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RESEARCH REPORT

Developing Recommendations for Allowable RAP Contents in Idaho Asphalt Mixes

RP 269

By

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16. Abstract

This research study focused on evaluating the effects of high recycled Asphalt Pavement (RAP) contents on asphalt mix performance. Until recently, the Idaho Transportation Department (ITD) did not impose any restriction on the amount of RAP allowed in an asphalt mix. As a result, pavement sections were constructed in Idaho with up to 54 percent RAP (by binder replacement). Some industry and DOT staff raised concerns regarding this practice. Subsequently, ITD placed a temporary limit of 30 percent as the maximum allowable RAP content in a mix. However, to find a permanent answer to this question, the current research study was initiated in collaboration with Boise State University, and later with Oklahoma State University. Extensive review of published literature was carried out on the effects of high RAP contents on asphalt mixture performance. A survey of state DOTs was carried out to gather information regarding their current practices with respect to maximum allowable RAP contents. Extensive laboratory testing was performed to assess the cracking resistance of different asphalt mixtures collected from across Idaho with varying RAP contents. Recommendations have been provided to help ITD adopt a systematic approach to facilitate the design of and construction with asphalt mixtures with high RAP contents.

17. Key Words
reclaimed asphalt pavements, asphalt mixtures, recycled materials

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Technical Advisory Committee

Each research project is overseen by a Technical Advisory Committee (TAC), which is led by an ITD project sponsor and project manager. The TAC is responsible for monitoring project progress, reviewing deliverables, ensuring that study objectives are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

- Project Sponsor: John P. Bilderback, P.E.
- Project Manager: John P. Bilderback, P.E.
- TAC Members:

  Mike Santi, P.E. (retired)

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  Idaho Associated General Contractors
- FHWA-Idaho Advisor: Kyle Holman, P.E.

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List of Abbreviations and Acronyms

ABR	Asphalt Binder Replacement
ALF	Accelerated Loading Facility
ACHD	Ada County Highway District
DCT	Disc-Shaped Compact Tension
DOT	Department of Transportation
HMA	Hot-Mix Asphalt
FHWA	Federal Highway Administration
IDT	Indirect Tensile Test
IDOT	Illinois Department of Transportation
ITD	Idaho Transportation Department
I-FIT	Illinois Flexibility Index Test
NMAS	Nominal Maximum Aggregate Size
TAC	Technical Advisory Committee
RAP	Recycled Asphalt Pavement
SCB	Semi-Circular Bending
FI	Flexibility Index
PAV	Pressure Aging Vessel
QC/QA	Quality Control / Quality Assurance
RAS	Recycled Asphalt Shingle
SBS	Styrene-Butadine-Styrene
SCB	Semi-Circular Bending
SHRP	Strategic Highway Research Program
TOL	Texas Overlay Test
TSR	Tensile Strength Ratio
U.S.	United States
VMA	Voids in Mineral Aggregates
VFA	Voids Filled with Asphalt

WMA	Warm-Mix Asphalt

Executive Summary

The use of Reclaimed (or Recycled) Asphalt Pavements (RAP) in asphalt mixtures is a sustainable approach that has caught a lot of attention over the years. Asphalt pavement is the most recycled material in the world. Existing/old pavement structures are usually milled, and the millings are fractionated into certain size fractions constituting RAP. RAP can be incorporated into the asphalt mix just like an aggregate.

The primary difference between conventional aggregates used in an asphalt mix, and RAP is that the RAP is coated with binder; when the RAP is heated, a certain portion of that binder is available to be used in the asphalt mix. Another major difference between conventional (virgin) aggregates and RAP aggregates is that asphalt absorption into the RAP aggregate has already taken place. Based on the amount of binder being released, the role of RAP in an asphalt mix can be mapped between two extremes. On one end, the RAP behaves like a "black rock", representing the scenario where RAP only plays a role to replace part of the virgin aggregates. It is assumed that heating of the RAP does not result in any significant release of binder, and therefore, the binder content of the virgin mix is not altered by the presence of the RAP. This scenario may occur in the case of highly aged RAP where the binder is very stiff and is not released from the RAP during mixing with the virgin aggregates. The other extreme represents a case, where all the effective binder in the RAP gets released upon heating, and blends with the virgin binder in the new mix. In other words, the amount of virgin binder added to the new mix can be reduced to account for the binder contribution from the RAP. In reality, the role of RAP in an asphalt mix lies somewhere between these two extremes; the binder released from the RAP into the new mix is greater than zero, but less than 100 percent (although research has shown that the number may be close to 100 percent in some cases).

Although the exact quantity of binder being released from RAP into the new mix is not unanimously agreed upon, the fact that the presence of RAP can significantly affect mix performance, remains unchallenged. As RAP is obtained from an old/existing pavement section, it has likely been subjected to prolonged periods of weathering and oxidation. Accordingly, the binder present in RAP is usually significantly more "hardened" compared to its original state during mix production. This hardened binder, when mixed with virgin binder (irrespective of the proportion), can significantly affect the engineering properties of the mix. Theoretically, engineering properties of the resultant mix lie somewhere between the two extremes of: (1) a mix produced by using the virgin binder only; and (2) a mix produced by only using the hardened binder (released from RAP).

To ensure adequate performance of a pavement section, it is important the asphalt mix being used has adequate resistance to rutting as well as cracking (along with other desirable properties like workability, etc.). When an asphalt mix is produced incorporating RAP, it is important to carefully monitor the effect of the RAP on the mixture's rutting and cracking behavior. Common sense would dictate that presence of the stiff binder being released from RAP would make a mix more resistant to rutting (stiffer binders lead to increased rut resistance). However, the increased binder stiffness due to the presence of RAP can also lead to increased crack-susceptibility. Under such circumstances, the mix may experience premature cracking, both load-related as well as climate-related. Therefore, even though the incorporation of RAP into an asphalt mix can result in significant cost savings (due to reduction in the amount of virgin aggregates needed as well as reduction in the amount of binder required), it is not practical to produce a mix with 100 percent RAP. Such a mix will not have the required “flexibility” to resist cracking. Ideally, engineers and contractors would want to use as much RAP as possible to make use of the recycled materials and reduce landfill requirements. The balance must be between cost savings due to the use of recycled materials and the adverse impact (if any) that RAP may have on mix properties. To address this critical issue, most state and local highway agencies follow well-defined specifications governing the amount of RAP allowed in an asphalt mix. This technical report documents findings from a research effort undertaken in collaboration with the Idaho Transportation Department (ITD) to clearly establish specifications with respect to RAP usage in an asphalt mix.

ITD has gone through different phases with respect to the use of RAP in an asphalt mix. When ITD first adopted the Superpave mix design approach, no RAP was allowed in asphalt mixes. Subsequently, at one point in time, there was no limit to the amount of RAP allowed in a mix. This resulted in asphalt mixes produced with RAP quantities as high as 54 percent in terms of Asphalt Binder Replacement (ABR). The ABR represents the percentage of the binder in the new mix being replaced by the binder being released from the RAP. Although the use of such high RAP percentages can be an excellent practice in terms of environmental sustainability, there were some concerns regarding the effect this had on the resulting mix properties. There were concerns among ITD engineers that pavement sections constructed with such high RAP percentages were undergoing premature cracking. On the other hand, the contracting community argued that the premature cracking should not be solely attributed to the presence of high RAP. This led to the conception of the current research effort that involved an extensive literature review on different practices with respect to the amount of RAP allowed in asphalt mixtures. This was supported by a nation-wide survey of highway agencies regarding their practices with respect to the usage of RAP in asphalt mixtures. Finally, extensive laboratory testing was carried out on asphalt mixes collected from different projects across the state of Idaho to evaluate the effects of RAP content on mixture cracking resistance. The primary cracking resistance test conducted was, the Illinois Flexibility Index Test, or I-FIT. Results from all these project tasks have been documented in different chapters of this report.

Based on the survey of state DOTs, it was observed that the maximum amount of RAP allowed in asphalt mixes by the responding agencies is usually around 30-35 percent. Most of the agencies expressed concerns about fatigue cracking of high-RAP mixtures. From the I-FIT testing carried out on different mixes collected from across Idaho, a generic trend of reduced (intermediate temperature) cracking resistance with increasing RAP content was observed. Extensive review of published literature also highlighted the benefits of diligent quality control of RAP stockpiles, particularly for mixtures with high RAP contents. This report provides ‘best-practices’ recommendations to ITD in case the threshold value of 30 percent is removed in the future, and ITD considers allowing greater percentages of RAP by asphalt binder replacement.

1. Introduction

Background

One of the primary sustainable design practices used in asphalt pavement construction involves the incorporation of Reclaimed Asphalt Pavement (RAP) into new asphalt mixtures. The asphalt industry has been reported to be the most ‘diligent recycler’ in the country, with more than 99 percent of RAP being put back to use (Williams et al., 2020). RAP can be incorporated into both Hot-Mix Asphalt (HMA) as well as Warm-Mix Asphalt (WMA). Moreover, RAP is often used to replace virgin aggregates in unbound aggregate base/subbase layers. Maintenance and rehabilitation of asphalt pavements typically involves removing one or more layers of existing asphalt pavement. The removed asphalt pavement is then reclaimed by crushing and screening to an appropriate size for use in a new asphalt mix. Virgin and RAP aggregates are both used to determine the mixture gradation and the percent of angular, flat, and elongated particles, etc. Similarly, both the virgin as well as RAP-derived binders contribute towards total binder content calculations. It should be noted that virgin aggregate refers to aggregate materials that are freshly obtained from a quarry or a pit and have not been previously used in any construction application. Similarly, virgin binder refers to fresh binder with no past usage.

During the design of asphalt mixtures comprising RAP, mix design calculations usually account for aggregate and binder replacement in the mix using either of the following two approaches: (1) RAP content expressed as percentage of total mix weight; or (2) Asphalt Binder Replacement (ABR) calculated as percent of RAP binder in total binder content of the mix. Incorporating RAP into asphalt mixes can reduce the demand for virgin aggregates. Similarly, the existing binder in the RAP mixes with the virgin binder, thus reducing the demand for virgin binder to achieve a target binder content for the mix. Reduced demand for virgin aggregates and binders can result in substantial energy and cost savings. Williams et al. (2020) reported that in 2019, the estimated RAP tonnage used in asphalt mixtures in the United States (U.S) was 89.2 million tons. This marked a nearly 8.5 percent increase compared to the number in 2018, and corresponded to 4.5 million tons (24 million barrels) of asphalt binder conserved, along with replacement of more than 84 million tons of aggregates. Reduction in demand for virgin aggregates is critical due to the ever-reducing amount of natural resources. Moreover, using the material generated by milling of old pavements leads to significant reductions in landfill space requirements. Therefore, the use of RAP in asphalt mixtures has multiple advantages, both from an economical as well as environmental sustainability point of view.

In the U.S., the Federal Highway Administration (FHWA) greatly encourages the use of RAP in asphalt mixtures. Extensive use of RAP in asphalt mixtures in the U.S. began in the 1970’s (McDaniel and Anderson, 2001). The original Superpave method of mix design, developed between 1987 and 1993, did not incorporate the use of RAP in asphalt mixtures. Therefore, initially this presented an obstacle to agencies who had adopted the Superpave method. Over the years, multiple research efforts have been undertaken to incorporate RAP into the Superpave mix design method. One of the most notable studies in this regard was NCHRP Project 9-12, titled “Incorporation of Reclaimed Asphalt Pavement in the

Superpave System" (McDaniel et al., 2000). Multiple subsequent studies have enabled asphalt producers to successfully incorporate RAP into HMA as well as WMA. The percentage of RAP plays an important role in governing pavement performance under traffic as well as environmental loading. Increasing RAP percentage can potentially have a negative impact on the durability of the pavement surface (Tran et al., 2012). As the binder released upon heating of RAP is stiffer compared to virgin binder, a higher percentage of RAP can lead to an increase in stiffness of the mix, which has the potential to eventually reduce the cracking resistance of the pavement. On the other hand, when it comes to rutting, presence of the stiffer binder from RAP in the mix improves the rut resistance of the resulting mix. Historically, most Departments of Transportation (DOTs) in the U.S. have preferred using 10 percent to 20 percent of RAP in a mix. Through constant effort at the federal as well as state level, and due to interest of the contractors, RAP usage in the U.S. has seen constant growth. From a survey of state practices in 2019, Williams et al. (2020) reported that the average percentage of RAP used in asphalt mixtures increased from 15.6 percent in 2009 to 21.1 percent in 2019. They also reported that the total amount of RAP usage in 2019 was equivalent to approximately $3.2 billion in cost savings through reduced demand for binder and virgin aggregates.

The advantages of incorporating RAP into asphalt mixtures have been widely recognized. At the same time multiple research studies have focused on evaluating whether there are detrimental effects associated with increased use of RAP in asphalt mixtures. The primary question to be addressed includes: *"What is the optimum amount of RAP that can be included in a new mix"?* Before RAP is successfully incorporated into mix, various design and production challenges must be overcome to ensure the resulting mix performs as well as, or better than a mix produced using virgin materials only. Some of the challenges associated with the design and production of asphalt mixes incorporating RAP have been presented in the following section.

Challenges

One challenge associated with RAP usage in HMA can be attributed to the multitude of sources from which RAP is often obtained. Cold milling and resurfacing of existing HMA pavements constitute common maintenance and rehabilitation practices. The cold milling operation provides a practical and economical source of recycled materials that can be used to construct new HMA pavements. RAP can also be produced from ripping and crushing existing HMA pavements. The HMA layer in an existing pavement structure is broken into large pieces and then crushed to appropriate sizes for use in a new mix. RAP, thus produced, can be of very high quality if care is taken to not introduce dirt, debris, and other deleterious materials during its production. RAP obtained from DOT-approved HMA pavements contain aggregates and binder that have already undergone strict Quality Control (QC) and Quality Assurance (QA) testing. If handled properly, these materials can be incorporated directly into new asphalt mixes. RAP produced from the cold milling or ripping and crushing of DOT-approved pavements are typically considered *classified RAP* and can be used in any layer within the pavement structure. Other sources of RAP including plant waste, private or non-DOT approved HMA pavements, or undocumented HMA pavements are typically considered *unclassified RAP* and are reserved for use in base or intermediate/binder courses. These materials haven't undergone the strict QC/QA testing protocols required for DOT pavements, and may need further mixing, screening, crushing, etc. to produce consistent RAP materials. Some contractors practice stockpiling large quantities of RAP from a single project separately to preserve material consistency. RAP from smaller projects and/or unclassified RAP are often stored in multi-source stockpiles. Though these stockpiles contain various types of RAP with different material properties, proper mixing, screening and crushing procedures can still provide a consistent and usable RAP. Many agencies allow the use of multi-source RAP provided the RAP aggregate meets specification requirements and the mix design also meets all volumetric requirements (West, 2013). Therefore, proper RAP processing and stockpile management is essential to the successful incorporation of RAP into any HMA mixture.

Another challenge of using RAP in an HMA mix is related to the age of the asphalt binder. With the possible exception of plant-produced waste, the asphalt binder in RAP has usually been subjected to rigors of the environment for an extended period. This environmental exposure results in oxidative hardening of the binder. Asphalt is a complex mixture of organic molecules ranging from nonpolar hydrocarbons to highly polar hydrocarbons with heteroatoms such as oxygen, nitrogen, and sulfur (Petersen, 2009). Atmospheric oxygen reacts with the asphalt, and creates oxygen-containing functional groups: a diverse collection of molecules having similar chemical reactivity. These oxygen-containing functional groups (sulfide, sulfoxide, anhydride, carboxylic acid, ketone, etc.) create secondary bonds with other polarized molecules in the asphalt due to hydrogen bonding, and other bi-pole and induced bi-pole interactions. The increase in oxygen-containing functional groups within the asphalt due to exposure to environmental oxygen, and the associated increase in the number of secondary bonds, results in a stiffening of the asphalt matrix (Petersen, 2009). The chemical composition of asphalt can vary widely depending on the asphalt source; consequently, oxidative hardening of RAP is highly source dependent. When using higher RAP contents in a new mix, the rheological properties of the RAP binder must be measured. In the context of the previous sentence, the term 'rheological' refers to the 'flowability' of the RAP binder. In other words, the RAP binder should be characterized for properties such as viscosity, stiffness, and phase angle. It should also be noted that based on AASHTO M 323, an asphalt mix containing more than 25 percent RAP (ABR) can be categorized as being a 'high-RAP' mix. However, based on the current definitions adopted by ITD, a mix with more than 30 percent RAP content (ABR) is termed as 'high-RAP'. A much softer virgin binder is then selected so that the virgin/RAP blend has the desired stiffness and ductility. However, the chemical composition of asphalts from various sources can reduce compatibility of the virgin/RAP blend resulting in decreased asphalt durability (Peterson, 2009). Another complicating factor is that the degree to which the stiffer oxidized binder disassociates from the RAP aggregate and becomes available as effective binder content for the mix is difficult to determine. The conventional assumption is that 100 percent of the RAP binder is available. However, studies have shown that the true value lies between 0 percent (a scenario where the RAP functions as nothing but a "black rock" in the new mix) and 100 percent mixing where there is an increase in mixing with an increase in RAP content (Copeland, 2011). Assuming 100 percent mixing may lead to overestimating the total binder content of the new mix, thus resulting in a dry (under-asphalted) mix with increased cracking potential. Aging of RAP binders and the resulting properties of blended RAP and virgin binders are factors that have significant impacts on the ultimate performance of an HMA with RAP. Changes in the rheological properties of the asphalt binder over time are unwanted but unavoidable results of asphalt chemical composition and environmental exposure. These changes must be accounted for when incorporating aged or oxidized binder into a new HMA mix.

Consequently, the source, age, and processing methods associated with RAP are important considerations when designing and producing HMAs with RAP. Failure to properly account for these factors may lead to inadequate or variable material properties making it necessary to limit the amount of RAP that can be used. RAP materials generally contain an increased amount of fine aggregates placing another potential limit on the amount of RAP that can be used while still meeting aggregate gradation requirements. Higher fine aggregate content can cause the Voids in Mineral Aggregates (VMA), Voids Filled with Asphalt (VFA), and dust to effective binder ratio of the final mixture to fall outside of specification requirements. Furthermore, increased stiffness of the oxidized binder may have a potentially negative impact on fatigue and low-temperature crack performance. Accordingly, some state agencies have chosen to set an upper limit on the amount of RAP materials that can be used.

Project Background and Research Tasks

Until recently, Idaho was the only member of the Western Association of State Transportation Officials (WASHTO) that did not have an upper limit on RAP content set for any HMA lift. Consequently, some recent asphalt pavement projects in Idaho have RAP binder replacement contents as high as 54 percent (Idaho Transportation Department, personal communication, 2017). Some at ITD have expressed concern that some of these high RAP content sections may show premature distresses raising concerns regarding the possibility that high RAP contents may have increased the crack susceptibility of the asphalt mixtures used in these projects. Specifically, some believe that the increased binder stiffness due to the blending of virgin binder with aged or oxidized binder may potentially lead to decreased fatigue and or low-temperature performance. To address these concerns, the Idaho Transportation Department (ITD) has set an upper limit of 30 percent RAP content by binder replacement. This new RAP limit has the potential to negatively impact Idaho contractors who have established procedures and processes to produce high-RAP asphalt pavements (>30 percent) that will meet ITD's current volumetric specifications but may not result in the long-lasting pavements the department desires. The current research project, titled, *"Assessing the Impact of High RAP Content on Pavement Performance in Idaho"*, was initiated to gain insight into the effect that high RAP content may have on asphalt mix performance. Additionally, this research study also intended to identify design and production techniques that can be implemented to produce high-performing, high-RAP HMAs in Idaho.

Change in Project Focus and Delay in Project Completion

At the time of its initiation, the primary tasks of this project were:

1. Investigating the correlation, if one exists, between high RAP content and premature distresses in Idaho flexible pavements.
2. Identifying and recommending design procedures, performance testing, and material processing protocols that will enable the use of high RAP content in Idaho pavements.

Originally during the conception of this research project, one of the main tasks of this project involved working with ITD engineers to collect cores from the different pavement sections across the state of Idaho, constructed with different RAP contents. Also, the plan was to identify existing pavement sections constructed over the past few years with different RAP percentages, to map the mix design information with actual performance of the mix in the field. However, the research team was presented with multiple challenges while performing these tasks.

First, due to limited budgets for most ITD districts (ITD operations are divided into six districts across the state of Idaho), it was not possible to schedule coring operations working with the district materials engineers. In most cases, the districts were short-staffed, and accordingly, could not allocate the personnel time required for traffic control and coring operations. This meant, there were no cores available for testing in the laboratory.

Second, even while collecting material from new construction projects, most districts were not able to supply the research team with cores. Rather, they supplied the team with lose asphalt mix. This required the team to compact the gyratory specimens in the lab (something that was not part of the original project scope), and also conduct additional volumetric tests to ensure the specimens being prepared were representative of what was put in the actual pavement sections. This created significant personnel challenge for the research team as the principal investigator's (PI) lab at Boise State University (the PI was a faculty member at Boise State University when this project was started; subsequently, the PI moved to Oklahoma State University, and the contract was continued to ensure completion) was not equipped for these additional tests. This required the PI to work with ITD as well as the local contractors (in Boise, Idaho) to loan certain equipment that could be used to perform the additional tests.

At the time of the initiation of this study, ITD had already implemented a practice restricting the RAP usage in new asphalt mixes to a maximum of 30 percent ABR. Therefore, most projects that the research team could obtain samples from, had RAP contents close to 30 percent. This prevented the research team from collecting and testing samples from projects with a wide range of RAP contents to adequately map the effect of RAP on mix cracking properties. Nevertheless, the PI reached out to the contracting community in Idaho to collect samples from different projects (even some from projects that were not controlled by ITD, but local counties such as the Ada County Highway District or ACHD) to ensure the laboratory testing involved samples with different RAP contents.

The lead graduate student, David (Kody) Johnson, working on this research project at Boise State University, left the graduate program in the middle of the research project, and did not contribute to writing of the final report. This required the PI to compile all the information into this report with the help of temporary student workers. Subsequently, the PI had to write the report completely by himself. This, combined with multiple other factors such as increased workloads due to COVID-19 restrictions, led to some delay in the preparation and submission of this final project report.

Owing to all the above factors, the focus of the research study was gradually changed in consultation with ITD engineers to the extent where most of the focus was on findings from the literature. Although a large volume of Semi-Circular Bending (SCB) tests (particularly, the I-FIT or Illinois Flexibility Index Test) were carried out in the lab (a total of more than 1,200 tests), along with additional mix compaction and volumetric tests (not part of the original scope of work), the author is not in a position to present strong claims about the cause-effect relationships reflected in the laboratory data. The author presents the trends observed from the laboratory test results based on mix design information obtained from ITD; the author did not verify the accuracy of the mix design and volumetrics data. Nevertheless, this report summarizes a large volume of information related to RAP usage in asphalt mixes both nationally as well as internationally. The conclusions, and recommendations presented in the report, are drawn based on findings from the laboratory tests as well as from those reported in the literature. The author makes recommendations regarding how the current practices in Idaho concerning the use of RAP in asphalt mixtures can be improved. It is the author's intention that the current report can be used as an extensive source of information for engineers and contractors interested in different aspects of RAP usage in asphalt mixes.

Report Organization

This report presents findings from all tasks undertaken under the scope of the current research project. The work carried out in this project can be divided into three broad categories: (1) Literature review concerning all aspects of RAP usage in asphalt mixes; (2) A survey of state highway agencies summarizing their practices with respect to RAP usage and handling; and (3) Laboratory testing of asphalt mixtures collected from different projects across Idaho to study the effect of RAP content on mix cracking performance. Accordingly, the report has been divided into five (5) chapters. Chapter 2, a rather long chapter, presents a summary of all information collected from the literature review effort. As already mentioned, the project scope had to be realigned to largely focus on literature review to gather extensive information on the effects of RAP content on mxi performance, and protocols to follow to successfully produce asphalt mixtures with high RAP contents. Therefore, this chapter constitutes a major portion of this research report. Chapter 3 presents findings from a nation-wide survey carried out to collect information on the current state of practice in states regarding the use of RAP in asphalt mixes. Chapter 4 presents findings from the laboratory testing effort carried out in this project. Chapter 5 presents a summary of project findings and conclusions, and makes recommendations to ITD regarding their practice

2. Review of Published Literature

An extensive review of published literature was carried out during the current study to collect information on the effects of RAP content on asphalt mix performance Information was collected from laboratory and field research studies, as well as from actual performance of pavement sections constructed with different RAP contents. The researchers collected information on rutting, fatigue, and low-temperature performance of asphalt mixtures containing different RAP contents to compare their performance with mixtures with no RAP content. Significant efforts were also devoted to collect information regarding best practices to ensure successful production of and paving with asphalt mixtures with high RAP contents. RAP material handling procedures such as fractionation and stockpile management were investigated to identify practices that can help limit material variability of RAP stockpiles. Additional mix design as well as laboratory and field-testing procedures were investigated to determine whether their implementation can facilitate the design and construction of high-RAP pavements that perform as well or better than virgin pavements.

Asphalt Composition, Compatibility, and Oxidation

Transportation Research Circular E-C140*, A Review of the Fundamentals of Asphalt Oxidation: Chemical, Physicochemical, Physical Property, and Durability Relationships* (Peterson, 2009), presents an extensive synthesis of the mechanisms of asphalt oxidation and their effects on durability. Much of the information presented in this section is derived from this authoritative work.

Asphalt, also referred to as bitumen, is a naturally occurring material that that has been used in adhesive and water proofing applications since 6,000 B.C. The naturally occurring asphalts are lake asphalt, rock asphalt and gilsonite. These natural asphalts are still in use today in waterproofing and high-stiffness asphalt mix applications. However, the primary source of asphalt used in asphalt pavement construction comes from fractional distillation of crude oil. Fractional distillation is a process in which crude oil is heated in large distillation towers and vapors with varying boiling ranges condense at different locations within the tower as they rise and lose heat. The heaviest fraction left at the bottom is called the bitumen residuum. The residuum is further processed at reduced pressure in a vacuum distillation unit to remove heavy gas oils. The resulting vacuum residuum is then used as feed stock to produce paving grade asphalt where the viscosity or temperature susceptibility of the asphalt is improved by continuous air-blowing of the residuum promoting oxidation (Roberts et al., 1996).

Asphalt cement is a complex mixture of hydrocarbons, hydrogen, sulfur, oxygen and nitrogen with a trace amount of various metals. The typical composition of asphalt is 82-88 percent carbon, 8-11 percent hydrogen, 0-6 percent sulfur, 0-1.5 percent oxygen, and 0-1 percent nitrogen (Mallick and El-Korchi, 2015). The overall behavior of an asphalt is the result of the combined effect and relative amount of component fractions. The relative amounts of each fraction are also related to oxidation. In general, oxidation results in a movement of molecules toward increasingly more polar fractions with the formation of oxygen containing functional groups (Peterson, 2009). The absence of a well-balanced distribution of polarity due to the relative concentration of the various fractions can lead to a break-down in the homogeneity of the asphalt colloidal solution. This incompatibility results in reduced asphalt durability or a reduced ability of the asphalt to resist oxidative age hardening.

A more quantitative analysis of the various components of asphalt is possible using the analytical technique of functional group analysis. This analysis is made possible largely using a Fourier Transform Infrared Spectroscopic (FT-IR) method. Of particular interest are the heteroatom containing functional groups. Heteroatoms are associated with strongly polar functional groups that have a large influence on the overall material behavior of asphalt. Due to the large influence of these functional groups on asphalt material properties, it is these functional groups that are most important to study thereby narrowing the number of molecular types needed for informative analysis. The functional groups identified using the aforementioned spectroscopic technique are *the carboxylic acids, anhydrides, ketones, 2-quinolone types, sulfoxides, pyrrolic types, and phenolic types*. Interestingly, the types of oxidation products formed during oxidation are consistently similar despite the source or chemical composition of the asphalt. The primary functional groups formed with oxidative aging are *ketones and sulfoxides*. The formation of these functional groups is governed by asphalt chemical composition and component compatibility. Consequently, the sensitivity of an asphalt to age hardening may be determined more by composition and compatibility and less by the quantities of oxidation products formed (Peterson, 2009). It has been observed that additives such as antioxidants and antistripping agents often alter the rate of oxidative age hardening in asphalt. According to Peterson (2009), the effect of these additives on altering the rate of age hardening may be due to their ability to change the dispersibility of the asphaltenes fraction and thereby changing the overall component compatibility of the asphalt. It has also been observed that in some cases an outsized reduction in viscosity results from the addition of antistripping agents that cannot be explained by dilution effects. Instead, this result is likely due to a change in compatibility of the asphalt. This again highlights the influence of component compatibility on asphalt material properties.

Molecular interactions between the various functional groups in asphalt are primarily responsible for its overall material properties and performance. These molecular interactions are secondary interaction forces such as hydrogen bonds, di-pole bonds, or induced di-pole bonds that are much weaker than primary covalent bonds. Consequently, these bonds are reversible and are heavily influenced by temperature and external stress. The temperature and stress dependence of these bonds lends asphalt its polymeric properties. Non-polar hydrocarbon components, such as those found in the ‘saturates’ fraction, have weak interaction forces, and consequently impart the asphalt its fluidity. The asphaltenes fraction on the other hand consists of highly polar molecules that have strong interaction forces. These molecules, despite having a similar molecular weight compared to the other fractions, are solids. Molecules in this fraction strongly associate through close packing of their planar aromatic rings. Oxidation results in an increase in the number of polarized or polarizable molecules. When the number of polarized molecules increases to the extent that the ability of molecules to move past one another becomes restricted, the asphalt becomes brittle and is prone to cracking. Treatment of asphalt with hydrated lime has been shown to decrease the rate of oxidation product formation as well as to remove (by absorption) carboxylic acids and other polar functionality. The removal of these polar functional groups increases compatibility and removes functional groups that otherwise would have interacted with oxidation products to increase viscosity.

Temperature is another important factor influencing the age hardening characteristics of asphalt. The rate of ketone and sulfoxide formation during oxidation increase significantly with temperature. One reason for this is that the reaction rate of organic compounds doubles for every 10°C increase in temperature. Additionally, the association of the most oxidation-reactive functional groups with other polar functional groups inhibits their mobility and reaction at lower temperatures. However, at higher temperatures, these interaction bonds are broken altering the molecular structure (microstructure) of the asphalt. This mobilizes a higher concentration of reactive species increasing oxidation rate. For these reasons, Peterson (2009) suggests that conventional laboratory aging procedures used in an effort to predict the long-term aging characteristics of asphalt are ineffective. Specifically, the Pressure Aging Vessel (PAV) laboratory accelerated aging technique as developed by the Strategic Highway Research Program (SHRP) is conducted at a temperature (100°C) that changes the microstructure significantly from what exists in the field. The combined effects of altered microstructure and increased reaction rates at higher temperatures increases oxygen uptake beyond levels that can be diffused into the sample during conditioning.

Peterson (2009) conducted a study of the oxidation of asphalt coated Ottawa sand at 45°C. At this low temperature and correspondingly low reaction rate, the oxidation was allowed to proceed for a period of 100 days. This temperature is within the range of pavement aging temperatures and well below the temperature at which the molecular structure becomes altered. What he found was that during the relatively short ‘spurt’ period in which oxidation products are formed at increased rates, the formation of ketones was very low compared to typical studies conducted at conventional temperatures. The large majority of oxidation products were sulfoxides. This behavior was largely missed by previous studies due to changes in microstructure and increased reaction kinetics but hinted at dual oxidation mechanisms. The first mechanism proposed by Peterson (2009) was a reaction with perhydroaromatic hydrocarbons to form hydrogen peroxide or perhydroaromatic hydroperoxide. Either of these peroxides could then react with sulfides to form sulfoxides. These reactions explain the reduced ketone formation at low temperatures due to the temperature sensitivity of hydroperoxide. Regardless of the oxidation mechanism responsible, Peterson (2009) showed that temperature plays an important role in asphalt oxidation and can have a significant impact on the predictive power of laboratory accelerated aging procedures.

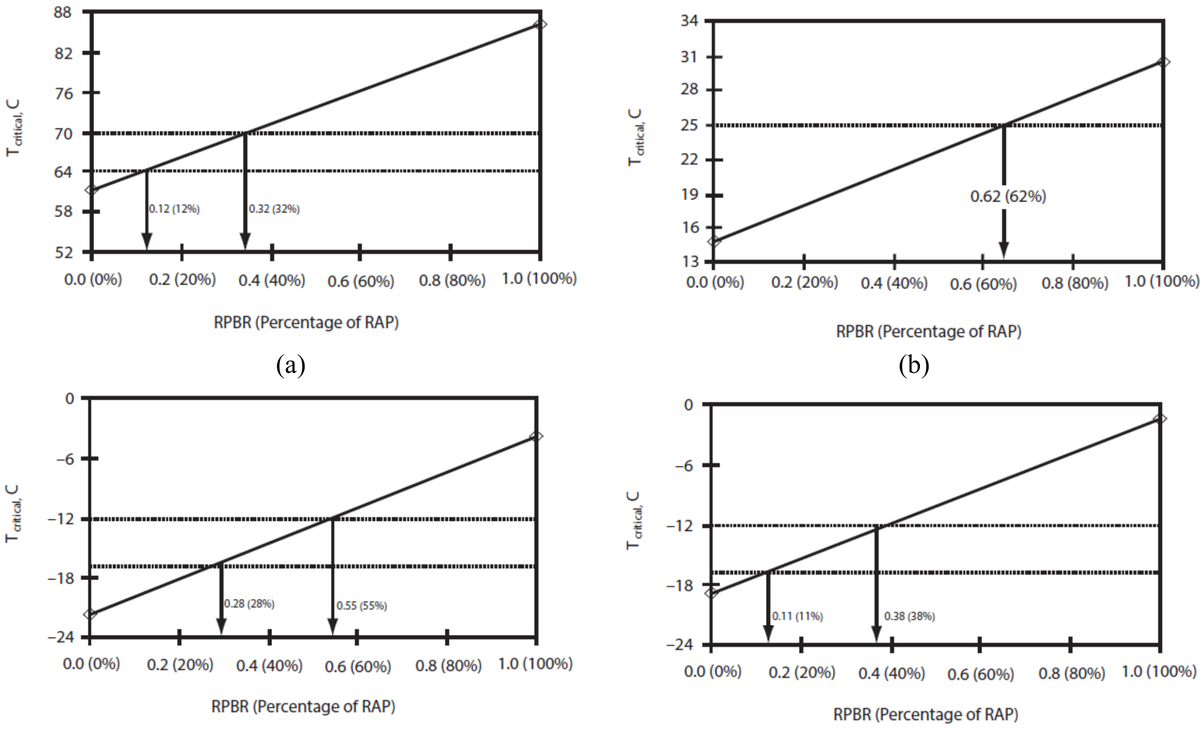
Virgin/RAP Binder Blending

As discussed previously, RAP binders have had extended exposure to environmental oxygen and have typically undergone a high degree of oxidation. This oxidation results in a loss in the polar aromatics fraction and a gain in the asphaltenes fraction due to ketone formation and corresponding asphaltenes formation. This results in a decrease in compatibility, durability, and an increase in viscosity making RAP binders much more susceptible to cracking (Al-Qadi et al., 2012; Tran et al., 2012). Blending virgin binder with RAP binder reduces the relative asphaltenes content and has the tendency to reduce viscosity and increase component compatibility. However, Altgelt and Harle (1975) showed that asphaltenes from different sources form various sized asphaltenes when dispersed in a common maltenes fraction (the maltenes fraction is the combination of all fractions after asphaltenes have been removed). Similarly, maltenes from different sources have varying degrees of dispersibility forming asphaltene agglomerations of varying effective sizes. Consequently, the degree to which a virgin binder will increase compatibility and reduce viscosity is unknown. The blending of a relatively incompatible virgin binder with highly oxidized RAP binder may result in an incompatible blended binder. This incompatibility can reduce the effective blending of RAP and virgin binders creating non-homogenous binder properties within a RAP-containing HMA. In the case of blending virgin aggregates and binder with RAP aggregates, the degree to which the virgin binder is able to penetrate the stiff oxidized RAP binder is also unknown. These unknown factors are of particular concern as the degree of compatibility and blending has a significant effect on the blended binder rheological properties and the volume of effective binder in the HMA mix. Incorrectly estimating the degree of virgin RAP binder blending can lead to a mix with too much or too little binder which can lead to a mix with reduced stability or durability, respectively.

Numerous studies have been conducted to determine the degree of binder blending that occurs upon mixing virgin binder with RAP. McDaniel et al. (2000) conducted a ‘black rock’ study to evaluate three potential binder blending scenarios: (1) black rock (0 percent mixing); (2) actual practice (unknown mixing); and (3) total blending (100 percent mixing). The black rock scenario used recovered RAP aggregates (no RAP binder) blended with virgin aggregates and binder. The actual practice scenario used the conventional method of blending RAP aggregates with virgin aggregates and binder. The total blending scenario used recovered binder blended with virgin binder (100 percent blending), and the blended binder was mixed with virgin and recovered aggregates. Three RAP sources categorized as low, medium, and high stiffness were used; two RAP percentages (10 percent and 40 percent), and two virgin binder grades were evaluated. The gradation for all mixes was kept constant. Frequency sweep, simple shear, and repeated shear at constant height tests were used to characterize the mixes at high and intermediate temperatures. Indirect tensile creep and indirect tensile strength tests were used to characterize the mixes at low temperature. The study found that the black rock case is not valid as some blending does occur. However, for very low levels of RAP percentage (10 percent or less) there isn’t enough binder to affect binder properties. For high RAP contents, the actual practice case was found to be much closer to the total blending case; this indicated a high degree of binder blending. Their research supported the concept of a ‘tiered approach’ to RAP usage. At low RAP contents, the effects of RAP binder were found to be negligible.

As far as determining the effects of blending at higher RAP contents, McDaniel et al. (2000) supported the use of linear blending equations. In this approach, the recovered RAP binder is tested in the Dynamic Shear Rheometer (DSR) to establish its critical high temperature as if it were unaged binder. The remainder of the recovered binder is aged in a Rolling Thin-Film Oven (RTFO). Then the high temperature stiffness of the RTFO-aged binder is determined. The RAP binder does not need to be aged in a PAV. Note that McDaniel et al. (2000) observed that some non-linearity with respect to blending begins to appear for RAP contents greater than 40 percent. The following conclusions were made from this study: *"At low RAP contents (<10 percent), the effects of the RAP binder are negligible. At intermediate RAP contents (15 to 25 percent), the effects of the RAP binder can be compensated for by using a virgin binder that is one grade softer on both the high- and low temperature grades. The RAP binder stiffens the blended binder. At higher RAP contents (> 25 percent), a blending chart should be used to either determine the appropriate virgin binder grade or to determine the maximum amount of RAP that can be used with a given virgin binder." (McDaniel et al. 2000).*

The 7th edition of the Asphalt Mix Design Methods book by the Asphalt Institute (Asphalt Institute, 2014) presents examples of different scenarios encountered by asphalt producers when it comes to incorporating RAP in an asphalt mix. The blending chart for a case where the final blended binder grade, the virgin asphalt binder grade, and the recovered RAP binder properties are known, are presented in Figure 1. In this case, the blending charts can be used to determine the amount of RAP that can be used without adversely affecting mix performance. The RAP percentage should be selected to meet the criteria at high, intermediate, as well as low temperatures. McDaniel et al. (2000) reported that the linear blending charts may be appropriate for up to 40 percent RAP. Beyond, that, some degree of non-linearity may appear in the blending process. Detailed explanation of the blending approach is beyond the scope of this study. The reader is encouraged to refer to the MS-2 publication by the Asphalt Institute for detailed discussion.



(a) (b)

(c) (d)

Fig. Source: Asphalt Institute (2014)

Figure 1: Blending Charts for Unknown RAP Percentage: (a) High Temperature; (b) Intermediate Temperature; (c) Low Temperature (S); (d) Low Temperature (m-value)

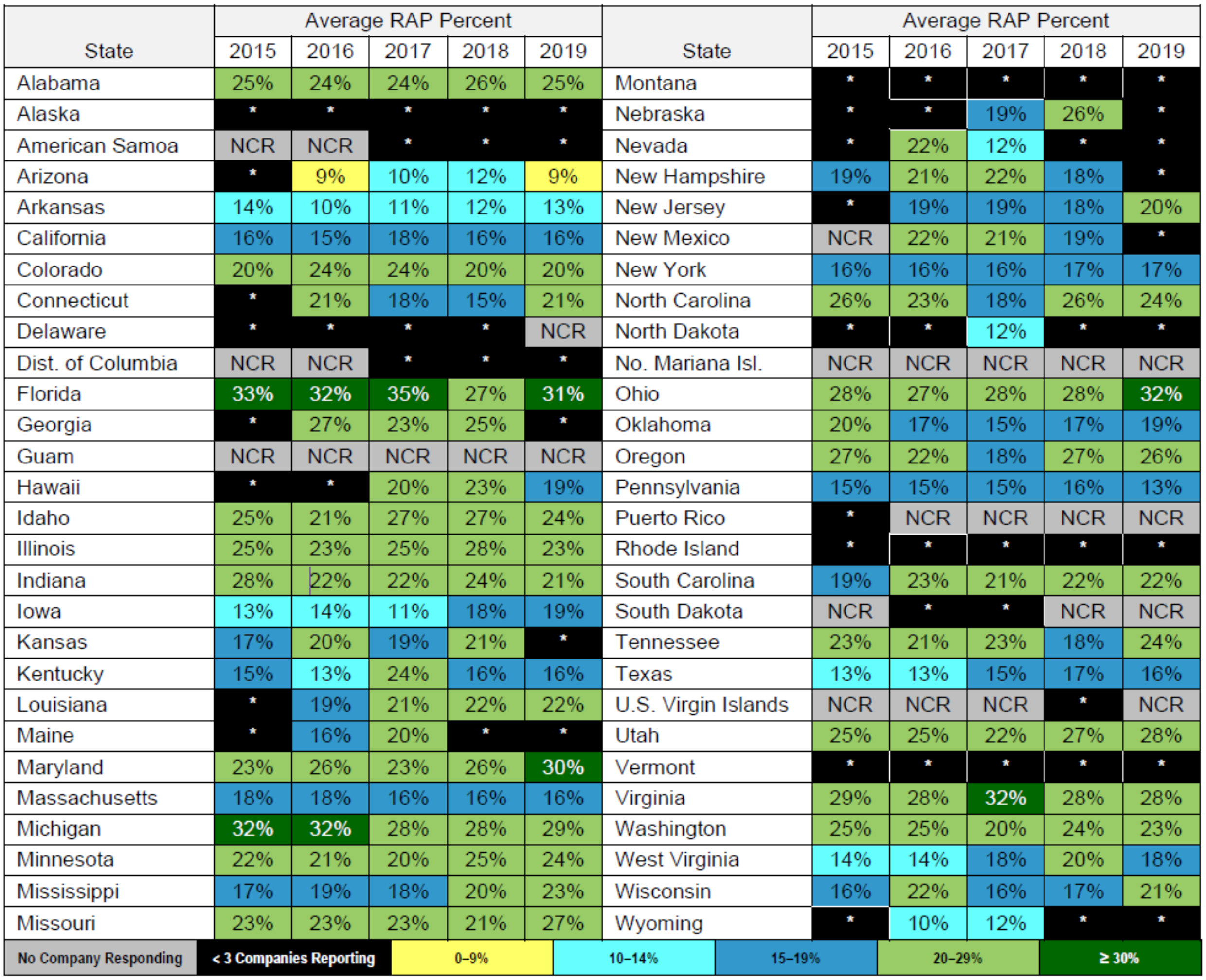
As apparent from the above discussion, for the blending process to work appropriately, the properties of the binder recovered from the RAP should be well-known. Without a good picture of the recovered RAP binder properties, it is not possible to determine the RAP content range that would lead to adequate mix performance. This further emphasizes the importance of preventing cross-contamination between RAP stockpiles. If the RAP materials from multiple sources are mixed, this introduces another variable to the entire system (the binder recovered from different RAP sources will have different properties). Therefore, even if the asphalt producer has a good idea of the recovered binder from some of the sources, the blending between RAP from different sources can affect the resulting binder properties. Therefore, production of a well-performing asphalt mix with high-RAP contents is largely dependent on quality control of the RAP stockpile, and also accurate determination of the binder properties recovered from the RAP.

Al Qadi et al. (2009) studied binder mixing for three mixes containing 0 percent, 20 percent, and 40 percent RAP. The 20 percent and 40 percent RAP mixes were prepared using an actual practice mix *(actual practice mix indicates a scenario where the blending percentage is unknown)*. Additional mixes were prepared with known degrees of binder mixing (0 percent, 50 percent, and 100 percent). Dynamic modulus testing was conducted to differentiate between the stiffness of the various mixes. Additionally, DSR tests were conducted to establish the complex shear modulus of the virgin, recovered, and blended binders. One practical outcome of the study was that none of the RAP mixtures required additional virgin binder to achieve the same density as the non-RAP mixtures, indicating a high degree of binder blending. Dynamic modulus testing showed an increase in stiffness with increasing RAP for all mixes consistent with increased binder stiffness due to oxidation. Note that for the complete binder mixing assumption to hold true, the test data for mixes corresponding to the actual practice case and the 100 percent blending case should be identical. However, the actual practice mixes showed consistently higher dynamic modulus values compared to the 100 percent blending specimens. Potential causes of this discrepancy were thought to be differences in aggregate structure, variations in fines content due to the incomplete release of fine aggregates in the actual practice case mix, variations in VMA, or a stiff aggregate-binder interface due to selective aggregate absorption of asphalt. *Nevertheless, the current practice of assuming 100 percent mixing for mix design calculations was considered acceptable.* Blended binder complex shear modulus testing showed a consistent increase in shear modulus for one RAP binder source, but no significant increase was observed for the other RAP binder source. This result raised questions regarding the compatibility between the RAP and virgin binders. However, no conclusions regarding compatibility could be drawn. There are other examples in the literature showing that, while complete blending may not occur in all cases, there is a high degree of blending between the virgin and the RAP binders (Daniel and Lachance 2005; Bonaquist 2007; Shirodkar et. al 2010; Mogawer et al. 2012).

RAP Usage in Asphalt Mixtures – State of the Practice

Williams et al. (2020) presented an overview of the yearly estimated RAP usage in different states in the US from 2015 until 2019. The survey was sent to asphalt mixture producers as well as state asphalt pavement associations. The summary data has been shown in Figure 2 (Williams et al., 2020). As seen from the figure, the average RAP percentage in asphalt mixes in Idaho was 25 percent, 21 percent, 27 percent, 27 percent, and 24 percent for years 2015 through 2019, respectively. Interestingly, only Florida, Michigan, and Virginia reported average RAP percentages of greater than 30 percent. Although typical RAP contents in the US are around 30 percent, there are examples where countries have consistently succeeded in using high RAP contents in asphalt mixtures. For example, West and Copeland (2015) report findings from an industry scanning tour to Japan to learn about Japan's use of high RAP in asphalt mixtures. They reported that as of 2015, the average RAP content in asphalt mixtures in Japan was approximately 47 percent, which is significantly higher than typical values in the US. West and Copeland (2015) reported that Japan's success in using high-RAP mixtures can primarily be attributed to attention to details in terms of material processing and quality control. The following key points were identified as being primarily responsible for Japan's success in this regard.

1. A focus on quality (reducing variability), including processing RAP (i.e., fractionating) and covering stockpiles.
2. Heating the RAP to drive out moisture and soften the RAP binder.
3. Using a softening agent (and other mixing best practices) to achieve desired mix characteristics.



State	Average RAP Percent					State	Average RAP Percent				
	2015	2016	2017	2018	2019		2015	2016	2017	2018	2019
Alabama	25%	24%	24%	26%	25%	Montana	*	*	*	*	*
Alaska	*	*	*	*	*	Nebraska	*	*	19%	26%	*
American Samoa	NCR	NCR	*	*	*	Nevada	*	22%	12%	*	*
Arizona	*	9%	10%	12%	9%	New Hampshire	19%	21%	22%	18%	*
Arkansas	14%	10%	11%	12%	13%	New Jersey	*	19%	19%	18%	20%
California	16%	15%	18%	16%	16%	New Mexico	NCR	22%	21%	19%	*
Colorado	20%	24%	24%	20%	20%	New York	16%	16%	16%	17%	17%
Connecticut	*	21%	18%	15%	21%	North Carolina	26%	23%	18%	26%	24%
Delaware	*	*	*	*	NCR	North Dakota	*	*	12%	*	*
Dist. of Columbia	NCR	NCR	*	*	*	No. Mariana Isl.	NCR	NCR	NCR	NCR	NCR
Florida	33%	32%	35%	27%	31%	Ohio	28%	27%	28%	28%	32%
Georgia	*	27%	23%	25%	*	Oklahoma	20%	17%	15%	17%	19%
Guam	NCR	NCR	NCR	NCR	NCR	Oregon	27%	22%	18%	27%	26%
Hawaii	*	*	20%	23%	19%	Pennsylvania	15%	15%	15%	16%	13%
Idaho	25%	21%	27%	27%	24%	Puerto Rico	*	NCR	NCR	NCR	NCR
Illinois	25%	23%	25%	28%	23%	Rhode Island	*	*	*	*	*
Indiana	28%	22%	22%	24%	21%	South Carolina	19%	23%	21%	22%	22%
Iowa	13%	14%	11%	18%	19%	South Dakota	NCR	*	*	NCR	NCR
Kansas	17%	20%	19%	21%	*	Tennessee	23%	21%	23%	18%	24%
Kentucky	15%	13%	24%	16%	16%	Texas	13%	13%	15%	17%	16%
Louisiana	*	19%	21%	22%	22%	U.S. Virgin Islands	NCR	NCR	NCR	*	NCR
Maine	*	16%	20%	*	*	Utah	25%	25%	22%	27%	28%
Maryland	23%	26%	23%	26%	30%	Vermont	*	*	*	*	*
Massachusetts	18%	18%	16%	16%	16%	Virginia	29%	28%	32%	28%	28%
Michigan	32%	32%	28%	28%	29%	Washington	25%	25%	20%	24%	23%
Minnesota	22%	21%	20%	25%	24%	West Virginia	14%	14%	18%	20%	18%
Mississippi	17%	19%	18%	20%	23%	Wisconsin	16%	22%	16%	17%	21%
Missouri	23%	23%	23%	21%	27%	Wyoming	*	10%	12%	*	*

No Company Responding	< 3 Companies Reporting	0–9%	10–14%	15–19%	20–29%	≥ 30%

Figure Source: Williams et al. (2020)

Figure 2: Average Estimated Percentage of RAP Used in Each State, 2015 – 2019

Effect of RAP on Mechanical Properties of Asphalt Mixtures

This section discusses the effect of RAP on the mechanical properties of an asphalt mix. Although there is close-to-unanimous consent about the increase in binder stiffness at high RAP contents, several researchers have found that carefully designed and prepared mixtures with high RAP contents perform as well as those with lower RAP contents. For example, Diefenderfer and Nair (2014), from an extensive laboratory study, concluded that a mixture containing up to 45 percent RAP can be successfully designed, produced, and paved. Zhou et al. (2013) observed that unlike rutting, the cracking performance of the RAP mixes are strongly connected to the surface of the pavement, and factors like climate, traffic, condition of the existing pavement for asphalt overlays, layer thickness, and pavement structure were influencing cracking performance the most.

Rutting Susceptibility

The effect that RAP content has on rutting susceptibility is clear from the literature. The oxidized RAP binder increases the stiffness of the blended binder, thereby increasing the overall stiffness of the mix. This increased stiffness generally results in improved rutting performance (Stroup-Gardiner and Wagner 1999; McDaniel et al. 2000; Al-Qadi et al. 2007, 2012, 2015; Xiao et al., 2007; Cooper et al. 2016). Reduced rutting resistance with increased RAP content has been observed by certain researchers (Apeagyei et al., 2011), however this is usually attributed to the practice of grade bumping to reduce crack susceptibility.

Moisture Susceptibility

Moisture susceptibility of asphalt mixtures has been observed to increase with increasing RAP content (Li et al., 2004; Hajj et al., 2009; Apeagyei et al., 2011). However, some other researchers have also reported that RAP content does not have a significant effect on the moisture susceptibility of asphalt mixtures (Loria et al. 2011; Lippert et al. 2017).

Cracking Susceptibility

Fatigue cracking susceptibility (intermediate temperature) is measured using a variety of testing protocols. It is generally believed that increasing RAP content also increases fatigue cracking susceptibility (McDaniel et al. 2000; Shu et al., 2010; Mohammad et al. 2011; Al-Qadi et al. 2012, 2015; West et al., 2013; Ahmad et al. 2015; Ozer et al. 2016). However, some studies have shown contradictory results. Huang et al. (2004) studied the laboratory fatigue characteristics of asphalt mixtures containing RAP, and observed that up to 30 percent RAP content, the RAP content can actually improve fatigue resistance. This discrepancy was explained by a reduction of the stress and strain concentration due to the hard coating of aged asphalt that remained on RAP aggregates due to incomplete mixing. According to this theory, the aged asphalt layer acts as a cushion between the hard aggregate and soft virgin binder and helps distribute stress and strain more evenly throughout the composite material. The theory was proven reasonable in a subsequent study (Huang, 2005) in which staged extraction of RAP binder was used to determine the binder properties of four (4) layers of aged binder coating the RAP aggregates. Each layer was found to be of roughly equivalent size with a soft near-virgin layer on the outside, and with each subsequent layer increasing in stiffness. The extracted binder properties were used in a Finite Element (FE) based model to estimate the resulting stress/strain reduction. The effects of binder compatibility and degree of mixing may have a significant impact on the degree to which this phenomenon is observed, if at all. West et al. (2013) measured fatigue fracture energy for mix designs from four (4) locations (New Hampshire, Utah, Minnesota, and Florida) using Indirect Tension Tests (IDT). Some trends of decreasing fracture energy with increasing RAP content were observed, however these trends did not hold true over all mixes. Generally, there was an initial drop in fracture energy from 0 to 25 percent RAP content with a slight increase in fracture energy for higher RAP contents.

Thermal cracking susceptibility (low temperature) is measured using many of the same testing protocols used for fatigue cracking. However, the temperature is lowered to a temperature (or range of temperatures) consistent with the low temperature grade of the binder. Semi-Circular Bending (SCB) and Disc-Shaped Compact Tension (DCT) tests are the two main tests used to characterize thermal cracking susceptibility. Much of the literature showing an increase in fatigue cracking susceptibility with increasing RAP content show similar results for thermal cracking (Al-Qadi et al. 2009; Daniel and Lachance 2005; Shah et al. 2007; Li et al. 2008, Stroup-Gardiner and Wagner 1999; Ozer et al. 2016)

To isolate the effect of increased binder stiffness from other mix-related changes, Al-Qadi et al. (2012) conducted a study that compared the structural response of HMA mixtures with varying RAP contents (all other mix properties were kept unchanged). The researchers designed a total of eight (8) HMA mixtures using two (2) different sources for virgin aggregates and RAP in the state of Illinois. HMA mixes with 0 percent, 30 percent, 40 percent, and 50 percent RAP were designed for each source. Two (2) coarse-aggregate types, two (2) fine-aggregate types, and two (2) RAP stockpiles were used from each material source, and the same baghouse fines were used for all mixtures. The RAP stockpiles were fractionated and re-blended to meet original stockpile gradation prior to the mix design process. The RAP stockpiles were fractionated to reduce material variability, help control the amount of fine-aggregates, and provide greater flexibility in meeting gradation requirements. The Bailey method of aggregate gradation selection (Vavrik et al., 2002) was used to determine the stockpile percentages used in each mix design. Using strict stockpile management procedures and the Bailey method allowed the researchers to produce all mixtures at similar VMA and VFA values making performance results independent of volumetric considerations. RAP binder was extracted and tested to determine critical temperatures, and corresponding performance grade classification. Additionally, the glassy transition temperatures of all binders were measured to better understand the thermal cracking susceptibility. Each HMA was tested for Indirect Tensile Strength (IDT), complex-modulus, flow number, wheel tracking, SCB and beam fatigue. Major findings from this testing effort have been listed below.

- IDT testing showed an increase in tensile strength with an increase in RAP content for all mixtures.
- The moisture susceptibility based on Tensile Strength Ratio (TSR) generally increased with RAP content for one source and decreased for the other. Visual inspection of split specimens showed similar stripping behavior for the control and RAP specimens. The TSR is established through split tensile tests each sample; the ratio of indirect tensile strength of a moisture-conditioned sample is compared to an unconditioned sample as a ratio.
- Complex modulus of the mixture increased nominally with an increase in RAP content for one source with a much more pronounced increase for the other.
- Flow number data showed a decrease in rutting susceptibility with an increase in RAP content.
- Beam fatigue data showed an increase in fatigue life with increasing RAP.
- Thermal cracking susceptibility increased with increased RAP content up to 30 percent based on a reduction in fracture energy. For RAP content above 30 percent, no significant increase in fracture potential was observed.
- The effects of single-bumped binder grade (decreasing the high temperature grade) and double-bumped binder grade (decreasing the high and low temperature grade) were investigated. For single-bumped binder grade, the mix complex modulus for all RAP contents decreased but was higher than the control mix (0 percent RAP). Rutting susceptibility increased while fatigue susceptibility decreased. For double-bumped binder grade, rutting susceptibility increased over single bumped binder, and fatigue performance did not show significant improvement over

single-bumped binder grade. Low-temperature fracture performance increased slightly over the single-bumped binder.

Based on these results, the researchers concluded that high performing pavements with as much as 50 percent RAP can be designed to meet volumetric and performance requirements, but that attention should be given to the potential for increased crack susceptibility. RAP fractionation and double bumping of binder grade for RAP contents greater than 30 percent were recommended as a best practice to reduce thermal cracking susceptibility. It is important to note that the results and recommendations of this study apply only to HMA that does not contain polymer or chemically modified asphalt. Extension of these findings to HMA containing polymer or chemically modified asphalt may lead to erroneous assumptions/conclusions.

Development of the Illinois Flexibility Index Test (I-FIT)

Based on the above recommendations, a subsequent study was conducted by Al-Qadi et al. (2015) that investigated conventional asphalt concrete performance tests to evaluate their effectiveness in adequately identifying changes in rutting and cracking performance with increased RAP and Recycled Asphalt Shingle (RAS) contents. Several other mix design and volumetric parameters were also investigated. The purpose of the study was to identify testing procedures and protocols that could adequately characterize the structural response of HMAs with various Asphalt Binder Replacement (ABR; resulting from binder contributions from RAP and RAS) contents and volumetrics. More specifically, the goal was to find a test protocol sensitive to ABR content based on fundamental crack formation mechanisms that could be implemented with conventional performance testing equipment. This research effort ultimately led to the development of a new test method (The Illinois Flexibility Index Test; I-FIT) that could differentiate between different asphalt mixtures based on a newly defined fracture-based Flexibility Index (FI) parameter. A rather extensive review of this research is presented here due to relevance and the potential of the Flexibility Index as a leading crack performance indicator.

The tests analyzed by Al-Qadi et al. (2015) were: the complex modulus test, the push-pull fatigue test, the Texas Overlay test (TOL), low-temperature SCB test, low-temperature Disc-shaped Compact Tension test (DCT), and the IDT test. Testing was conducted on eleven (11) laboratory mixes, twenty-two (22) plant mixes, and numerous core specimens from nine districts in the state of Illinois. The specimens tested comprised different PG binders with various ABR levels to determine the effects of single and double grade bumping; an SBS polymer-modified binder (PG 70-22) was also used in their study.

Laboratory mixes maintained a constant VMA (15.3 percent ±1 percent), air void content (4 percent), and total binder content (6 percent). This enabled the researchers to determine the effect of ABR on performance characteristics. Strict control of volumetric properties while changing a single variable with subsequent mixes allowed the researchers to determine the effect on performance for variables such as RAP source, binder grade, and binder adjustment. It is important to note that the dust to binder ratio of some higher RAP/RAS mixtures exceeded Illinois Department of Transportation (IDOT) specifications due to increased fine aggregate content. A high dust to binder ratio increases aggregate surface area, reduces asphalt film thickness and can cause an increase in moisture susceptibility (Shannon et al., 2017). Some of these mixtures required 1 percent anti-striping agents to meet TSR requirements resulting in one laboratory mix with a 6.1 percent asphalt content (AC). Plant produced mixes with various design loads (N-design), ABR, AC, VMA etc. were analyzed to determine the effects of these variables on rutting and crack performance as well as to develop the I-FIT performance test and finalize the testing specifications. Field core and accelerated load testing data were used to validate the I-FIT test. Design, and performance data were compared with FI values to determine the ability of the FI to predict field crack performance and to establish threshold values.

Conventional performance test protocols were evaluated by Al-Qadi et al. (2015) to determine the sensitivity of these tests to changes in mix parameters and identify a test protocol sensitive to ABR and related to crack performance. Complex modulus test results showed that the test was able to differentiate between changes in various mix parameters (aggregate size, gradation, binder content, ABR percentage, VMA, etc.). However, the researchers eliminated this test from further consideration because the test is time consuming, complex, and according to the researchers, did not have the required accuracy. The push-pull fatigue test results did show some reduction in fatigue resistance for plant-produced mixes. However, the same trend was not observed for laboratory mixes. In general, this protocol was not considered for further analysis due to its time-consuming nature and lack of repeatability. The TOL test was able to distinguish between high and poor performing mixtures on a qualitative basis. However, due to the long test duration, high percent error, and complicated test setup, this test was not pursued for further analysis. DCT testing did not show any clear trends between increased ABR and fracture energy. Additionally, the range of fracture energy was very small compared to the large variation in ABR percentage of the laboratory samples tested. The researchers pointed to other studies (Buttlar et al. 2015, Al-Qadi et al. 2009) which showed that the DCT test was insensitive to changes in mix parameters at low temperatures and that the difference in fracture energy between various mixes decreased as test temperature decreased. Due to the results of these past research efforts, and the lack of any identifiable trends and low sensitivity of the test results, the DCT test protocol was eliminated from further consideration. Similarly, SCB test results showed a decrease in the range of fracture energy between various mixes at low temperatures. However, the low temperature fracture energy range for SCB tests was double that of the DCT test. As seen from Figure 3, the range in fracture energy between plant produced mixes with a variety of mix parameters is 250 J/m^2, and in many cases this value was only slightly larger than the experimental error. Conventional fatigue tests and low temperature monotonic fracture energy tests were thus eliminated from further consideration.

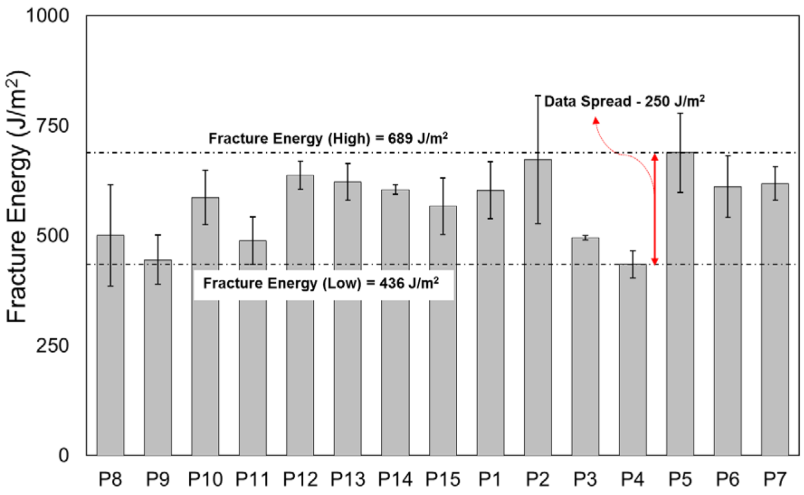


Figure 3: SCB Plant Mixture Results for Fracture Testing at -12 C (Al-Qadi et al., 2015)

Due to the simplicity of the SCB test in regard to specimen preparation and testing, the SCB test was selected for further testing and analysis at a range of various temperatures and loading rates. The objective of this testing was to determine the temperature and loading rate combination that would provide the greatest possible change in fracture energy with changes in mix characteristics such as aggregate gradation, ABR, binder grade, etc. The results were adjusted to compare the effect of temperature and loading rate on fracture energy with respect to a single reference temperature. The adjustment was made using the equivalent time concept introduced by Nguyen et al. (2013).

Based on extensive parametric studies, Al-Qadi et al. (2015) selected the SCB test at 25°C as the testing protocol of choice. They conducted further SCB testing at 25°C and determined that a loading rate of 50mm/min provided the maximum fracture energy compared to other load rates at 25°C. In addition, they determined that the test under these conditions exhibited adequate repeatability with an average coefficient of variation (COV) of under 10 percent for the specimens tested. Using FEM modelling and DIC measurements, they also determined the relative energy dissipation within the bulk material compared to the fracture energy. It was determined that as load rate increases, the increase in fracture energy outpaced the increase in bulk energy dissipation within the specimen validating the use of higher loading rates. Finally, an analysis of plastic damage near the loading head determined that the additional energy dissipation due to loading head damage was negligible.

Typical results from the modified SCB procedure are presented in Figure 4. This figure shows the load-displacement response of two control mixes with two different binder grades and corresponding mixes with 30 percent ABR (with grade bumping for L6, and no bumping for L5). The figure shows the effect that binder grade, grade bumping, and ABR content has on fracture energy. As binder stiffness increases, peak load increases while total displacement decreases. These results are consistent with an expected increase in brittleness as binder stiffness increases.

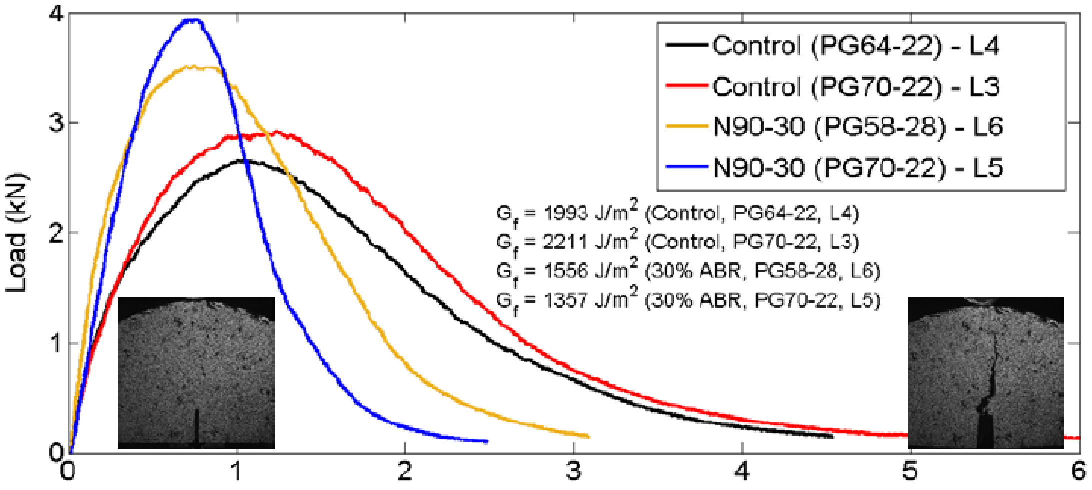


Fig. Source: Al-Qadi et al. (2015)

Figure 4: Typical Load-Displacement Curves and Corresponding Fracture Energy for Modified SCB Tests Conducted at a Loading Rate of 50mm/min and a Temperature of 25°C

However, as shown in Figure 5, fracture energy alone was not sufficient to differentiate between mixes having different mix characteristics. The control mix displayed a more ductile structural response (lower peak load and larger total displacement at end of test) while the 30 percent ABR mix displayed a much more brittle response (higher peak load and smaller displacement at end of test). However, the fracture energy for both tests were nearly the same. Using fracture energy alone, these two mixes would appear to have the same susceptibility to fracture. However, it is apparent from the figure that these two mixes would have very different fracture behaviors. Therefore, an additional parameter is needed that incorporates the shape of the load-displacement response helping to discriminate between brittle and ductile behavior.

To capture changes in the structural response of various mixes due to changes in mix characteristics, a fracture-based flexibility index was introduced. Inspired by a definition of the rate of crack growth (for concrete) provided by Bazant and Prat (1988). Using an approximate crack velocity (constant velocity) determined directly from the modified SCB test data (hereafter referred to as I-FIT), a correlation between crack velocity and the various forms of the FI index were established. Based on a good correlation with approximate crack velocity, its simple form, and physical relevance, the final form of the FI chosen by Al-Qadi et al. (2015) was:

$$FI = \frac{G_f}{|m|} \times A$$

$where:$

G_f : Fracture Energy

$|m|$: Absolute value of the post-peak slope of the load-deflection curve

A : Scaling factor (A = 0.01)

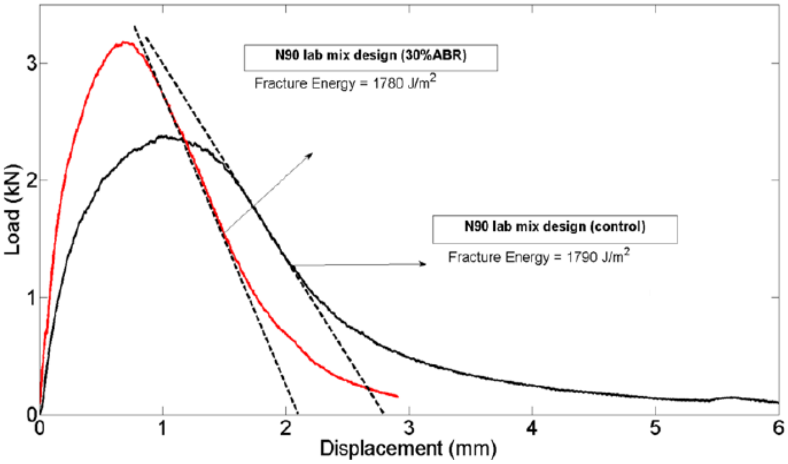


Fig. Source: Al-Qadi et al. (2015)

Figure 5: Load-Displacement Curves for Two Lab Produced Mixes with Similar Fracture Energy While Exhibiting Dissimilar Structural Response

Figure 6 shows a clear correlation between ABR and Flexibility Index (FI). As ABR increases, FI decreases with a much more pronounced trend as compared to fracture energy. Note that in this figure, mix design designations with AS, S1, and S2 following binder PG grade refer to mixes with anti-striping agents, RAS source 1, and RAS source 2 respectively. Also, Binder grade, RAP percentage, RAS percentage and source, and anti-stripping agents are the only variable parameters between mixes.

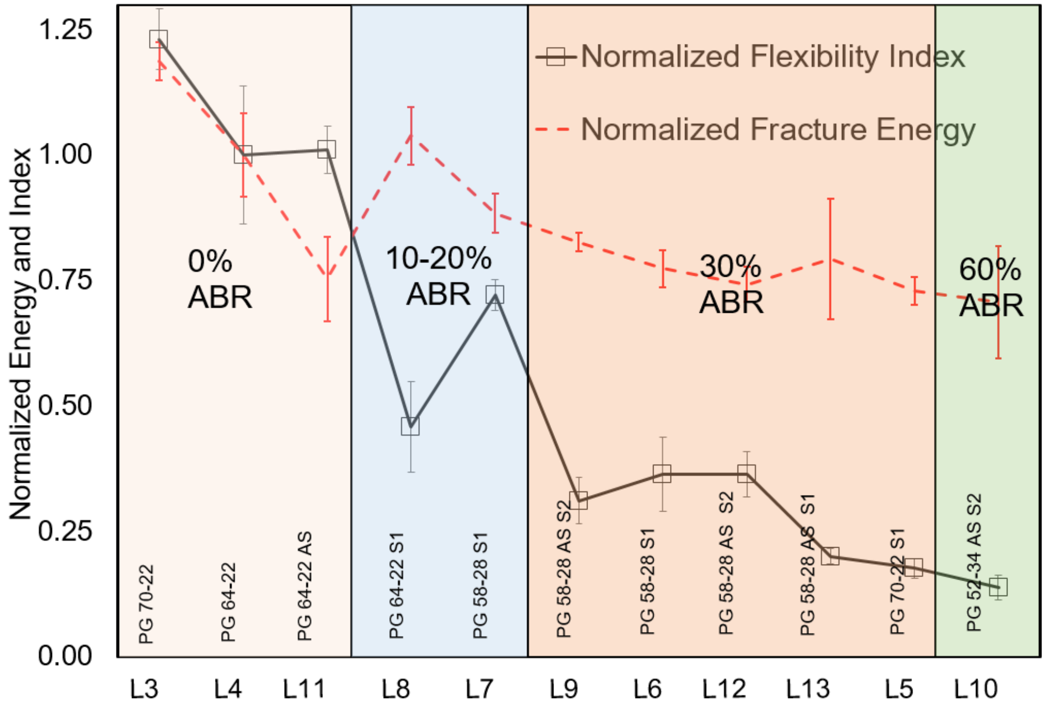


Fig. Source: Al-Qadi et al. (2015)

Figure 6: Normalized I-FIT Fracture Energy and FI for Laboratory Produced Mixtures

Data from the FHWA Turner Fairbanks' Accelerated Loading Facility (ALF) in McLean, Virginia was used to correlate field performance data with I-FIT test results. The sections were built in 2013 to determine the effect that ABR and Warm-Mix Asphalt technology have on fatigue cracking. All sections were built with the same structural thickness design while changes were made to the mix parameters of the AC layer. As Figure 7 shows, there is a strong correlation between ALF performance data and FI. High and low performing lanes are clearly identified by FI values. For intermediate performing lanes, the FI appears to overestimate fracture resistance. However, as noted by the research team, this can potentially be explained by documented variability during construction.

Field core data was also used to correlate I-FIT test data to field performance of 35 pavement sections in 9 districts throughout the state of Illinois. Pavement sections were divided into three general categories of performance based on distress severity, condition rating survey data, and field observation. As shown in Figure 8, FI values from I-FIT testing showed fairly good correlation with field performance data with a few exceptions. In the case of the 1-13 section which was a low performing section with a high FI value, significant frost heaving was reported which could have affected field performance data. Sections 867S1 and 5-US136-1 were incorrectly categorized using FI. However, all other sections showed good correlation between FI and field performance. Due to the many factors that can affect pavement performance which are unrelated to the AC layer, as well as the strong correlation between FI and ALF data, these exceptions were considered acceptable.

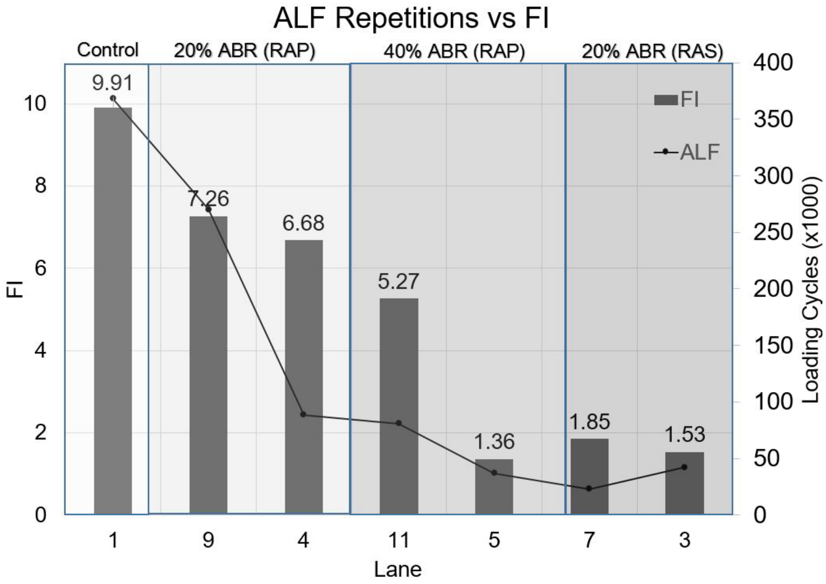


Fig. Source: Al-Qadi et al. (2015)

Figure 7: Correlation of FI with ALF Fatigue Cracking Measurements

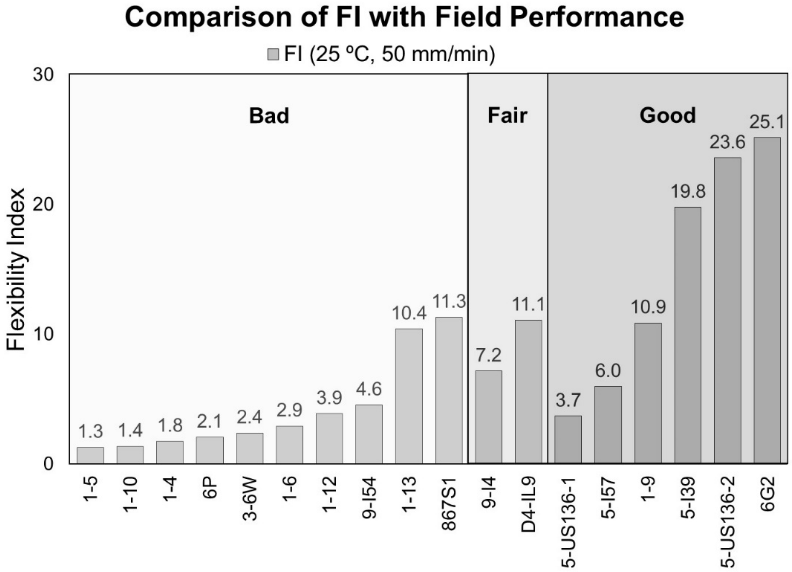


Fig. Source: Al-Qadi et al. (2015)

Figure 8: Correlation Between FI and Field Performance

Al-Qadi et al. (2015) also reported a strong correlation between FI measurements and pavement age as should be expected due to the increased binder stiffness associated with the oxidative hardening resulting from environmental exposure. Figure 9 shows the FI values for pavements constructed between 2003 and 2014 with a clear trend of increasing FI for newer pavements.

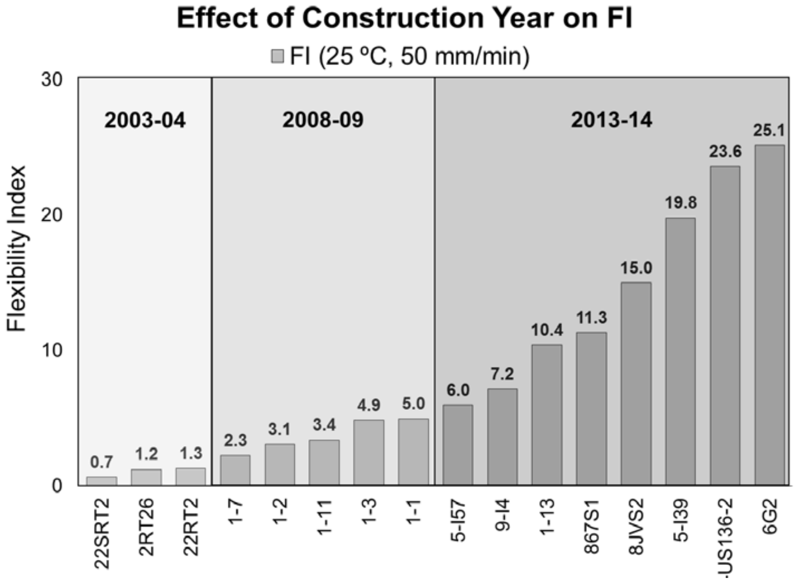


Fig. Source: Al-Qadi et al. (2015)

Figure 9: Effect of Pavement Age on Flexibility Index (FI)

Based on the results of this study, the I-FIT test was determined to be a cracking performance characterization test that showed a sensitivity to various mix design parameters and was able to detect changes in ABR percentages. Consequently, this test has been accepted as provisional American Association of State Highway Officials (AASHTO) standard TP 124: *Provisional Standard Method of Test for Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperature*.

The Louisiana Semi-Circular Bend Test (SCB-LA)

The Louisiana SCB test (SCB-LA) is another form of the monotonic SCB test similar to the I-FIT test. However, for this protocol, the measured parameter is the critical strain energy release rate or J-integral (J_c) originally proposed by Rice (1968). Both tests are conducted at 25°C but the SCB-LA test uses a monotonic loading rate of 0.5 mm/min as opposed to 50 mm/min used for the I-FIT test. Additionally, the SCB-LA test uses three specimens with different notch depths (25.4 mm, 31.8 mm, and 38.1mm). The J-integral is then calculated according to:

$$J_c = -\left(\frac{1}{b}\right) \times \frac{dU}{da}$$

where

a is the notch depth

$\frac{dU}{da}$ is the change in strain energy with notch depth

b is the specimen thickness

For each notch depth, the strain energy (area under the pre-peak load-displacement curve) is calculated and plotted vs. notch depth. The slope of a linear regression line of the strain energy versus notch depth is then determined and divided by the specimen thickness to determine J_c. Figure 10 shows typical load deformation curves from the SCB-LA test.

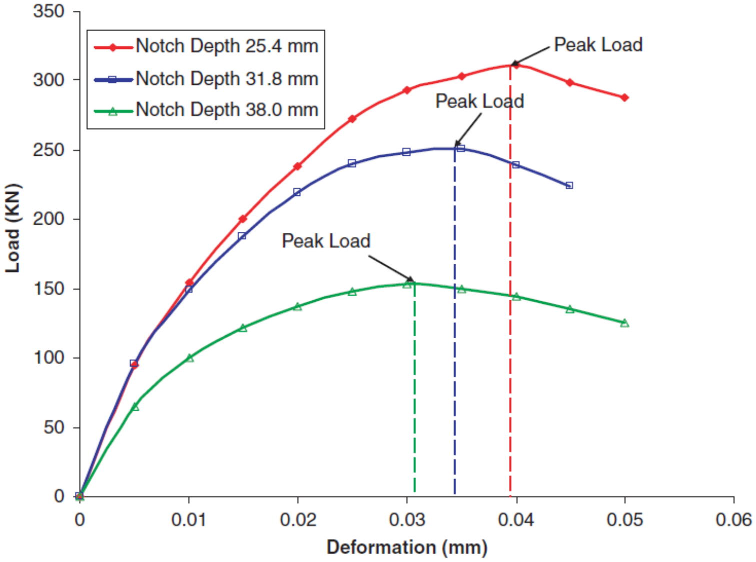


Fig. Source: Kim et al. (2012)

Figure 10: Typical Load-Displacement Curves for the SCB-LA Test

Researchers at the Louisiana Transportation Research Center (LTRC) conducted a study to determine the ability for the SCB-LA test to discriminate between various mix parameters (Wu et al. 2005). Thirteen (13) plant produced mixes consisting of four (4) binder grades, two (2) NMAS aggregate gradations, and four (4) gyratory compaction levels were tested. The test protocol was found to adequately differentiate between these parameters, and it was concluded that the SCB-LA test was a potentially effective test for determining fracture susceptibility.

In a subsequent study, Mohammad et al. (2011), returned to the same pavements studied by Wu et al. (2005) to determine if there was a correlation between laboratory SCB test data and field crack performance after over ten (10) years of traffic and environmental exposure. Field cracking measurements were compiled from Automated Road Analyzer survey data collected by the Louisiana Department of Transportation and Development. The data collected in the survey included transverse, alligator, longitudinal and random cracking counts categorized as low, medium, or high severity. Longitudinal and random cracking counts were left out of the study as they might not be related to fatigue resistance. The results are shown in Figure 11 on a semi-log plot of critical J-integral versus crack length per mile per million ESAL. An exponential regression of the data is shown with an R^2 value of 0.58. This value was considered to show good correlation between critical J-integral and field performance as many factors that influence field performance (environmental conditions, subgrade and base quality, etc.) were not considered in the study.

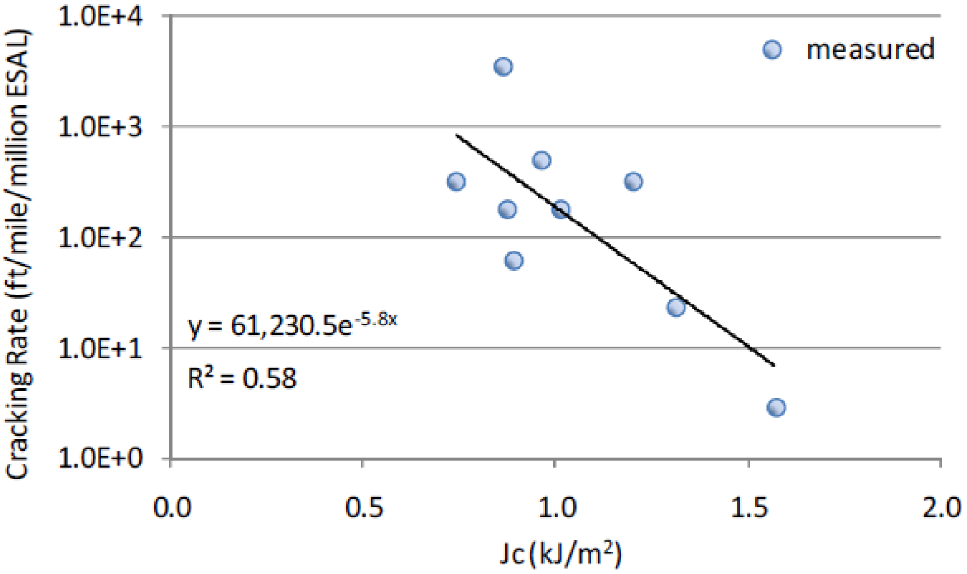


Fig. Source: Mohammad et al. (2011)

Figure 11: Correlation between Cracking Rate and J_c

A study conducted for the Wisconsin Highway Research Program (Bonaquist, 2016) to improve the durability of Wisconsin pavements evaluated the impacts of effective binder volume, low temperature performance grade, recycled binder content, and polymer modification on resistance to aging and load-associated cracking. The impacts of these parameters on durability was determined using SCB-LA testing conducted at 15°C. The change in test temperature was made based on the results of SCB testing from a previous RAP pilot project and the subsequent determination that 25°C, while appropriate for Louisiana where the protocol was developed, was not an appropriate test temperature for Wisconsin pavements (Hanz et al., 2015). In addition, the FI parameter was calculated from SCB-LA data using the 25 mm notch depth. Though performed at a lower temperature than recommended for the SCB-LA and I-FIT tests, this study provides a direct comparison between the Jc and FI parameters. The effect of aging (based on short-term vs long-term laboratory conditioning) was determined using both parameters. *It was found that strain energy release rate was not significantly impacted by aging, whereas the FI value was very sensitive to age conditioning which is consistent with increased binder stiffness due to* *oxidation.* The FI was correspondingly found to be much more sensitive to RAP content when compared to J_c. In addition, the value of the J_c parameter increased with higher low temperature grade which is inconsistent with engineering intuition. The FI on the other hand decreased with higher low temperature grade as expected. The binder was extracted from both short-term and long-term aged samples and the extracted binder properties were determined. A correlation was found between the recovered intermediate continuous grade temperature and flexibility index again indicating the ability of the FI to detect changes in binder stiffness. No such correlation was found between the recovered intermediate temperature grade and strain energy release rate. Due to these findings, the modified monotonic SCB-LA test using the FI parameter was selected for further analysis in the study which consisted of evaluating the effects of various specification changes on mix durability. Some general results from the study were:

1. The laboratory age conditioning procedure was more severe than plant aging resulting in lower FI values.
2. FI was very sensitive to effective binder volume.
3. Crack resistance improved with increased effective binder content.
4. Crack resistance improved as low temperature performance grade decreased.
5. Polymer modification improved crack resistance.

In a subsequent study conducted by Bahia et al. (2016) aimed at developing a performance-based durability specification for the Wisconsin Department of Transportation, a similar comparison between the J_c and FI parameters was made using the SCB-LA test (conducted at 15°C). In addition, the I-FIT test protocol was also included for comparison. The J_c parameter provided variable and inconsistent results similar to the results shown in the previous study by Bonaquist (2016). Logical trends between mix parameters and the FI as measured by both the SCB-LA, and I-FIT test procedure were observed. However, according to a sensitivity analysis done on the I-FIT test results, the I-FIT FI was found to be insensitive to ABR which contradicts the findings of Al-Qadi et al. (2015). It should be noted that in the development of the I-FIT test, Al-Qadi et al. (2015) exercised strict control over all volumetric parameters which were held constant for all laboratory mixtures tested. However, the Bahia (2016) study allowed mix parameters to vary within approved mix design specification limits which may explain the contradictory results. The sensitivity analysis also showed a very high sensitivity of the FI parameter to percent effective binder when using the I-FIT protocol. *Furthermore, a correlation between recovered binder properties and FI could not be found*. These results were concerning to the research team, and ultimately the modified SCB-LA test protocol was recommended for FI determination in the performance specification framework.

Comparison of intermediate temperature SCB test protocols

Based on the preceding discussions, the strain energy release rate does not show consistent logical trends in mix durability characterization. The J-integral is a path-independent integral that can be used to approximate the strain field near the crack tip. This approximation is valid for homogenous linear-elastic and elastic-plastic materials as long as small-scale yielding applies: yielding for an area much smaller than the size of the notch dimensions, un-notched specimen dimensions, etc. (Rice 1968). Rice (1968) showed that the rate of potential energy decrease per unit thickness with respect to an increase in notch length is equal to the parameter J, which is an averaged strain energy on the notch tip. Therefore, the critical J-integral provides a method for approximating the strain energy consumed (measured at peak load) and the associated cracking resistance. This is a fundamentally different formulation than the FI parameter developed in the I-FIT test as the FI formulation was based on an empirical correlation between total fracture energy, the rate of crack growth (after fracture), and the ductile/brittle response of the load-deformation curve. Just as with the total fracture energy parameter the measurement of an averaged strain energy consumed in the yielding region around the crack tip may potentially be insensitive to the ductile/brittle yield response of the load-deformation curve; the ductile/brittle behavior after fracture may have a significant impact on field performance. The assumptions for J-integral validity along with the fact that the J-integral parameter does not incorporate post-peak load-displacement characteristics may explain why the strain energy release rate showed some inconsistent and illogical results. The FI data on the other hand showed logical trends consistent with engineering intuition making the FI parameter a potentially superior test protocol for crack performance characterization.

A similar comparison between the I-FIT protocol and the modified SCB-LA protocol selected in the Bahia (2016) study leads to the following observations. The I-FIT test and FI parameter were developed to maximize the sensitivity of the test to changes in various mix parameters. A lack of correlation between I-FIT FI and ABR was cited by Bahia (2016) as another area of concern regarding the I-FIT test protocol. However, the mixes in the study had a wide range of effective binder content values (4.1 to 5.6 percent) which, as the sensitivity analysis showed, the I-FIT FI is highly sensitive to, potentially confounding any correlation. On the other hand, the mixes in the Al-Qadi et al. (2015) study had effective binder contents ranging from 4.61 to 4.92 percent. Over this much smaller range of effective binder content, the Al-Qadi et al. (2015) study was able to detect a strong correlation between ABR and FI.

A more recent study conducted by Ling et al. (2017) tested the sensitivity of the I-FIT test protocol and the FI parameter to changes in RAP content, design traffic levels, binder grades, binder modification, and aging conditions of commonly used Wisconsin mixes, and the sensitivity of the protocol to production variability. The study found that the FI was most sensitive to aging which is consistent with previous findings (Al-Qadi et al., 2015, Ozer et al., 2016). In addition, they found that ABR was a significant factor affecting the FI parameter with higher ABR resulting in lower FI as expected. Binder modification also had a positive effect, with FI improving for modified binders. In general, softer binders tended to improve cracking resistance. The dust to binder ratio and percent passing 200 were both found to have a significant effect on FI, and the design traffic level had a negative effect on FI which was pointed out as an area for concern as designing for higher traffic loads should result in a more durable pavement. The analysis of production variation found that variation in binder content and filler content within specification requirements was within the range of the I-FIT test variation. Overall, the research team deemed the I-FIT test ready for implementation in Wisconsin but recommended that FI thresholds should be calibrated against field performance.

Strategies for Producing High RAP Content Mixtures

Zhou et al. (2013) proposed different approaches for improving the cracking resistance of RAP/RAS mixes. Four approaches were suggested for improving cracking resistance: (1) reducing RAP/RAS usage; (2) using rejuvenators in the mix design process; (3) lowering design air voids (increasing design density); and (4) using a soft virgin binder. They showed that using softer binders or modified binders (PG xx-28, PG xx-34) can substantially help improve cracking resistance of recycled asphalt pavement mixes without influencing moisture/rutting damage resistance.

Kaseer et al. (2017) observed that the use of a softer and less stiff virgin binder, and including recycling agents at higher doses resulted in recycled mixtures with desirable stiffness and relaxation properties, and therefore recommended the use of recycling agents for high-RAP mixtures. They also recommended further research to evaluate the long-term cracking resistance of the recycled asphalt mixtures.

McDaniel et. al (2002) reported that mixtures that can perform successfully with high-RAP contents up to 50 percent can be designed by binder replacement. Maupin et. al, (2008) observed that although addition of RAP can raise the high-temperature grade of the combined binder by few grades, there was no notable difference between the laboratory performance test results of low-RAP mixtures (Less than 20 percent RAP content) and high-RAP (between 21 to 30 percent RAP content) mixtures.

Al-Qadi et al. (2012), from an extensive study, concluded that high-performing asphalt mixtures with as much as 50 percent RAP can be designed to meet volumetric as well as performance requirements. However, to achieve this, they strongly recommended RAP fractionation as well stockpile management practices, and double grade bumping (decreasing of both the high- and low-temperature grades) for mixtures containing more than 30 percent RAP. Note that Al-Qadi et al. (2012) cautioned against using their results for all mix types. Their laboratory test matrix included HMA with no polymer- or chemically modified asphalt. Accordingly, extending their findings to mixes that contain such modified binders, may lead to erroneous assumptions/conclusions.

Bennert et al. (2014) conducted a research study, where the following three strategies were adopted to ensure adequate performance of asphalt mixture containing RAP: (1) using a softer binder grade to offset the stiffening effect of the RAP binder; (2) limiting the amount of Binder credited to the total asphalt content in the mix; and (3) performance testing to achieve minimum cracking and rutting resistance. They discussed the advantages and disadvantages of each method. For example, the first approach, to use a softer binder grade, does not require any additional efforts with respect to mix design. However, it may create challenges related to binder availability. For example, the binder with the softer grade may not be locally available where desired. The second strategy, to limit the amount of RAP binder that is counted in the total binder content of the mix, requires the addition of higher amounts of virgin binder to achieve the same total asphalt content in the mix. In other words, redesign of the asphalt mixture is usually required. Nevertheless, once the mixture has been redesigned, the original binder PG grade, commonly used in the region, can be used, thus avoiding challenges related to local binder availability. The third approach, involving performance testing of the mixture, usually requires alteration to the binder type as well as the mix design. However, by adopting this approach, the agency is usually confident about performance of the mix in the field. From extensive laboratory testing, Bennert et al. (2014) observed mixed results regarding the benefits of the first two approaches. They recommended that the final approach (performance testing), although complex, may be the best approach to adopt by agencies.

West and Copeland (2015) recommended that in the US, agency specifications should allow the use of RAP in asphalt pavement layers at the contractor's discretion. They also recommended that agencies should provide simple and clear criteria for ensuring pavement performance, including simple lab mix stiffness tests, and criteria for mixture suitability. They also recommended using rejuvenators, softening binders, or other agents, to facilitate high RAP amounts in asphalt mixtures. Similarly, Nair et al. (2019) concluded that mixtures containing up to 45 percent RAP can be designed, produced, and constructed, if proper procedures are followed, and attention to details is paid during design production, and construction.

West and Copeland (2015) also recommended implementing best practices for RAP processing, storage, mixture production, paving, minimizing moisture in RAP, fractionation for high RAP use, covered RAP stockpiles, and longer mixing times during production. They observed that keeping the RAP stockpile dry was probably the biggest factor. Keeping the RAP dry will eliminate the need for super-heating the virgin aggregates (necessary for indirect heating of the RAP). This also helps increase production rates.

Kaseer et al. (2019) discussed strategies that can be used for producing asphalt mixtures with a high percentage of RAP. First, they used a sample with maximum allowable RAP content according to WisDOT 2017 (Wisconsin Department of Transport) specification. Second, they used a sample with RAP content which exceeded the maximum allowable limit. Third, a softer binder mixed with high RAP content mix. Fourth, they used a mix containing high RAP content along with a dose of recycling agent which is sufficient to reduce the grade of the virgin binder by just one grade for both the low and high temperature ends. Fifth, the mix containing the chosen amount of recycling agent's dose along with RAP content to match the continuous high-temperature performance grade of the target temperature (PG58-28 for Wisconsin climate and traffic conditions). Allowable recycled binder ratio (RBR) according to WisDOT specification is 0.25 (or 25 percent) for upper asphalt mixture layers. All the samples were examined and tested using the Illinois flexibility index test, Hamburg wheel-track test, Asphalt Pavement Analyzer, uniaxial thermal stress, and strain test, Bending Beam rheology test, Disk-shaped compaction tension test, and dynamic modulus.

Results stated that, in the binder blend test, added RAP binder increased the stiffness of the material as compared to the virgin binder (PG58-28) without a RAP binder. A low dose of recycling agent or using softer virgin binder helped in reducing the stiffness, but in the fifth case, adding the chosen dose of recycling agent to match the continuous high-temperature performance grade (PGH) of the target climate resulted in yielding the lowest stiffness and potential ductility improvement. When recycled binder ratio (RBR) was increased to 0.31, lower cracking resistance was obtained in all the tests. This indicated that if proper balance/adjustments are not made to the mix design (using recycling agents or softer binders), it will lead to the poor performance of the mixtures with high RBR. In the third case, using softer virgin binder was effective in improving cracking resistance, but couldn't consistently attain the best performance as compared to the rest of the mixtures. Similar results were noticed when low doses of recycling agents were used. The also observed that mixtures that contained a high dose of recycling agents to match the continuous PGH of target climate, consistently obtained the best performance as compared to other mixtures as their RBR value was higher (0.31 and 0.5). Based on the results, the conclusion was made that the use of recycling agents instead of a softer binder can help engineers design asphalt mixes with higher RAP content. Also, the authors recommended that for high RAP mixtures, recycling agents at a dose which can match the continuous PGH of the target climate will help obtain the best performance.

Production of high-RAP mixtures in Japan

West and Copeland (2015), in their report of a technical scanning tour to Japan, reported about the following standard practices in Japan, that have contributed to successful design and production of asphalt mixtures with high RAP contents.

1. Covering of stockpiles, and placing stockpiles on paved surfaces
2. Controlling the moisture and dust contents of the RAP during crushing, processing, and storage
3. Recovery of RAP binders and testing to evaluate their stiffness
4. Fractionation of RAP, and equipping plants with multiple RAP feed bins.

Note: West and Copeland (2015) highlight that although the benefits of most of these practices are recognized in the US, they are not widely implemented by U.S. asphalt mix producers. In Japan, it is standard practice for the RAP to be heated in a separate dryer. The RAP is then mixed and conditioned with a rejuvenator for several hours before it is mixed with hot virgin aggregate and asphalt. Moreover, the production facilities in Japan primarily comprised batch plants, whereas in the U.S., continuous mix plants are more prevalent.

RAP: Material Processing and Handling

RAP processing and material handling procedures are important considerations when using RAP in HMA pavements. Material variability, quality of RAP materials, and stockpile management are some of the key factors that when managed properly, ensure high-quality RAP materials. This section provides a brief summary of some of the 'best practice' material processing and handling procedures compiled from FHWA-HRT-11-021 Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice (Copeland, 2011), and NAPA Improvement Series 129: Best Practices for RAP and RAS Management (West, 2015).

RAP sources and stockpiling procedures

A large percentage of RAP used today comes from the milling of existing pavements. Milling is an effective rehabilitation technique as it allows the removal of distressed pavement without disturbing structurally viable asphalt layers or base materials below. It also eliminates unwanted elevation changes around sidewalks and gutters, under bridges, and other elevation critical areas. When done properly, the milled RAP material will be a consistent high-quality material that can be incorporated directly into a new HMA pavement. Milling depths should be chosen carefully to prevent the contamination by underlying layers, geosynthetic materials, or other deleterious materials. Separate passes should be considered for surface, intermediate, or base courses if large differences in NMAS exist between the layers to provide a more consistent RAP material. Additionally, it may be advantageous to mill and process surface courses containing high value friction aggregates, high specific gravity steel slag, or asphalt rubber binder separately. Milled RAP from large projects or from DOT-approved pavements are frequently stored in separate stockpiles to preserve the quality of the RAP. The decision to use single-sourced stockpiles must be made based on a number of factors such as storage area requirements and the size of the reclamation project. However, it is recommended to use single-source stockpiles whenever possible. A single-source stockpile can typically be used without further processing, provided proper mixing is ensured.

Full-depth replacement through ripping and crushing is another source of RAP material. This method is time-consuming and produces large chunks of asphalt that are more difficult to process. Care should be taken to not introduce debris from underlying layers. If the pavement rubble becomes contaminated with debris, this material should be crushed, and used for base or shoulder material rather than incorporated into the HMA. The quality of pavement rubble should be closely monitored for deleterious debris when unloading and stockpiling. Pavement rubble is frequently obtained from various sources and stockpiled in multi-source stockpiles.

Asphalt plants produce waste asphalt mix during plant start-up and shutdown (typically low in binder content). Additionally, plant waste is generated when plant mix temperatures don’t meet project requirements, gradation limits are exceeded, or other operational problems are experienced. Field-rejected mix, mix produced in quantities exceeding project requirements, or mix that could not be laid down due to inclement weather are other examples of plant-generated waste. Plant waste has not been exposed to environmental oxidation, and therefore the binder is typically softer compared to a typical RAP binder. Plant-waste is typically stored in multi-source stockpiles with other sources of RAP. Multi-source stockpiles frequently need further processing and mixing prior to use; however, these stockpiles can still provide a high-quality source of RAP. Nevertheless, it should be noted that when plant waste is used as a source of RAP, the grade bumping procedure during mix design needs to be adjusted. Grade bumping is carried out to account for the stiffer binder being released from RAP. However, the binder released from plant-waste RAP is not as stiff, and therefore, may not require as significant a grade bump.

Proper RAP stockpile management is key to controlling RAP variability. RAP stockpiles frequently contain RAP from various sources having different aggregates, gradations, asphalt binders, and asphalt binder contents. To accurately determine the material properties of the stockpile for mix design purposes, the stockpile must be well-blended into one consistent material. To facilitate this blending, newly delivered RAP should be added to existing or new stockpiles in layers. A small bulldozer should be used to push the RAP onto the stockpile. Care should be taken to not push the material over the edge of the stockpile slope as this promotes segregation. When moving RAP from stockpiles to the plant, the RAP should be excavated from the side, working through the layers. Additionally, the loader should excavate from random locations around the stockpile rather than working in one location. Screening and crushing operations are very effective blending techniques and should be used for multi-source stockpiles to construct stockpiles with consistent properties. When building stockpiles using conveyors (crushing, screening, etc.), conical stockpiles should be built and the distance the RAP is allowed to drop should be minimized to minimize segregation. To prevent the accumulation of water, flat stockpiles or stockpiles with depressions should be avoided. Sloped stockpiles will naturally shed water and avoid excessive water content. High water content can cause problems when crushing, may need to be removed prior to adding RAP to super-heated virgin aggregates, and can increase overall production costs. Covering RAP stockpiles with an open-walled shelter is the best method for controlling water content. When covering stockpiles is impractical, stockpiles should be built on sloped paved surfaces to promote drainage and eliminate contamination from underlying soils

RAP processing

RAP processing typically consists of screening, crushing, fractionation, or some combination thereof. Screening provides an opportunity to remove large aggregates or rubble, while simultaneously blending stockpiles. Screening can also be used during crushing to remove smaller aggregate from the crusher so that only larger aggregates are crushed, thereby reducing the amount of fines that are produced. Crushing is used to break-down larger agglomerations and aggregate into a smaller size for the more effective incorporation into a variety of new mixtures. Some crushers are designed to break down large chunks or agglomerations of RAP without breaking down the aggregate, whereas others are designed to break the aggregate to a desired top-size. However, a balance must be achieved between crushing to a smaller size, and the corresponding increase in dust proportion and P_{200} content (the amount of aggregate passing the No. 200 sieve). Fractionation is a process where RAP is screened into two or more sizes. The primary benefit of fractionation is that it results in multiple stockpiles of various sizes providing added flexibility in meeting mix gradation requirements. Fractionation is particularly helpful when producing mixtures with 20 percent or more RAP content as it can aid in controlling dust proportion, P_{200} content, and meeting minimum VMA and other QC/QA requirements. However, fractionation requires additional stockpile area, and may not be beneficial if most mixes a plant produces use less than 20 percent RAP. In addition, fine-fractionated stockpiles can form agglomerations which may be difficult to feed through the plant. Fractionation is required by some DOTs for high-RAP mixtures due to the belief that RAP stockpiles have highly variable material properties. However, according West (2015), RAP stockpiles, when constructed following recommended practices, have a more consistent gradation than virgin aggregates and can have very consistent asphalt content and asphalt binder properties. Rather than requiring fractionation, DOTs are encouraged to use variability limits to control high RAP mixtures. This leaves the fractionation decision in the hands of the contractor. Well-managed stockpiles may be able to produce consistent materials precluding the need for fractionation, and thereby reducing production costs.

RAP sampling and testing

RAP stockpiles should be tested from a minimum of ten (10) random locations throughout the stockpile to adequately establish material variability in terms of gradation and binder content. It is preferable to sample a stockpile as it is being constructed in the location where it will be fed into the plant, as this will provide the most representative sample. When it comes to quality testing of the RAP aggregate and binder, a minimum of 1 test for every 1,000 tons of RAP processed should also be established. It should be noted that these are generic recommendation from the references cited at the beginning of this section. The author acknowledges that these requirements may change from one agency to another and may also vary depending on the stockpile size. For example, ITD requires a quality control plan from the contractor with detailed information about the processing and stockpiling practices.

The most effective way to obtain representative samples from a RAP stockpile is with the help of a front-end loader. The recommended procedure is detailed in Section X1.2 of AASHTO T 2-91 (2015). The basic procedure is listed below:

1. Dig-up through the stockpile layers using the front-end loader and then create a mini-stockpile with the excavated material.
2. Back-blade across the top of this mini-stockpile creating a flat surface.
3. From this surface, collect three random samples from different locations and combine them together.
4. Repeat this process for other locations around the stockpile (minimum 10).

For projects using a portable asphalt plant adjacent to proposed milling areas, the samples must be taken directly from the roadway prior to plant construction for mix-design purposes. The best method for collecting representative samples directly from an existing pavement is to mill several small areas along the roadway with a full-sized milling machine. Other methods such as coring the pavement and crushing the cores or using a small mill head do not provide samples representative of the material that will be produced by the full-scale milling process.

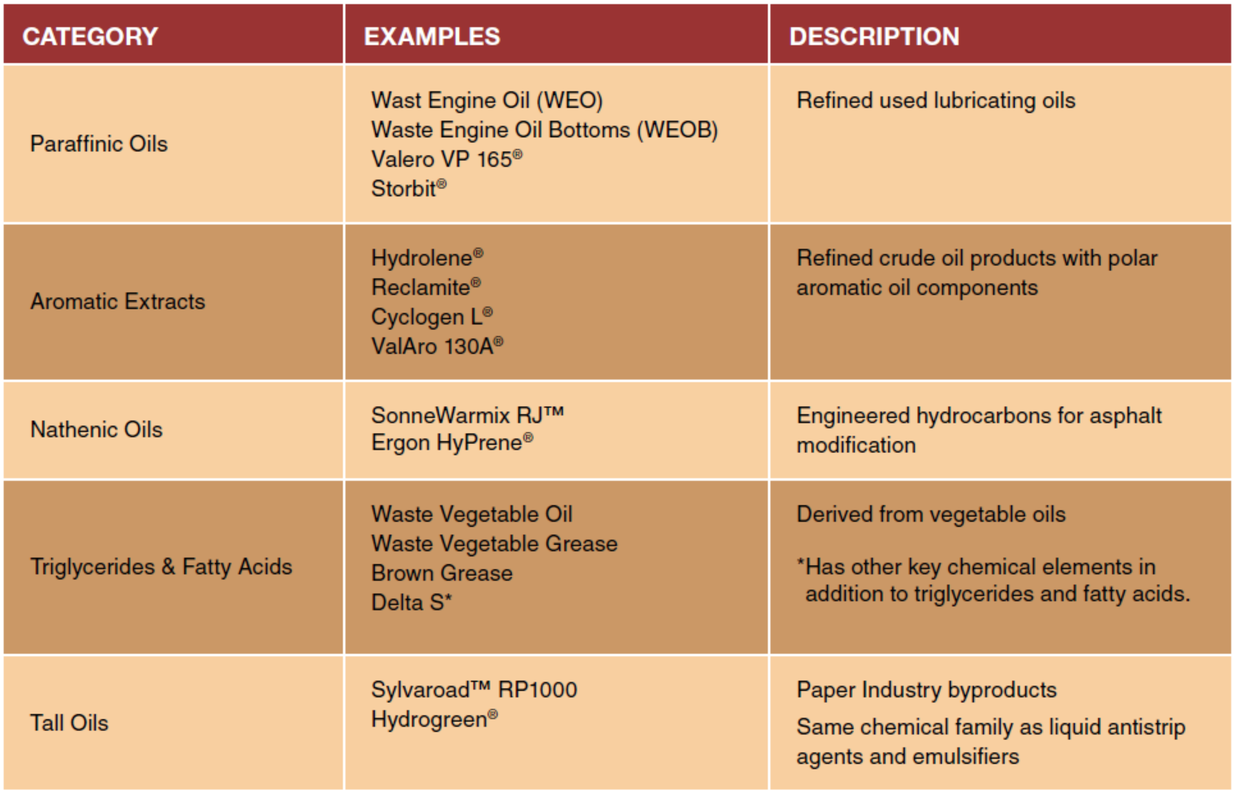
The samples collected from each location within the stockpile, or pavement are used to establish the variability of the aggregate gradation and binder content. The recommended limits in standard deviation of asphalt content, percent passing the median sieve, and the percent passing the No. 200 sieve are 0.5 percent, 5 percent, and 1.5 percent, respectively (West, 2015). These values are based on data gathered from contractors using many of the recommended best practices. Once the variability of the stockpile has been established, the remaining portion of the samples from each location should be blended to obtain one representative sample for mix design purposes. RAP testing should include the asphalt binder content, gradation, bulk specific gravity, and the consensus properties of the recovered RAP aggregate. The asphalt binder properties must also be determined when a RAP/virgin blending chart is required for high RAP contents. From AASHTO M 323, for RAP percentages less than 15 percent, no virgin binder adjustment is required. However, for RAP contents between 15 to 25 percent the virgin binder selected is one grade softer than would normally be used. For RAP contents above 25 percent, a blending chart of RAP and virgin binder is developed through rheological testing of RAP and virgin binders. It should be noted that different agencies may adopt modified versions of these specifications. For example, per ITD specifications, no grade bumping is required when the RAP content is less than 17 percent. One grade bump is required for RAP contents between 17 and 30 percent, whereas blending chart should be used for RAP contents greater than 30 percent (when RAP percentages greater than 30 percent were allowed).

There are three common methods used to determine RAP asphalt content, and to recover aggregates for sieve analysis and testing: (1) the ignition method, and (2) two different solvent extraction methods. The ignition method is the most commonly used method due to its relative simplicity, accuracy, and repeatability. The other two methods, centrifuge extraction and reflux extraction, use chlorinated solvents. Due to health and environmental concerns, these methods are used less frequently. In the ignition method, the RAP aggregates are placed in an oven and heated to 538°C or less until the asphalt is ignited. The estimated asphalt content is the change in mass after ignition, corrected for moisture content, and an aggregate correction factor. The aggregate correction factor is the difference between the true asphalt content, and the asphalt content measured by the ignition method. The aggregate correction factor must be determined for each oven and aggregate by repeated testing of a mixture with a known asphalt content. However, for RAP aggregates, the aggregate correction factor can't be determined directly. Instead, because these factors remain fairly constant for aggregates from the same source, historical correction factors can be used to estimate the asphalt content of RAP with aggregates from known sources. For RAP with an unknown aggregate source, or for RAP with aggregates that have significant changes in mass when heated, solvent extraction methods should be used. According to West (2015), it is not recommended to use solvent extraction methods to determine the aggregate correction factor for the ignition method; solvent extraction methods are less accurate than the ignition method for determining asphalt binder content. Although this statement is mostly valid for virgin mixes, whether it applies widely to mixture containing RAP, is still unknown. The reader should note that recently, ITD procured an automated extractor that can perform the tasks with minimal environmental/health related concerns.

The determination of the bulk specific gravity (G_{sb}) of RAP aggregates is very important for accurately determining the VMA for the final mix. All three extraction methods cause changes in aggregate gradation and properties, and therefore, can provide inaccurate G_{sb} values. One method to obtain a better estimate of G_{sb} uses the binder content and the maximum theoretical specific gravity (G_{mm}) of the RAP to determine the effective specific gravity (G_{se}). The aggregate G_{sb} is then calculated using an equation based on local aggregate absorption. The accuracy of this estimate is highly dependent on the accuracy of the assumed aggregate absorption. ITD's method for G_{sb} determination (IT-146-16) uses an assumed value for percent binder absorption (P_{ba}) of two-thirds the water absorption of the virgin aggregates used in the project. Using this assumed value of P_{ba} may provide an accurate value of absorption for typical Idaho aggregates. However, this value may not be appropriate for other aggregate sources. Historical aggregate absorption data for RAP aggregates should be used wherever available. If the absorption of local aggregates is not accurately known, extractions should be used to determine G_{sb}. For RAP aggregates with a known aggregate correction factor, and those that are relatively unaffected by ignition oven temperatures, the ignition method can be used to recover RAP aggregates, and determine specific gravity values; otherwise, solvent extraction methods can be used. However, these methods can leave small amounts of binder on the aggregates leading to errors in G_{sb} results.

Use of Recycling Agents or Rejuvenators

Another approach to produce asphalt mixtures with high RAP contents involves the use of rejuvenators or recycling agents. Recycling agents or rejuvenators, possess physical and chemical features that help restore the rheological properties of aged asphalt binders in order to enhance recycled asphalt mixture's performance that has a high content of RAP. Rejuvenators can promote environmental as well as economic benefits (Kaseer, 2019). Principally, rejuvenators reactivate the bitumen to restore performance and durability, but cannot undo oxidative aging (Tabatabaee, 2020). Though some researchers interchangeably use both terms recycling agents and softening agents, a proper differentiation should be done between them as both are different in their own ways. Whereas recycling agents are used for restoring the aged binder's chemical properties and physical properties by asphaltene/maltene ratio restoration, softening agents (also known as fluxing agents) are used to reduce the aged binder's viscosity. (Kaseer et al., 2019). Slurry oil, asphalt flux oil, and lube stock are some examples of softening agents. (Roberts et al., 1991). Different types of rejuvenators are available in the market. Willis and Tran (2015) present examples of categories of rejuvenators, and their respective examples (see Figure 12).



CATEGORY	EXAMPLES	DESCRIPTION
Paraffinic Oils	Wast Engine Oil (WEO) Waste Engine Oil Bottoms (WEOB) Valero VP 165® Storbit®	Refined used lubricating oils
Aromatic Extracts	Hydrolene® Reclamite® Cyclogen L® ValAro 130A®	Refined crude oil products with polar aromatic oil components
Nathenic Oils	SonneWarmix RJ™ Ergon HyPrene®	Engineered hydrocarbons for asphalt modification
Triglycerides & Fatty Acids	Waste Vegetable Oil Waste Vegetable Grease Brown Grease Delta S*	Derived from vegetable oils *Has other key chemical elements in addition to triglycerides and fatty acids.
Tall Oils	Sylvaroad™ RP1000 Hydrogreen®	Paper Industry byproducts Same chemical family as liquid antistrip agents and emulsifiers

Fig. Source: Willis and Tran (2015)

Figure 12: Types of Rejuvenators and Corresponding Examples

Effectiveness of recycling agents or rejuvenators

The effectiveness of a recycling agent depends upon various factors. Mix design factors like recycling agent's type, recycling agent's dose, recycled material quantity, source from which recycling agent was obtained, and virgin binder's source and grade affects the recycling agent's short-term and long-term effectiveness in asphalt mixtures and rejuvenated binder blends. Effectiveness of the recycling agents is also affected by production factors such as recycling agent incorporation method (whether adding to recycled materials/mixtures directly or adding to virgin binder), and mixing temperature and mixing time (Kaseer et al., 2017; Kaseer et al., 2018; Yin et al., 2017; Cucalon et al., 2017; Cucalon et al., 2018; Kaseer et al.,2019).

Changes in the chemical properties of the recycling agents and reduction in the maltene phase's dispersive power can also take place due to the aging of rejuvenated binders and asphalt mixtures. In asphalt mixtures and rejuvenated binders, due to aging, recycling agents lose their effectiveness. The intensity of loss depends upon the type of recycling agent and dosage selected (Kaseer et al., 2017; Yin et al., 2017; Ali et al., 2015; Menapace et al., 2018; Kaseer et al.,2019).

Ali et al. (2015) investigated the impact of RAP content and aging on the rejuvenator's effectiveness. For their study, multiple sets of asphalt mixtures containing 25 and 45 percent RAP were prepared and five different binder rejuvenators were used (An Oleic Acid, a Paraffinic Oil, a Naphthenic oil, an Aromatic Extracts, and a Tall oil). Rejuvenator blended with PG 76-22 polymer-modified asphalt binder at a dosage recommended by the rejuvenator manufacturer was used. Experiments were conducted to evaluate the different types of rejuvenator's capability to lower the PG (Performance Grade) of the mixture containing high RAP and to scrutinize the RAP content and aging impact on the five different rejuvenator's capability in restoring aged RAP binder's temperature grade. Results showed that compared to the control binder without rejuvenator (PG 88-22), rejuvenated binder extracted from mixtures containing RAP possessed lower high-temperature performance grade (PG 82-22). As all the five types of rejuvenators used for the experiment showed that they lowered the aged binder's true PGH, it was concluded that using rejuvenators is a feasible option to produce mixtures containing high RAP percentage up-to 45 percent. Results also showed that asphalt mixture's aging did not substantially impact all the five rejuvenator's capability to lower the PGH and PGL of the extracted rejuvenated binders.

The capability of all five rejuvenators to rejuvenate mixtures containing 25 percent RAP was similar to mixtures containing 45 percent RAP material. This suggests that the effectiveness of rejuvenators in rejuvenating is the same regardless of the RAP percentage (up to 45 percent). DSR results also suggested that while producing mixtures with a high content of RAP, rejuvenators can help in improving fatigue cracking resistance of the mixtures. Lastly, experimenters recommended to use rejuvenator obtained from Paraffinic Oil as it was most effective in rejuvenating the aged RAP binder's high temperature and low-temperature characteristics (Ali et al., 2016).

A detailed study presented by Zaumanis et al. (2013) discussed the effectiveness of rejuvenator with conventional mix testing for mixtures containing 100 percent RAP. For experimental study purpose, nine different types of rejuvenators which were obtained from waste-derived oils, plant oils, engineered products, and traditional refinery base oils and non-traditional refinery base oils were used. Results suggested that softening efficiency of the rejuvenators varied by a factor of twelve between the least effective and the most effective at 25°C. Test results demonstrated that four out of nine rejuvenators helped in increasing the cracking resistance of mixtures containing high content of RAP at lower temperatures and helped in reducing the consistency of extracted asphalt binder to the required level.

Use of Rejuvenators for Producing High-RAP Content Mixtures

Aging of an asphalt layer in a pavement takes place because of porosity (air permeability), UV rays, climate conditions, etc. Aging first takes place at the surface layer, and then moves in the downward direction towards the base layer. As the bitumen is aged, it becomes more brittle and less durable, which eventually leads to crack formation, and penetration of water through the cracks. Tabatabaee (2020) discuss the use of rejuvenators to produce mixtures with high RAP and RAS contents. The incorporation of the rejuvenators takes place in the plant itself. There are many methods for dosing the rejuvenators into the bitumen. Pre-blending rejuvenators into virgin bitumen, pre-treatment of the RAP, dosing in the virgin bitumen with the help of an anti-strip pump, injection into the pugmill, inline dosing, etc. are some of the dosing methods in practice. Among all the dosing methods, inline dosing methods are the preferred method (Tabatabaee, 2020). Based on results obtained from the MnRoad and the NCAT tests facilities, Tabatabaee (2020) reported that mixtures with 45 percent RAP and rejuvenators performed as well as those with 25 percent RAP.

Veeraragavan et al. (2017) reported about a research study carried out for the Maine DOT, and compared the performance of rejuvenated 50 percent RAP mix with that of a 20 percent RAP mix. Two types of rejuvenators were used for testing purpose- (i) (CAR) commercially available rejuvenator (Bio-based) and (ii) generic waste vegetable oil (non-petroleum based). From their testing effort, they observed that mixtures with 50 percent RAP and rejuvenator could perform as well as, or better than conventional mixtures with 20 percent RAP (no rejuvenator). Low- and intermediate-temperature cracking resistance, often a major concern for high-RAP mixtures, was found to benefit significantly from the use of rejuvenators.

Effect of Rejuvenator Mixing Procedure on Asphalt Mix Performance

Rejuvenator dosage plays a major role in governing the mixture's performance. Usually, the correlation between the blended binder's critical performance grade temperatures is used to determine the rejuvenator dosage for mixtures containing high RAP (Shen et al., 2002, 2007). A rejuvenator's effectiveness depends upon how it is been introduced to the RAP mixtures as the reaction between RAP's binder and newly added rejuvenator is a function of the mixing procedure when producing high-RAP mixtures (Martin et al., 2015). Xie et al. (2019) investigated the effect of the type of rejuvenators and mixing procedures on the asphalt's volumetric properties of 50 percent RAP mixture. Rejuvenators can counteract the RAP binder's aging effect and impact the volumetric properties as well. For the experimental study purpose, three different types of rejuvenators, and three mixing procedures were used to prepare mixtures containing 50 percent RAP. Tests were conducted to determine the following volumetric properties: voids in mineral aggregate (VMA), air voids, and dust to binder ratio. Results demonstrated that, for all the rejuvenator types, mixing procedures and rejuvenator type drastically impacted the air voids. Results also showed that only when rejuvenator, RAP material, virgin aggregates, and virgin binder were mixed in the mixing bowl, the type of rejuvenator significantly affected the voids in mineral aggregate (VMA). Also, there was no practical difference seen in the dust to binder ratio because of the rejuvenator type and mixing procedure. Based on the experimental study, researchers suggested that as rejuvenator types and different mixing procedures can significantly affect the air voids and VMA (volumetric properties) while designing mixture with rejuvenator and high RAP content, rejuvenator types and mixing procedures should be considered and should not be ignored.

Challenges to incorporating recycling agents

Although rejuvenators have been found to be quite effective in improving the properties of asphalt mixtures with high RAP contents, there are some challenges associated with incorporating them into the mix. Kaseer et al. (2019) listed the following challenges associated with incorporating rejuvenators into mixture with high RAP-contents.

1. No standard procedure or test method exists for the recycling agent’s characterization.
2. Scarce knowledge regarding the evaluation of the recycling agent’s effectiveness in asphalt mixture.
3. Scarce knowledge regarding integrating/blending recycling agents.
4. Scarce knowledge regarding recycling agent type selection and determining suitable/required recycling agent dosage.
5. Scarce knowledge regarding the recycling agent’s cost-effectiveness.
6. Scarce knowledge regarding the recycling agent’s long-term effectiveness.

Nevertheless, there is strong evidence suggesting that properties of high-RAP asphalt mixtures can be significantly improved through the use of rejuvenators.

Other Approaches

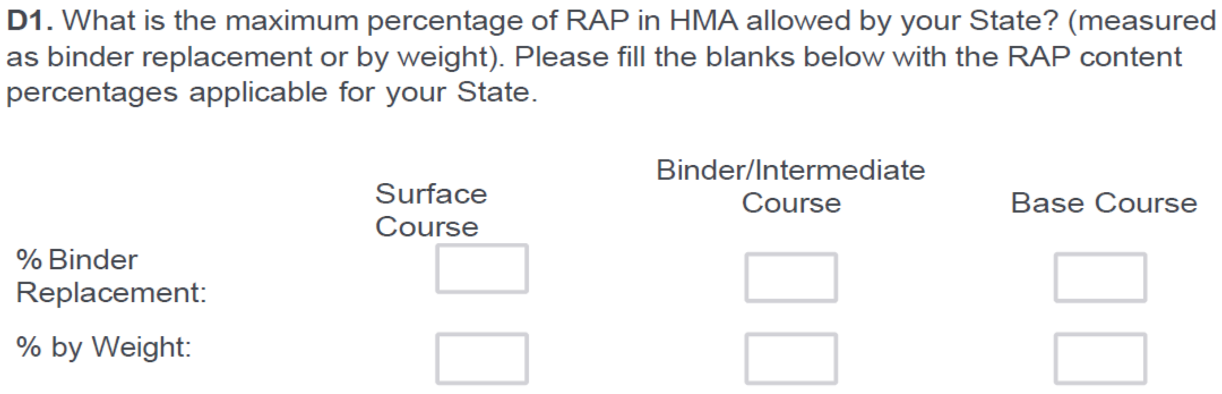
Willis et al. (2013) conducted an experimental study to evaluate the effects of changing virgin binder grade on mixture properties of high RAP content mixtures. Their objective was to study ways to improve the high RAP content mixture’s durability. Two approaches were analyzed: increasing the mixture’s asphalt content by 0.25 percent and 0.5 percent or using a softer virgin binder grade. For the experimental study, mixes containing 0 percent RAP, 25 percent RAP, and 50 percent RAP were designed with the help of softer binder grade PG 58-28 and a virgin binder PG 67-22. They recommended that to improve cracking resistance, the amount of virgin asphalt should be increased by 0.1 percent for every 10 percent of RAP binder in the mixture, for up to 30 percent RAP binder. Once the RAP binder exceeds 30 percent, a softer grade of asphalt should be used to increase the mixture’s resistance to cracking.

3. Findings from Survey of State Highway Agencies

One of the tasks in this research study involved conducting a survey of state highway agencies across the United States to gather information regarding their current practices with respect to the maximum amount of RAP allowed in asphalt mixtures. A questionnaire, comprising a total nine (9) questions, was prepared, and distributed to the (asphalt) materials engineers in each state Department of Transportation (DOT). The questionnaire has been included in Appendix A of the current report. Responses were received from a total of thirty (30) DOTs, and the results have been presented in this chapter. Note: due to the long period of performance of this research project, the survey results represent the practice in different states back in 2017. The author acknowledges that some of the practices may have changed at different DOTs since 2017.

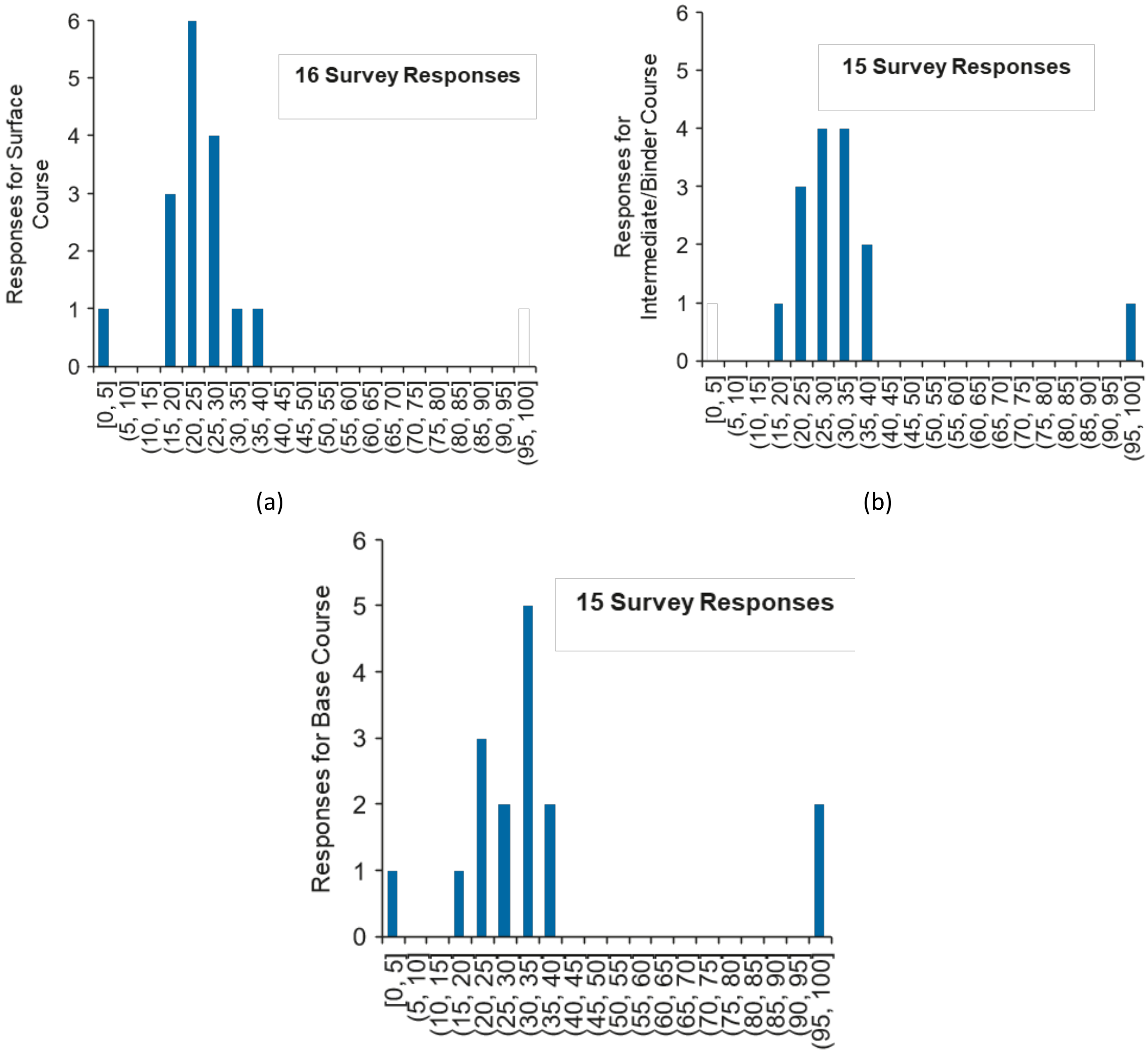
Analysis of Responses from State DOTs

This section includes the different questions included in the questionnaire as well as a summary of the responses received. The plots also indicate the number of responses received per question. Figure 13 and Figure 14 show the responses received regarding the maximum RAP contents allowed by different DOTs in HMA. Note that the data was collected for the surface course, binder/intermediate course, as well as the base course. The data was also collected based on percent weight of the mixture as well as Asphalt Binder Replacement (ABR). As seen from Figure 13a, most of the agencies allowed less than 30 percent RAP for the surface course. One agency reported allowing up to 30-35 percent in the surface course, whereas another agency reported allowing between 35-40 percent. The numbers for the binder/intermediate course as well as the base course are also less than 40 percent for most agencies. One agency reported allowing up to 95-100 percent RAP in the binder/intermediate and base courses. In summary, it appears like most agencies keep the maximum allowable RAP content to below 30 percent for the surface course, and below 40 percent for the underlying layers.



D1. What is the maximum percentage of RAP in HMA allowed by your State? (measured as binder replacement or by weight). Please fill the blanks below with the RAP content percentages applicable for your State.

	Surface Course	Binder/Intermediate Course	Base Course
% Binder Replacement:	☐	☐	☐
% by Weight:	☐	☐	☐

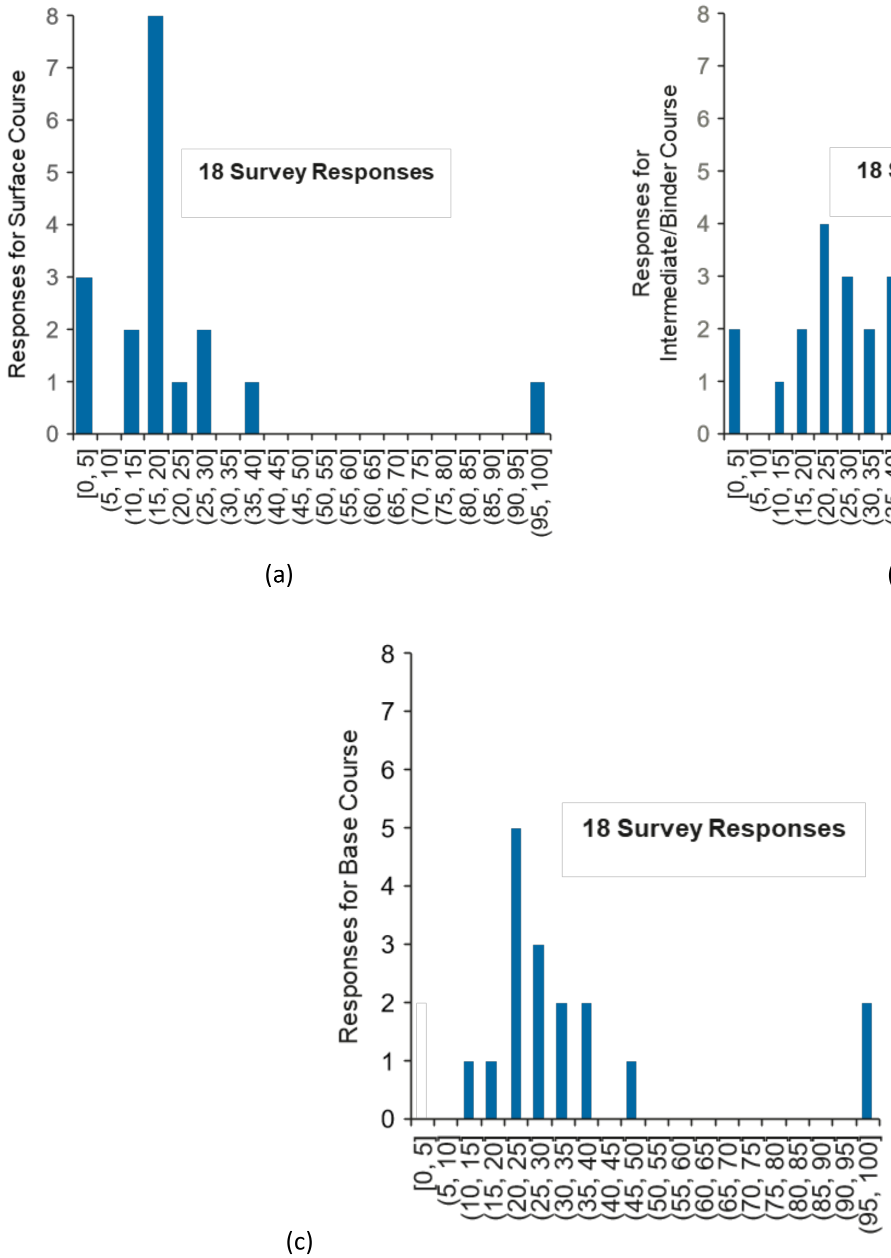


(a)

(b)

(c)

Figure 13: Summary of Survey Responses on Maximum RAP Percentages (by Binder Replacement) Allowed by the Agency



(a)

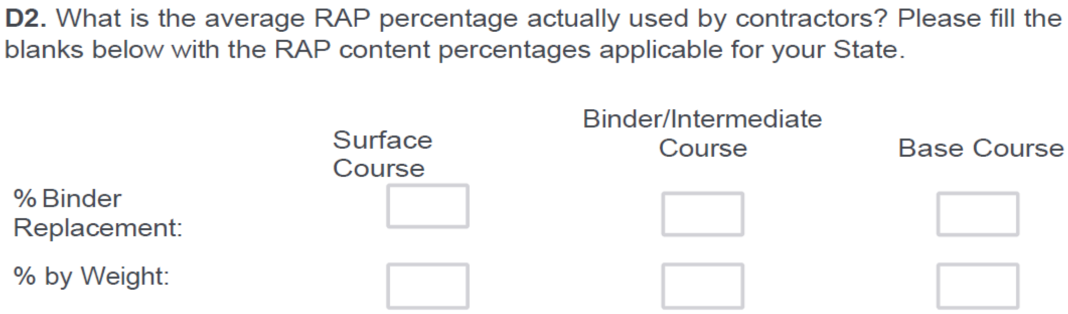
(b)

(c)

Figure 14: Summary of Survey Responses on Maximum RAP Percentages (by Weight) Allowed by the Agency

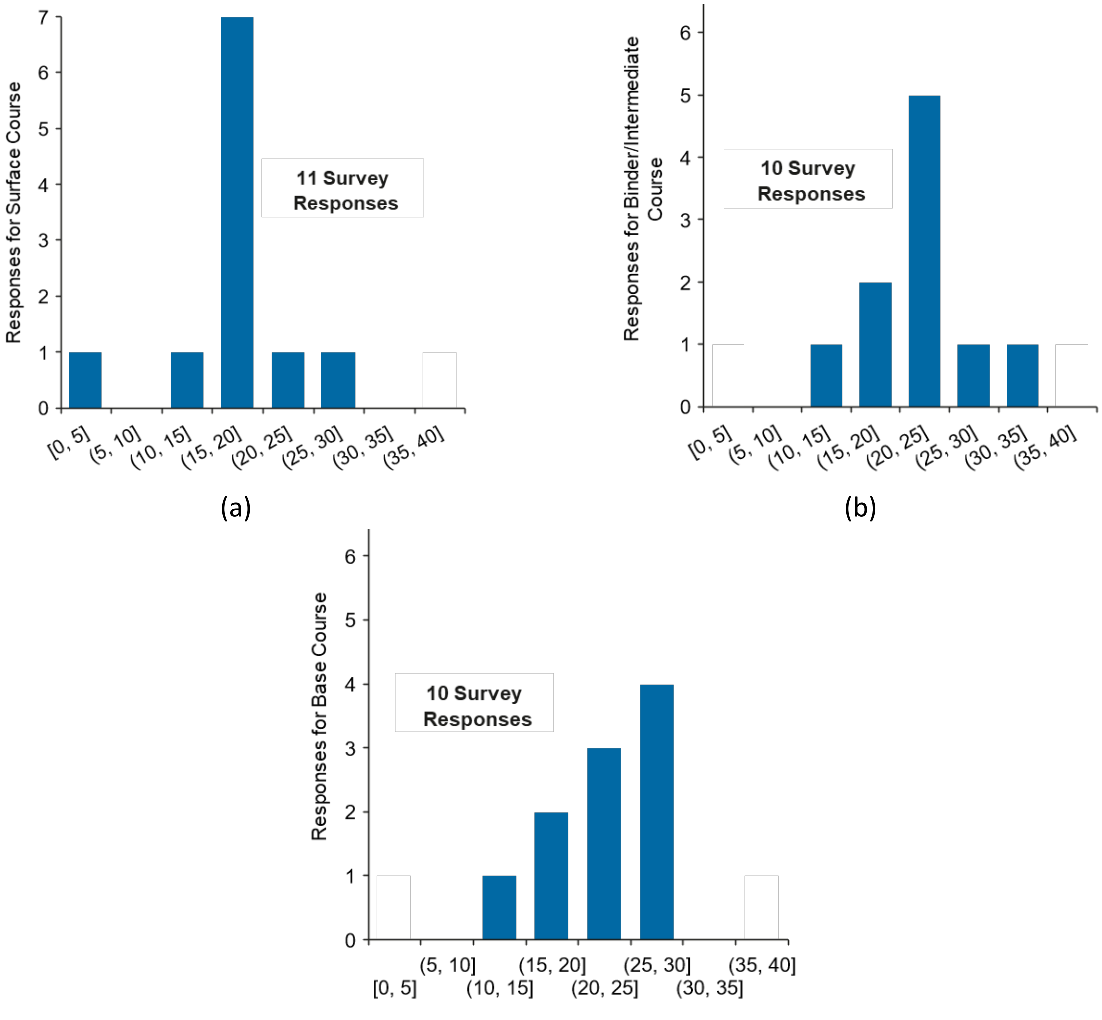
Although an agency may allow up to a certain amount of RAP in a mix, the amount of RAP typically used by contractors during mix design and production may very well be different from the maximum allowed amounts. The second question in the questionnaire attempted to collect this information, and the results have been plotted in Figure 15 and Figure 16. As seen from the figures, in no instance contractors were reported as using more than 30 percent RAP in a mix for the surface course. Even for the binder/intermediate course, no state reported their contractors as using more than 35 percent RAP.

Interestingly, even though one state reported allowing up to 95-100 percent RAP in the intermediate/binder course as well as the base course, apparently, contractors in that state do not typically use more than 35 percent RAP in a mix.



D2. What is the average RAP percentage actually used by contractors? Please fill the blanks below with the RAP content percentages applicable for your State.

	Surface Course	Binder/Intermediate Course	Base Course
% Binder Replacement:	☐	☐	☐
% by Weight:	☐	☐	☐

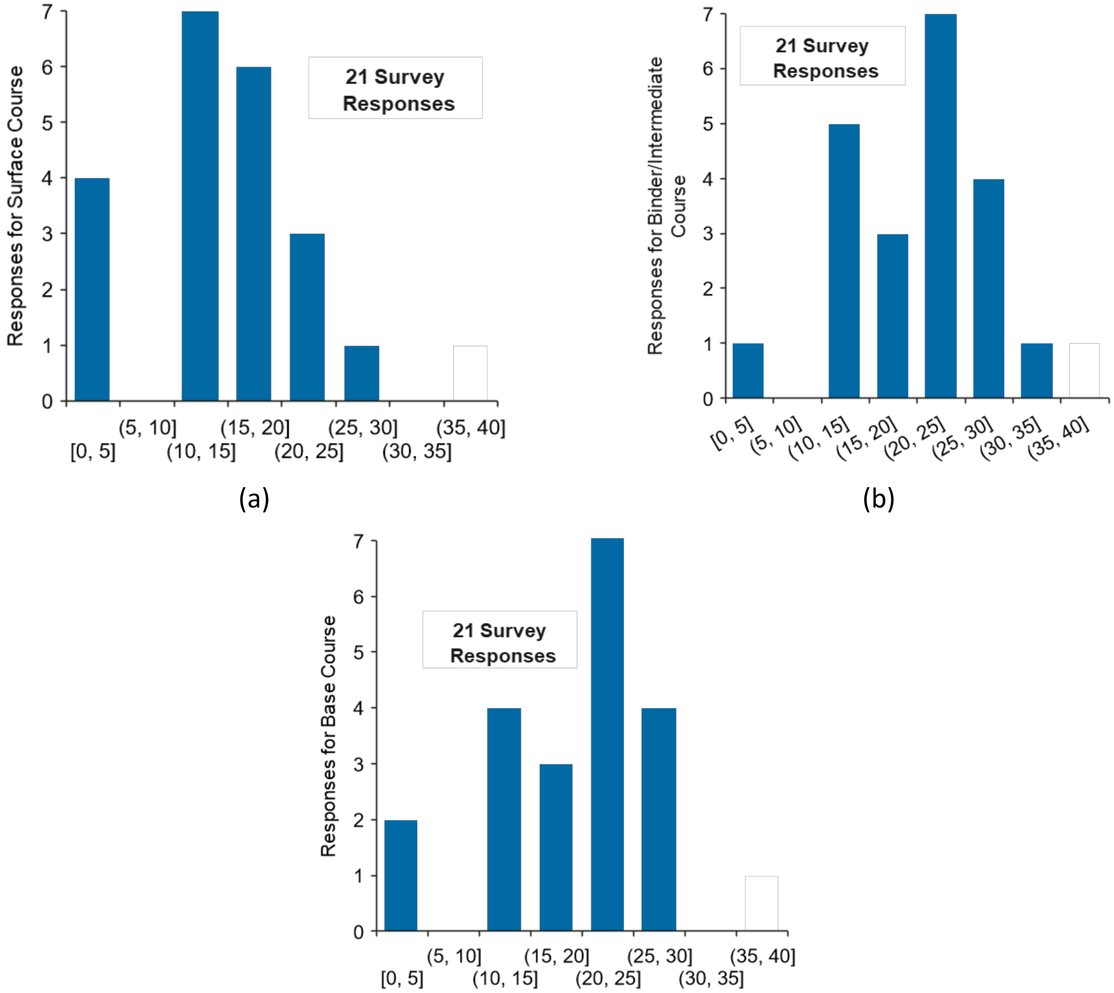


(a)

(b)

(c)

Figure 15: Summary of Survey Responses on Maximum RAP Percentages (by Binder Replacement) Typically used by Contractors

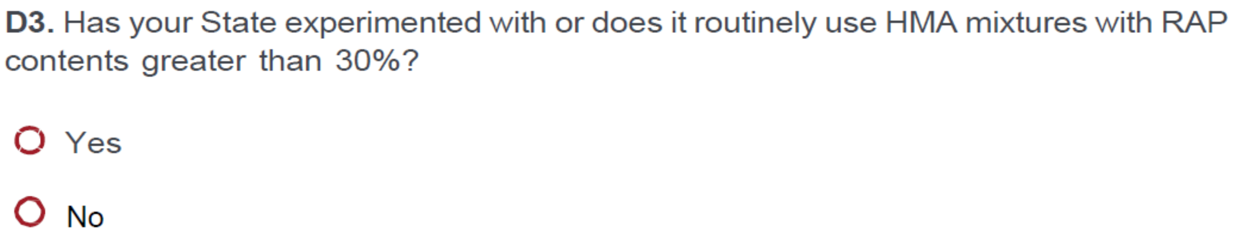


(a)

(b)

(c)

Figure 16: Summary of Survey Responses on Maximum RAP Percentages (by Weight) Typically used by Contractors



D3. Has your State experimented with or does it routinely use HMA mixtures with RAP contents greater than 30%?

○ Yes

○ No

As already mentioned, one of the actions taken by ITD in an effort to prevent the adverse effects (if any) of excessive RAP usage on pavement performance, was by setting an upper limit of 30 percent for the maximum amount of RAP allowed in a mix. To gauge whether this was consistent with practices by other agencies, one of the questions in the survey included whether the agency has tried allowing more than

30 percent RAP in a mix. Interestingly, equal number (14 each) of agencies reported “Yes” and “No” to this question. It is important to note that the pool of “Yes” respondents includes those that allow a maximum of 35 percent of RAP in a mix. Even if an agency allows up to 35 percent RAP, there may be a need to set an upper limit to the maximum RAP content.

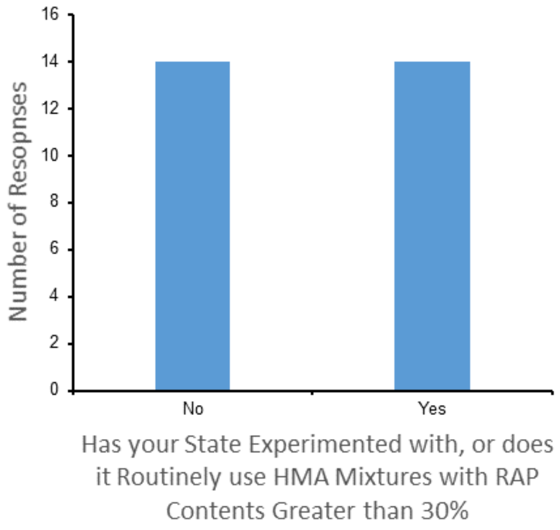
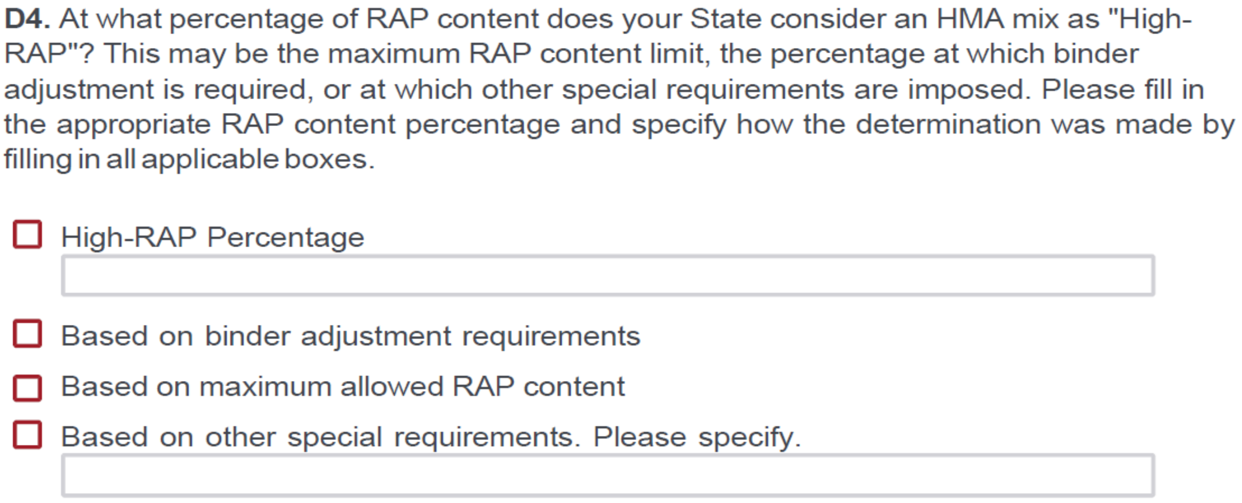


Figure 17: Summary of Survey Responses on Whether the Agency has Ever used Asphalt Mixture with Greater than 30 Percent RAP

The next question asked the respondents to define what could be categorized as a “High-RAP” mix in their respective states. The results are plotted in Figure 18. As seen from the figure, the highest number of agencies reported 30 percent as being the threshold for high-RAP mixtures. In fact, five agencies reported defining high-RAP mixes as those with greater than 20 percent RAP. One agency reported allowing up to 50 percent RAP before a certain mix is termed as ‘high-RAP”.



D4. At what percentage of RAP content does your State consider an HMA mix as "High-RAP"? This may be the maximum RAP content limit, the percentage at which binder adjustment is required, or at which other special requirements are imposed. Please fill in the appropriate RAP content percentage and specify how the determination was made by filling in all applicable boxes.

☐ High-RAP Percentage

☐ Based on binder adjustment requirements
☐ Based on maximum allowed RAP content
☐ Based on other special requirements. Please specify.

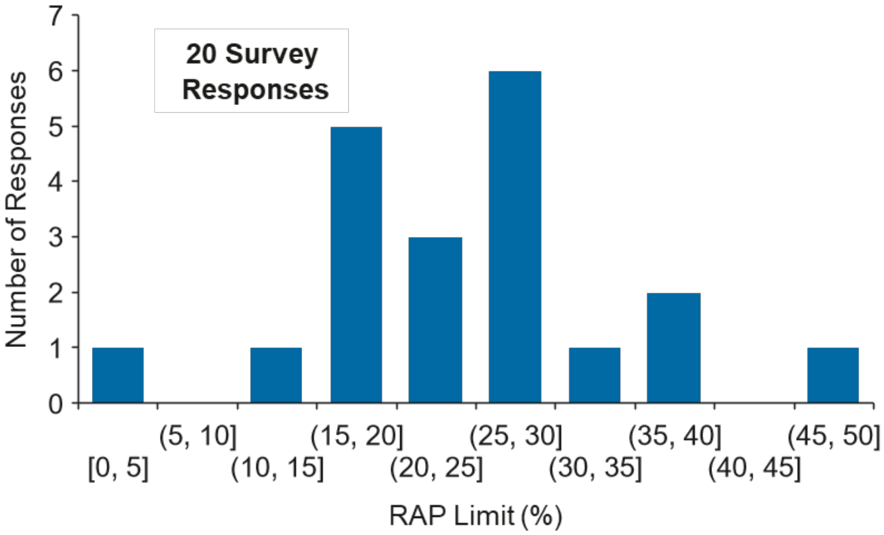
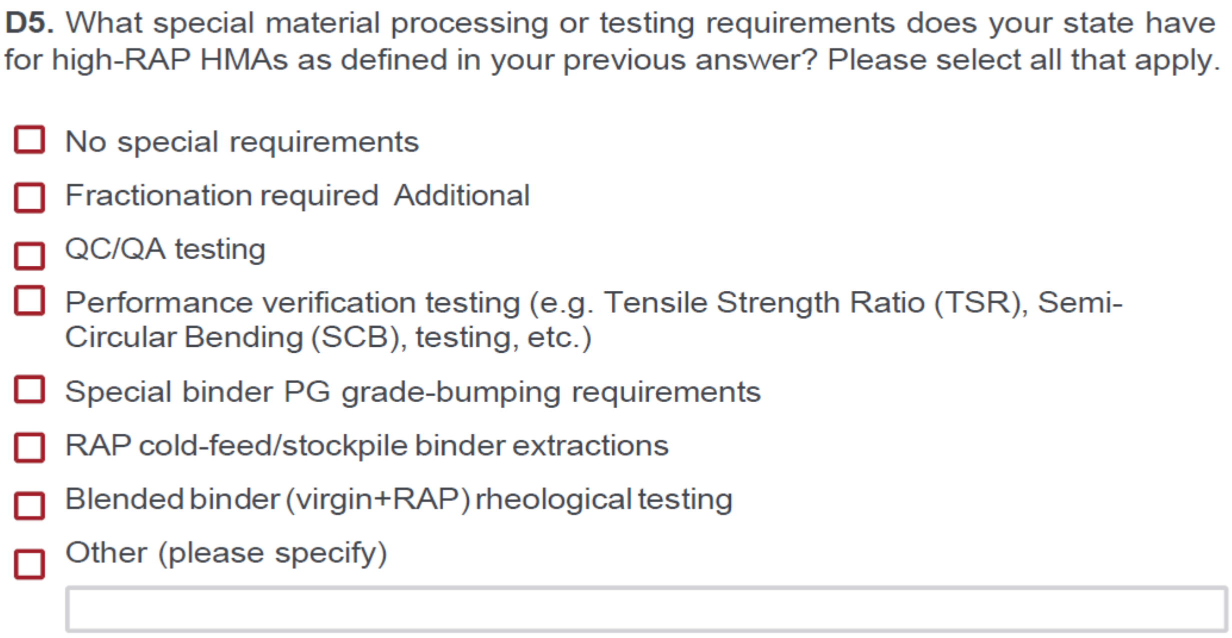


Figure 18: Summary of Survey Responses on the RAP Content at which a Mix is Considered as being "High-RAP"

As mentioned in Chapter 2, agencies may adopt different approaches to accommodate high RAP contents in asphalt mixtures. The next question in the survey attempted to gather information concerning the current practice in this regard. The results have been plotted in Figure 19. As seen from the figure, some of the common taken by agencies were: (1) Binder Grade-Bumping; (2) Blended Binder Rheological Testing; and (3) Performance Verification Testing. Five of the agencies also reported taking no action to verify binder/mix properties even when high RAP contents are used.



D5. What special material processing or testing requirements does your state have for high-RAP HMAs as defined in your previous answer? Please select all that apply.

☐ No special requirements
☐ Fractionation required Additional
☐ QC/QA testing
☐ Performance verification testing (e.g. Tensile Strength Ratio (TSR), Semi-Circular Bending (SCB), testing, etc.)
☐ Special binder PG grade-bumping requirements
☐ RAP cold-feed/stockpile binder extractions
☐ Blended binder (virgin+RAP) rheological testing
☐ Other (please specify)

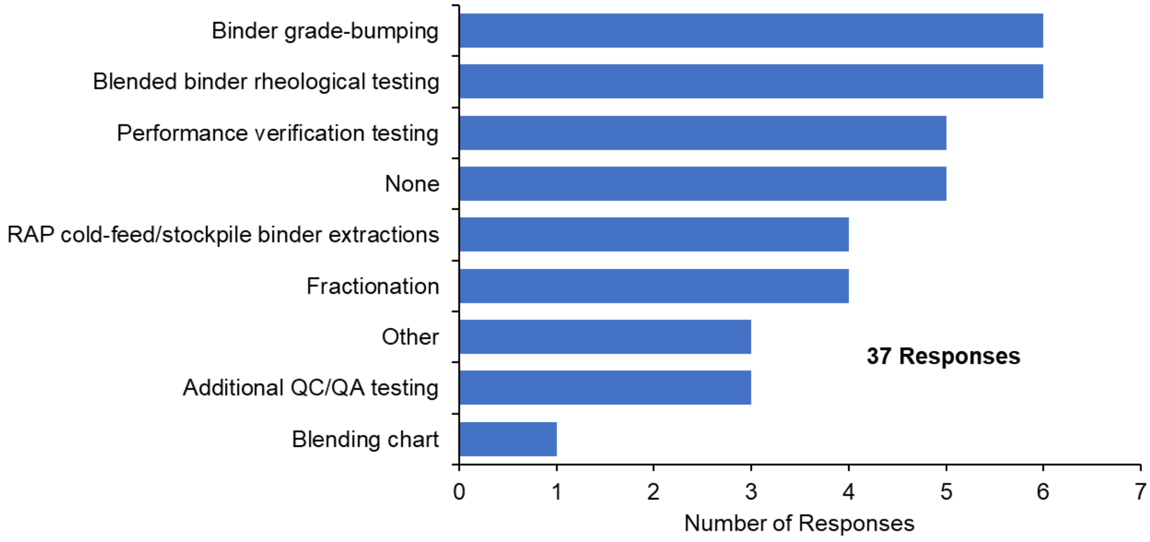
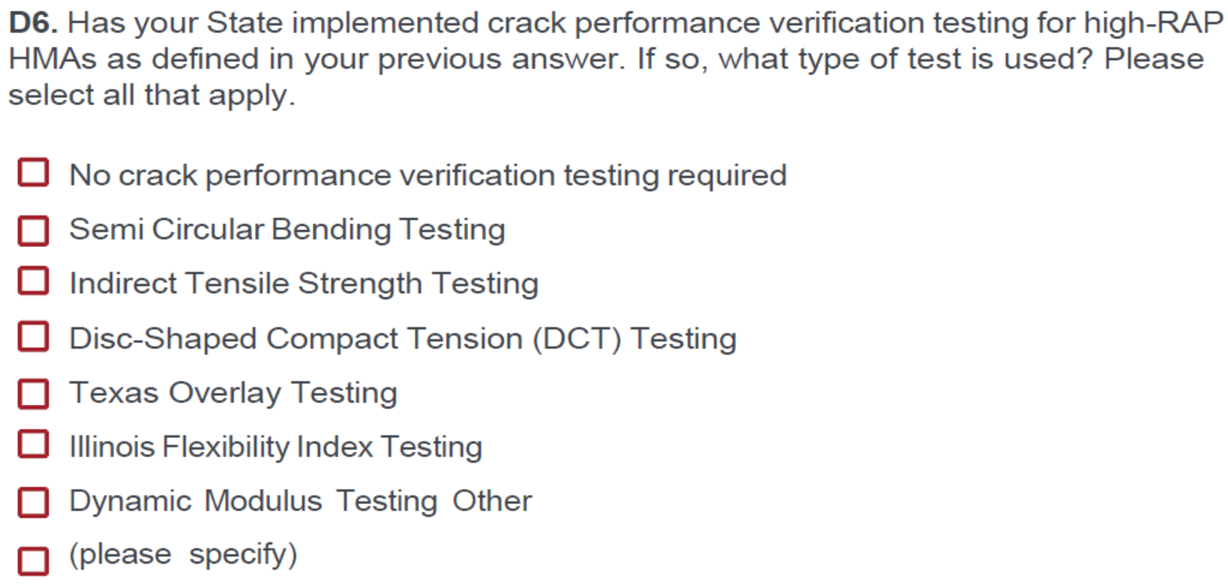


Figure 19: Summary of Survey Responses on Material Processing and Testing Requirements Implemented by Agencies for High-RAP Mixes

The next question gathered information on the type of crack performance verification test implemented by different agencies. As seen from Figure 20, most of the agencies reported not implementing any cracking tests to verify the performance of high-RAP mixes. Several agencies were in the planning stage for implementing different cracking tests. *It is important to note that these results reflect the state of practice in 2017, and the authors acknowledges several of the state practices may have changed since the survey was conducted.* Nevertheless, the survey results clearly indicated that no cracking test was widely accepted among agencies in 2017 to check the cracking resistance of high-RAP mixtures.



D6. Has your State implemented crack performance verification testing for high-RAP HMAs as defined in your previous answer. If so, what type of test is used? Please select all that apply.

- ☐ No crack performance verification testing required
- ☐ Semi Circular Bending Testing
- ☐ Indirect Tensile Strength Testing
- ☐ Disc-Shaped Compact Tension (DCT) Testing
- ☐ Texas Overlay Testing
- ☐ Illinois Flexibility Index Testing
- ☐ Dynamic Modulus Testing Other
- ☐ (please specify)

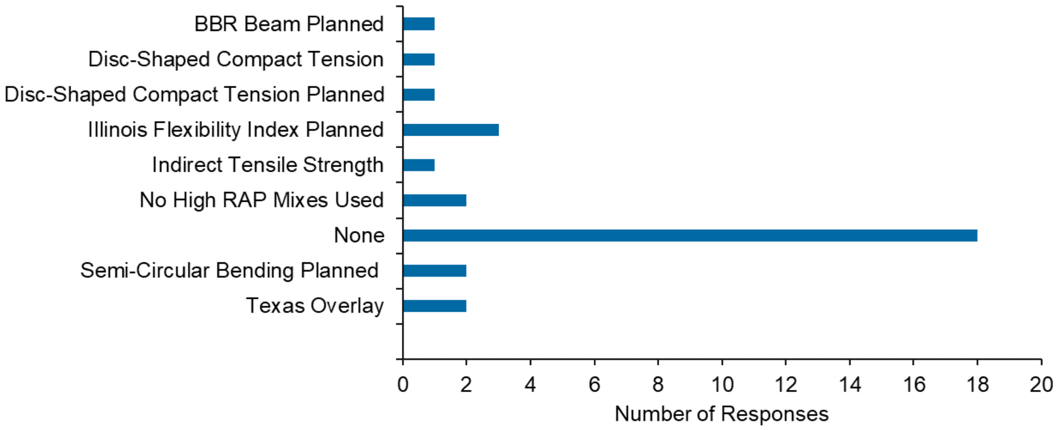
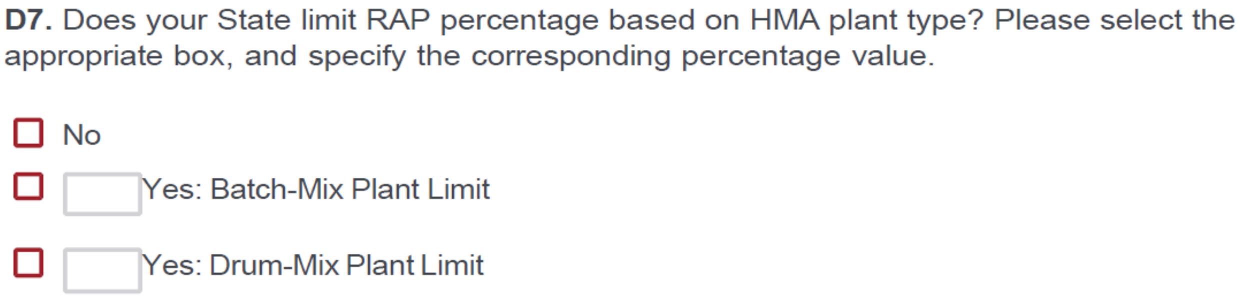


Figure 20: Summary of Survey Responses on Different Cracking Tests Implemented by Agencies for Testing High-RAP Mixes

In an effort to identify whether the maximum allowable RAP content is different for different asphalt plant types, the research team observed that twenty-four (24) out of twenty-seven respondent reported no correlation between the maximum allowable RAP content and the type of plant.



D7. Does your State limit RAP percentage based on HMA plant type? Please select the appropriate box, and specify the corresponding percentage value.

☐ No

☐ ☐ Yes: Batch-Mix Plant Limit

☐ ☐ Yes: Drum-Mix Plant Limit

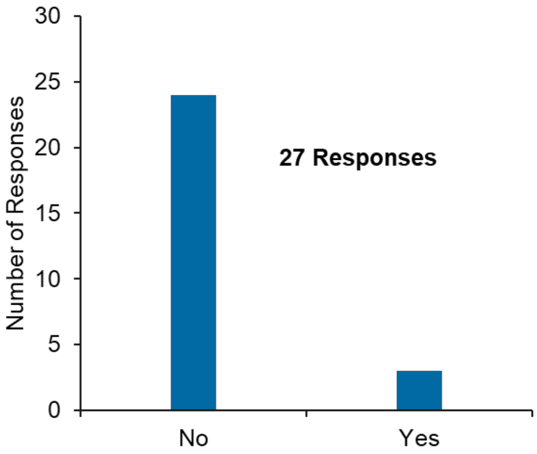
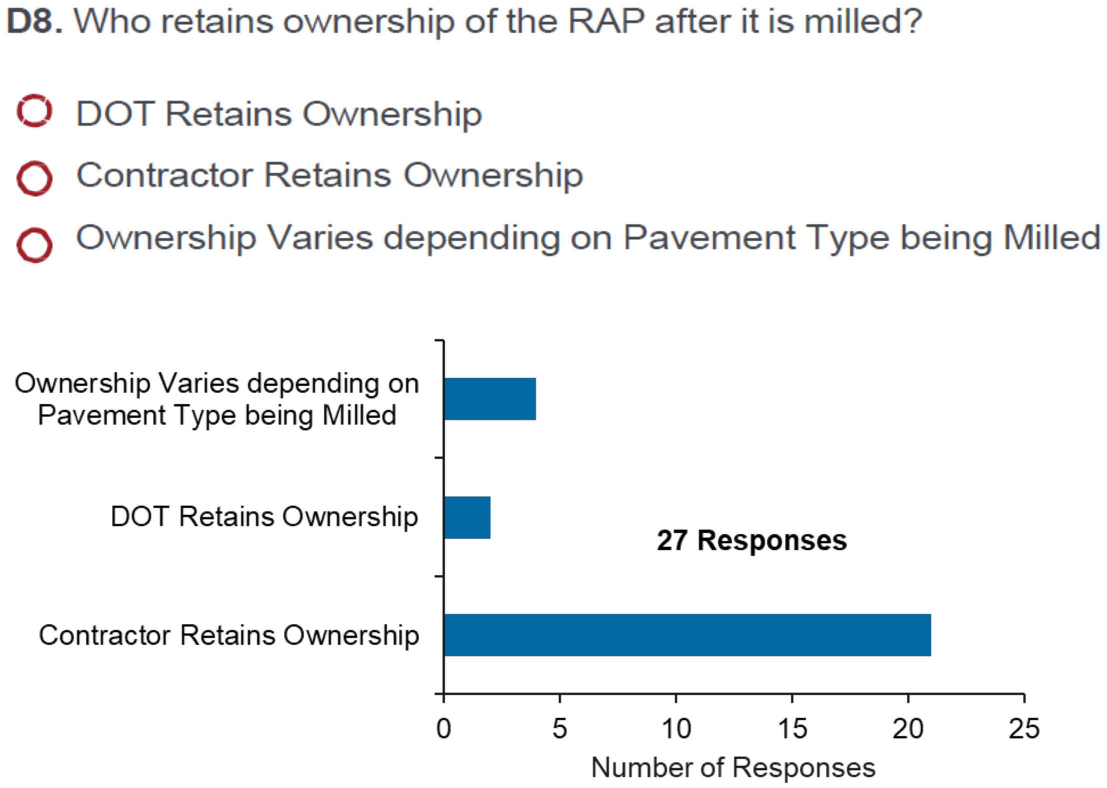


Figure 21: Summary of Survey Responses on Whether the Maximum Allowable RAP Content Changes Based on Asphalt Plant Type

The literature review carried out under the scope of this project clearly identified that cross-contamination between different RAP stockpiles was one of the primary things to avoid ensuring the availability of good quality RAP for asphalt mixes. To avoid cross-contamination, it is important that a consistent practice be maintained with respect to the ownership of the RAP material upon milling. Twenty-two (22) out of twenty-seven (27) respondents in the current study reported that the contractors retained ownership of the RAP material after it is milled. Only one agency reported DOT ownership of the RAP millings.

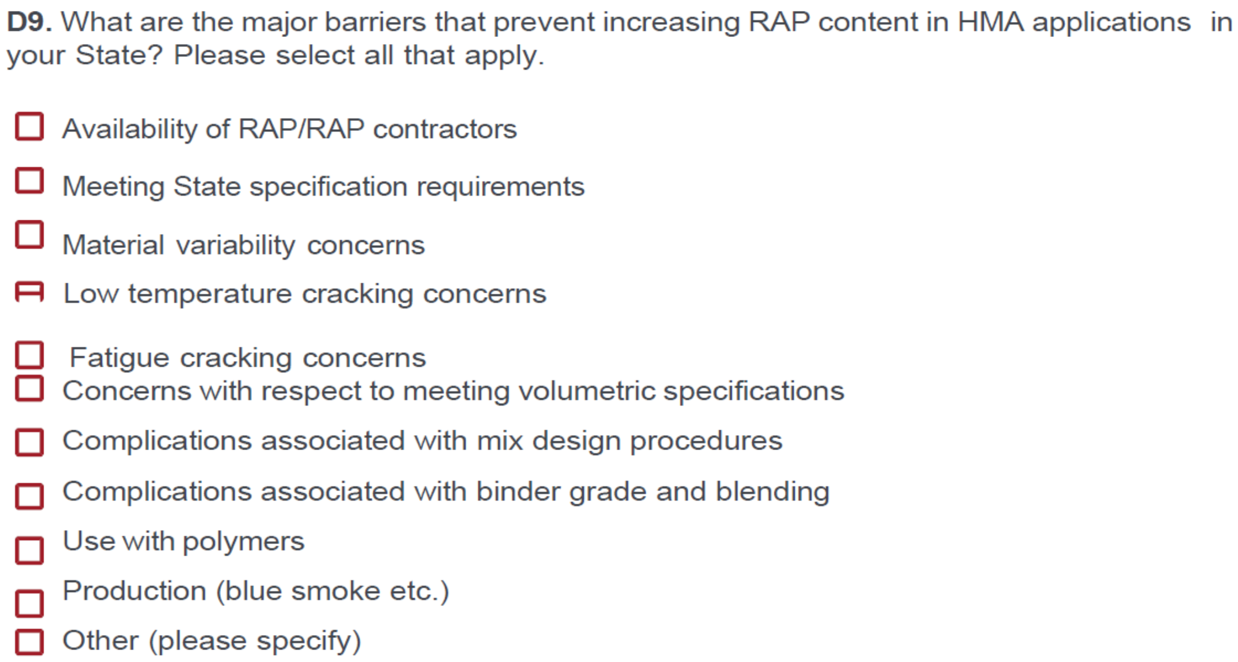


D8. Who retains ownership of the RAP after it is milled?

○ DOT Retains Ownership
○ Contractor Retains Ownership
○ Ownership Varies depending on Pavement Type being Milled

Figure 22: Summary of Survey Responses on Ownership of RAP Mixtures after Milling

The final question in this survey focused on identifying the different barriers that prevent increased RAP contents in the respective states. The survey results have been plotted in Figure 23. As seen from the above figure, fatigue cracking was identified as the most common concern related to high-RAP HMAs. Low-temperature cracking was identified the second most concerning item. It is quite apparent that DOTs expressed sincere concerns about the cracking resistance of asphalt mixtures produced with high RAP contents.



D9. What are the major barriers that prevent increasing RAP content in HMA applications in your State? Please select all that apply.

☐ Availability of RAP/RAP contractors

☐ Meeting State specification requirements

☐ Material variability concerns

☐ Low temperature cracking concerns

☐ Fatigue cracking concerns

☐ Concerns with respect to meeting volumetric specifications

☐ Complications associated with mix design procedures

☐ Complications associated with binder grade and blending

☐ Use with polymers

☐ Production (blue smoke etc.)

☐ Other (please specify)

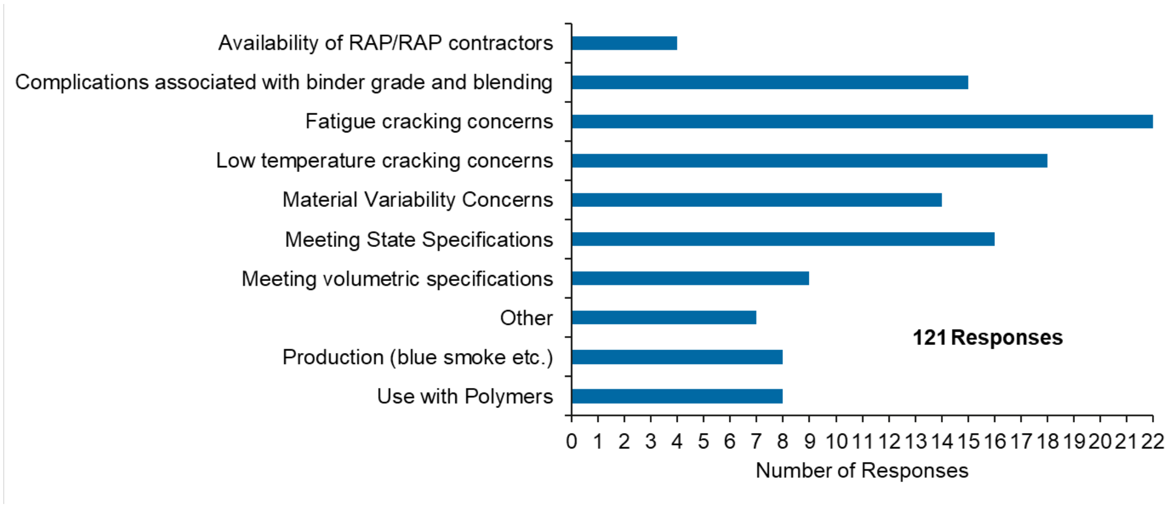


Figure 23: Summary of Survey Responses on Barriers Preventing the use of High-RAP in Asphalt Mixtures

Summary of Survey Findings

As already mentioned, the primary objective of this survey effort was to get a picture of different state DOT practices when it comes to use of high RAP contents in asphalt mixes. From the results it was observed that most states limit the maximum allowable RAP content in a mix to somewhere between 30-35 percent. Although some agencies reported allowing higher RAP contents in the intermediate/binder course, the number was consistently around 30 percent for the surface course. Although only thirty (30) agencies responded to the questionnaire, none of the agencies reported not having an upper limit on the maximum allowable RAP content. Although it is technically possible to produce asphalt mixtures with significantly higher RAP contents, based on the survey results, it appears that most of the agencies limit the maximum RAP contents to approximately 30-35 percent.

4. Findings from Laboratory Testing of Asphalt Mixes with Different RAP Contents

As already mentioned, the Illinois Flexibility Index Test (I-FIT) was selected in this study to quantify the cracking resistance of asphalt mixtures with different RAP contents. The original objective of the project was to collect cores from different pavement sections constructed with varying RAP percentages and test them in the laboratory. However, due to multiple reasons (already discussed in Chapter 1 of this report), the laboratory testing could not comprise as wide a variety of samples as planned. Nevertheless, more than 1000 I-FIT tests were conducted in the laboratory for a total of sixteen (16) different asphalt mixtures. This chapter contains details about the laboratory testing effort, as well as analysis of the test results.

Although the plan at the conception of the project involved collecting pavement cores in collaboration with ITD, this plan did not materialize due to logistics and resources required which were outside the control of the researchers. Accordingly, the research team worked with individual ITD districts and contractors to collect loose asphalt mix from the paving sites that were later compacted using a Superpave gyratory compactor loaned to the researchers from one of the contractors. The scope of work increased significantly due to the inclusion of gyratory compaction and volumetric testing. However, this was necessary to accomplish the project objectives. The following sections present basic details related to the I-FIT tests carried out in the laboratory to test the asphalt mixes for cracking susceptibility. This is followed by analysis of the laboratory data to draw relevant inferences.

All samples were stored in a temperature-controlled room to prevent excessive exposure to heat. The loose mix was heated in the oven to compaction temperature, and then the compacted specimen was allowed to cool to room temperature for cutting. Once the specimens were cut, each specimen was conditioned for two hours at 25° C ± 0.5° C. Excessive aging of the mix was avoided by not putting the mix in the oven at elevated temperatures for prolonged times. Nevertheless, it should be noted that the loose mix obtained from the projects were stored in the lab for approximately 1-2 weeks before testing. Whether this affected the results in any way, is unknown.

Introduction to the Illinois Flexibility Index Test (I-FIT)

The Illinois Flexibility Index Test or I-FIT was developed at the University of Illinois at Urbana-Champaign (Al-Qadi et al, 2015), and has been widely accepted as a viable test method that can measure the susceptibility of asphalt mixtures to cracking at intermediate temperatures. In other words, this test is a good method to evaluate the resistance offered by a particular mix to fatigue cracking. The test is run at room temperature (25° C), and is very quick to perform (the test itself takes usually a few seconds). This makes the I-FIT a viable test that can be implemented into regular quality acceptance testing programs by state DOTs. The primary disadvantage associated with the I-FIT is that it requires the cutting of a vertical notch parallel to the loading axis. This notch cutting can potentially introduce some variability into the specimen preparation process. The I-FIT is a special case of the Semi-Circular Bending (SCB) test; the primary difference involves cutting of a vertical notch parallel to the loading axis. The specimen is then loaded until failure under bending, and the fracture energy and a specialized index derived from it are used to make inferences about the cracking resistance of the mix. Figure 24 shows a photograph of an I-FIT specimen being loaded until failure. Figure 25 shows a schematic of the process to obtain four I-FIT specimens from one Superpave gyratory compactor specimen (160-mm tall). Figure 26 shows a photograph of multiple gyratory compactor specimens ready for cutting. Figure 27 shows photograph of the specimens being saw-cut, where as Figure 28 shows a photograph of multiple specimens after saw-cutting, ready for I-FIT testing. Figure 29 shows a photograph of the test system used in this research project.

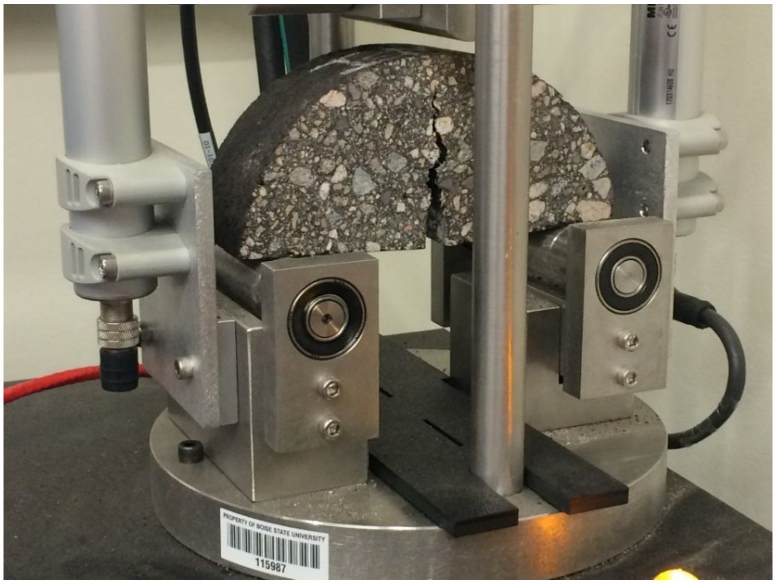
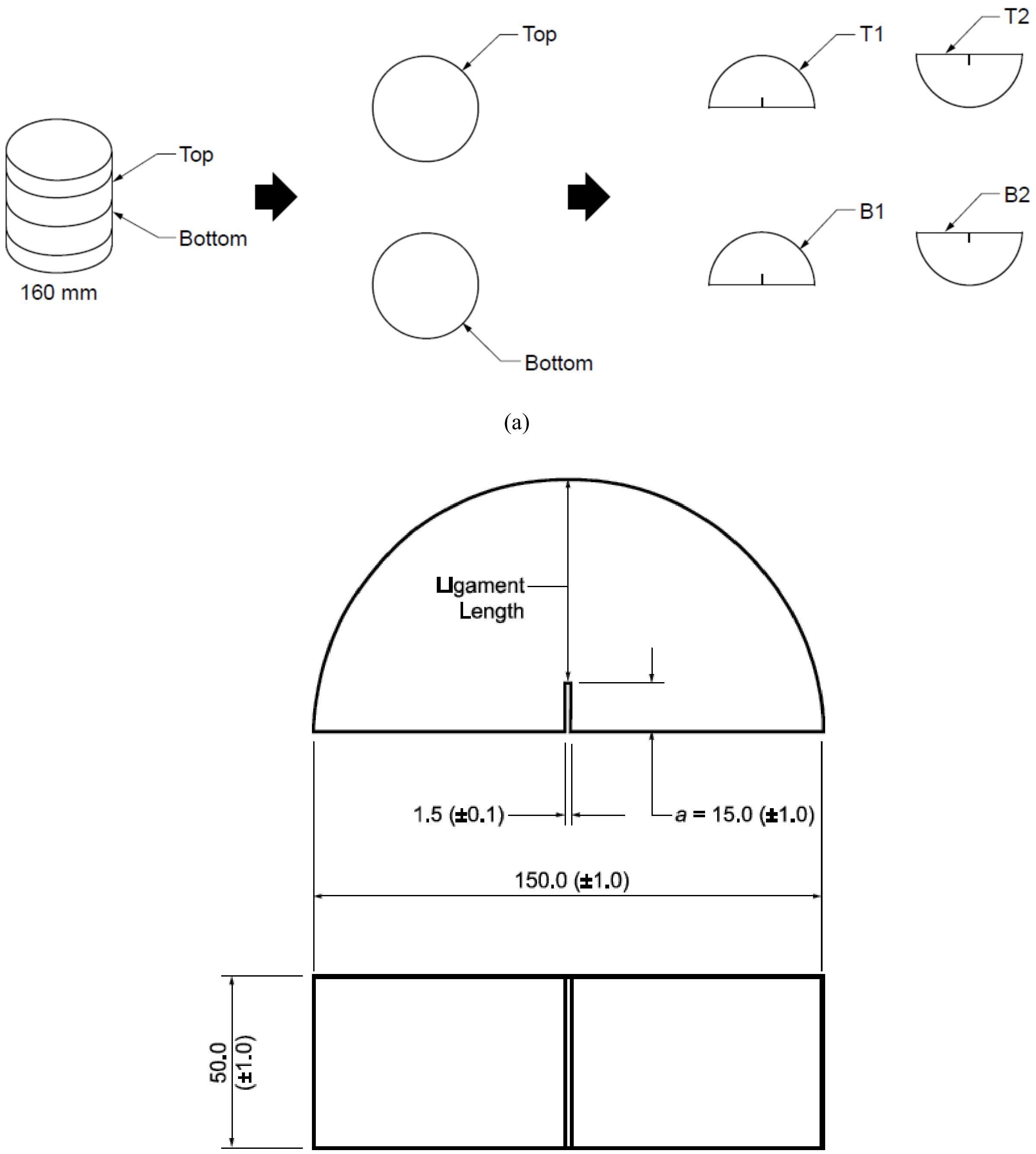


Figure 24: Photograph Showing a Cracked I-FIT Specimen at the End of Testing



(a)

(b)

Fig Source: AASHTO TP 124

Figure 25: (a) Schematic Showing the Process of Obtaining Four SCB Specimens from One Superpave Gyratory Compactor Specimen; (b) Diagram Showing Different Dimensions of the SCB Sepcimen

Figure 26: Photograph Showing Compacted Superpave Gyratory Specimens

(a)

(b)

Figure 27: Photographs Showing: (a) Saw Cutting to Obtain the SCB Specimens; (b) Cutting the Notch into the SCB Puck

Figure 28: Photograph Showing Labeled Compacted Gyratory Specimens and the Cut Semi-Circular Specimens

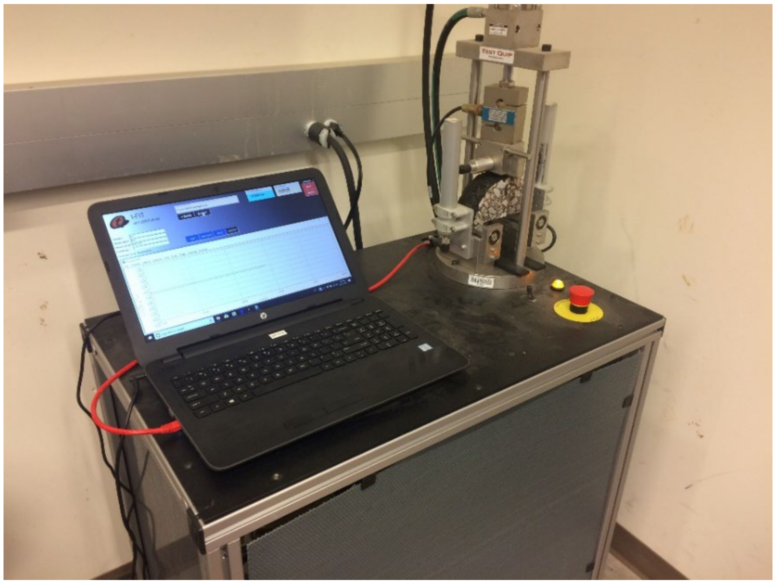


Figure 29: Photograph of the Test Set-Up used in the Current Study

The test procedure requires the specimen to be loaded at a rate of 50 mm/min. The load and displacement values are continuously monitored, and the load-deflection plot (see Figure 30) is used to calculate the fracture energy as well as Flexibility Index (FI) value. Note that the test procedure can be applied to test specimens having a nominal maximum aggregate size (NMAS) of 19 mm or less. Lab compacted and field core specimens can be used. Lab compacted specimens are 150 ± 1 mm in diameter and 50 ± 1 mm thick. When field cores are used, specimens can be 150 ± 8 mm in diameter and 25 to 50 mm thick. (AASHTO TP 124-2020).

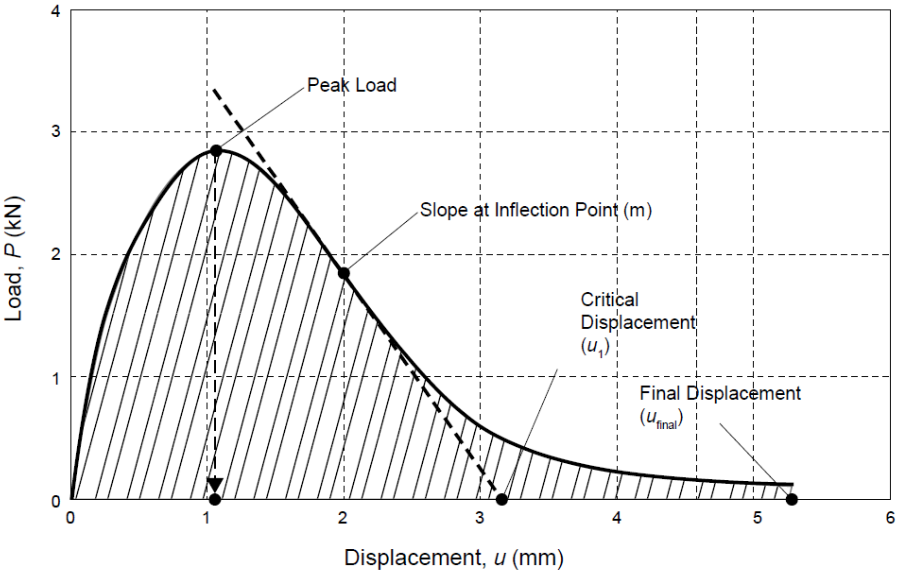


Figure 30: Typical Load vs. Displacement Curve Obtained during I-FIT Testing

The fracture energy G_F is calculated by dividing the work of fracture (the area under the load versus the average load line displacement curve) by the ligament area (the product of the ligament length (refer to Figure 25) and the thickness of the specimen) of the SCB specimen prior to testing:

$$G_f = \frac{W_f}{Area_{lig}} \times 10^6$$

$where:$

$G_f =$ Fracture Energy (Joules/m^2)

$W_f =$ Work of fracture (Joules)

$P =$ load (kN)

$u =$ load line displacement (mm); and

$Area_{lig} =$ ligament area (mm^2) = ligament length (mm) x spcimen thickness (t, mm)

The Flexibility Index (FI) is calculated from parameters obtained using the load-displacement curve.

$$FI = \frac{G_f}{|m|} \times A$$

$where:$

$|m| =$ absolute value of post-peak load slope m (kN / mm)

The factor A is used for unit conversion and scaling. $A =$ 0.01

IFIT Data Analysis

To ensure the test parameters were kept constant throughout the testing effort, a histogram of the Load Line Displacement (LLD; mm/min) values was plotted (see Figure 31). The test specification requires the LLD to be maintained at 50 mm/min. As seen from, the figure, the LLD rates were consistently between 50.0 to 50.4 mm for most of the specimens.

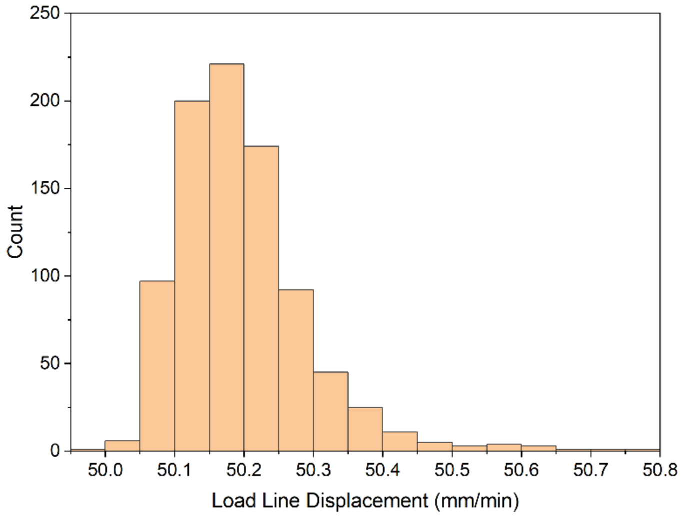


Figure 31: Effect of Test Rate (mm/min) on Flexibility Index (FI)

Once the test parameters we confirmed, the next step involved verifying that the test results did not show excessive variability due to inconsistent sample preparation or operating procedures. Therefore, the calculated FI values were compared between three gyratory specimens (per mix), as well as two 50-mm thick cylindrical slices per gyratory specimens. The results are plotted in Figure 32 and Figure 33. As seen from the figures, no significant variation was observed between the gyratory specimens or the circular slices. This clearly establishes that the sample preparation and the testing did not involve significant operator or equipment related variabilities.

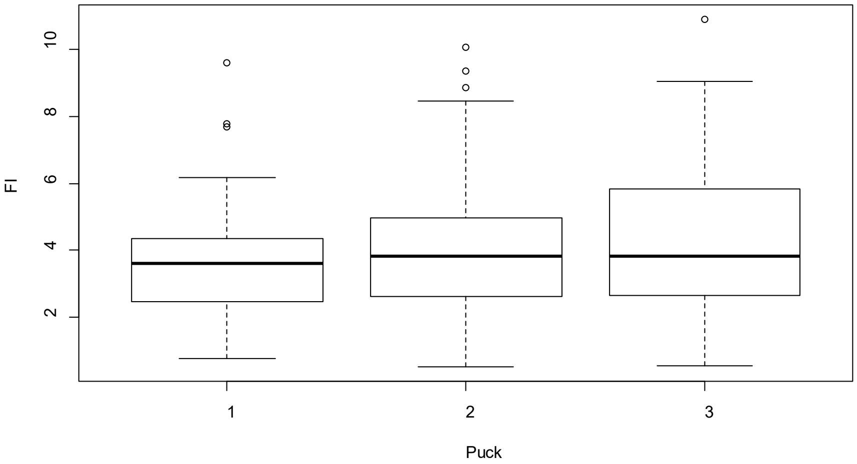


Figure 32: Box Plots Showing the Variation in Flexibility Index (FI) between Three Gyratory Specimens Tested for Each Mix

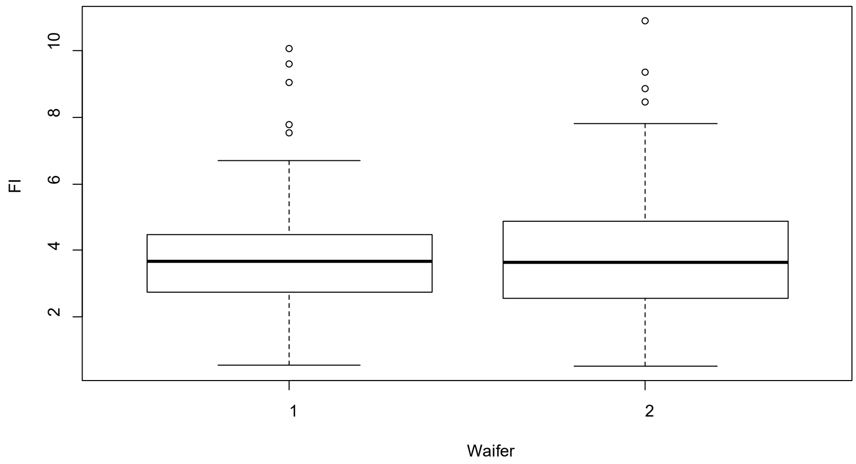


Figure 33: Box Plots Showing the Variation in Flexibility Index (FI) between Two 50-mm Thick Cylindrical Slices obtained from Each Gyratory Specimen

Figure 34 shows a box plot of the range of FI values obtained for all samples tested in this project. As seen from the figure, the median FI value was 4.00, with the highest value being 20.4. Figure 35 shows the same data in the form of a histogram. As seen from these figures, most of the mixtures tested under the scope of this project had FI values less than 10. As already mentioned, the loose mix was heated to the compaction temperature before putting in the superpave gyratory compactor. The compacted specimens were allowed to cool to room temperature before the SCB specimens were cut. Finally, the SCB specimens were conditioned at 25 °C for two hours before testing. During gyratory compaction, a target air void of 7 percent was used. This was selected to match the criteria used during Hamburg Wheel Tracking Test (AASHTO T 324).

Al-Qadi et al. (2015) observed that FI values of 2.0 and 6.0 were cut-off values distinguishing poor-(less than 2.0), intermediate- (2.0 to 6.0), and good- (greater than 6.0) performing pavement sections. Based on such a classification, one would conclude that most of the Idaho mixes tested in the laboratory in this project belong to the poor- or intermediate- performing categories from a cracking point of view. *Note: this statement is solely based on the thresholds established by Al-Qadi et al. (2015), and therefore, is not intended to make overarching conclusions regarding the quality of asphalt mixes used in Idaho.*

As already mentioned, calculation of the FI values is dependent on the fracture energy of the specimen. However, Al-Qadi et al. (2015) reported that the FI was a better indicator of the crack susceptibility of a mix compared to fracture energy. Figure 36 shows a scatter plot of the FI values for all the specimens tested in this project against the corresponding fracture energy values. As seen from the plot, in general, the FI value increases with increasing fracture energy. However, there are some samples for which a significantly high fracture energy value does not necessarily correspond to a high FI value. This is an effect of differing post-peak slopes in the load-displacement curves. Nevertheless, a high value of fracture energy in general corresponded to a high value of FI.

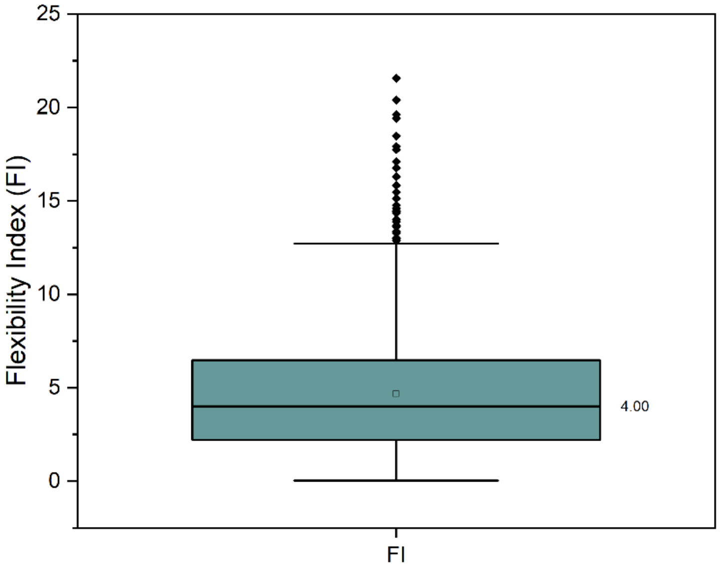


Figure 34: Range of FI Values for All Mixtures Tested in the Laboratory

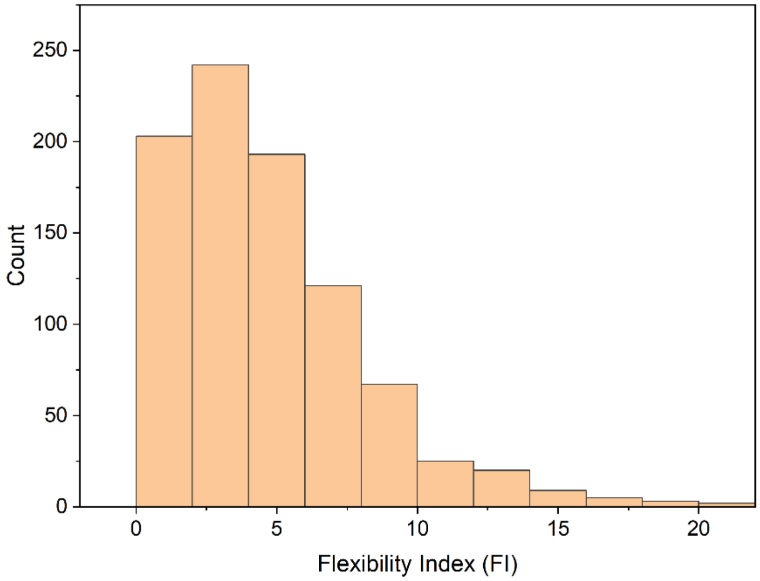


Figure 35: Histogram of FI Values for All Mixtures Tested in the Laboratory

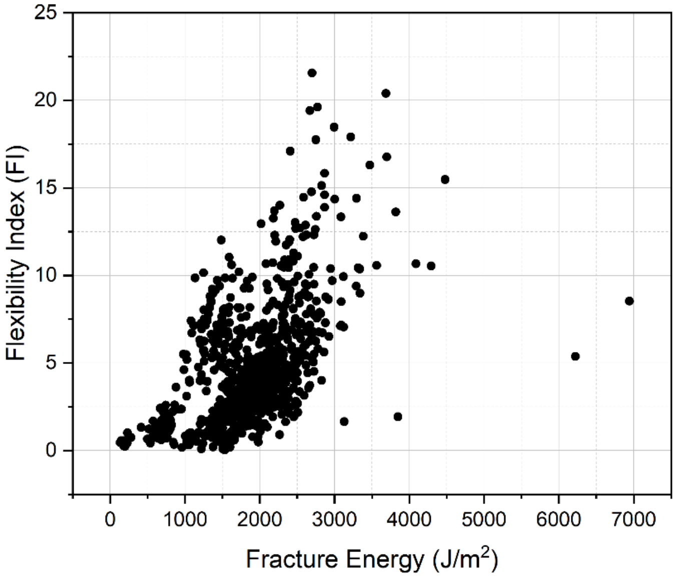


Figure 36: Relationship between Fracture Energy and Flexibility Index (FI) for the Mixes Tested in the Lab

The variation in FI with Asphalt Binder Replacement (ABR) has been shown in the form of box plots in Figure 37. Remember: ABR is used to express the RAP content in a given mix. As seen from the figure, there is generally, a decreasing trend in the FI values with increasing ABR. However, there are exceptions in the data set that introduce some degree of ambiguity into the interpretation. For example, the mix with 45.2 percent ABR resulted in significantly high FI values, with the median value being comparable to the mix with 0 percent RAP.

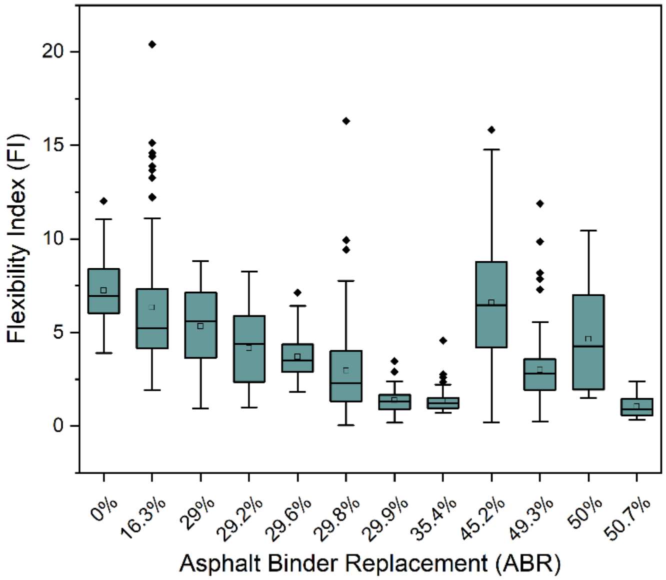


Figure 37: Box Plots Showing the Variation in Flexibility Index (FI) with ABR

Coincidentally, the mix with 45.2 percent ABR was obtained from a project in ITD District 5 (Key Number 18784), where three test sections, each with 16.3 percent, 29.8 percent, and 45.2 percent ABR respectively, were constructed in an effort to study the effect of RAP content on pavement performance. The three sections were adjacent to each other, and the same RAP (with a true RAP PG grade of PG 74.2-30.6) was used in all three mixes. FI values obtained from testing of the three mixes from Key Number 18784 have been plotted in Figure 38. As seen from the figure, there is a noticeable reduction in the FI values when the ABR value increases from 16.3 to 29.8 percent. However, the trend gets reversed when the ABR increases to 45.2 percent. No particular justification for this trend could be found. With all the variables in asphalt mix production and the associated material testing, the researcher recommends further, and more extensive studies to further investigate such unexpected trends.

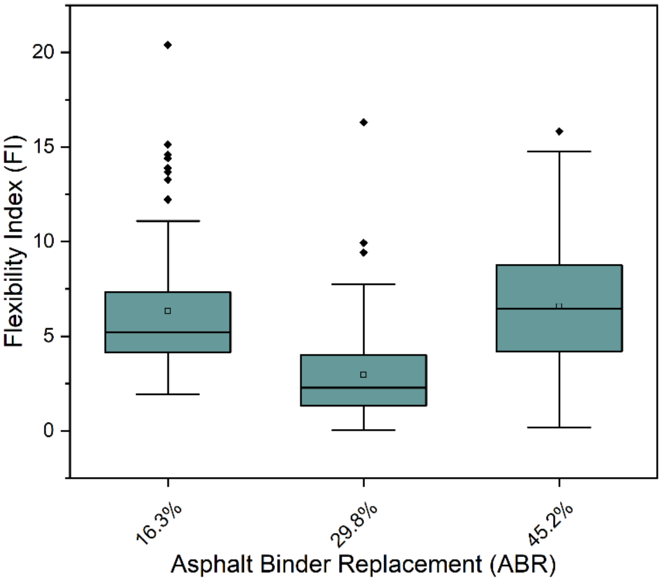


Figure 38: Box Plots Showing the Variation in Flexibility Index (FI) with ABR for Key Number 18784 in ITD District 5

Going back to Figure 37, it should be noted that the mix with ABR = 50 percent also resulted in FI values that were significantly higher than most of the other mixes. As already mentioned in Chapter 1 of this report, during the period of performance of this project, a parallel investigation by ITD discovered several discrepancies in the data reporting system implemented during acceptance testing of asphalt mix designs and pavement construction. Therefore, the mix design data collected for this project was not 100% reliable. This rendered some of the correlations observed in this study to be “questionable”. For example, there was no way for the author to confirm whether the mix labeled as having 50% ABR was actually prepared with 50 percent ABR or not. *Accordingly, the author intentionally refrains from making strong claims about the cause-effect nature of any trends observed in the data. It is up to the reader’s discretion to make engineering inferences from the data presented*.

Figure 39 shows the variation in fracture energy with ABR. This was plotted to check whether the fracture energy values presented a more consistent trend of mixture crack resistance with RAP content, compared to the FI plots. As seen from the figure, the fracture energy data does not show any sort of trend with ABR. This corroborates the claim by Al-Qadi et al. (2015) that the FI values are more reliable in detecting changes in mixture properties compared to fracture Energy. Figure 40 shows the variation in FI with total asphalt content in the mix. Once again, no consistent trend was observed in the results. One would expect that increase in total asphalt content would improve the cracking resistance of a mix, thereby leading to higher FI values. However, no such trend is observed from the data.

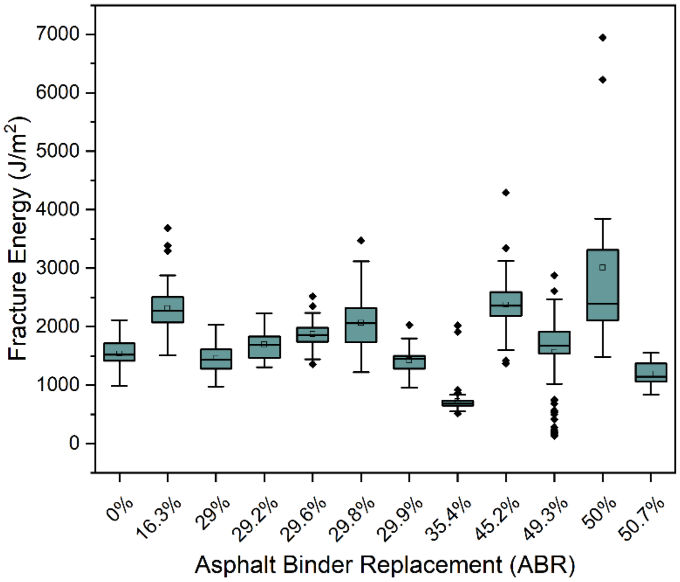


Figure 39: Box Plots Showing the Variation in Fracture Energy with ABR

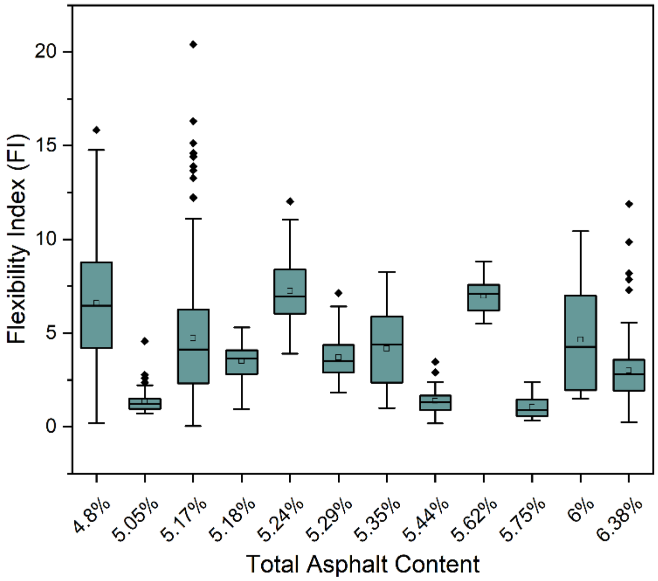


Figure 40: Box Plots Showing the Variation in Fracture Energy with Total Asphalt Content

Summary of Findings from Laboratory Tests

This chapter presented findings from laboratory testing of asphalt mixture with varying RAP contents carried out under the scope of the current project. Based on extensive review of published literature, the Illinois Flexibility Index Test (I-FIT) was selected as the most suitable test to make inferences regarding the susceptibility of different mixtures to fatigue cracking. The I-FIT was deemed to be simple enough to be implemented into practice by ITD. Previous research has clearly established the I-FIT as a viable test method that can effectively detect any change in mix behavior introduced through factors such as changes in RAP content.

More than one thousand (1,000) I-FIT tests were carried out in the laboratory on asphalt mixes containing different amounts of RAP. Obtaining cores from existing pavement sections was not possible due to multiple logistical issues. Therefore, the testing effort primarily focused on new asphalt mixtures being placed at construction projects throughout the state of Idaho. In some cases, quality control gyratory specimens prepared by the contractor could be obtained. In most cases, only loose mix could be obtained from the paver, and the specimens were reheated and compacted at the Boise State University asphalt materials laboratory. It should be noted that before the initiation of this research study, ITD had placed a temporary limit of 30 percent ABR for the maximum allowable RAP content in surface mixes. Therefore, most of the pavement sections being constructed, comprised mix designs where the ABR value was close to 30 percent. This significantly limited the range of ABR values in asphalt mixtures made available to the research team for testing. Nevertheless, the research team was successful in working with ITD engineers to collect samples from any mixes that were being placed at different RAP contents.

Based on the laboratory test results, it was observed that the FI values generally showed a decreasing trend with increasing RAP contents (expresses in terms of ABR). This means in general, as the RAP content in a mix increases, it becomes more susceptible to fatigue cracking. Having said that, it is important to emphasize that two of the mixes with relatively high RAP contents (45.2 percent and 50 percent ABR), exhibited significantly high FI values. In fact, the FI values for these mixes were similar to those for a mix with no RAP. No particular justification for this unexpected behavior could be found.

5. Summary, Conclusions, and Recommendations

This research project focused on studying the effects of high RAP contents on asphalt mix performance. According to AASHTO M 323, high RAP content mixtures are defined as those that have more than 25 percent of RAP (by binder replacement). Until recently, ITD did not impose any upper limit on the amount of RAP allowed in an asphalt mix. With some of the pavement sections constructed with high RAP contents (sometimes as high as 54 percent), there were concerns within ITD regarding the possible adverse effects of such high RAP contents. As a result, ITD set a threshold of 30 percent as the maximum allowable RAP content in an asphalt mix. This corresponds to ITD's definition of high RAP as anything greater than 30 percent by binder replacement. In an effort to further understand how high RAP contents may affect asphalt mix performance, the current research study was initiated. The current research study comprised an extensive review of published literature, survey of state DOT practices, and laboratory testing of asphalt mixtures with different RAP contents. Findings from these research tasks were documented in the current report.

Conclusions

Use of high RAP amounts can be significantly beneficial both in terms of cost as well as environmental sustainability. However, production of well-performing asphalt mixtures with high RAP contents is largely dependent on the material handling and production processes implemented. In general, increasing RAP content leads to better rutting performance, but potentially increases cracking susceptibility of HMA pavements. However, through proper mix design, quality assurance protocols, and material handling procedures, it has been shown that pavements high in RAP content can be constructed to perform as well or better than virgin mixtures. Special attention to the crack susceptibility of high-RAP mixtures is recommended. A balanced mix design approach which incorporates rutting and cracking performance criteria in the mix-design process has been identified as a promising method to successfully produce high-RAP mixtures. Researchers have also reported about significant benefits realized from the use of rejuvenators (or recycling agents) with high RAP content asphalt mixtures. Based on the survey of state DOTs carried out under the scope of this project, it was observed that the maximum amount of RAP allowed in asphalt mixes by the responding agencies is usually around 30-35 percent. Most of the agencies expressed concerns about fatigue cracking of high-RAP mixtures, which can be addressed through the implementation of performance-based specifications. From the I-FIT testing carried out on different mixes collected from across Idaho, a generic trend of reduced (intermediate temperature) cracking resistance with increasing RAP content was observed. Extensive review of published literature also highlighted the benefits of diligent quality control of RAP stockpiles, particularly for mixtures with high RAP contents.

Recommendations for Path Forward

At this time, ITD has established a threshold of 30% RAP binder by weight of the total binder in the asphalt mixture. If ITD wants to consider allowing greater percentages (>30%) of RAP by asphalt binder replacement, they should do this methodically, considering the findings of this research in their decision-making process and the specific recommendations that follow.

1. A tiered approach can be adopted when it comes to the use of RAP in asphalt mixtures. From AASHTO M 323, when less than 15 percent RAP is used, no modifications to the mix design or binder type is required as the binder contribution from such a low quantity of RAP is negligible. In this case, the RAP primarily serves as a "Black Rock". For mixtures with 15-25 percent RAP, usually the use of a softer virgin binder grade suffices to account for the 'stiffening' effects of the binder released from RAP. On the other hand, when RAP contents greater than 25 percent are used, blending charts should be used (as recommended by the Asphalt Institute). Significant challenges are faced when higher RAP contents are used, as the use of the linear blending charts may no longer be sufficient. In such cases, special care and additional measures should be taken to ensure adequate mix performance. Note: AASHTO M 323 defines 'high-RAP' mixes as those containing more than 25 percent RAP (ABR). However, based on ITD's definitions, 'high-RAP' mixes are those with greater than 30 percent RAP (ABR). Therefore, in this report, recommendations regarding 'high-RAP' mixtures have been made referring to mixes with greater than 30 percent RAP (ABR). At present, ITD allows up to 30 percent RAP (by binder replacement) in asphalt mixtures. If ITD considers removing this upper limit, a strategic approach should be adopted with particular attention to quality control and performance testing. Note that survey of other state DOTs carried out during this study indicated most DOTs limit the maximum allowable RAP content to approximately 30-35 percent.

2. Several research studies have proved the effectiveness of recycling agents (or rejuvenator) in high-RAP mixtures. *It is recommended that ITD should recommend the use of recycling agents for all mixes that contain greater than 30% RAP*.

3. If high percentages of RAP are to be used, then special care needs to be taken to ensure adequate performance. With the move to performance-based mix design and acceptance practices, it may be possible to allow the use of higher RAP contents in asphalt mixes. *The use of recycling agents (or rejuvenators) should be encouraged for mixtures with greater than 30% RAP (if ITD moves back to allowing more than 30 percent RAP in asphalt mixtures in the future), with primary emphasis on performance-based mix design.*

4. Careful RAP stockpile management practices have been shown to significantly improve the quality of mix produced. To promote the construction of well-performing asphalt pavements incorporating RAP, ITD should incentivize contractors to follow careful RAP fractionation and processing practices. Control over the quality of mix being produced with high RAP percentages is best if the quality of RAP being added is carefully controlled. At the time this research study was initiated, ITD's specifications did not require fractionation of the RAP stockpiles. Moreover, ITD did not impose any restriction on whether the RAP was obtained from ITD-approved pavements or not. Although mixed information is available in the literature regarding the 'must-have' nature of RAP fractionation, it is

generally accepted that practices such as fractionation and good stockpile management help improve the quality of a mix. *It is recommended that ITD encourage contractors to implement adequate stockpile management practices for RAP. This involves keeping the stockpiles covered, fractionating the stockpiles, and when possible, use multiple feeder bins for the RAP.* *Requirements on stockpile management, fractionating and multiple feeder bins become even more critical when (in the future) ITD allows the use of more than 30 percent RAP in asphalt mixtures.* Collaboration and communication between ITD and contractors can facilitate the development of well-documented quality control plans that would lead to the production of better performing asphalt mixes.

5. If in the future ITD resumes allowing more than 30 percent RAP in asphalt mixtures, it is recommended that ITD should rely on performance tests (rutting and cracking tests). Moreover, for mixtures with such high RAP contents, ITD should also consider encouraging the use of rejuvenators and/or chemical warm-mix additives (depending on the type of mix being produced). Adopting such a flexible, performance-based acceptance criterion will provide contractors with avenues for innovation. One example of this can be seen in the success story reported by the Illinois Toll-Way (https://www.roadsbridges.com/illinois-tollway-continues-be-big-asphalt-player-contractors) where mixes have been produced with as much as 60 percent RAP with Fractionated RAP (FRAP), with excellent performance. What ultimately matters is: *how the mix performs in the field*. Therefore, it is possible to move away from a recipe-based approach, to promote sustainable and economical paving practices.

Through careful attention to details, well-performing high-RAP mixtures can be produced. With implementation of balanced (or performance-based) mix design approaches, state agencies can move away from recipe-type specifications and leave most of the mix parameters at the contractor's discretion. If the resulting mix meets all performance criteria, including rutting and cracking tests, it should be approved for placement. This will create an environment that promotes innovation and will also lead to sustainable practices in the fields of asphalt mix design, production, and paving.

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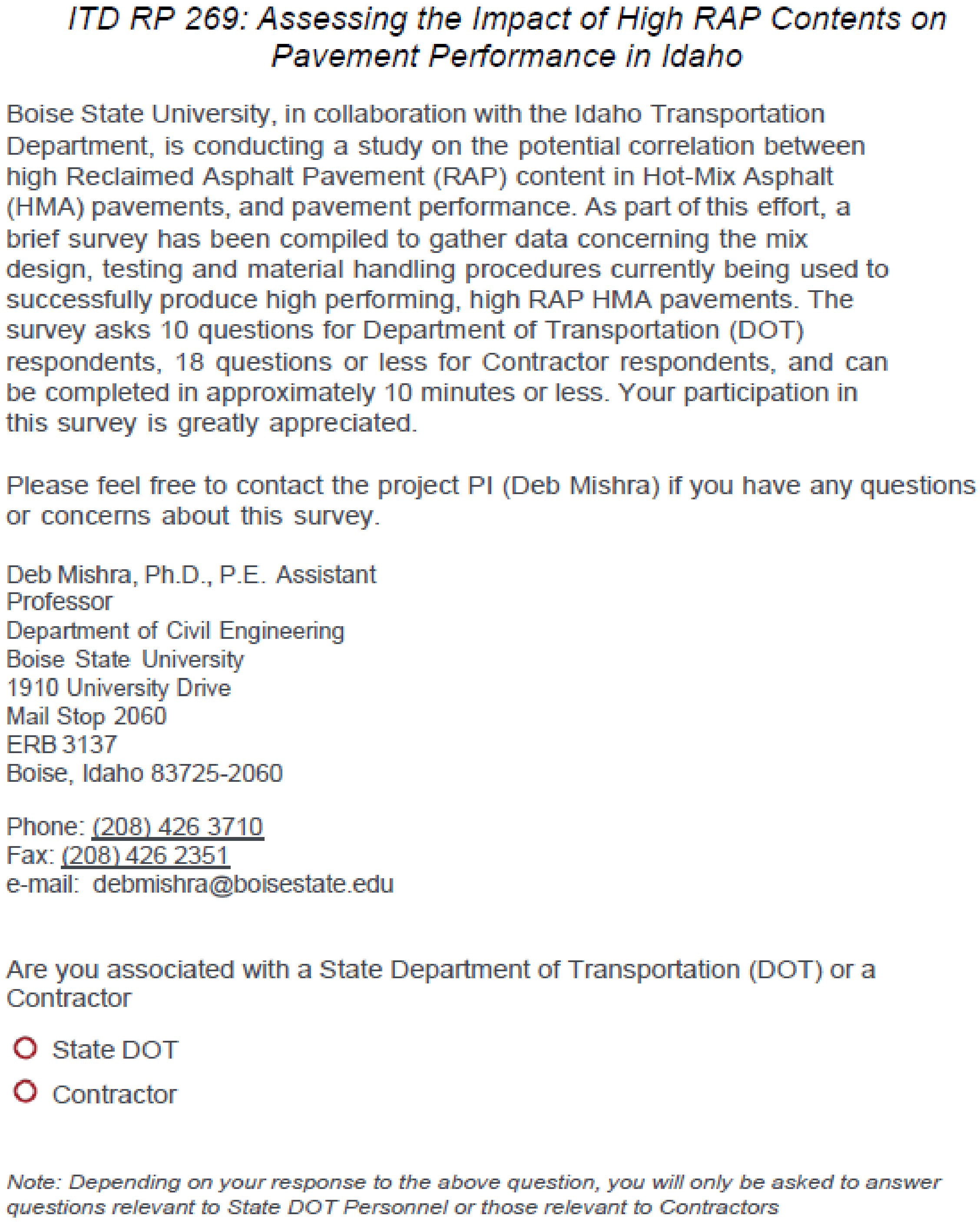
Appendix A. Survey Questionnaire Sent to State DOTs



ITD RP 269: Assessing the Impact of High RAP Contents on Pavement Performance in Idaho

Boise State University, in collaboration with the Idaho Transportation Department, is conducting a study on the potential correlation between high Reclaimed Asphalt Pavement (RAP) content in Hot-Mix Asphalt (HMA) pavements, and pavement performance. As part of this effort, a brief survey has been compiled to gather data concerning the mix design, testing and material handling procedures currently being used to successfully produce high performing, high RAP HMA pavements. The survey asks 10 questions for Department of Transportation (DOT) respondents, 18 questions or less for Contractor respondents, and can be completed in approximately 10 minutes or less. Your participation in this survey is greatly appreciated.

Please feel free to contact the project PI (Deb Mishra) if you have any questions or concerns about this survey.

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Professor
Department of Civil Engineering
Boise State University
1910 University Drive
Mail Stop 2060
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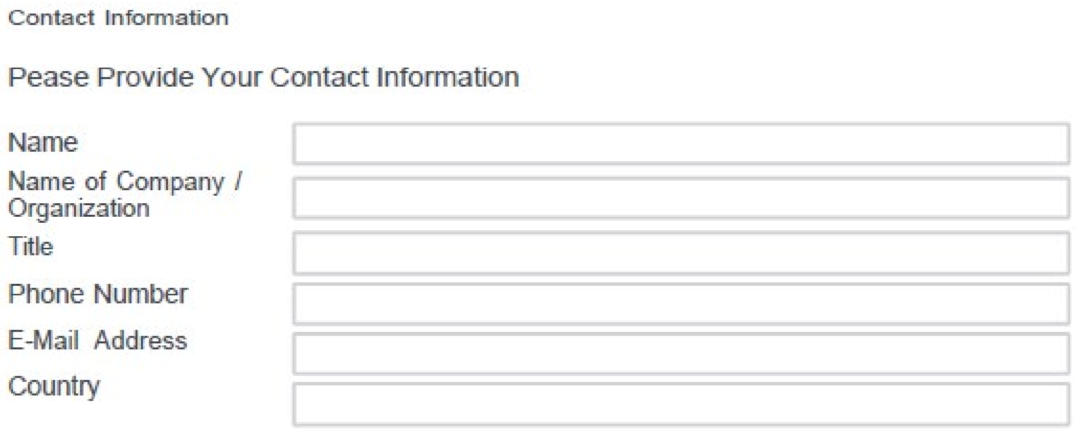
Phone: (208) 426 3710
Fax: (208) 426 2351
e-mail: debmishra@boisestate.edu

Are you associated with a State Department of Transportation (DOT) or a Contractor

○ State DOT

○ Contractor

Note: Depending on your response to the above question, you will only be asked to answer questions relevant to State DOT Personnel or those relevant to Contractors



Contact Information

Pease Provide Your Contact Information

Name

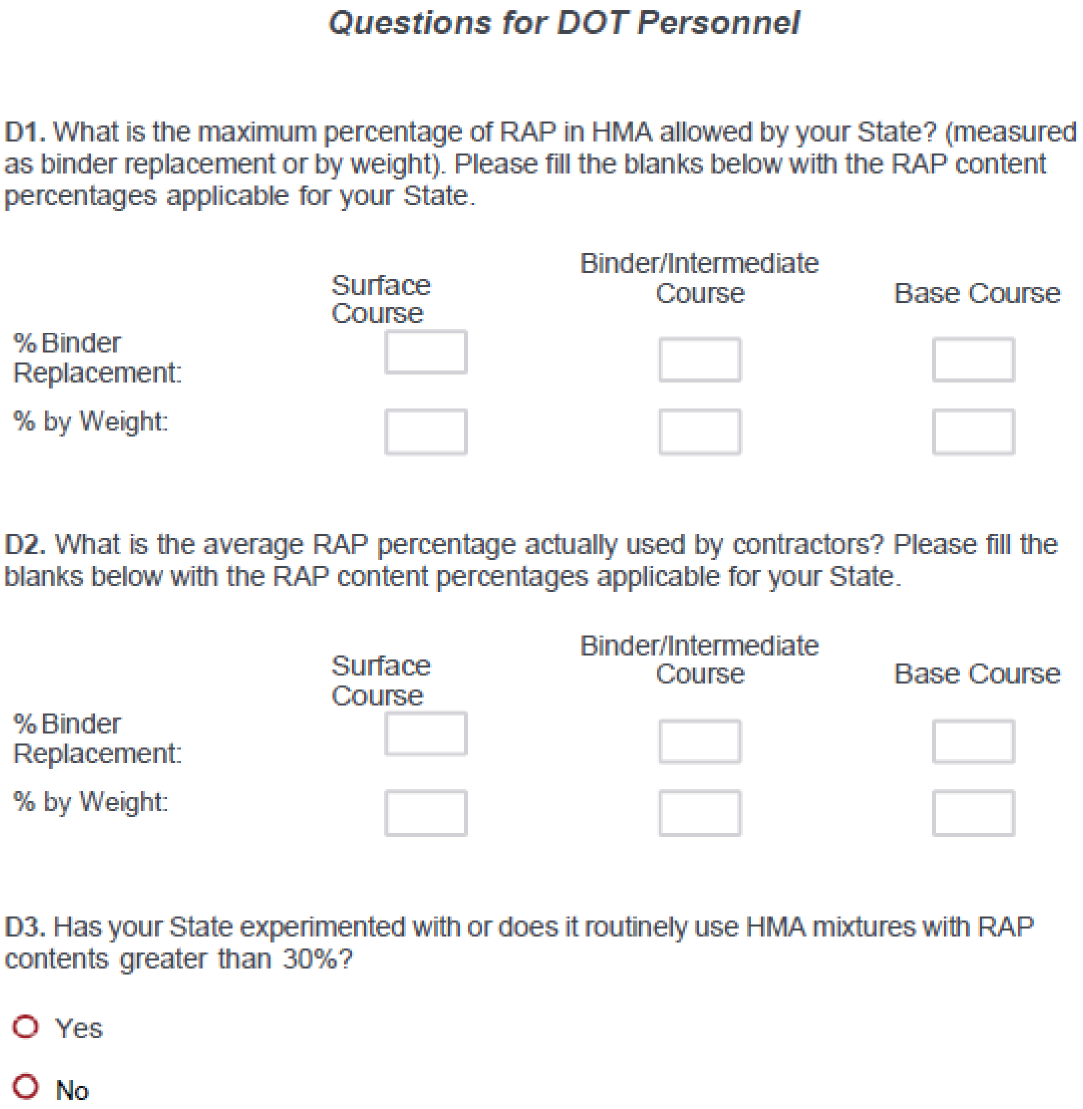
Name of Company / Organization

Title

Phone Number

E-Mail Address

Country



Questions for DOT Personnel

D1. What is the maximum percentage of RAP in HMA allowed by your State? (measured as binder replacement or by weight). Please fill the blanks below with the RAP content percentages applicable for your State.

	Surface Course	Binder/Intermediate Course	Base Course
% Binder Replacement:			
% by Weight:			

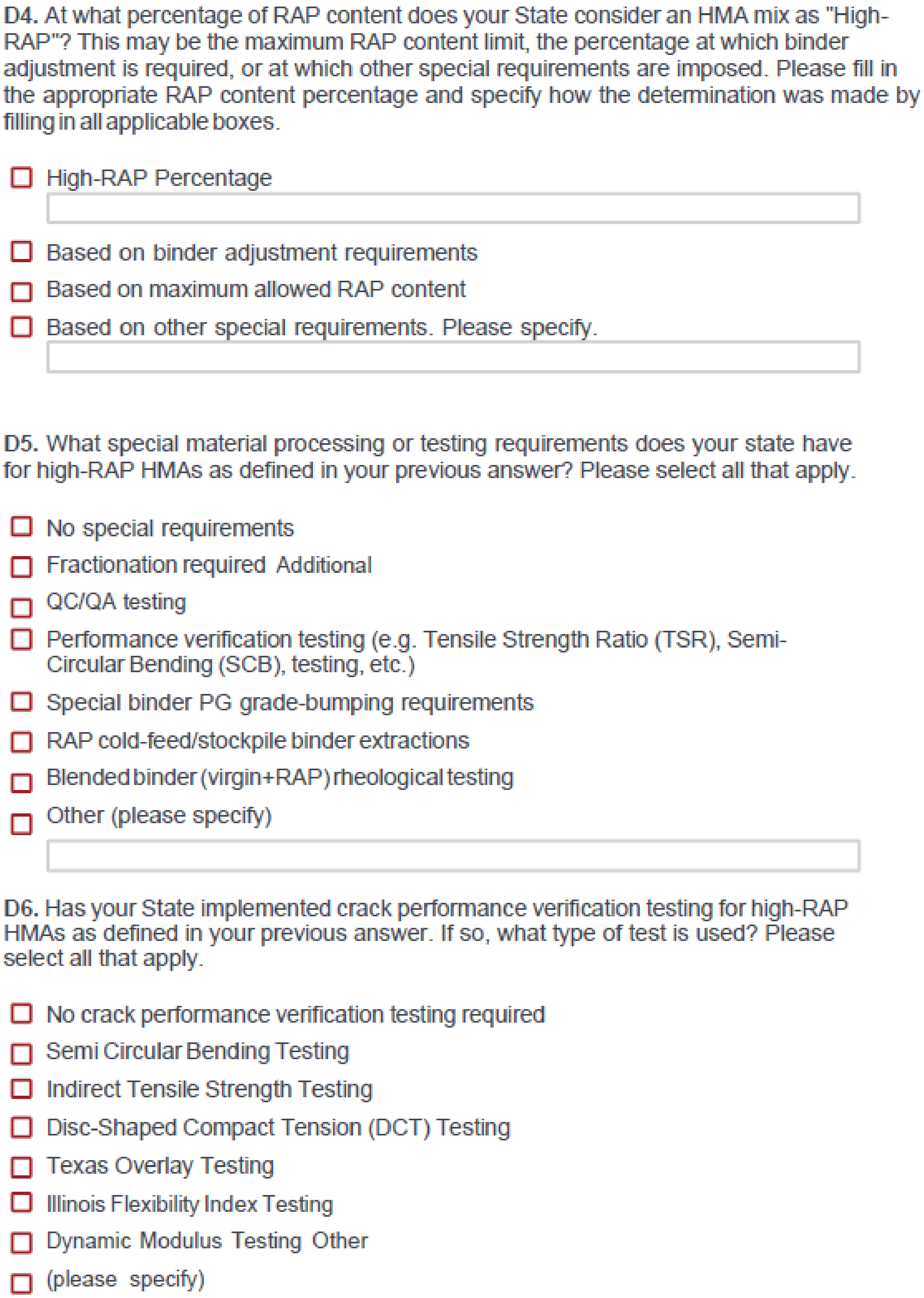
D2. What is the average RAP percentage actually used by contractors? Please fill the blanks below with the RAP content percentages applicable for your State.

	Surface Course	Binder/Intermediate Course	Base Course
% Binder Replacement:			
% by Weight:			

D3. Has your State experimented with or does it routinely use HMA mixtures with RAP contents greater than 30%?

○ Yes

○ No



D4. At what percentage of RAP content does your State consider an HMA mix as "High-RAP"? This may be the maximum RAP content limit, the percentage at which binder adjustment is required, or at which other special requirements are imposed. Please fill in the appropriate RAP content percentage and specify how the determination was made by filling in all applicable boxes.

☐ High-RAP Percentage

☐ Based on binder adjustment requirements
☐ Based on maximum allowed RAP content
☐ Based on other special requirements. Please specify.

D5. What special material processing or testing requirements does your state have for high-RAP HMAs as defined in your previous answer? Please select all that apply.

☐ No special requirements
☐ Fractionation required Additional
☐ QC/QA testing
☐ Performance verification testing (e.g. Tensile Strength Ratio (TSR), Semi-Circular Bending (SCB), testing, etc.)
☐ Special binder PG grade-bumping requirements
☐ RAP cold-feed/stockpile binder extractions
☐ Blended binder (virgin+RAP) rheological testing
☐ Other (please specify)

D6. Has your State implemented crack performance verification testing for high-RAP HMAs as defined in your previous answer. If so, what type of test is used? Please select all that apply.

☐ No crack performance verification testing required
☐ Semi Circular Bending Testing
☐ Indirect Tensile Strength Testing
☐ Disc-Shaped Compact Tension (DCT) Testing
☐ Texas Overlay Testing
☐ Illinois Flexibility Index Testing
☐ Dynamic Modulus Testing Other
☐ (please specify)

D7. Does your State limit RAP percentage based on HMA plant type? Please select the appropriate box, and specify the corresponding percentage value.

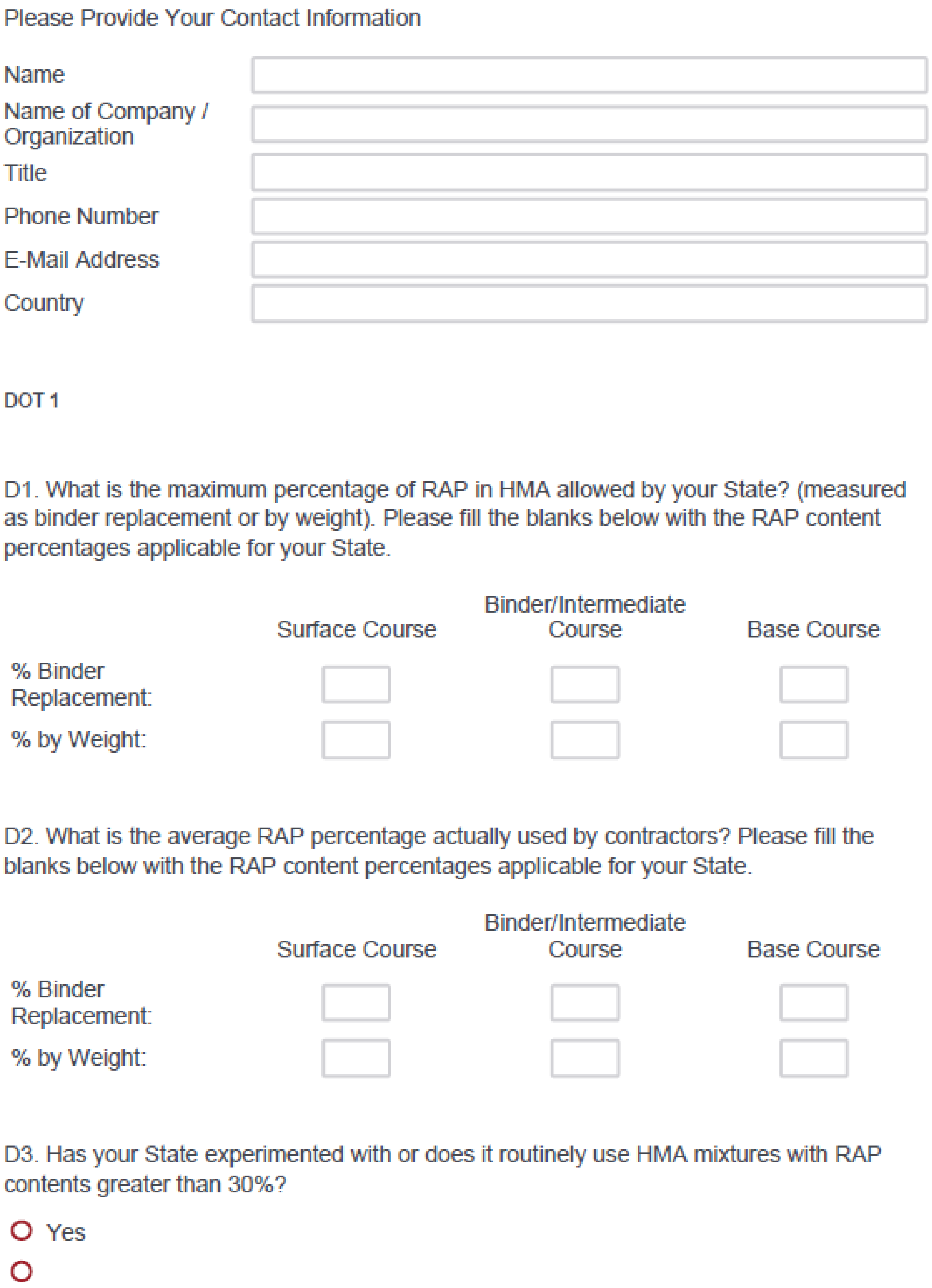
☐ No
☐ Yes: Batch-Mix Plant Limit
☐ Yes: Drum-Mix Plant Limit

D8. Who retains ownership of the RAP after it is milled?

○ DOT Retains Ownership
○ Contractor Retains Ownership
○ Ownership Varies depending on Pavement Type being Milled

D9. What are the major barriers that prevent increasing RAP content in HMA applications in your State? Please select all that apply.

☐ Availability of RAP/RAP contractors
☐ Meeting State specification requirements
☐ Material variability concerns
☐ Low temperature cracking concerns
☐ Fatigue cracking concerns
☐ Concerns with respect to meeting volumetric specifications
☐ Complications associated with mix design procedures
☐ Complications associated with binder grade and blending
☐ Use with polymers
☐ Production (blue smoke etc.)
☐ Other (please specify)



Please Provide Your Contact Information

Name	
Name of Company / Organization	
Title	
Phone Number	
E-Mail Address	
Country	

DOT 1

D1. What is the maximum percentage of RAP in HMA allowed by your State? (measured as binder replacement or by weight). Please fill the blanks below with the RAP content percentages applicable for your State.

	Surface Course	Binder/Intermediate Course	Base Course
% Binder Replacement:			
% by Weight:			

D2. What is the average RAP percentage actually used by contractors? Please fill the blanks below with the RAP content percentages applicable for your State.

	Surface Course	Binder/Intermediate Course	Base Course
% Binder Replacement:			
% by Weight:			

D3. Has your State experimented with or does it routinely use HMA mixtures with RAP contents greater than 30%?

○ Yes

○