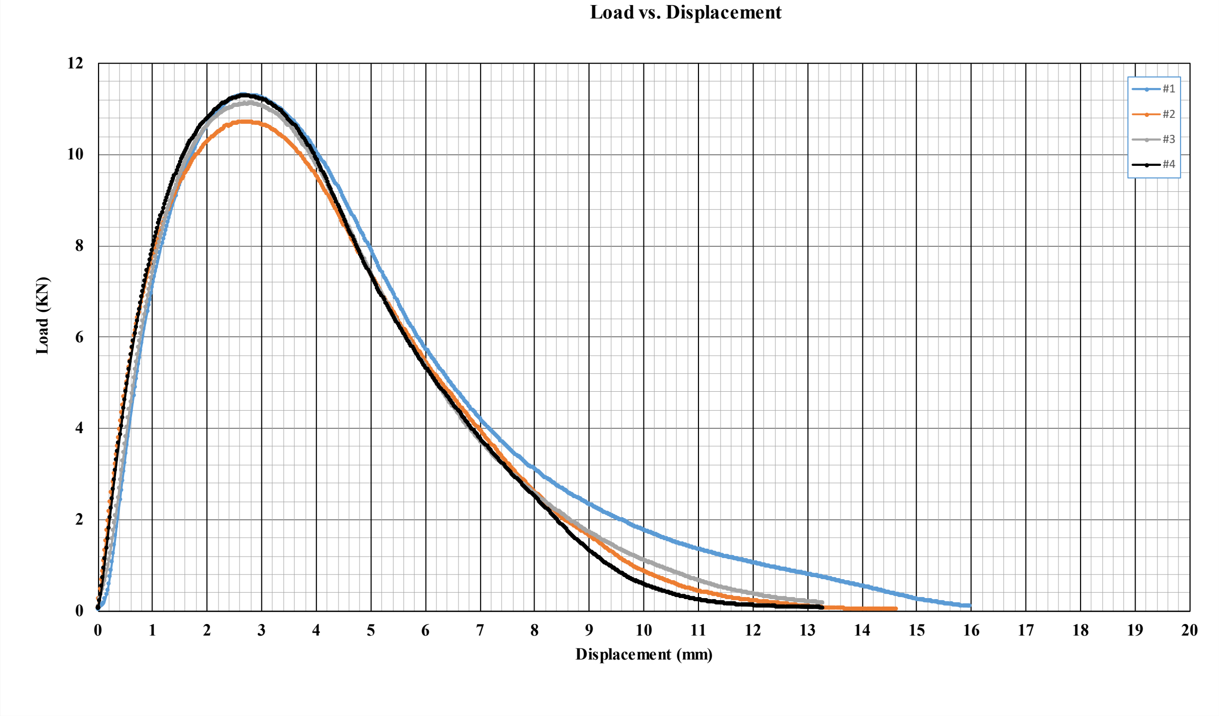


Figure 31. Load-displacement curve from IDEAL-CT test mix 23.

Table 21. Summary of results for all mixtures tested in IDEAL-CT.

Mix Information		IDEAL-CT Test Results				
MIX ID	**Specimen**	**Peak Load (N)**	**Fracture Energy (J/m^2)**	**IDEAL-CT Index**	**Peak Tensile Stress**	**Strain at Peak Stress (%)**
Specimens are short-term aged at 135C for 4 hours, followed by conditioning at 150C for 1 hour before compaction.						
Experimental Mixes (i.e., mixes with the recycling agents)						
#4	Average	16,953.6	7,248.1	25.8	1165	1.41
#5	Average	12,333.4	7,347.2	75.6	843	1.91
#18	Average	15,329.3	8,880.5	77.5	1052	2.01
#20	Average	15,131.8	8,459.0	67.0	1032	1.64
#21	Average	12,143.9	7,035.3	80.0	831	1.81
#23	Average	11111.7	6875.9	90.7	761.0	1.82
#38	Average	12378.5	8524.5	134.9	849.5	2.06
#24	Average	11326.0	6432.9	65.1	776.5	1.77
#39	Average	13292.2	9061.4	128.4	913.8	1.96
#40	Average	13044.1	8894.2	126.8	894.8	2.08
#42	Average	14310.8	9207.8	101.3	979.5	1.96
#35	Average	12469.0	8047.1	101.1	857.5	2.2
#36	Average	13413.5	8290.6	93.2	921.3	2.2
#25	Average	14224.7	9018.3	97.5	974	1.93
#26	Average	14968.8	9462.1	94.6	1025	1.82
Specimens are long-term aged at 135C for 8 hours, followed by conditioning at 150C for 2 hours before compaction.						
Experimental Mixes (i.e., mixes with the recycling agents)						
#24	Average	19017.6	9065.4	37.2	1301	1.59
#33	Average	17762.9	9912.0	62.5	1216	1.70
#39	Average	16046.9	9877.7	87.4	1099	1.90
#23	Average	15391.0	8746.4	66.9	1053	1.84
#38	Average	14534.6	9433.8	102.4	996	2.02
Specimens are short-term aged at 135C for 4 hours, followed by conditioning at 150C for 1 hour before compaction.						
Control Mixes (i.e., mixes without recycling agents)						
#19	Average	18254.8	9471.5	50.6	1247.0	1.62
#33	Average	15093.4	8872.8	80.8	1035.0	1.68
#37	Average	14452.9	9116.0	91.0	993.0	1.93

For a better understanding of the results presented in Table 21, the reader is referred to Figure 32, presenting the results for one of the recycling agents. As shown in this figure, in the case of Ingevity CA-7 and for the 15/5 mixture, adding RA has dramatically increased the value of the

IDEAL-CT index, taking it from a value of almost 50 up to an acceptable value of almost 90, an 80% increase. A similar impact is seen for the 35/0 mixture, for which the rejuvenator has resulted in an approximately 70% increase in the IDEAL-CT index. The impact is not as pronounced for the 0/5 mixture, but still the index has increased from 90 to 100. It is important to note that the amount of rejuvenator is not the same for these three mixes. The highest content belongs to the 15/5 mixture and the lowest content to the 5/0 mixture. These values should be analyzed in combination with those obtained from HWT tests in light of the balanced mix design. Changing the mix parameters, including the type and content of the rejuvenator, must be assessed considering both ends of the performance spectrum. Increasing the rejuvenator content may be warranted if the rutting from HWT is not compromised.

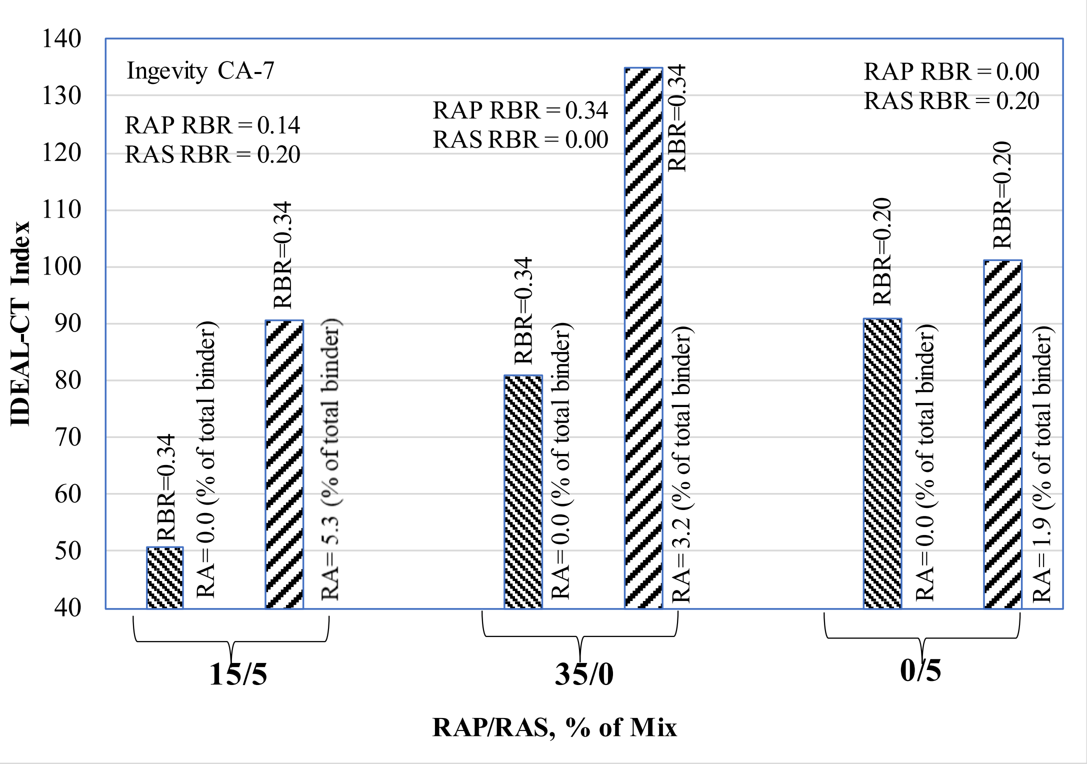


Figure 32. IDEAL-CT test results for the RAP/RAS mixtures containing RA CA-7.

One can see test results similar to what was discussed for CA-7 for the other three rejuvenators, as presented in Figures 33 through 35. For the RA Anova, similar to the RA CA-7, the largest impact is for the RAP/RAS mixture, and the smallest impact is for the RAS mixture. For the

RA Hydrolene H90T and the RA Hydrogreen S, results are only available for the RAP/RAS mixture and the RAP mixtures, and for both of these cases significant improvement in IDEAL-CT is observed.

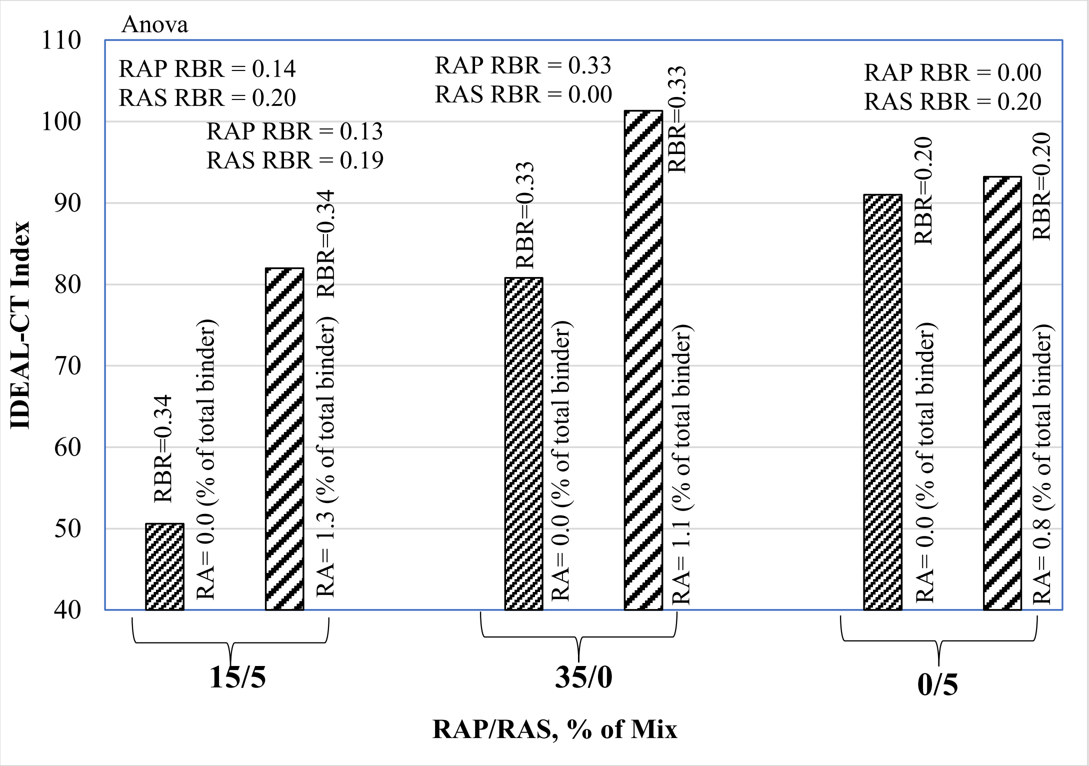


Figure 33. IDEAL-CT test results for the RAP/RAS mixtures containing RA Anova.

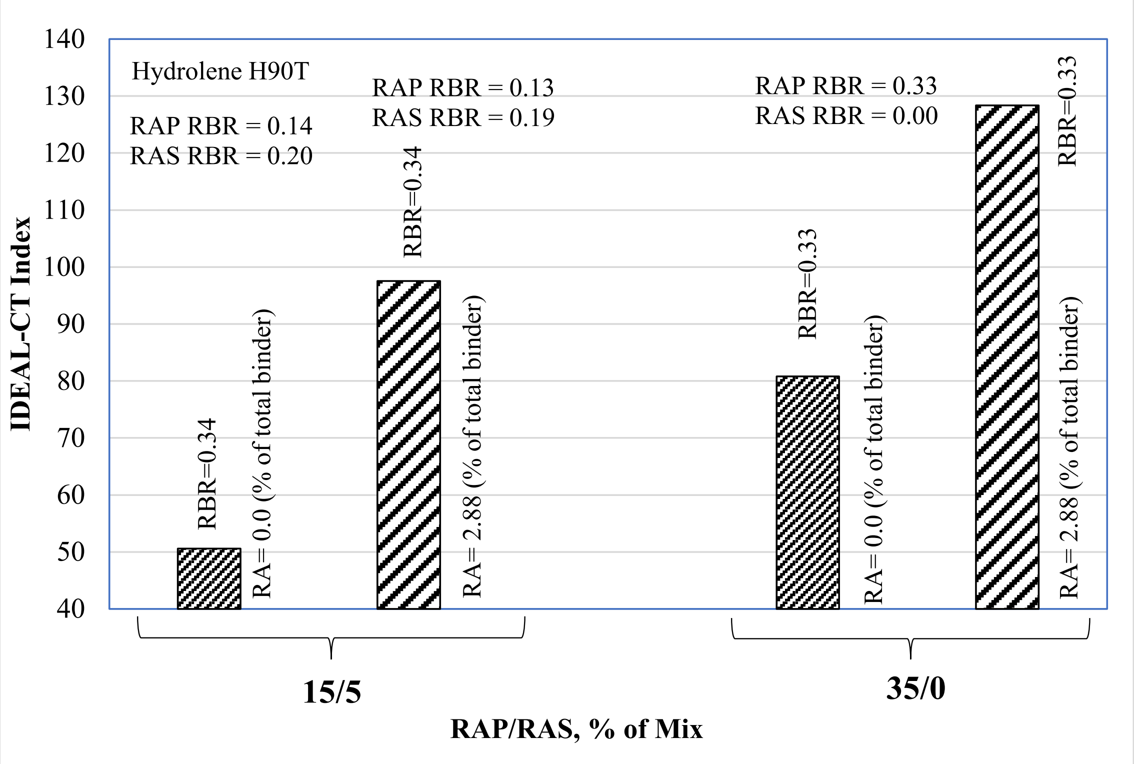


Figure 34. IDEAL-CT test results for the RAP/RAS mixtures containing RA Hydrolene.

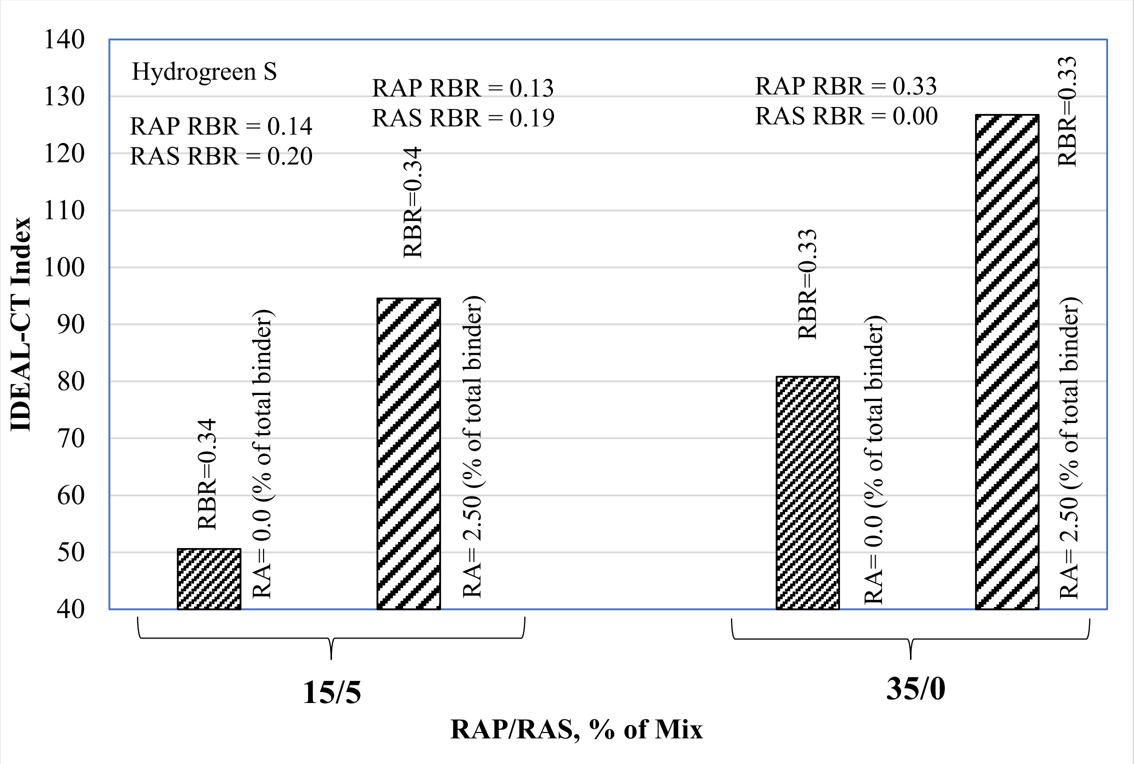


Figure 35. IDEAL-CT test results for the RAP/RAS mixtures containing RA Hydrogreen S.

A comparison of IDEAL-CT index among the four rejuvenators is provided in Figures 36 and 37 for the mixtures with 15% RAP/5% RAS and with 35% RAP, respectively. From these figures it can be seen that all of the agents increase the index significantly. Once again, it should be noted that the dosage rate of RA (rejuvenator) varied depending on the manufacturer. The RA content is shown in the graphs.

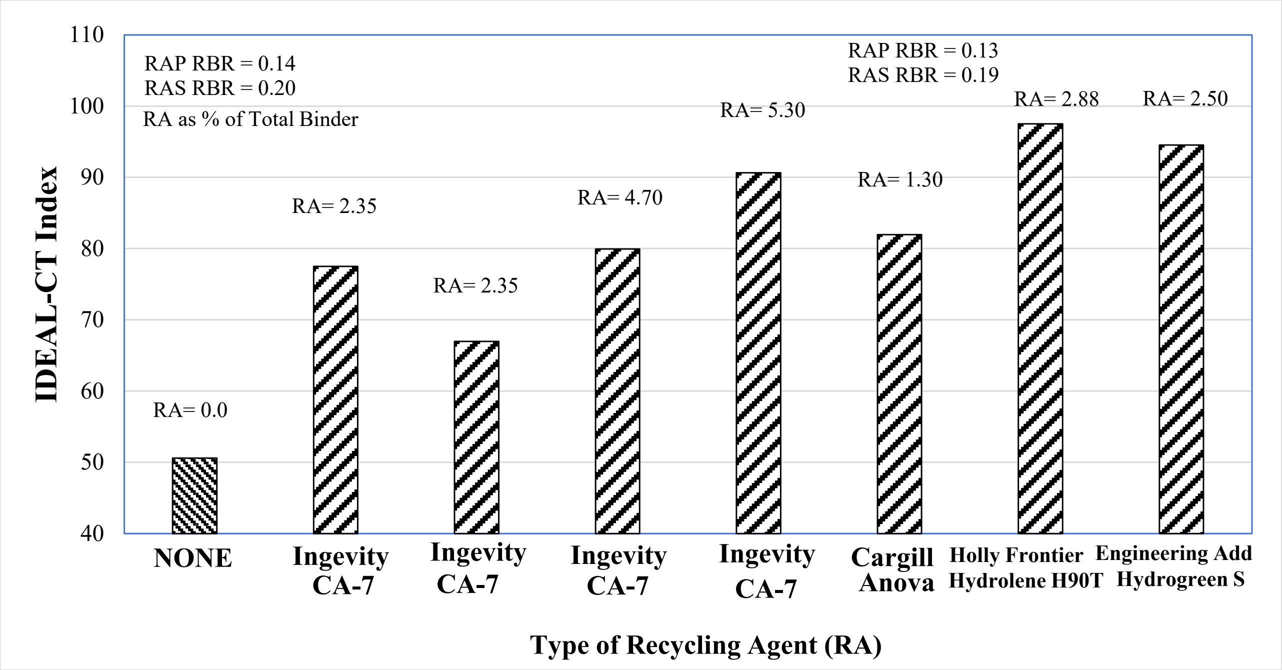


Figure 36. IDEAL-CT index presented for the mixture containing 15% RAP/5% RAS for all the rejuvenators.

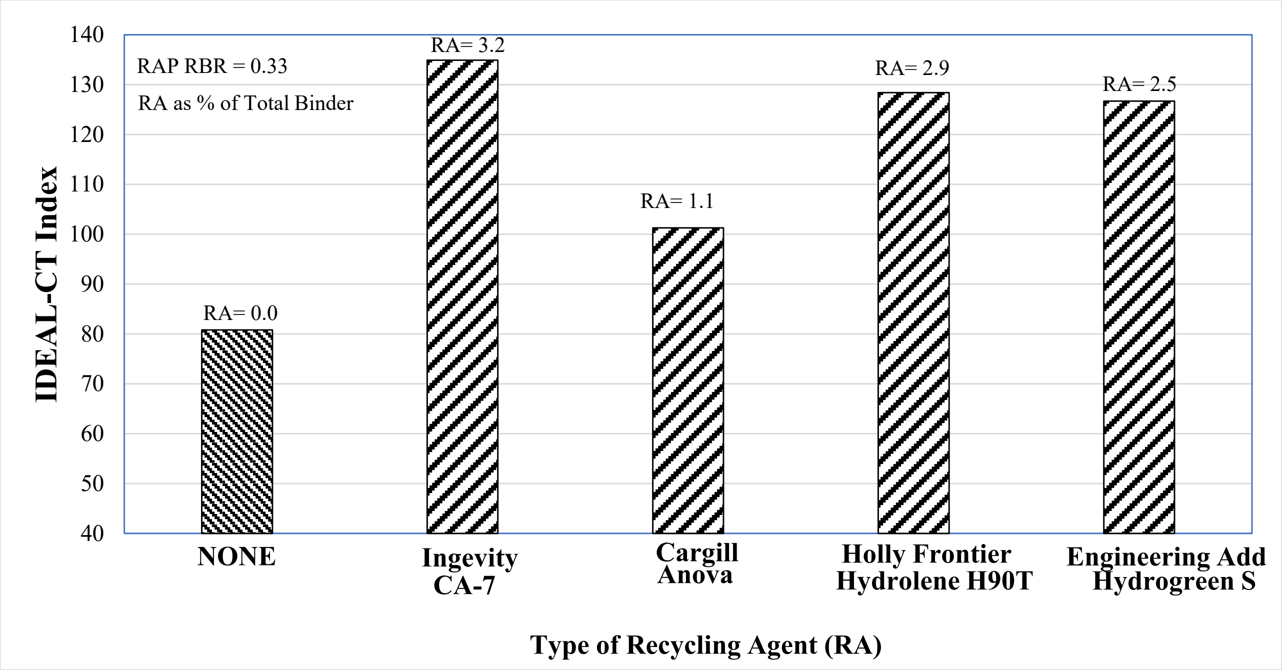


Figure 37. IDEAL-CT presented for the mixture containing 35% RAP for all the rejuvenators.

It was clearly shown that with the addition of the rejuvenator, the mix IDEAL-CT increases; however, one should note that with the increase of flexibility, the mix strength decreases, as shown in Figures 38 through 41. Therefore, attention should be given to the strength reduction, and it is recommended that the strength not drop below 100 psi. It can be seen from the figures that, in spite of the reduction of strength with the addition of RA, the strength remains significantly higher than 100 psi for all mixtures and combinations.

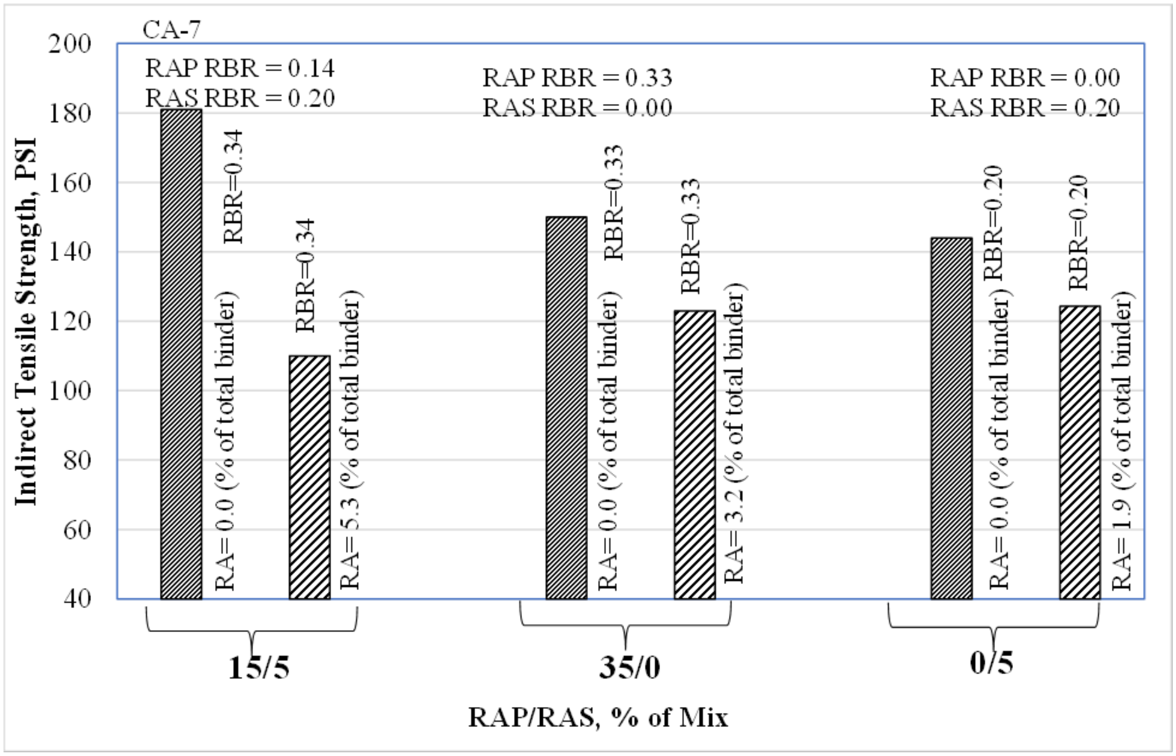


Figure 38. Indirect tensile strength results for the RAP/RAS mixtures containing RA CA-7.

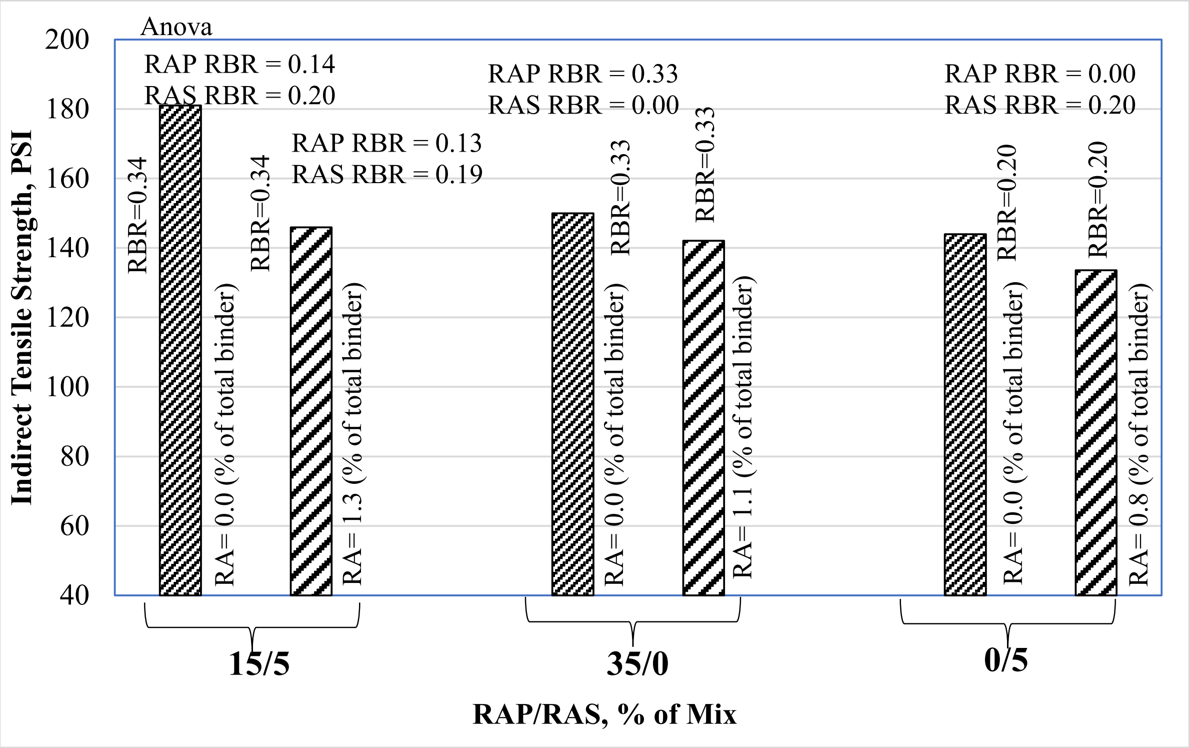


Figure 39. Indirect tensile strength results for the RAP/RAS mixtures containing RA Anova.

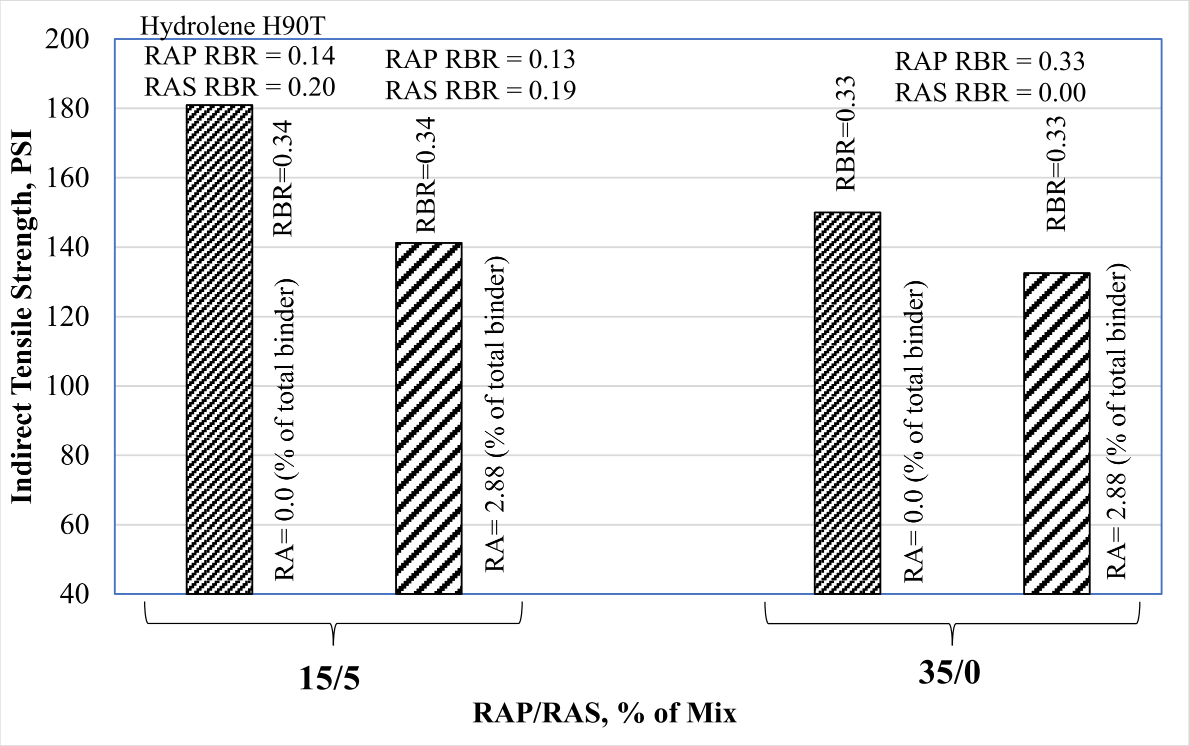


Figure 40. Indirect tensile strength results for the RAP/RAS mixtures containing RA Hydrolene H90T.

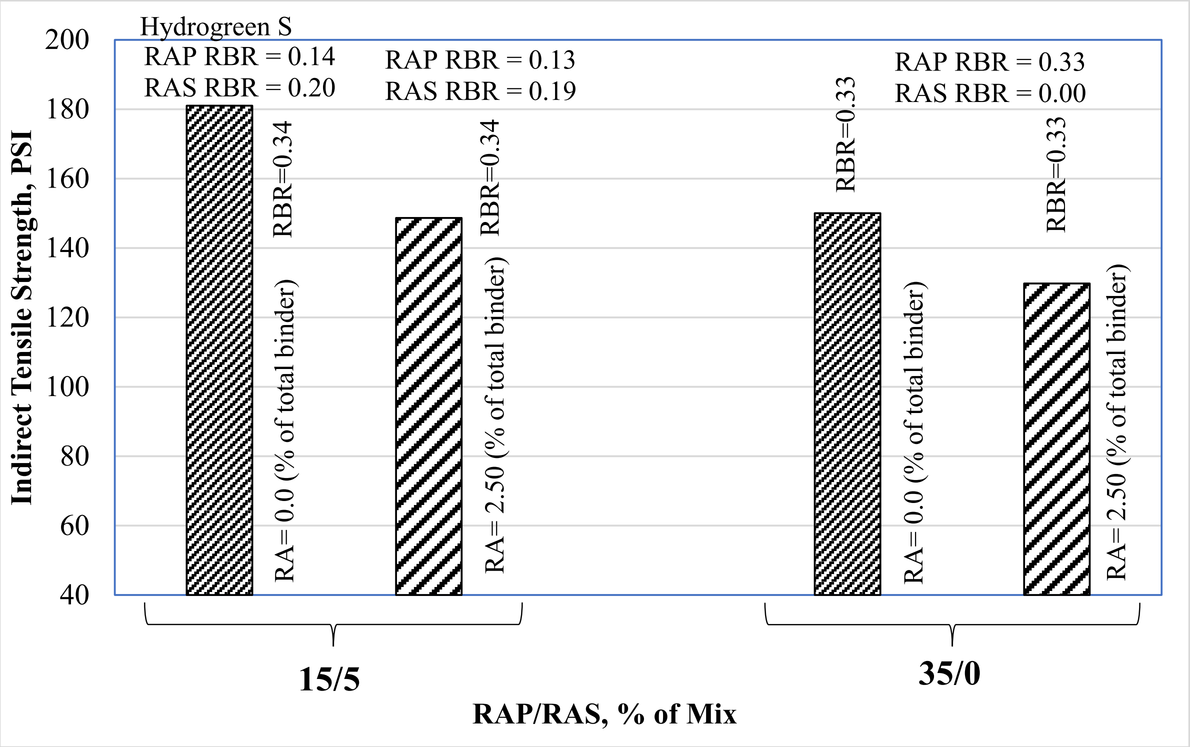


Figure 41. Indirect tensile strength results for the RAP/RAS mixtures containing RA Hydrogreen S.

The Effect of Long-Term Aging on IDEAL-CT Index

Currently, most agencies that are using the IDEAL-CT index test to determine the mix cracking potential conduct the tests on short-term aged specimens. The reality is that short-term aged specimens are suitable to use for evaluation of rutting, for example in the HWT test. However, cracking is more a long-term issue, and the pavement is more susceptible to cracking after several years in service when it has been aged and has become more brittle. Hence, it is more appropriate to conduct the IDEAL-CT test on the laboratory specimens that have been exposed to long-term conditioning. However, it is acknowledged that doing so requires a longer wait time and a more extensive testing scheme. Perhaps, as more data become available, a reliable relationship could be established between the test results from the short-term aged and long-term aged specimens. Having such a relationship could make it possible to continue testing the short-term aged specimens with corresponding threshold values.

The results presented previously in this report are for short-term aged (ST) specimens, as that is the common practice. A limited study was undertaken to assess the impact of long-term conditioning (LT) on the IDEAL-CT test results. There are three options available for such conditioning. One is the standard practice presented under AASHTO R 30, which requires conditioning of compacted specimens at 85 °C for 120 hours. The second is the procedure established under NCHRP 9-54 as presented in NCHRP Report 871 (Kim et al., 2017). This protocol requires conditioning the loose mixture at 95 °C, but duration of conditioning is dependent on the pavement depth for which conditioning is to be conducted, the pavement location, and the target year of conditioning. Typically, this conditioning process results in durations from just a few days to a few weeks, depending on the target depth and the pavement location. Finally, there is the protocol established by the National Center for Asphalt Technology (Chen et al., 2018) that requires conditioning the loose mixture at 135 °C for 8 hours, and then 2 hours at 150 °C before compaction. In this research, it was decided to use the last method, as it was the fastest. However, two of the mixtures were also tested according to AASHTO R 30 for comparison.

Results from Conditioning According to the NCAT Protocol

The results are presented in Figure 42. Five mixtures are presented, with the first one being the control mixture with no rejuvenating agent. Three rejuvenators were used with the remaining four mixtures. One rejuvenator was used with both 15/5 and 35/0 mixtures. One rejuvenator was used with only the 15/5 mixture, and finally one rejuvenator was used with only the 35/0 mixture. It can be seen that, consistently for all of the presented mixtures, the long-term aging delivers a lower IDEAL-CT index compared with the short-term aging, albeit to varying degrees depending on the type and amount of RA and the RAP/RAS content. Another important observation is that the effectiveness of the rejuvenator is not lost due to long-term aging. It is true that for the rejuvenator-modified mixtures, the IDEAL-CT index of LT mixtures is lower than that of ST mixtures, but it is still considerably higher than the IDEAL-CT index of LT specimens without the rejuvenator. It is evident from Figure 41, for example, that for the 35% RAP mixtures, the LT mixtures containing rejuvenators yield an IDEAL-CT index of almost 85 and 100 compared with the LT mixture with no rejuvenator delivering an index of almost 62.

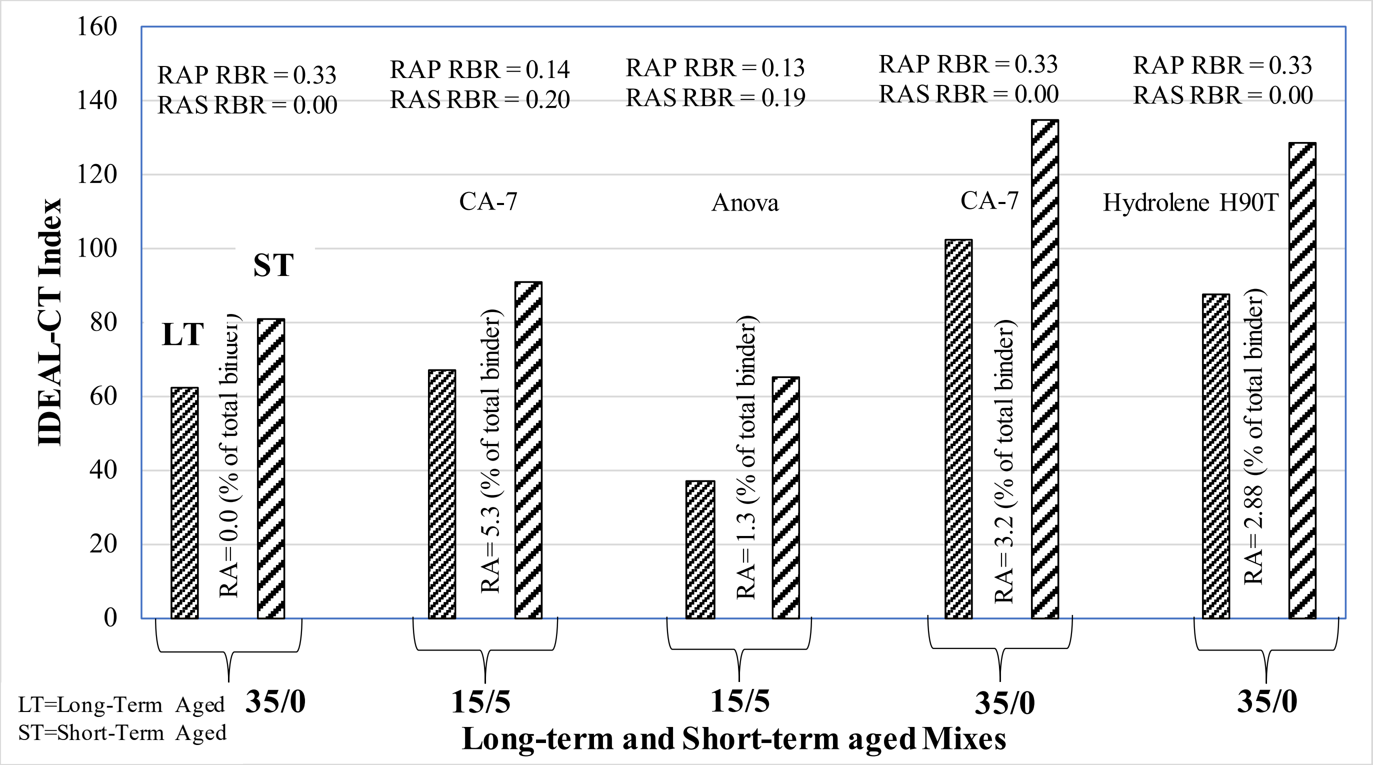


Figure 42. Comparison of IDEAL-CT index for long-term aged mixes and short-term aged mixes.

As expected, the LT mixtures consistently deliver a higher indirect tensile strength due to the stiffening effect of aging, as shown in Figure 43. Interestingly, this higher strength has resulted in higher fracture energy of LT mixtures (Figure 44). The fracture energy is calculated from work energy that is the area under the load-displacement curve. The major contributor to the higher fracture energy of LT mixtures is the higher strength of these mixtures. It appears that the stiffening does not result in reducing the strain at fracture and thus is not affecting the fracture energy. Figure 45 shows the relationship between the strain at peak stress (strain at fracture) for ST mixtures versus that for LT mixtures, and it can be seen that the strain level at the time of fracture for ST mixtures is almost similar to that for the LT mixtures for four of the mixtures, hence not affecting the fracture energy. Only in the case of one of the rejuvenating agents is the fracture strain after long-term aging reduced. This mixture with reduced fracture strain is also the one giving the highest strength among all the LT mixtures as well as yielding the highest increase in fracture energy compared with the ST mixtures.

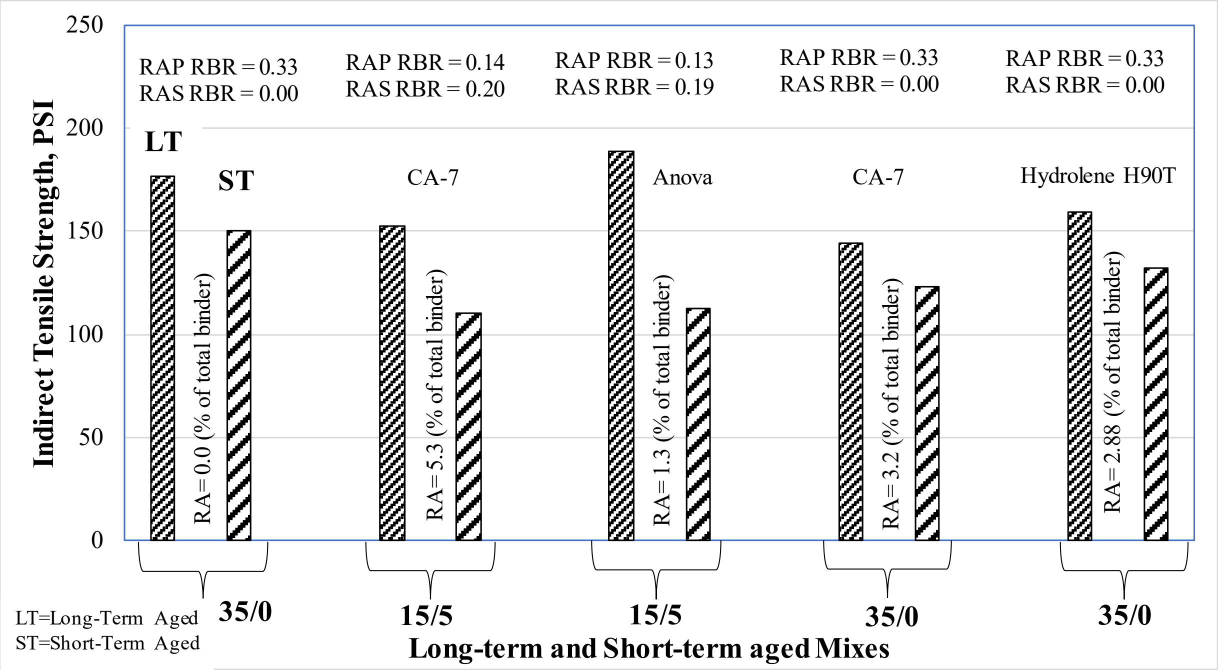


Figure 43. Indirect tensile strength of long-term aged mixes versus short-term aged mixes.

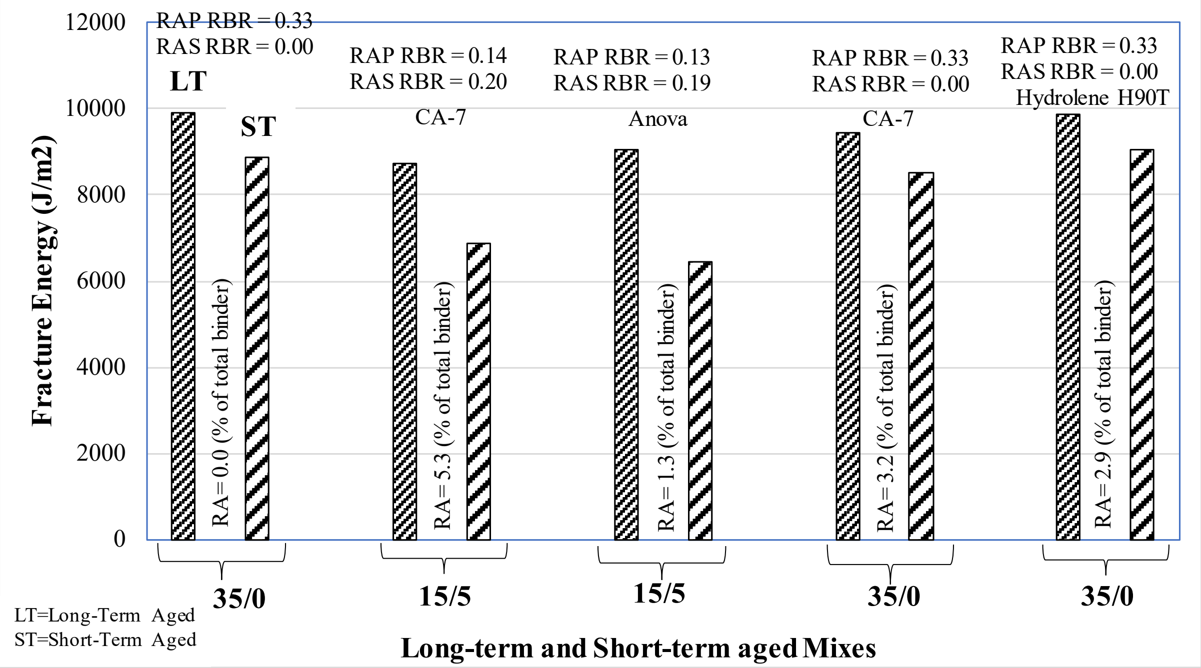


Figure 44. Fracture energy of long-term aged mixes versus short-term aged mixes.

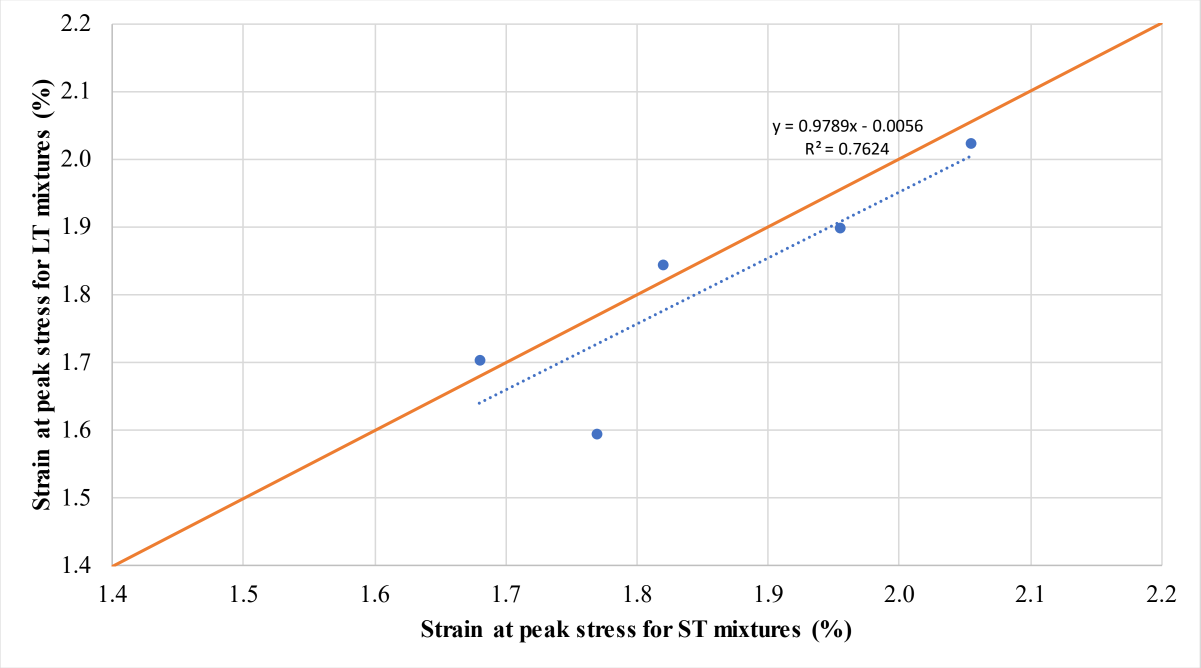


Figure 45. Fracture strain of ST mixtures versus LT mixtures.

Conditioning According to AASHOT R 30

It was mentioned previously that one of the mixtures was also conditioned according to AASHTO R 30. The main long-term conditioning protocol, discussed previously, is hereby referred to as the LT Conditioning 1, and the AASHTO R 30 protocol, which was only applied to two of the mixtures, is referred to as LT Conditioning 2. Two different rejuvenators were applied to two different mixtures, one with 35% RAP and one with 15% RAP and 5% RAS. It can be seen from the results presented in Figure 46 that in the case of the 15/5 mixture, the loose mix conditioning shows a more severe conditioning, as the IDEAL-CT index is lower. However, no difference is observed for the 35/0 mix between the two conditioning protocols. It should be noted that the rejuvenator content and the type of rejuvenator are different between these two cases, and most possibly contributing to the outcome. The severity of the loose mix conditioning is also observed from Figure 47, where for both 15/5 and 35/0 mixtures the loose conditioning delivers a higher indirect tensile strength compared with the AASHTO R 30 protocol.

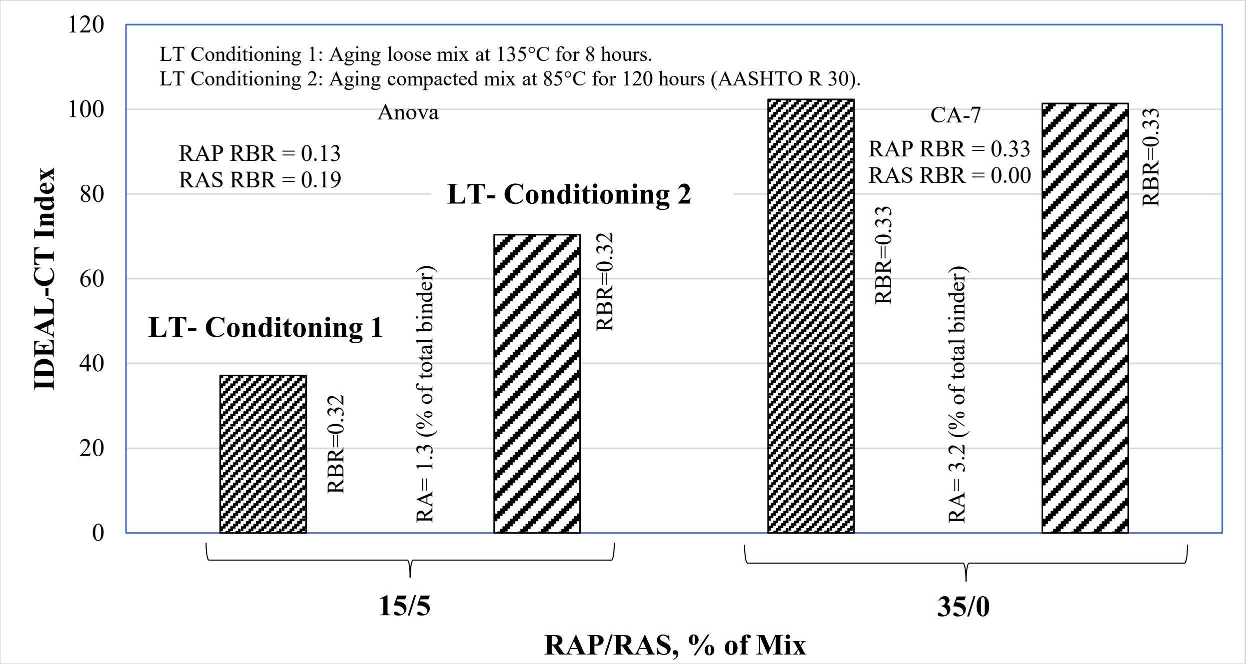


Figure 46. The effect of long-term conditioning technique on IDEAL-CT index.

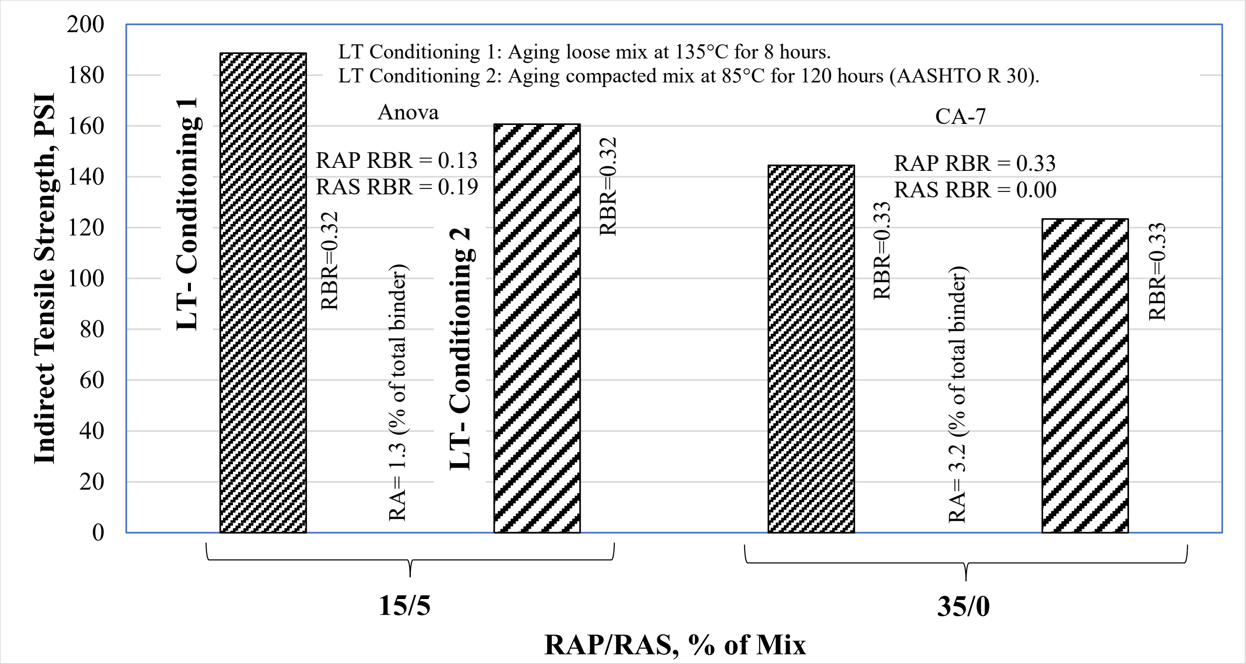


Figure 47. The effect of long-term conditioning technique on IDEAL-CT index.

The Effect of Blending Technique

It was discussed in Chapter 3 that two different methods were used to incorporate the rejuvenator into the asphalt mixtures: adding it directly to the virgin asphalt binder or incorporating it into the RAP, allowing it some time to interact with the aged binder. Details of these two methods were described in Chapter 3. To assess how these two different methods affect the results, for two of the mixtures the rejuvenator was applied using these two different techniques. For all other mixes, only method 2 was applied. The comparative results are presented in Figures 48 and 49 for the two mixes subjected to both techniques. It can be seen from both graphs that there is a higher IDEAL-CT index for method 2 (adding rejuvenator to the RAP) compared to method 1 (adding to the virgin binder). Statistical t-test indicated no significant difference between the IDEAL-CT index from the two methods for the mixture shown in Figure 48, but it did indicate that there is a statistically significant difference between the IDEAL-CT test results for the mixture shown in Figure 49. It appears that, in general, one may conclude that adding the rejuvenator to the RAP rather than adding it to the virgin binder most probably results in higher effectiveness of the RA. One can see that the results are similar. In a similar study, Xie et al. (2020) looked at four different methods of adding rejuvenators and concluded that statistically similar results were observed.

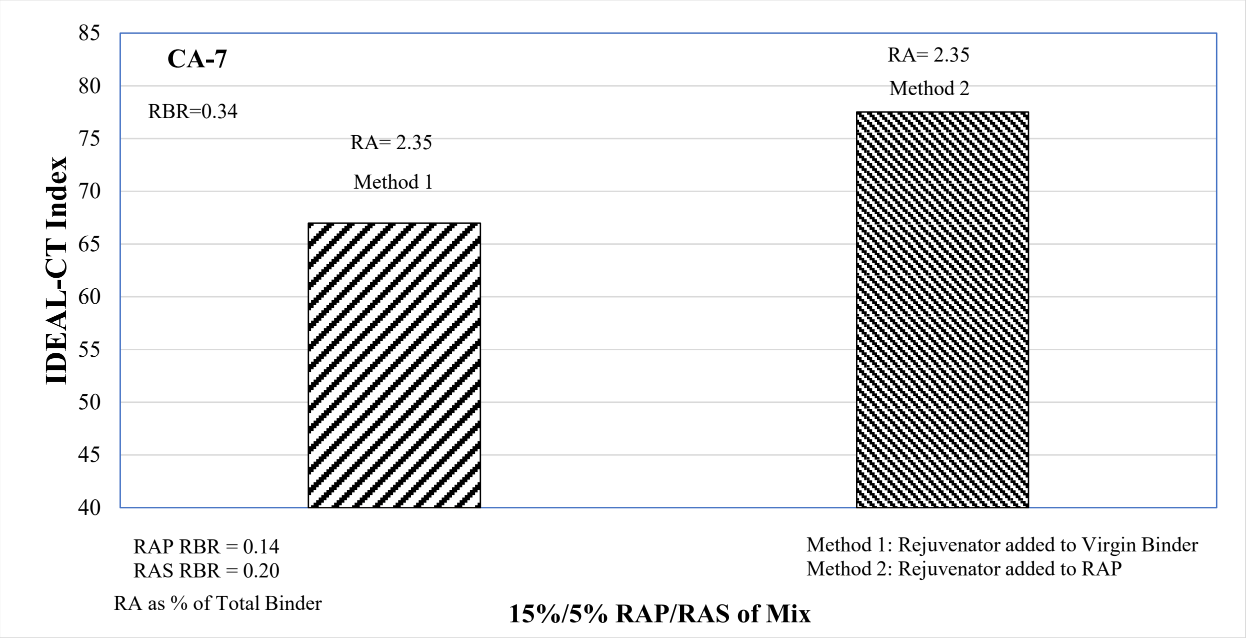


Figure 48. IDEAL-CT index for two methods of incorporating the rejuvenators (15% RAP/5% RAS mix).

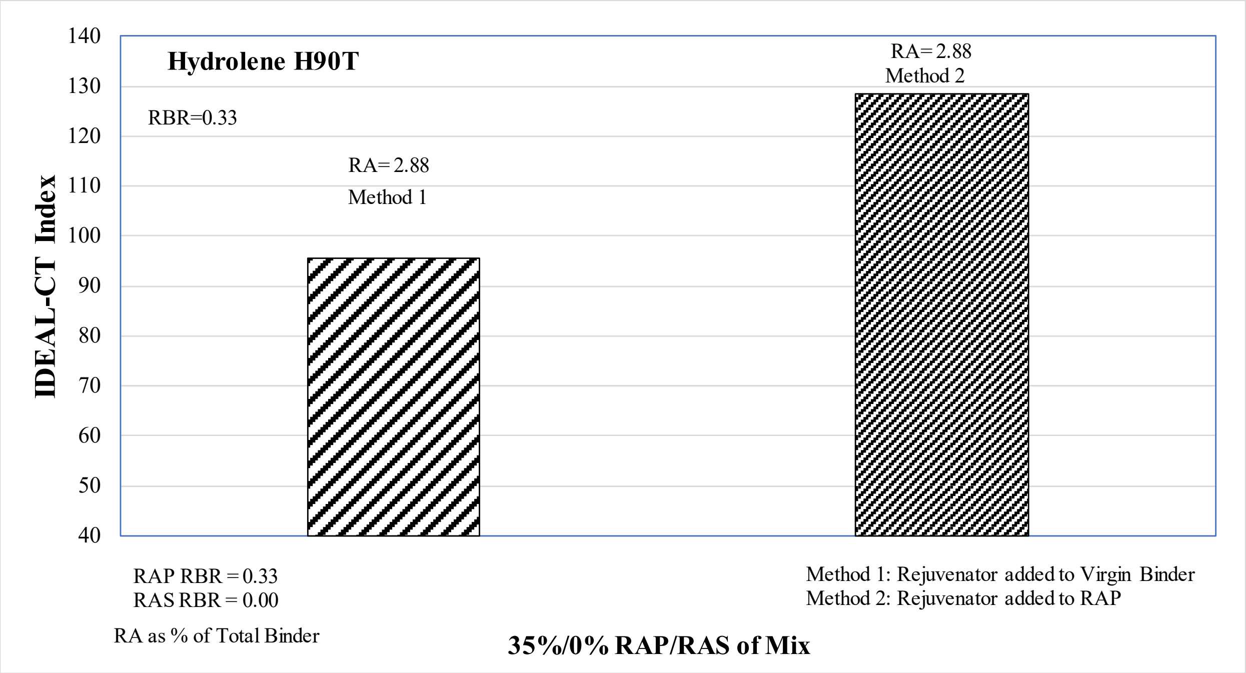


Figure 49. IDEAL-CT index for two methods of incorporating the rejuvenators (35% RAP mix).

For all other parameters (indirect tensile strength and fracture energy of IDEAL-CT test and rutting from HWT test) similar results were found. These results are presented in Figures 50 through 55.

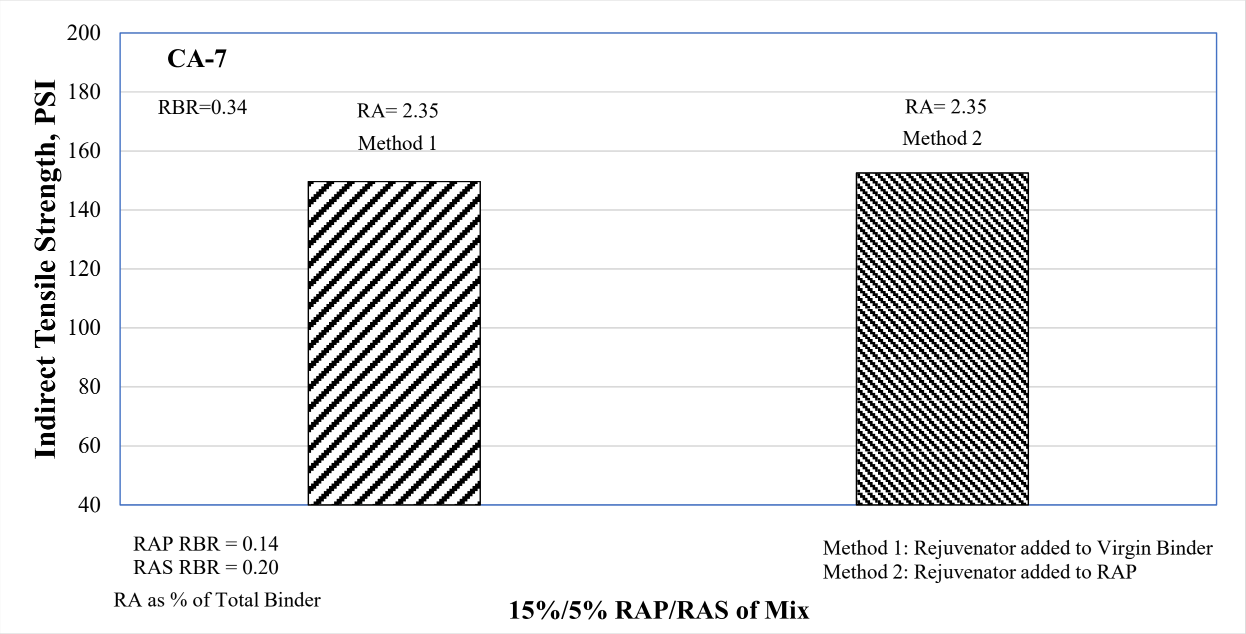


Figure 50. Indirect tensile strength for two methods of incorporating the rejuvenators.

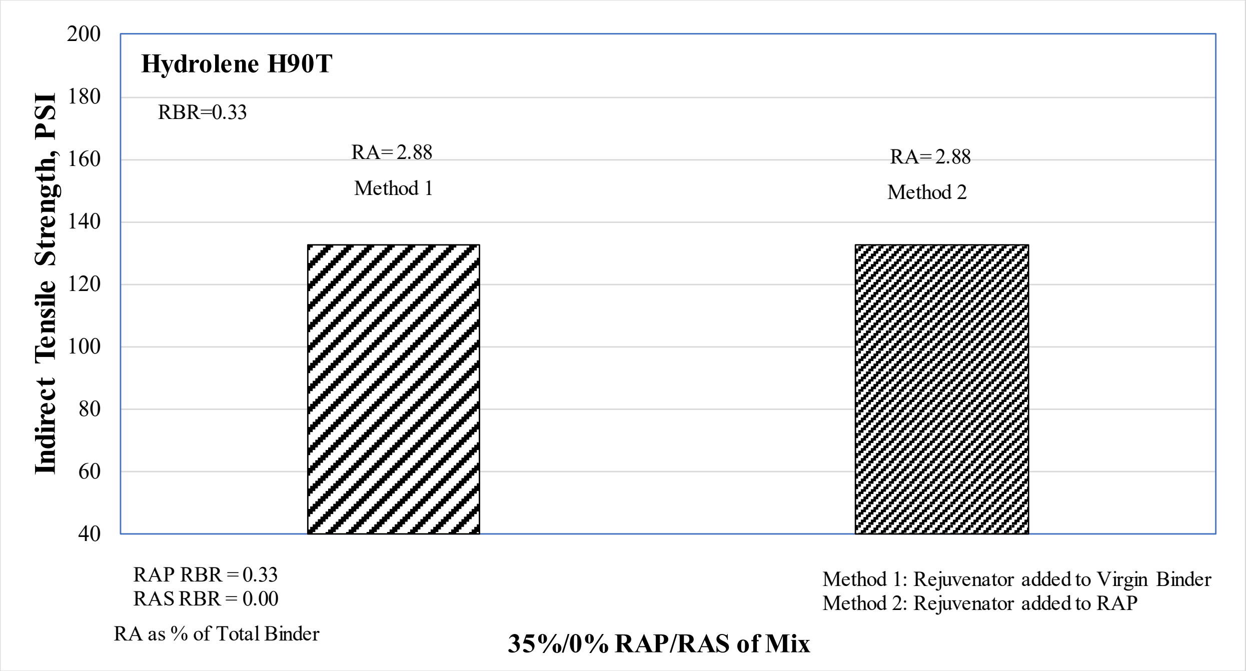


Figure 51. Indirect tensile strength for two methods of incorporating the rejuvenators.

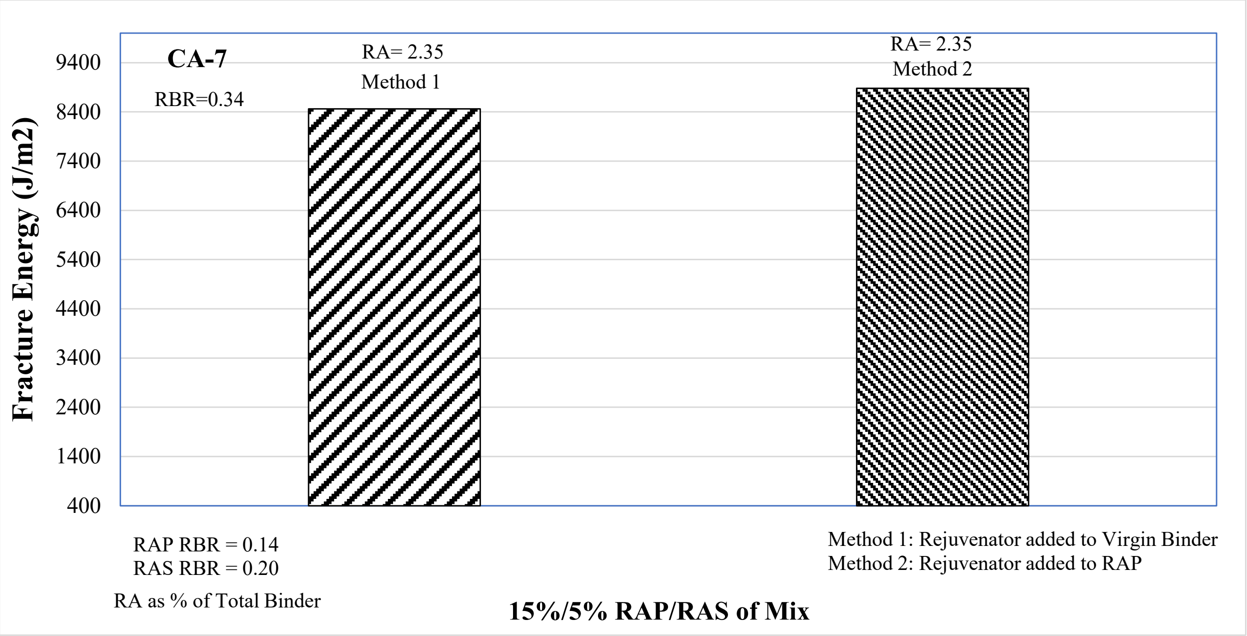


Figure 52. Fracture energy for two methods of incorporating the rejuvenators (15% RAP/5% RAS mix).

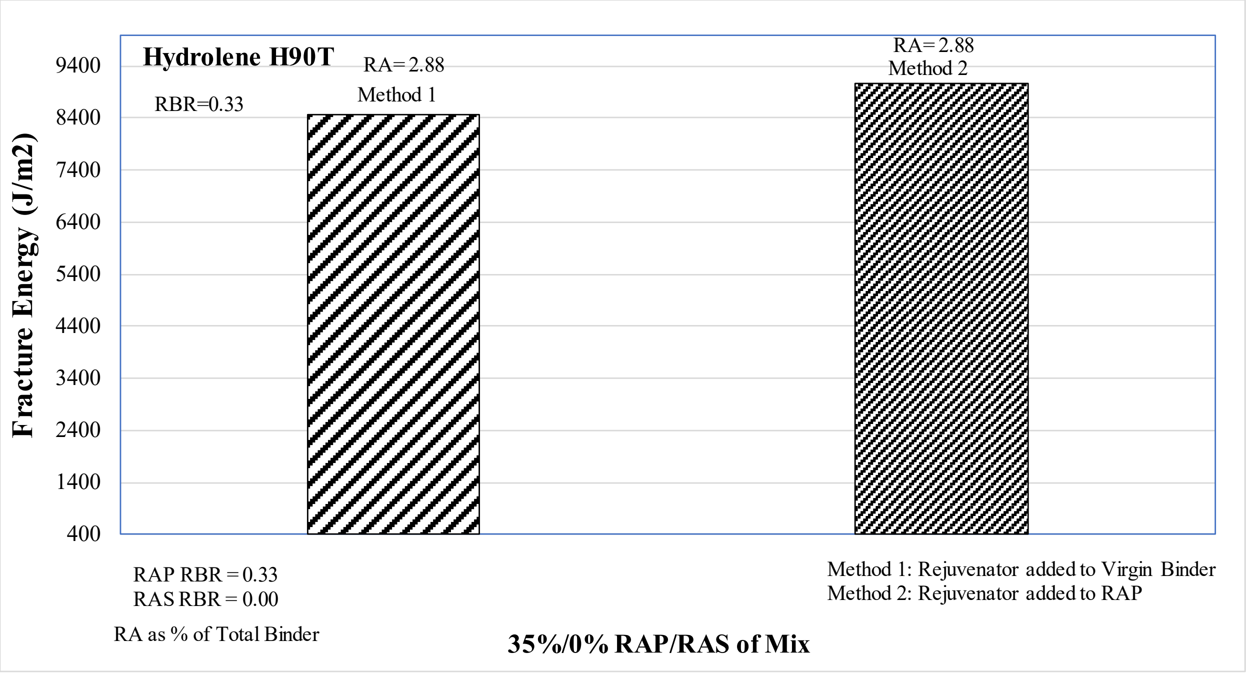


Figure 53. Fracture energy for two methods of incorporating the rejuvenators (35% RAP mix).

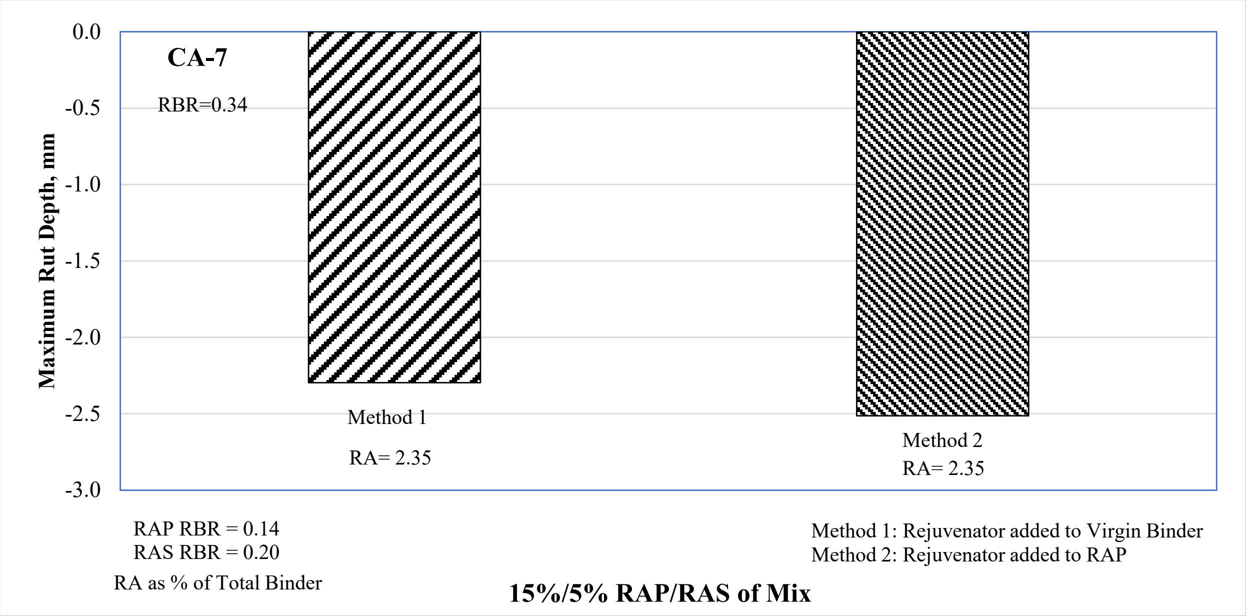


Figure 54. Max. rut depth for two methods of incorporating the rejuvenators (15% RAP/5% RAS mix).

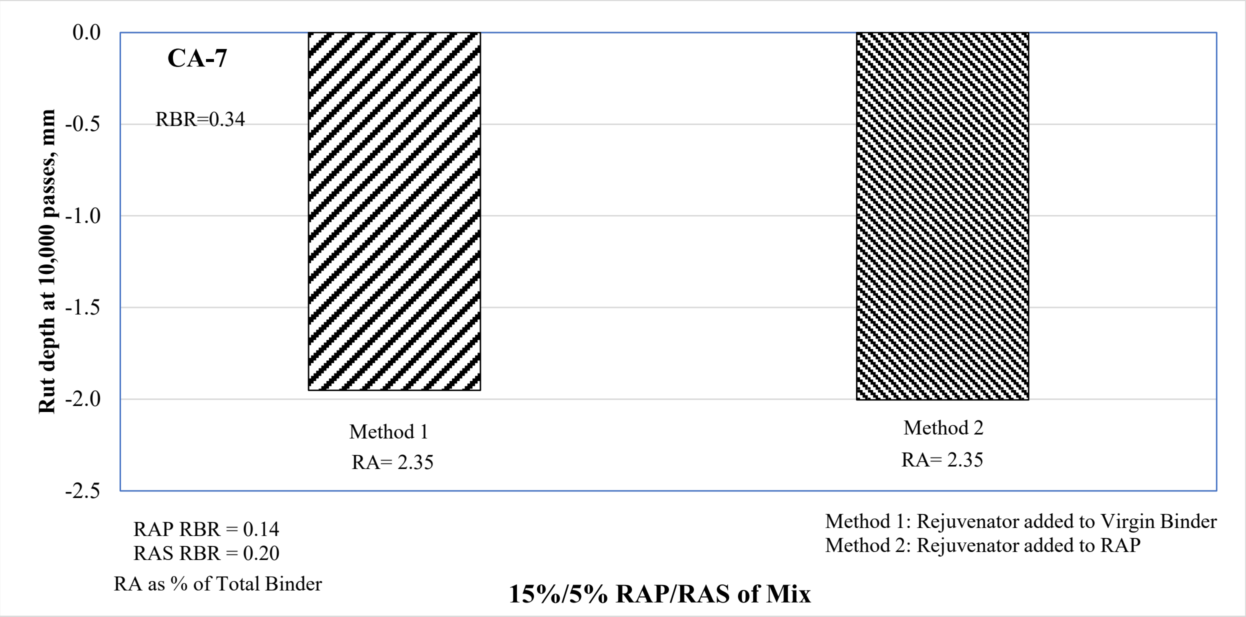


Figure 55. Rut depth at 10,000 passes for two methods of incorporating the rejuvenators (15% RAP/5% RAS mix).

CHAPTER 6

Summary, Conclusions, Recommendations

SUMMARY

A PennDOT-sponsored research effort was undertaken to investigate the use of recycling agents (RA, also referred to as rejuvenators) with Pennsylvania asphalt mixtures and establish guidelines for their application. The study included an extensive laboratory testing of both asphalt binders and asphalt mixtures. The study was focused on asphalt mixtures with a 9.5-mm nominal aggregate size, containing reclaimed asphalt pavement, recycled asphalt shingles, or a combination of RAP and RAS. Five different rejuvenating agents were included in the binder study and four in the mixture study. One of the rejuvenating agents was petroleum based and the rest were bio-based and vegetable-oil based. In the binder study, these recycling agents were incorporated at various dosage rates into the virgin binder or into the RAP binder. The binder study only included RAP, and no RAS was included. Rheological properties of the blended binders were determined at various aging conditionings (unaged, short-term aged, and long-term aged) to assess the impact of the RA.

In the mixture study, the rejuvenators were incorporated at the manufacturers' recommended dosage rates. They were added to the RAP for all of the mixtures studied. For one of the mixtures, the rejuvenator was also added to the virgin binder. The design for these mixes was verified based on the Superpave volumetric mix design process before preparation of the gyratory specimens for testing. The mixtures were subjected to the Hamburg wheel tracking test and Indirect Tensile Cracking (IDEAL-CT) test. In general, the study of these asphalt mixtures was conducted with the goal of investigating the following:

- how the RA impacts the rutting and cracking potential of the asphalt mixtures;
- how the blending technique impacts the results (adding RA to the binder versus adding to the RAP);
- how the aging process impacts the results (long-term aging versus short-term aging of the asphalt mixtures); and
- what are the performance grade and characteristics of the binders in the asphalt mixture.

The last item of the preceding list was studied after recovering the binder from the mixture and conducting rheological tests on the recovered binder.

CONCLUSIONS

Results from the Binder Study

The first section of the study dealt with the effects of rejuvenating agents on the binder rheological properties when directly incorporated into the binders. Five different rejuvenators, two virgin binders, and one RAP source were considered for part of the research study. The study included investigating the effect of rejuvenators on the rheological properties of binders when subjected to different aging levels and was conducted in four parts: (1) study of the virgin binder, (2) study of the RAP binder, (3) study the blend of virgin and RAP binders, and (4) study of the binder recovered from the asphalt mixtures containing RAP/RAS and rejuvenating agents.

The binder study was conducted in four parts. In Part 1, PG 64-22 binder was modified with all five rejuvenators at 3% dosage rate. The exception was the binder modified with Ingevity CA-7, for which 0.4% of P25 liquid antistripping agent was also added following the manufacturer's recommendation. In Part 1, PG 64-22 and PG 58-28 were also tested as control (reference) materials. The reference binders and all modified binders were tested unaged and also tested after short-term and long-term aging. There were two conclusions from this part of the study. First, it was determined that the 3% dosage rate, while softening the binder, did not completely bring it to a level of PG 58-28. The more important finding was related to the effect of conditioning. The concern was that the rejuvenator may lose its effectiveness as the binder ages and oxidizes. However, the results of the Case I study indicated that all the rejuvenators could maintain their effectiveness even after aging, albeit to various degrees.

In Part 2, two dosage levels of rejuvenator (5% and 10%) were incorporated with extracted RAP binders. Numerous extraction and recovery tests were conducted to obtain an adequate amount of RAP binder for this part of the study that included three of the five rejuvenators. The unmodified RAP binder and the rejuvenator-modified RAP binders were tested for rheological properties at both high and low temperatures and before and after short-term aging. Two of the modified binders were also long-term aged with pressure aging vessel to determine the long-term properties.

In Part 3, two of the rejuvenators were added to the blend of virgin binder (PG 58-28) and the RAP binder at a ratio of 65/35% (recycled binder ratio, RBR = 0.35). The rejuvenator was added in at the rate of 2% by the mass of total binder (5.7% based on mass of RAP binder, and 3.1% based on mass of virgin binder). The results in Part 2 were utilized to develop two blending charts (one targeting high temperature and one targeting low temperature) for determination of the rejuvenator dosage rate. To utilize the chart, the virgin binder grade, the design binder grade, the RAP binder grade, and RBR need to be known. Study of Parts 1 and 2 again indicated that the rejuvenator does not lose effectiveness with aging. It was also found that ΔT_c, a measure of binder potential for non-load-related cracking, tends to decrease in the negative direction with further aging, but the rejuvenation counteracts this behavior.

In Part 4, the binder was recovered from the asphalt mixtures containing RAP, RAS, and rejuvenators. The mixture study included four rejuvenators, but two of the four rejuvenators were included in the recovered binder study. The recovered binders were subjected to aging and rheological testing. The results indicated that at the dosage levels recommended by the manufacturer, even after RTFO aging, the rejuvenators were beneficial in reducing the cracking potential of the binders.

Results from the Mixture Study

The results from the mixture study addressed the effect of rejuvenators on the mixture performance indices, the effect of blending techniques, and the effect of aging. Consistently, it was found that the rejuvenators would not compromise the rutting and moisture damage resistance of the mixtures when incorporated at the manufacturers' recommended dosage rates. The HWT results indicated good to excellent performance for all of the mixtures. No stripping inflection point was reached for the tested mixtures, except a few cases for which SIP was reached at a high number of wheel passes. Even for those mixtures, the maximum rutting was very limited and well below the acceptance threshold. The IDEAL-CT test results consistently exhibited an increase in the mixture IDEAL-CT index when RA was incorporated into the mixture. The increase in this index was accompanied by a reduction in indirect tensile strength. However, the decrease in strength was limited and still maintained at an acceptable level. There was also a decrease in fracture energy as a result of incorporating RA, even though to varying degrees depending on the type and amount of RA in the mixtures.

Investigating the blending technique was limited to one of the mixtures. The widely used approach in this research was adding the RA to the RAP, except one mixture for which RA was also added to the virgin binder. For this mixture, it was found that HWT test results were almost the same for both methods; however, there was some increase in IDEAL-CT index when RA was added to the RAP compared to when it was added to the binder. Statistical analysis indicated no significant difference between the IDEAL-CT index obtained from these two methods of RA application.

Four of the mixtures were subjected to long-term aging before performance index testing. This was done to assess the impact of long-term aging, as cracking potential increases when the pavement undergoes aging with time. The results indicated that, consistently, the IDEAL-CT decreased and indirect tensile strength increased as a result of long-term aging. This is obviously expected, indicating the importance of establishing the acceptance/rejection criterion for a mixture based on the aging and conditioning scheme.

Several of the asphalt mixtures were processed for extraction and recovery of the binder. The recovered binder was tested at different aging levels to establish the binder grade and ΔT_c. It was again consistently shown that the RA reduced the performance-grade temperature of the binder both at the high and the low temperatures. The decrease in the high-temperature grade still maintained the asphalt mixture at a rut-resistance level and did not appear to be of concern. In practice, the amount of rejuvenator is mainly established based on the low-temperature grade to reduce the cracking potential, and the results from this study indicate that indeed an improvement is made in this regard when RA is utilized.

The findings of this study on the properties of modified binders are generally consistent with the results of the literature review conducted under Task 1 of this research. This work, in line with past research, indicated that the selected rejuvenators acted as true rejuvenators rather than simply softeners, as evidenced from the rheological data from testing long-term-aged, modified binders, and indeed improved the rheological properties of the RAP binder and virgin binder blends. There were differences among the rejuvenators in terms of their effectiveness and the needed dosage rate, as expected. One observation in this research, which is also in line with the findings from the literature review, is the effect of the petroleum-based rejuvenator. In this research, it was found that the single petroleum-based rejuvenator had to be applied at a higher dosage rate to deliver the same effect as the bio-based rejuvenators, as evidenced in some of the past research.

RECOMMENDATIONS

General Recommendations

This research showed that when rejuvenators are added to mixtures with a high RAP content or mixtures containing a combination of RAP and RAS, the mix performance is improved when it comes to low-temperature cracking and fatigue cracking. However, one should not lose the sight of the fact that this research was solely dedicated to a laboratory investigation on laboratory-prepared asphalt mixtures, and extension of this work to field pilot projects is essential to ensure effective application of the rejuvenating products. As was shown in the research report NCHRP 927 (Epps et al., 2020), the laboratory results may not necessarily be indicative of field performance of the asphalt mixtures when recycling agents are involved.

Appendix A of this document, *A Guide to the Use of Recycling Agents in Asphalt Paving Mixtures*, provides recommended protocols on how to establish the dosage rate for a given recycling agent and how to evaluate its long-term effectiveness. The guide shows how the dosage rate can be determined based on three different methods. One is through providing the RA manufacturer with the required mix and binder information to establish the appropriate dosage rate; one is based on using the blending chart; and the last one is based on the mix performance testing and balanced mix design.

The guide in Appendix A also presents the processes used to ensure that the rejuvenating agent maintains its effectiveness with time as the asphalt pavement ages and becomes more brittle. Evaluation of such effectiveness can be either conducted through binder testing or asphalt mixture testing. In the case of the latter, the long-term effectiveness is evaluated using an asphalt concrete cracking test such as the IDEAL-CT index test. Currently, the IDEAL-CT index values recommended for inclusion in the PennDOT Bulletin 27 are based on short-term conditioning of the asphalt mixtures. To ensure long-term effectiveness, there will be a need to include threshold values for the index when tested after the mixture has been subjected to long-term conditioning.

Implementation Plan

First and foremost, it is crucial that an implementation plan be set in place in Pennsylvania to take the results from this laboratory work into the field application. Such a plan should include testing plant-produced mixes and comparing the results versus laboratory-prepared mixes at the mix design stage and at early stages of the project. The plan should also address the methods of incorporating the rejuvenator into the mixtures—whether it should be added to the virgin binder, which is the most common approach, or added to the RAP/RAS and allowed some cure time. It may be best to include both techniques in an implementation plan and compare the results. Obviously, what can be done at a plant is highly dependent on feasibility and without complicating the plant operation. Finally, it will be important to include small strips of control sections without incorporation of rejuvenating agents for comparison.

Full implementation of the revised PennDOT specifications will require planning and taking a sequence of steps to ensure success of the system. Taking the results from this research into practice and building pilot projects under special provisional standards is a necessary step toward revising relevant PennDOT publications and standard specifications. It is expected that ultimately changes will be applied to Section 413 of Pub. 408, Chapter 2A of Bulletin 27, and the *Project Office Manual* (Pub. 2).

Preparation and planning must be well thought out and developed before action. Lack of planning, without having a clear vision of the goal and the approach that needs to be taken, will probably lead to failure of the implementation program. Expectations must be realistic in regard to time and the requirements, as the change in mix production using RAP/RAS under new specifications will probably cause some anxiety initially. Partial implementation, such as using pilot projects, increases the chances of success before going the full implementation route. The plan is proposed to include eight critical steps.

1. Identify Requirements for Implementation
2. Identify Producers
3. Conduct Pre-implementation Orientation
4. Develop Implementation Schedule
5. Develop/Execute Performance Monitoring
6. Develop/Execute Measures of Success
7. Conduct Post-Implementation Meeting
8. Conduct Technology Transfer/Training

The first step to a successful implementation will be to set a clear roadmap (identify requirements for implementation). This step will be followed by identifying producers who have the experience and who would be willing to participate in this plan. Once producers are established, orientation, scheduling, and performance monitoring take place. The success of the executed project must be decided based on the established metrics. Finally, the results should be communicated with

PennDOT and industry stakeholders through a reasonable program of training and technology transfer.

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APPENDICES

APPENDIX A
A Guide to the Use of Recycling Agents in Asphalt Paving Mixtures

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August 24, 2022

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Objective of this Document

The objective of this document is to provide guidance on the use of recycling agents (rejuvenators) with Pennsylvania asphalt mixtures. It is intended for use by PennDOT, asphalt producing contractors, consultants, and those involved with the design and construction of asphalt pavements in PA.

Scope

This guide consists of two parts. Part 1 covers relevant terminology, references, and background information on recycling agents (rejuvenators). Part 2 presents the asphalt mix design considerations, concerns when incorporating rejuvenators, and guidance on evaluating the effectiveness of rejuvenators when used with the asphalt mixtures. This guide applies only to the asphalt mixtures produced in a hot-mix or warm-mix asphalt plant. It does not apply to surface seals, chip seals, stress-absorbing membranes, or cold mixes.

Part 1: Terminology, References, and Background Information

Terminology

- **Rejuvenator:** (also referred to as **recycling agent** or **rejuvenating agent**): the material incorporated in asphalt binder or asphalt mixture in liquid form to enhance performance properties and reduce cracking potential of the asphalt mixture by rebalancing the asphalt binder constituents.
- **RAS:** Recycled asphalt shingles, either post-consumer or a by-product of manufacturing.
- **RAP:** Reclaimed asphalt pavement, the asphalt mixture milled from the asphalt pavement.
- **RBR:** Reclaimed binder ratio.

Reference Documents

- **ASMT D2170:** Standard Test Method for Kinematic Viscosity of Asphalts
- **ASTM D4552-20:** Standard Classification for Hot-Mix Recycling Agents
- **ASTM D8225-19:** Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature
- **AASHTO R 30**: Standard Practice for Mixture Conditioning of Hot Mix Asphalt
- **AASHTO R 28:** Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)
- **AASHTO M 320:** Standard Specification for Performance-Graded Asphalt Binder
- **AASHTO M 332:** Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test
- **AASHTO T 240:** Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt (Rolling Thin-Film Oven Test)
- **AASHTO T 315:** Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)
- **AASHTO T 313:** Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)
- **PennDOT Bulletin 15 (Pub 35):** Qualified Products List for Construction
- **PennDOT SOL** 481-22-01: Bulletin 27 (Pub. 27) BMD Revisions

Background

Recycled materials such as reclaimed asphalt pavement (RAP) have been utilized in asphalt mixtures for decades, but their application has significantly increased with time, since incorporating these materials in asphalt is believed to reduce the cost of asphalt mixtures, conserve energy, and protect the environment. Similarly, the use of recycled asphalt shingles (RAS) has attracted considerable attention lately and their use in asphalt mixtures is currently pursued by several state highway agencies. However, unless necessary measures are taken, as the amount of RAP and RAS increases in the asphalt mixture, the mix tends to become more brittle, increasing the risk of cracking and raveling of the asphalt pavement. The mix will also be less workable and more difficult to compact in the field, again increasing the potential for premature field failure. Among ways of allowing more RAP and RAS in the asphalt mixtures is the use of special recycling agents (RA), sometimes referred to as rejuvenating agents or simply rejuvenators. The term "rejuvenator" may not be a suitable term, as this modifier rebalances the proportions of the binder composition rather than breaking the oxidation within the binder, but it is a common term used by many in the asphalt industry, including this guide. Aging of the asphalt mixture during construction and during the long-term service of asphalt pavements results in oxidation of the mix and loss of a large portion of the maltenes in the binder composition. Maltenes provide the softening effect in the binder, and these recycling agents, when properly used, are expected to compensate for this reduction of maltenes. The final effect of the act of rebalancing the constituents will be softening of the aged binder and improving its crack resistance.

Types of Rejuvenators

Not all additives promoted as rejuvenators are "true" rejuvenators. It is important to distinguish between those that work as softeners or plasticizers and those that restore the asphalt binder properties long-term. A true rejuvenator will interact with the aged binder in a way that breaks the bond between layers of asphaltene (heavy component in asphalt) and peptizes asphaltenes (i.e., reduces the size of asphaltene agglomerations). Through such action, the rejuvenator restores the binder properties associated with the maltene (the oily component of asphalt). Ideally, a good rejuvenator will not only improve properties of aged binder but also be easy and safe to use. A suitable rejuvenator must also be stable and fully miscible with asphalt.

The asphalt paving industry has been exposed to numerous brands of rejuvenators over the last three decades. These rejuvenators can, in general, be classified into two groups: petroleum driven and agricultural/plant driven. The petroleum-based rejuvenators are mainly promoted as additives capable of enriching the maltene concentration in the aged asphalt and breaking asphaltene clusters, creating a compatible colloidal system. Examples of petroleum-based rejuvenators include paraffinic oil and aromatic extracts, engine oil or re-refined engine oil bottom (REOB), even though the last one has been shown to deliver poor long-term performance. In regard to petroleum-based rejuvenators, the use of those with high paraffin content (saturated compounds) is discouraged, while the use of those with high aromatic extracts (unsaturated hydrocarbons) is promoted. Past research indicates that asphalts with higher content of polar compounds and reactive aromatics and lower amounts of paraffins are more stable (White et al., 1970).

The plant-derived additives, also known as bio-based additives, are promoted to enhance performance based on their viscosity reduction capabilities, composition, and peptizing of asphaltenes. The plant-derived rejuvenators include those produced from vegetables and plants. Examples include vegetable oil (glyceride and fatty acid), modified vegetable oil, and tall oil that is a by-product of the paper manufacturing process from pine trees (Epps et al., 2020). To this list one could add waste vegetable oil and reacted bio-based oils. The reacted bio-based oil is engineered to reduce oxidative aging of the binder.

ASTM D4552 provides a classification of the recycling agents based on their viscosity when measured according to ASTM D2170. This classification defines the recycling agents in seven groups depending on their viscosity. The range in viscosity is extremely wide based on this classification. For example, for Group RA 0 (the lowest viscosity group), the range in viscosity is between 10 and 49 mm^2/s, whereas for Group RA 500 (the highest viscosity group), the range is between 37,500 to 60,000 mm^2/s. However, this standard does not address the binder and mixture performance when recycling agents are used, and it does not cover the effect of the recycling agent on the binder performance grade.

Blending Techniques

Regardless of whether RA is blended into asphalt in a laboratory environment or in a field application, the recycling agent can be incorporated into the asphalt mixture in two general ways: (1) adding it to the virgin binder or (2) adding it to the mixture. In the latter case, there are several approaches that one can follow. For example, it could be added to the RAP, or the RAS, if applicable. It could also be directly placed into the hot mixture at the same time the virgin binder is added to the mixture of asphalt and aggregate. Since the main purpose of RA is rebalancing the recycled binder composition and reducing its brittleness, it is believed that the best and most effective approach will be adding it directly to the RAP and allowing some time for interaction and diffusion of the RA into the RAP binder before feeding it into the mixing drum or the pugmill. Figure 1 presents various techniques that are available for incorporating the recycling agent into the asphalt mixture.

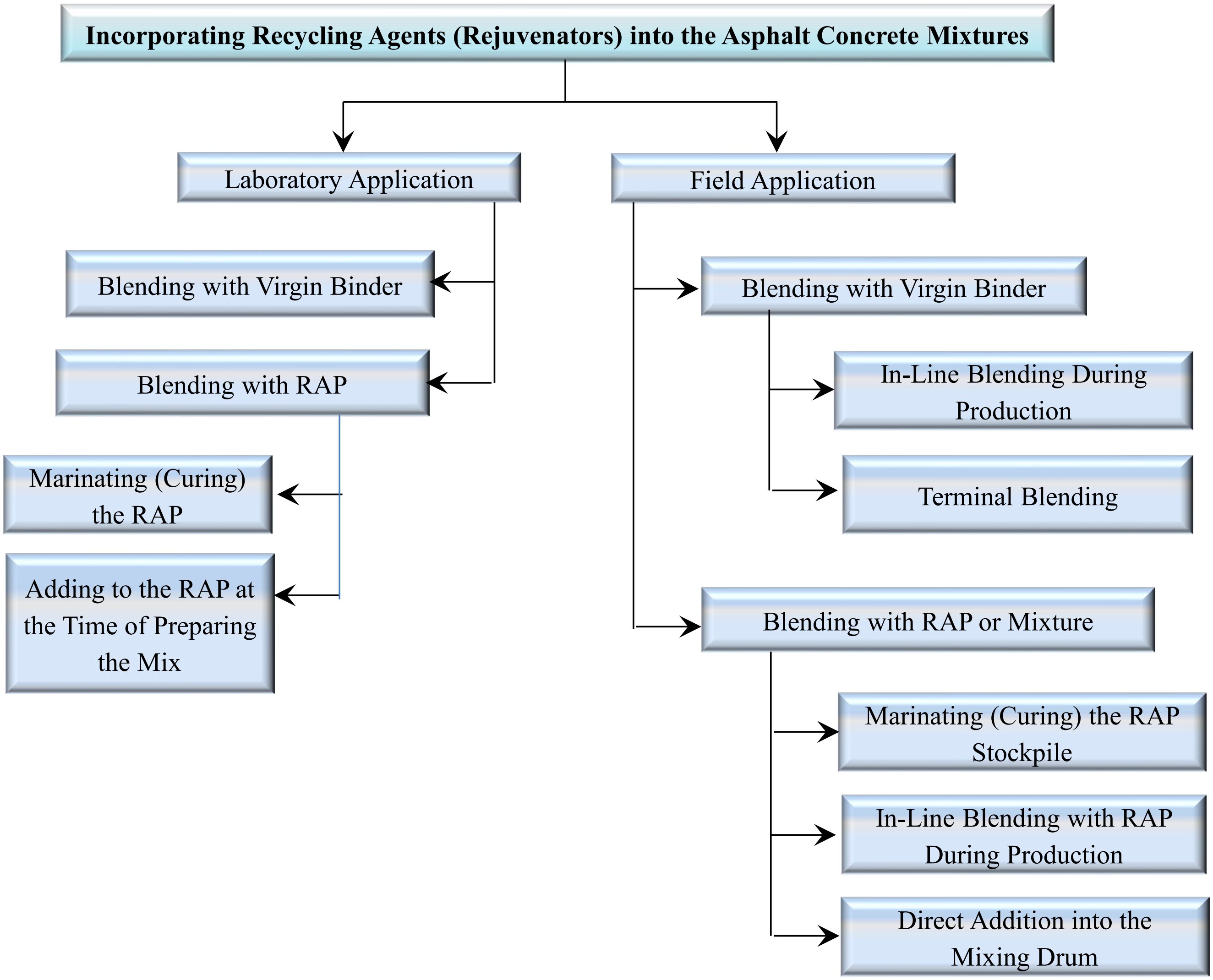

Figure 1. Various techniques of incorporating the recycling agent into the asphalt mixtures.

Research on the blending techniques has produced mixed results on which method is the best. It appears that adding it to the virgin binder has been the most common approach, as it is a simpler method compared to other options. Consideration must always be given to the feasibility of application in the plant, whether modifications to the existing equipment will be needed, and to the production cost. In case of using RAS, it is best to maintain the RAS stockpile at a proportioned blend with fine aggregate (for example, a blend of 50 percent RAS and 50 percent fine aggregate) to avoid agglomeration of the RAS due to high binder content. In this case, RA could be added to this blend, giving it sufficient time to cure and to diffuse into the RAS binder before feeding it into the drum. Further research is needed to determine if the marination process would indeed produce a more effective blending technique compared to direct application into the virgin binder. At this point, however, it is recommended that, for the conditions presented in Table 1, the RA be blended with the RAP or both the RAP and RAS to allow sufficient time for interaction instead of adding it to the virgin binder. In other cases, either direction incorporation into the virgin binder or adding to the RAP/RAS could be utilized.

Table 1. Adding RA to RAP/RAS is the preferred option for the following conditions.

Recycled Material	RBR	RAP High-Temperature Grade (HTG), C
RAP Only	0.40	≥ 90
RAP Only	0.45	≥ 82
RAP/RAS Combination	0.35	

It is also recommended that the blending technique selected for use during production also be applied during the mix design stage. In other words, it is best to utilize the same approach during both design and production of the mix.

Part 2: Mix Design Considerations for Asphalt Mixtures Containing RA

Selection of the Recycling Agent

The recycling agent for use with asphalt mixtures on PennDOT construction projects must be selected from the listing of prequalified products, as covered in PennDOT Bulletin 15 (Publication 35).

Determination of the Rejuvenator Content Based on Performance Grades of the Binders

Factors to Consider for Dosage Rate Determination

Different manufacturers of recycling agents rely on different sources, materials, and techniques in their production, and subsequently their products are vastly different in nature and origin. As a result, the appropriate or optimum amount of the recycling agent for use in a specific asphalt mixture is expected to be different depending on the type of RA used. The dosage rate selected for a specific RA must not be assumed to be suitable for a different RA. It is obvious that the rejuvenator content not only depends on the type of rejuvenator but also on several other factors, including the properties and amount of the virgin binder, the RAP, and the RAS, as well as the target binder grade and the design binder content.

An Example Scenario

Consider the information provided in Table 2 as an example for designing a specific asphalt mixture. This type of information is needed to determine the suitable RA dosage rate. Table 3 provides examples of the amount of a rejuvenator needed for different RAP/RAS content scenarios and based on the input information provided in Table 1. It is important to note that the information provided in Tables 2 and 3 are just examples for an imaginary rejuvenating agent. The appropriate amount of RA depends on the specific type of RA incorporated into the mixture.

Table 2. Example binder information for an asphalt mixture.

Material	Amount (Content)	Binder Grade (°C)
Virgin Binder	Variable	PG 58S-28 (True Grade: PG 60-29)
RAP Binder	5.9 (% of RAP)	PG 89-14
RAS Binder	23.0% (% of RAS)	PG 137+2 (+2 is the low-temperature grade)
Design Binder (Final Blend)	5.4% (% of total mix)	See Table 2

Table 3. An example scenario for rejuvenator content to achieve a target binder grade.

					Amount of Rejuvenator Needed to Satisfy the Final Grade				
% RAP in Mix	% RAS in Mix	RAP RBR	RAS RBR	Target Temperature	% of Total Binder	% of Virgin Binder	% of Recycled Binder	% of Mix	Final PG, °C
35	0.00	0.38	0.0	Low End	1.83	3.06	4.79	0.10	67.5-2.1
				High Temp	0.56	0.91	1.46	0.03	70.0-24.4
45	0.00	0.49	0.0	Low End	2.63	5.47	5.36	0.14	69.1-27.0
				High Temp	2.18	4.49	4.44	0.12	70.0-26.1
0	5	0.0	0.21	Low End	2.26	2.95	10.59	0.12	72.0-27.0
				High Temp	3.28	4.35	15.41	0.18	70.0-29.1
0	8	0.00	0.34	Low End	4.20	6.8	12.32	0.23	78.1-27.0
				High Temp	8.33	14.46	24.44	0.45	70.0-35.4
15	5	0.16	0.21	Low End	3.46	5.88	9.18	0.19	74.4-27.0
				High Temp	5.72	10.10	15.17	0.31	70.0-31.6

Most often, the RA content is reported as a percent of total binder content, virgin binder content, or recycled material binder content. The rejuvenator content in Table 2 is reported as a percent of all these three parameters, also as a percent of the total mix. Reporting the RA content as a percent of total mix mass is useful to indicate how the total fluid content of the mix changes. For example, when total binder content is 5.4% of the mass of the mix (as is the case assumed here) and 0.2% RA is added based on the mass of the mix, the total fluid content will be 5.6%. One can see that, for the example provided, the amount of rejuvenator as a percent of total mix varies in the range of 0.03 to 0.45. What this implies is that for an RA content of 0.45% (which is a very high end) as percent of the mix, the total fluid content in the mixture will be 5.95% (5.4% total binder content + 0.45% RA content).

It can be seen from Table 2 that for the example shown, depending on the RAP/RAS content, the rejuvenator content varies in a range of 0.56% to 8.33% when calculated as a percent of the total binder content of the mix. It is also very important to recognize that for a specific target grade, the dosage rate varies depending on whether the high-temperature grade (HTG) is targeted or the low-temperature grade (LTG). For example, for the case of asphalt mixture with 15% RAP and 5% RAS (with total RBR of 0.37), a dosage rate of 3.5% based on the total binder mass yields PG 74.4-27.0, matching the desired LTG (recall from the assumptions that the target grade is PG 70-27). However, to match the high-temperature grade, a dosage rate of 5.7% is needed. For a case like this, obviously, any dosage rate between these two numbers will be acceptable, as both high and low ends of the temperature grade will be satisfied.

In the example above, for the case of asphalt mixture with 15% RAP and 5% RAS, it can be seen that the dosage rate to achieve HTG is higher than that needed for LTG (5.7% versus 3.5%). However, in cases where a higher rate is needed to satisfy LTG compared to the dosage rate needed to satisfy HTG, only one end can be exactly satisfied. For example, in the case of 35% RAP (with RBR of 0.38), the dosage rates based on total binder are 1.8% and 0.6%, respectively. At 1.8% rejuvenator content, the target HTG is not satisfied. As we tend to decrease the amount of rejuvenator to satisfy HTG, the low-temperature grade gets compromised. Therefore, only one end can be satisfied at a time. In a case like this, if the intent becomes to truly satisfy both ends, there will be a need for further adjustments to the mix. However, it is mostly the low temperature which is of great concern due to the mix cracking potential, and typically the rejuvenator dosage rate is determined to ensure that the modified binder performance grade satisfies the low-temperature requirements.

Determination of the Rejuvenator Dosage Rate Based on Manufacturer's Recommendation

The diversity in the recycling agents and their corresponding properties make it impossible to use a dosage rate established for one rejuvenator for another. Every recycling agent is unique in properties and must be directly evaluated for optimum usage. The best approach is to provide the RA manufacturer with the information needed to recommend a suitable dosage rate. Information such as performance grade of the virgin binder, the RAP binder, and the RAS binder are needed along with the amount of each in the mixture and the target performance grade.

Determination of the Rejuvenator Dosage Rate Based on Blending Charts

It appears that the most common approach for determination of the RA dosage rate is the use of blending charts. Through these charts, one can determine the dosage rate that provides target properties for a given set of conditions (grades of virgin binder, RAP binder, RAS binder, and corresponding amounts in the mixture). In cases of softer RAP material (for example, HTG of 82 °C and LTG of -20 °C) and/or low RAP content (for example, RBR=0.20), in most cases it will not be necessary to use RA in the asphalt mixture. An example of such is presented in Figure 2 for the binder grade conditions and RBR shown on the graph. Note should be made again that HTG and LTG, as shown in the figure, refer to high-temperature performance grade and low-temperature performance grade, respectively. HTG is determined for the unaged binder or the binder that has been subjected to short-term oven aging according to AASHTO T 240. LTG is determined for the long-term conditioned binder according to AASHTO R 28.

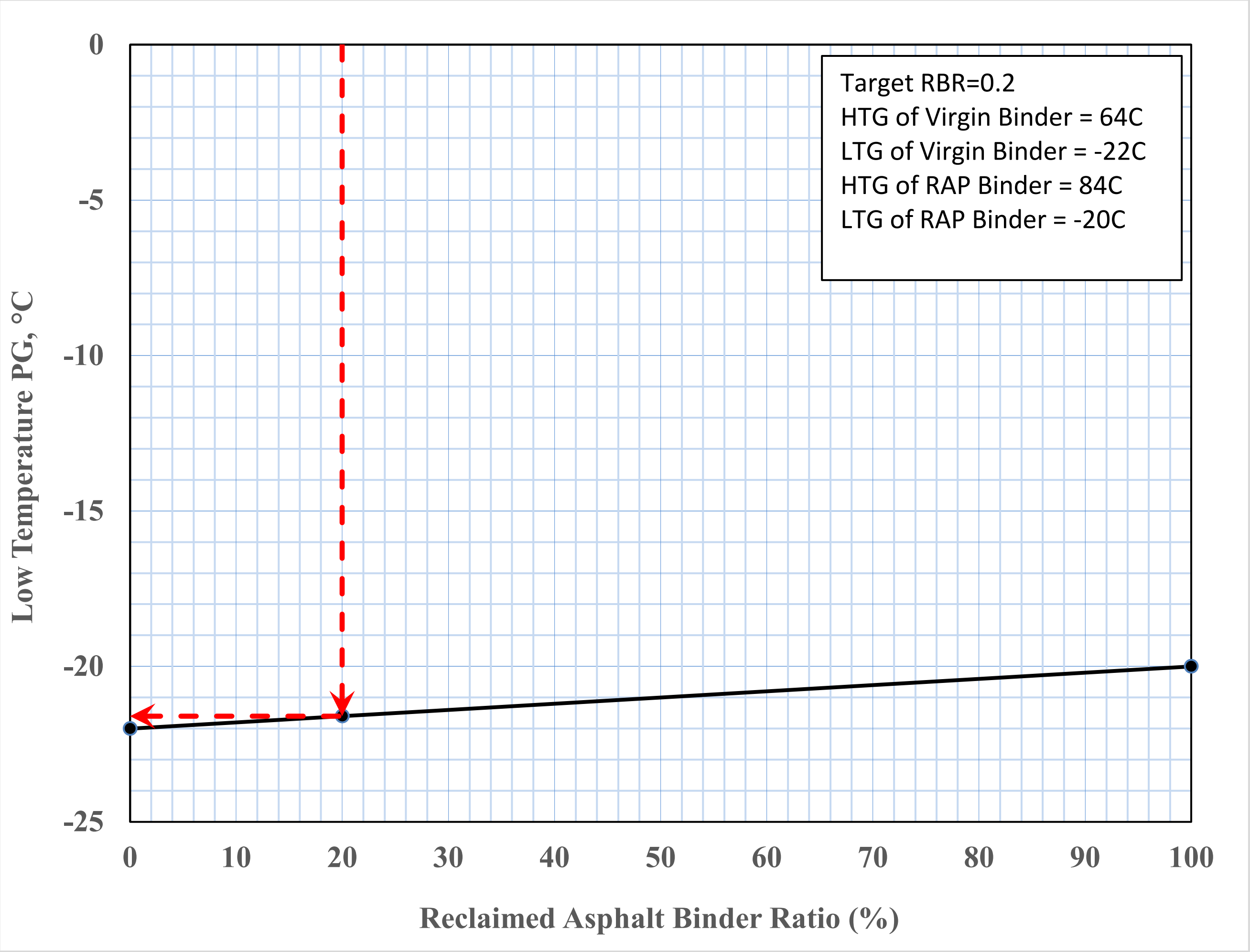

Figure 2. An example of a situation not requiring RA if targeting LTG of -22 °C.

The conditions shown in Figure 2 deliver a target binder grade of PG 68-22. If the goal is to extend the LTG of the blended binder (for example, reducing it from -22 °C to -28 °C), then it may be necessary to either use a softer binder or a recycling agent. Of course, it will be subsequently necessary to ensure that the HTG is not compromised because of the addition of RA.

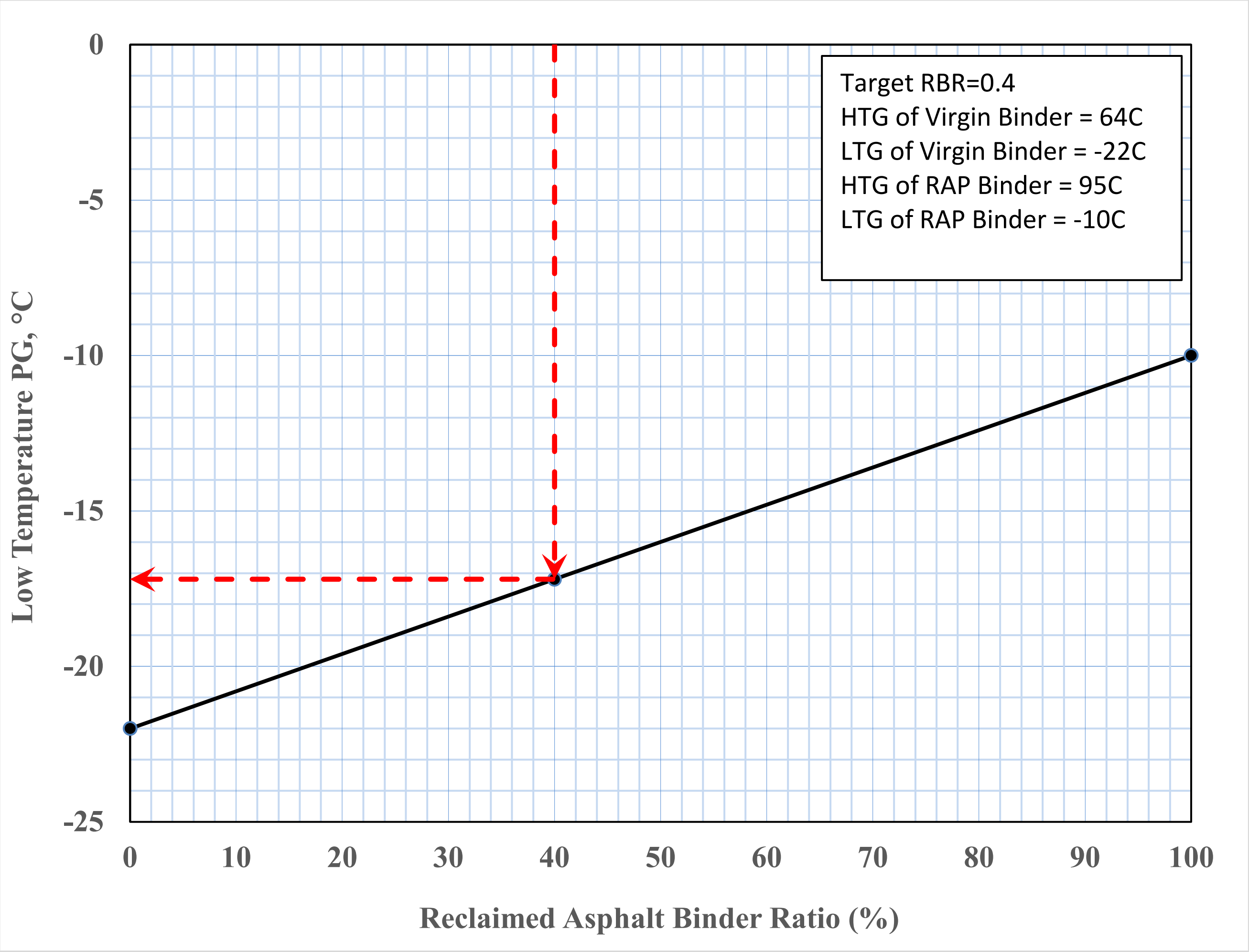

Figure 3. An example of a situation where RA is required.

An example of a scenario where a high content of a highly aged RAP is used is presented in Figure 3. The parameters used to deliver the target blend are shown on the graph. In this case, the blended binder will be graded as PG 76-17 without RA. The low temperature of -17 °C will not be acceptable for most situations. Replacing the PG 64-22 binder with a PG 58-28 binder will bring the low temperature to -21 °C, and that may not be acceptable either. In this case, the use of RA is warranted.

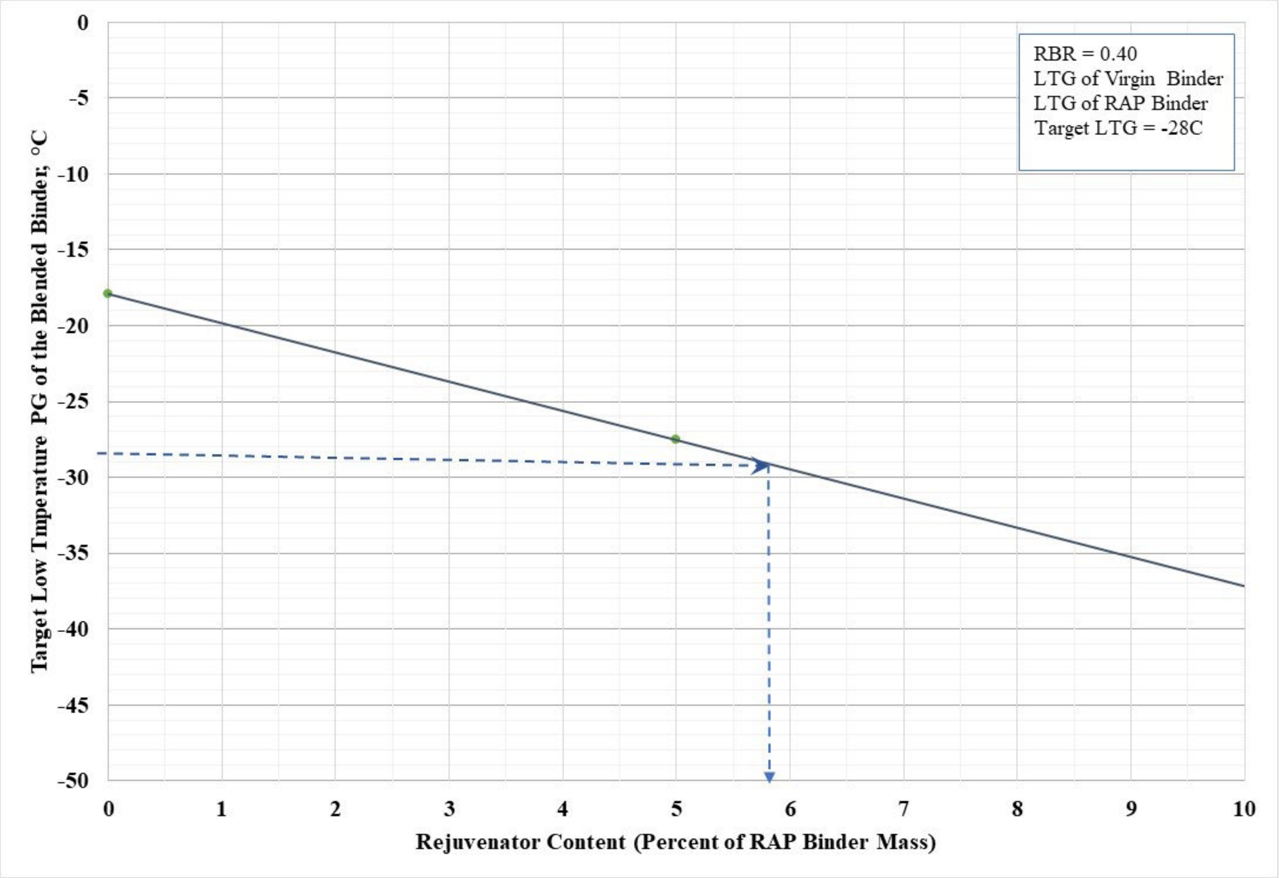

Figure 4. An example of using blending chart for determination of RA dosage rate.

Once it is decided that RA is required, the next step is determination of the dosage rate for the particular RA to be used with the asphalt mixture. This step requires preparation of at least two mixtures with two different dosage rates and finding the low-temperature grade of the blended binder according to specifications. Having these data along with the LTG of the blended binder without RA, one can plot the relationship between the dosage rate and the resulting grade, as shown in Figure 4. If the goals is, for example, obtaining LTG of -28 °C, then the dosage rate will be 5.8%, calculated as a percent of the RAP binder.

Determination of the Rejuvenator Dosage Rate Based on Performance Index Testing and Balanced Mix Design

It was discussed that the manufacturer of the recycling agent must be provided by performance grades and the amounts of the virgin binder, RAP binder, RAS binder, as well as target binder grade in order to be able to provide a suitable dosage rate of RA. This is an acceptable approach in practice, but the final validation of the rejuvenator content must come through the asphalt mix performance index testing and balanced mix design. There are two ways to finalize the RA content using performance index testing. One is to use the manufacturer's recommended dosage rate in the mixture and conduct performance index tests to ensure that the criteria on rutting and cracking are satisfied. An alternative is to use three separate dosage rates within the range typically used for a specific RA based on past experience for similar conditions and conduct performance index tests for all three to determine optimum RA content. In this case, since determination of the dosage rate is solely relying on the performance index test results, it may be possible to do so without the need to grade the RAP or RAS binders in the mix, as discussed previously.

Evaluating Long-Term Effectiveness of the Rejuvenator

Rejuvenators are mainly used to reduce the cracking potential of mixes containing RAS or high RAP content. The asphalt mixture cracking is mainly a long-term phenomenon and becomes of concern after the asphalt pavement has been exposed to oxidation and aging for a long time after opening to traffic. Therefore, it is important that the rejuvenated binder preserves its effectiveness through years of service. Laboratory research has shown that indeed the rejuvenating agents are capable of keeping their effectiveness with time, albeit to various degrees. Two approaches are recommended to determine long-term efficiency of the rejuvenating agent: (1) through asphalt binder testing and (2) through asphalt mixture testing.

Evaluation of Long-Term Effectiveness through Binder Testing

A standard binder such as PG 64S-22 or PG 58S-28 should be used as a reference for which prior characterization has been conducted based on AASHTO Specification M 332. A blend of this binder with a known RAP binder can be prepared and characterized according to AASHTO M 332. The RAP binder can be blended with the virgin binder to yield a reclaimed binder ratio of 0.40 (i.e., 35 percent of the total binder will be the RAP binder). The rejuvenator will be stirred in this blend at a temperature of 150 °C for 60 seconds. This modified blend will be characterized according to AASHTO M 332. Part of this characterization requires testing long-term aged material in a dynamic shear rheometer (DSR) according to AASHTO T 315 and in the bending beam rheometer (BBR) according to AASHTO T 313. The long-term aging before conducting these tests should be accomplished according to AASHTO standard practice R 28 using a pressure aging vessel (PAV), except a change in conditioning time or conditioning mass will be applied, as explained subsequently, for determination of binder ΔT_c. Suggested dosage rate of RA for such evaluation will be based on either the manufacturer's recommendation or the outcome of the binder blending chart, as discussed previously.

Binder ΔT_c is one of the parameters recommended to be used for assessing long-term effectiveness of the rejuvenators. It is a binder parameter related to durability and cracking potential of asphalt mixture. It is defined as the difference between two critical cracking temperatures: one associated with threshold criterion on the binder stiffness (S=300 MPa), and the other with creep rate (relaxation parameter) m (m=0.3). To establish critical temperatures for limiting values of stiffness and creep rate, the bending beam rheometer test (AASHTO T 313) must be conducted at at least two temperatures. Ideally, these two temperatures bracket the threshold value of 300 MPa for S and 0.3 for m, so that the critical temperatures are calculated through interpolation. Once the critical temperatures are established, ΔT_c is calculated using Equation 1.

$$\Delta T_c = T_{c,S} - T_{c,m} \tag{1}$$

Where

$T_{c,S}$ = critical cracking temperature to satisfy stiffness threshold value of 300 MPa
$T_{c,m}$= critical cracking temperature to satisfy stiffness creep rate value of 0.3

One of the recommendations provided in recent research on long-term aging of asphalt binders, as documented in NCHRP Research Report 967 (Bonaquist et al., 2021), is that for determination of ΔT_c, one should use either 12.5 g, 20-hr, 2.1 MPa PAV conditioning or 50.0 g, 40-hr, 2.1 MPa conditioning. Therefore, there will be a modification to AASHTO R 28 in this regard, i.e., either reducing the mass or increasing the time, as discussed above.

Upon completion of this rheological testing, one could assess the long-term effectiveness of the rejuvenating agent by comparing the rheological test results before and after incorporation of the rejuvenator using the following parameters.

Table 4. Parameters used to ensure long-term effectiveness of rejuvenating agents.

Parameter (measured on PAV-aged binder)	Change after incorporation of the rejuvenator at the recommended dosage rate
G*.sinδ at intermediate test temperature	Decrease of at least 25% in G*.sinδ
Stiffness (*S*) at low temperature	<300 MPa, and decrease of at least 25% in *S*
Relaxation parameter (*m*-value) at low temperature	Increase of at least 25% in *m*
ΔT_c at low temperature	>-5 °C, and increase of at least 25% in ΔT_c

Evaluation of Long-Term Effectiveness through Mixture Testing

An alternative to the process of assessing the long-term effectiveness of rejuvenators through binder testing is through performance testing of the asphalt mixtures containing the rejuvenating agents and subjecting them to long-term conditioning. Mixture testing could also be utilized in support of the binder evaluation if an agency desires to apply both the binder and mixture evaluation testing. For this purpose, one could utilize one of the test protocols currently used in practice to evaluate cracking resistance. In Pennsylvania, IDEAL-CT is currently considered as the test protocol for evaluation of the cracking resistance. Upon completion of the mix volumetric design, the mixture is prepared and long-term aged according to AASHTO R 30; afterward, the mix is subjected to the IDEAL-CT test according to ASTM D8225. An alternative to AASHTO R 30 conditioning protocol is the protocol established by the National Center for Asphalt Technology (NCAT) (Xie et al., 2020), which results in a faster conditioning period compared with AASHTO R 30. In the R 30 practice, the compacted mixture is conditioned at 85 °C for 120 hours (5 days). In the NCAT protocol, the loose mixture is conditioned for 8 hours at 135 °C. The rejuvenator is effective if it has caused an increase of at least 25% in the index value from this cracking test.

Summary

This document was developed with the goal of providing guidance for the use of recycling agents with Pennsylvania asphalt mixtures containing RAS or high RAP content. The guide provides basic information on the recycling agents and their types followed by determination of dosage rate and blending techniques. There are generally three ways to determine the dosage rate: (1) based on the manufacturer's recommendation once the required information on the binder grades, binder content, and target binder grade are known; (2) using blending charts to achieve a desired binder grade; and (3) using the balanced mix design approach and utilization of asphalt mixture performance tests. The preceding three approaches were discussed in this guide. Finally, two methods were presented for evaluating the long-term effectiveness of the recycling agents, one through binder characterization of the blended binder after long-term aging, and the other through mixture performance testing after long-term aging of the mixture.

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Xie, Z., Tran, N., Taylor, A.J., and Turnera, P. (2020). "Laboratory Evaluation of Effect of Addition Methods of Rejuvenators on Properties of Recycled Asphalt Mixtures," American Society of Civil Engineers, *Journal of Materials in Civil Engineering*, 32(5):04020101.

APPENDIX B

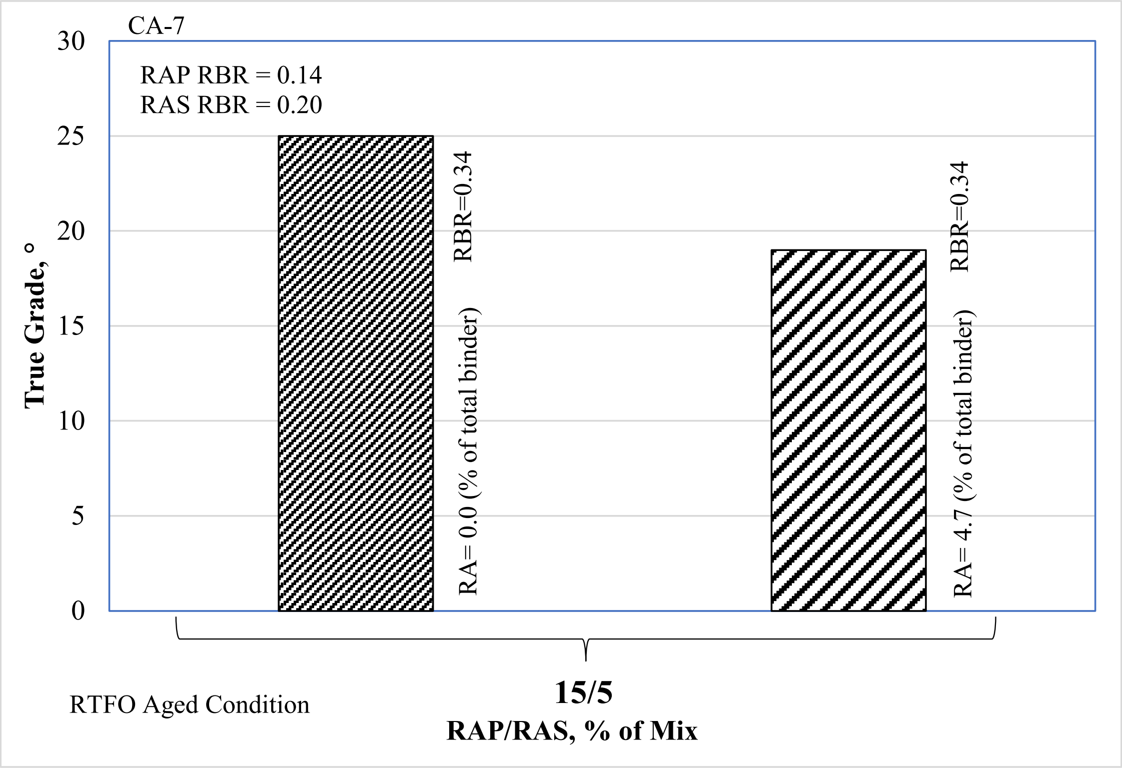
Summary of Results from Rheological Testing of Binders Modified with Rejuvenating Agents (Binders Recovered from the Asphalt Mixtures)

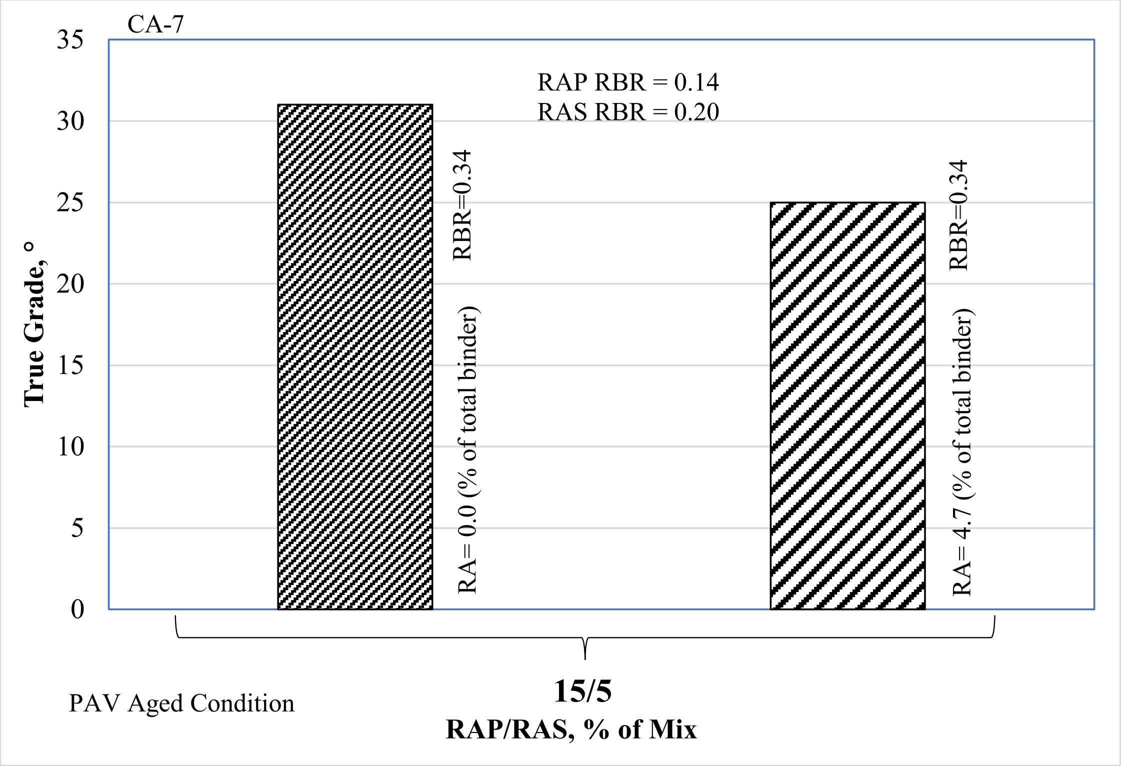
Mix Information	PG for Recovered Binders Results							
MIX ID	Test, Temp, C	G*, Kpa	Phase Angle, °	G*/sinδ, Kpa	True Grade, °	RBR from RAP Binder	RBR from RAS Binder	Total RBR
#4	52	103.53	62.23	117.01	91.8	0.13	0.19	0.32
	58	51.39	64.51	56.93				
	64	25.08	67.41	27.17				
	70	12.18	70.66	12.91				
	76	5.96	73.97	6.20				
	82	2.96	77.11	3.03				
	88	1.50	79.94	1.52				
	94	0.78	82.43	0.79				
	64	25.32	67.40	27.43	84.9	0.13	0.19	0.32
	70	12.29	70.58	13.03				
	76	6.00	73.93	6.24				
	82	2.98	77.10	3.06				
	88	1.51	79.96	1.53				
#5	64	8.19	74.43	8.51	81.8	0.11	0.16	0.27
	70	3.93	77.47	4.03				
	76	1.93	80.27	1.96				
	82	0.97	82.71	0.98				
	64	8.22	74.29	8.53	75.0	0.11	0.16	0.27
	70	3.93	77.37	4.03				
	76	1.92	80.20	1.95				
#19	64	26.47	66.73	28.81	92.9	0.14	0.20	0.34
	70	13.10	69.69	13.97				
	76	6.51	72.90	6.81				
	82	3.27	76.03	3.37				
	88	1.67	78.91	1.70				
	94	0.87	81.48	0.88				
	64	46.83	62.95	52.58	91.0	0.14	0.20	0.34
	70	23.44	65.68	25.72				
	76	11.68	68.83	12.53				
	82	5.85	72.12	6.15				
	88	2.97	75.36	3.07				
	94	1.52	78.36	1.55				
#21	64	7.35	74.45	7.63	81.6	0.14	0.20	0.34
	70	3.62	77.33	3.71				
	76	1.83	80.02	1.86				
	82	0.95	82.39	0.96				
	64	17.18	69.11	18.39	81.9	0.14	0.20	0.34

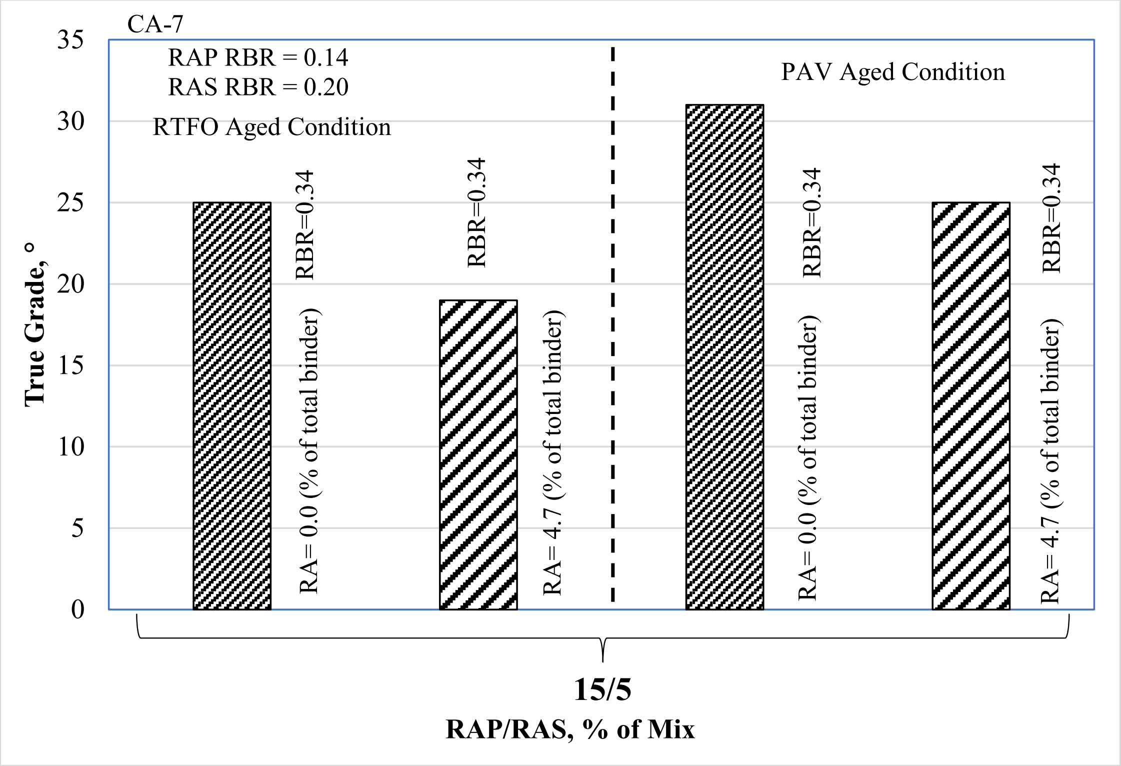
Mix Information	PG for Recovered Binders Results							
	70	8.42	72.20	8.84				
	76	4.18	75.30	4.32				
	82	2.12	78.20	2.17				
#24	64	27.26	66.44	29.74	93.1	0.13	0.19	0.32
	70	13.47	69.38	14.39				
	76	6.68	72.53	7.01				
	82	3.37	75.61	3.48				
	88	1.73	78.46	1.77				
	94	0.90	81.01	0.91				
	64	38.36	63.53	42.85	89.6	0.13	0.19	0.32
	70	19.36	66.29	21.14				
	76	9.74	69.43	10.41				
	82	4.93	72.64	5.17				
	88	2.54	75.74	2.62				
	94	1.33	78.60	1.36				
#42	64	6.27	78.20	6.40	79.3	0.33	0.00	0.33
	70	2.96	80.85	3.00				
	76	1.45	83.19	1.46				
	82	0.73	85.18	0.73				
	64	14.78	73.56	15.41	79.4	0.33	0.00	0.33
	70	6.83	76.62	7.02				
	76	3.24	79.53	3.30				
	82	1.59	82.09	1.60				
#38	64	4.88	80.12	4.95	77.0	0.33	0.00	0.33
	70	2.28	82.57	2.30				
	76	1.11	84.69	1.12				
	82	0.57	86.39	0.57				
	64	9.62	76.51	9.90	75.80	0.33	0.00	0.33
	70	4.43	79.41	4.51				
	76	2.11	82.01	2.13				
#35	64	13.40	70.59	14.21	86.40	0.00	0.20	0.20
	70	6.53	73.77	6.80				
	76	3.22	76.89	3.31				
	82	1.62	79.70	1.65				
	88	0.83	82.16	0.84				
	64	27.51	65.32	30.27	86.0	0.00	0.20	0.20
	70	13.62	68.39	14.65				
	76	6.76	71.71	7.12				
	82	3.39	74.98	3.51				
	88	1.71	78.02	1.75				

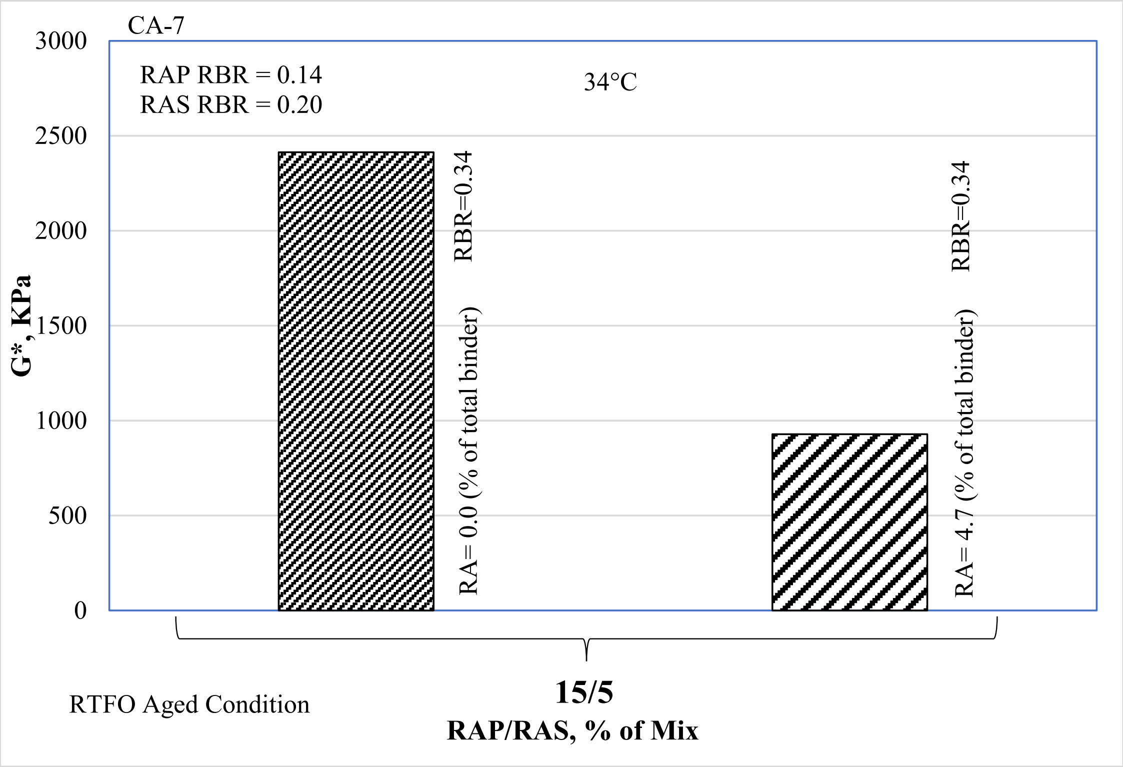
Mix Information	PG for Recovered Binders Results							
#37	64	24.57	66.77	26.73	91.8	0.00	0.20	0.20
	70	12.07	69.85	12.85				
	76	5.95	73.12	6.22				
	82	2.98	76.59	3.06				
	88	1.51	79.18	1.53				
	94	0.78	81.70	0.79				
	64	39.39	63.28	44.10	89.3	0.00	0.20	0.20
	70	19.71	66.15	21.55				
	76	9.78	69.45	10.45				
	82	4.89	72.84	5.12				
	88	2.47	76.08	2.55				
	94	1.26	79.04	1.28				
#33	64	11.09	76.23	11.41	83.5	0.33	0.00	0.33
	70	5.08	79.09	5.17				
	76	2.41	81.69	2.43				
	82	1.18	83.94	1.19				
	88	0.60	85.81	0.60				
#25	64	20.82	68.86	22.32	89.9	0.13	0.19	0.32
	70	10.03	71.99	10.55				
	76	4.88	75.18	5.05				
	82	2.42	78.19	2.47				
	88	1.22	80.87	1.23				
	94	0.63	83.17	0.64				

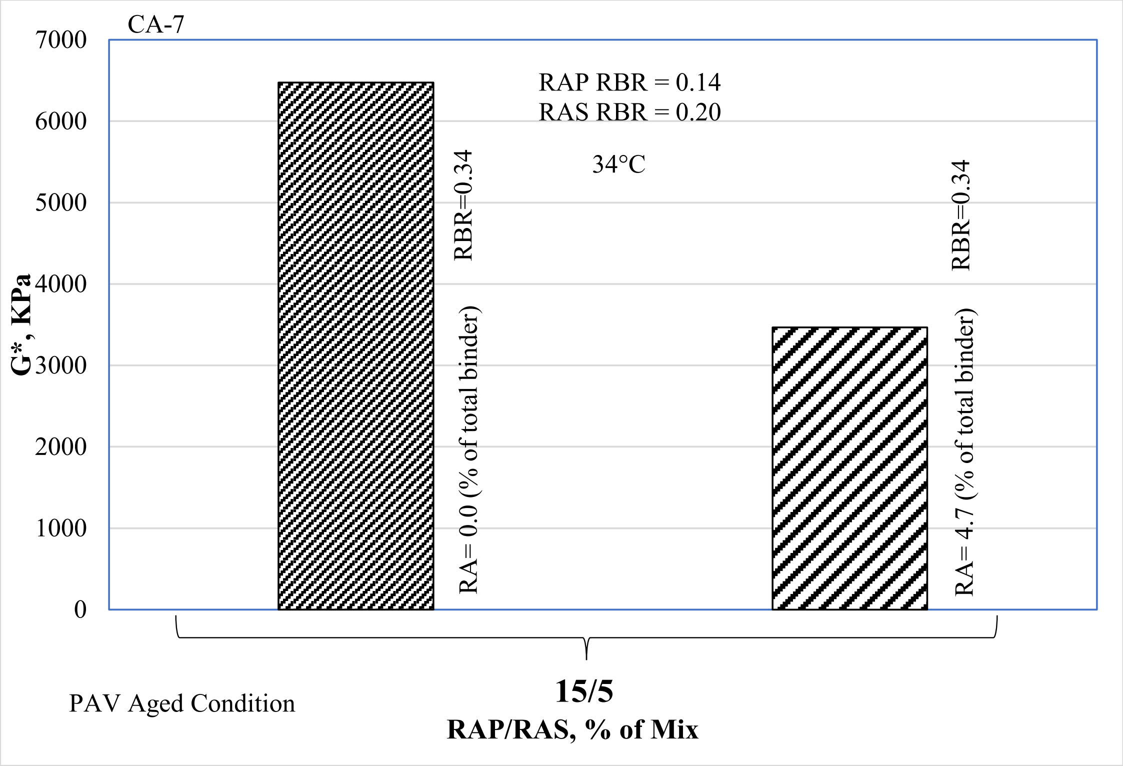
Intermediate temperature

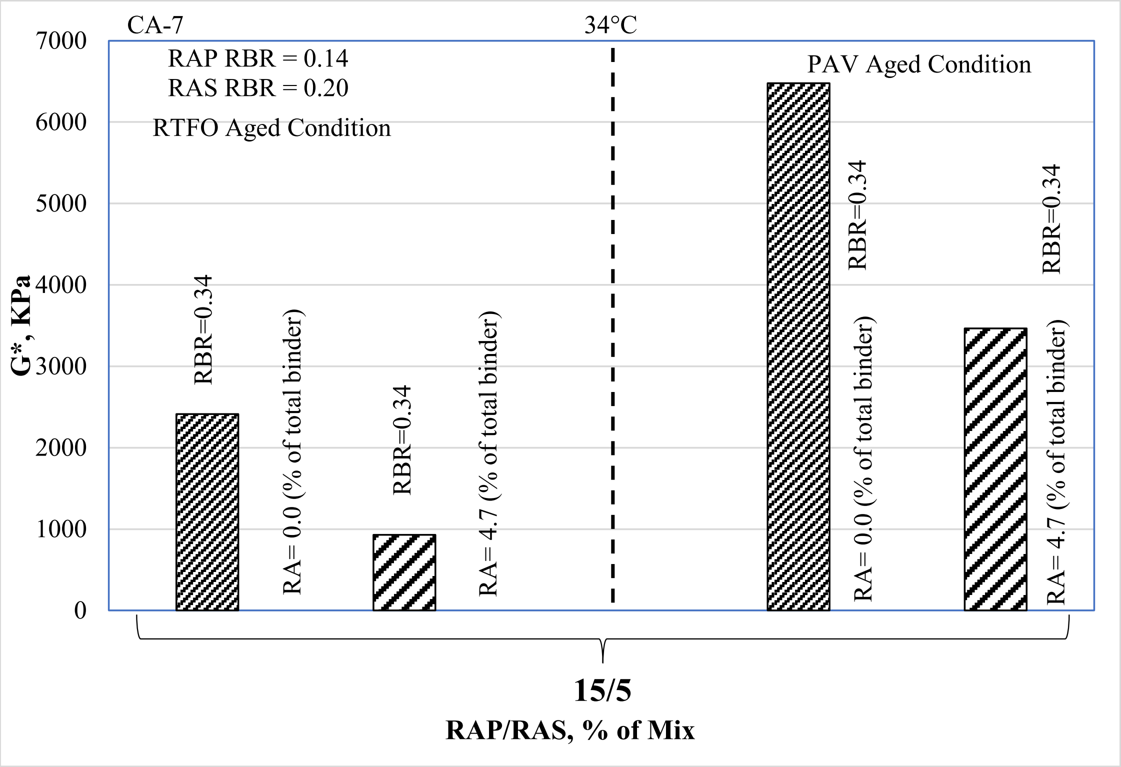


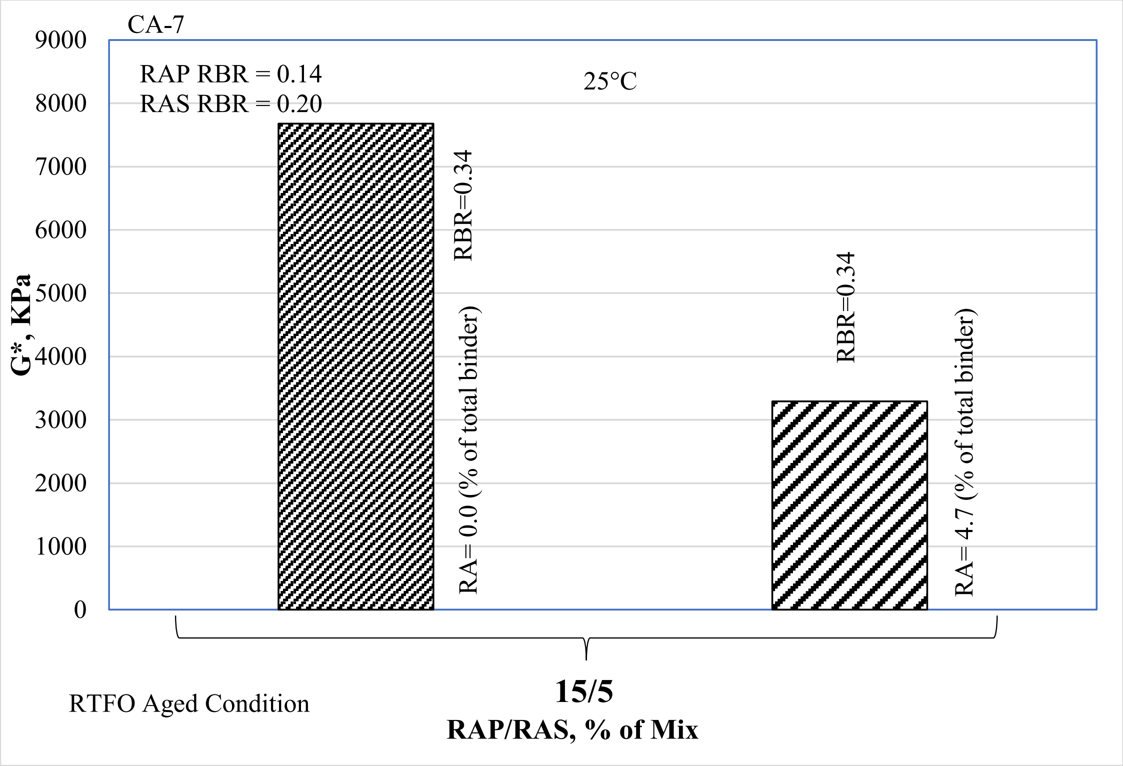

CA-7
35
30
25
20
15
10
5
0
True Grade, °
RAP RBR = 0.14
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
PAV Aged Condition
15/5
RAP/RAS, % of Mix

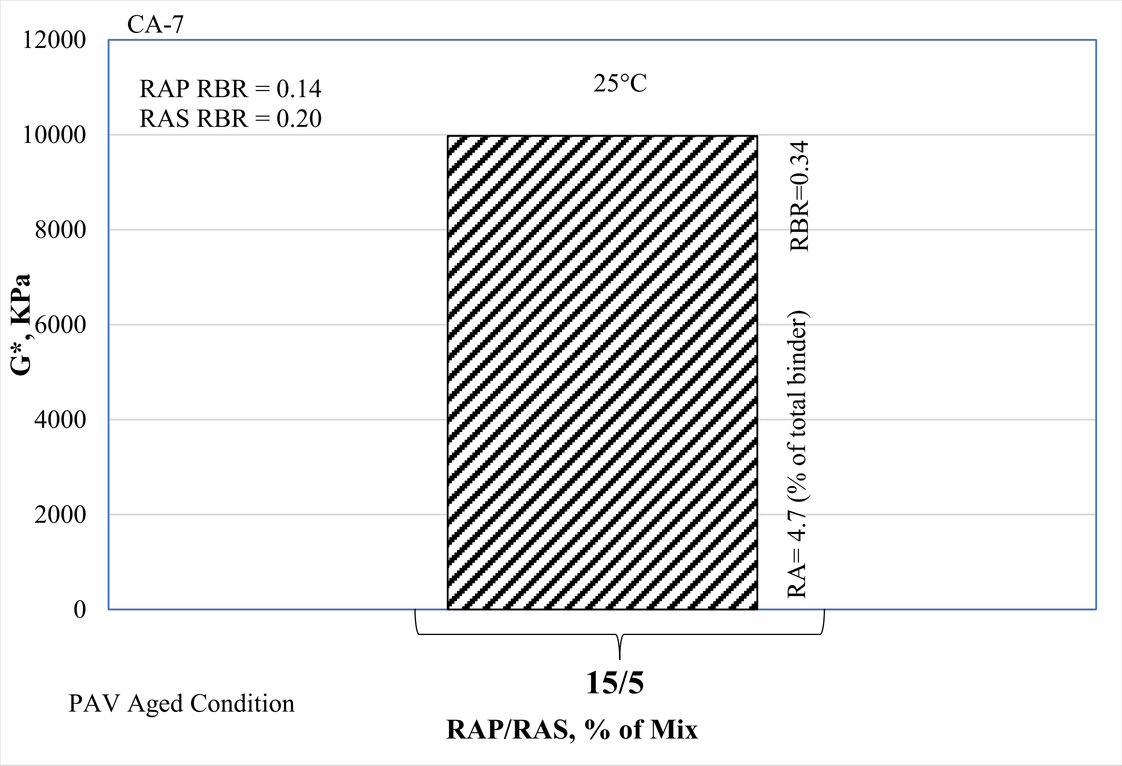

CA-7
35
30
25
20
15
10
5
0
True Grade, °
RAP RBR = 0.14
RAS RBR = 0.20
RTFO Aged Condition
PAV Aged Condition
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
15/5
RAP/RAS, % of Mix

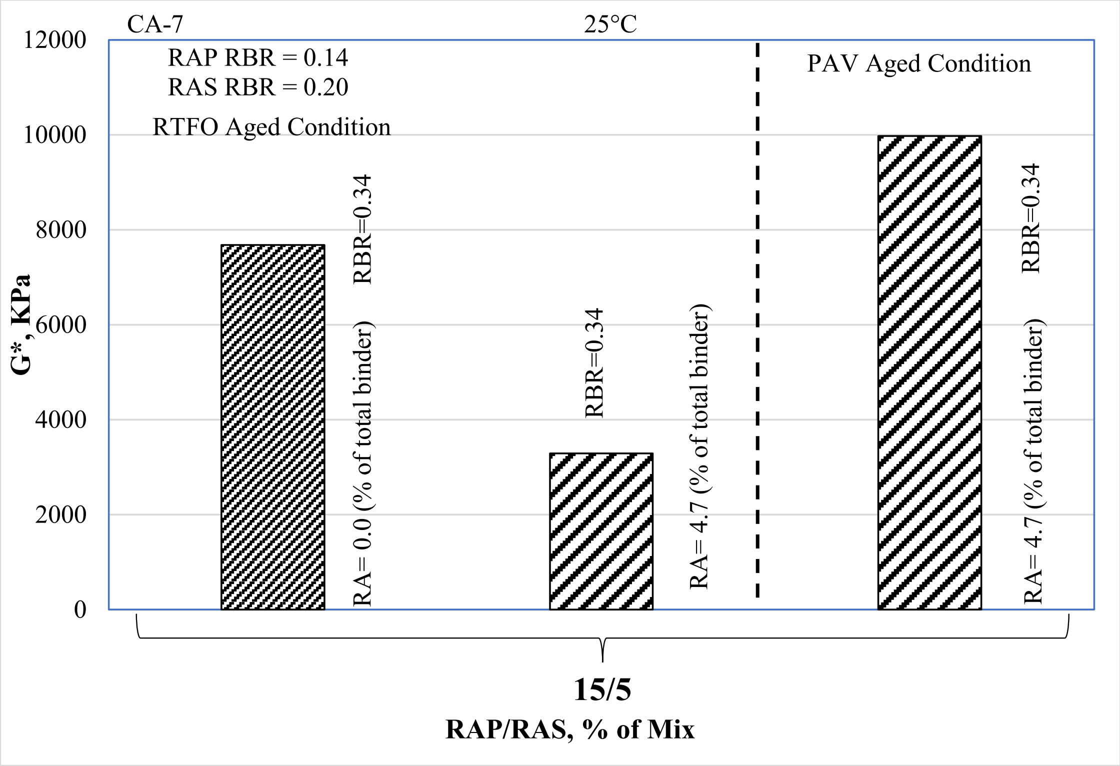

CA-7
3000
2500
2000
1500
1000
500
0
G*, KPa
RAP RBR = 0.14
RAS RBR = 0.20
34°C
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RTFO Aged Condition
15/5
RAP/RAS, % of Mix

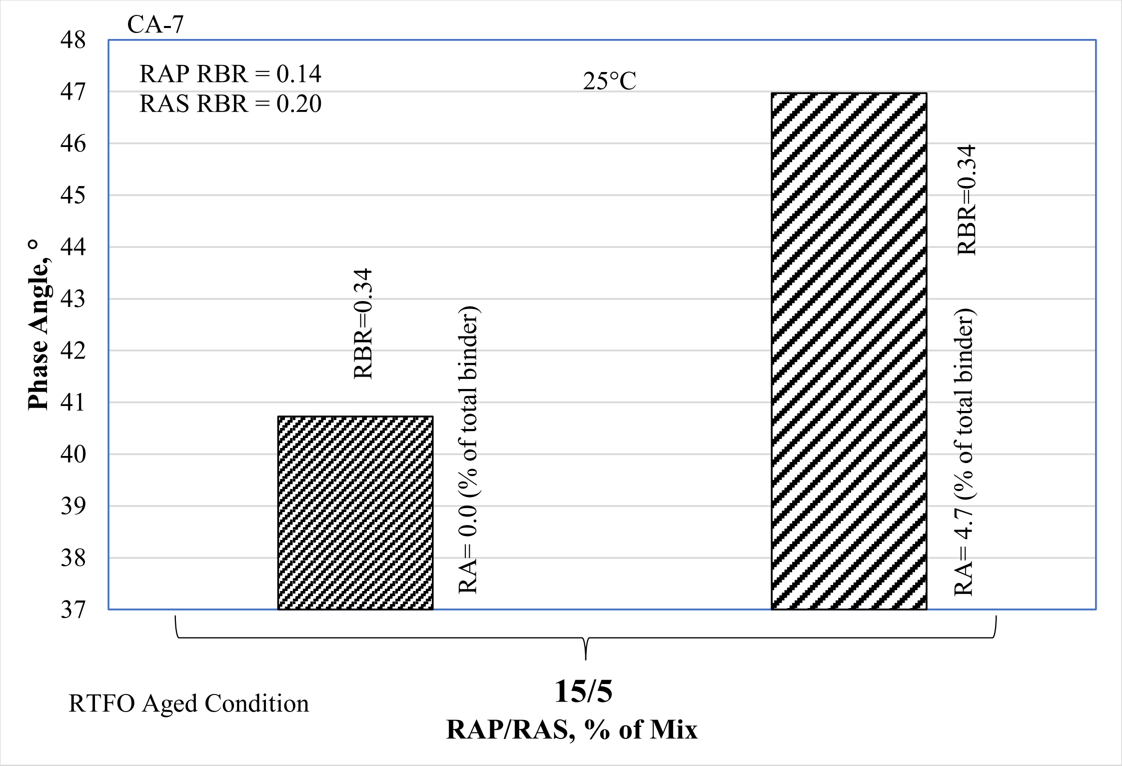

CA-7
7000
6000
5000
4000
3000
2000
1000
0
G*, KPa
RAP RBR = 0.14
RAS RBR = 0.20
34°C
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
PAV Aged Condition
15/5
RAP/RAS, % of Mix

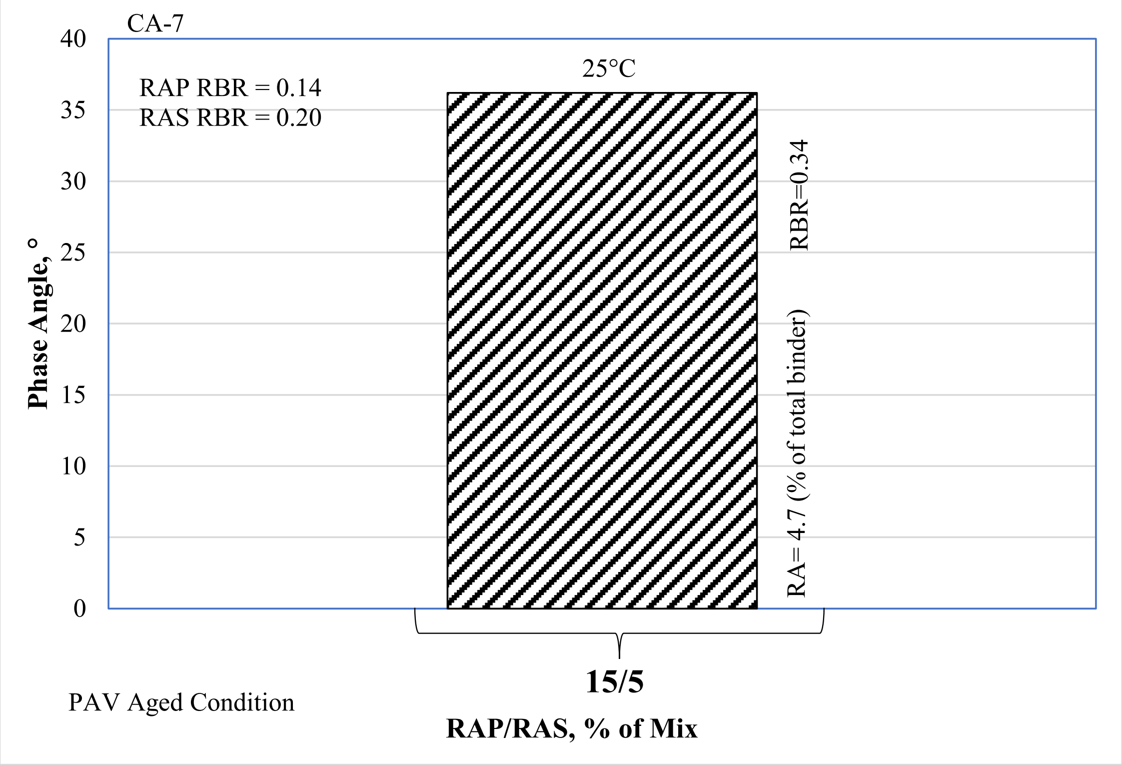

CA-7
34°C
RAP RBR = 0.14
RAS RBR = 0.20
RTFO Aged Condition
PAV Aged Condition
G*, KPa
0
1000
2000
3000
4000
5000
6000
7000
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
15/5
RAP/RAS, % of Mix

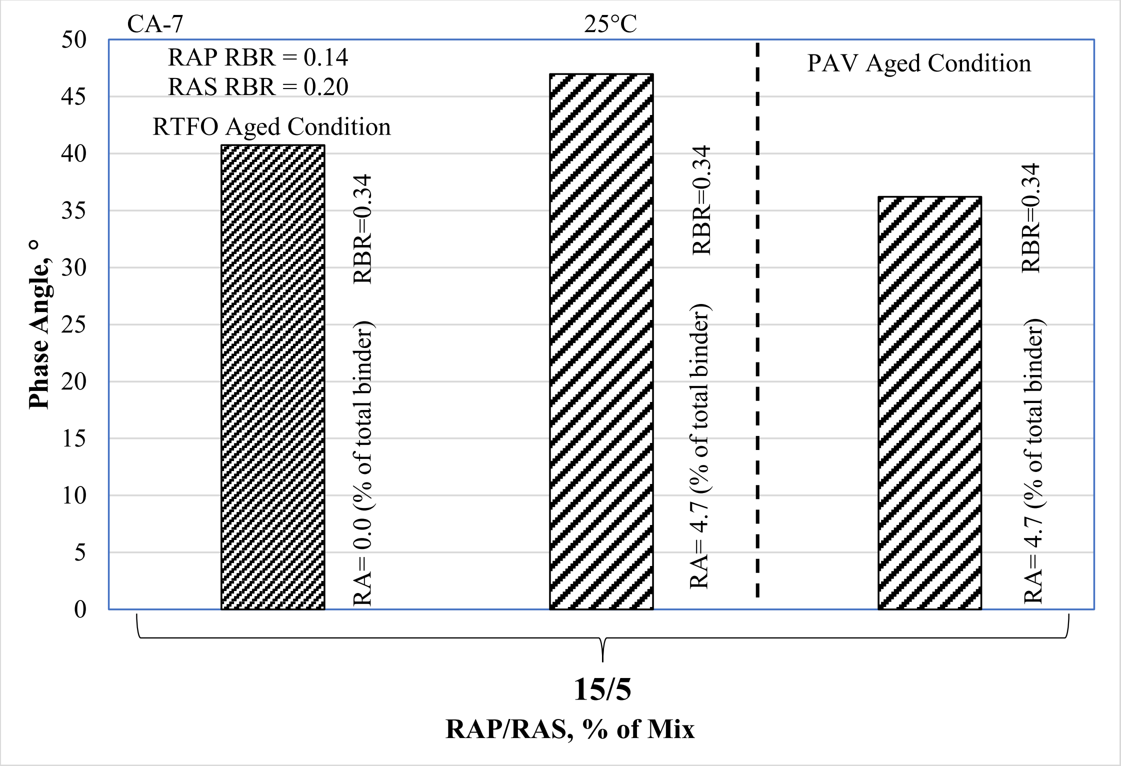

CA-7
RAP RBR = 0.14
RAS RBR = 0.20
25°C
G*, KPa
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RTFO Aged Condition
15/5
RAP/RAS, % of Mix

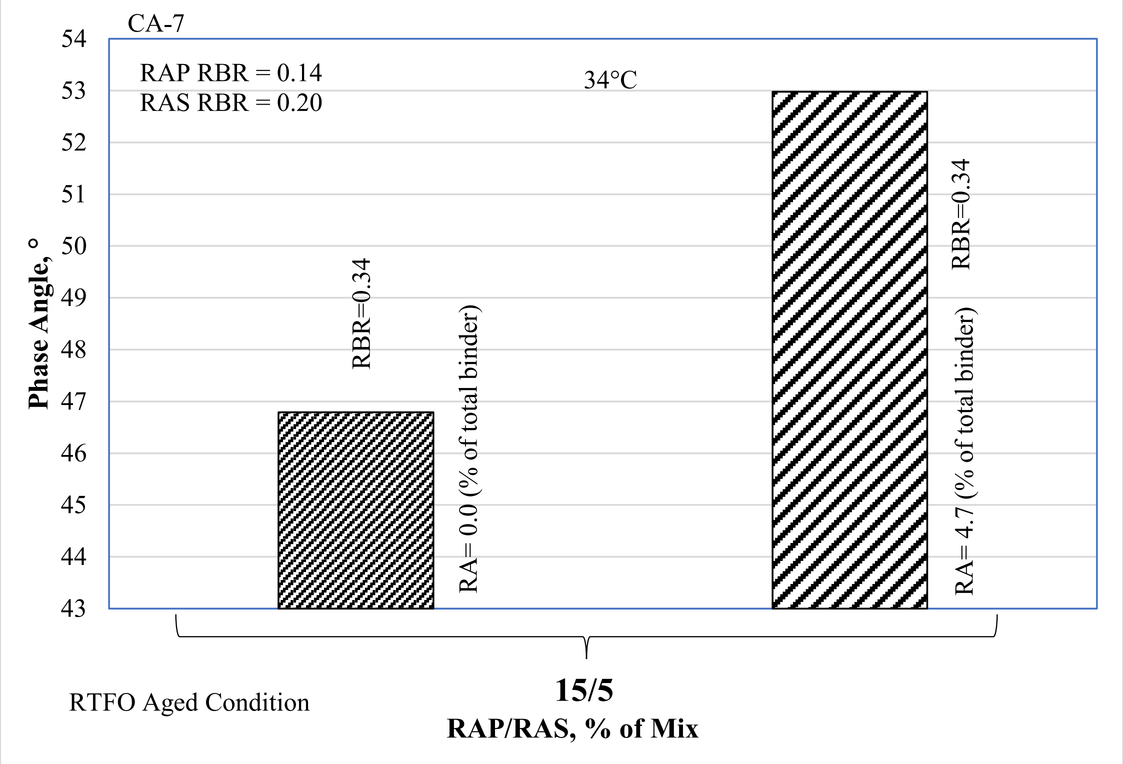

CA-7
12000
10000
8000
6000
4000
2000
0
G*, KPa
RAP RBR = 0.14
RAS RBR = 0.20
25°C
RBR=0.34
RA= 4.7 (% of total binder)
15/5
PAV Aged Condition
RAP/RAS, % of Mix

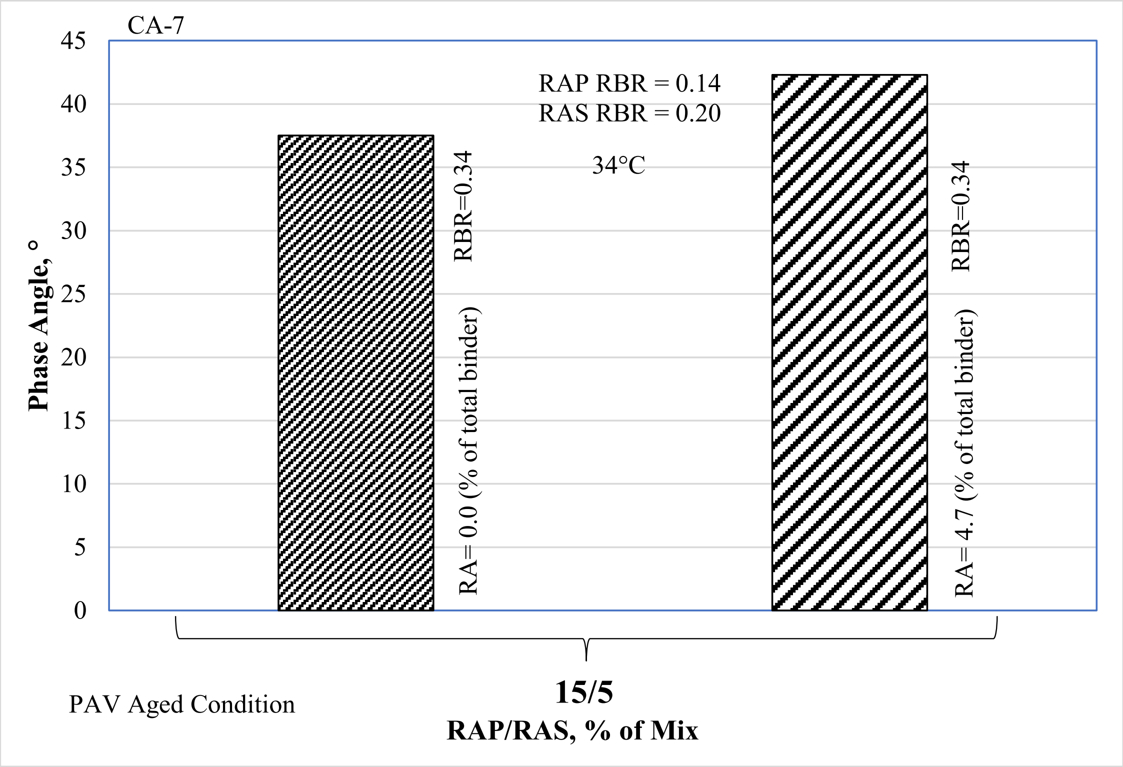

CA-7
25°C
12000
10000
8000
6000
4000
2000
0
G*, KPa
RAP RBR = 0.14
RAS RBR = 0.20
RTFO Aged Condition
PAV Aged Condition
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
15/5
RAP/RAS, % of Mix

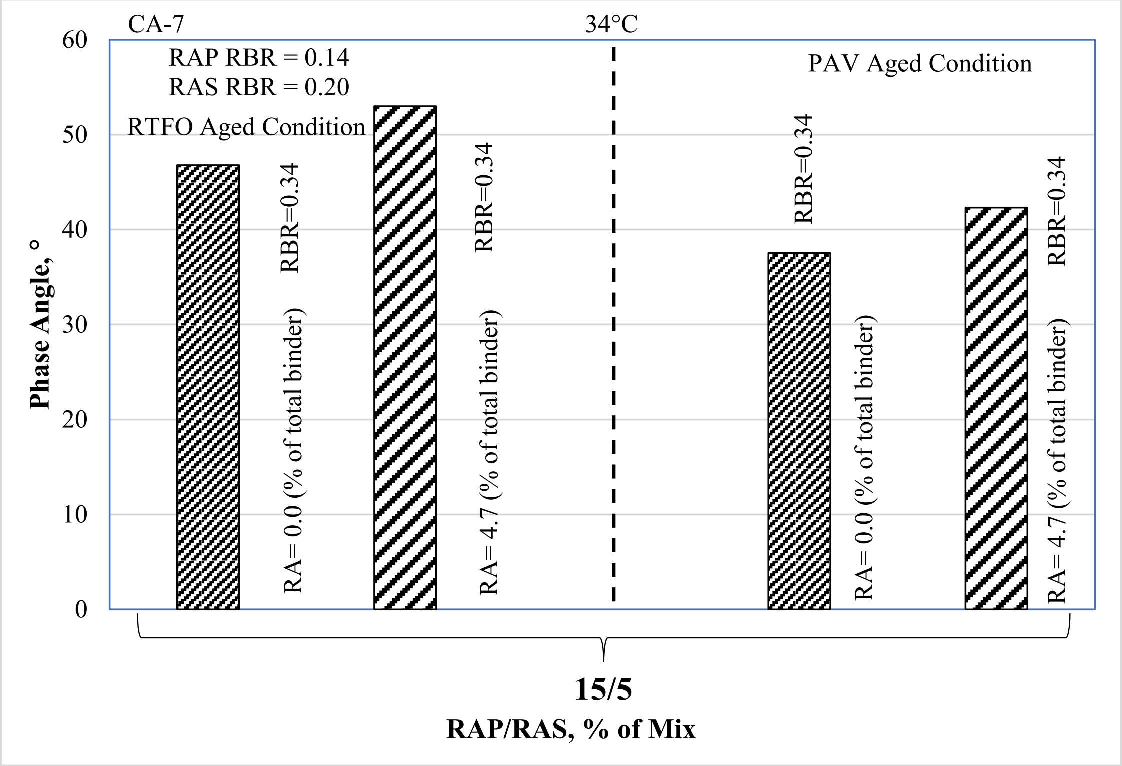

CA-7
48
47
46
45
44
43
42
41
40
39
38
37
Phase Angle, °
RAP RBR = 0.14
RAS RBR = 0.20
25°C
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RTFO Aged Condition
15/5
RAP/RAS, % of Mix

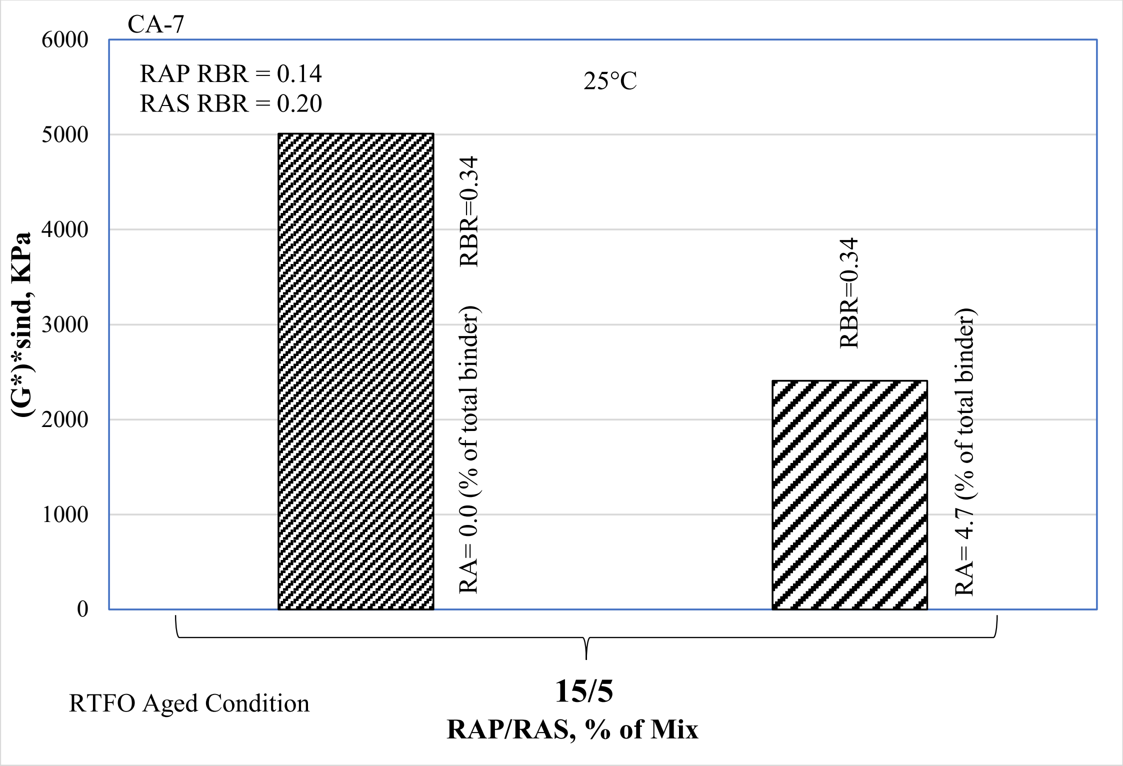

CA-7
40
35
30
25
20
15
10
5
0
Phase Angle, °
RAP RBR = 0.14
RAS RBR = 0.20
25°C
RBR=0.34
RA= 4.7 (% of total binder)
PAV Aged Condition
15/5
RAP/RAS, % of Mix

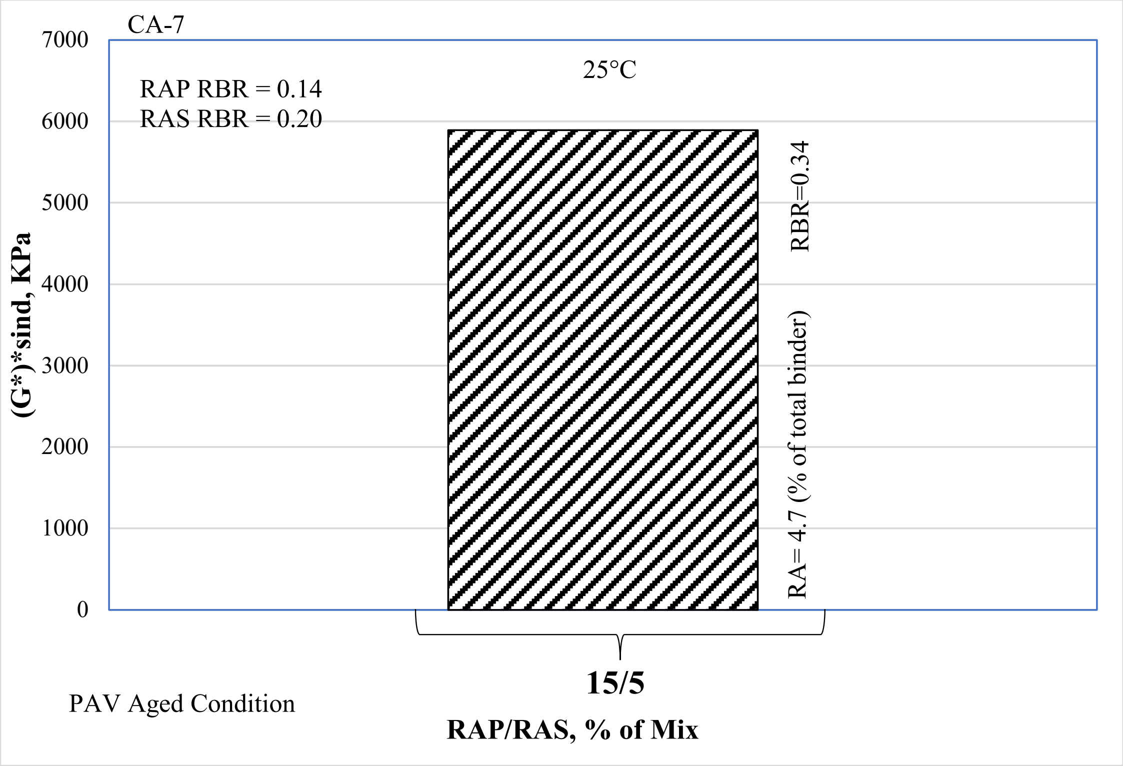

CA-7
25°C
RAP RBR = 0.14
RAS RBR = 0.20
RTFO Aged Condition
PAV Aged Condition
Phase Angle, °
0
5
10
15
20
25
30
35
40
45
50
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
15/5
RAP/RAS, % of Mix

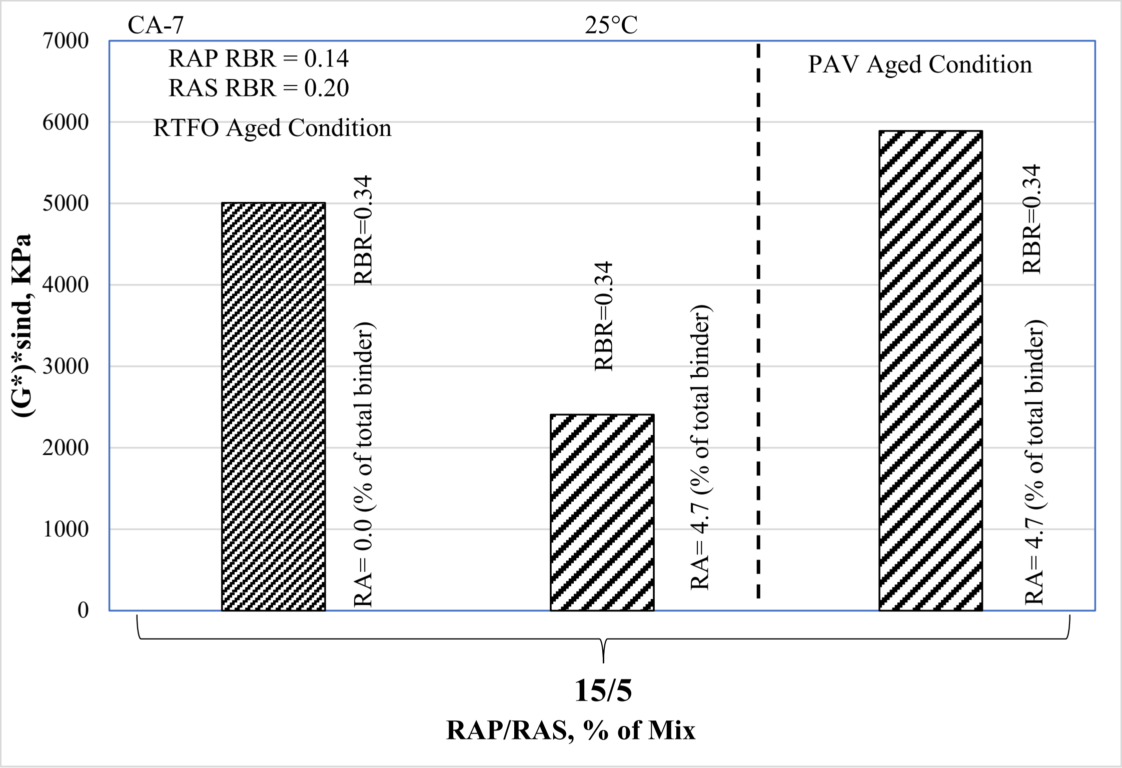

CA-7
34°C
RAP RBR = 0.14
RAS RBR = 0.20
Phase Angle, °
43
44
45
46
47
48
49
50
51
52
53
54
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RTFO Aged Condition
15/5
RAP/RAS, % of Mix

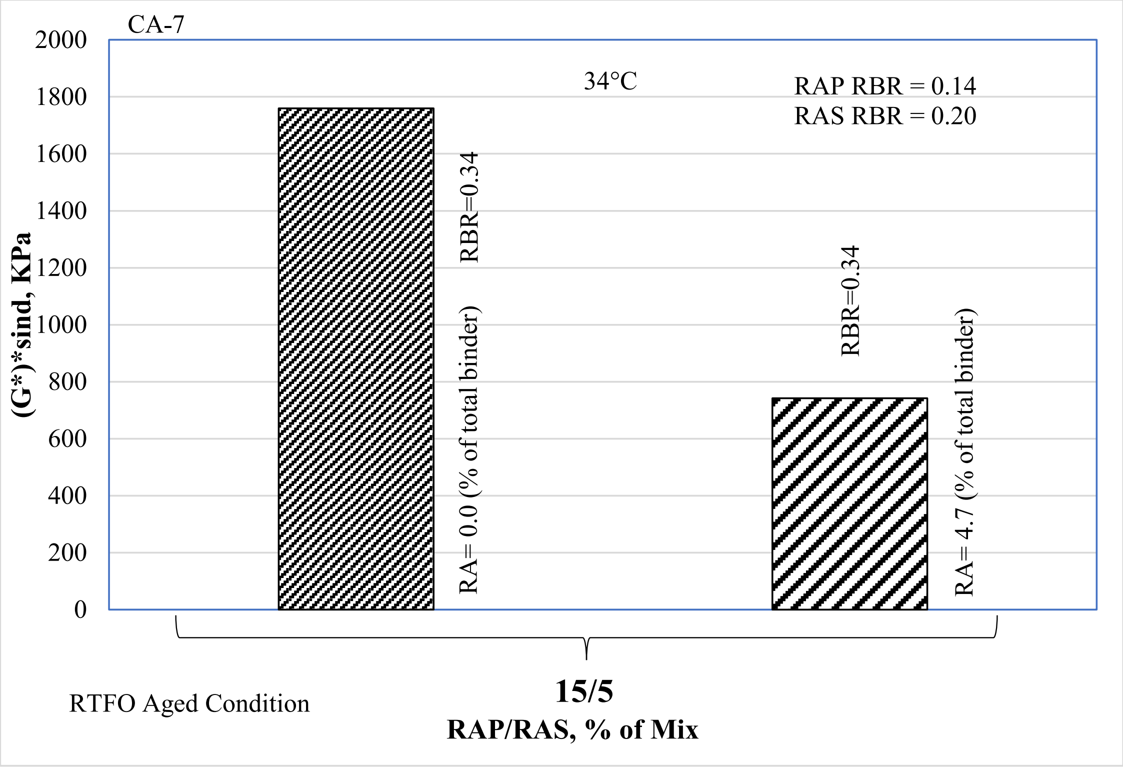

CA-7
45
40
35
30
25
20
15
10
5
0
Phase Angle, °
RAP RBR = 0.14
RAS RBR = 0.20
34°C
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
PAV Aged Condition
15/5
RAP/RAS, % of Mix

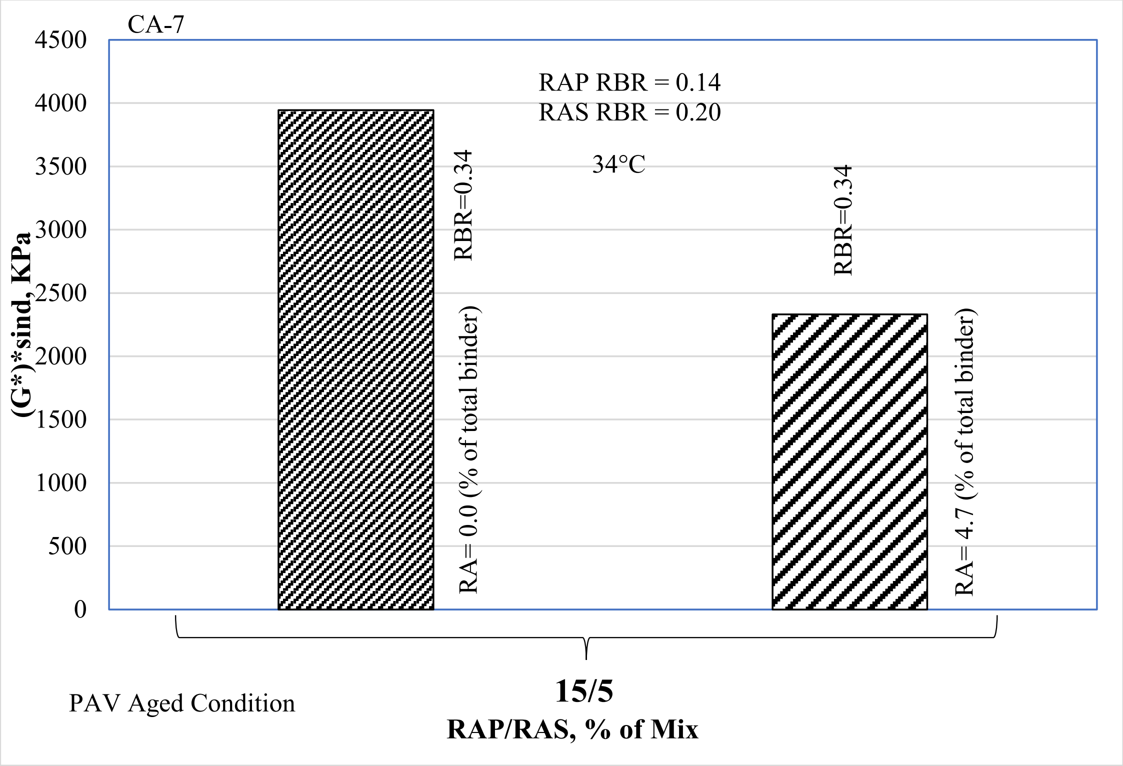

CA-7
34°C
60
50
40
30
20
10
0
Phase Angle, °
RAP RBR = 0.14
RAS RBR = 0.20
RTFO Aged Condition
PAV Aged Condition
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
15/5
RAP/RAS, % of Mix

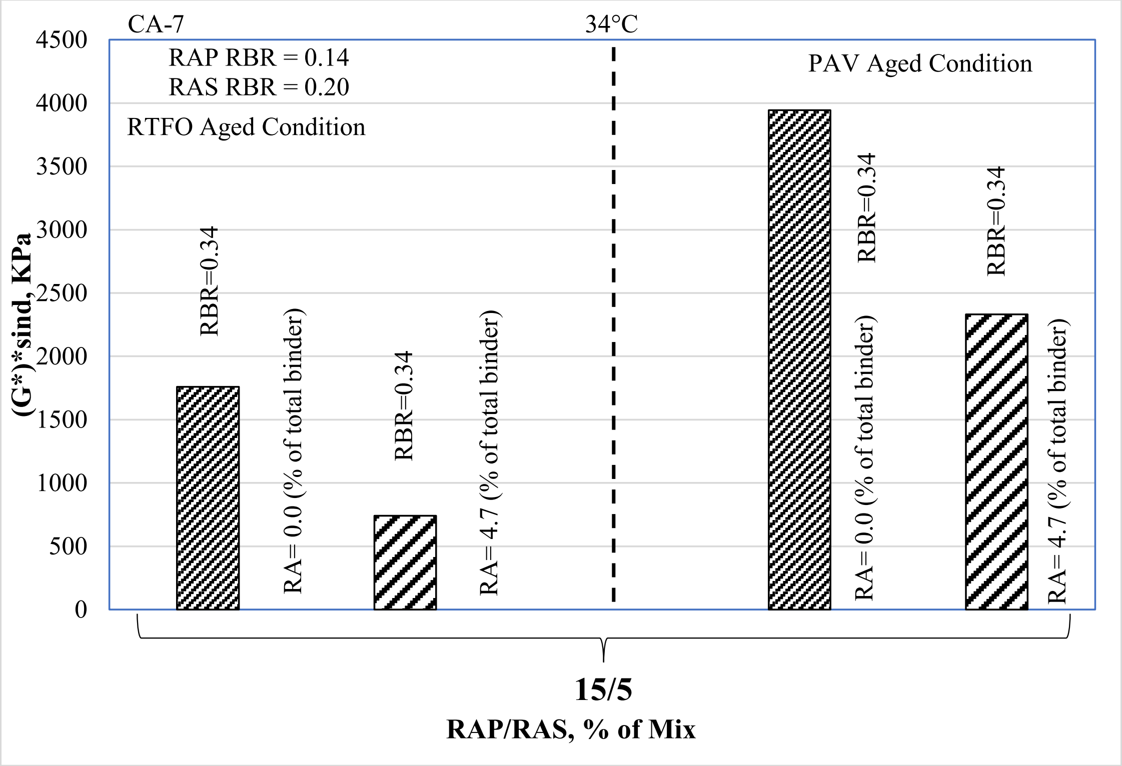

CA-7
6000
5000
4000
3000
2000
1000
0
(G*)*sind, KPa
RAP RBR = 0.14
RAS RBR = 0.20
25°C
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RTFO Aged Condition
15/5
RAP/RAS, % of Mix


CA-7
7000
6000
5000
4000
3000
2000
1000
0
(G*)*sind, KPa
RAP RBR = 0.14
RAS RBR = 0.20
25°C
RBR=0.34
RA= 4.7 (% of total binder)
15/5
PAV Aged Condition
RAP/RAS, % of Mix

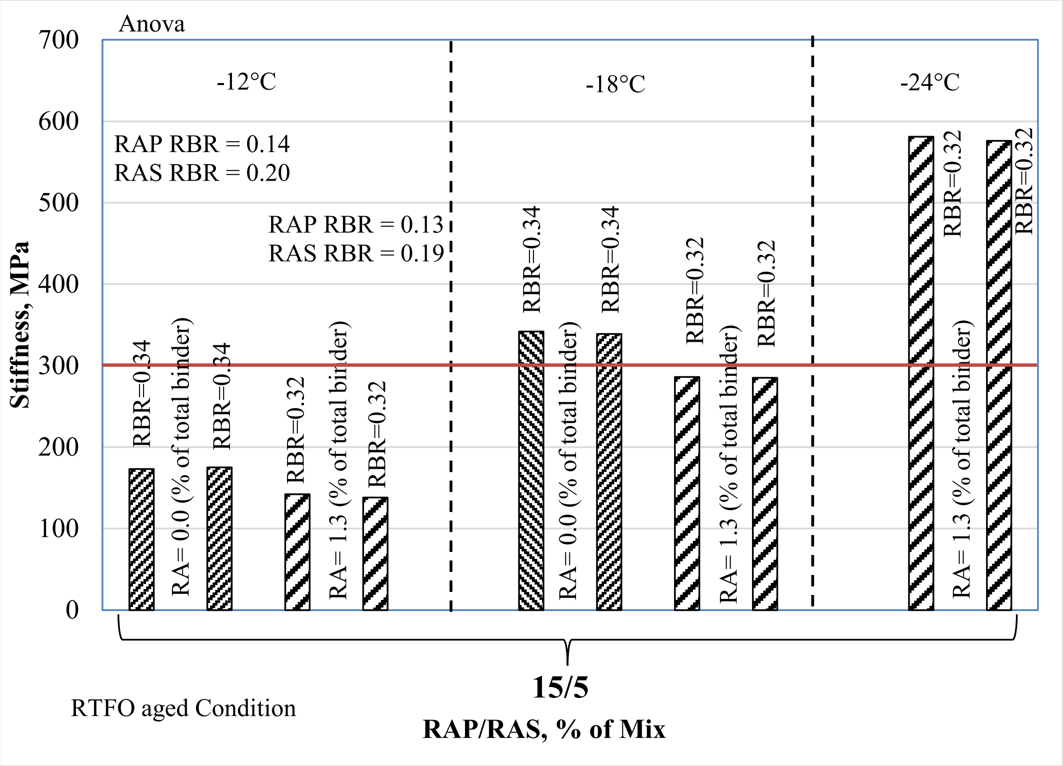

CA-7
25°C
RAP RBR = 0.14
RAS RBR = 0.20
RTFO Aged Condition
PAV Aged Condition
7000
6000
5000
4000
3000
2000
1000
0
(G*)*sind, KPa
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
15/5
RAP/RAS, % of Mix

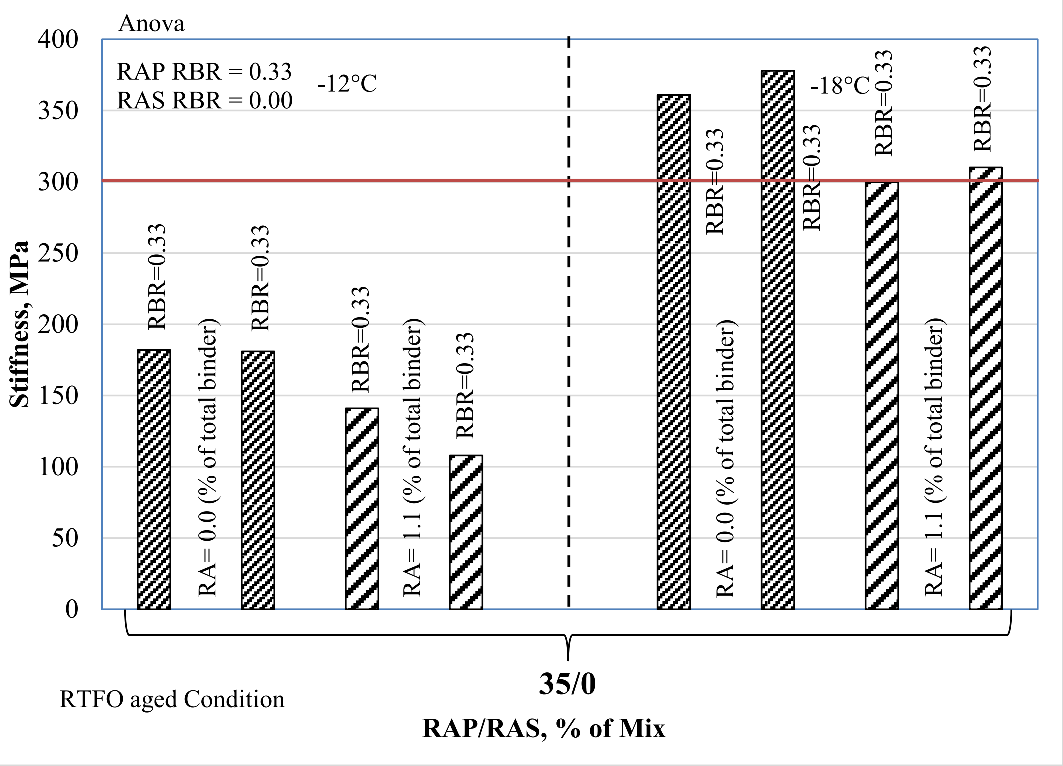

CA-7
34°C
RAP RBR = 0.14
RAS RBR = 0.20
2000
1800
1600
1400
1200
1000
800
600
400
200
0
(G*)*sind, KPa
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RTFO Aged Condition
15/5
RAP/RAS, % of Mix

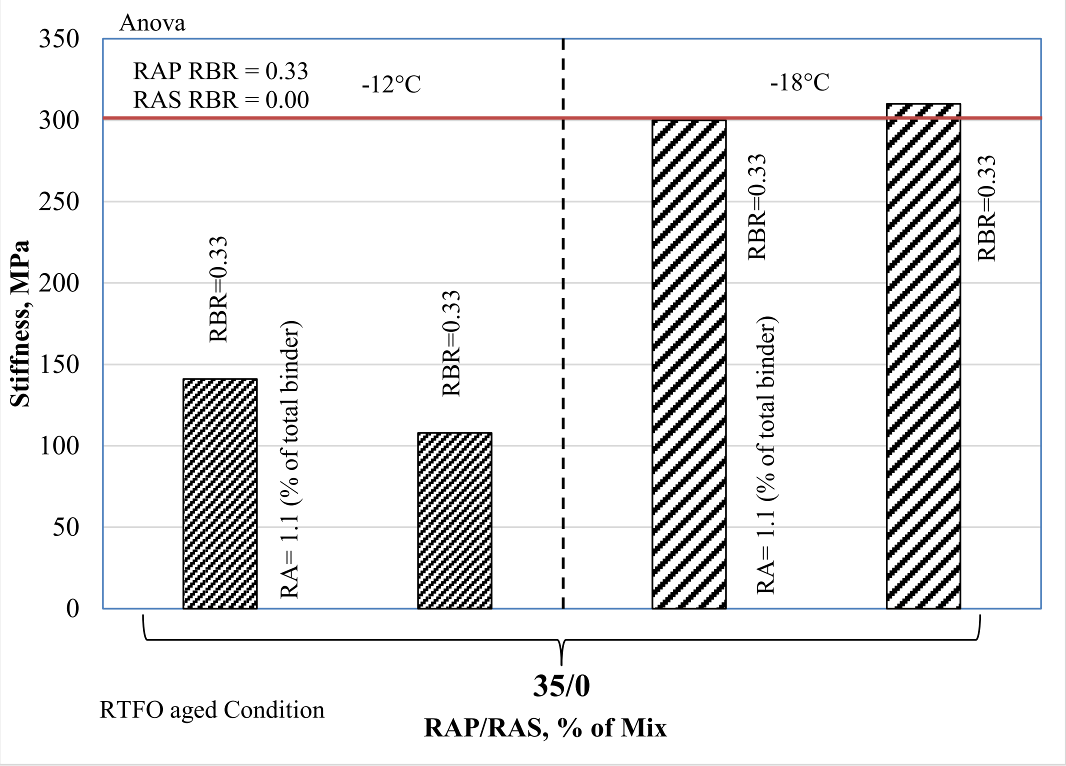

CA-7
RAP RBR = 0.14
RAS RBR = 0.20
34°C
(G*)*sind, KPa
4500
4000
3500
3000
2500
2000
1500
1000
500
0
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
PAV Aged Condition
15/5
RAP/RAS, % of Mix

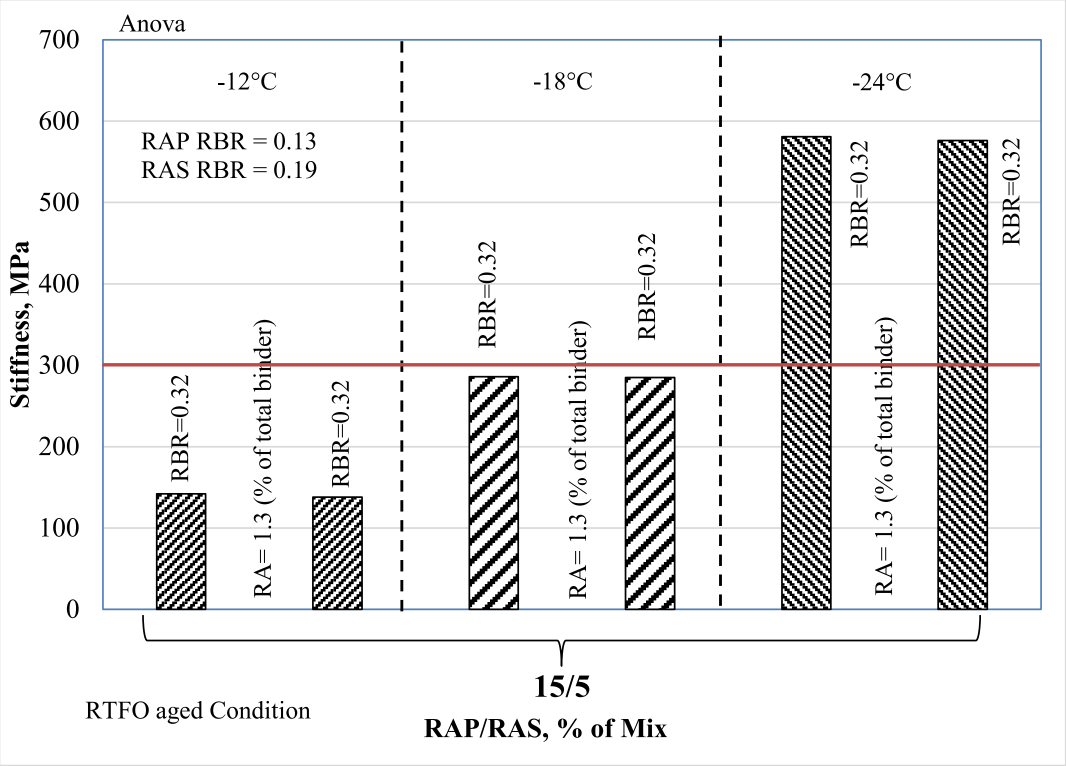

CA-7
34°C
RAP RBR = 0.14
RAS RBR = 0.20
RTFO Aged Condition
PAV Aged Condition
(G*)*sind, KPa
4500
4000
3500
3000
2500
2000
1500
1000
500
0
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.7 (% of total binder)
15/5
RAP/RAS, % of Mix

BBR Graphs:

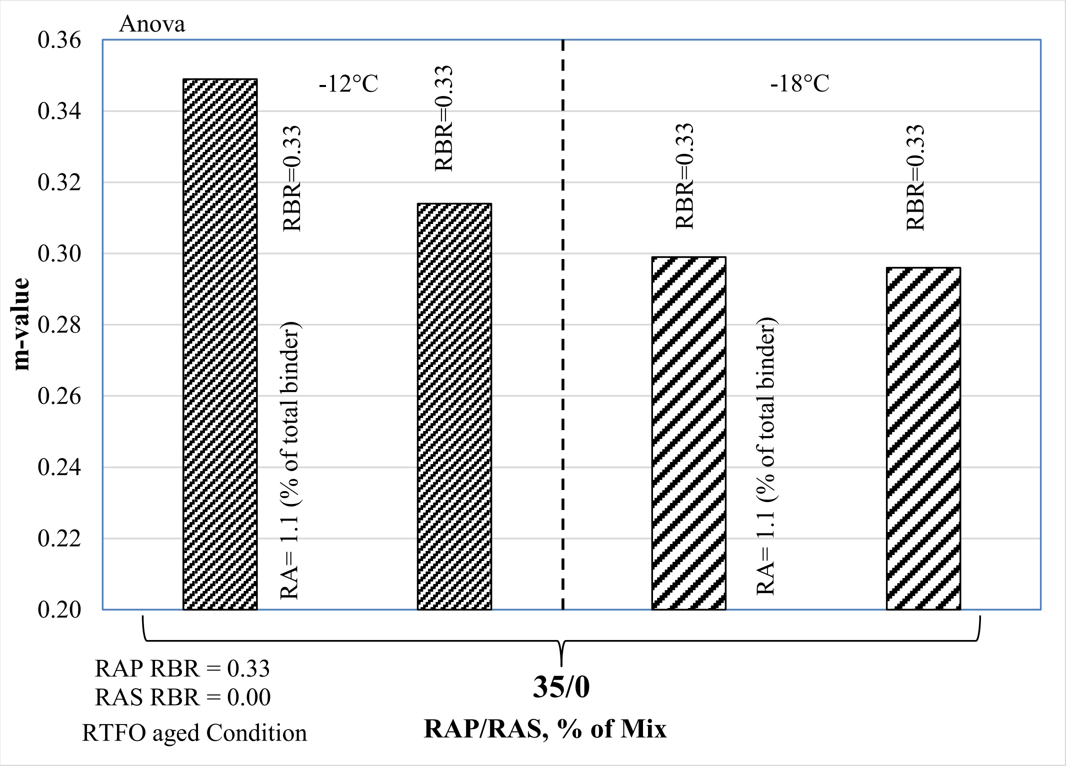

Anova
700
600
500
400
300
200
100
0
Stiffness, MPa
-12°C
-18°C
-24°C
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.32
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.32
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.32
15/5
RAP/RAS, % of Mix
RTFO aged Condition


Anova
RAP RBR = 0.33
RAS RBR = 0.00
-12°C
-18°C
Stiffness, MPa
0
50
100
150
200
250
300
350
400
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RA= 0.0 (% of total binder)
RA= 1.1 (% of total binder)
RA= 0.0 (% of total binder)
RA= 1.1 (% of total binder)
35/0
RTFO aged Condition
RAP/RAS, % of Mix

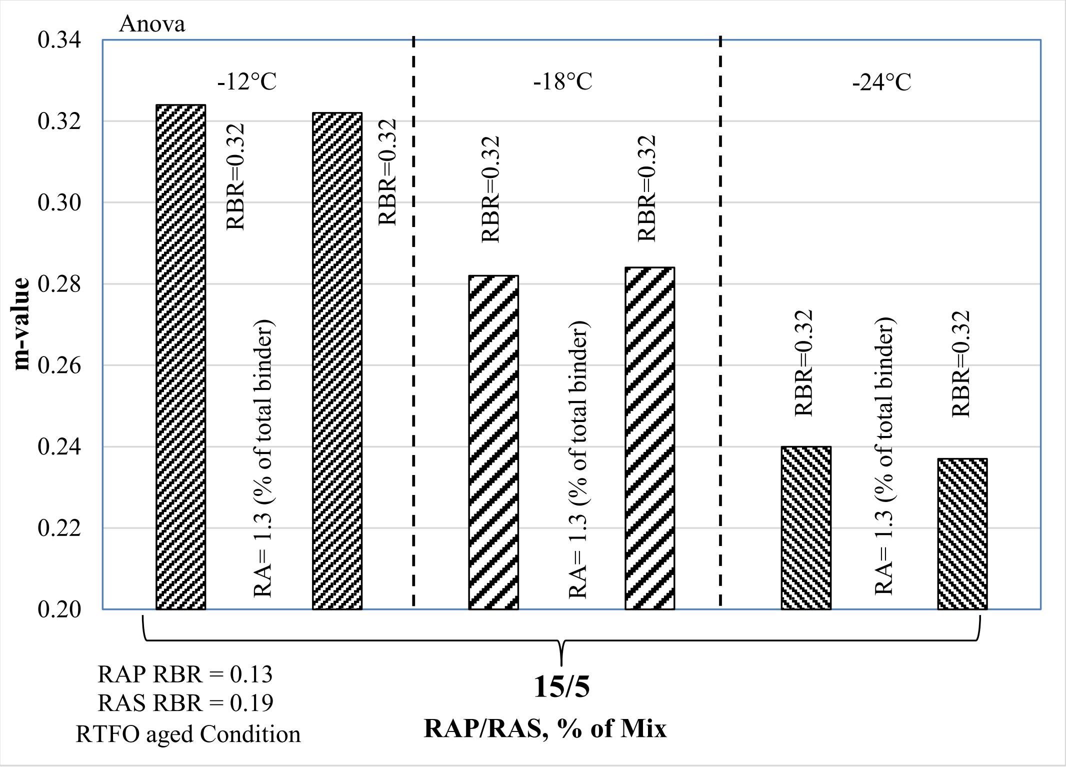

Anova
RAP RBR = 0.33
RAS RBR = 0.00
-12°C
-18°C
Stiffness, MPa
0
50
100
150
200
250
300
350
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RA= 1.1 (% of total binder)
RA= 1.1 (% of total binder)
35/0
RTFO aged Condition
RAP/RAS, % of Mix

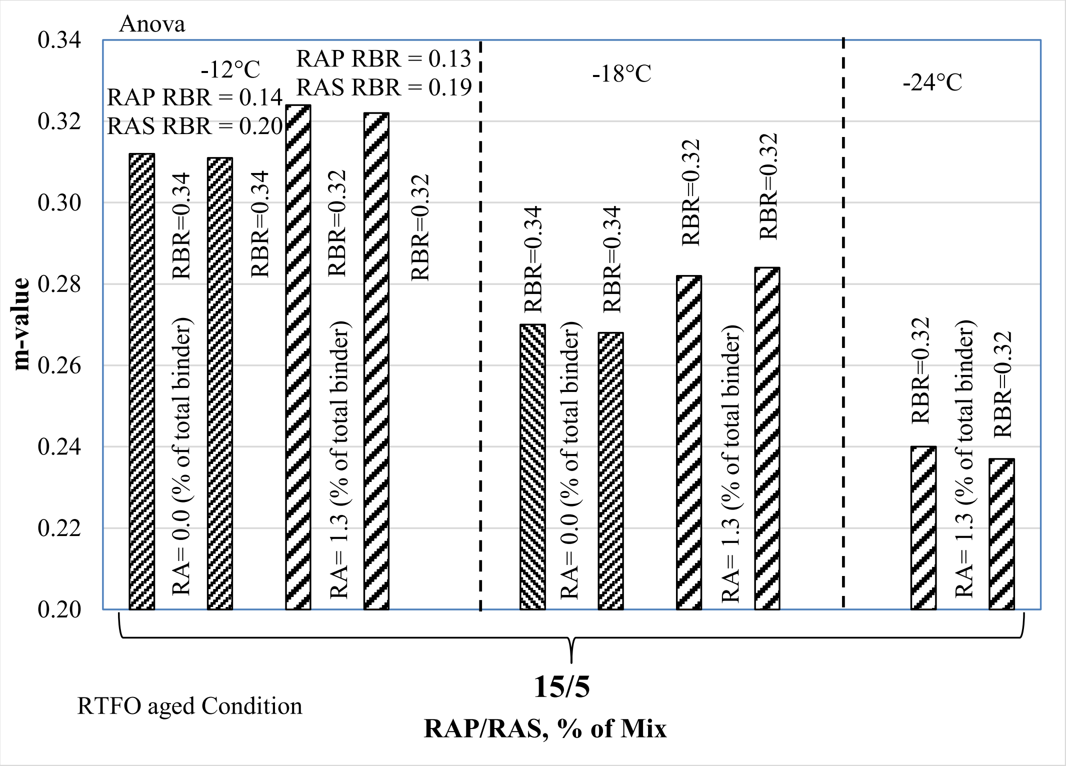


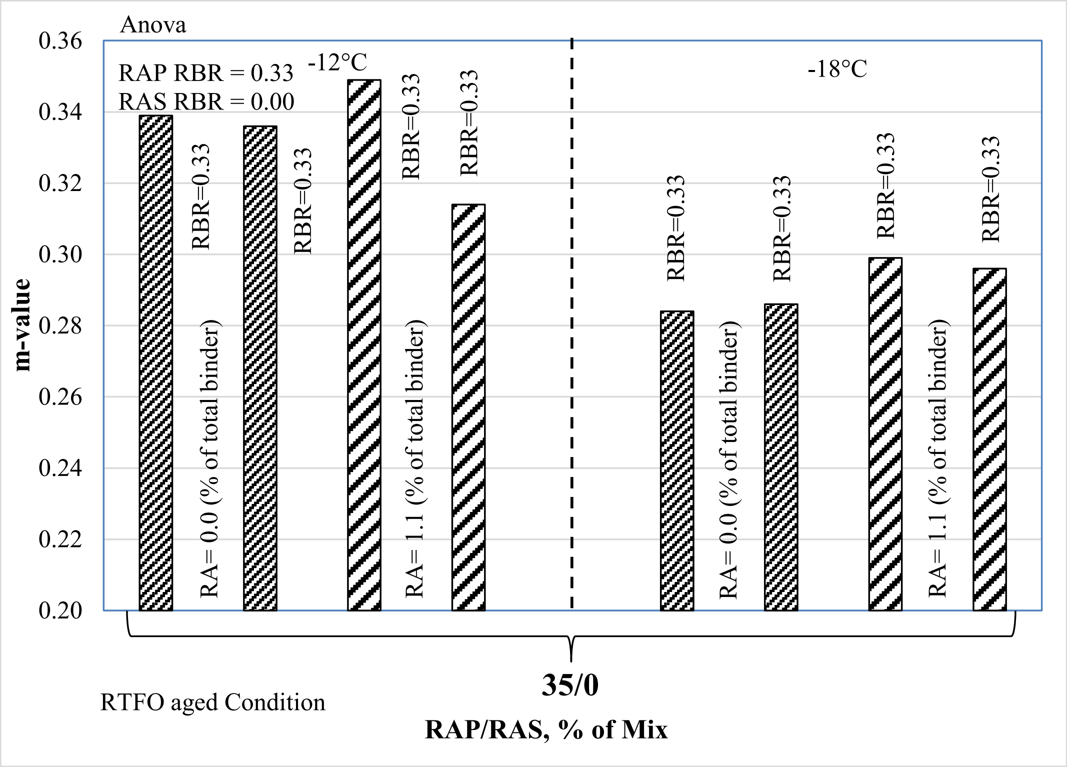
Anova
700
600
500
400
300
200
100
0
Stiffness, MPa
-12°C
-18°C
-24°C
RAP RBR = 0.13
RAS RBR = 0.19
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.32
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.32
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.32
15/5
RTFO aged Condition
RAP/RAS, % of Mix

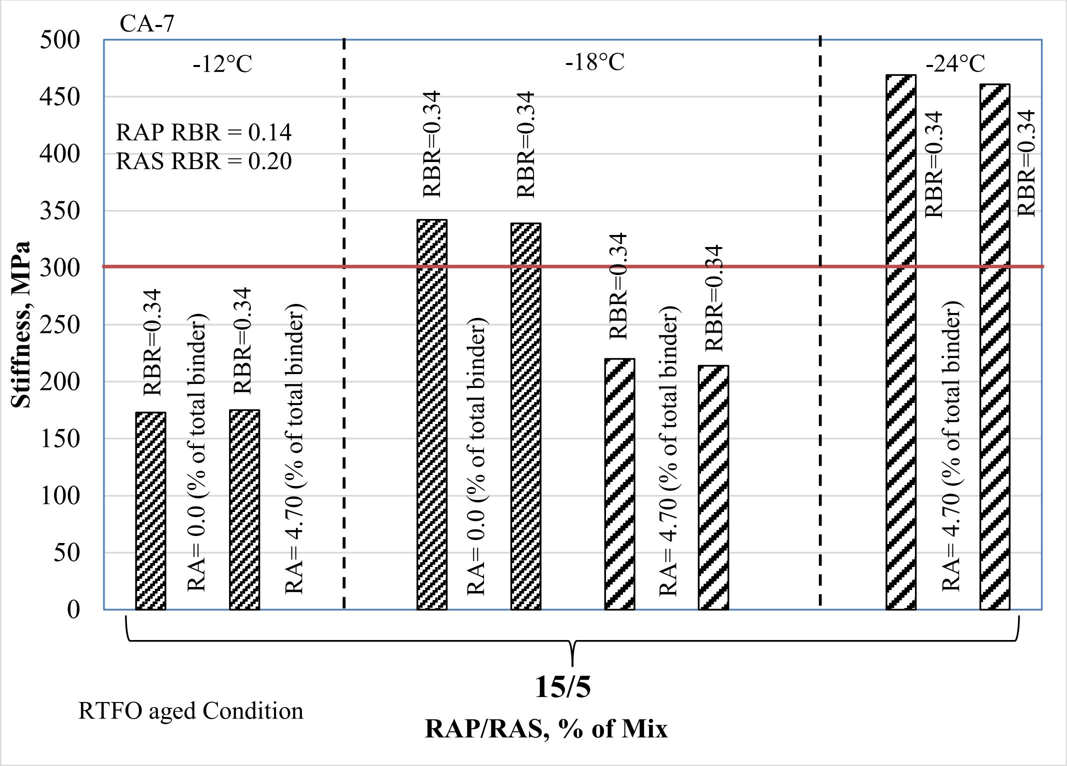


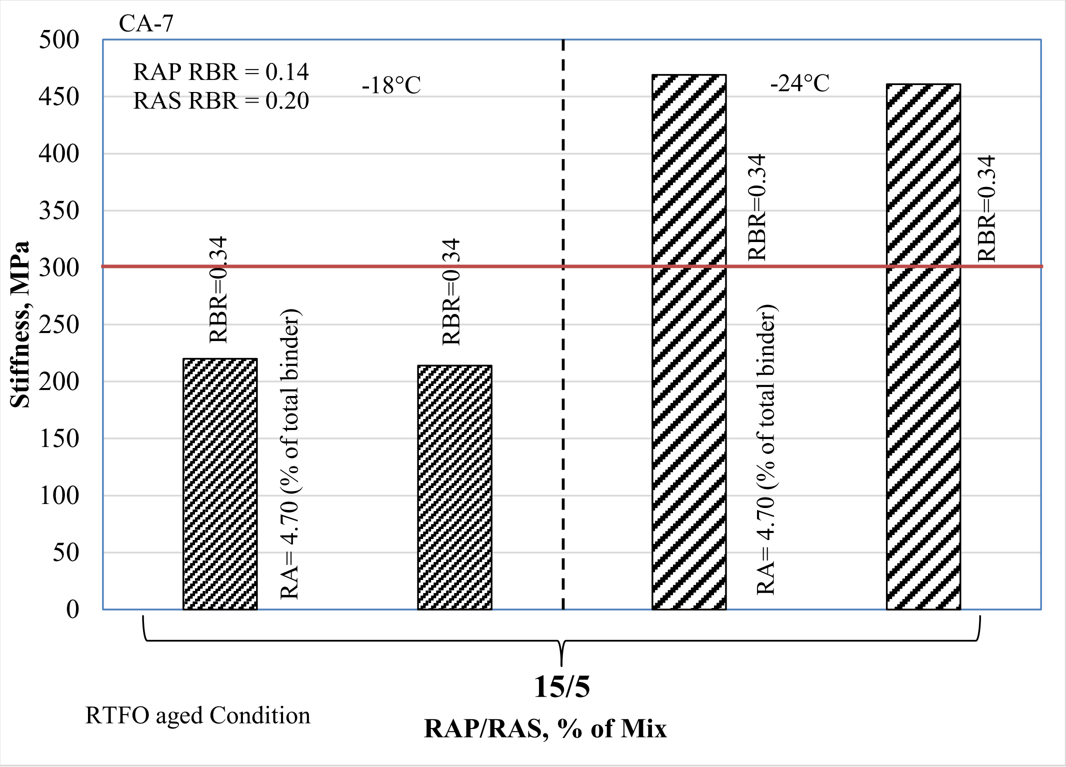
Anova
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
m-value
-12°C
-18°C
RBR=0.33
RA= 1.1 (% of total binder)
RBR=0.33
RBR=0.33
RA= 1.1 (% of total binder)
RBR=0.33
RAP RBR = 0.33
RAS RBR = 0.00
RTFO aged Condition
35/0
RAP/RAS, % of Mix

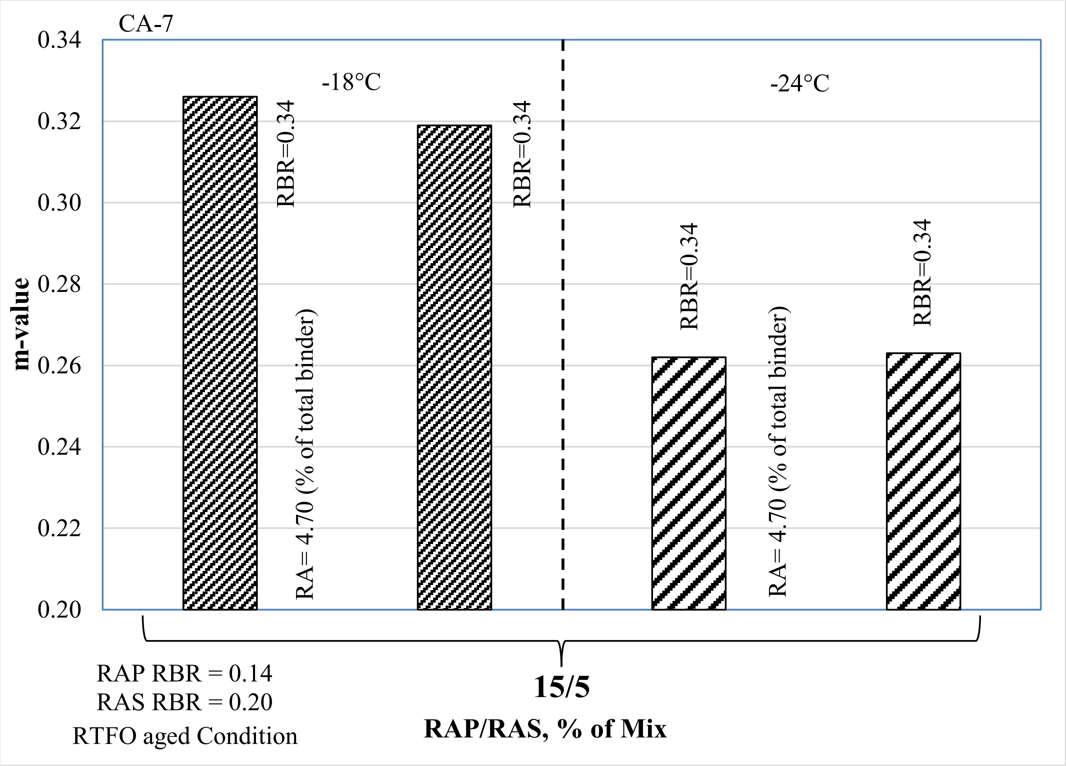

Anova
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
m-value
-12°C
-18°C
-24°C
RBR=0.32
RBR=0.32
RBR=0.32
RBR=0.32
RBR=0.32
RBR=0.32
RA= 1.3 (% of total binder)
RA= 1.3 (% of total binder)
RA= 1.3 (% of total binder)
RAP RBR = 0.13
RAS RBR = 0.19
RTFO aged Condition
15/5
RAP/RAS, % of Mix

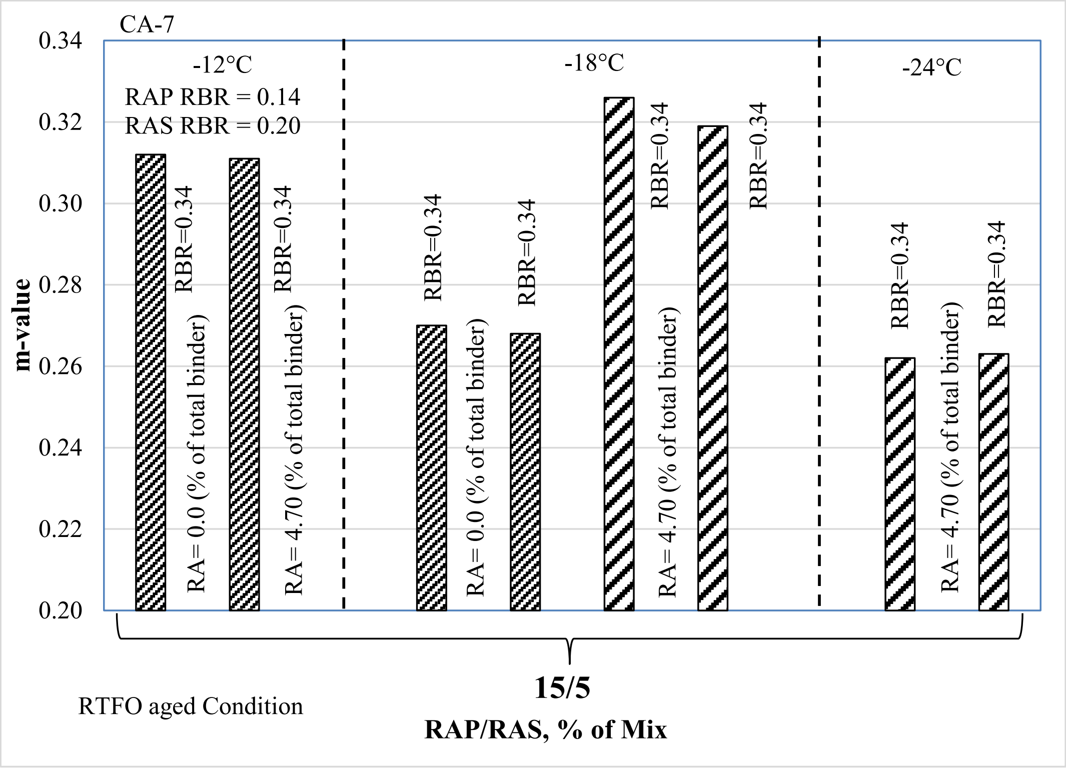

Anova
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
m-value
-12°C
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
-18°C
-24°C
RBR=0.34
RBR=0.34
RBR=0.32
RBR=0.32
RBR=0.34
RBR=0.34
RBR=0.32
RBR=0.32
RBR=0.32
RBR=0.32
RA= 0.0 (% of total binder)
RA= 1.3 (% of total binder)
RA= 0.0 (% of total binder)
RA= 1.3 (% of total binder)
RA= 1.3 (% of total binder)
RTFO aged Condition
15/5
RAP/RAS, % of Mix

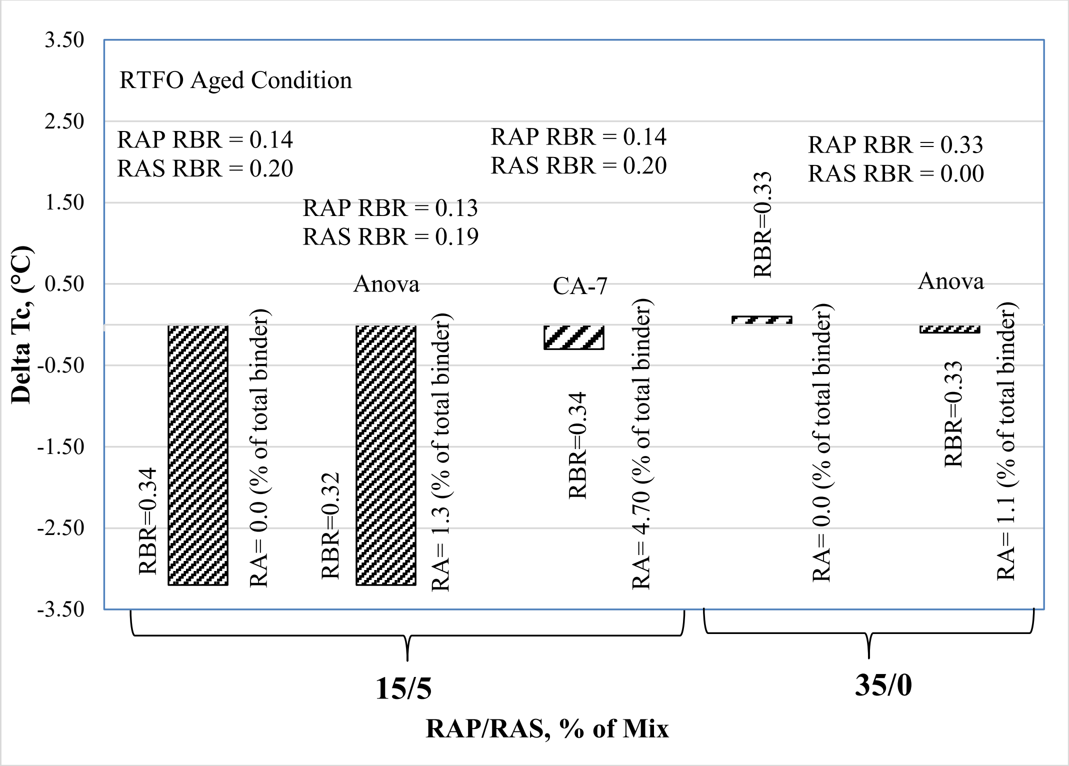

Anova
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
m-value
RAP RBR = 0.33
RAS RBR = 0.00
-12°C
-18°C
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RBR=0.33
RA= 0.0 (% of total binder)
RA= 1.1 (% of total binder)
RA= 0.0 (% of total binder)
RA= 1.1 (% of total binder)
35/0
RTFO aged Condition
RAP/RAS, % of Mix


CA-7
500
450
400
350
300
250
200
150
100
50
0
Stiffness, MPa
-12°C
-18°C
-24°C
RAP RBR = 0.14
RAS RBR = 0.20
RBR=0.34
RBR=0.34
RBR=0.34
RBR=0.34
RBR=0.34
RBR=0.34
RBR=0.34
RBR=0.34
RA= 0.0 (% of total binder)
RA= 4.70 (% of total binder)
RA= 0.0 (% of total binder)
RA= 4.70 (% of total binder)
RA= 4.70 (% of total binder)
15/5
RTFO aged Condition
RAP/RAS, % of Mix


CA-7
500
450
400
350
300
250
200
150
100
50
0
Stiffness, MPa
RAP RBR = 0.14
RAS RBR = 0.20
-18°C
-24°C
RBR=0.34
RBR=0.34
RBR=0.34
RBR=0.34
RA= 4.70 (% of total binder)
RA= 4.70 (% of total binder)
15/5
RTFO aged Condition
RAP/RAS, % of Mix


CA-7
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
m-value
-18°C
-24°C
RBR=0.34
RBR=0.34
RBR=0.34
RBR=0.34
RA= 4.70 (% of total binder)
RA= 4.70 (% of total binder)
RAP RBR = 0.14
RAS RBR = 0.20
RTFO aged Condition
15/5
RAP/RAS, % of Mix


CA-7
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
m-value
-12°C
RAP RBR = 0.14
RAS RBR = 0.20
-18°C
-24°C
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 4.70 (% of total binder)
RTFO aged Condition
15/5
RAP/RAS, % of Mix

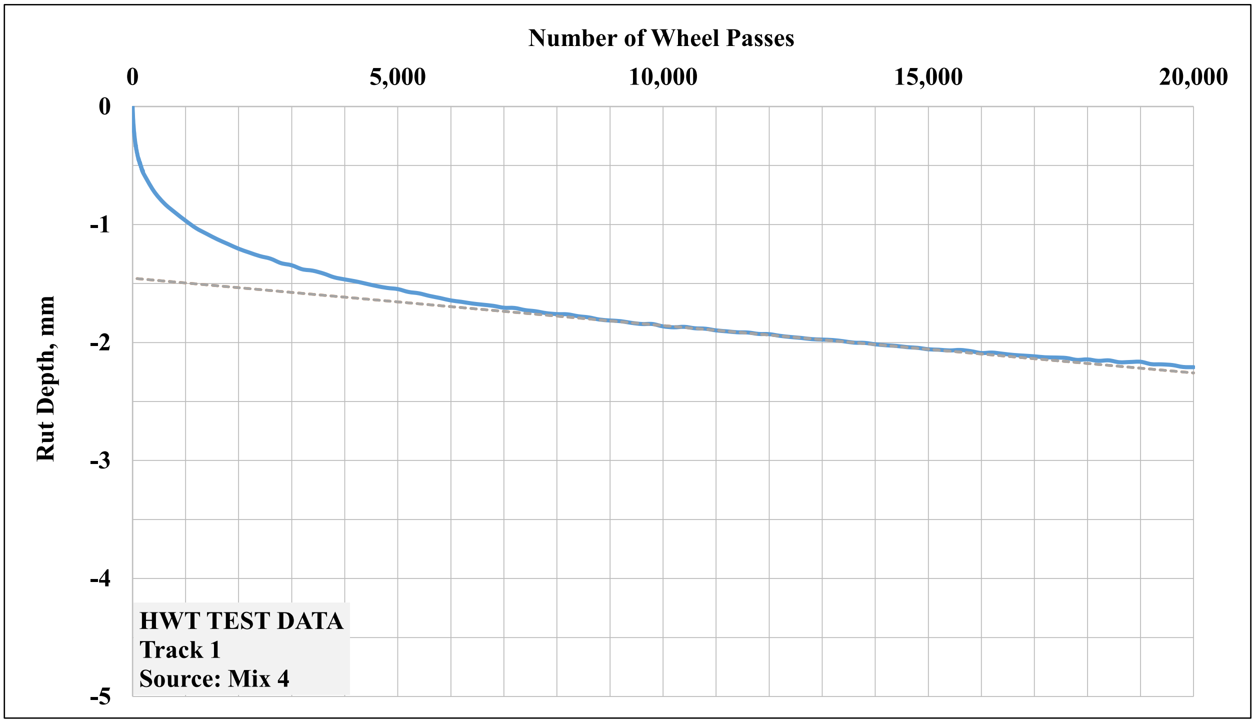

3.50
2.50
1.50
0.50
-0.50
-1.50
-2.50
-3.50
Delta Tc, (°C)
RTFO Aged Condition
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
Anova
CA-7
Anova
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.34
RA= 4.70 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
15/5
35/0
RAP/RAS, % of Mix

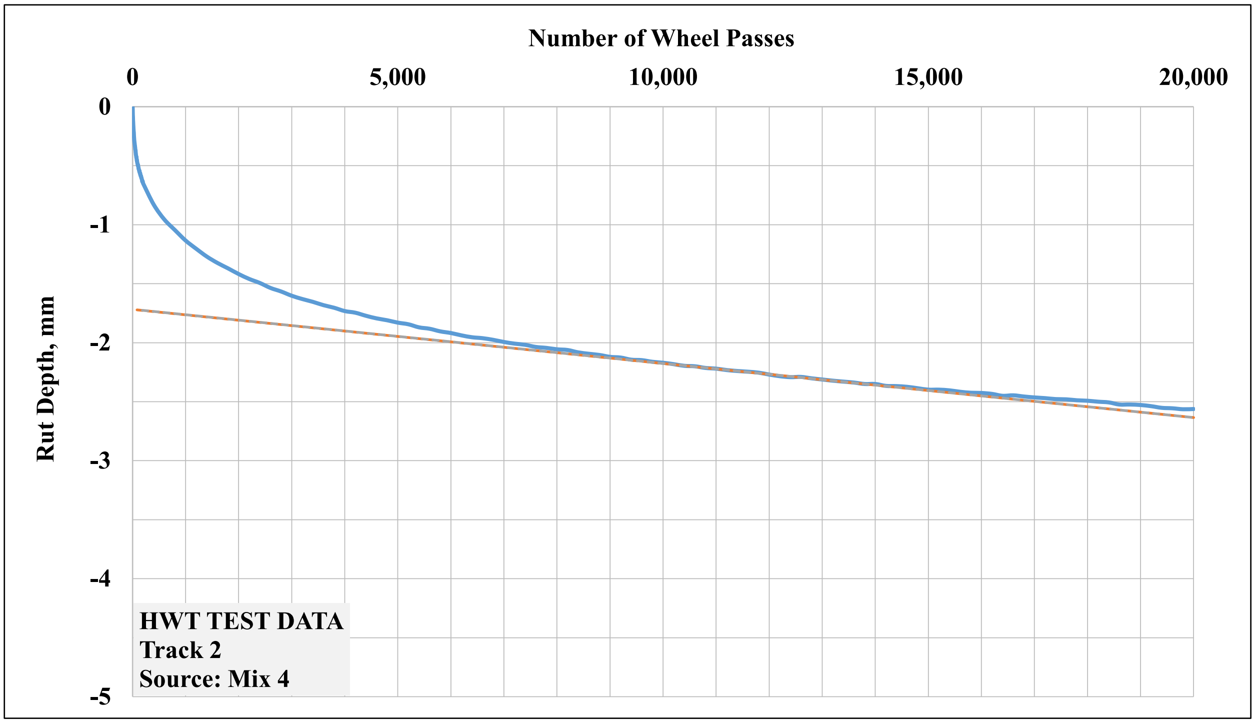
APPENDIX C

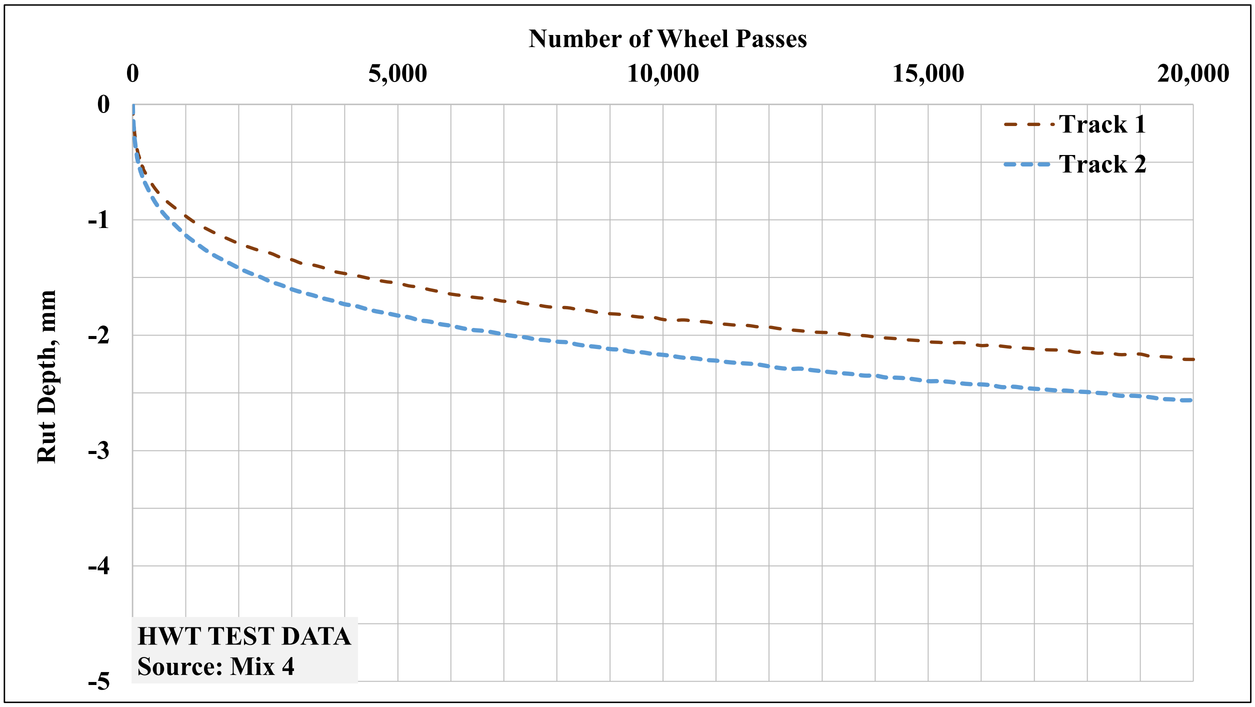
Results from Hamburg Wheel Tracking Test for Different Mixes

MIX CODE
4

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-2.21	-2.56	-2.39
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	213,116	180,709	196,913
No. of Passes to 12.5 mm rut depth	275,474	235,255	255,364
Rut depth at 10,000 passes, mm	-1.86	-2.17	-2.02
Creep Slope (mm/1000 passes)	0.04	0.05	0.04
Stripping Slope (mm/1000 passes)	NA	NA	NA

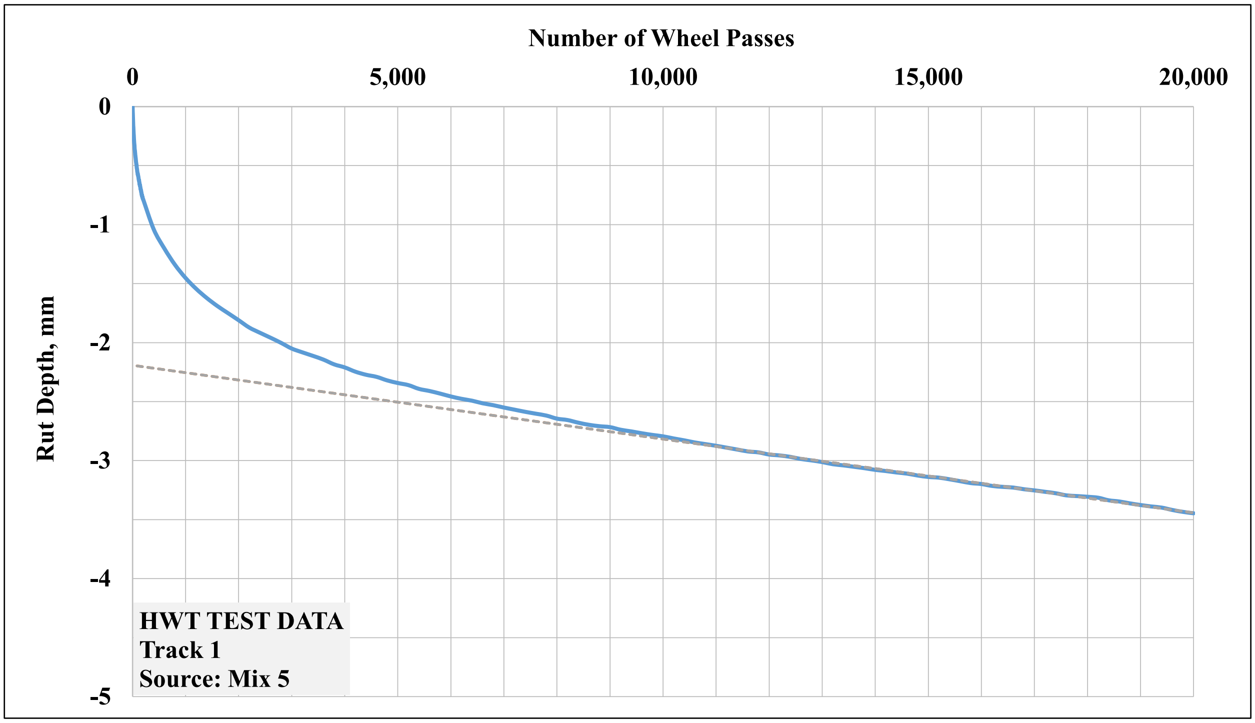


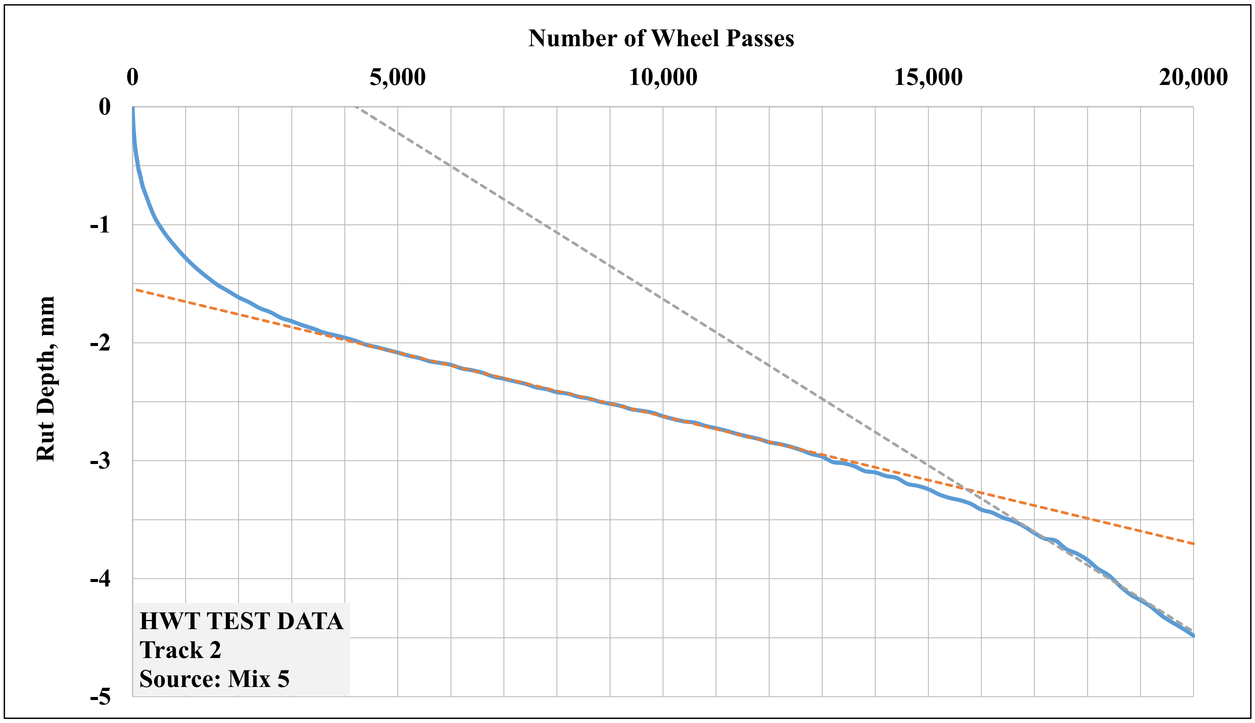

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 4

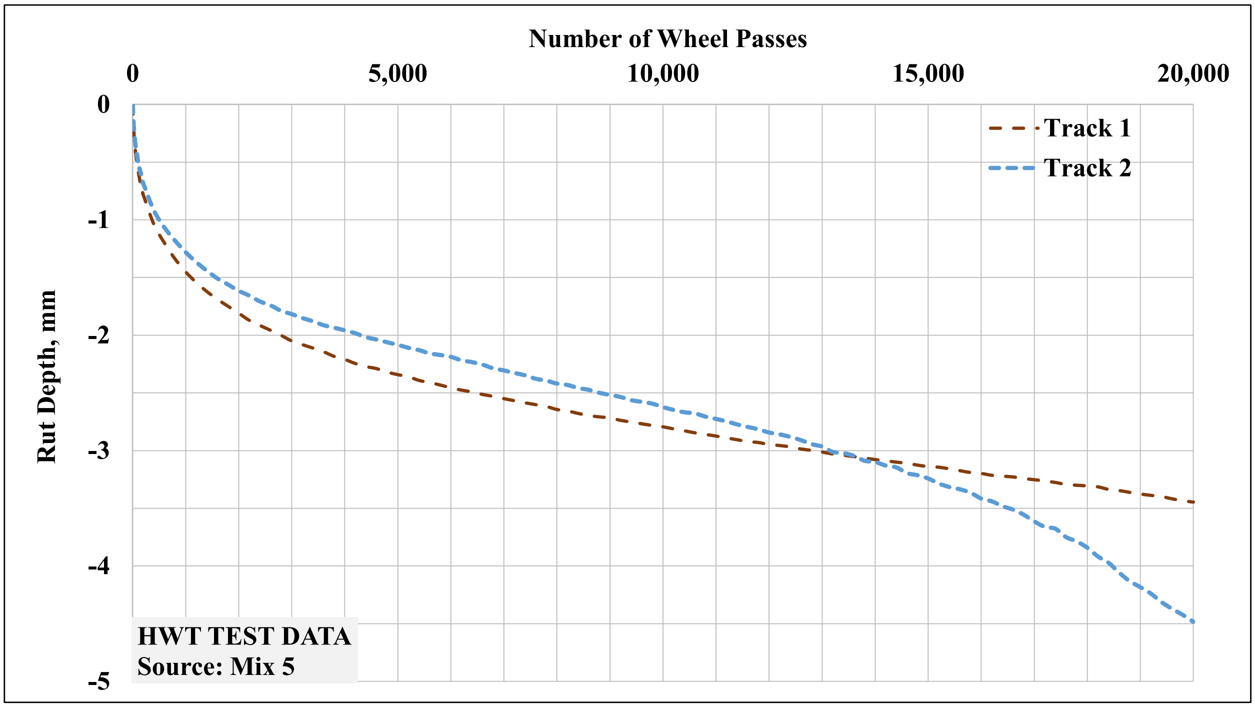

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 4

MIX CODE
5

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	15,715	NA
Ratio of the slope (strip/creep)	1.00	2.61	1.80
Max Rut (mm)	-3.45	-4.48	-3.97
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	124,846	39,708	82,277
No. of Passes to 12.5 mm rut depth	164,819	48,582	106,700
Rut depth at 10,000 passes, mm	-2.79	-2.62	-2.71
Creep Slope (mm/1000 passes)	0.06	0.11	0.09
Stripping Slope (mm/1000 passes)	NA	0.28	NA

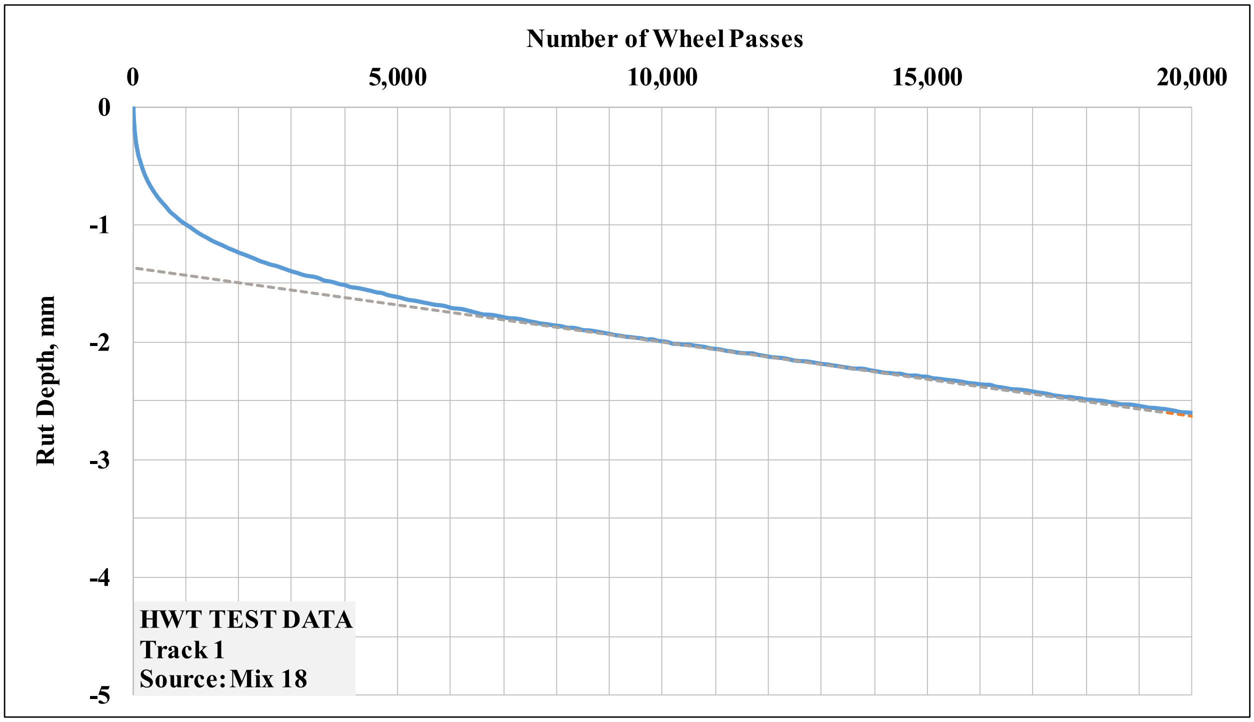


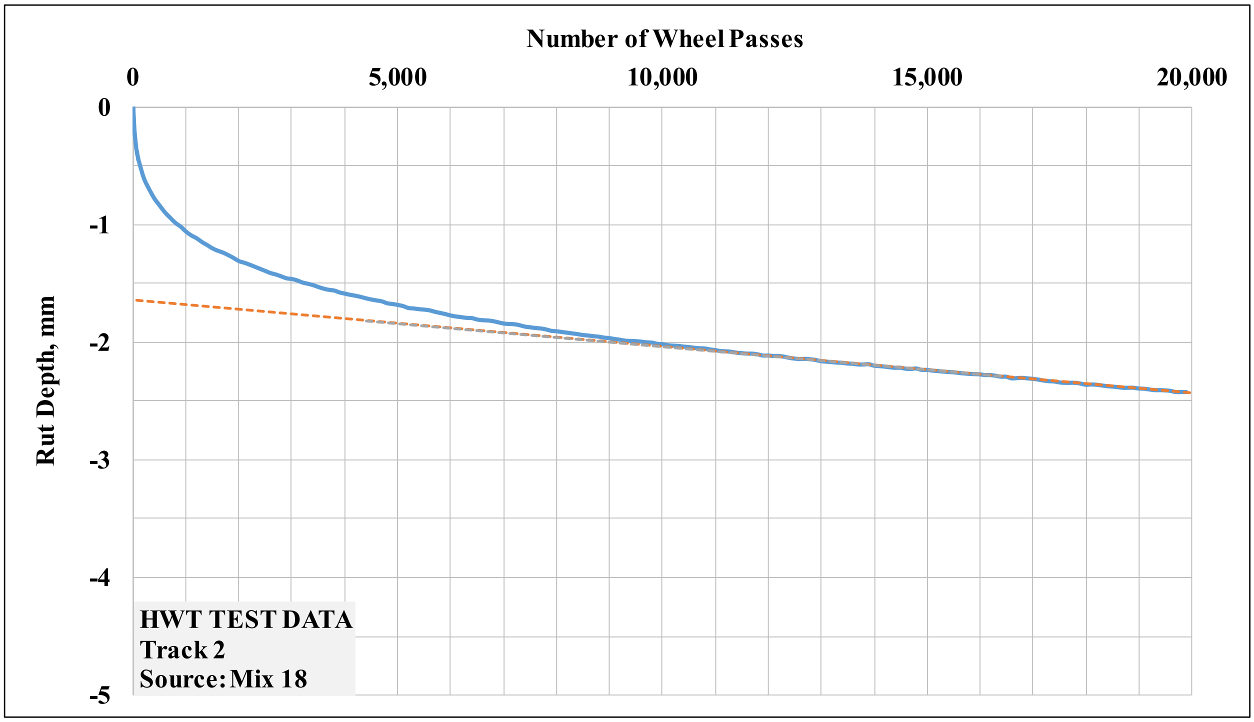

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
HWT TEST DATA
Track 2
Source: Mix 5

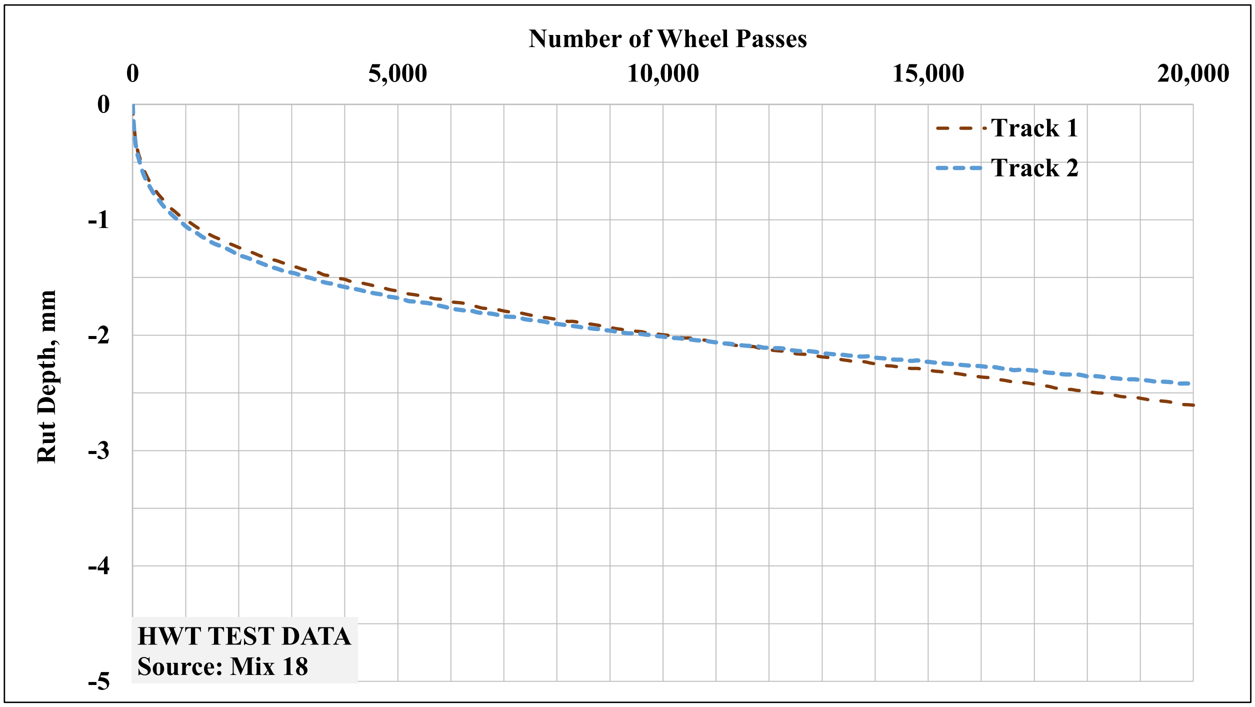

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
Track 1
Track 2
HWT TEST DATA
Source: Mix 5

MIX CODE
18

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-2.61	-2.42	-2.51
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	137,286	213,150	175,218
No. of Passes to 12.5 mm rut depth	177,056	276,925	226,991
Rut depth at 10,000 passes, mm	-2.00	-2.01	-2.00
Creep Slope (mm/1000 passes)	0.06	0.04	0.05
Stripping Slope (mm/1000 passes)	NA	NA	NA

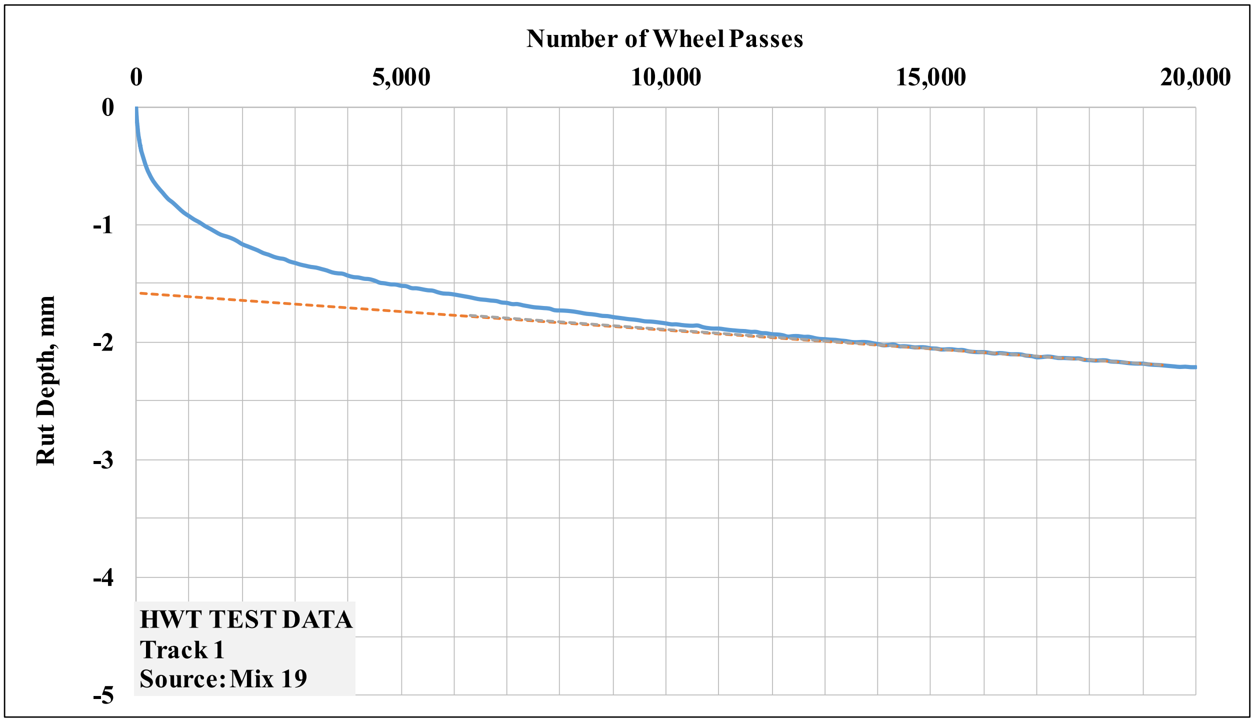


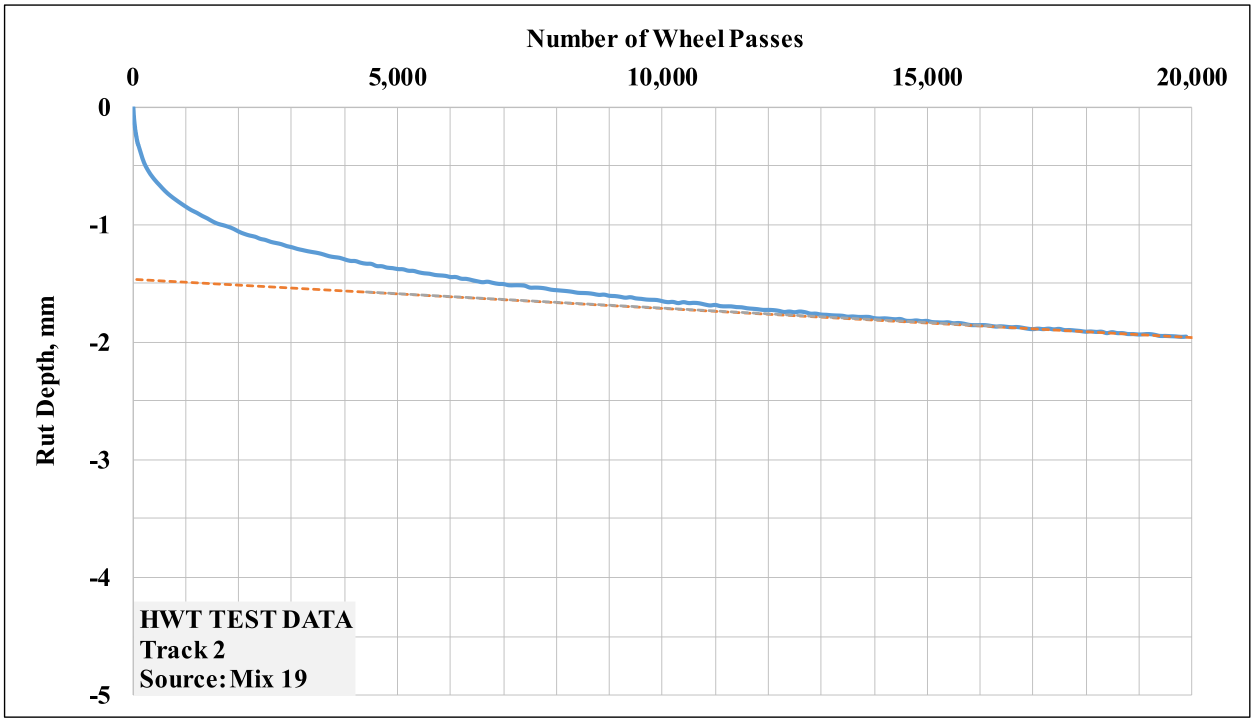

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 18

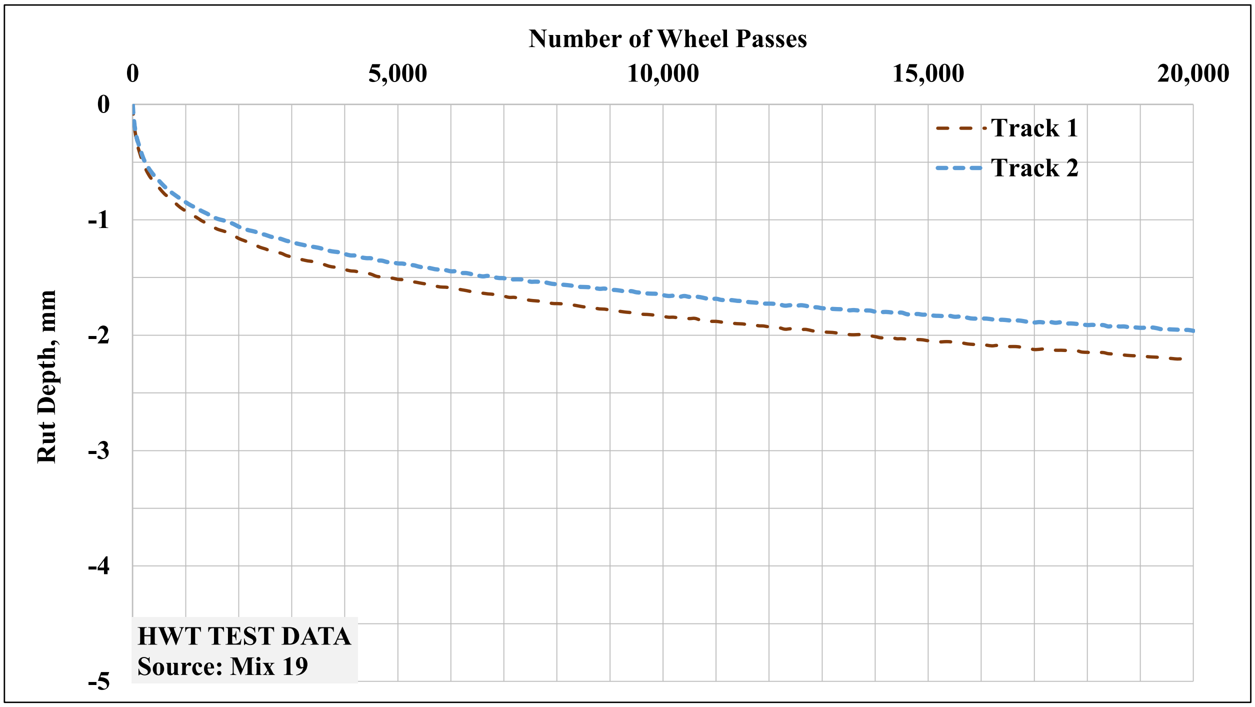

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 18

MIX CODE
19

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-2.21	-1.96	-2.09
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	266,390	342,472	304,431
No. of Passes to 12.5 mm rut depth	345,452	442,713	394,083
Rut depth at 10,000 passes, mm	-1.84	-1.65	-1.74
Creep Slope (mm/1000 passes)	0.03	0.02	0.03
Stripping Slope (mm/1000 passes)	NA	NA	NA

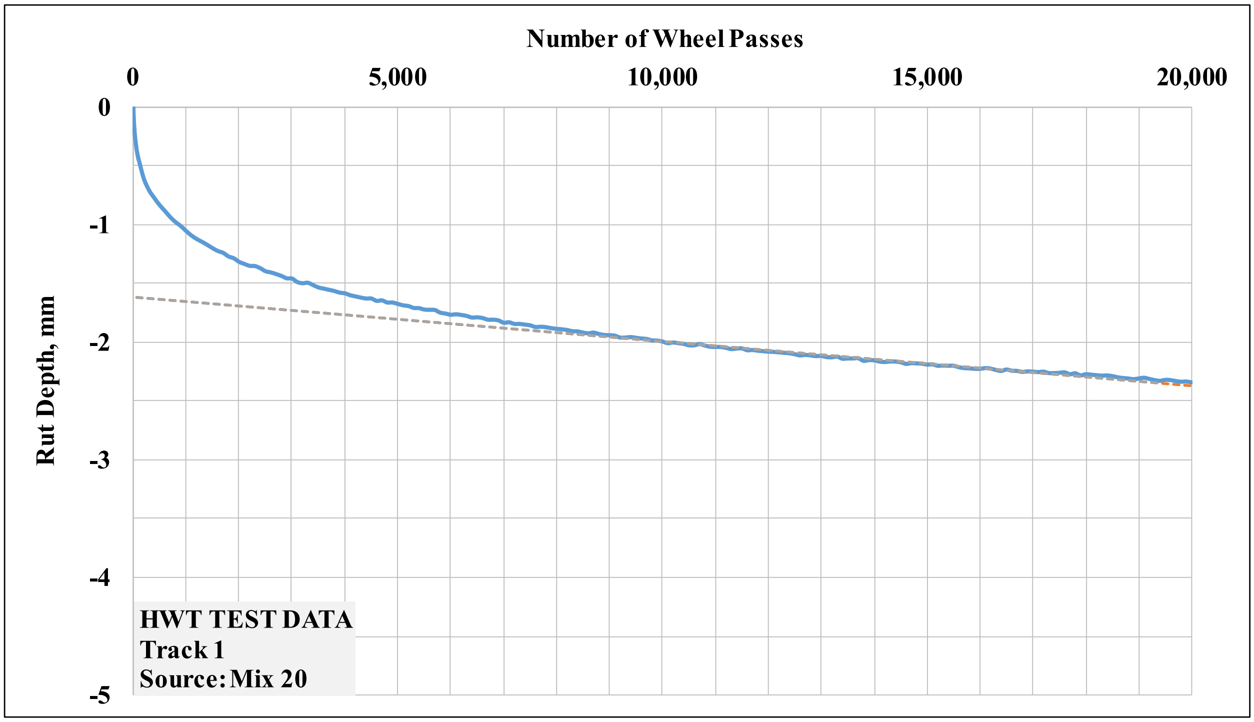


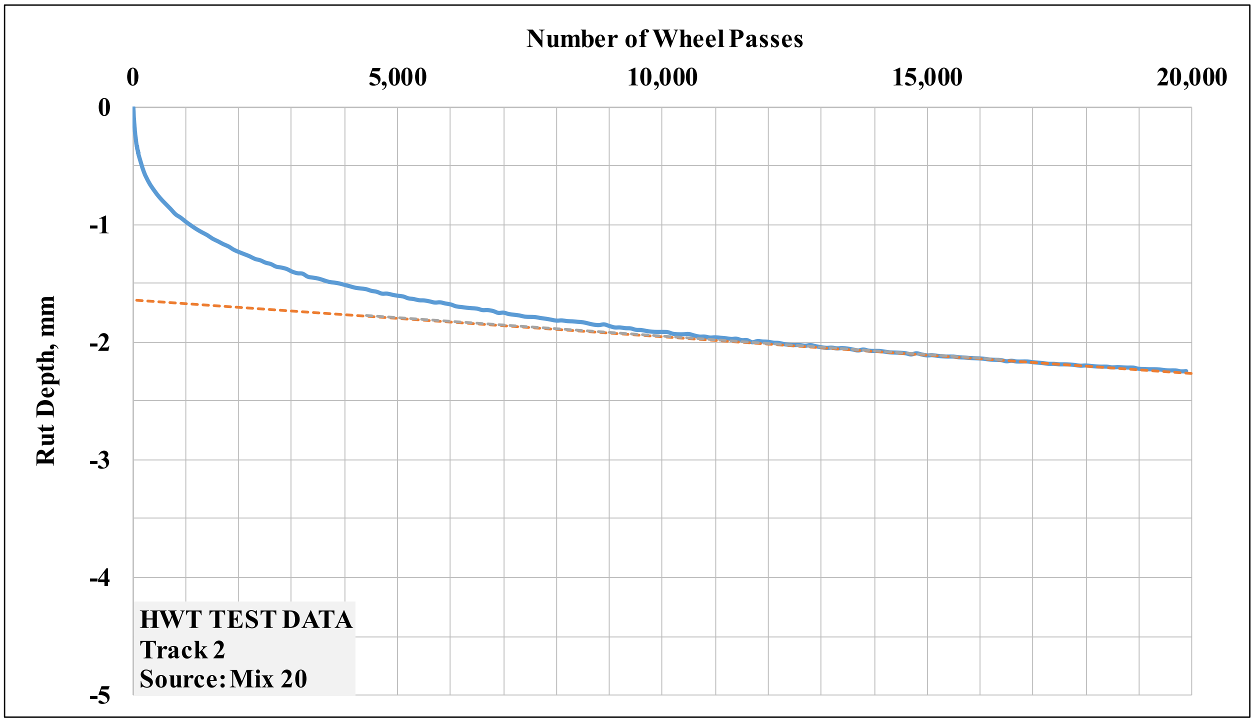

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 19

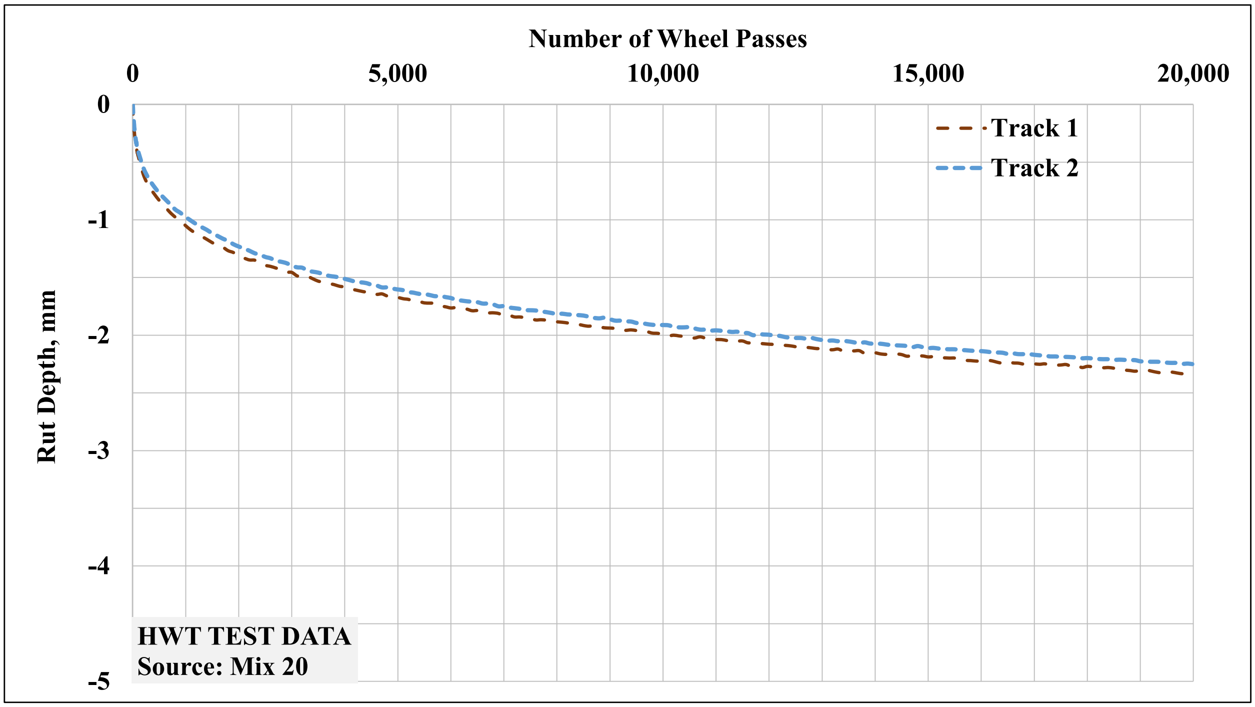

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 19

MIX CODE
20

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-2.34	-2.25	-2.30
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	221,496	267,619	244,558
No. of Passes to 12.5 mm rut depth	287,506	347,598	317,552
Rut depth at 10,000 passes, mm	-1.99	-1.91	-1.95
Creep Slope (mm/1000 passes)	0.04	0.03	0.03
Stripping Slope (mm/1000 passes)	NA	NA	NA

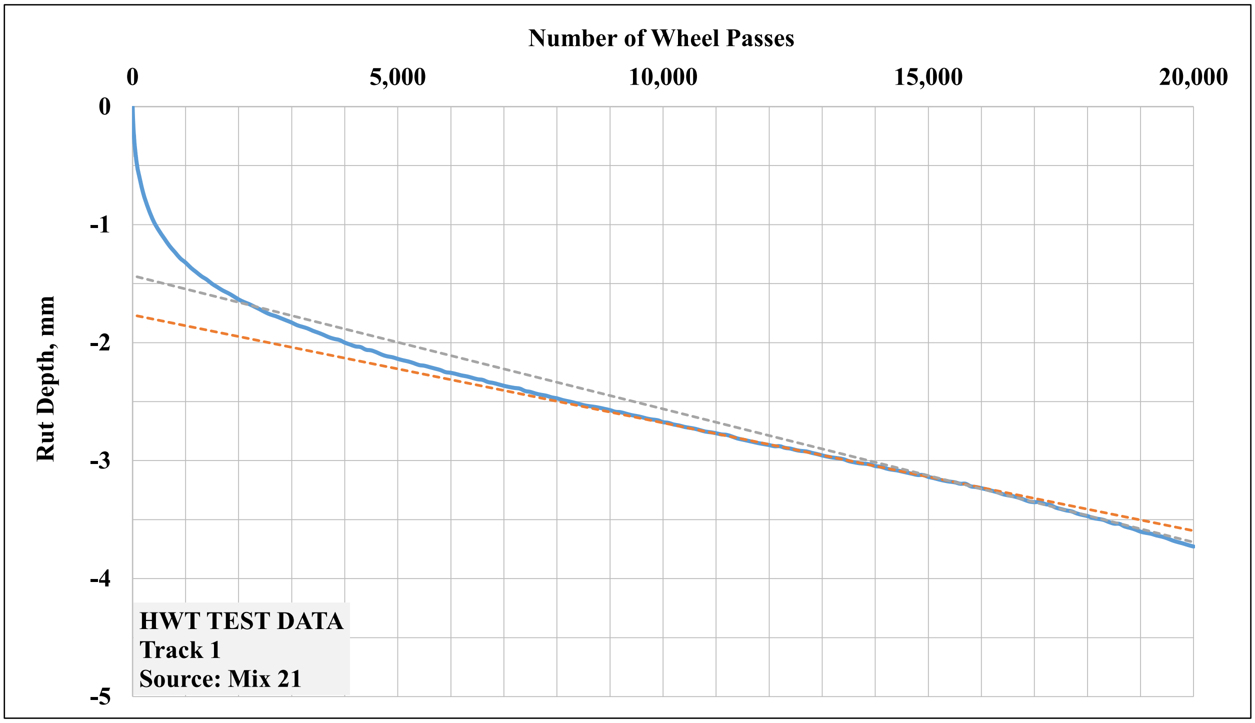


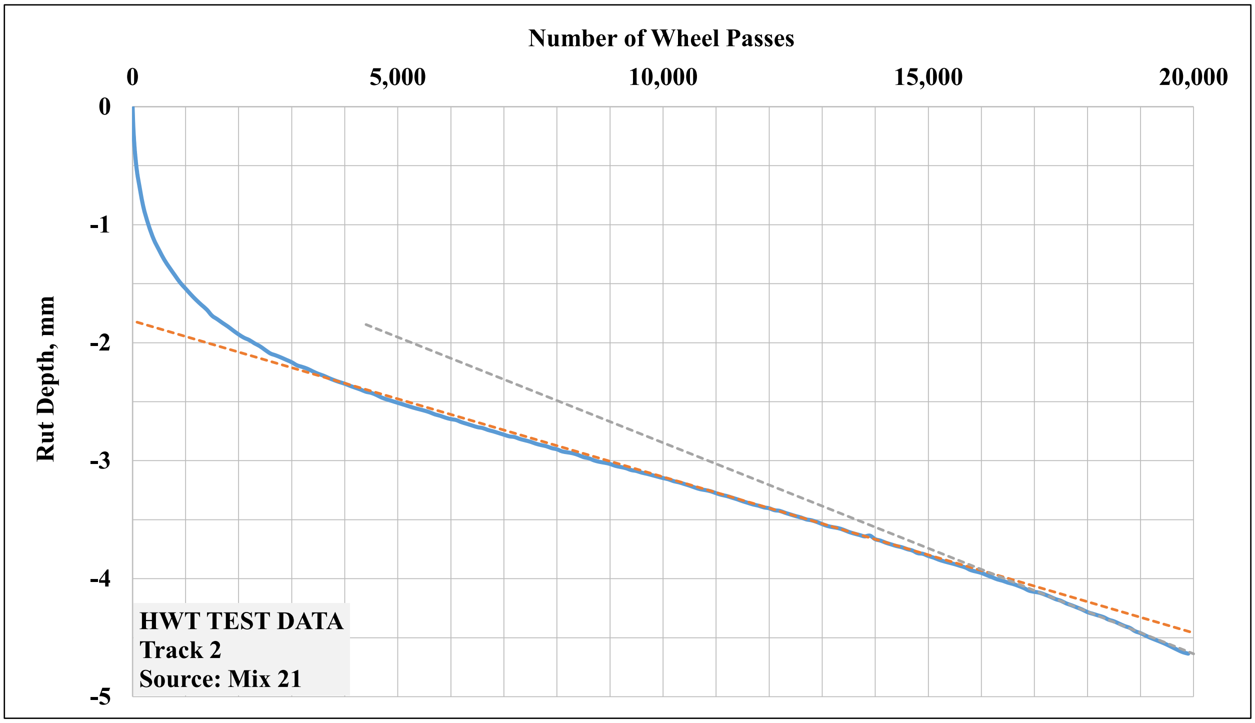

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 20

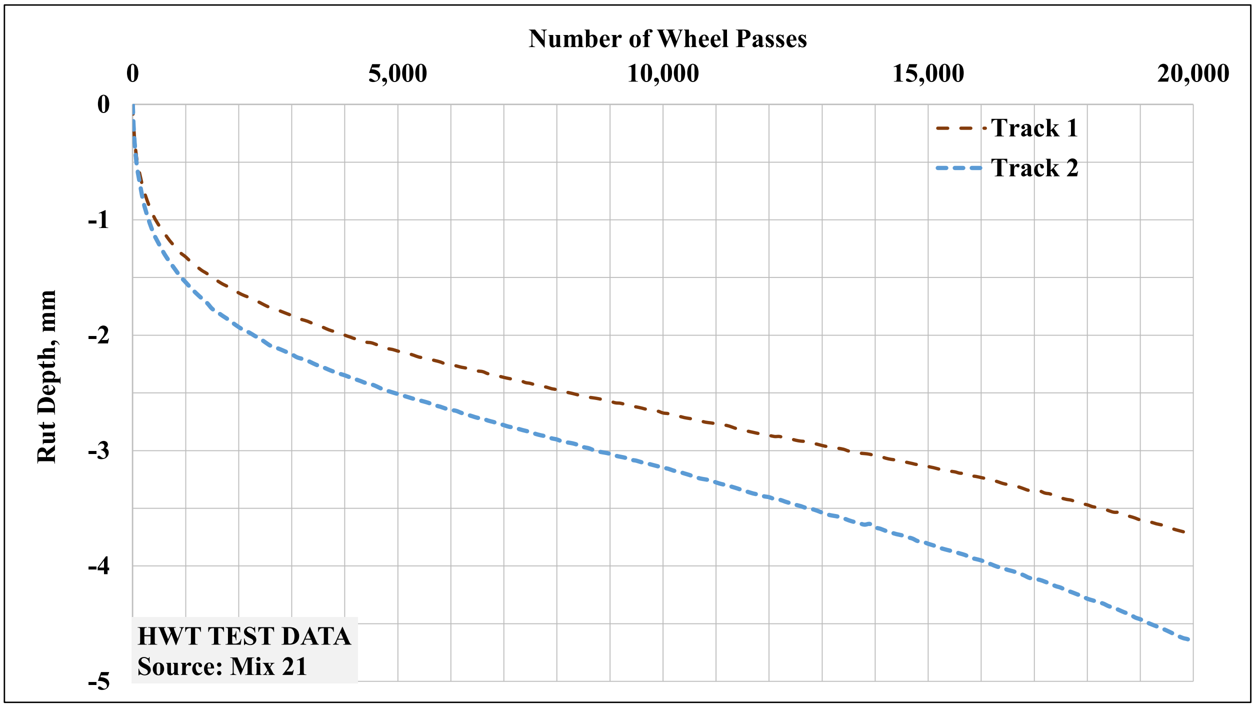

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 20

MIX CODE
21

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	15,520	16,198	15,859
Ratio of the slope (strip/creep)	1.23	1.35	1.29
Max Rut (mm)	-3.73	-4.66	-4.19
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	75,834	49,981	62,908
No. of Passes to 12.5 mm rut depth	97,960	63,956	80,958
Rut depth at 10,000 passes, mm	-2.67	-3.15	-2.91
Creep Slope (mm/1000 passes)	0.09	0.13	0.11
Stripping Slope (mm/1000 passes)	0.11	0.18	0.15

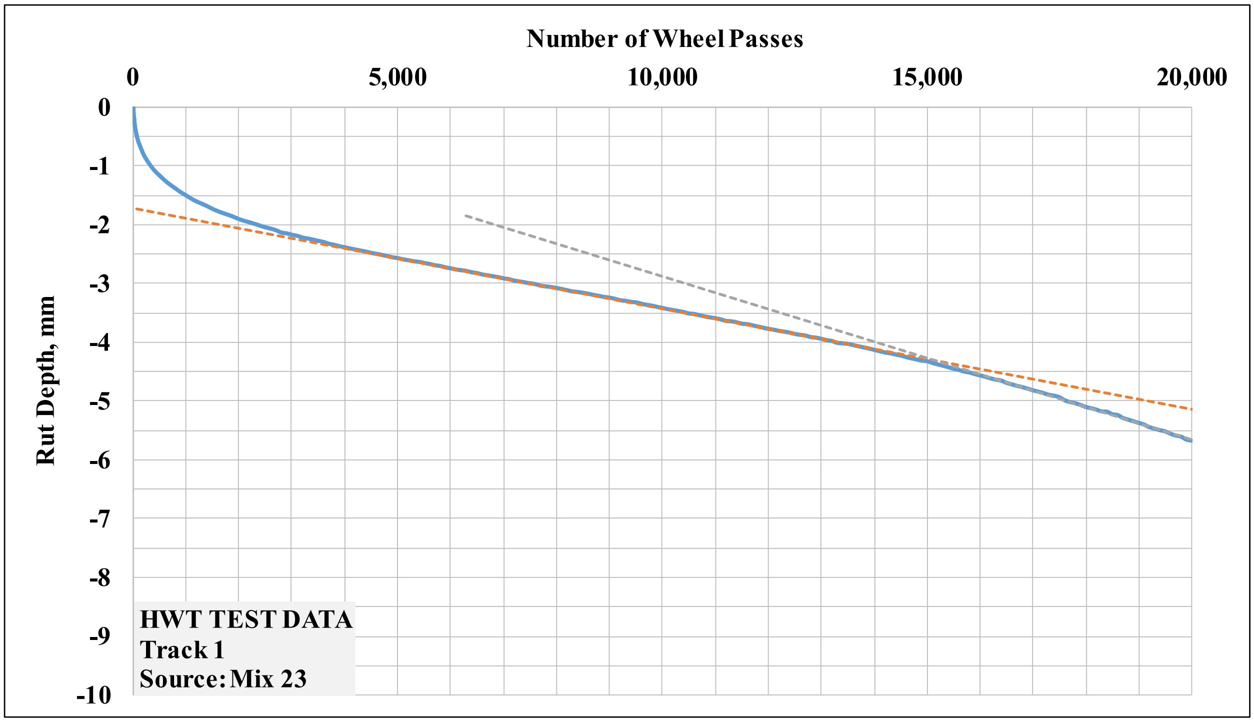


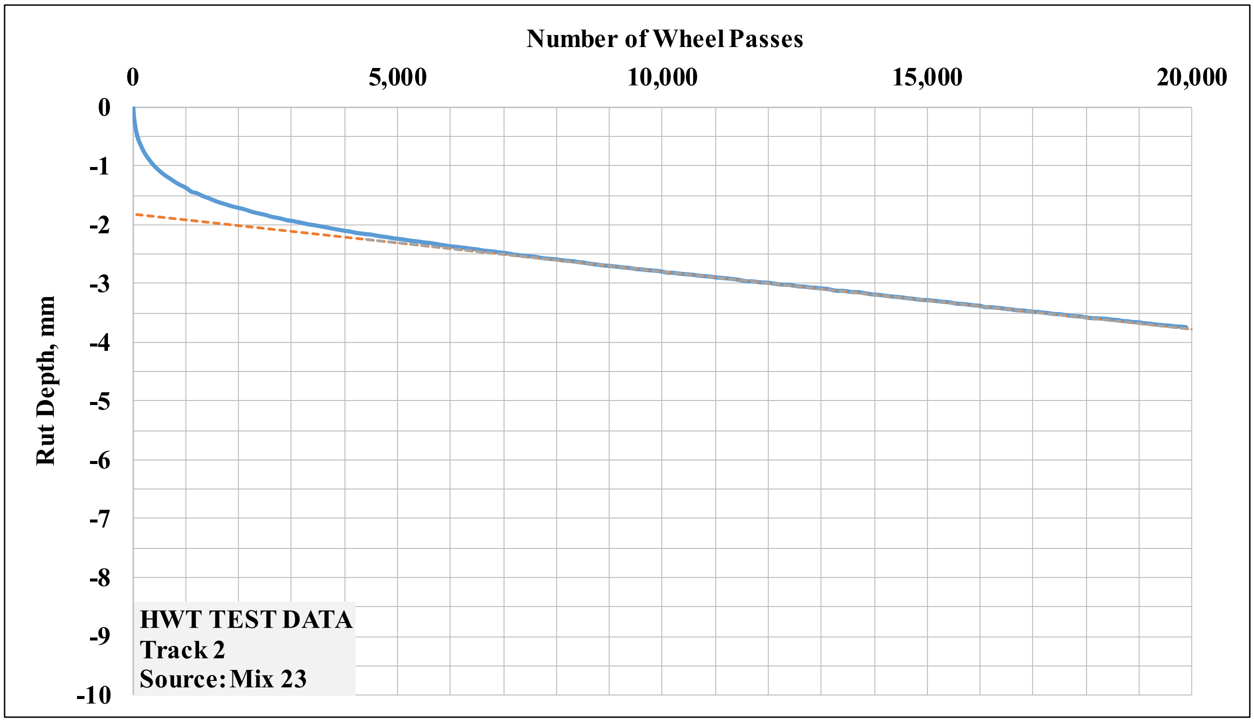

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 21

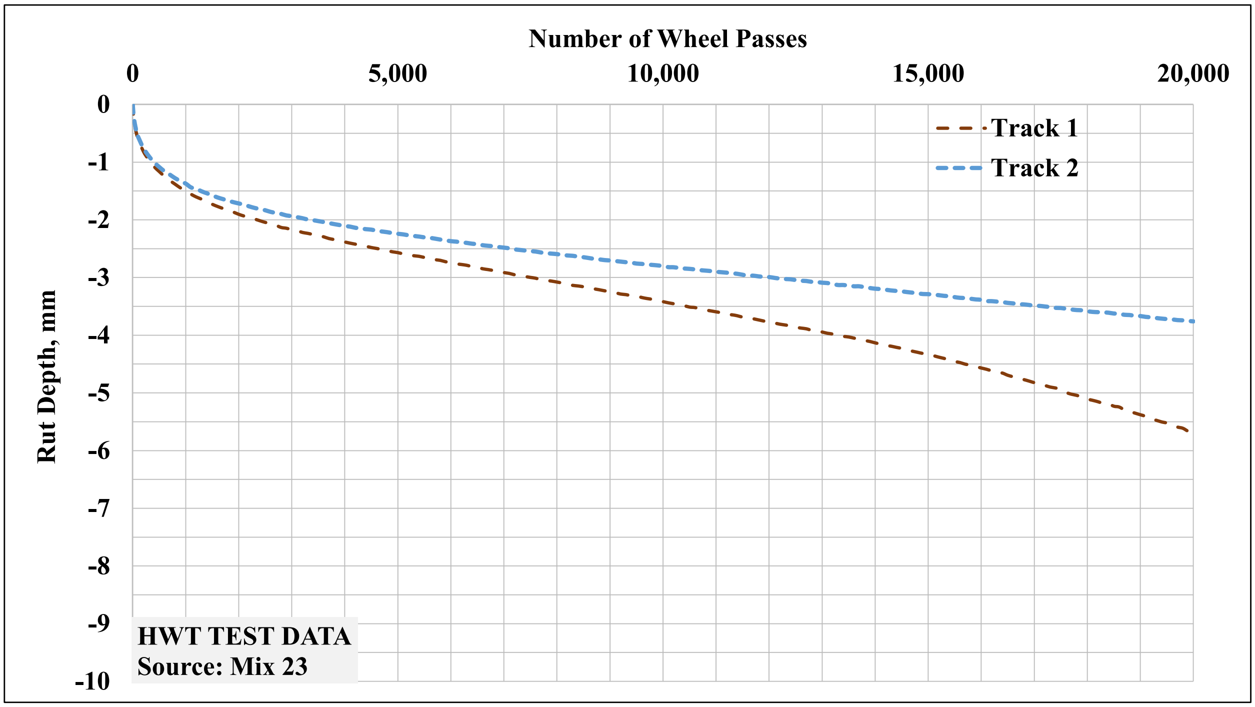

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 21

MIX CODE
23

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	15,199	Not Reached	NA
Ratio of the slope (strip/creep)	1.61	1.00	1.31
Max Rut (mm)	-5.68	-3.76	-4.72
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	35,719	83,466	59,593
No. of Passes to 12.5 mm rut depth	44,754	108,993	76,874
Rut depth at 10,000 passes, mm	-3.42	-2.80	-3.11
Creep Slope (mm/1000 passes)	0.17	0.10	0.13
Stripping Slope (mm/1000 passes)	0.28	NA	NA

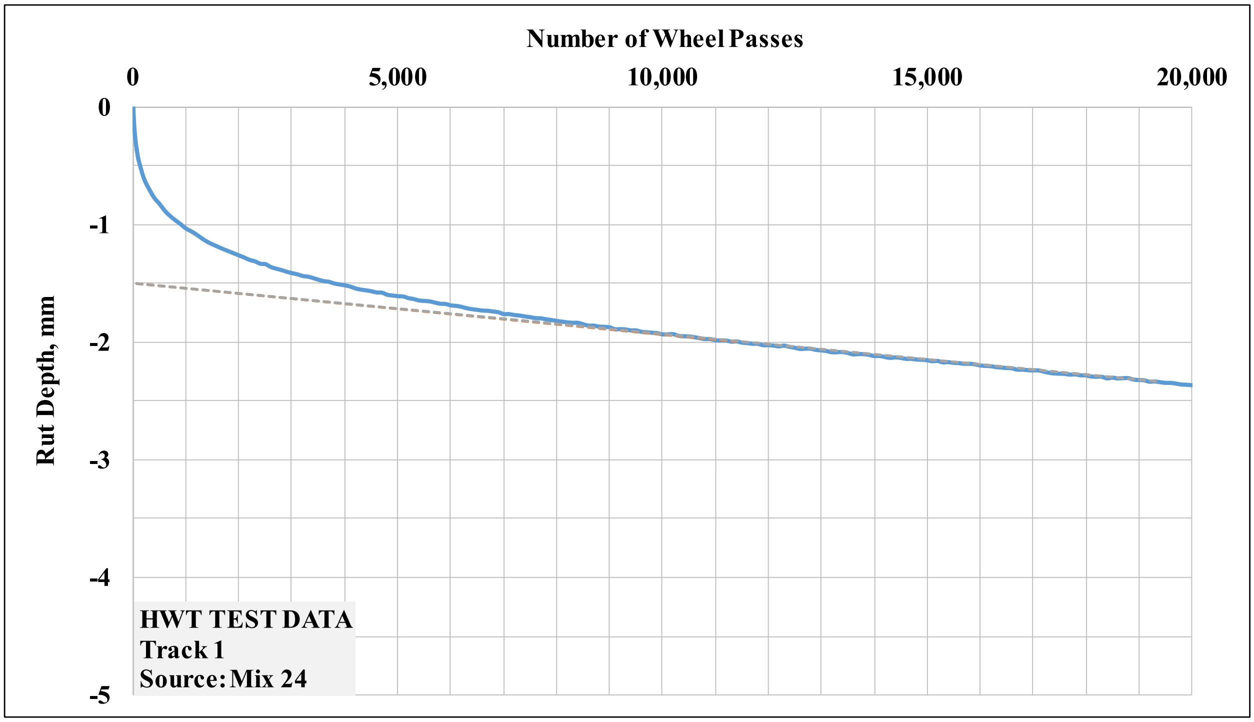


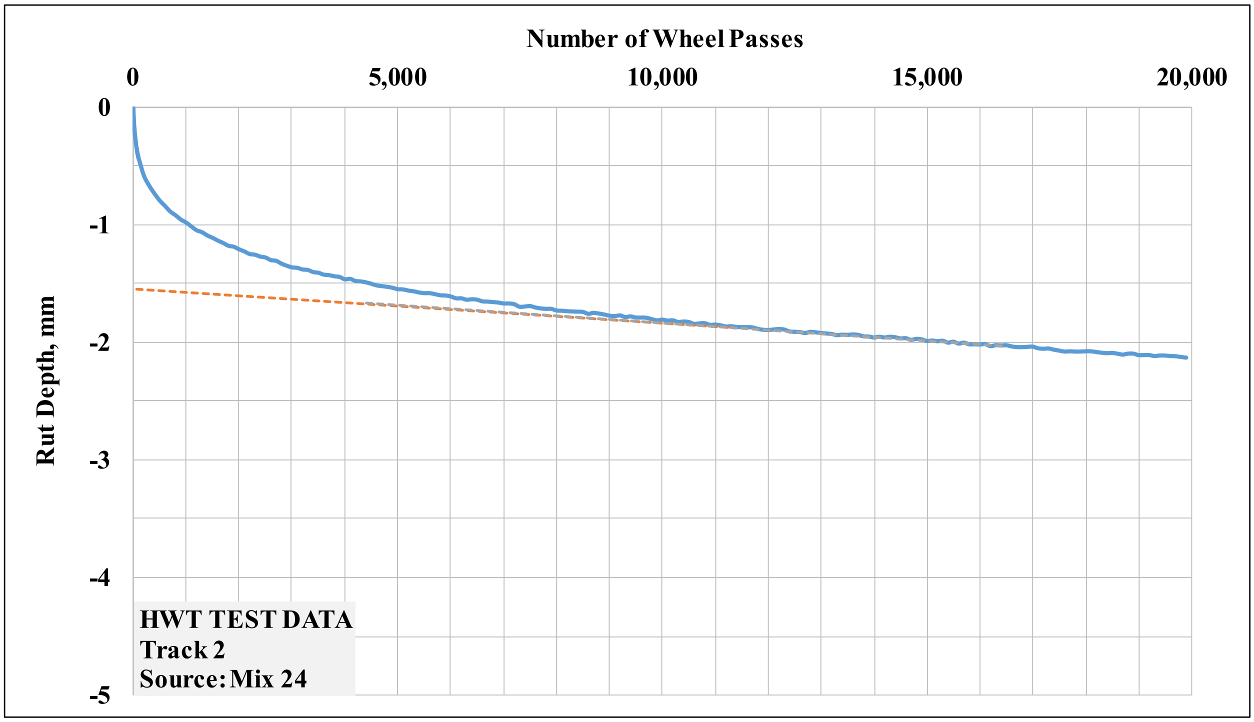

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 23

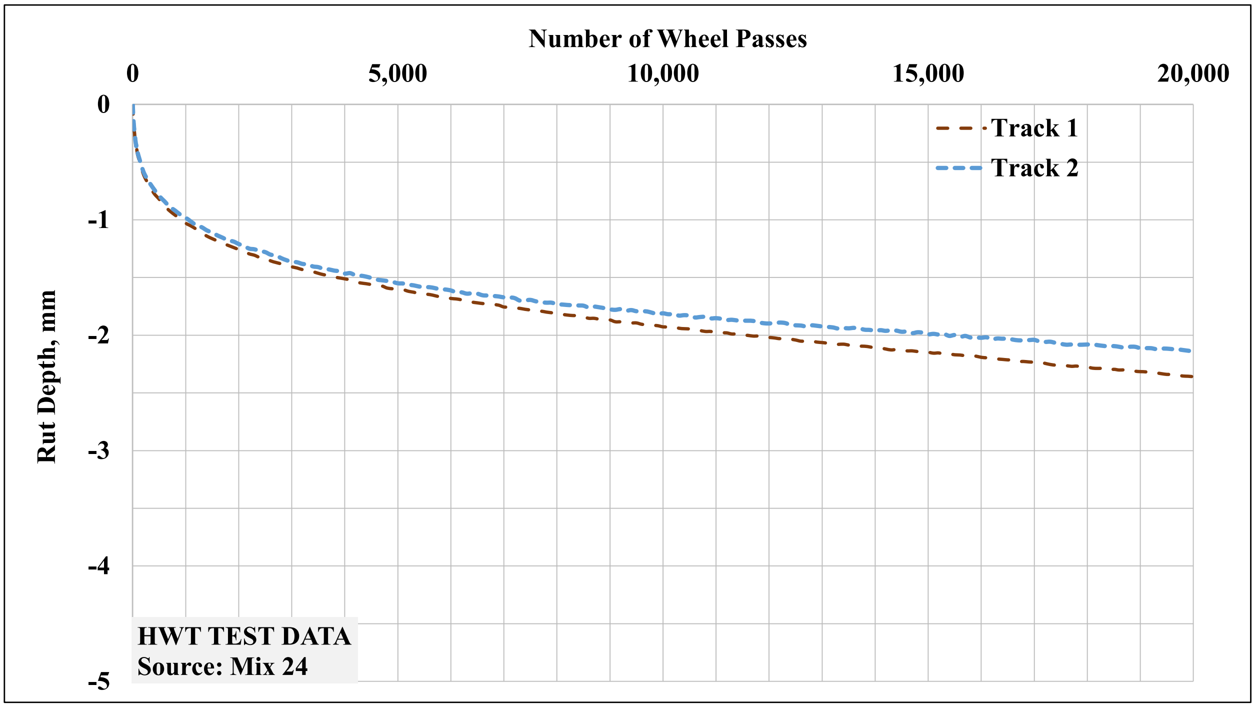

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 23

MIX CODE
24

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-2.36	-2.14	-2.25
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	197,198	286,703	241,951
No. of Passes to 12.5 mm rut depth	255,219	371,434	313,326
Rut depth at 10,000 passes, mm	-1.93	-1.81	-1.87
Creep Slope (mm/1000 passes)	0.04	0.03	0.04
Stripping Slope (mm/1000 passes)	NA	NA	NA

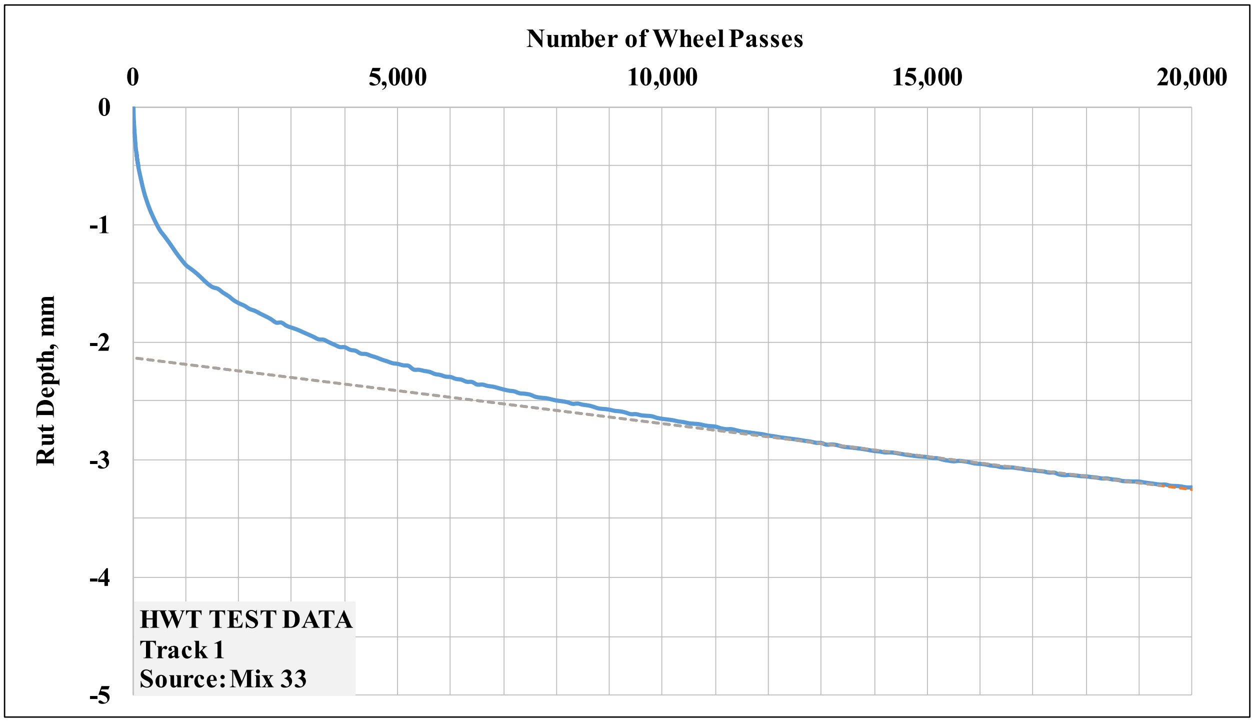


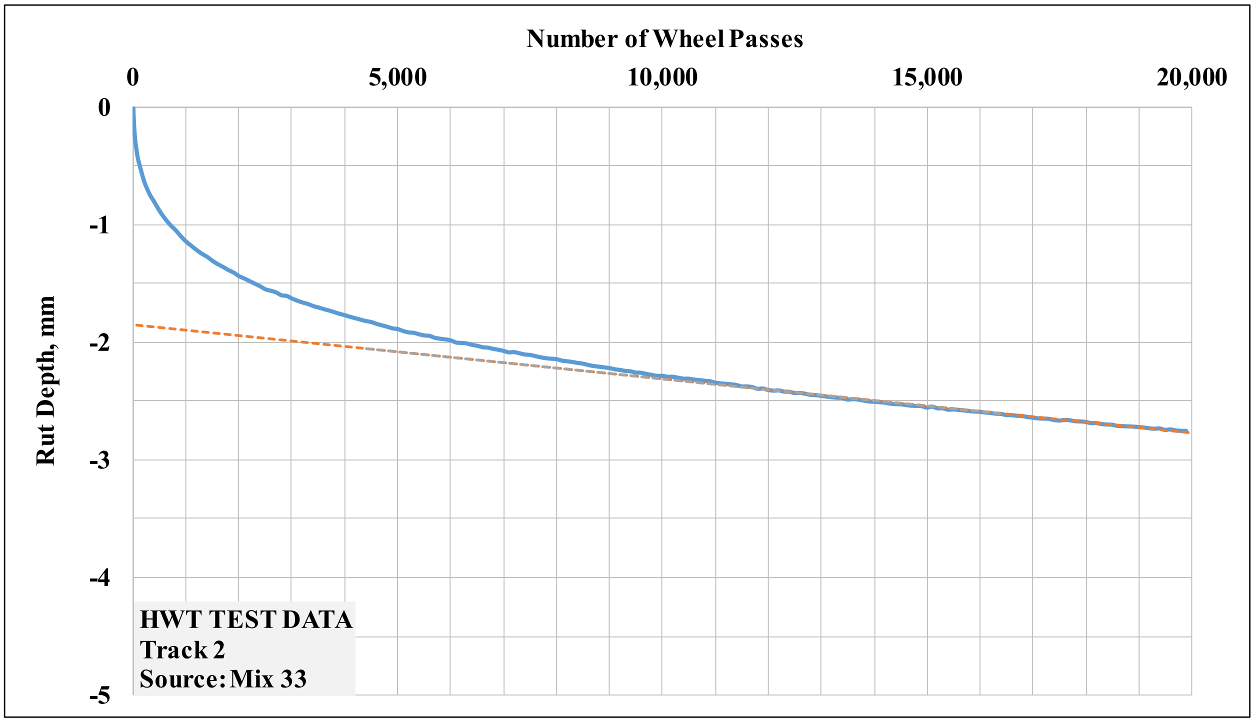

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 24

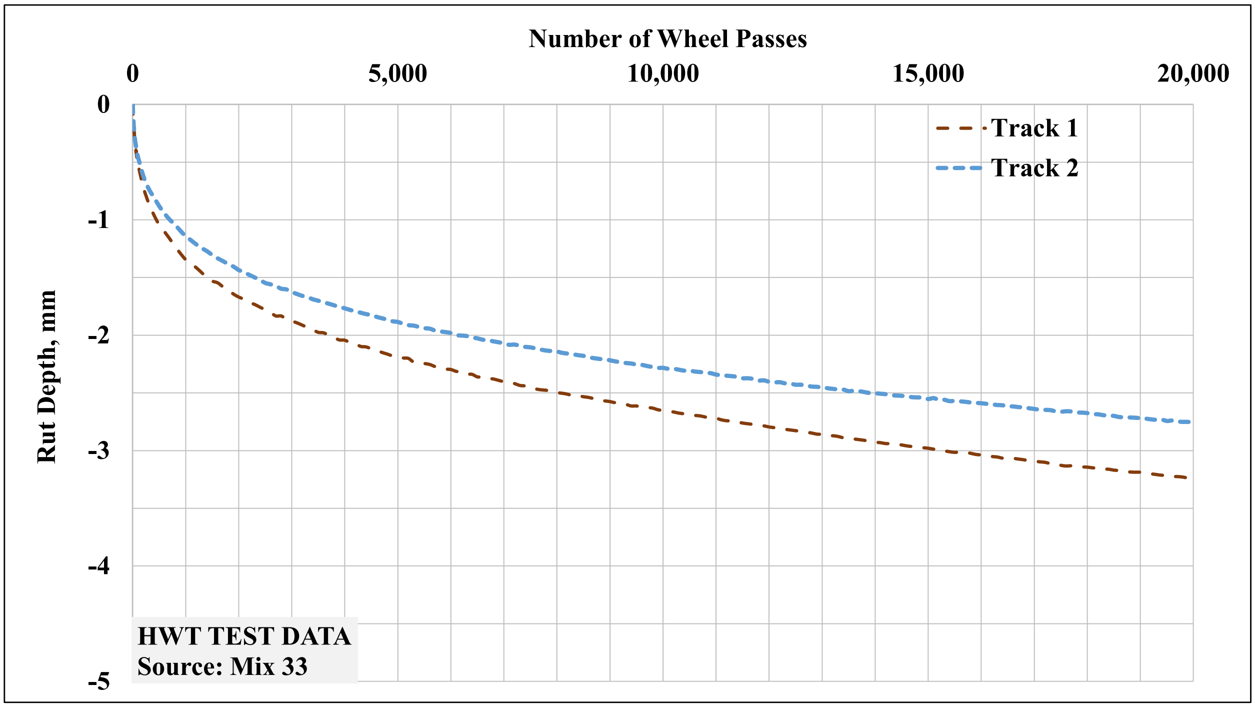

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 24

MIX CODE
33

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-3.24	-2.76	-3.00
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	140,188	176,605	158,396
No. of Passes to 12.5 mm rut depth	184,745	230,803	207,774
Rut depth at 10,000 passes, mm	-2.65	-2.28	-2.47
Creep Slope (mm/1000 passes)	0.06	0.05	0.05
Stripping Slope (mm/1000 passes)	NA	NA	NA

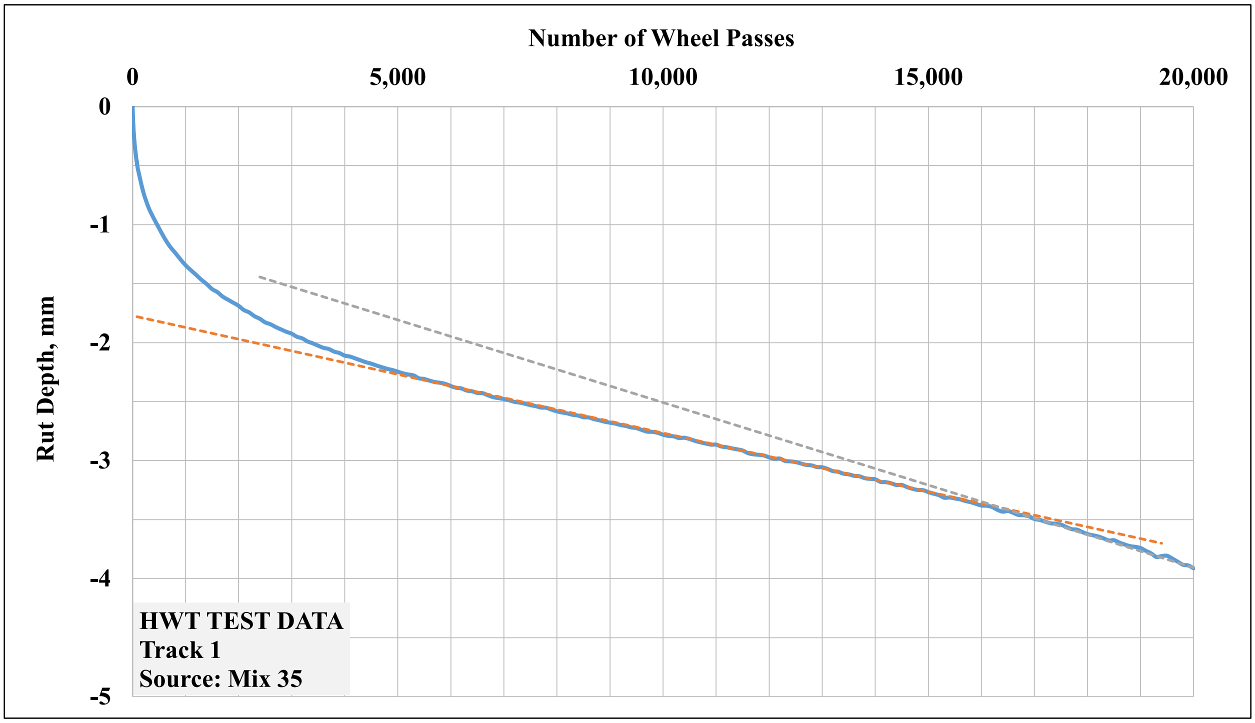


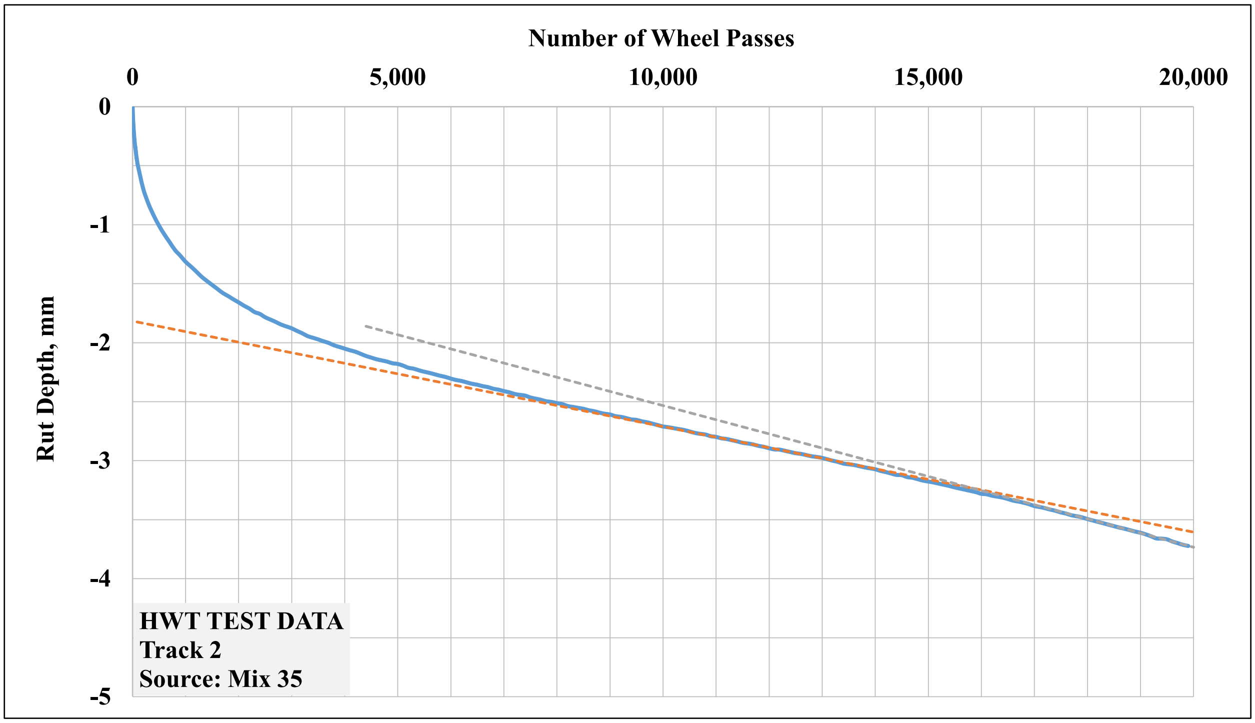

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
HWT TEST DATA
Track 2
Source: Mix 33

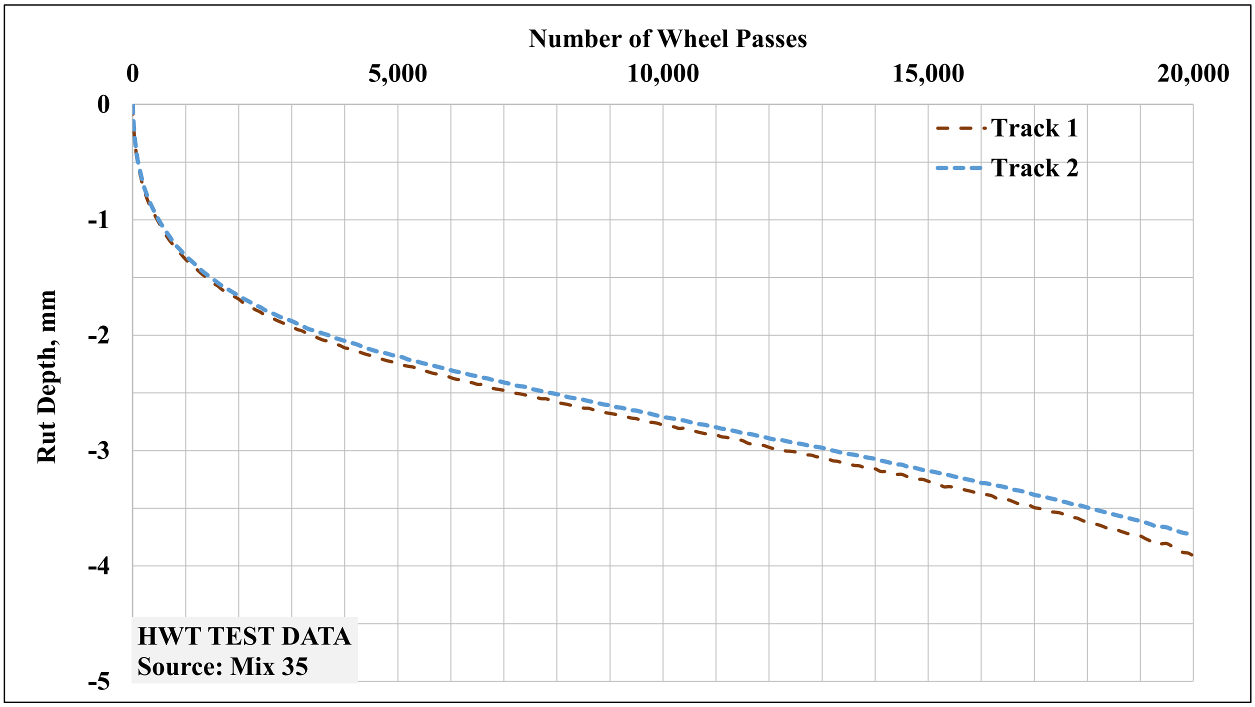

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
Track 1
Track 2
HWT TEST DATA
Source: Mix 33

MIX CODE
35

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	16,374	15,816	16,095
Ratio of the slope (strip/creep)	1.41	1.34	1.37
Max Rut (mm)	-3.91	-3.74	-3.83
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	63,514	72,220	67,867
No. of Passes to 12.5 mm rut depth	81,371	93,054	87,213
Rut depth at 10,000 passes, mm	-2.78	-2.71	-2.75
Creep Slope (mm/1000 passes)	0.10	0.09	0.09
Stripping Slope (mm/1000 passes)	0.14	0.12	0.13

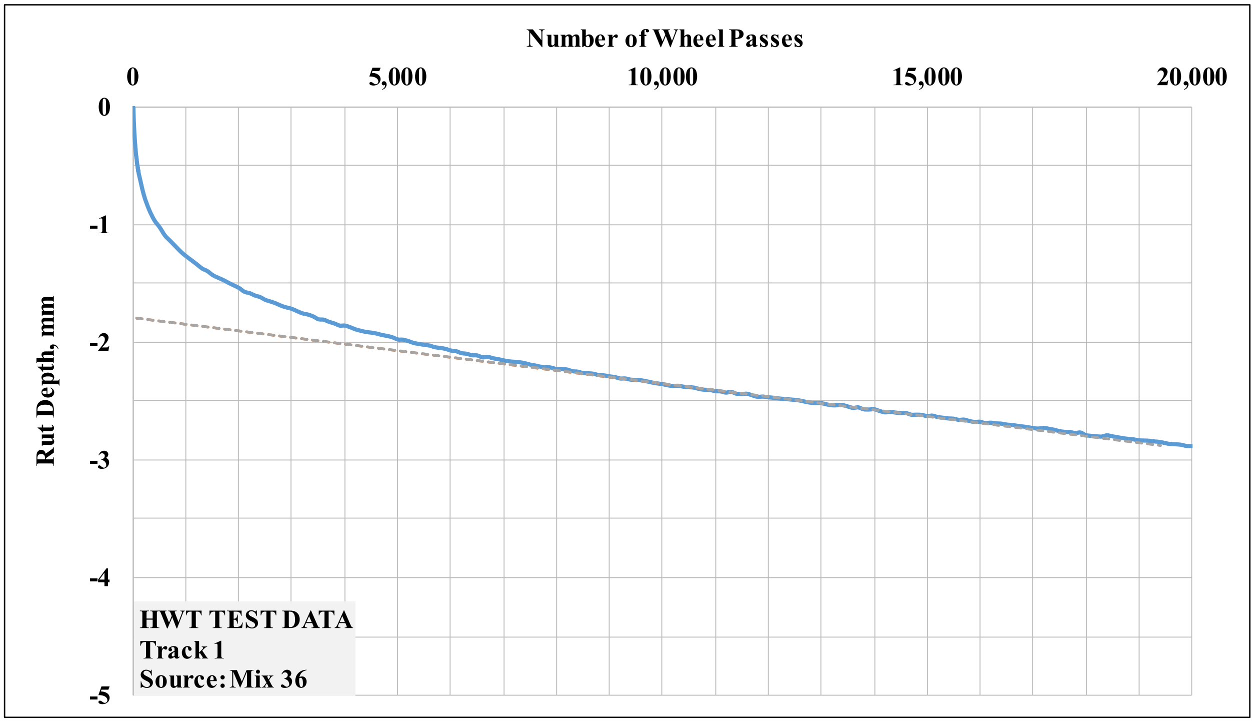


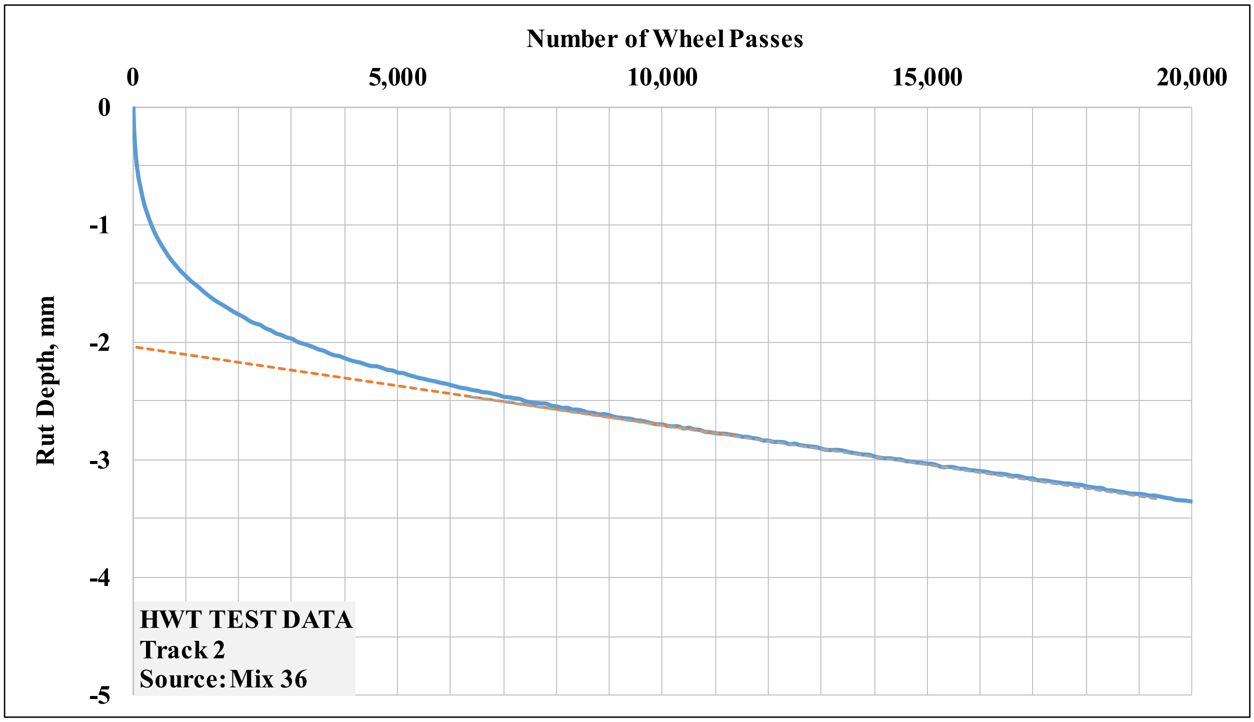

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 35

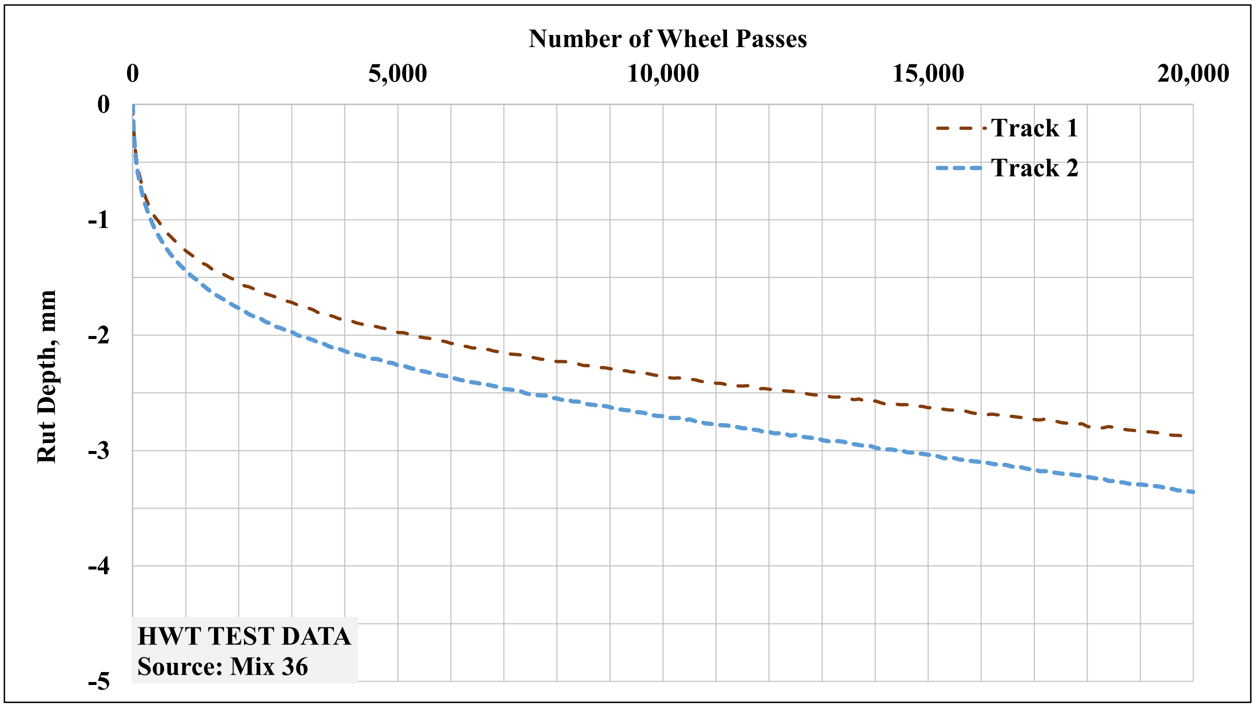

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 35

MIX CODE
36

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-2.88	-3.36	-3.12
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	146,252	119,108	132,680
No. of Passes to 12.5 mm rut depth	190,772	156,494	173,633
Rut depth at 10,000 passes, mm	-2.36	-2.70	-2.53
Creep Slope (mm/1000 passes)	0.06	0.07	0.06
Stripping Slope (mm/1000 passes)	NA	NA	NA

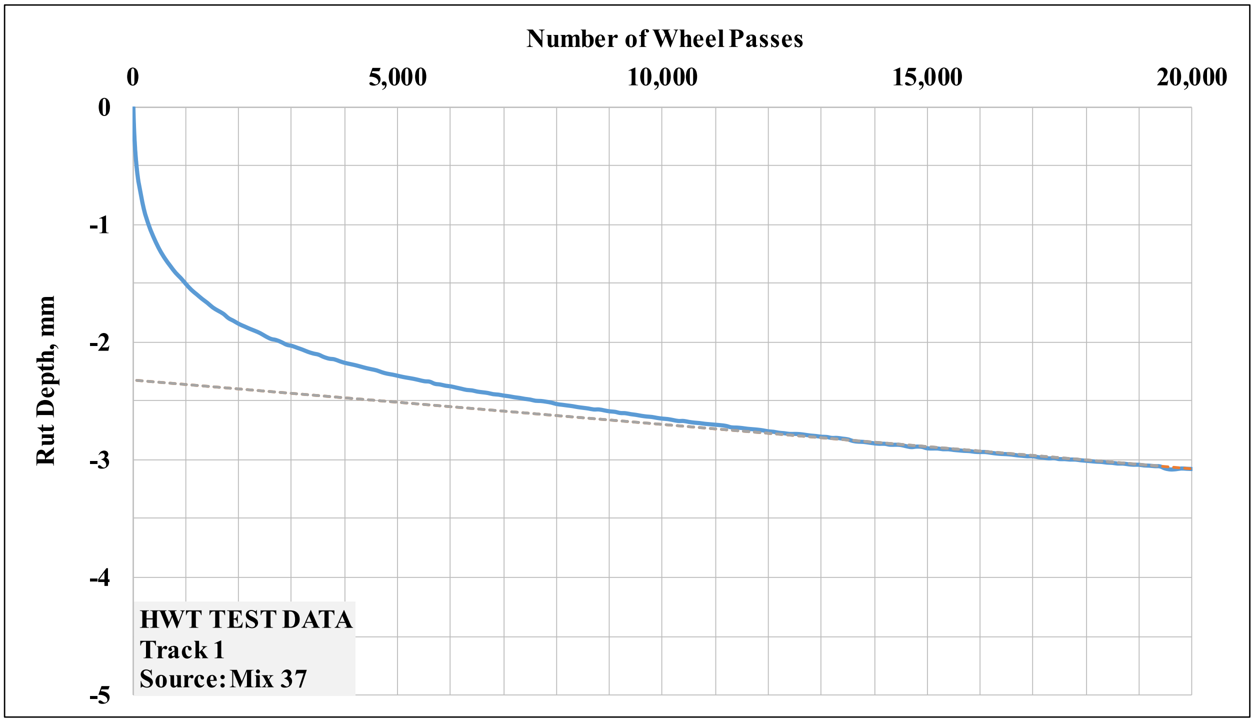


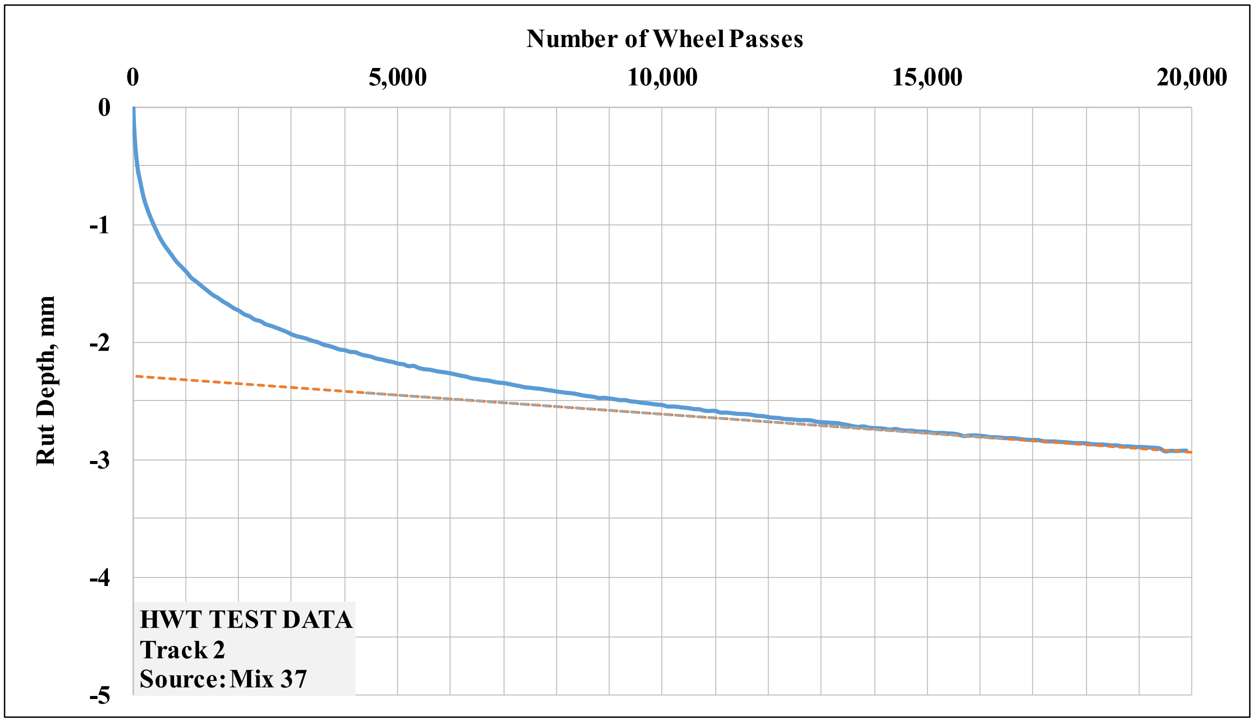

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
HWT TEST DATA
Track 2
Source: Mix 36

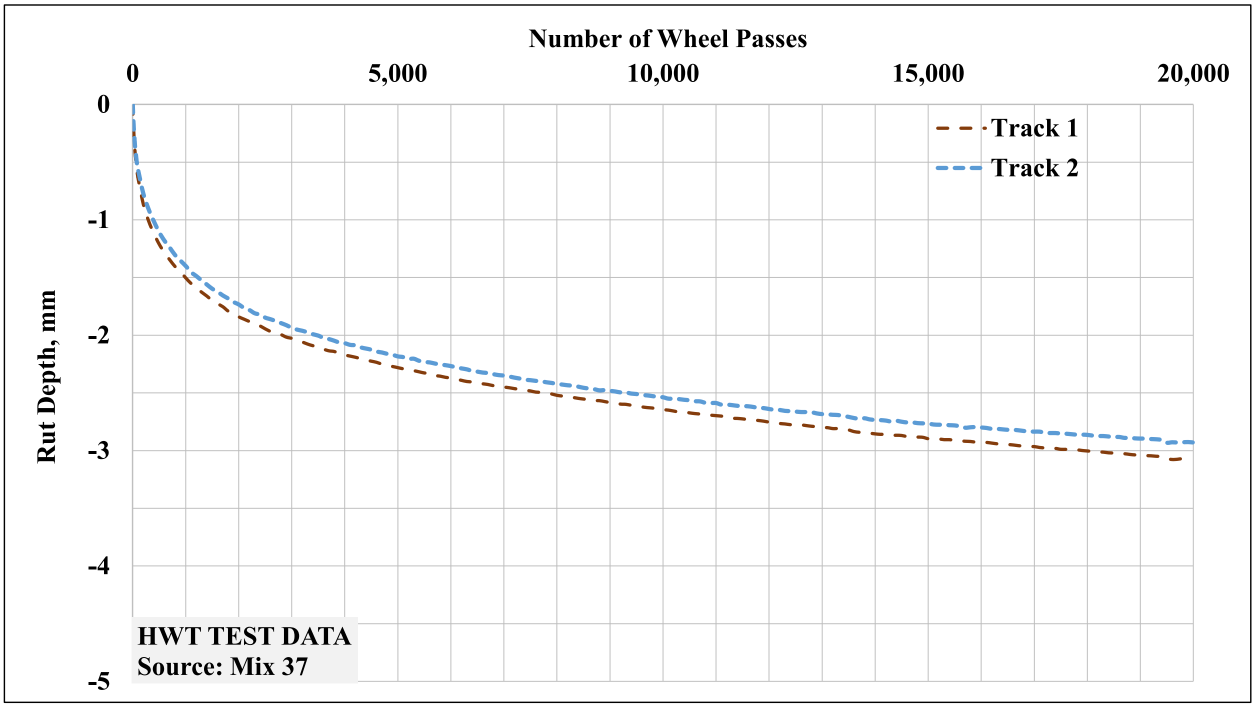

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
Track 1
Track 2
HWT TEST DATA
Source: Mix 36

MIX CODE
37

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-3.08	-2.93	-3.01
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	201,021	238,643	219,832
No. of Passes to 12.5 mm rut depth	266,433	315,976	291,205
Rut depth at 10,000 passes, mm	-2.65	-2.54	-2.59
Creep Slope (mm/1000 passes)	0.04	0.03	0.04
Stripping Slope (mm/1000 passes)	NA	NA	NA

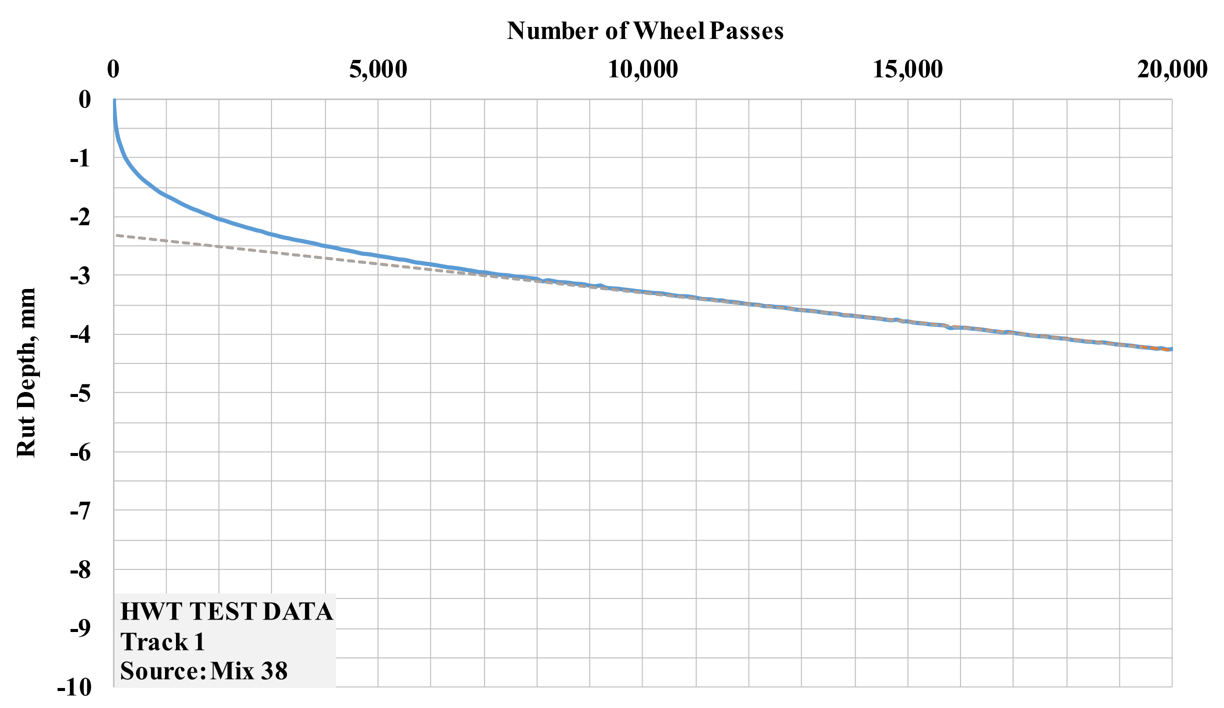


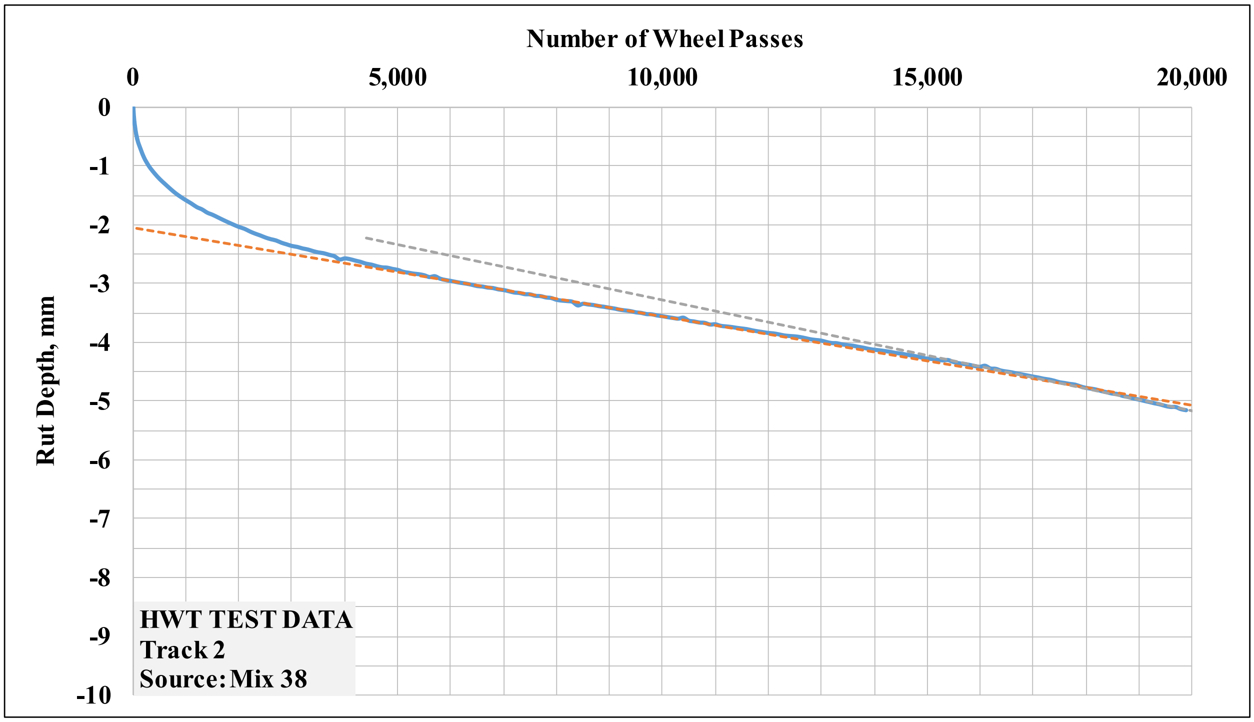

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
HWT TEST DATA
Track 2
Source: Mix 37

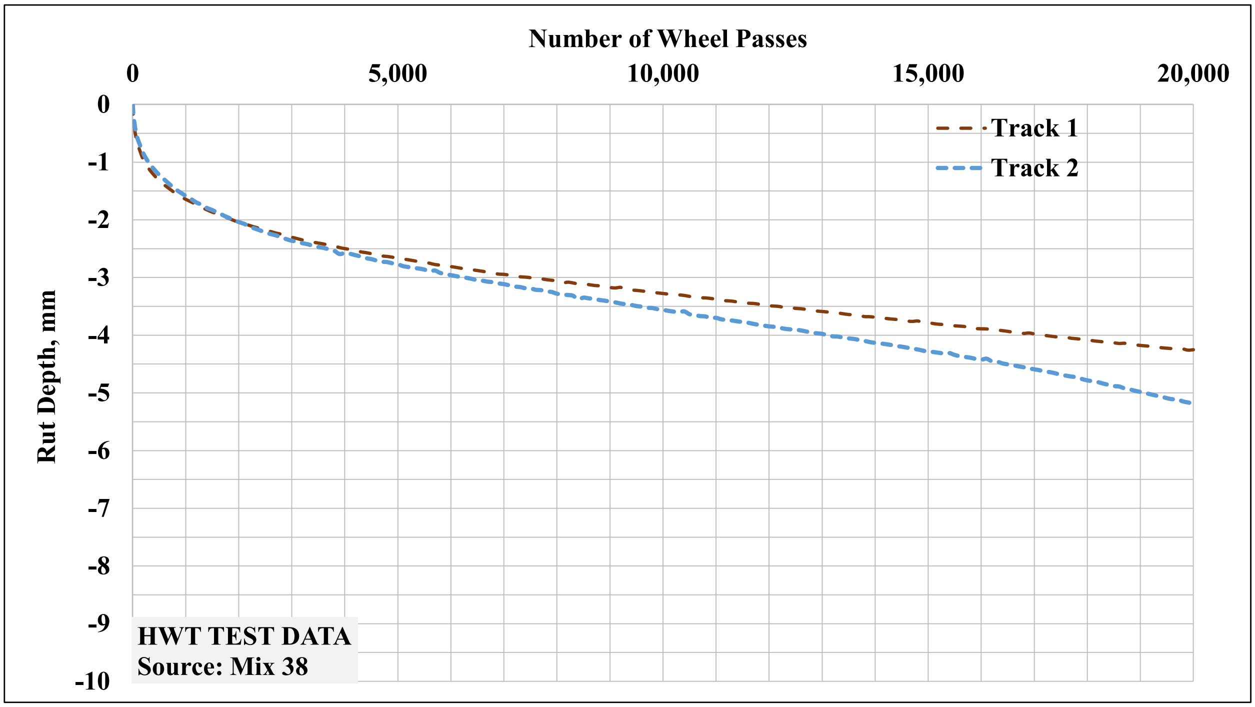

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
Track 1
Track 2
HWT TEST DATA
Source: Mix 37

MIX CODE
38

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	17,517	NA
Ratio of the slope (strip/creep)	1.00	1.25	1.12
Max Rut (mm)	-4.26	-5.19	-4.73
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	77,859	45,604	61,732
No. of Passes to 12.5 mm rut depth	103,150	58,839	80,995
Rut depth at 10,000 passes, mm	-3.28	-3.56	-3.42
Creep Slope (mm/1000 passes)	0.10	0.15	0.13
Stripping Slope (mm/1000 passes)	NA	0.19	NA

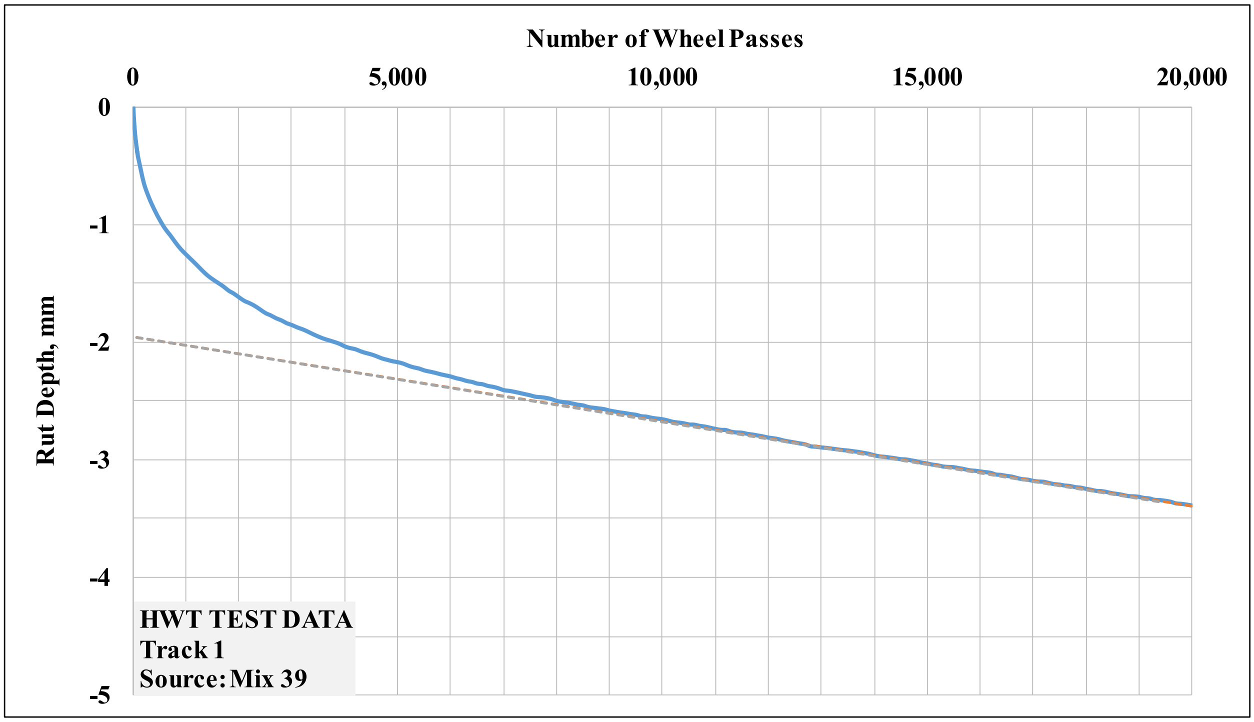


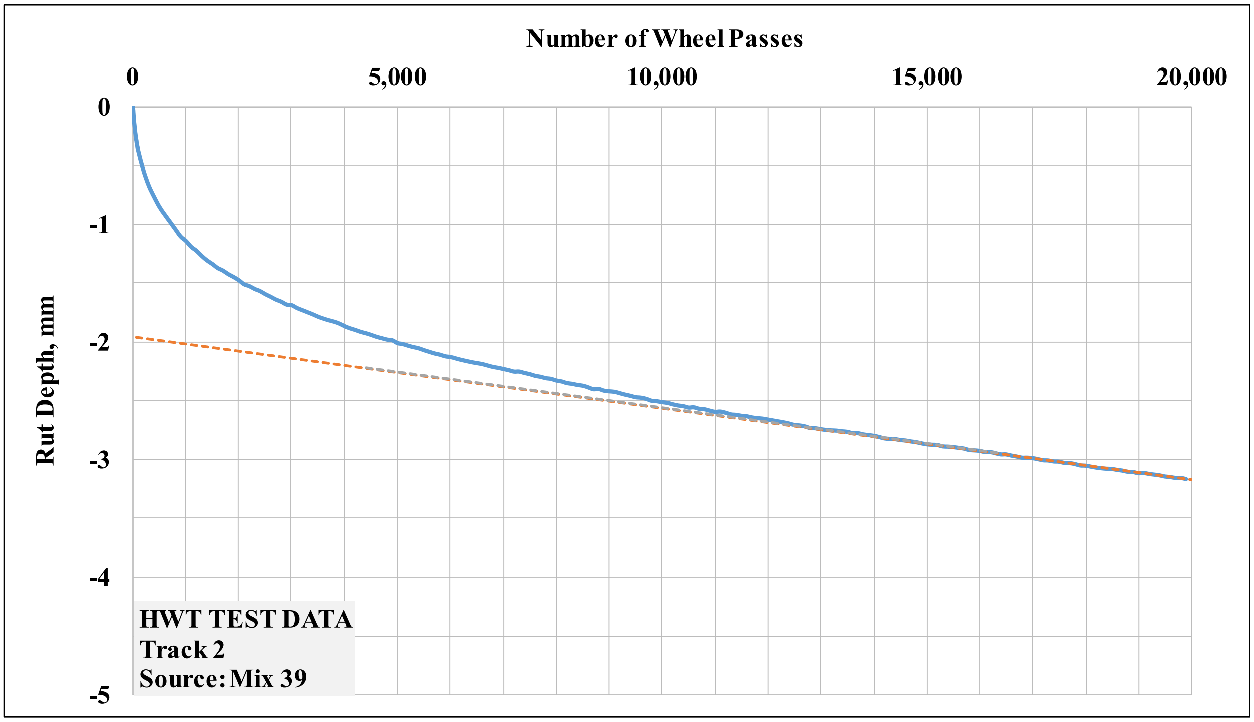

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
HWT TEST DATA
Track 2
Source: Mix 38

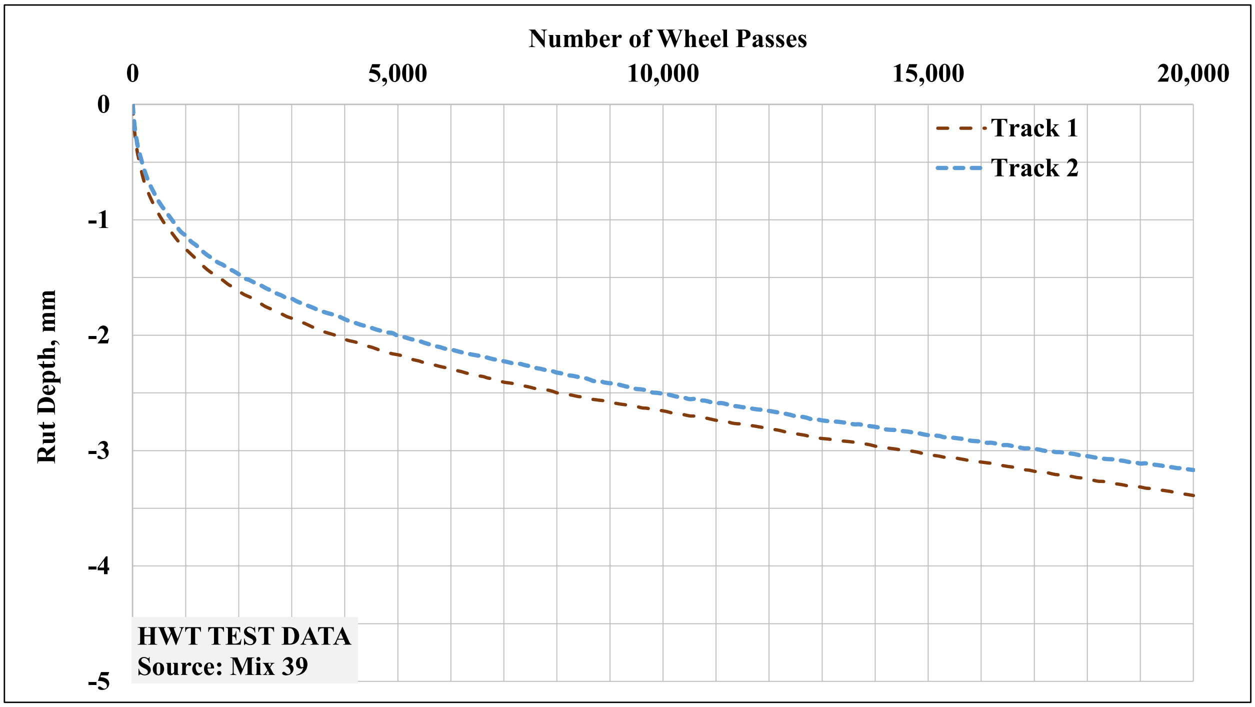

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Track 1
Track 2
HWT TEST DATA
Source: Mix 38

MIX CODE
39

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	Not Reached	Not Reached
Ratio of the slope (strip/creep)	1.00	1.00	1.00
Max Rut (mm)	-3.39	-3.17	-3.28
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	111,464	132,727	122,096
No. of Passes to 12.5 mm rut depth	146,099	173,985	160,042
Rut depth at 10,000 passes, mm	-2.66	-2.51	-2.58
Creep Slope (mm/1000 passes)	0.07	0.06	0.07
Stripping Slope (mm/1000 passes)	NA	NA	NA

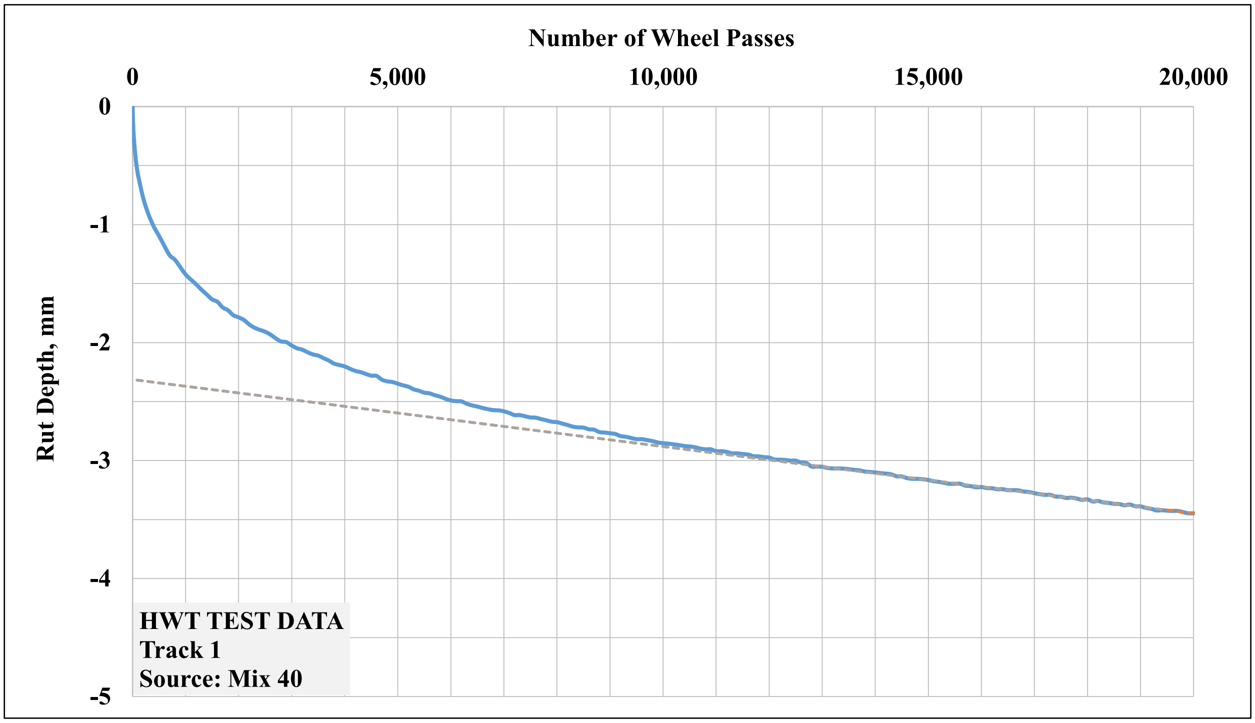


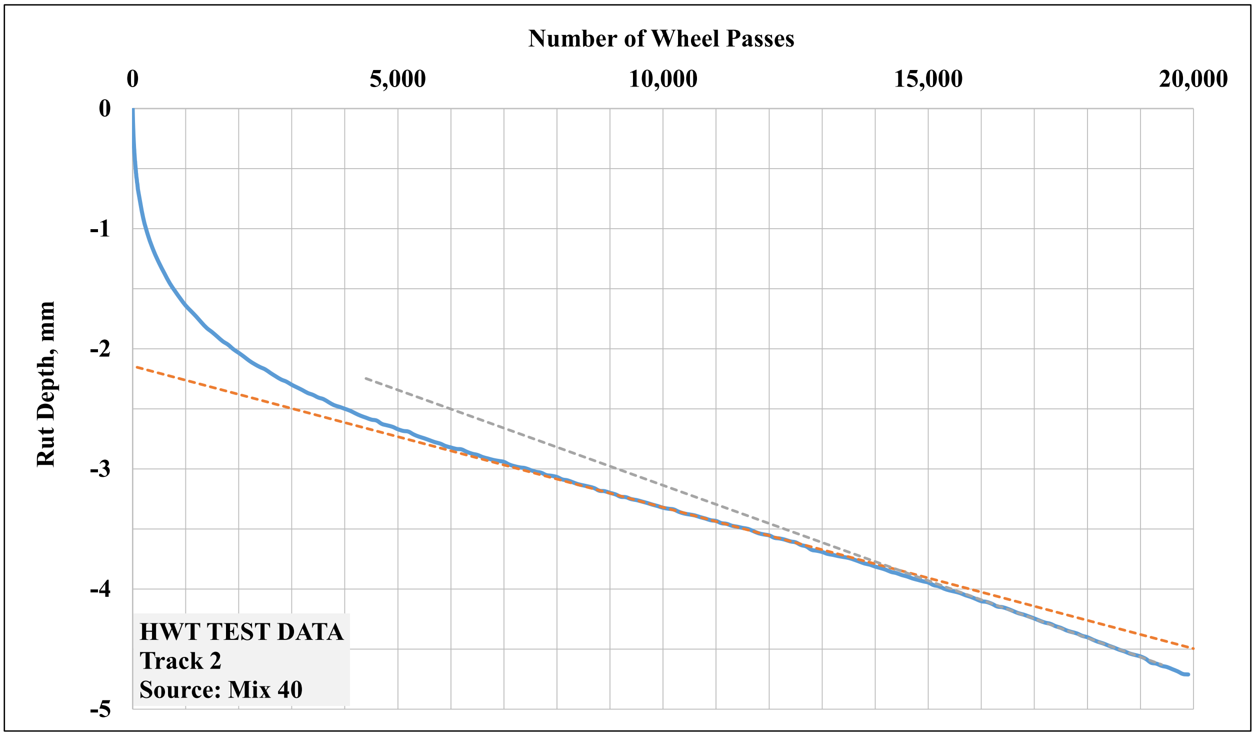

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
HWT TEST DATA
Track 2
Source: Mix 39

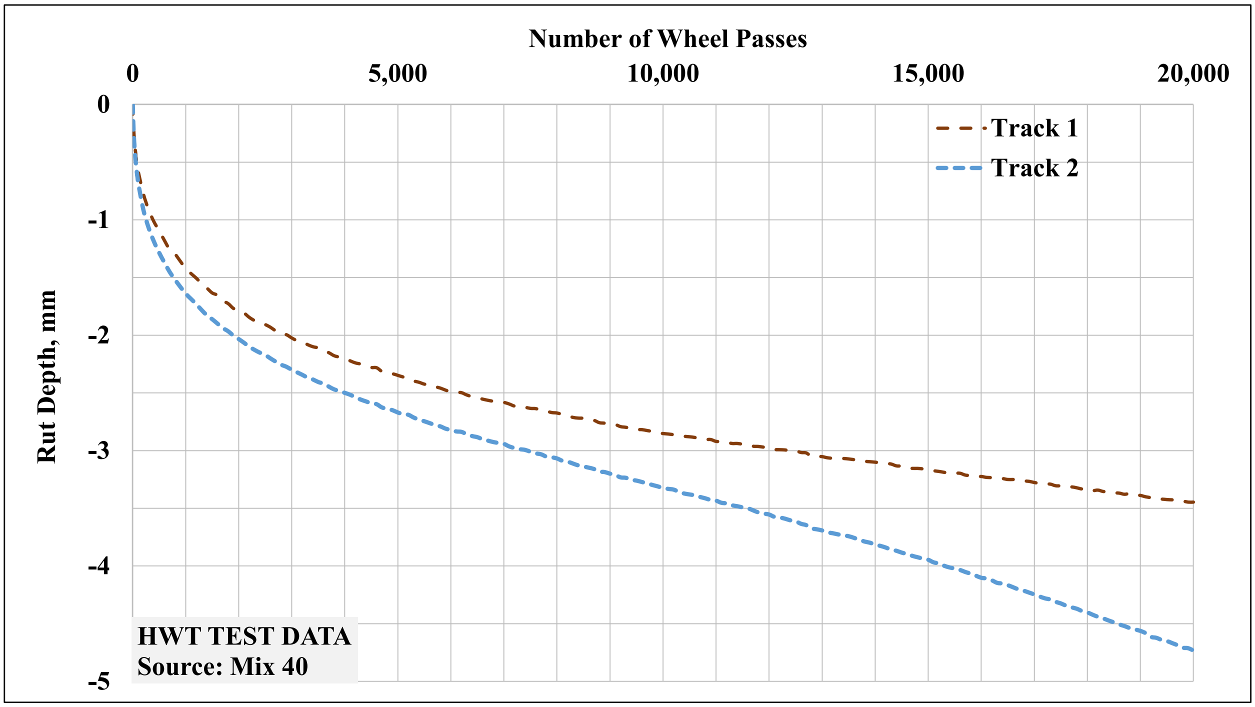

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
0
-1
-2
-3
-4
-5
Rut Depth, mm
Track 1
Track 2
HWT TEST DATA
Source: Mix 39

MIX CODE
40

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	14,456	NA
Ratio of the slope (strip/creep)	1.00	1.35	1.18
Max Rut (mm)	-3.45	-4.73	-4.09
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	135,269	53,228	94,248
No. of Passes to 12.5 mm rut depth	179,259	68,973	124,116
Rut depth at 10,000 passes, mm	-2.85	-3.32	-3.09
Creep Slope (mm/1000 passes)	0.06	0.12	0.09
Stripping Slope (mm/1000 passes)	NA	0.16	NA

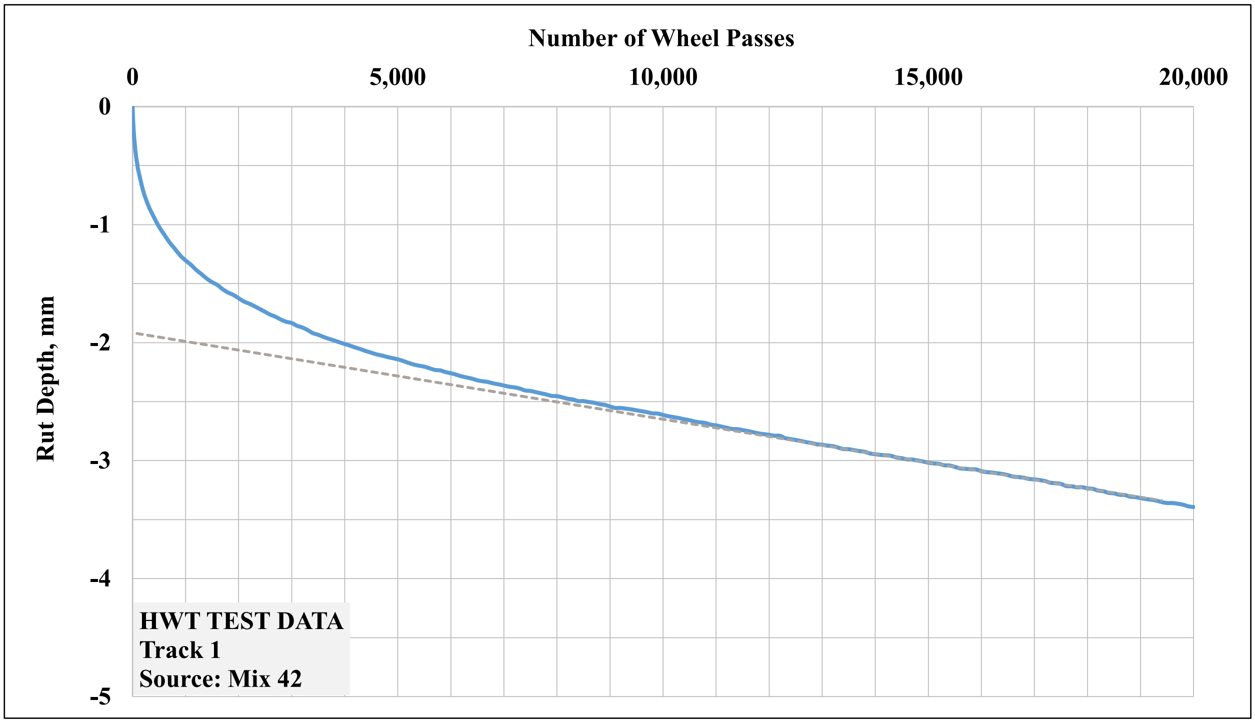


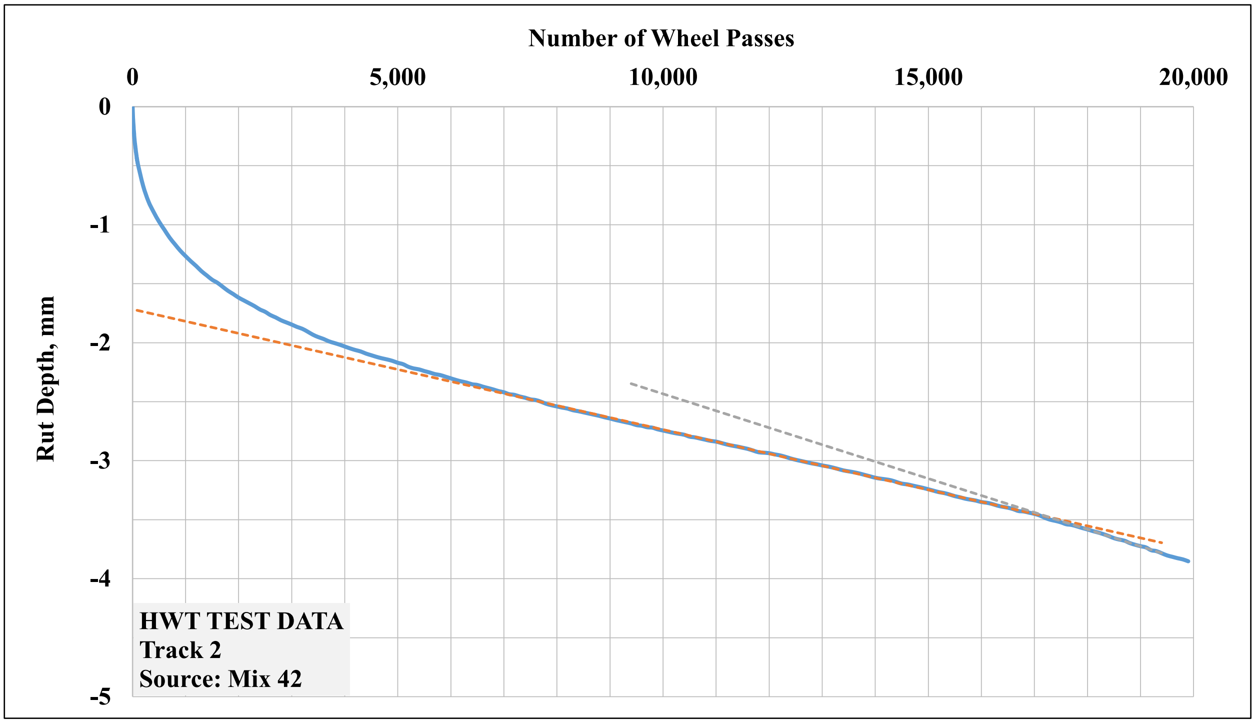

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
HWT TEST DATA
Track 2
Source: Mix 40

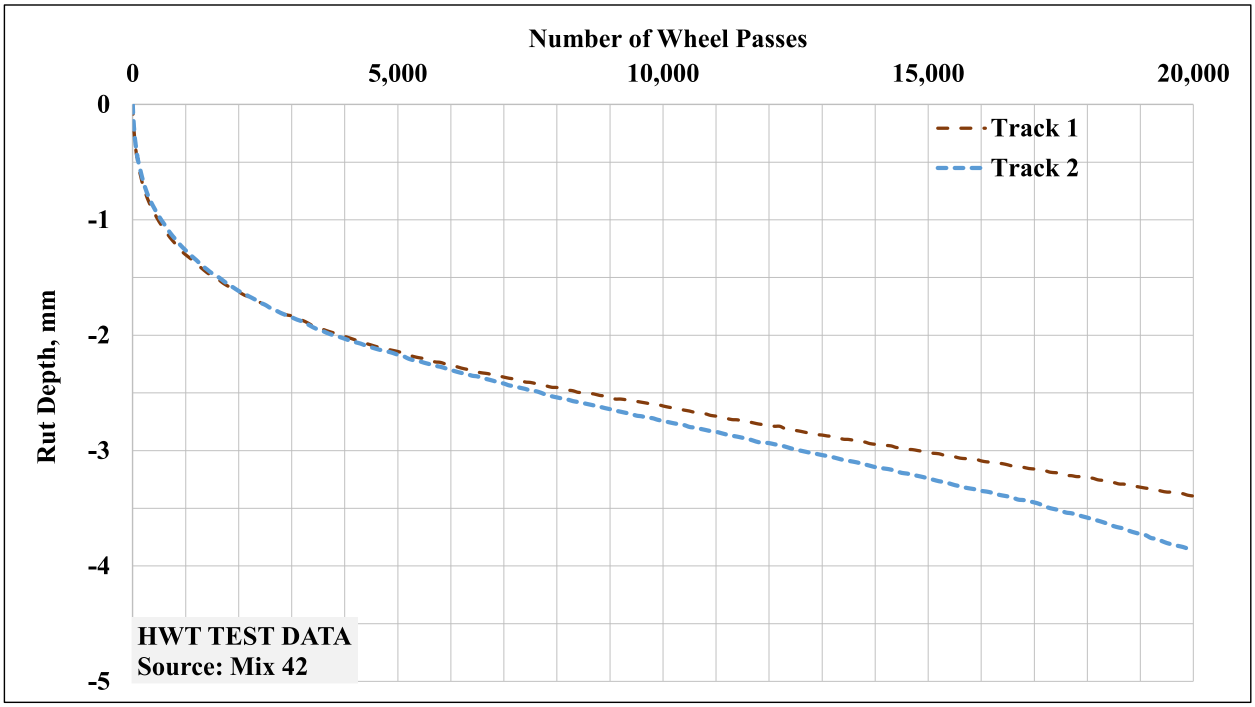

Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
Track 1
Track 2
HWT TEST DATA
Source: Mix 40

MIX CODE
42

PARAMETERS	Track 1	Track 2	Average
SIP (# of passes)	Not Reached	17,299	NA
Ratio of the slope (strip/creep)	1.00	1.41	1.20
Max Rut (mm)	-3.39	-3.87	-3.63
No. of Passes to maximum rut depth	20,000	20,000	20,000
No. of Passes to 10 mm rut depth	110,363	62,742	86,552
No. of Passes to 12.5 mm rut depth	144,499	80,169	112,334
Rut depth at 10,000 passes, mm	-2.61	-2.74	-2.68
Creep Slope (mm/1000 passes)	0.07	0.10	0.09
Stripping Slope (mm/1000 passes)	NA	0.14	NA




Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
HWT TEST DATA
Track 2
Source: Mix 42


Number of Wheel Passes
0
5,000
10,000
15,000
20,000
Rut Depth, mm
0
-1
-2
-3
-4
-5
Track 1
Track 2
HWT TEST DATA
Source: Mix 42

APPENDIX D

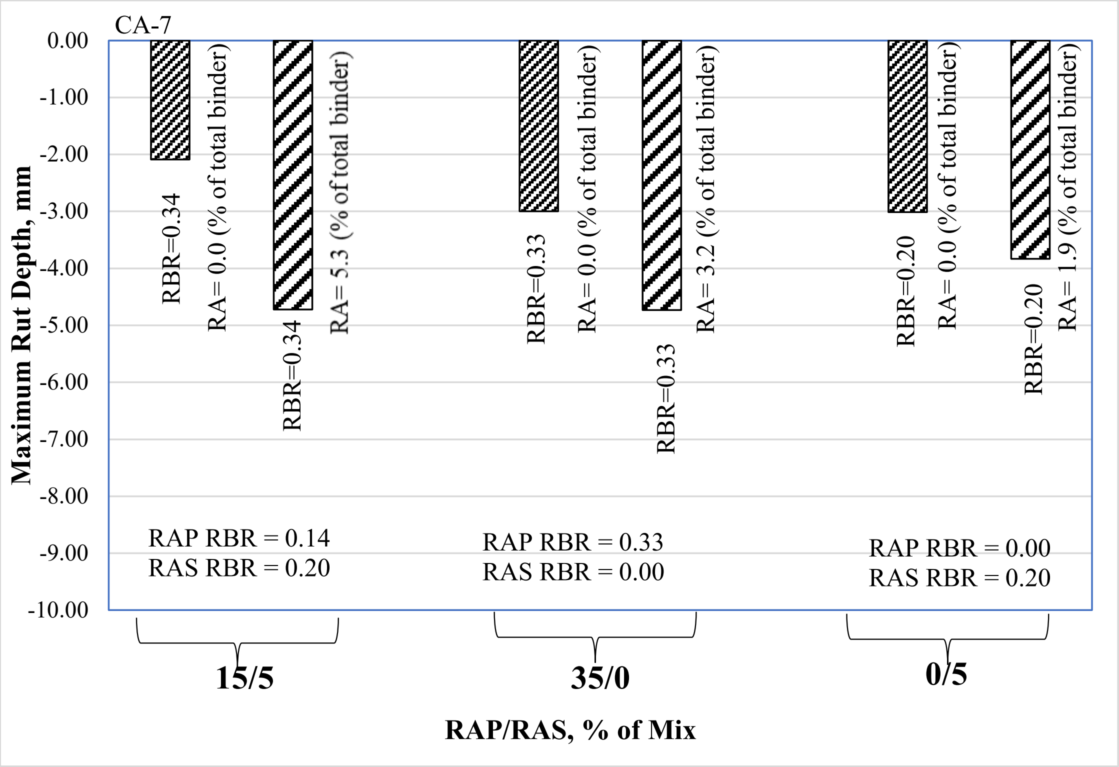
Results from

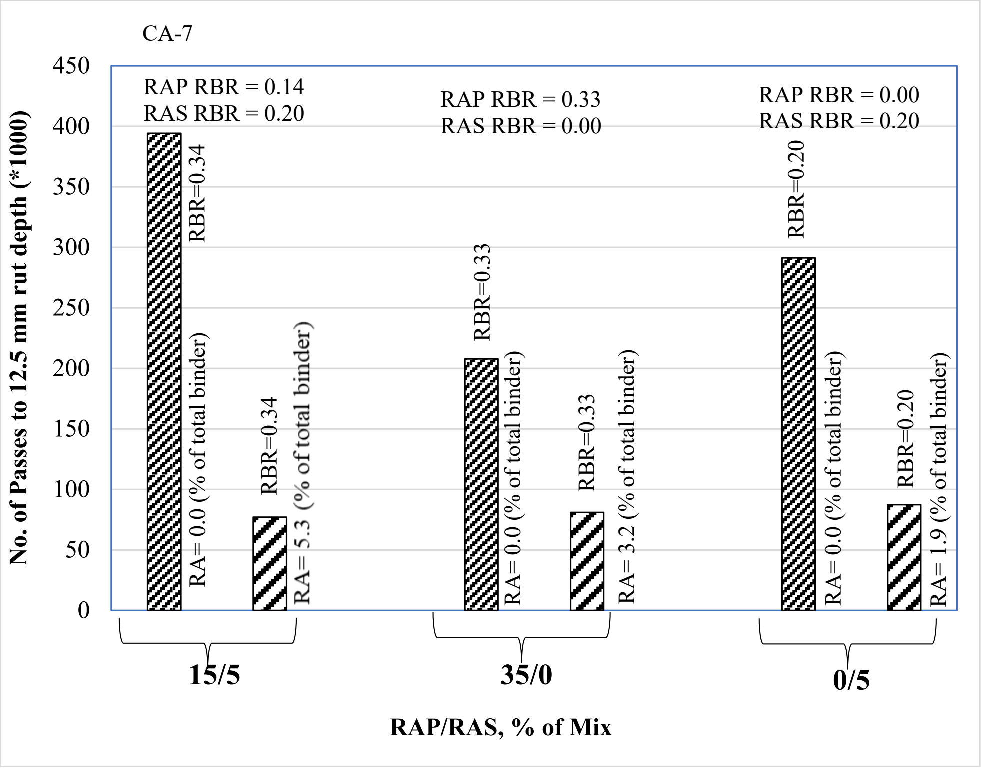
Hamburg Wheel Tracking Test:

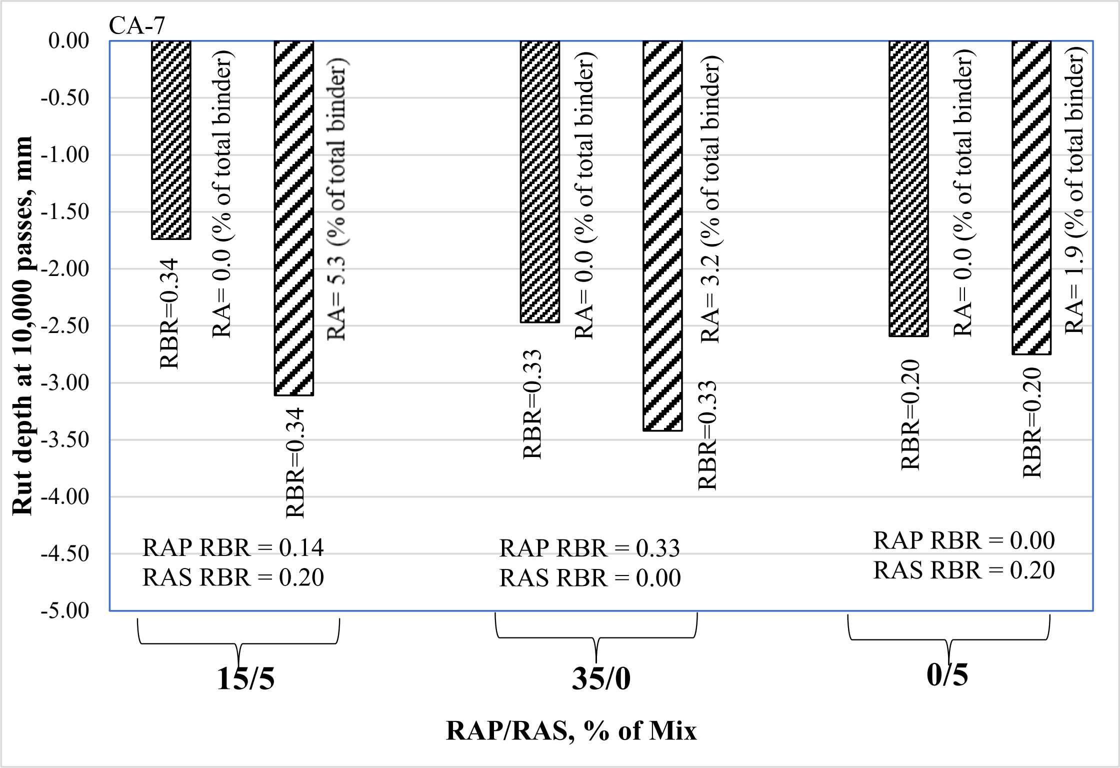
Comparison Graphs

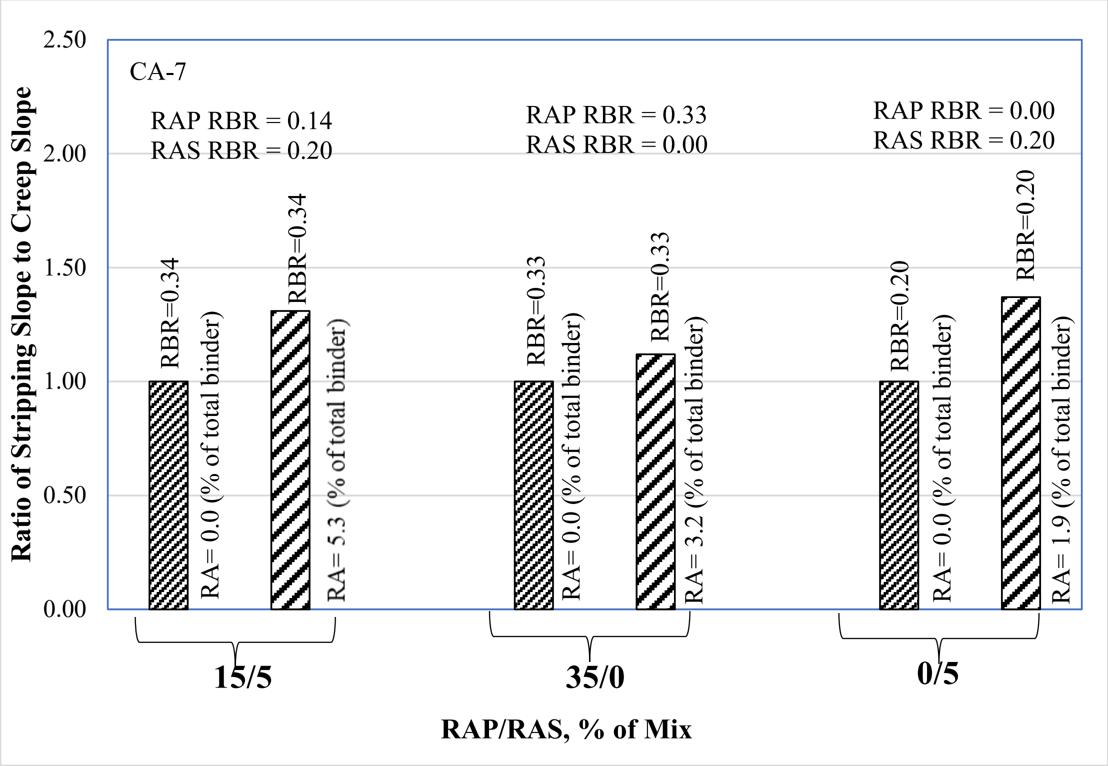
HWT:
Individual Rejuvenators:
Max Rut
Passes to 12.5 mm rut
Rut at 10000 passes
Strip/Creep Slope
Creep Slope

Ingevity:

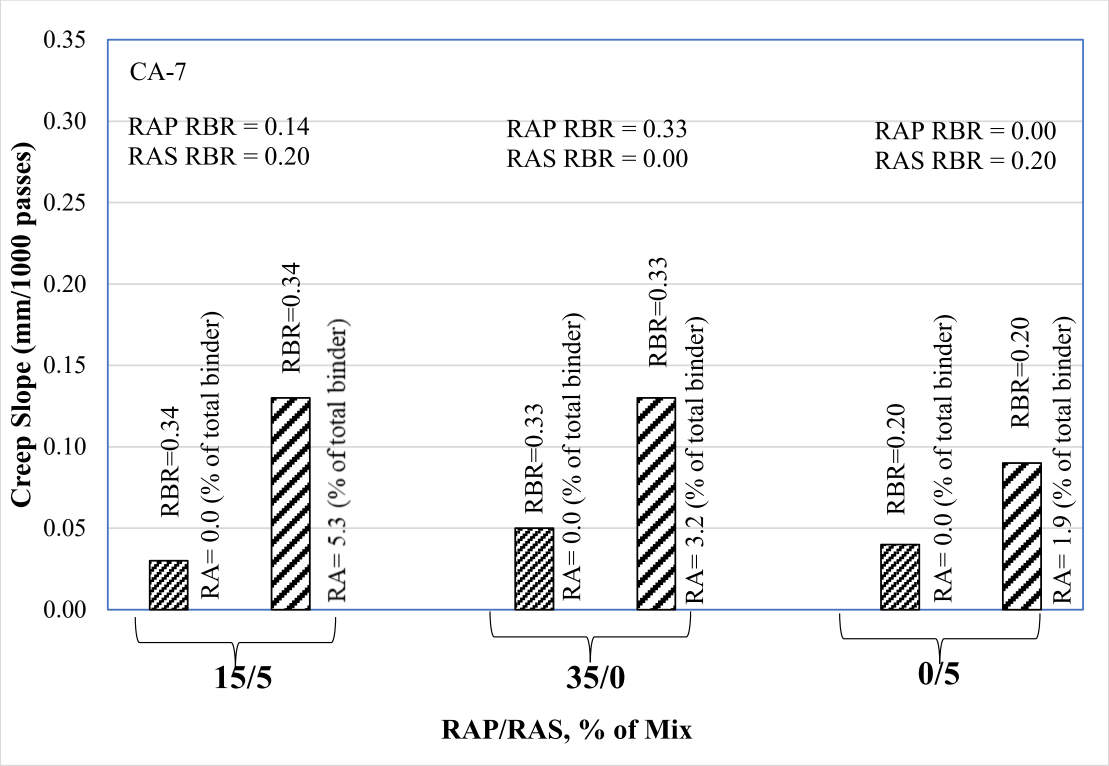



CA-7
No. of Passes to 12.5 mm rut depth (*1000)
0
50
100
150
200
250
300
350
400
450
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 5.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 3.2 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 1.9 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix


CA-7
Rut depth at 10,000 passes, mm
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 5.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 3.2 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 1.9 (% of total binder)
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
15/5
35/0
0/5
RAP/RAS, % of Mix

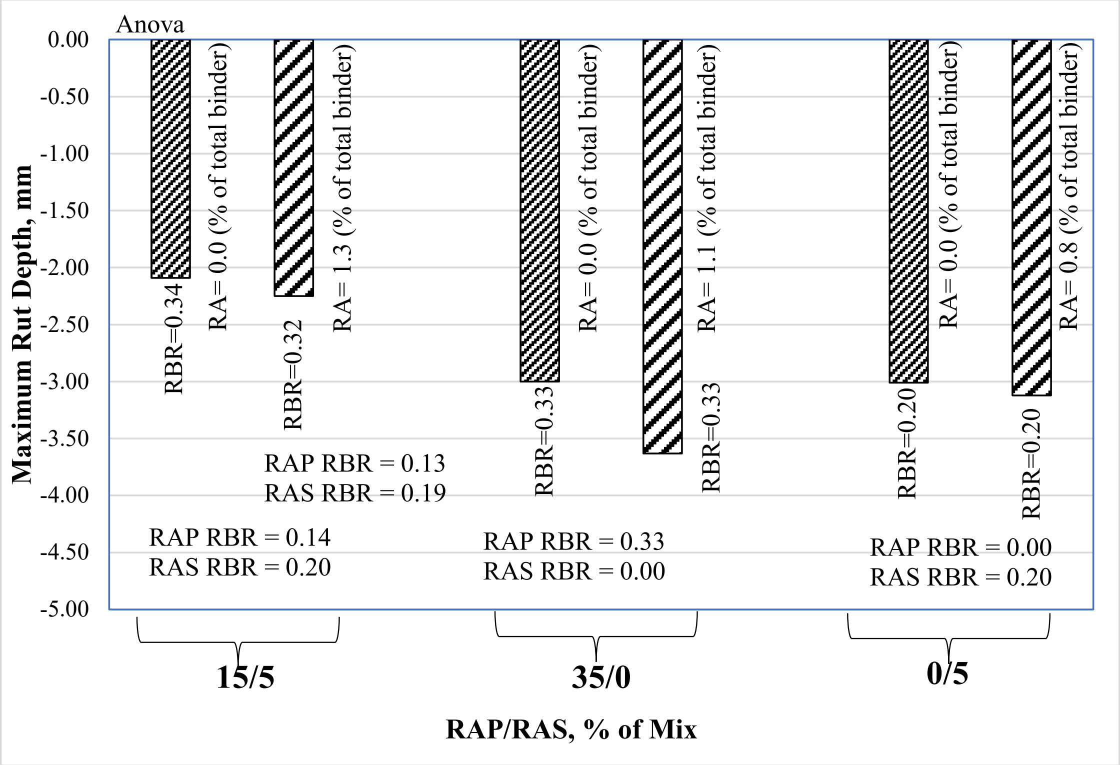


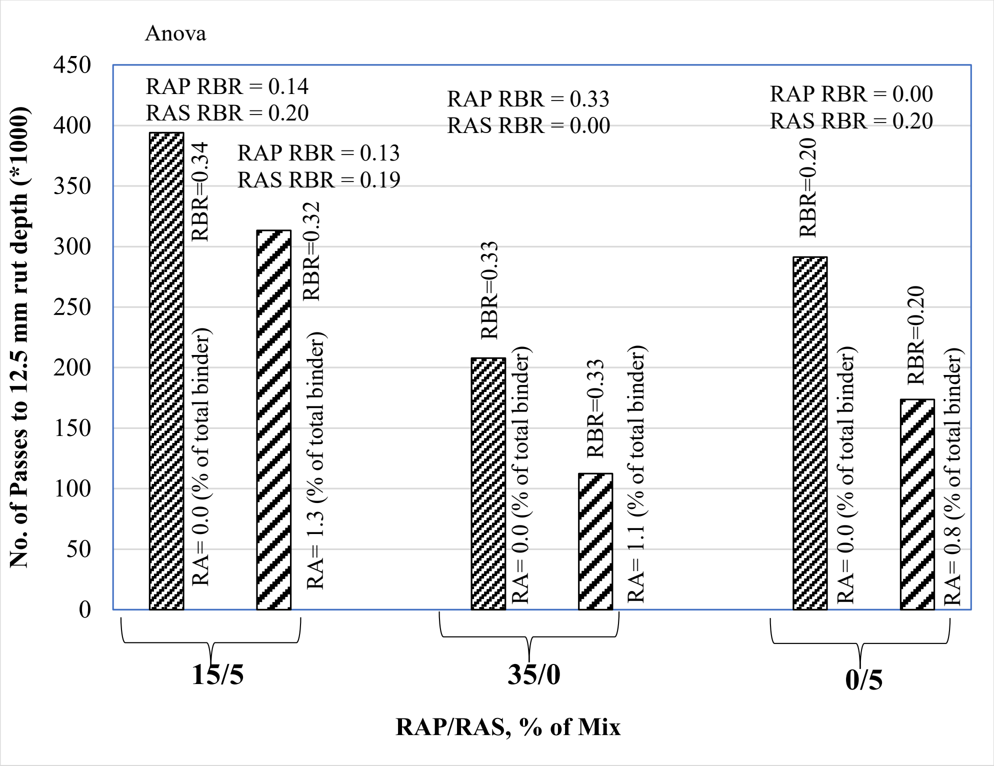
CA-7
Ratio of Stripping Slope to Creep Slope
2.50
2.00
1.50
1.00
0.50
0.00
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 5.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 3.2 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 1.9 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix

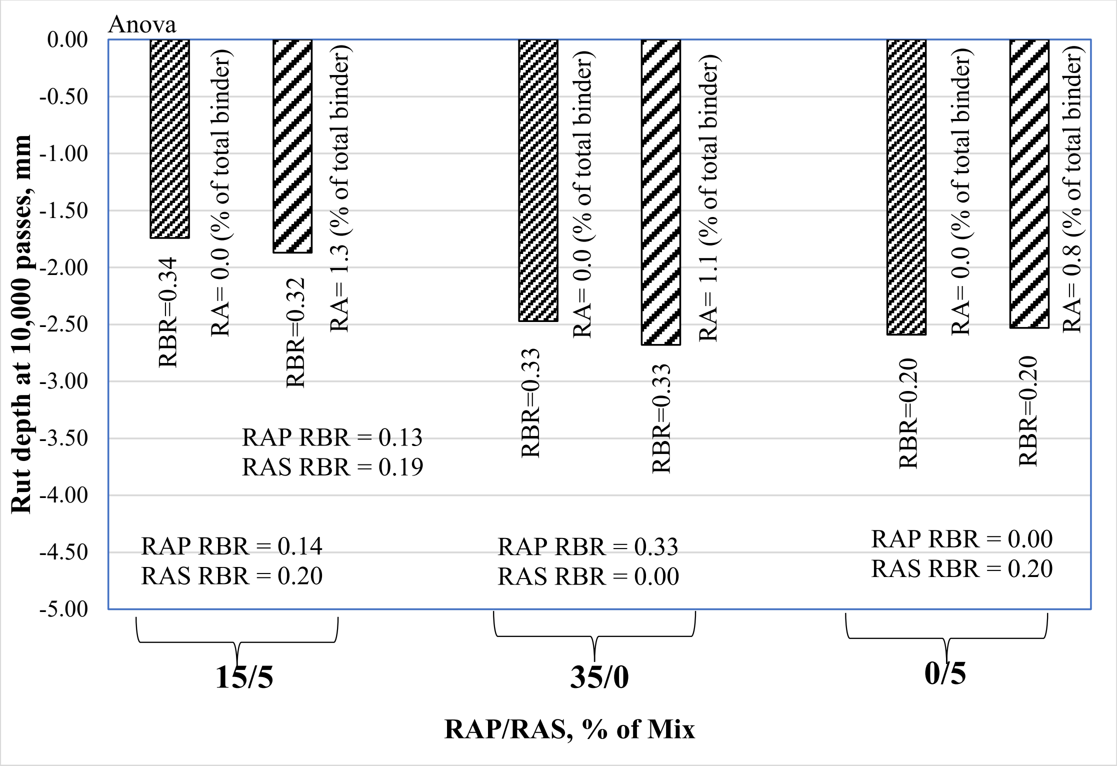


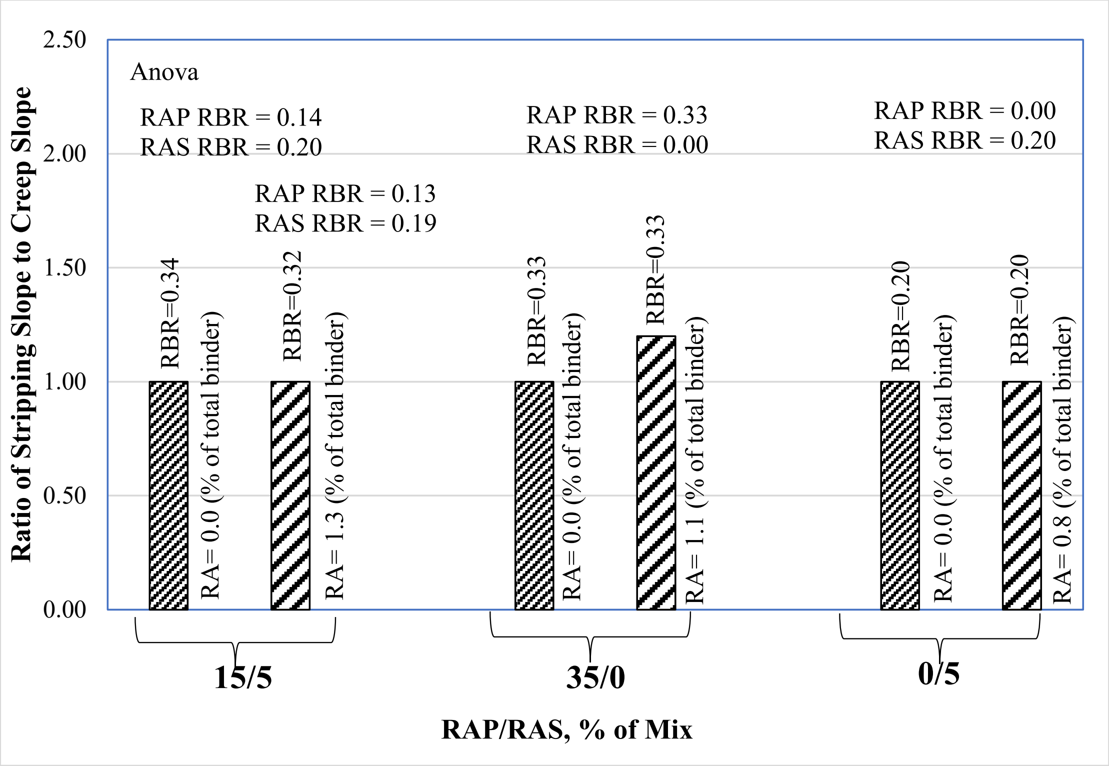
CA-7
Creep Slope (mm/1000 passes)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 5.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 3.2 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 1.9 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix

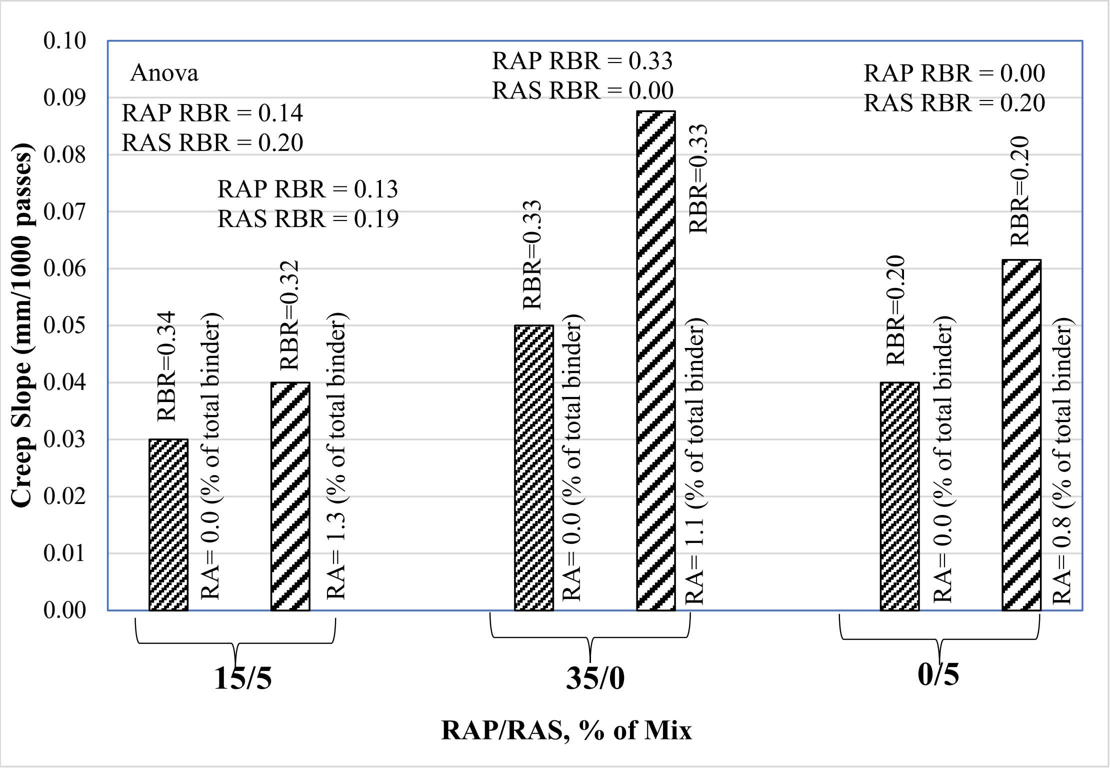
Anova:


Anova
Maximum Rut Depth, mm
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.32
RA= 1.3 (% of total binder)
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.14
RAS RBR = 0.20
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
RAP RBR = 0.33
RAS RBR = 0.00
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 0.8 (% of total binder)
RAP RBR = 0.00
RAS RBR = 0.20
15/5
35/0
0/5
RAP/RAS, % of Mix

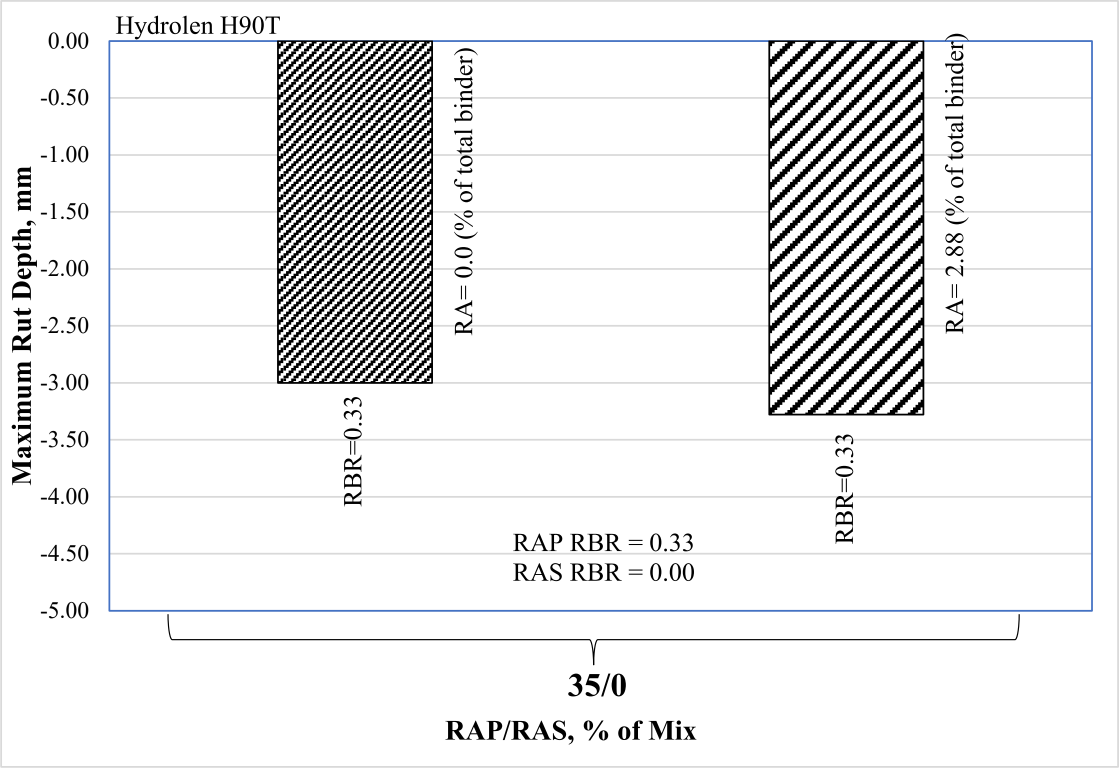

Anova
No. of Passes to 12.5 mm rut depth (*1000)
450
400
350
300
250
200
150
100
50
0
RAP RBR = 0.14
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RAP RBR = 0.13
RAS RBR = 0.19
RBR=0.32
RA= 1.3 (% of total binder)
RAP RBR = 0.33
RAS RBR = 0.00
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 0.8 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix

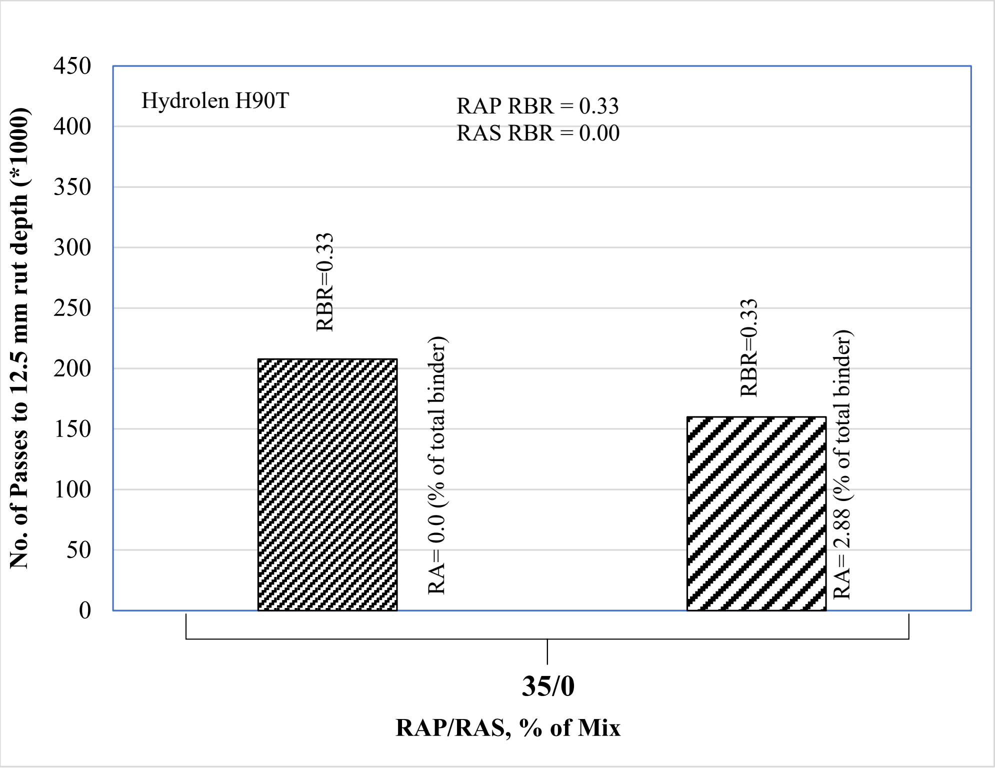

Anova
Rut depth at 10,000 passes, mm
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 0.8 (% of total binder)
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
15/5
35/0
0/5
RAP/RAS, % of Mix

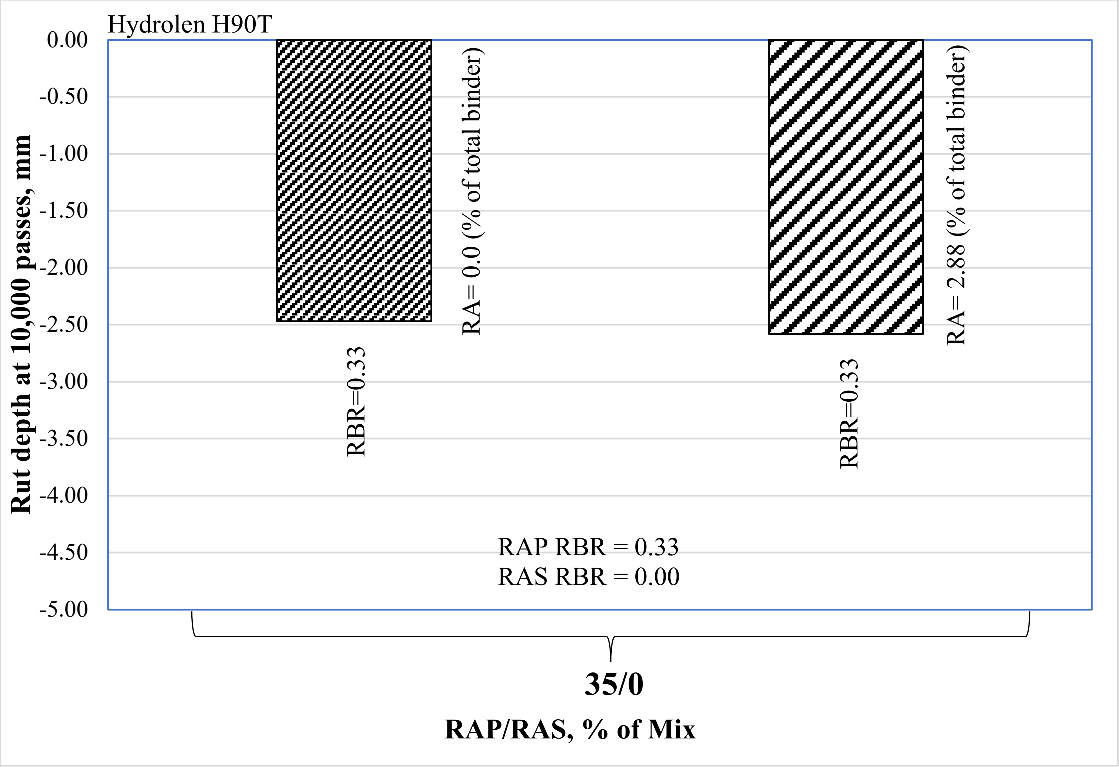

Ratio of Stripping Slope to Creep Slope
2.50
2.00
1.50
1.00
0.50
0.00
Anova
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.32
RA= 1.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 0.8 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix

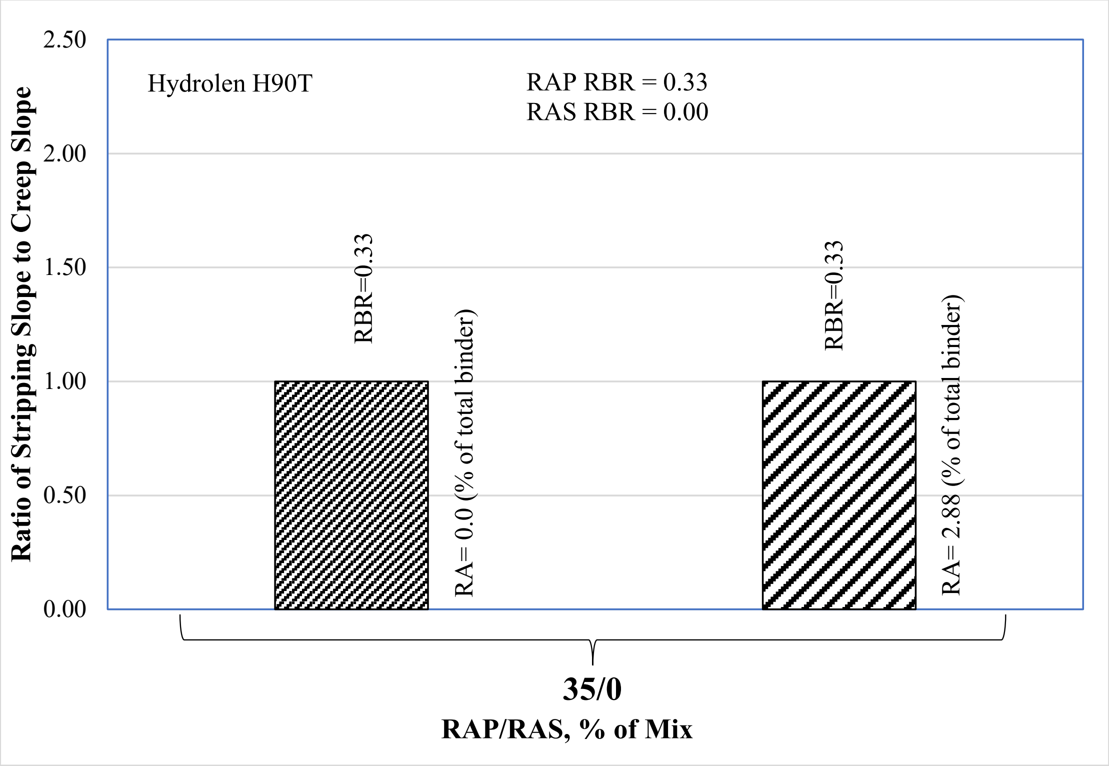


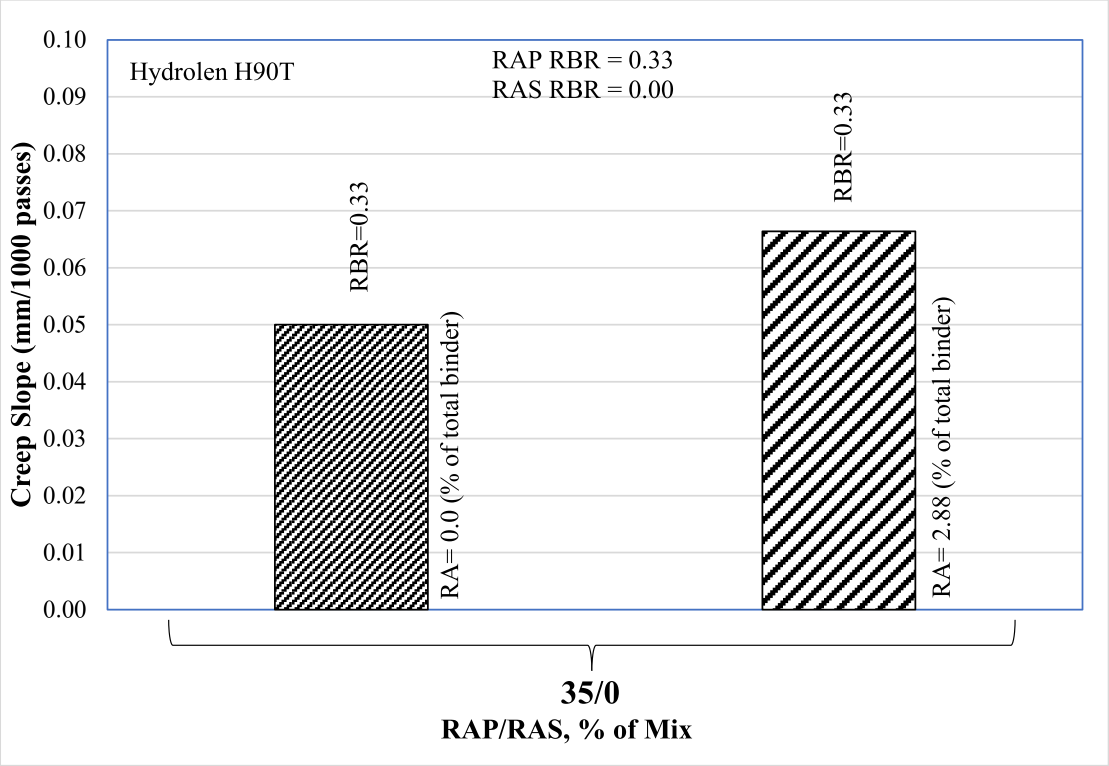
Hydrolene H90T:



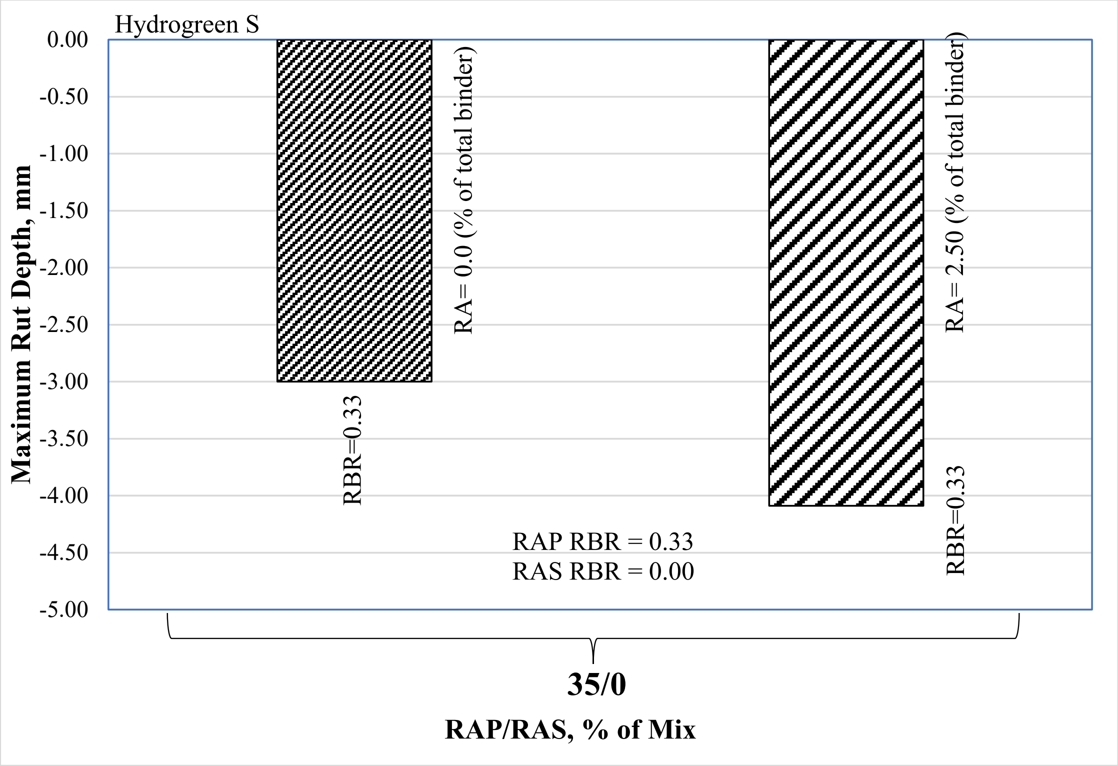

450
400
350
300
250
200
150
100
50
0
No. of Passes to 12.5 mm rut depth (*1000)
Hydrolen H90T
RAP RBR = 0.33
RAS RBR = 0.00
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 2.88 (% of total binder)
35/0
RAP/RAS, % of Mix

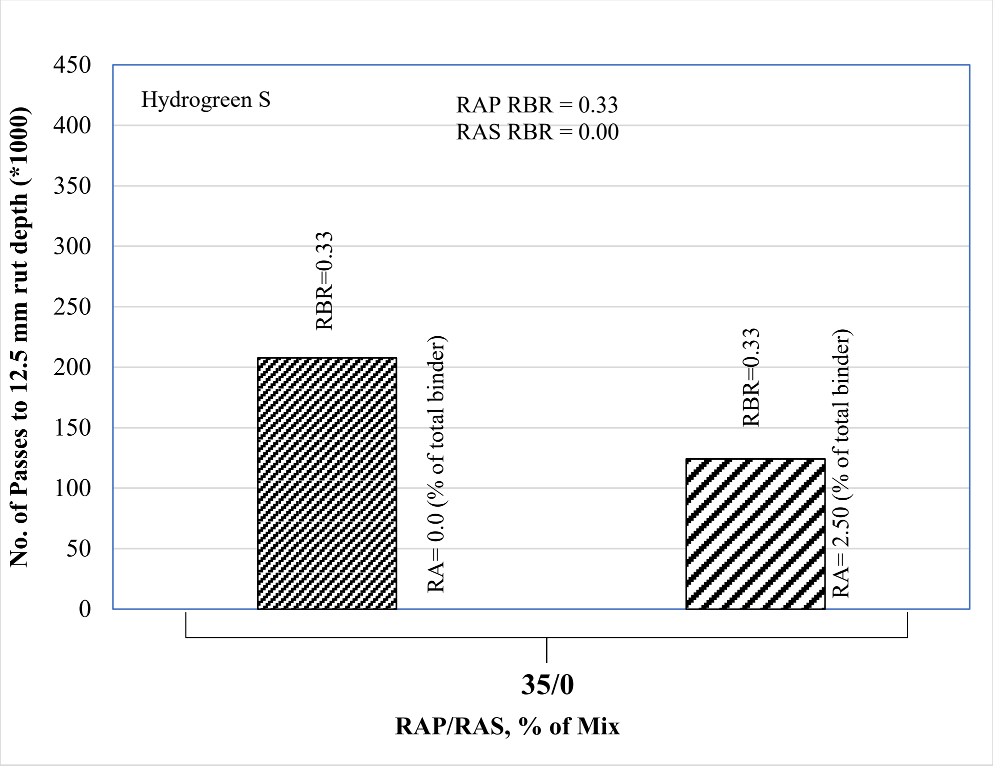

Hydrolen H90T
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
Rut depth at 10,000 passes, mm
RA= 0.0 (% of total binder)
RBR=0.33
RA= 2.88 (% of total binder)
RBR=0.33
RAP RBR = 0.33
RAS RBR = 0.00
35/0
RAP/RAS, % of Mix

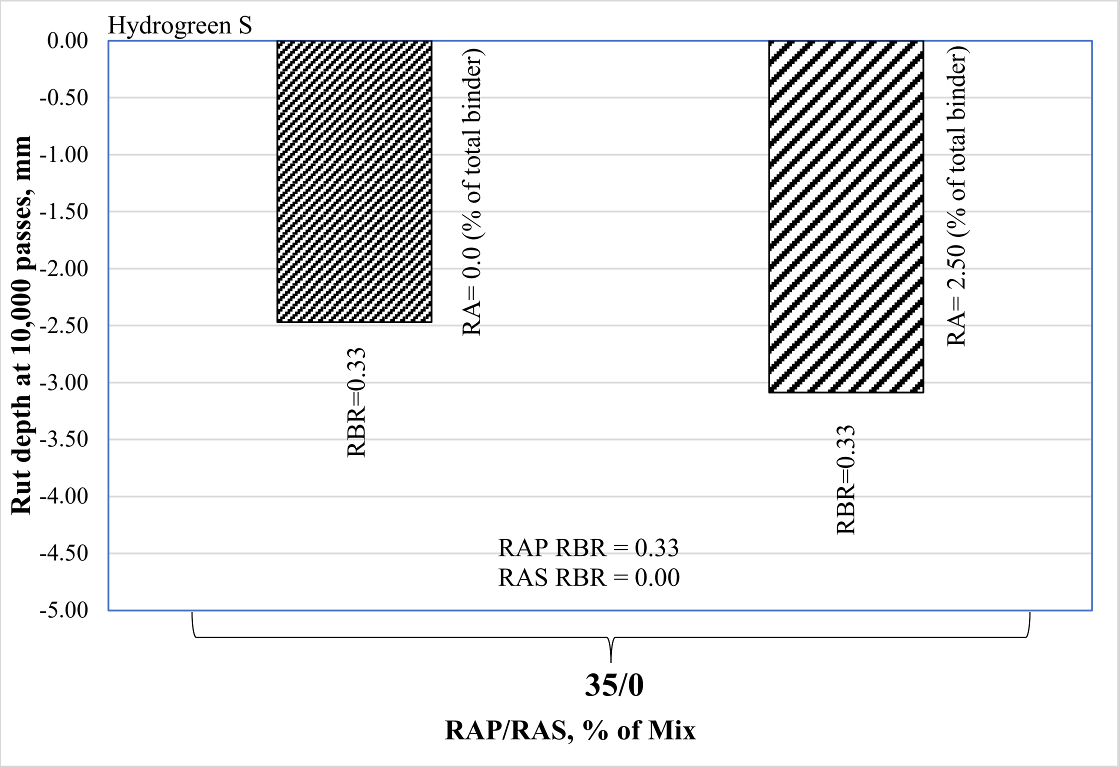

Hydrolen H90T
RAP RBR = 0.33
RAS RBR = 0.00
Ratio of Stripping Slope to Creep Slope
2.50
2.00
1.50
1.00
0.50
0.00
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 2.88 (% of total binder)
35/0
RAP/RAS, % of Mix

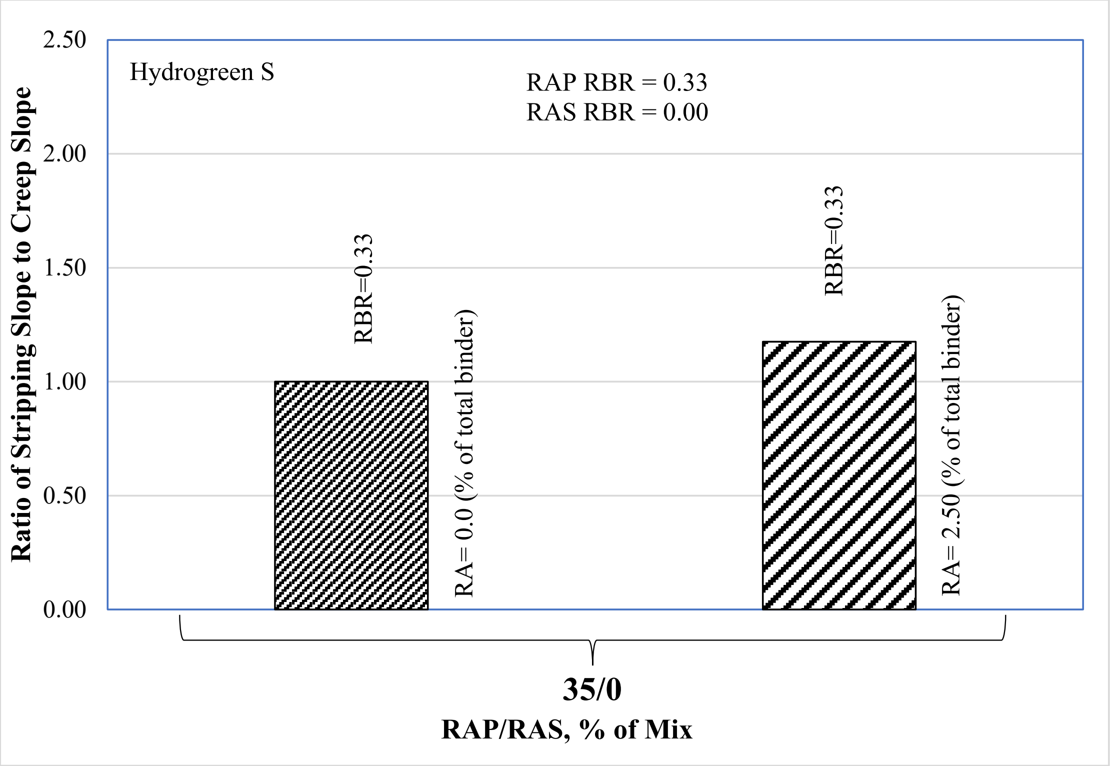

Hydrolen H90T
RAP RBR = 0.33
RAS RBR = 0.00
Creep Slope (mm/1000 passes)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 2.88 (% of total binder)
35/0
RAP/RAS, % of Mix

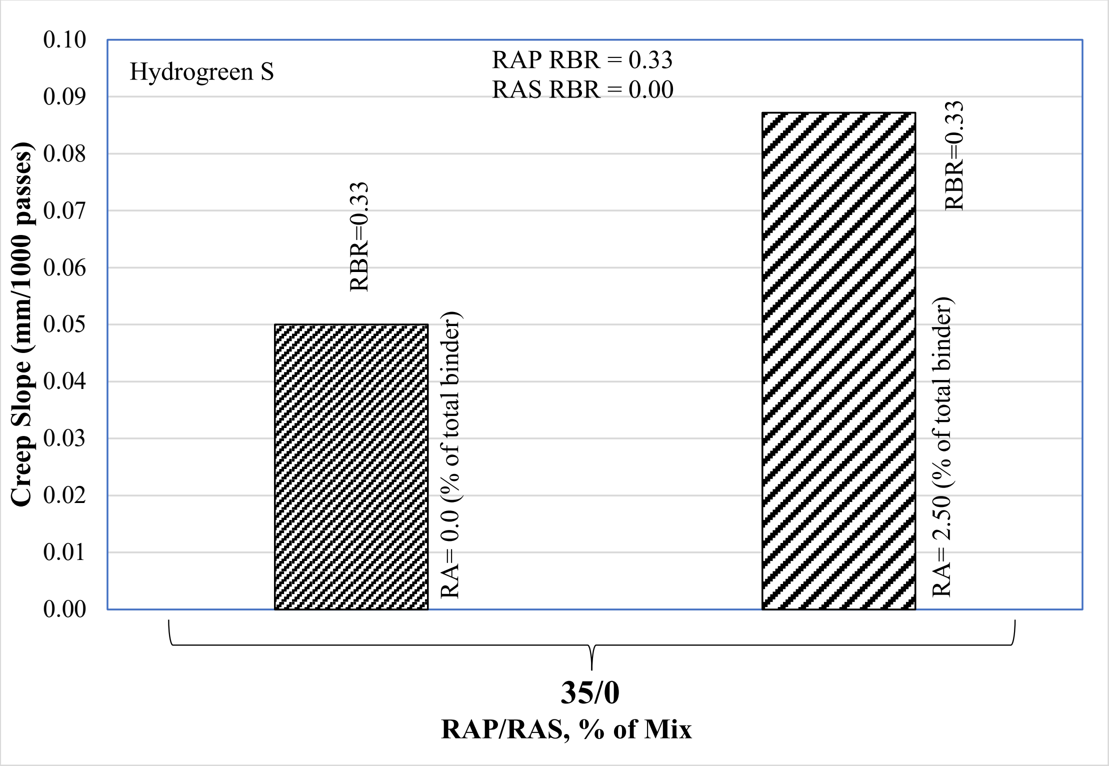
Hydrogreen S:





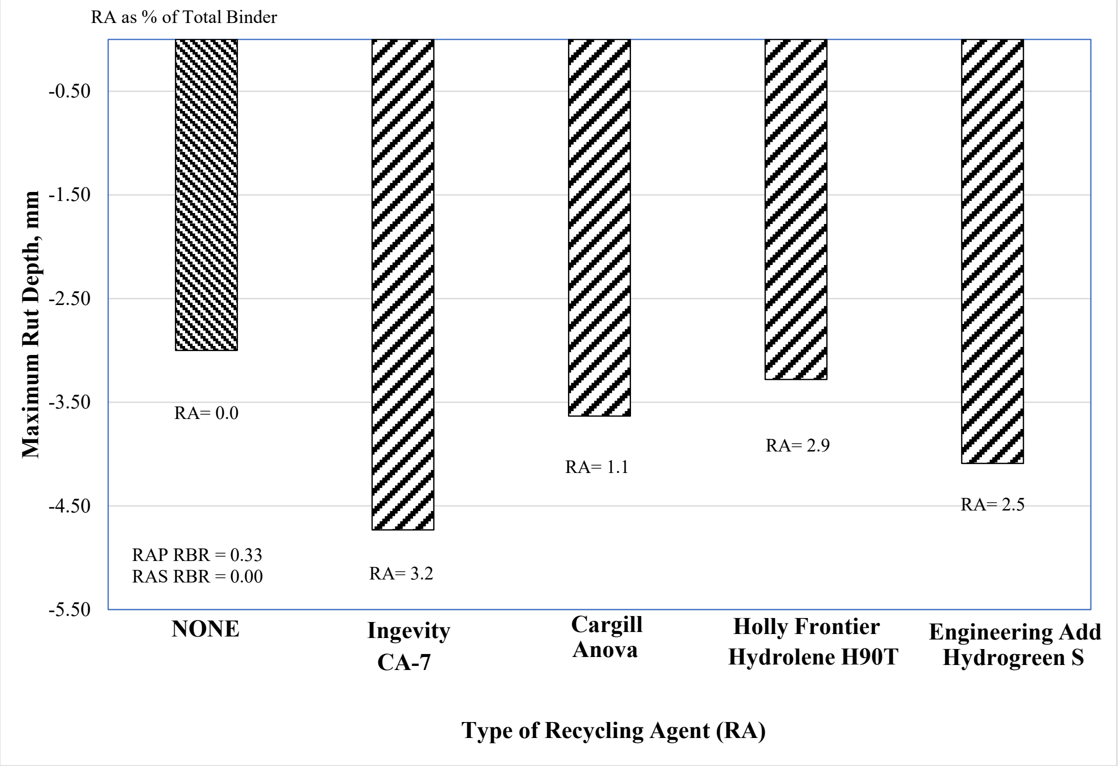

Hydrogreen S
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
Rut depth at 10,000 passes, mm
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 2.50 (% of total binder)
RAP RBR = 0.33
RAS RBR = 0.00
35/0
RAP/RAS, % of Mix

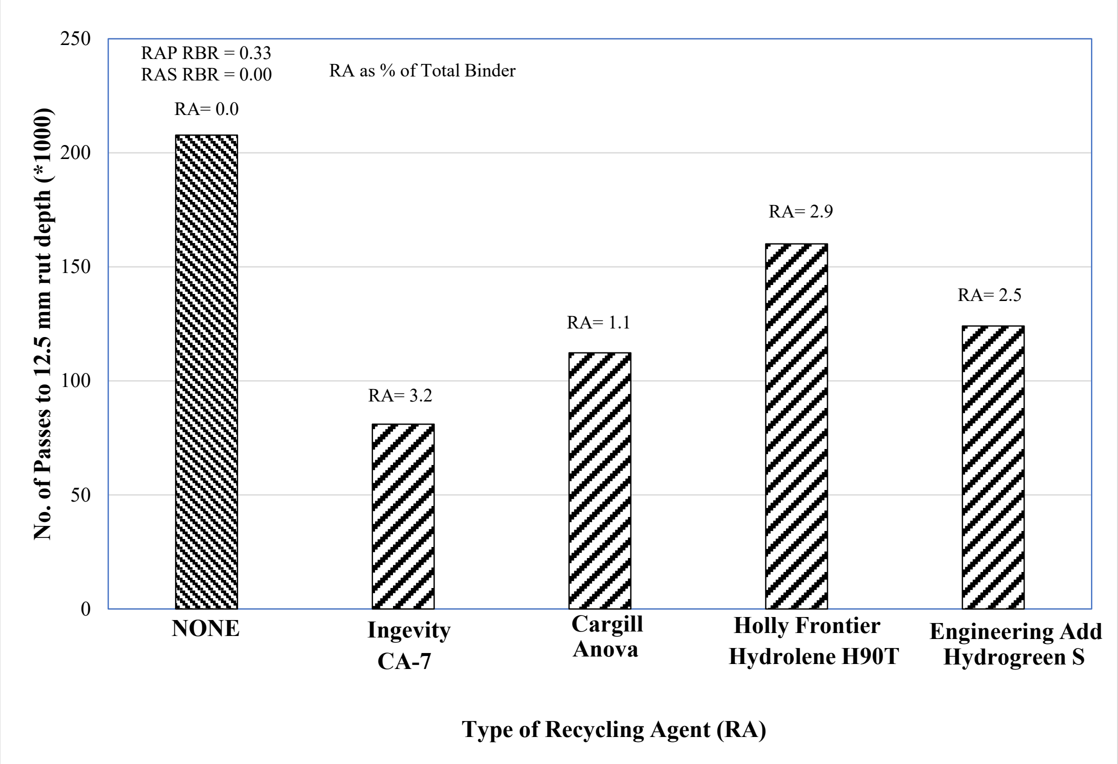

2.50
2.00
1.50
1.00
0.50
0.00
Ratio of Stripping Slope to Creep Slope
Hydrogreen S
RAP RBR = 0.33
RAS RBR = 0.00
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 2.50 (% of total binder)
35/0
RAP/RAS, % of Mix

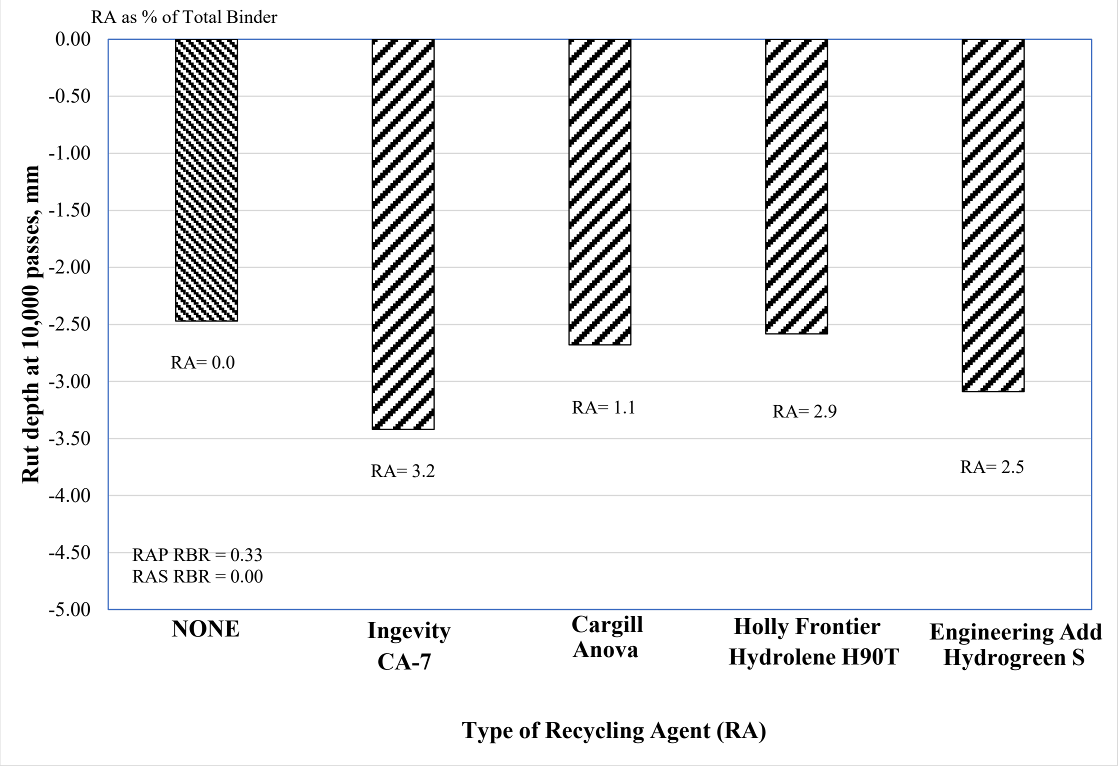

Hydrogreen S
RAP RBR = 0.33
RAS RBR = 0.00
Creep Slope (mm/1000 passes)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 2.50 (% of total binder)
35/0
RAP/RAS, % of Mix

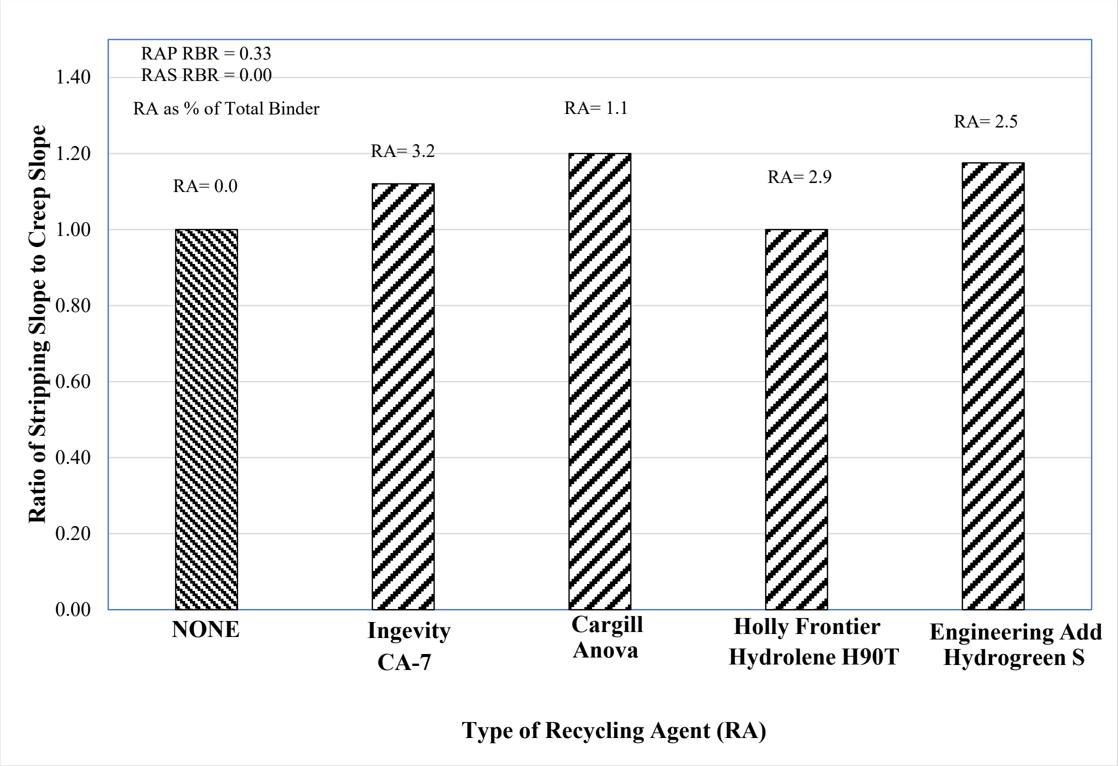
HWT, comparison charts: comparing across the rejuvenator type for the same RAP/RAS content.

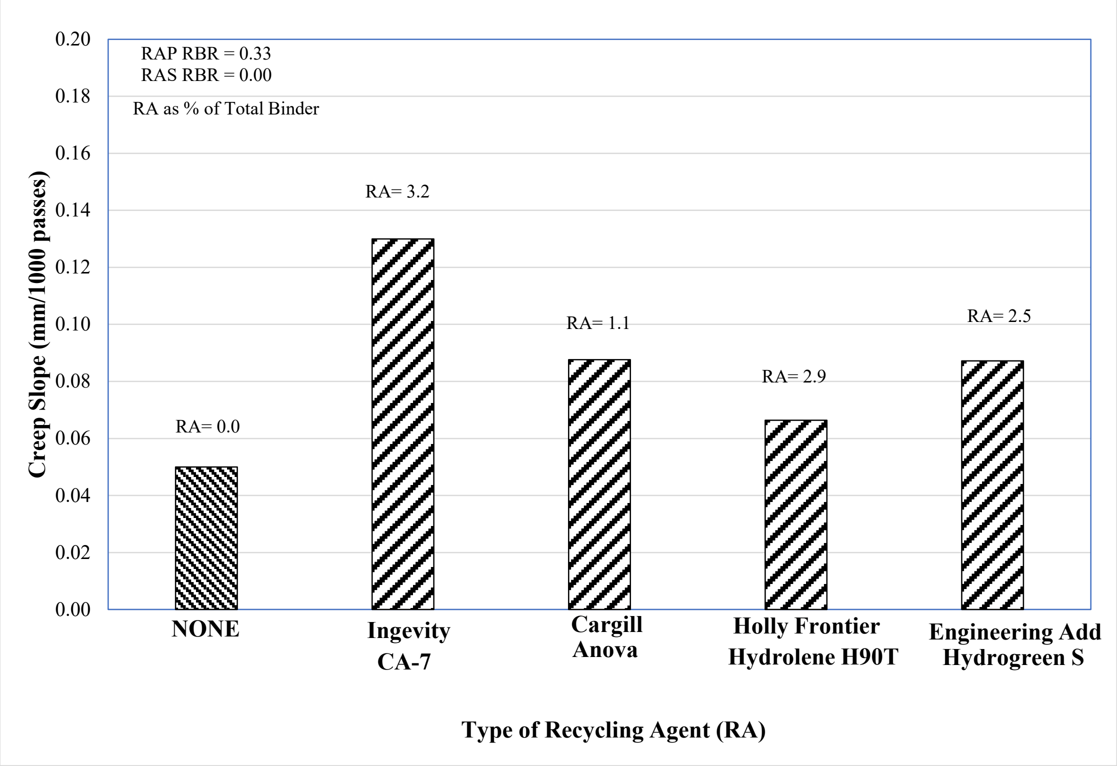
35/0% RAP/ RAS:





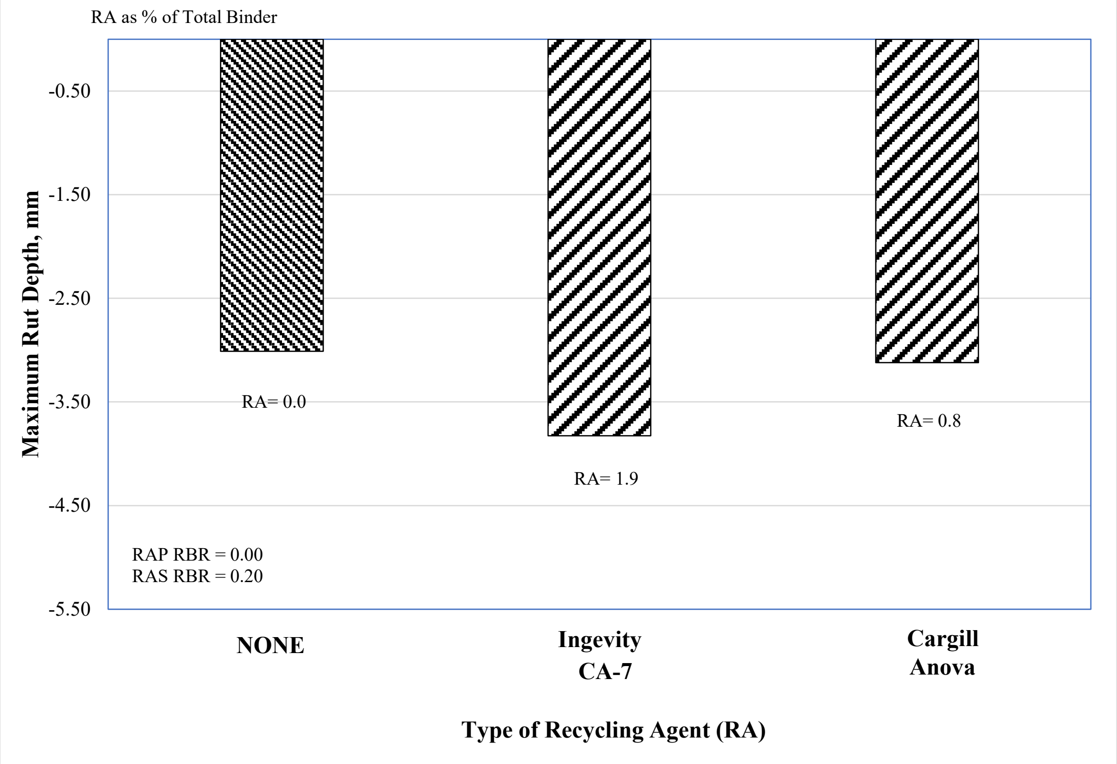

RA as % of Total Binder
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
Rut depth at 10,000 passes, mm
RA= 0.0
RA= 3.2
RA= 1.1
RA= 2.9
RA= 2.5
RAP RBR = 0.33
RAS RBR = 0.00
NONE
Ingevity CA-7
Cargill Anova
Holly Frontier Hydrolene H90T
Engineering Add Hydrogreen S
Type of Recycling Agent (RA)

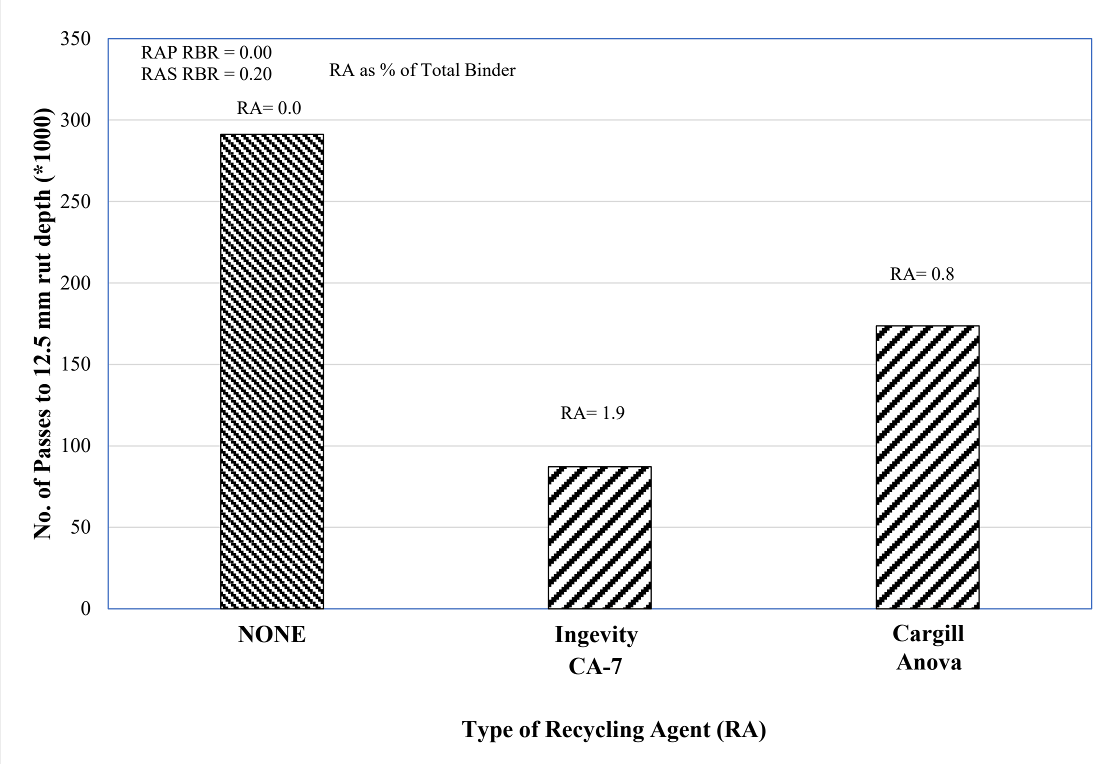

RAP RBR = 0.33
RAS RBR = 0.00
RA as % of Total Binder
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Ratio of Stripping Slope to Creep Slope
RA= 0.0
RA= 3.2
RA= 1.1
RA= 2.9
RA= 2.5
NONE
Ingevity CA-7
Cargill Anova
Holly Frontier Hydrolene H90T
Engineering Add Hydrogreen S
Type of Recycling Agent (RA)

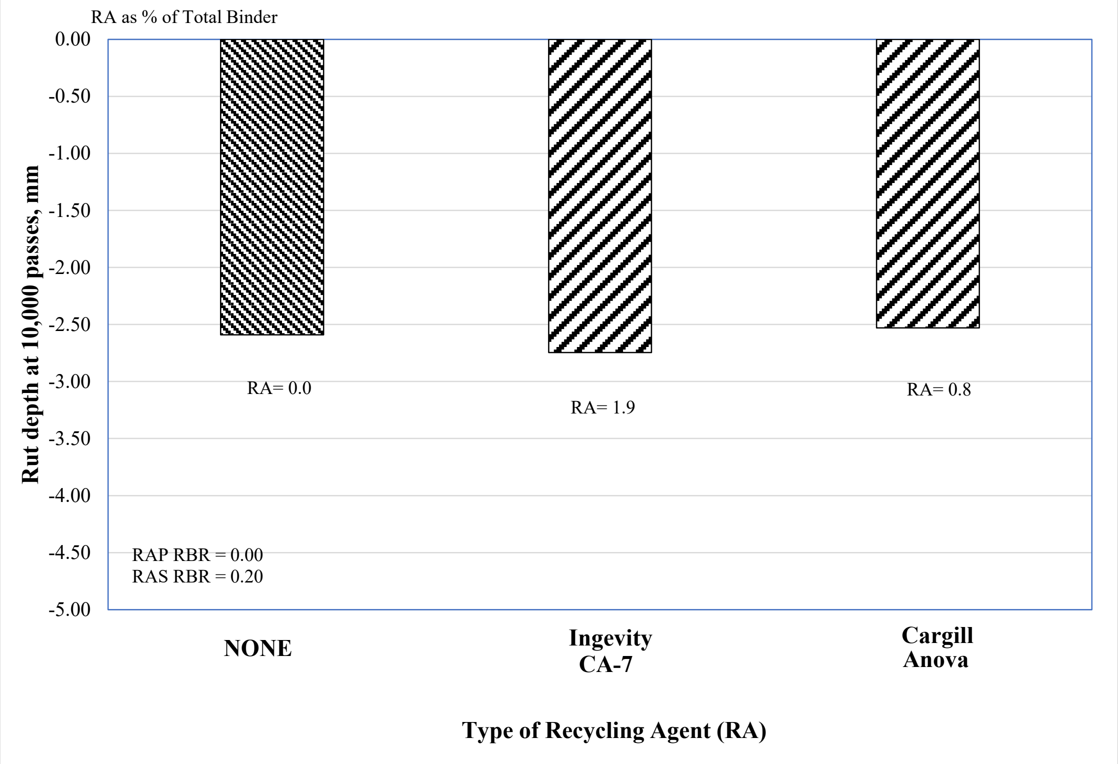


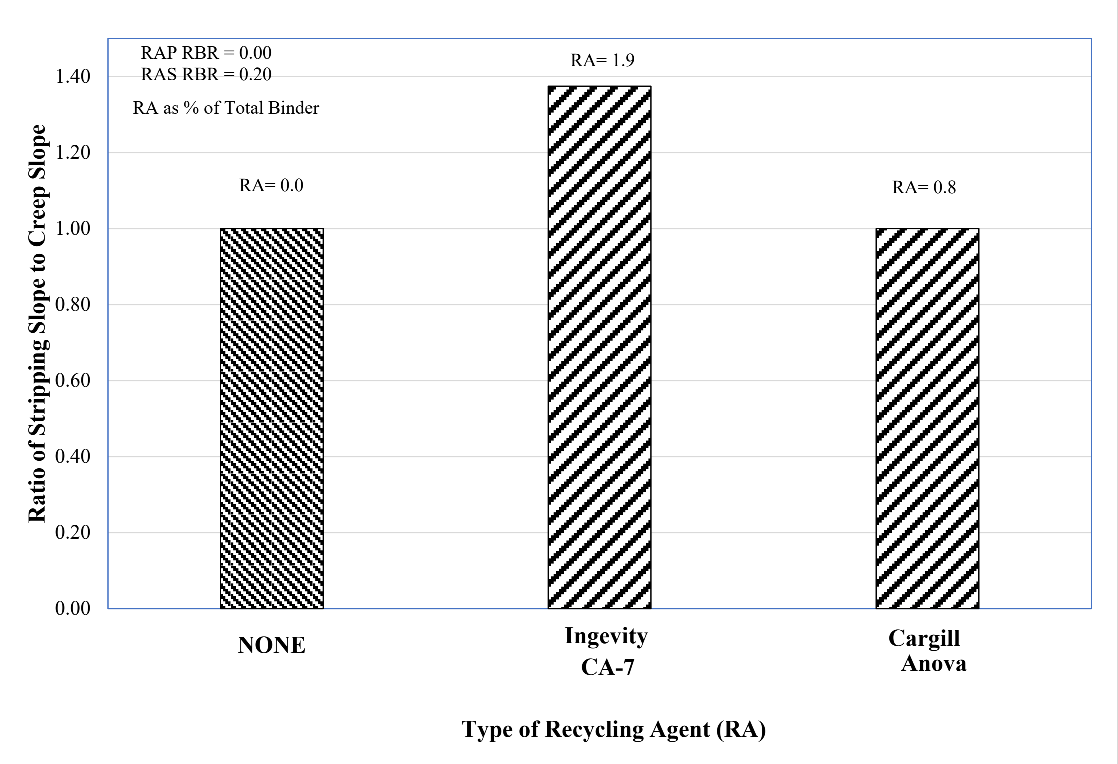
RAP RBR = 0.33
RAS RBR = 0.00
RA as % of Total Binder
Creep Slope (mm/1000 passes)
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
RA= 0.0
RA= 3.2
RA= 1.1
RA= 2.9
RA= 2.5
NONE
Ingevity CA-7
Cargill Anova
Holly Frontier Hydrolene H90T
Engineering Add Hydrogreen S
Type of Recycling Agent (RA)

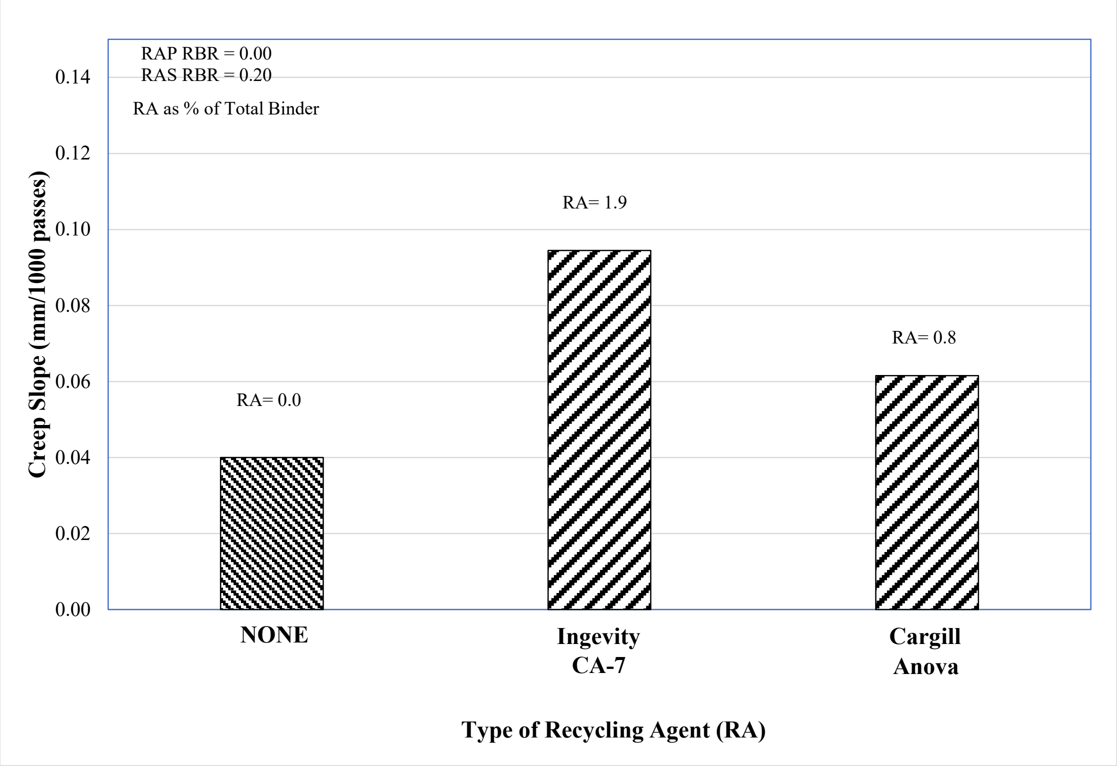
0/5% RAP/RAS:


RA as % of Total Binder
Maximum Rut Depth, mm
-0.50
-1.50
-2.50
-3.50
-4.50
-5.50
RA= 0.0
RA= 1.9
RA= 0.8
RAP RBR = 0.00
RAS RBR = 0.20
NONE
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

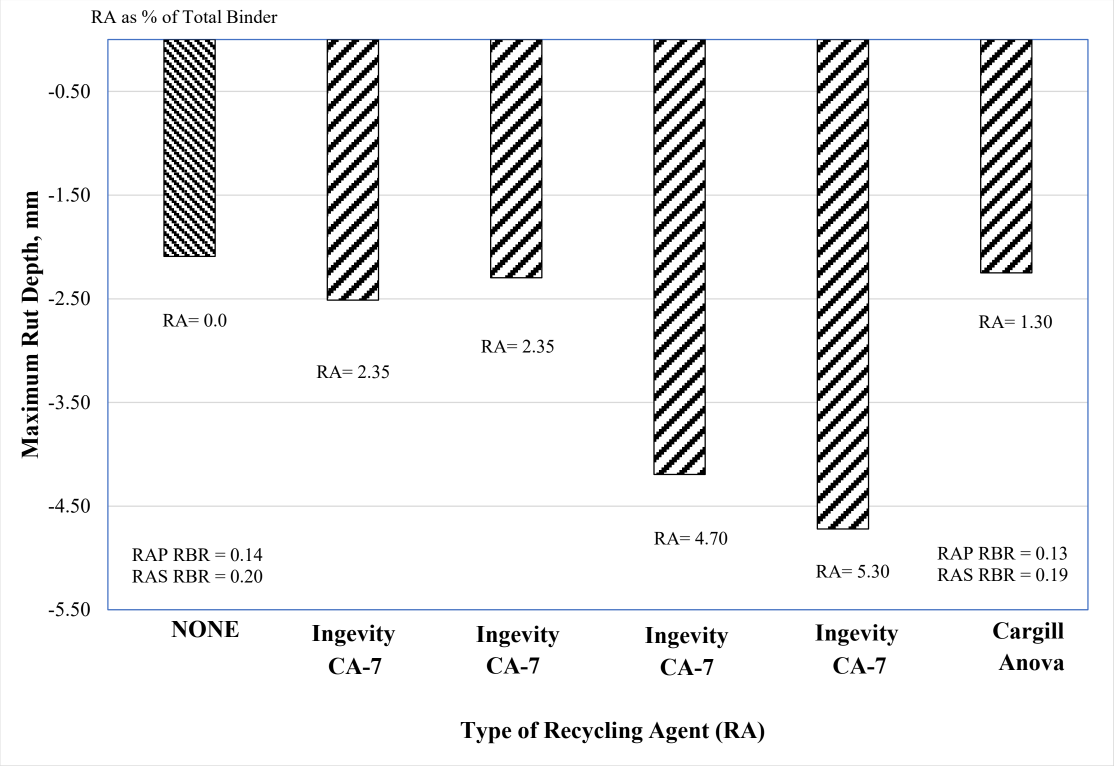

350
300
250
200
150
100
50
0
RAP RBR = 0.00
RAS RBR = 0.20
RA as % of Total Binder
RA= 0.0
RA= 1.9
RA= 0.8
No. of Passes to 12.5 mm rut depth (*1000)
NONE
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

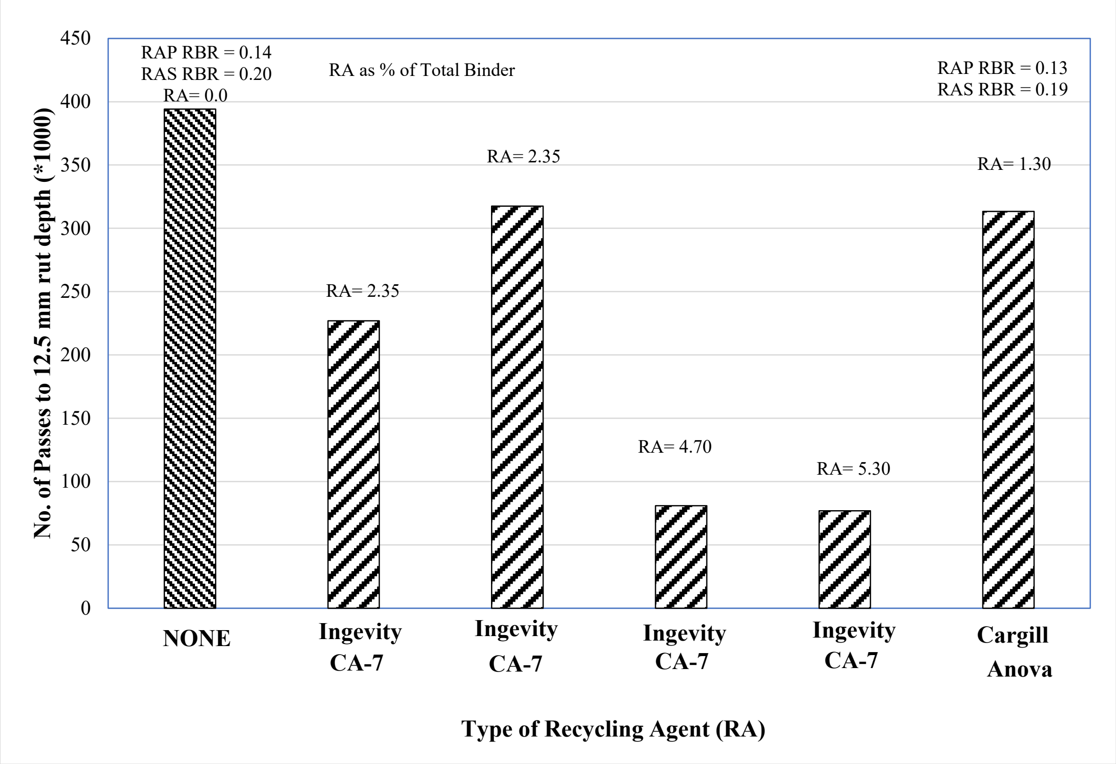

RA as % of Total Binder
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
Rut depth at 10,000 passes, mm
RA= 0.0
RA= 1.9
RA= 0.8
RAP RBR = 0.00
RAS RBR = 0.20
NONE
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

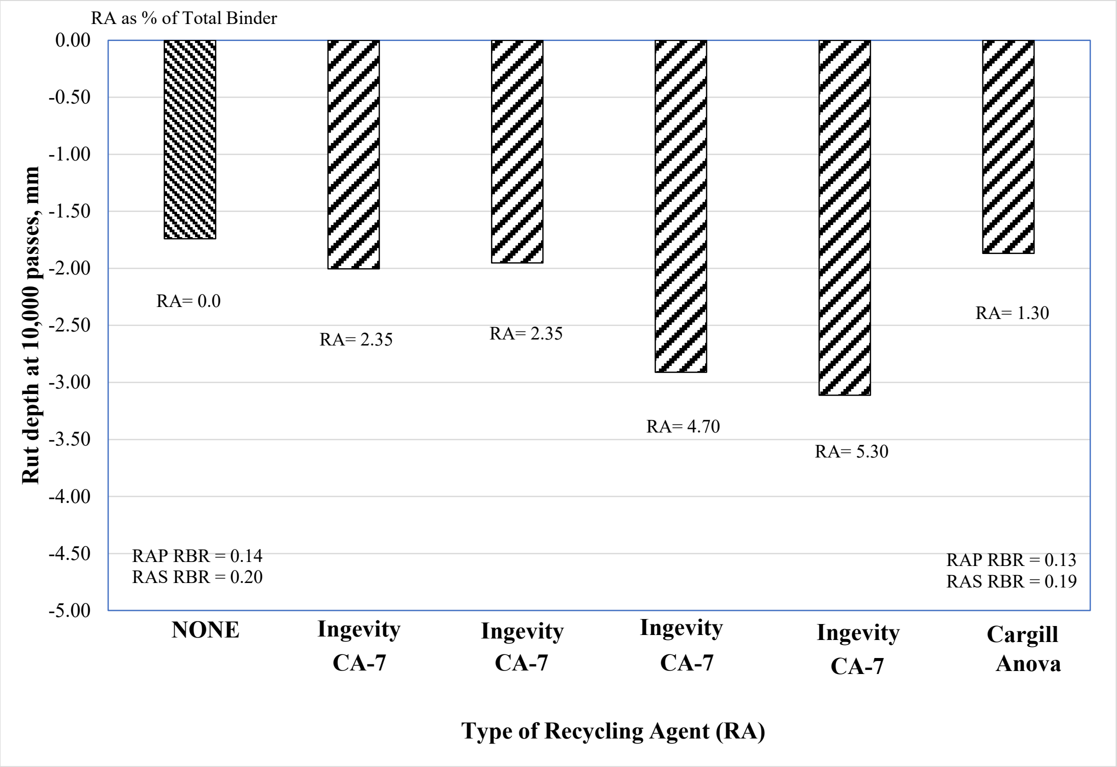

RAP RBR = 0.00
RAS RBR = 0.20
RA as % of Total Binder
RA= 1.9
RA= 0.0
RA= 0.8
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Ratio of Stripping Slope to Creep Slope
NONE
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

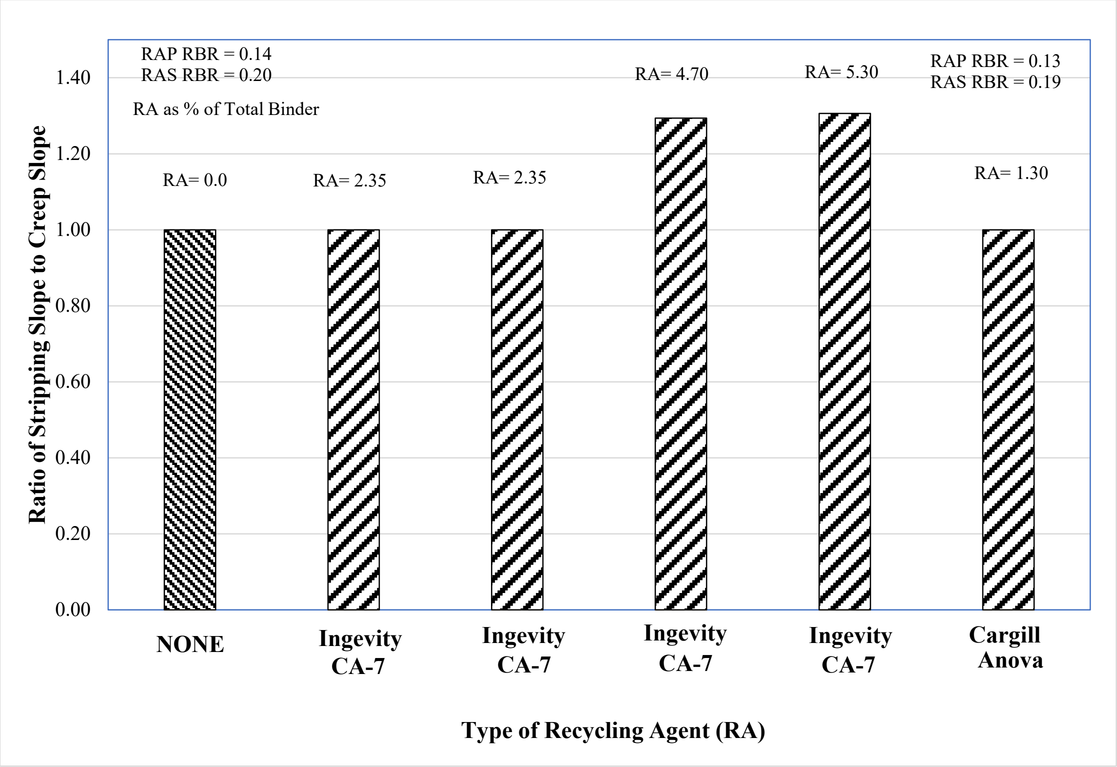

RAP RBR = 0.00
RAS RBR = 0.20
RA as % of Total Binder
Creep Slope (mm/1000 passes)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
RA= 0.0
RA= 1.9
RA= 0.8
NONE
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

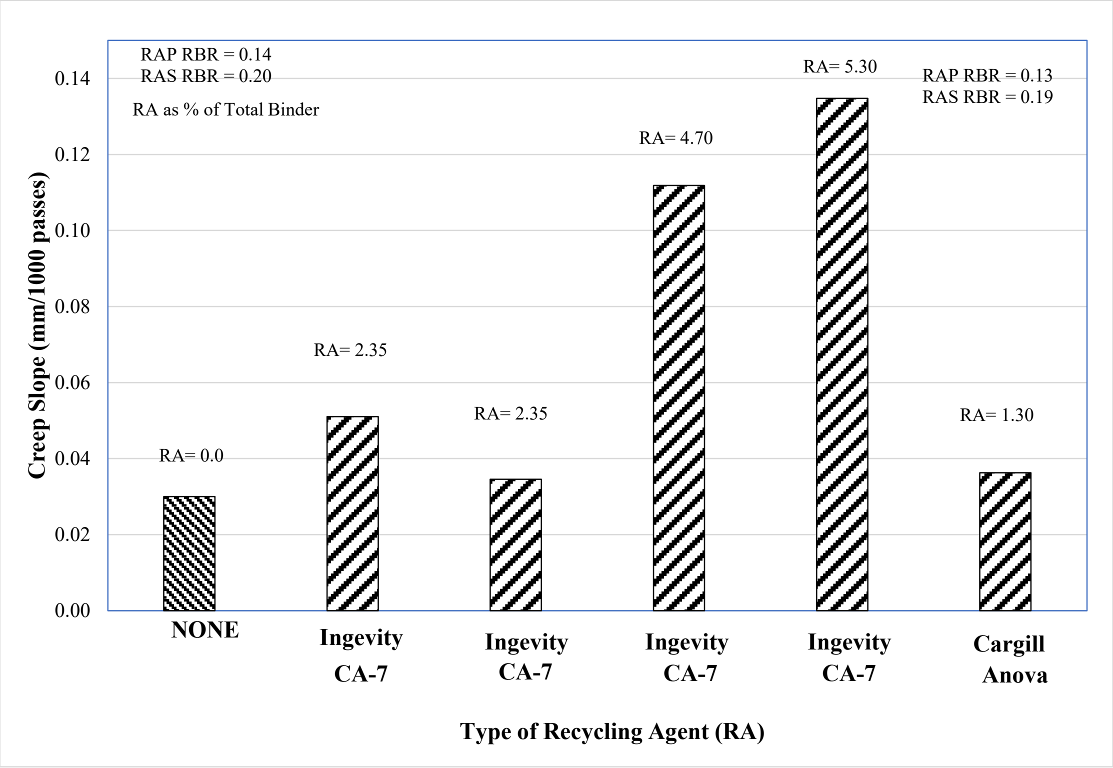
15/5 % RAP/RAS:


RA as % of Total Binder
Maximum Rut Depth, mm
-0.50
-1.50
-2.50
-3.50
-4.50
-5.50
RA= 0.0
RA= 2.35
RA= 2.35
RA= 4.70
RA= 5.30
RA= 1.30
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)


No. of Passes to 12.5 mm rut depth (*1000)
450
400
350
300
250
200
150
100
50
0
RAP RBR = 0.14
RAS RBR = 0.20
RA= 0.0
RA as % of Total Binder
RAP RBR = 0.13
RAS RBR = 0.19
RA= 2.35
RA= 2.35
RA= 4.70
RA= 5.30
RA= 1.30
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)


RA as % of Total Binder
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
Rut depth at 10,000 passes, mm
RA= 0.0
RA= 2.35
RA= 2.35
RA= 4.70
RA= 5.30
RA= 1.30
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)


RAP RBR = 0.14
RAS RBR = 0.20
RA as % of Total Binder
RA=4.70
RA= 5.30
RAP RBR = 0.13
RAS RBR = 0.19
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
Ratio of Stripping Slope to Creep Slope
RA= 0.0
RA= 2.35
RA= 2.35
RA= 1.30
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

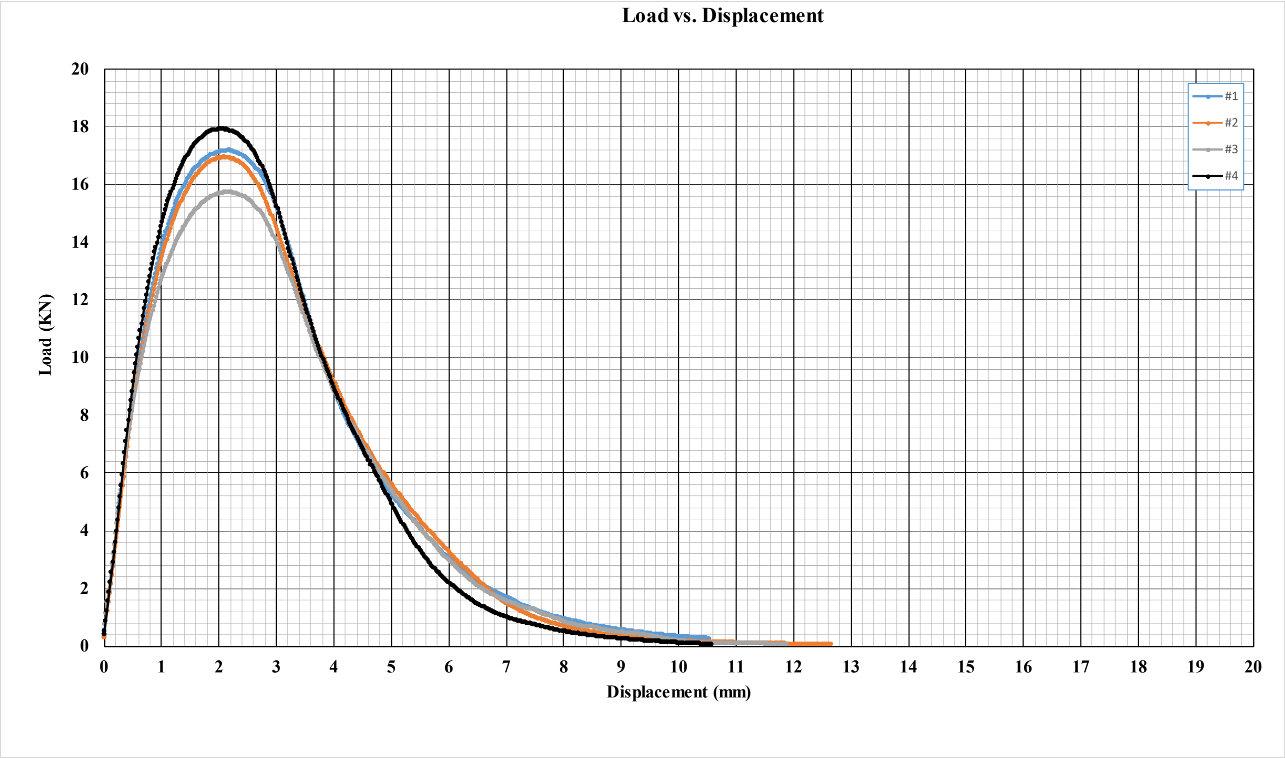

RAP RBR = 0.14
RAS RBR = 0.20
RA as % of Total Binder
RAP RBR = 0.13
RAS RBR = 0.19
Creep Slope (mm/1000 passes)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
RA= 0.0
RA= 2.35
RA= 2.35
RA= 4.70
RA= 5.30
RA= 1.30
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

APPENDIX E

Results from IDEAL-CT Index Test for Different Mixes

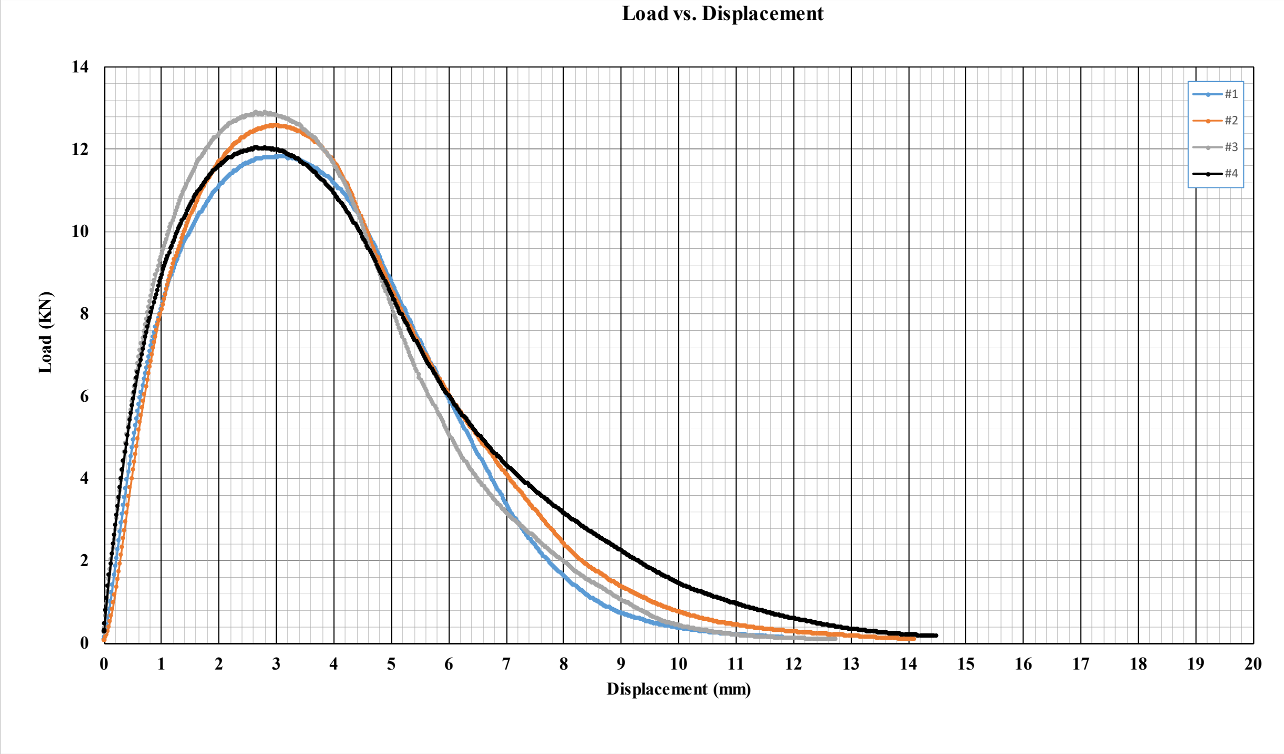
MIX CODE
4

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 2	**17184.3**	**7386.7**	**23.8**	**1178**	**171**	**1.45**
IDEAL 3	**16953.4**	**7299.9**	**28.4**	**1166**	**169**	**1.40**
IDEAL 4	**15738.7**	**7001.5**	**28.1**	**1083**	**157**	**1.43**
IDEAL 5	**17938.1**	**7304.2**	**22.9**	**1234**	**179**	**1.35**
Average	16953.6	7248.1	25.8	1165	169	1.41
Stand. Dev.	912.6	169.1	2.8	62.5	9.1	0.04
Coef. of Var.	5.4	2.3	11.0	5.4	5.4	3.1



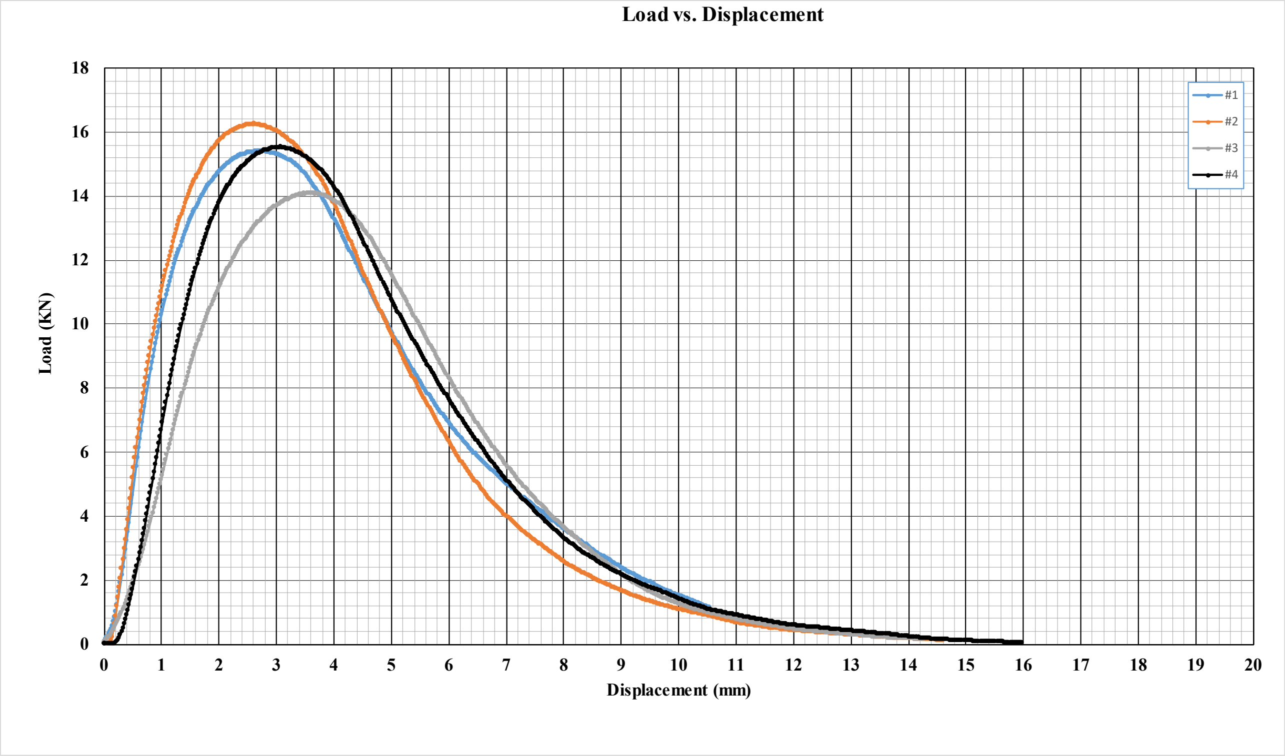
MIX CODE
5

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 6	**11829.8**	**6885.1**	**78.5**	**806**	**117**	**2.06**
IDEAL 7	**12570.9**	**7387.5**	**71.5**	**858**	**124**	**1.94**
IDEAL 8	**12890.9**	**7304.7**	**60.0**	**882**	**128**	**1.86**
IDEAL 9	**12042.0**	**7811.4**	**92.4**	**824**	**120**	**1.77**
Average	12333.4	7347.2	75.6	843	122	1.91
Stand. Dev.	485.0	379.6	13.5	34.1	5.0	0.12
Coef. of Var.	3.9	5.2	17.9	4.1	4.1	6.4



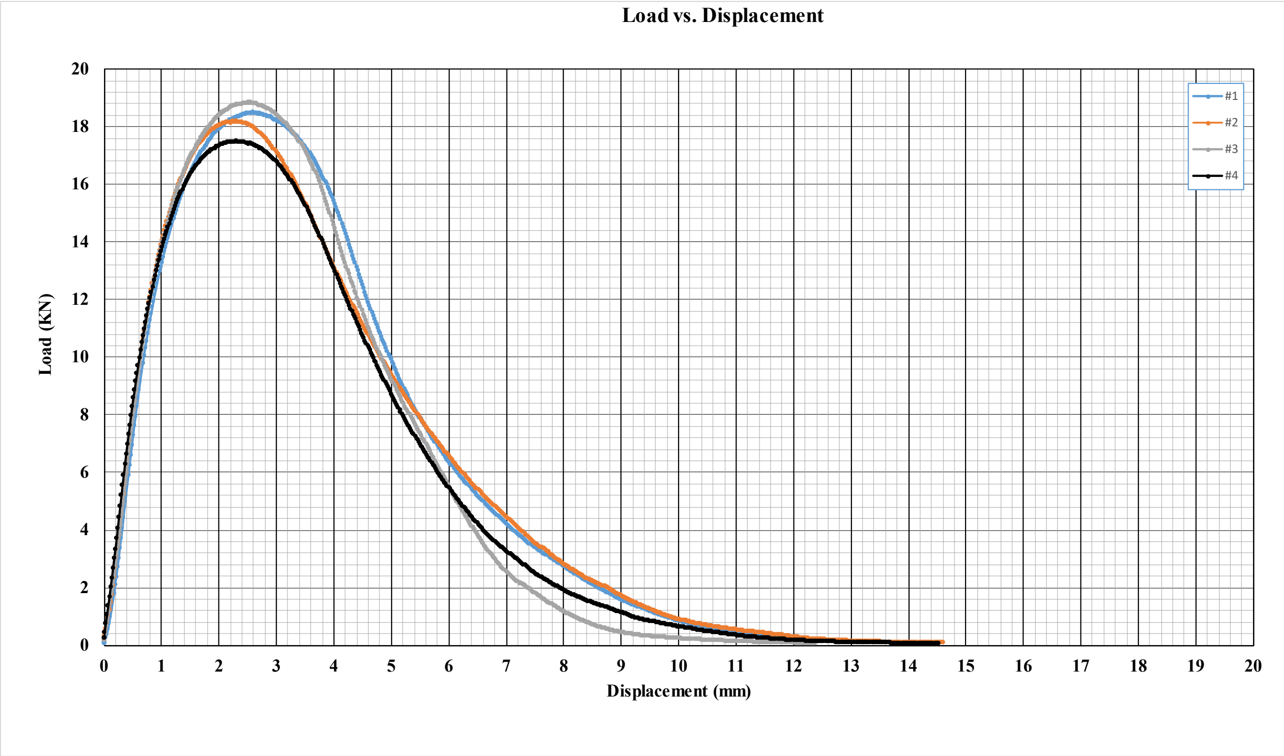
MIX CODE
18

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL I1	15409.4	8991.9	75.9	1058	153	1.86
IDEAL I2	16269.5	9079.6	64.1	1116	162	1.75
IDEAL I3	14101.6	8486.4	92.4	967	140	2.38
IDEAL I4	15536.5	8964.1	77.6	1067	155	2.05
Average	**15329.3**	**8880.5**	**77.5**	**1052**	**153**	**2.01**
Stand. Dev.	**902.0**	**267.3**	**11.6**	**62.0**	**9.0**	**0.28**
Coef. of Var.	**5.9**	**3.0**	**14.9**	**5.9**	**5.9**	**13.9**



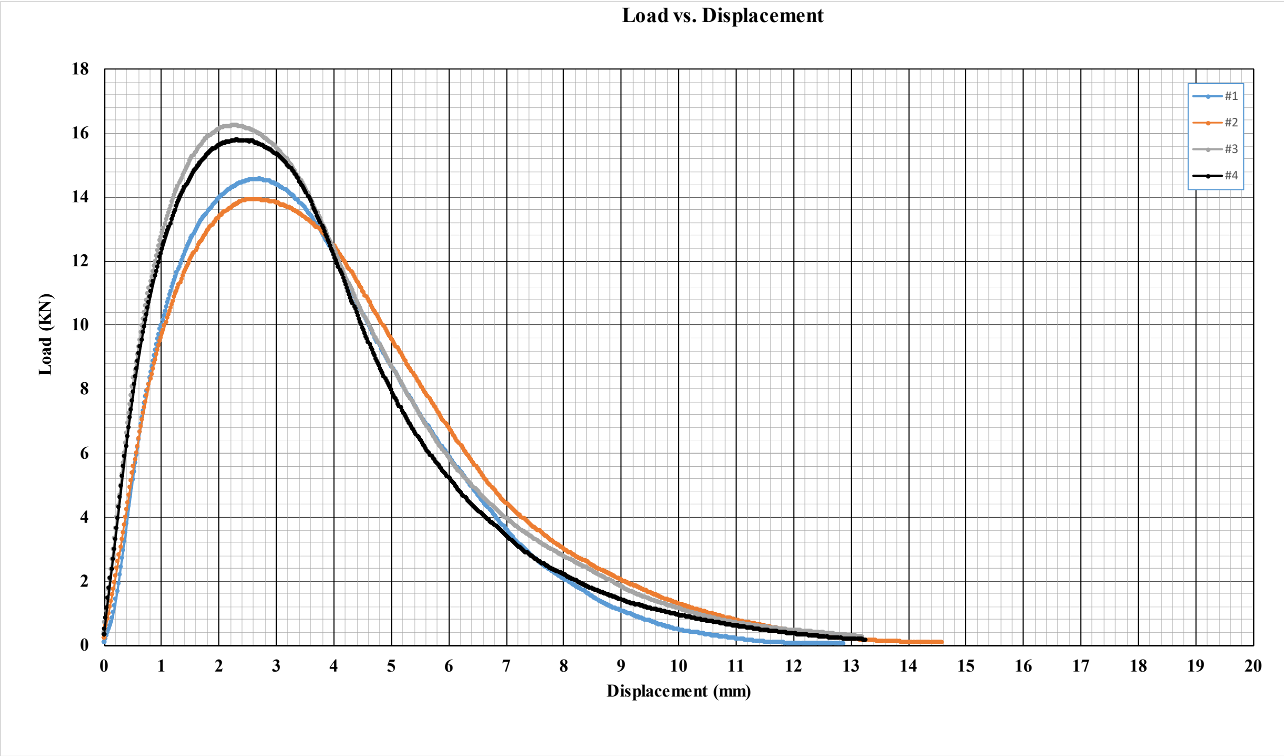
MIX CODE
19

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL I5	18488.3	9891.2	49.4	1262	183	1.73
IDEAL I6	18193.6	9735.6	58.8	1245	181	1.54
IDEAL I7	18847.8	9212.0	41.3	1286	187	1.68
IDEAL I8	17489.3	9047.0	53.0	1193	173	1.53
Average	**18254.8**	**9471.5**	**50.6**	**1247**	**181**	**1.62**
Stand. Dev.	**576.2**	**405.5**	**7.3**	**39.2**	**5.7**	**0.10**
Coef. of Var.	**3.2**	**4.3**	**14.5**	**3.1**	**3.1**	**6.1**



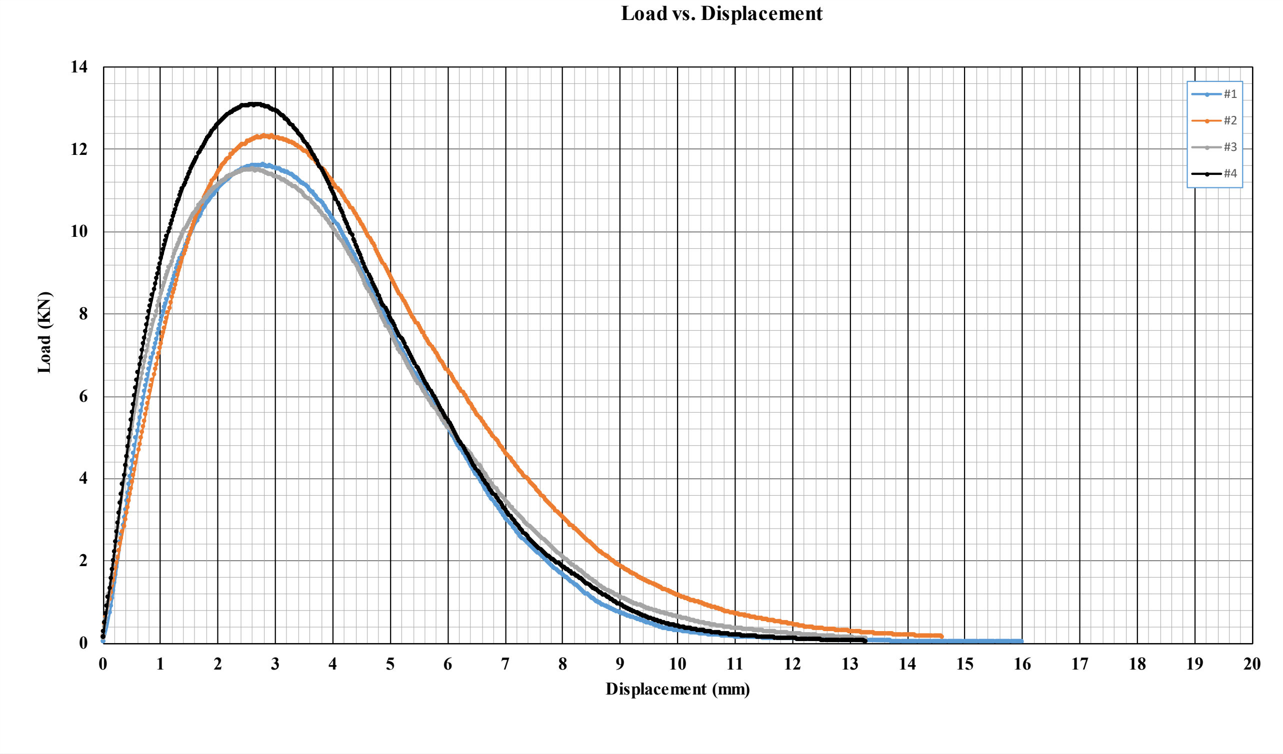
MIX CODE
20

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL I9	14564.1	7901.1	63.3	999	145	1.80
IDEAL I10	13932.1	8326.5	89.0	936	136	1.69
IDEAL I11	16247.2	9079.1	62.4	1112	161	1.51
IDEAL I12	15783.7	8529.3	53.2	1080	157	1.54
Average	**15131.8**	**8459.0**	**67.0**	**1032**	**150**	**1.64**
Stand. Dev.	**1069.4**	**489.3**	**15.4**	**80.0**	**11.6**	**0.14**
Coef. of Var.	**7.1**	**5.8**	**23.0**	**7.8**	**7.8**	**8.4**



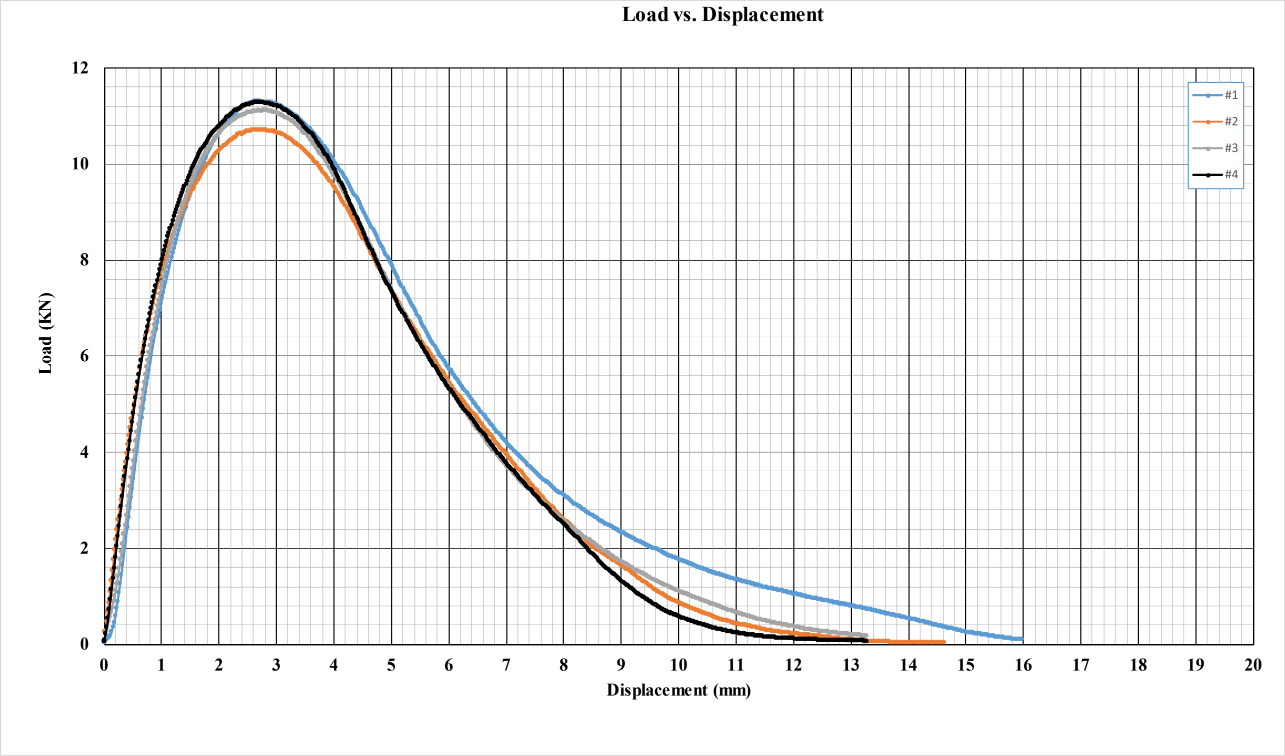
MIX CODE
21

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL I13	11623.3	6511.6	73.4	796	115	1.85
IDEAL I14	12332.5	7647.0	99.9	844	122	1.87
IDEAL I15	11523.3	6786.3	80.4	789	114	1.73
IDEAL I16	13096.4	7196.3	66.1	897	130	1.80
Average	**12143.9**	**7035.3**	**80.0**	**831**	**121**	**1.81**
Stand. Dev.	**730.1**	**495.4**	**14.5**	**50.0**	**7.2**	**0.06**
Coef. of Var.	**6.0**	**7.0**	**18.2**	**6.0**	**6.0**	**3.5**



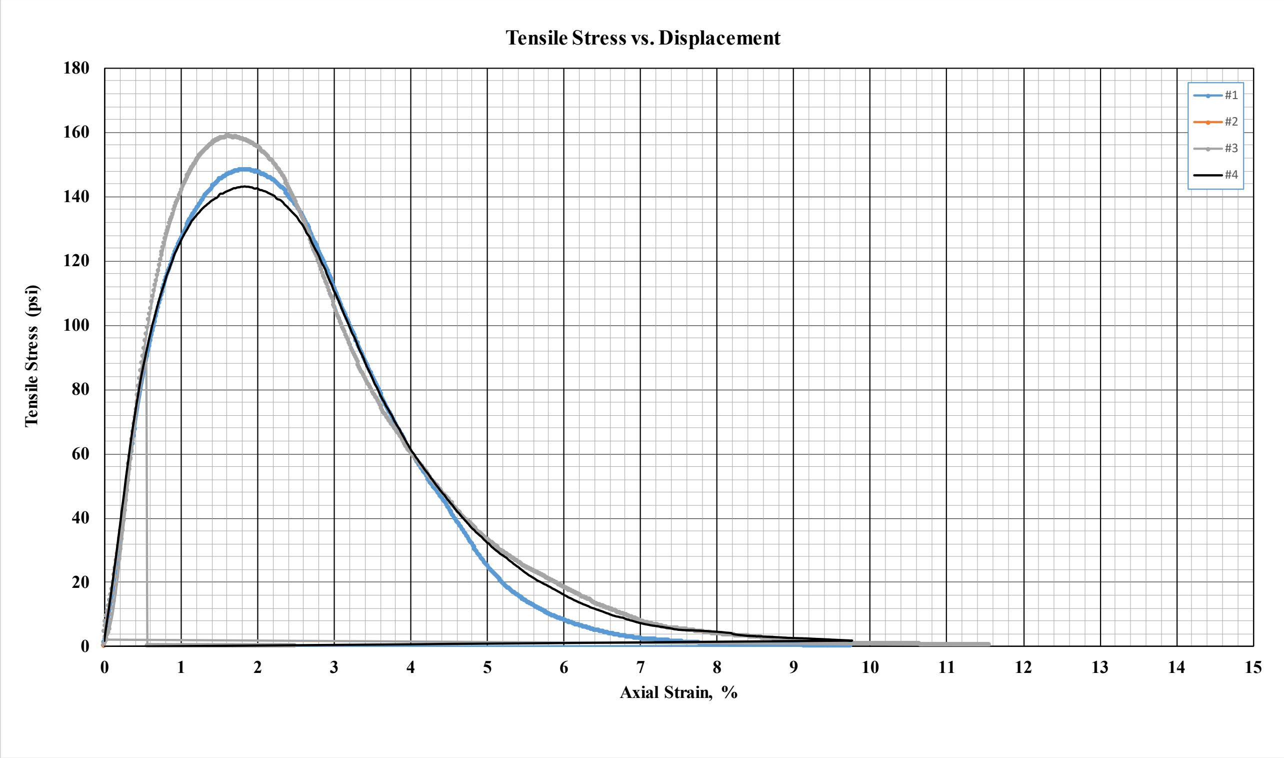
MIX CODE
23

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL I17	11306.8	7393.7	102.8	775	112	1.78
IDEAL I18	10721.6	6670.2	96.9	735	107	1.81
IDEAL I19	11125.6	6761.9	84.9	762	110	1.87
IDEAL I20	11292.9	6677.6	78.0	772	112	1.81
Average	**11111.7**	**6875.8**	**90.7**	**761**	**110**	**1.82**
Stand. Dev.	**272.8**	**347.7**	**11.2**	**18.2**	**2.6**	**0.04**
Coef. of Var.	**2.5**	**5.1**	**12.4**	**2.4**	**2.4**	**2.0**



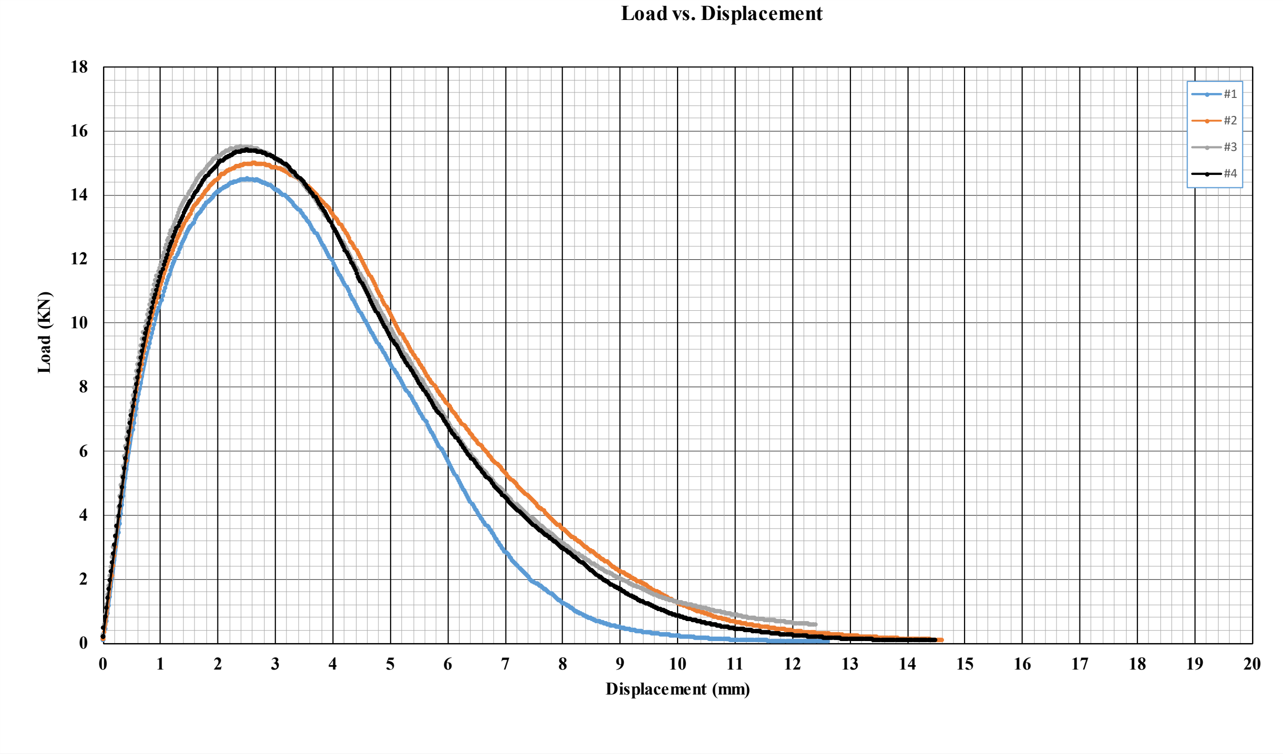
MIX CODE
24

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	14918.6	8148.7	64.5	1023	148	1.86
IDEAL 2	0.0	0.0	#N/A	0	0	#REF!
IDEAL 3	15977.2	9076.5	59.6	1095	159	1.61
IDEAL 4	14408.0	8506.2	71.1	988	143	1.84
Average	**11325.9**	**6432.8**	**#N/A**	**777**	**113**	**#REF!**
Stand. Dev.	**7578.9**	**4305.6**	**#N/A**	**519.6**	**75.4**	**#REF!**
Coef. of Var.	**66.9**	**66.9**	**#N/A**	**66.9**	**66.9**	**#REF!**


Tensile Stress vs. Displacement

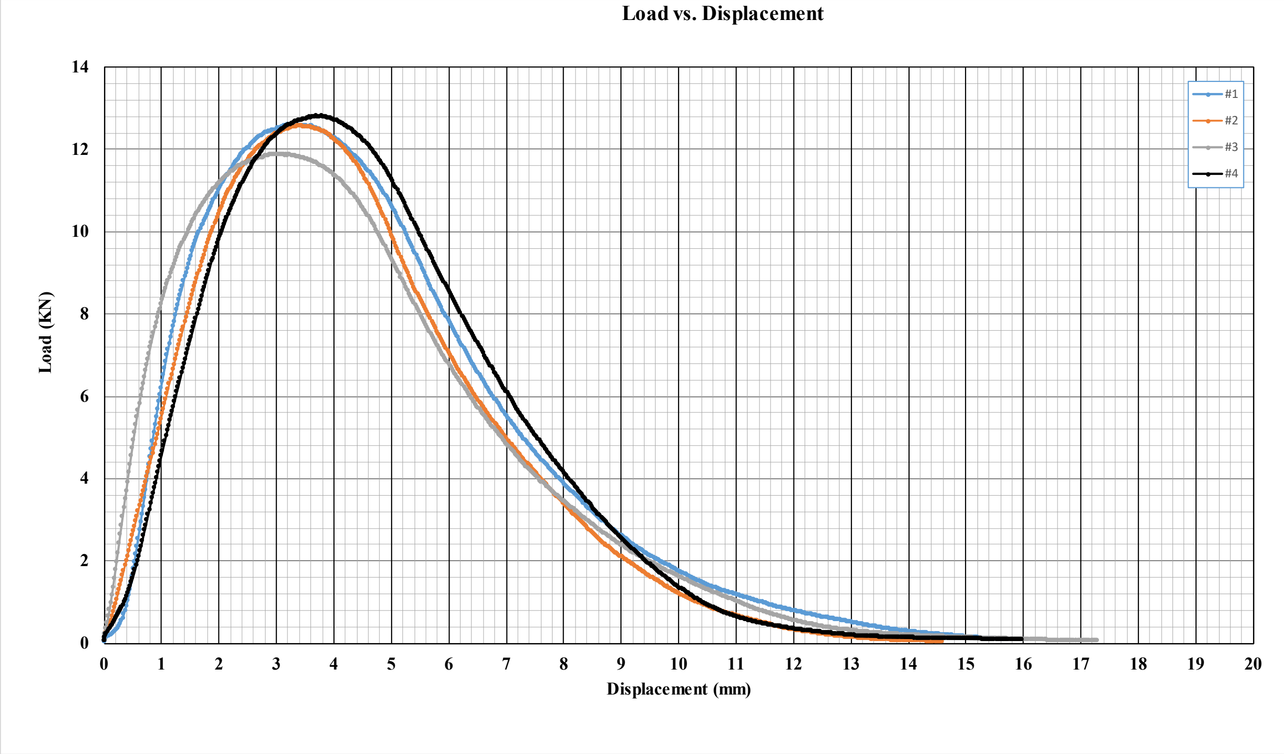
MIX CODE
33

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL I1	14494.7	7697.3	67.9	994	144	1.68
IDEAL I2	14983.8	9369.7	89.3	1027	149	1.75
IDEAL I3	15499.4	9445.8	89.8	1063	154	1.60
IDEAL I4	15395.6	8978.2	76.4	1056	153	1.68
Average	**15093.4**	**8872.8**	**80.8**	**1035**	**150**	**1.68**
Stand. Dev.	**457.1**	**810.0**	**10.6**	**31.3**	**4.5**	**0.06**
Coef. of Var.	**3.0**	**9.1**	**13.2**	**3.0**	**3.0**	**3.8**



MIX CODE
35

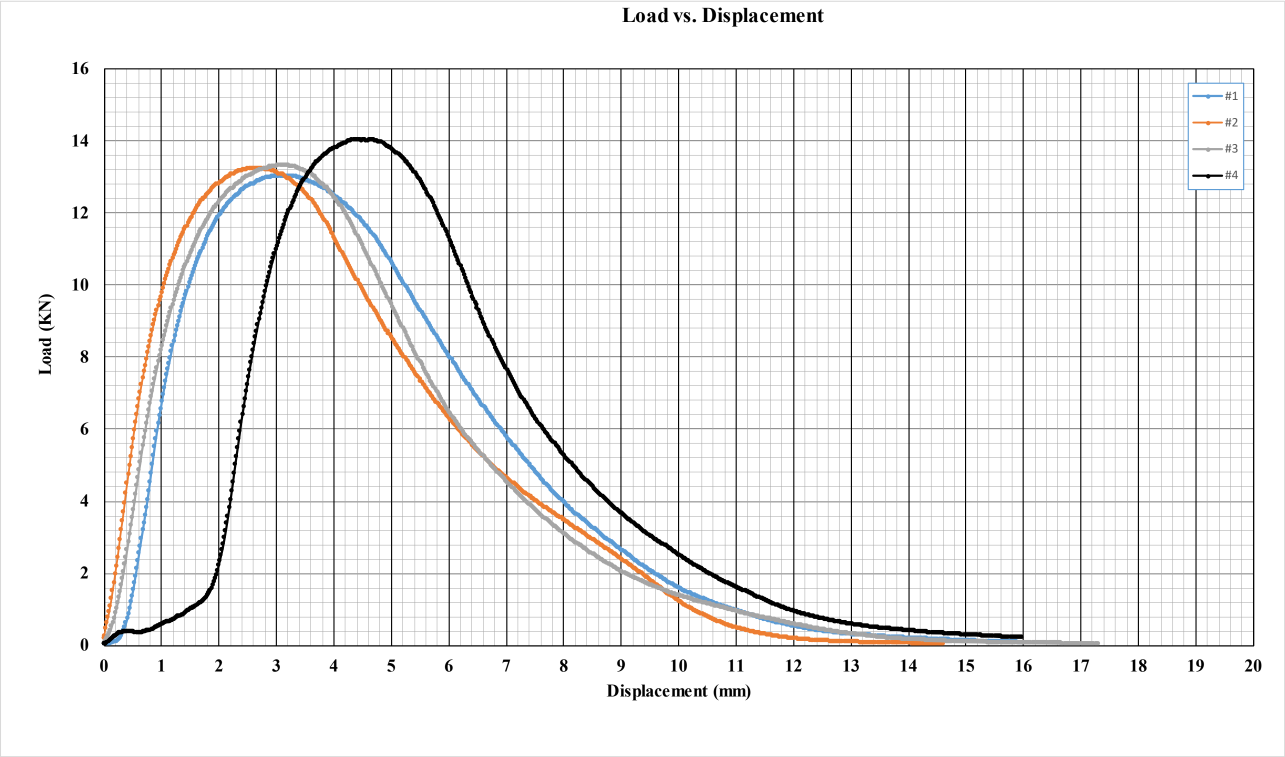
Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	12614.8	8359.1	106.5	868	126	2.20
IDEAL 2	12570.6	7672.8	84.4	865	125	2.28
IDEAL 3	11879.7	8035.6	103.1	816	118	1.98
IDEAL 4	12810.7	8121.0	110.4	881	128	2.52
Average	**12468.9**	**8047.1**	**101.1**	**857**	**124**	**2.25**
Stand. Dev.	**406.5**	**284.6**	**11.5**	**28.6**	**4.1**	**0.22**
Coef. of Var.	**3.3**	**3.5**	**11.4**	**3.3**	**3.3**	**10.0**



MIX CODE
36

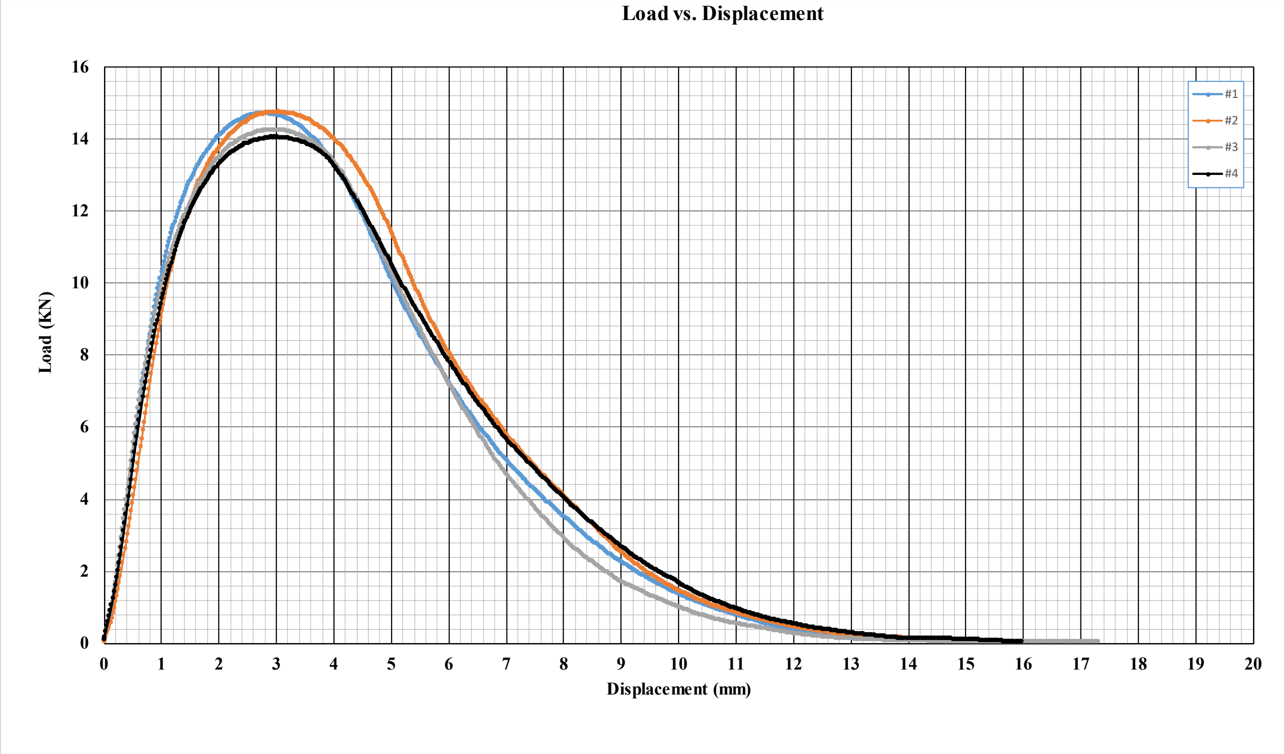
Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	13036.2	8538.5	115.3	895	130	2.11
IDEAL 2	13243.8	8161.9	87.7	910	132	1.73
IDEAL 3	13333.9	8205.7	82.1	916	133	2.11
IDEAL 4	14039.9	8256.2	87.8	964	140	3.03
Average	**13413.4**	**8290.6**	**93.2**	**921**	**134**	**2.25**
Stand. Dev.	**435.8**	**169.7**	**15.0**	**29.9**	**4.3**	**0.55**
Coef. of Var.	**3.2**	**2.0**	**16.1**	**3.2**	**3.2**	**24.7**

Remarks: The specimen was not seated correctly in the holder and after the pre-load was set and test started, the specimen then got seated correctly in the holder, giving the short flat load before the real test load.



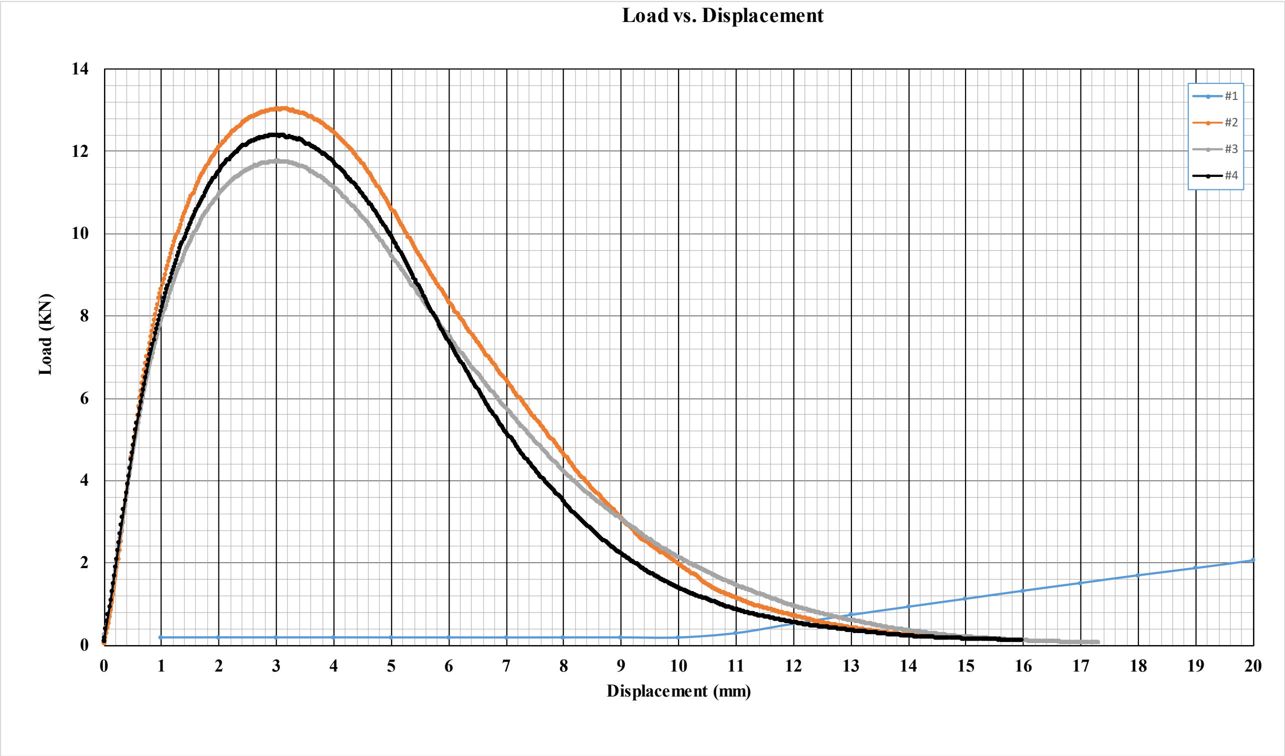
MIX CODE
37

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	14727.0	9072.8	84.3	1011	147	1.86
IDEAL 2	14766.5	9433.8	91.8	1014	147	2.02
IDEAL 3	14259.2	8732.0	84.4	979	142	1.91
IDEAL 4	14059.0	9225.3	103.7	967	140	1.94
Average	**14452.9**	**9116.0**	**91.0**	**993**	**144**	**1.93**
Stand. Dev.	**349.4**	**295.7**	**9.2**	**23.4**	**3.4**	**0.07**
Coef. of Var.	**2.4**	**3.2**	**10.1**	**2.4**	**2.4**	**3.4**



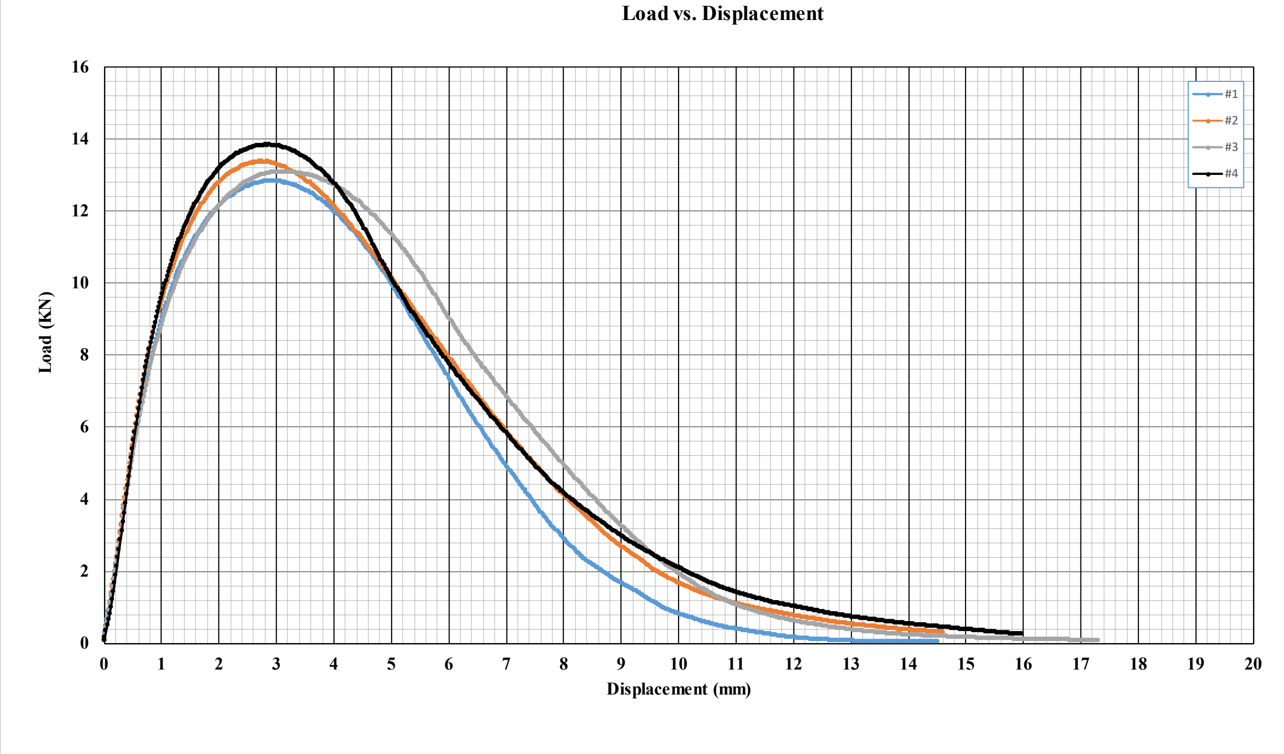
MIX CODE
38

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	12323.8	8198.9	122.1	845	123	2.01
IDEAL 2	13037.7	9169.9	145.5	895	130	2.11
IDEAL 3	11757.5	8475.7	153.7	807	117	2.02
IDEAL 4	12395.1	8253.3	118.2	851	123	2.08
Average	**12378.5**	**8524.4**	**134.9**	**850**	**123**	**2.05**
Stand. Dev.	**523.9**	**446.7**	**17.4**	**36.0**	**5.2**	**0.05**
Coef. of Var.	**4.2**	**5.2**	**12.9**	**4.2**	**4.2**	**2.3**



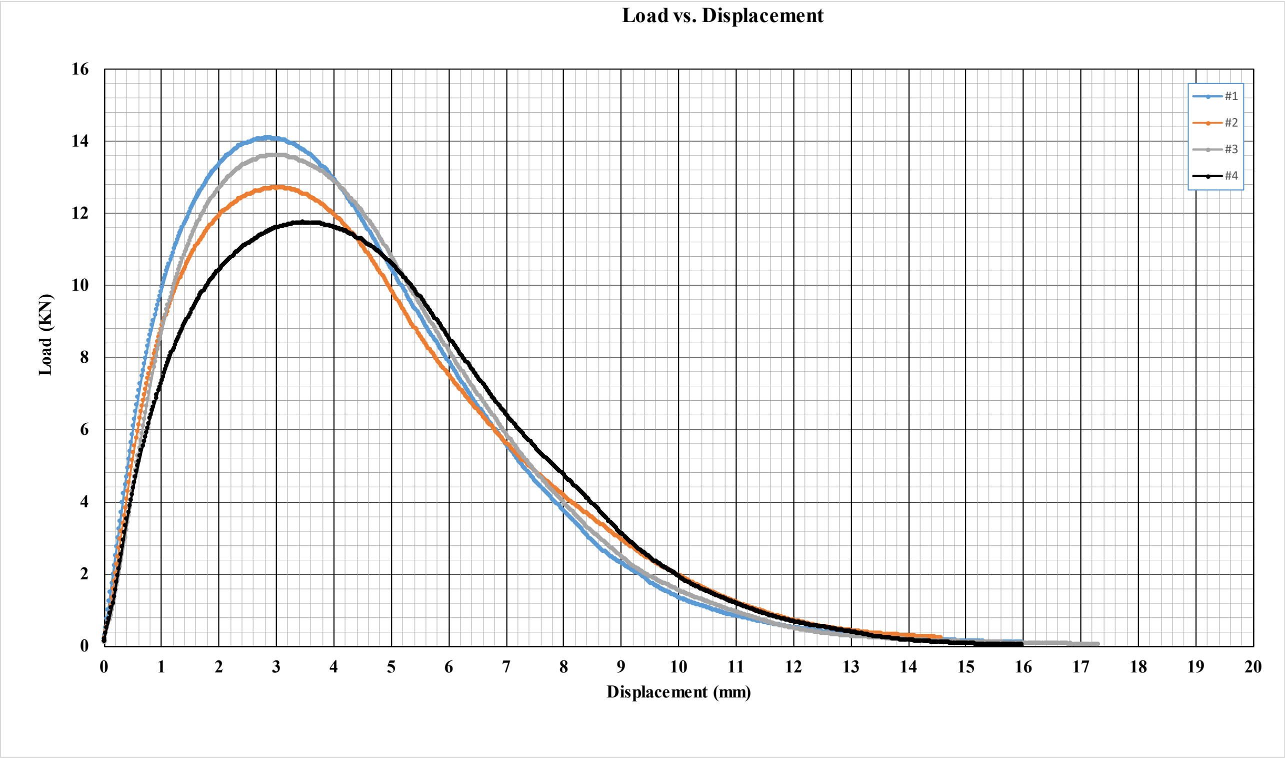
MIX CODE
39

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	12842.9	8138.4	112.0	883	128	1.92
IDEAL 2	13383.2	9165.5	140.2	921	134	1.89
IDEAL 3	13098.4	9497.5	150.7	900	130	2.10
IDEAL 4	13844.3	9444.2	110.6	951	138	1.91
Average	**13292.2**	**9061.4**	**128.4**	**914**	**133**	**1.96**
Stand. Dev.	**429.1**	**632.3**	**20.2**	**29.1**	**4.2**	**0.10**
Coef. of Var.	**3.2**	**7.0**	**15.7**	**3.2**	**3.2**	**4.9**



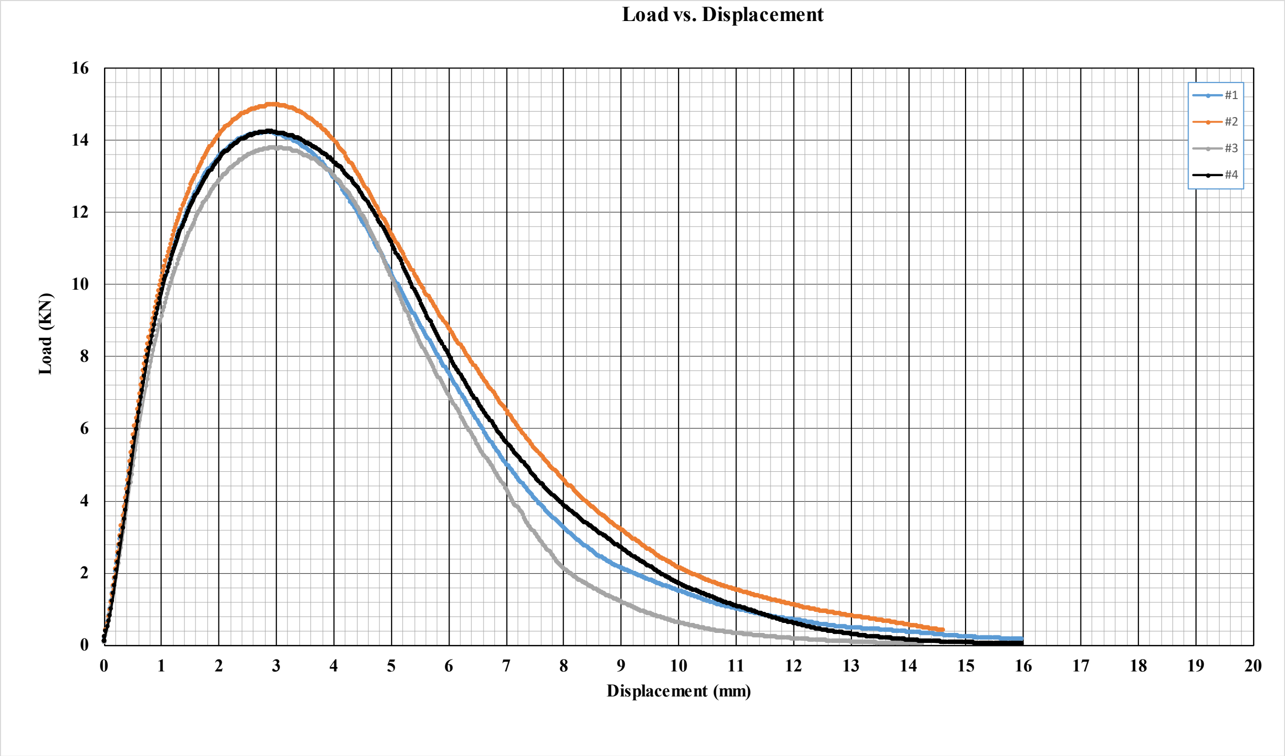
MIX CODE
40

Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	14092.9	9151.8	113.3	966	140	1.92
IDEAL 2	12716.9	8813.2	122.6	873	127	1.97
IDEAL 3	13619.0	9022.8	119.5	935	136	1.97
IDEAL 4	11747.5	8589.0	151.6	805	117	2.31
Average	**13044.1**	**8894.2**	**126.7**	**895**	**130**	**2.04**
Stand. Dev.	**1035.8**	**246.7**	**17.0**	**71.2**	**10.3**	**0.18**
Coef. of Var.	**7.9**	**2.8**	**13.4**	**7.9**	**7.9**	**8.8**



MIX CODE
42

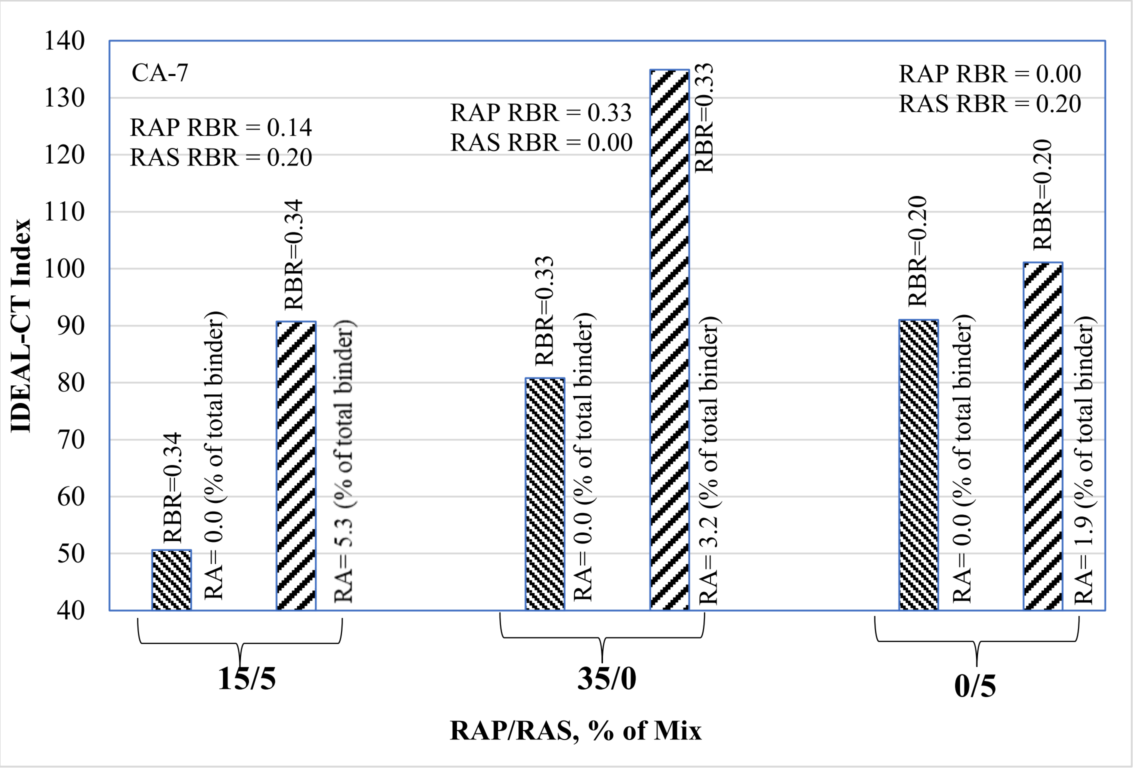
Specimen	Peak Load (N)	Fracture Energy (J/m^2)	IDEAL-CT Index	Peak Tensile Stress (KPa)	Peak Tensile Stress (PSI)	Strain at Peak Stress (%)
IDEAL 1	14220.2	9066.8	100.9	973	141	1.91
IDEAL 2	14982.9	10292.9	124.5	1027	149	1.97
IDEAL 3	13795.3	8130.8	74.6	944	137	2.06
IDEAL 4	14244.9	9340.6	105.2	974	141	1.91
Average	**14310.8**	**9207.8**	**101.3**	**980**	**142**	**1.96**
Stand. Dev.	**493.3**	**889.8**	**20.5**	**34.6**	**5.0**	**0.07**
Coef. of Var.	**3.4**	**9.7**	**20.3**	**3.5**	**3.5**	**3.5**

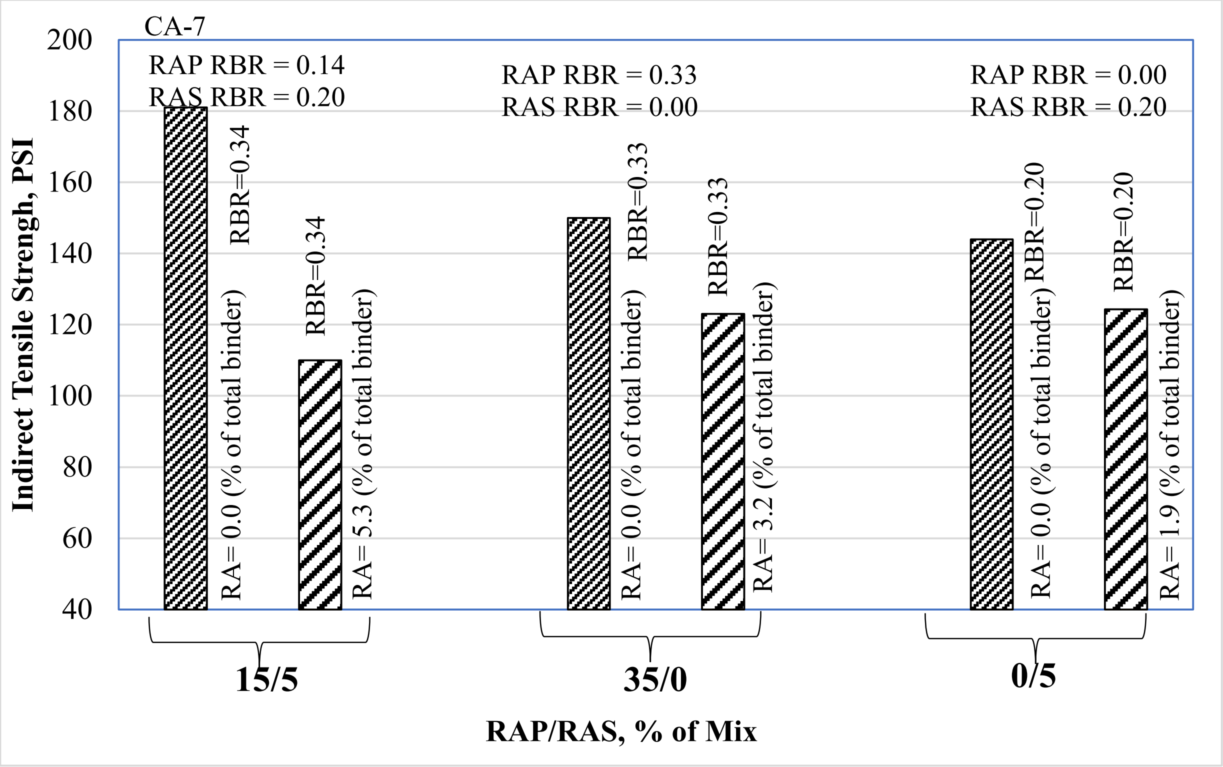


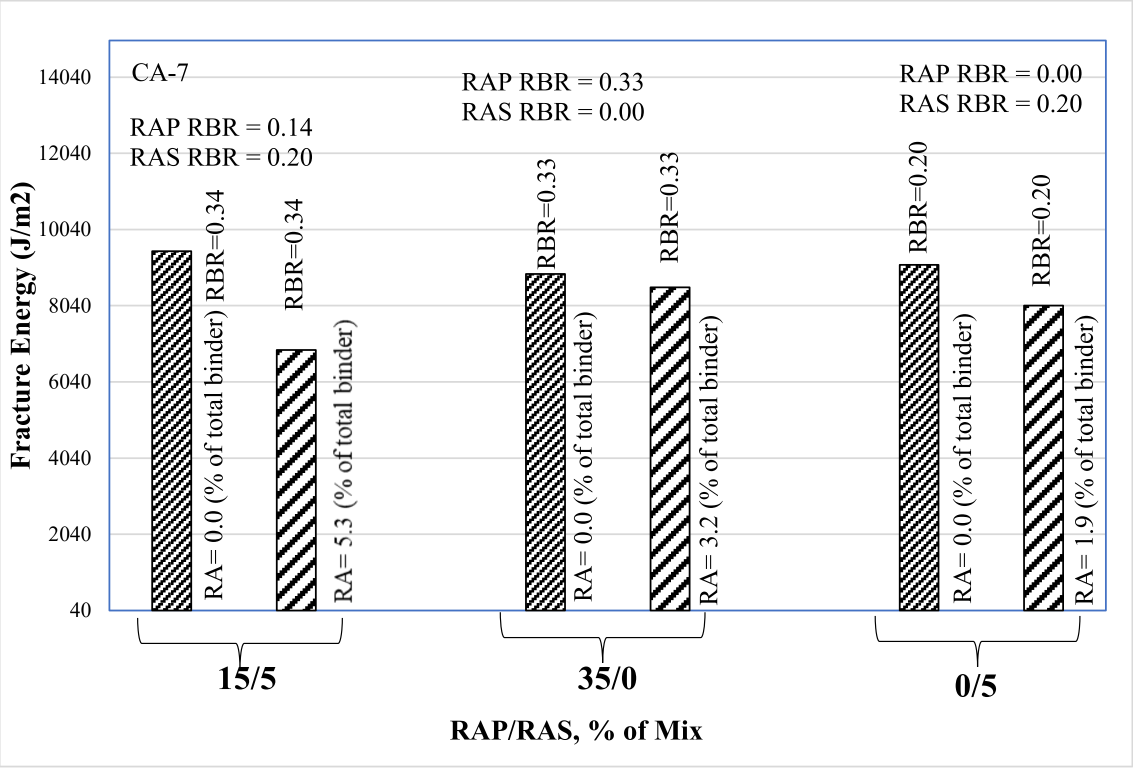
APPENDIX F

Results from IDEAL-CT Index Test: Comparison Graphs

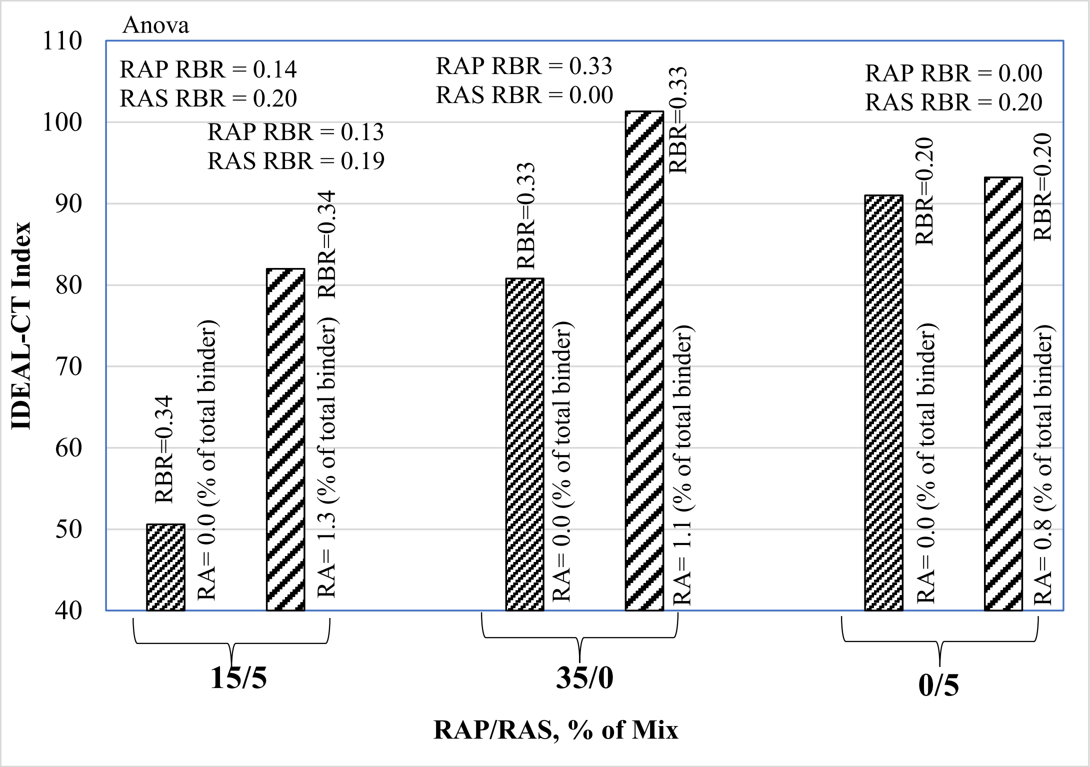
Ingevity

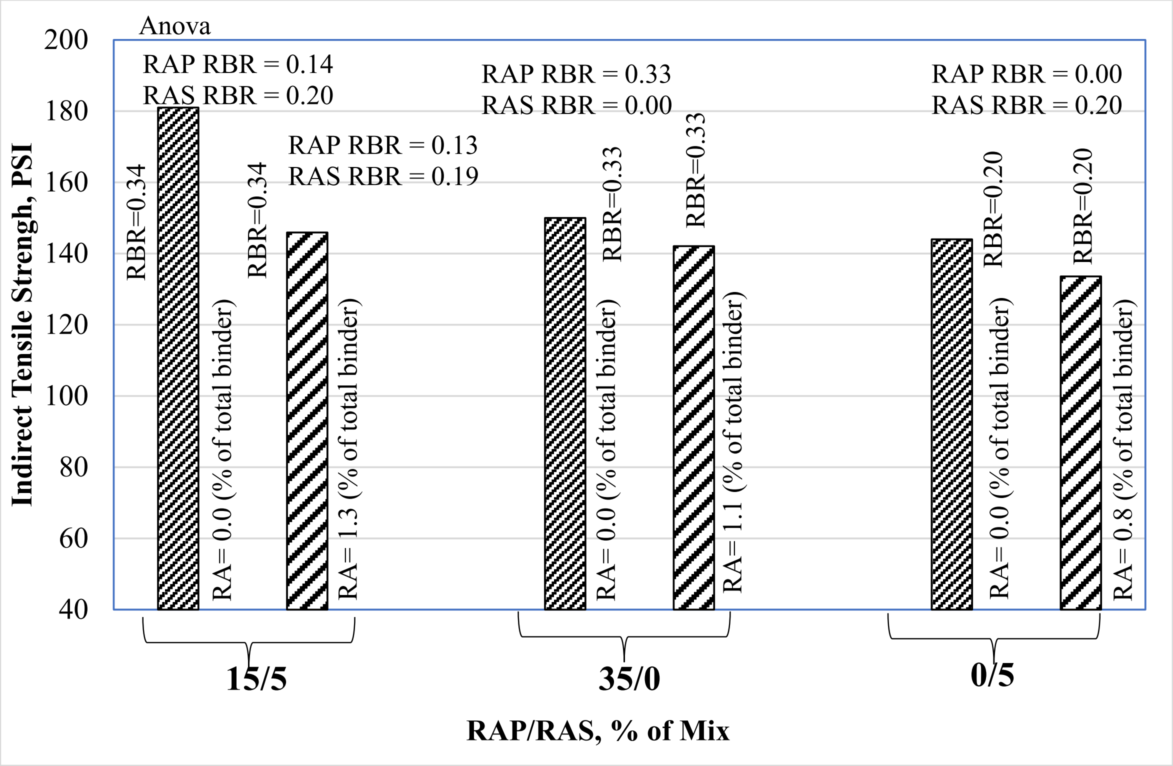

CA-7
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
IDEAL-CT Index
140
130
120
110
100
90
80
70
60
50
40
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 5.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 3.2 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 1.9 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix

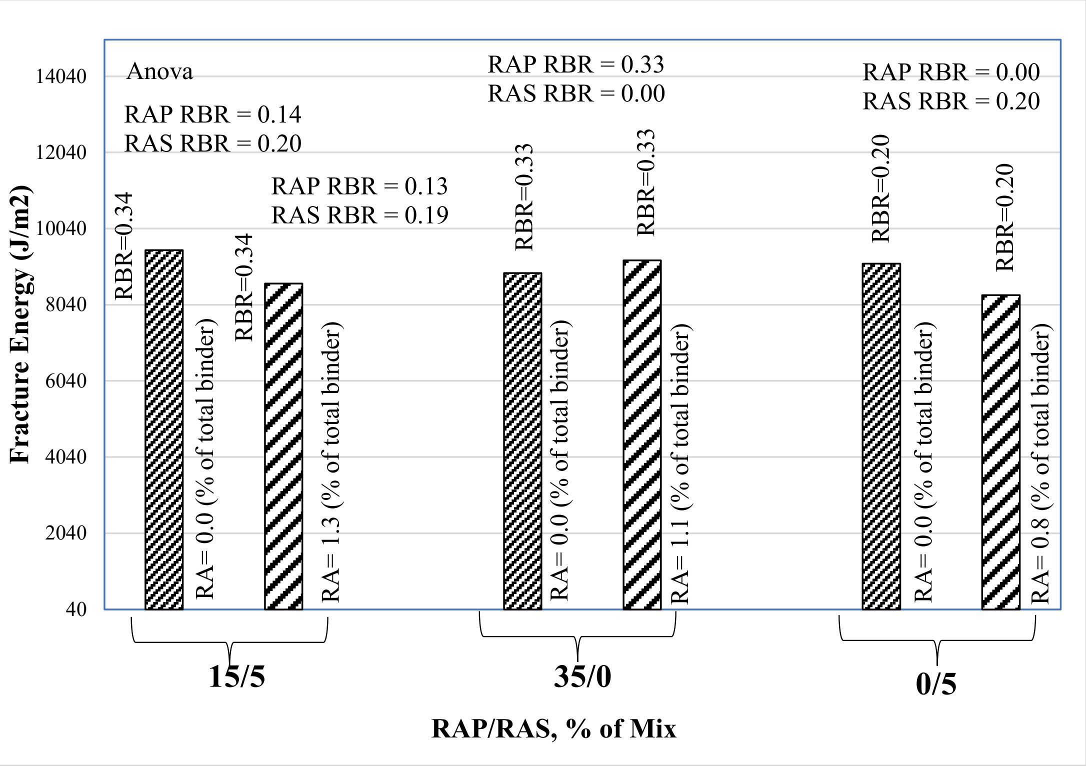

CA-7
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
Indirect Tensile Strengh, PSI
200
180
160
140
120
100
80
60
40
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 5.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 3.2 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 1.9 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix


CA-7
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 5.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 3.2 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 1.9 (% of total binder)
Fracture Energy (J/m2)
14040
12040
10040
8040
6040
4040
2040
40
15/5
35/0
0/5
RAP/RAS, % of Mix

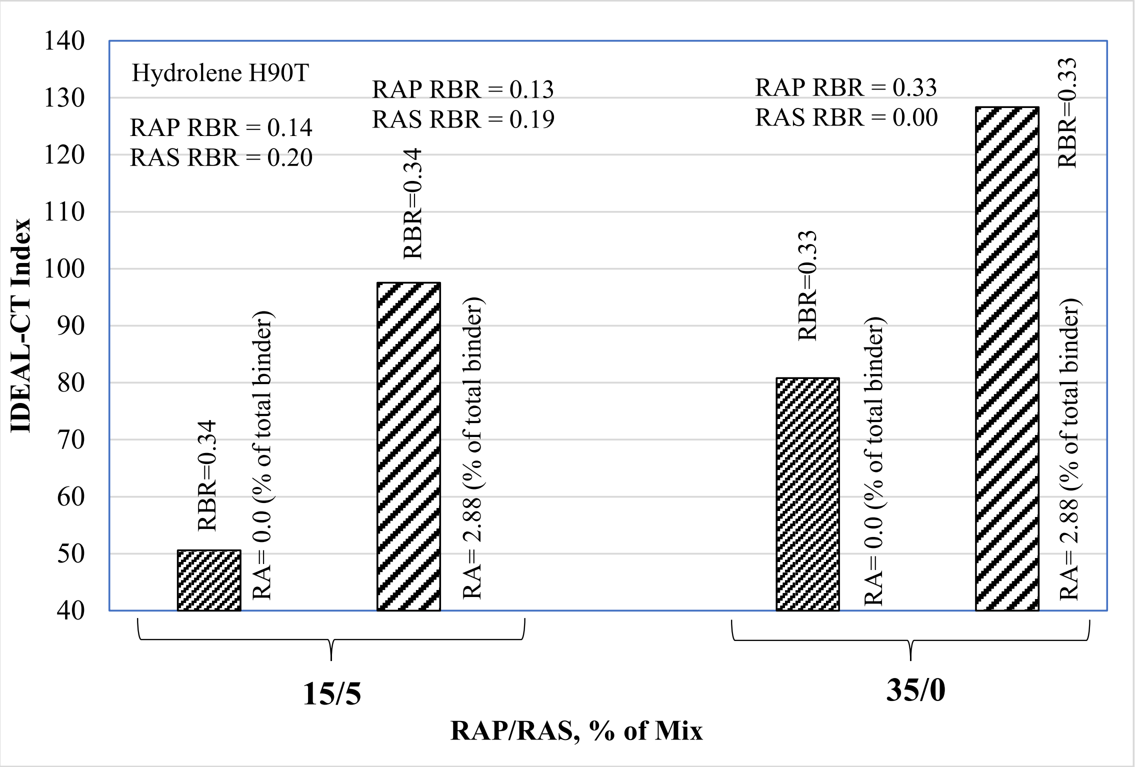
CARGILL:

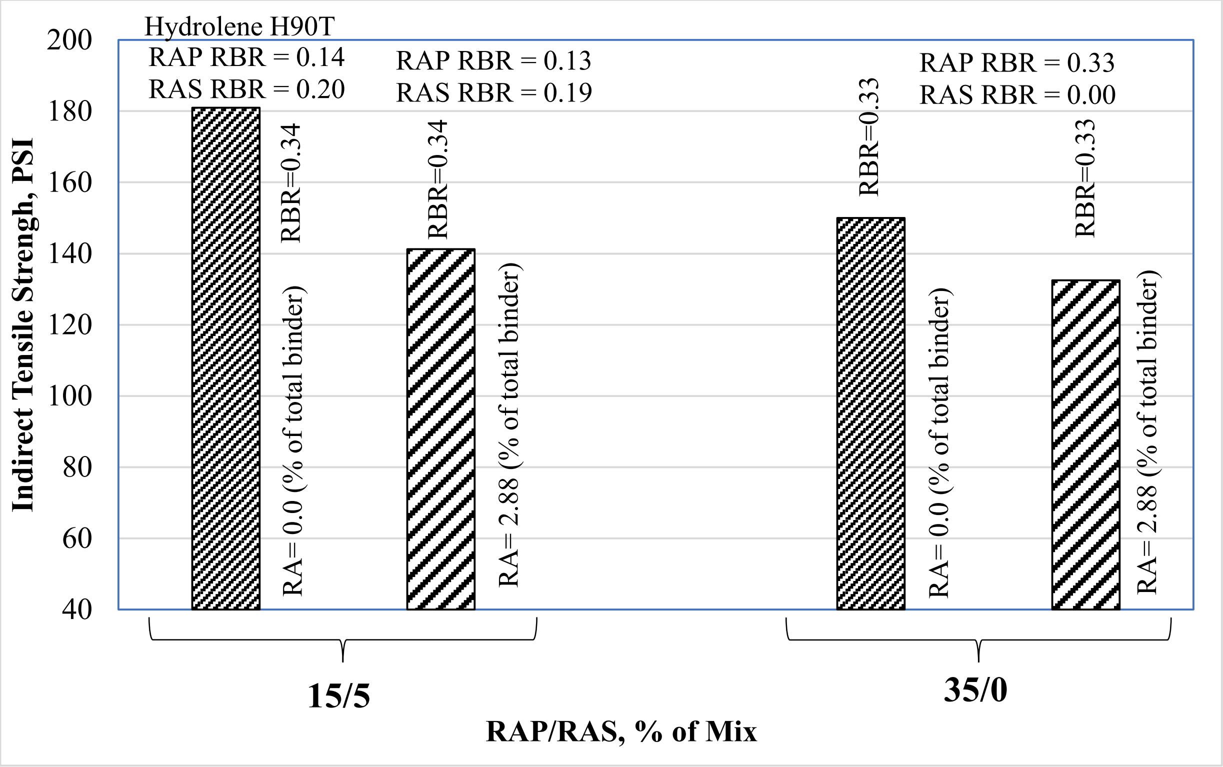

Anova
IDEAL-CT Index
110
100
90
80
70
60
50
40
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 1.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 0.8 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix

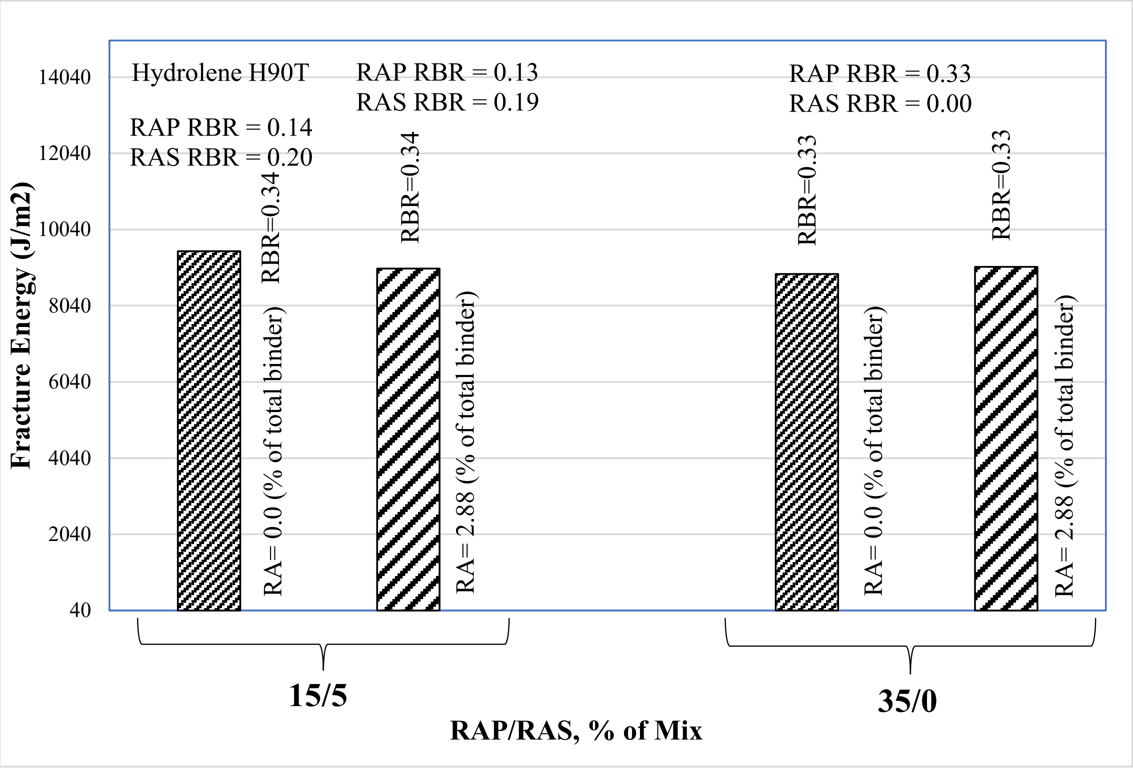

Anova
Indirect Tensile Strengh, PSI
200
180
160
140
120
100
80
60
40
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 1.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 0.8 (% of total binder)
15/5
35/0
0/5
RAP/RAS, % of Mix


Anova
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.33
RAS RBR = 0.00
RAP RBR = 0.00
RAS RBR = 0.20
RBR=0.34
RA= 0.0 (% of total binder)
RBR=0.34
RA= 1.3 (% of total binder)
RBR=0.33
RA= 0.0 (% of total binder)
RBR=0.33
RA= 1.1 (% of total binder)
RBR=0.20
RA= 0.0 (% of total binder)
RBR=0.20
RA= 0.8 (% of total binder)
Fracture Energy (J/m2)
14040
12040
10040
8040
6040
4040
2040
40
15/5
35/0
0/5
RAP/RAS, % of Mix

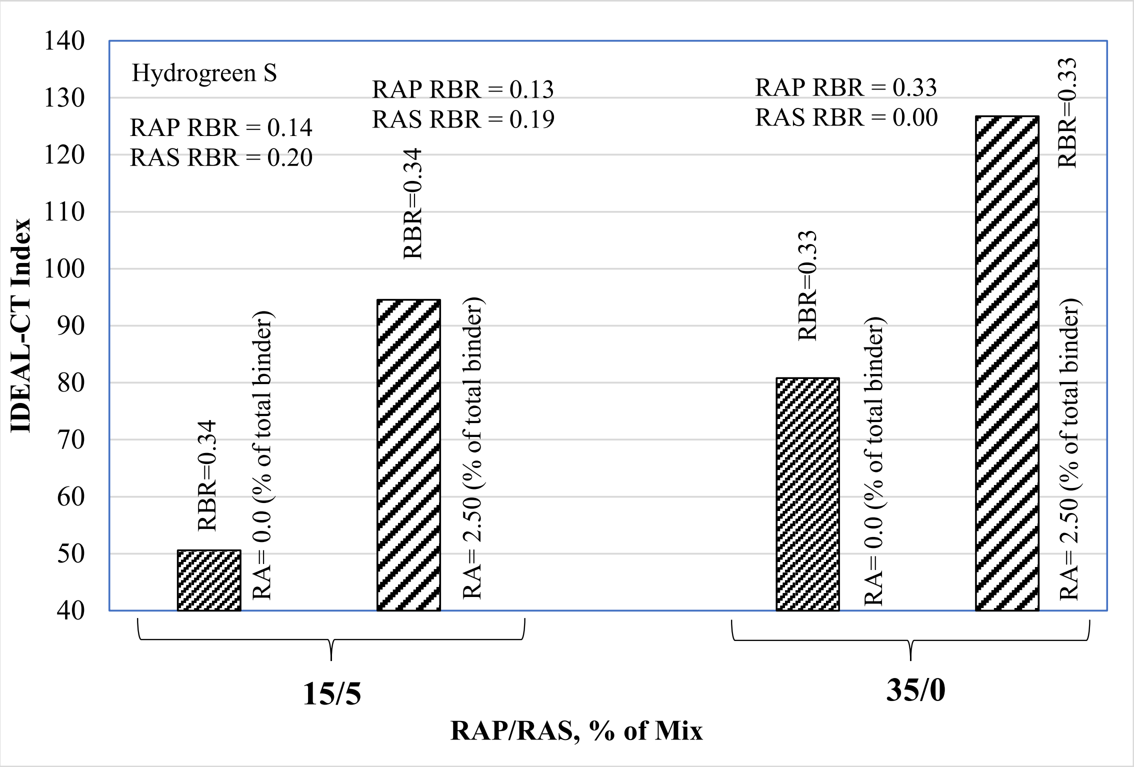
Holly Frontier:

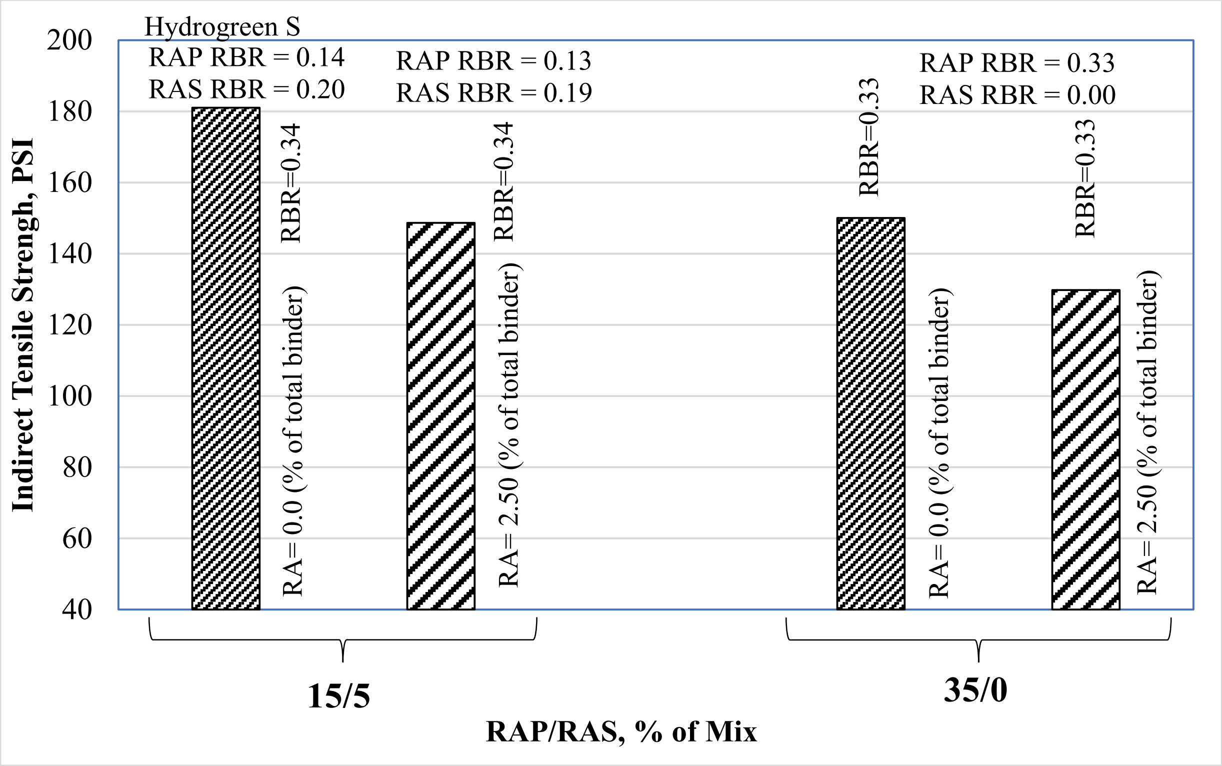


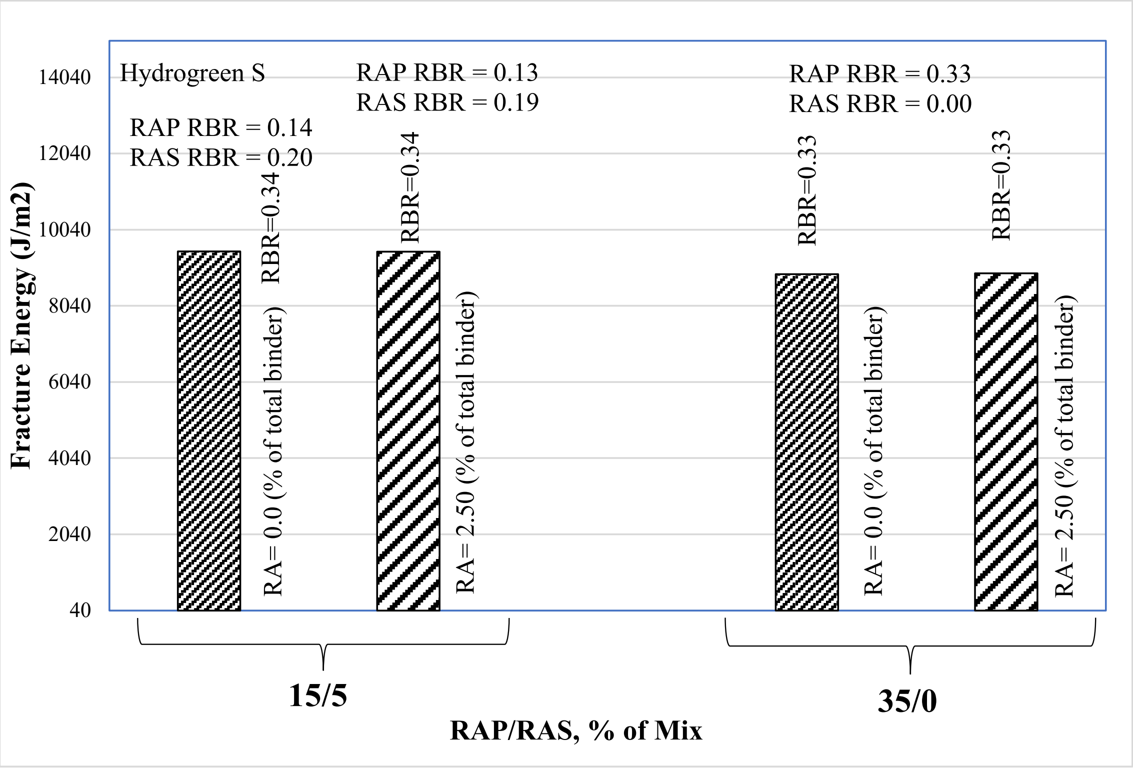



Hydrolene H90T
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.33
RAS RBR = 0.00
RBR=0.34
RBR=0.34
RBR=0.33
RBR=0.33
RA= 0.0 (% of total binder)
RA= 2.88 (% of total binder)
RA= 0.0 (% of total binder)
RA= 2.88 (% of total binder)
Fracture Energy (J/m2)
14040
12040
10040
8040
6040
4040
2040
40
15/5
35/0
RAP/RAS, % of Mix

Green Asphalt Tech:



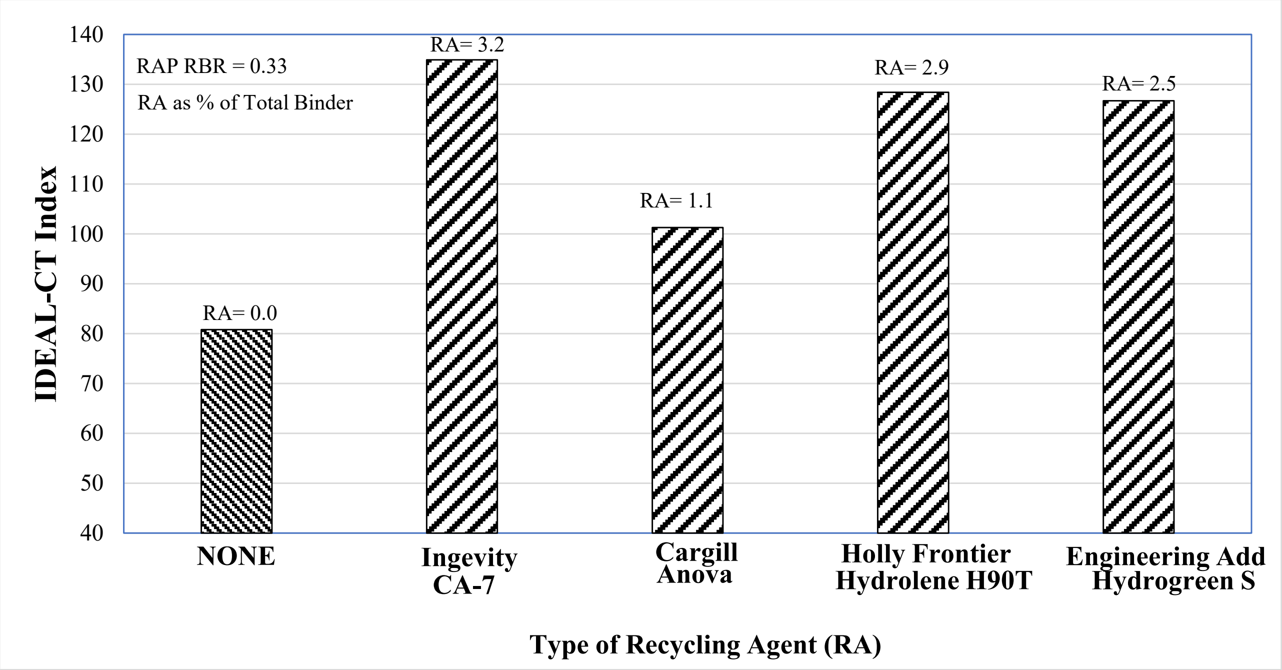


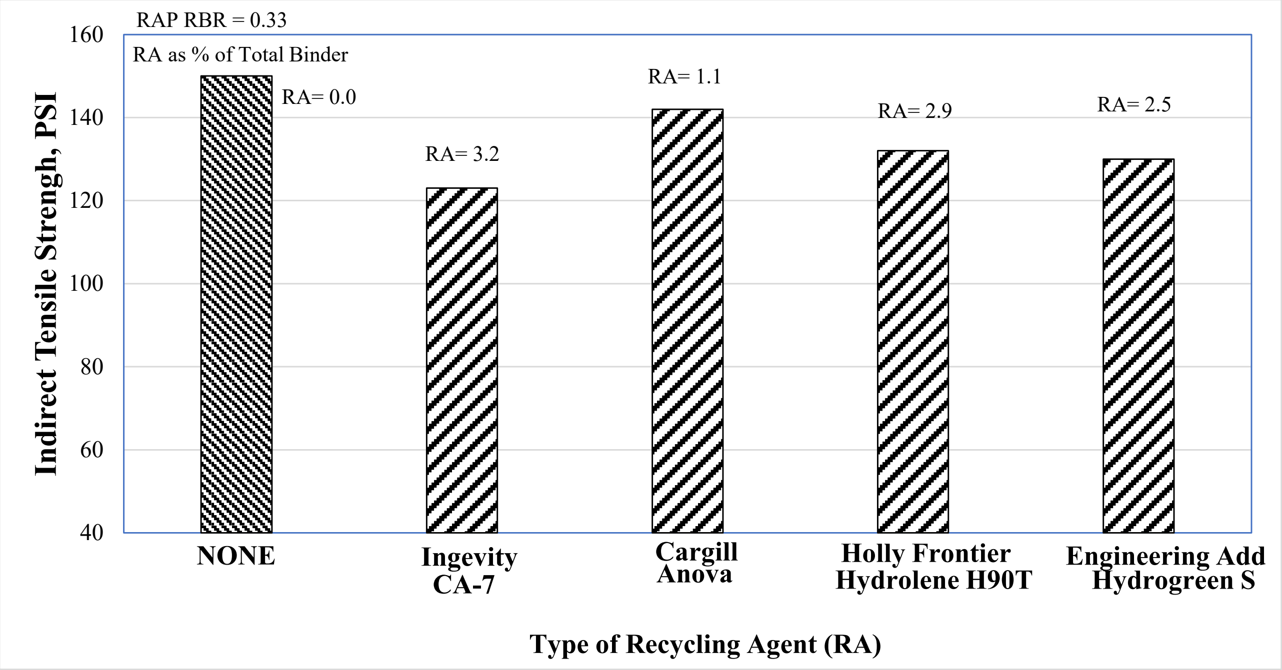

Hydrogreen S
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RAP RBR = 0.33
RAS RBR = 0.00
RBR=0.34
RBR=0.34
RBR=0.33
RBR=0.33
RA= 0.0 (% of total binder)
RA= 2.50 (% of total binder)
RA= 0.0 (% of total binder)
RA= 2.50 (% of total binder)
Fracture Energy (J/m2)
14040
12040
10040
8040
6040
4040
2040
40
15/5
35/0
RAP/RAS, % of Mix

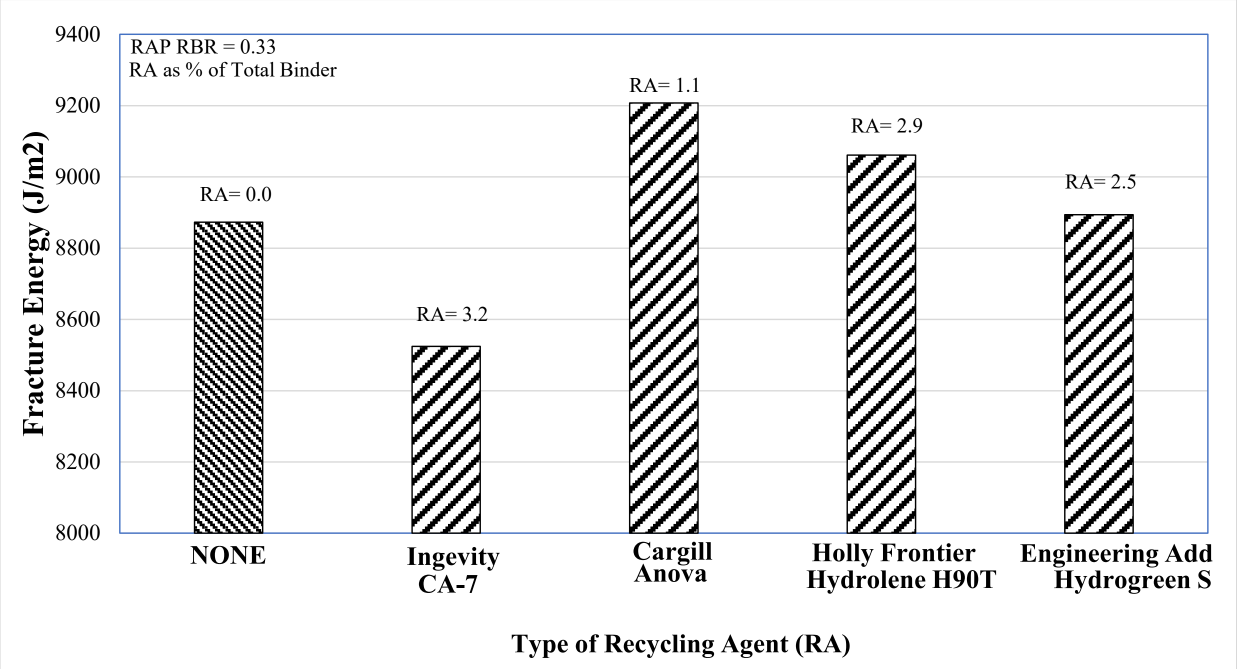
IDEAL Test comparison charts:

Comparing across the rejuvenator type for the same RAP/RAS content.

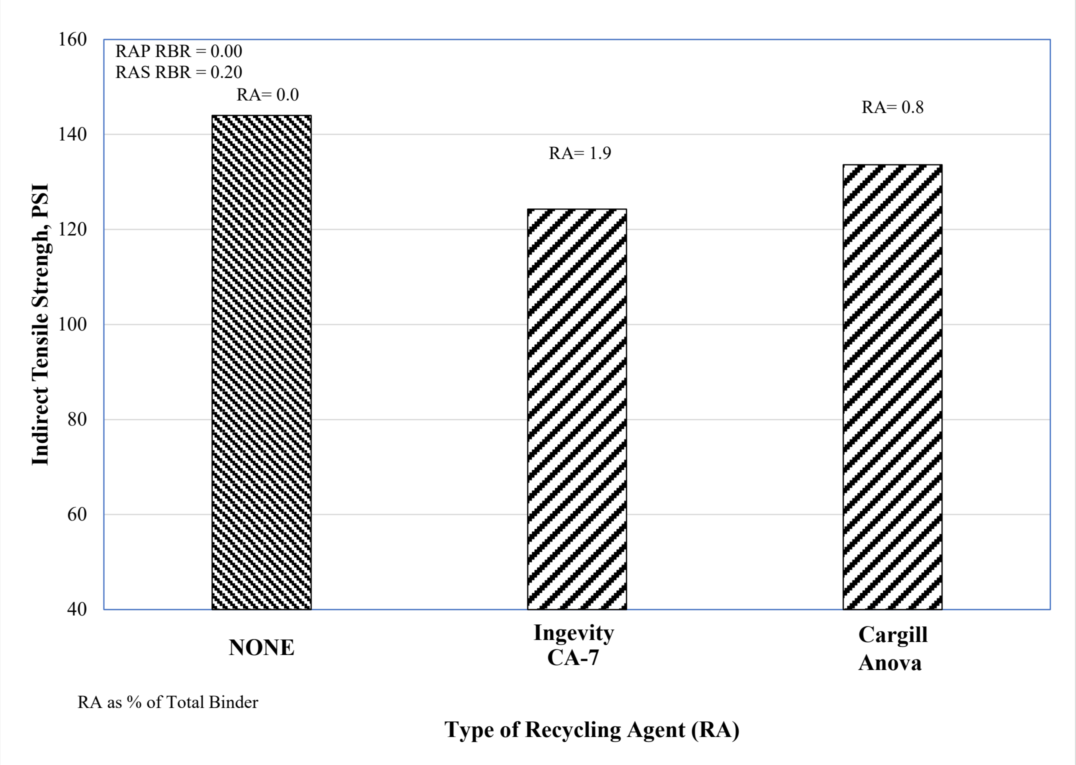
35/0% RAP/RAS:

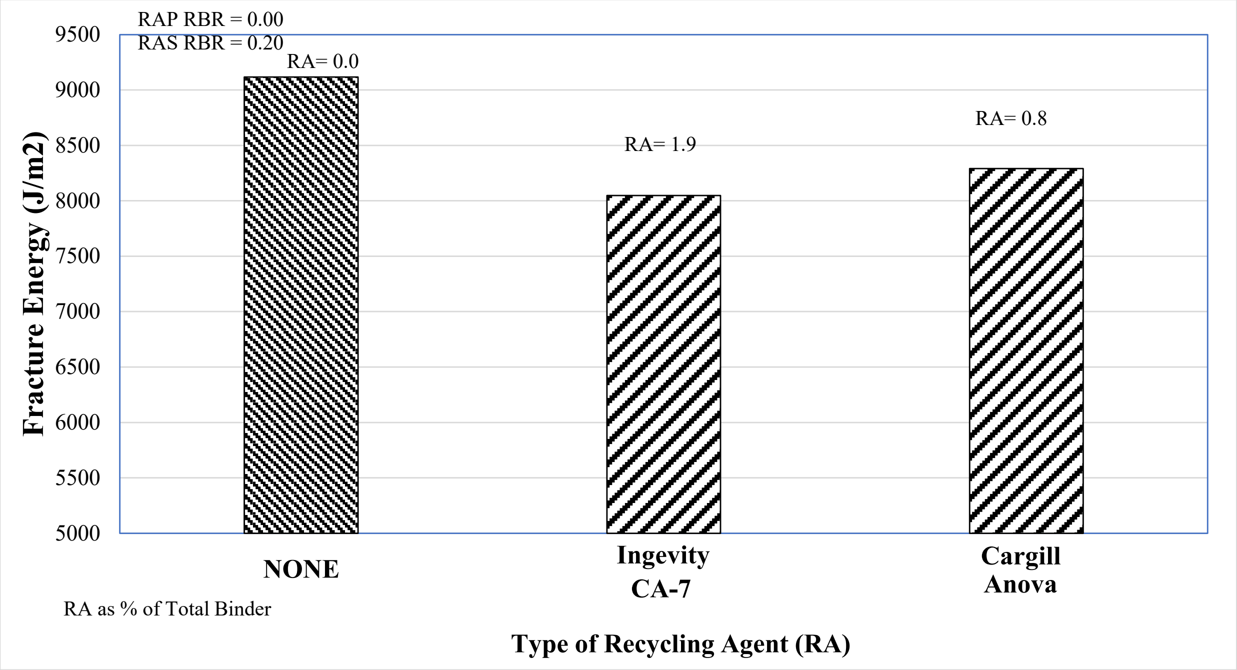


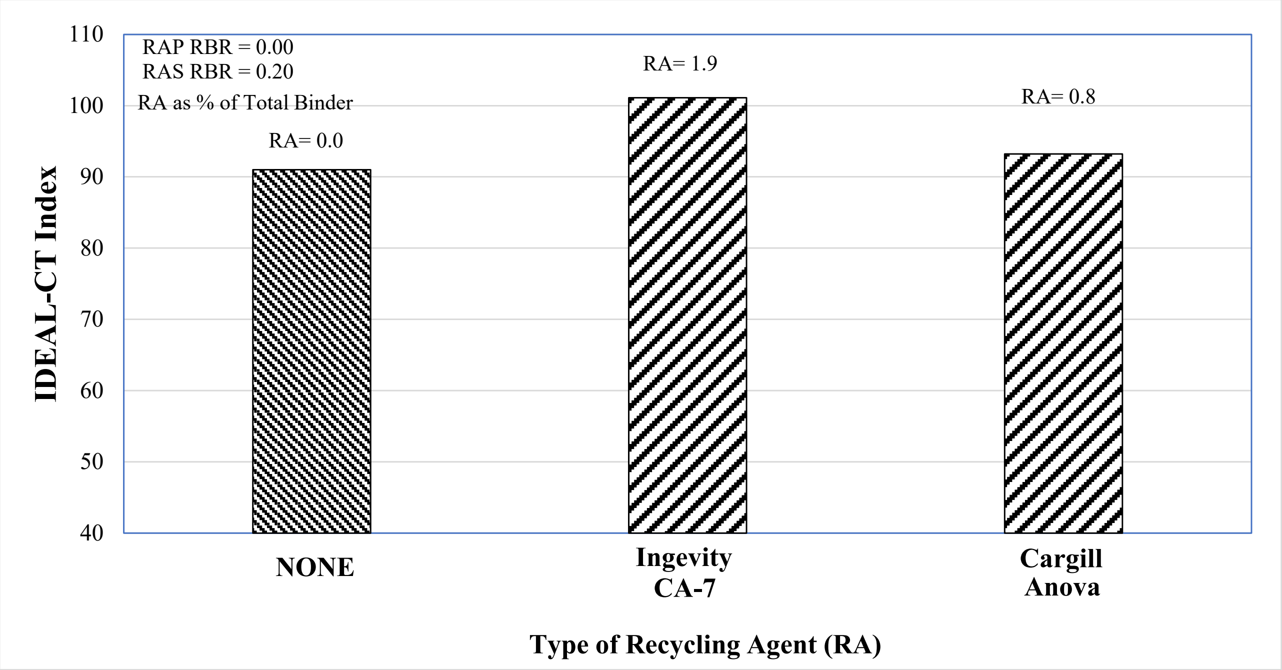



RAP RBR = 0.33
RA as % of Total Binder
RA= 0.0
RA= 3.2
RA= 1.1
RA= 2.9
RA= 2.5
9400
9200
9000
8800
8600
8400
8200
8000
Fracture Energy (J/m2)
NONE
Ingevity CA-7
Cargill Anova
Holly Frontier Hydrolene H90T
Engineering Add Hydrogreen S
Type of Recycling Agent (RA)

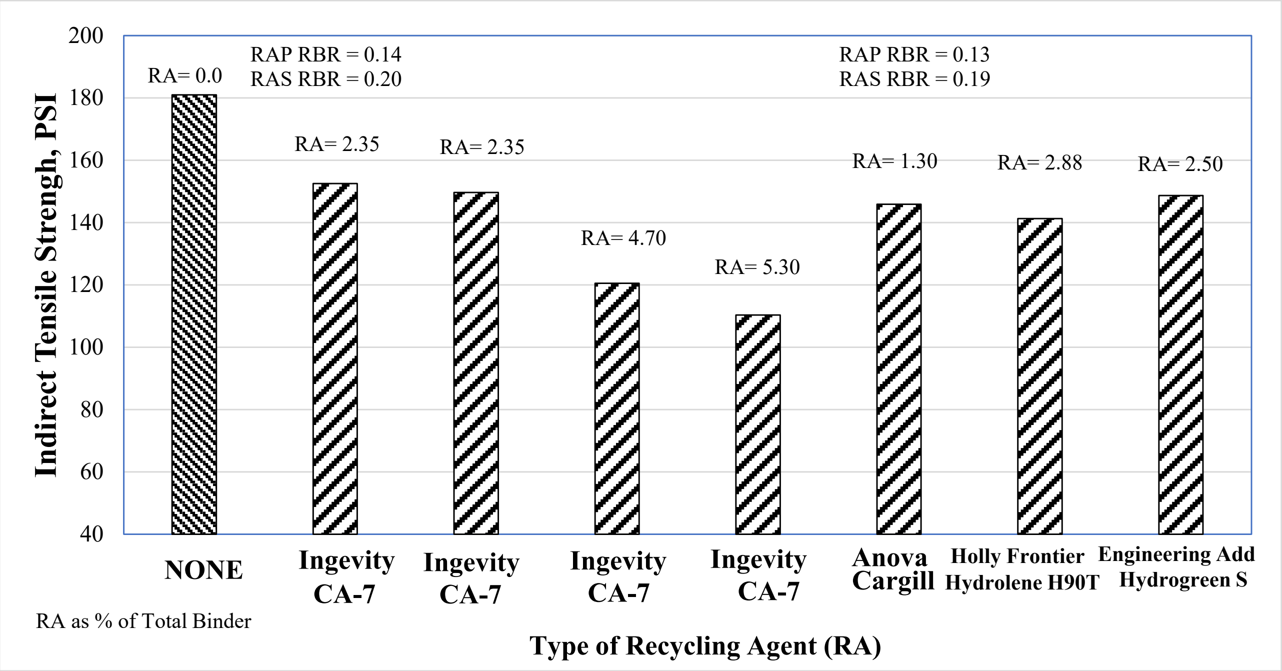
0/5 % RAP/RAS:

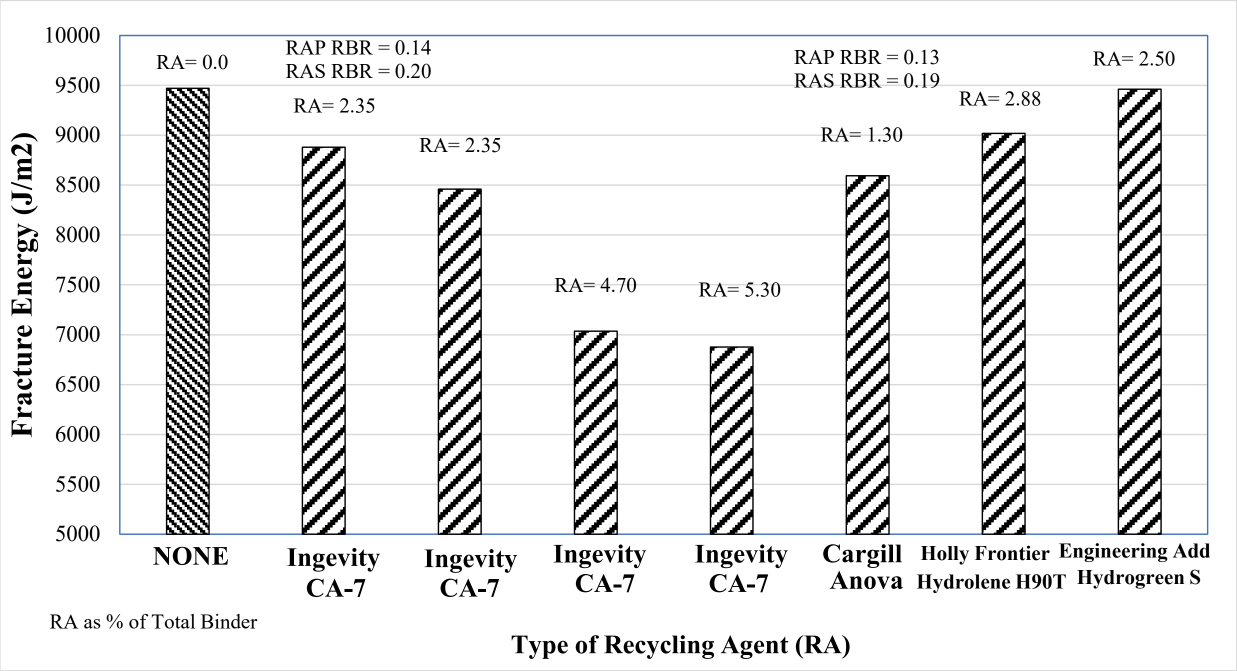

RAP RBR = 0.00
RAS RBR = 0.20
RA= 0.0
RA= 1.9
RA= 0.8
160
140
120
100
80
60
40
Indirect Tensile Strength, PSI
NONE
Ingevity CA-7
Cargill Anova
RA as % of Total Binder
Type of Recycling Agent (RA)


RAP RBR = 0.00
RAS RBR = 0.20
RA= 0.0
RA= 1.9
RA= 0.8
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
Fracture Energy (J/m2)
NONE
Ingevity CA-7
Cargill Anova
RA as % of Total Binder
Type of Recycling Agent (RA)

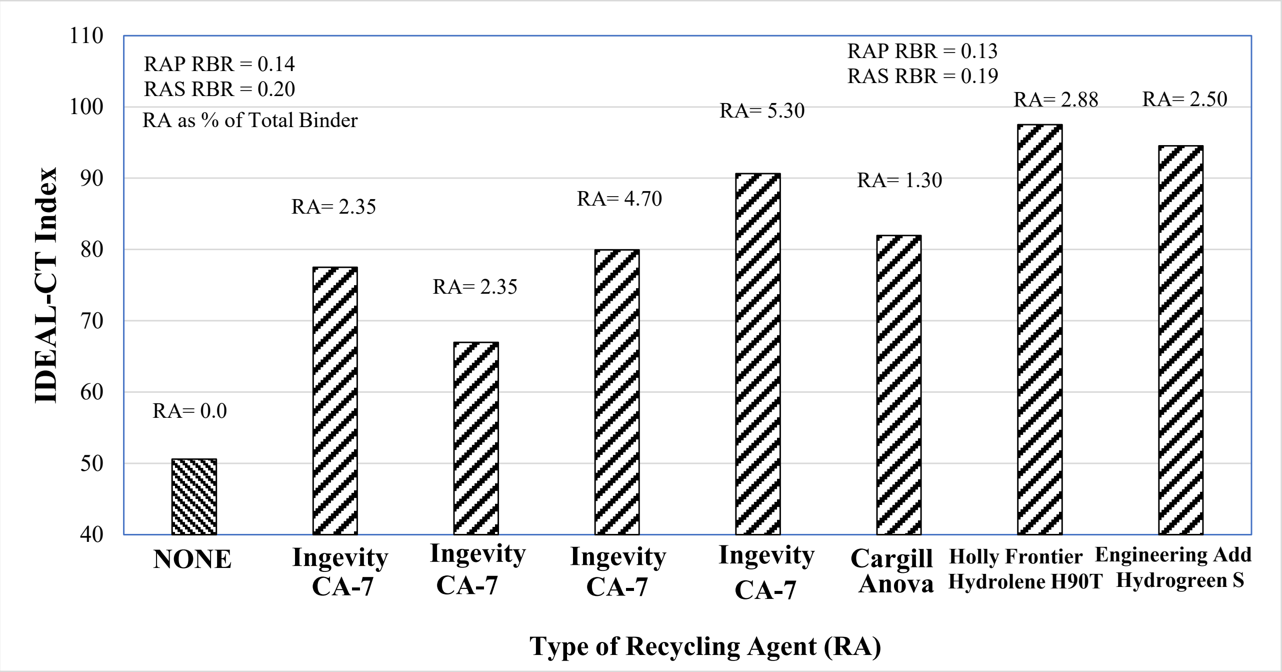

110
100
90
80
70
60
50
40
IDEAL-CT Index
RAP RBR = 0.00
RAS RBR = 0.20
RA as % of Total Binder
RA= 0.0
RA= 1.9
RA= 0.8
NONE
Ingevity CA-7
Cargill Anova
Type of Recycling Agent (RA)

15/5 % RAP/ RAS:


200
180
160
140
120
100
80
60
40
Indirect Tensile Strengh, PSI
RA= 0.0
RAP RBR = 0.14
RAS RBR = 0.20
RAP RBR = 0.13
RAS RBR = 0.19
RA= 2.35
RA= 2.35
RA= 4.70
RA= 5.30
RA= 1.30
RA= 2.88
RA= 2.50
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Anova Cargill
Holly Frontier Hydrolene H90T
Engineering Add Hydrogreen S
RA as % of Total Binder
Type of Recycling Agent (RA)



10000
9500
9000
8500
8000
7500
7000
6500
6000
5500
5000
Fracture Energy (J/m2)
RA= 0.0
RAP RBR = 0.14
RAS RBR = 0.20
RA= 2.35
RA= 2.35
RA= 4.70
RA= 5.30
RAP RBR = 0.13
RAS RBR = 0.19
RA= 1.30
RA= 2.88
RA= 2.50
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Cargill Anova
Holly Frontier Hydrolene H90T
Engineering Add Hydrogreen S
RA as % of Total Binder
Type of Recycling Agent (RA)



110
100
90
80
70
60
50
40
IDEAL-CT Index
RAP RBR = 0.14
RAS RBR = 0.20
RA as % of Total Binder
RAP RBR = 0.13
RAS RBR = 0.19
RA= 5.30
RA= 2.88
RA= 2.50
RA= 2.35
RA= 4.70
RA= 1.30
RA= 2.35
RA= 0.0
NONE
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Ingevity CA-7
Cargill Anova
Holly Frontier Hydrolene H90T
Engineering Add Hydrogreen S
Type of Recycling Agent (RA)