Evaluating Recycling Efficiency of Asphalt Plants

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16. Abstract

This study aims to determine recycling efficiency of mixtures containing recycled asphalt pavement (RAP) and recycled asphalt shingle (RAS) from different asphalt plants and to investigate the influence of mixture design and production conditions on recycling efficiency. A new procedure was developed by using fluorescence microscopy to differentiate between RAP/RAS and virgin binders as well as their blends, in which a new parameter, mean grey value (MGV) based on fluorescence image, was utilized to quantitatively determine the mobilization rates of aged asphalt binder in RAP/RAS. By generating the "Blending Chart" to show the change of MGV with RAP/RAS binder content, the mobilization rate of aged binder in RAP/RAS can be directly measured. A total of 14 plant-produced asphalt mixtures were tested for their RAP/RAS binder mobilization rate using fluorescence microscopy and GPC. Linear regression analyses were conducted to evaluate the influence of mixture design and production condition parameters on the mobilization rate. In addition, a preliminary study was performed to investigate the influence of different rejuvenator incorporation methods on the rheological and aging properties of asphalt binders containing RAP/RAS. The major conclusions from the study are summarized as follows:

1) The mobilization rates were different for large and small aggregates because of different RAP/RAS contents. The overall mobilization rate of a mixture could be determined by considering the surface area of large and small aggregates.

2) The overall mobilization rates of 14 plant mixtures were in the range of 0.4 to 1.0 for the fluorescence microscopy method and 0.37 to 0.83 for the GPC method. The mobilization rates from fluorescence microscopy and GPC method were different but showed similar trend among 14 plant mixtures. The R^2 of the linear regression between GPC and fluorescence results is 0.557.

3) Among the production condition parameters of asphalt mixture plants, the mixing temperature and the percentage of RAP/RAS showed significant influences on the mobilization rate. In addition, the ageing level of the RAP/RAS binder also had a significant influence on the mobilization rate.

4) The sensitivity of MGV to the aged binder content was affected by the test conditions. An index, Differentiation Factor, was used to measure the sensitivity of MGV to aged binder content. Results indicate that the MGV measured at the wavelength of 450-490 nm and the exposure time of 0.5-1.5 s was most sensitive to the aged binder content. For the construction of a blending chart, it was found that there existed a linear relationship between the MGV of a binder blend and its RAP binder content, and a quadratic relationship between the MGV of a binder blend and its RAS binder content.

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Executive Summary

The current trend in the paving industry is to increase the use of recycled asphalt pavement (RAP) and recycled asphalt shingle (RAS). However, one of the reasons that limit higher recycled content is the unknown blending process between virgin and RAP/RAS binders. The Tennessee Department of Transportation (TDOT) Materials and Tests Division has been collaborating with the University of Tennessee to investigate the recycling efficiency of asphalt mixtures containing RAP/RAS, with an aim to address the recycling efficiency of recycled asphalt mixtures from different asphalt plants in Tennessee. The recycling efficiency in this study was quantified through the blending efficiency developed in previous studies. The findings from this study will help maximize the use of RAP/RAS in asphalt mixtures and enhance the properties and performance of the mixtures containing RAP/RAS. The major research activities are summarized as follows:

1) A series of studies were conducted to evaluate the blending efficiency in asphalt plant mixtures containing RAP and RAS. A new method was developed using fluorescence microscopy to differentiate between RAP/RAS and virgin binders as well as their blends, in which a new parameter, mean grey value (MGV) based on fluorescence image, was utilized to quantitatively determine the mobilization rates of aged asphalt binder in RAP/RAS. By generating the "Blending Chart" to show the change of MGV corresponding to RAP/RAS binder content, the mobilization rate of aged binder in RAP/RAS can be directly measured.
2) A total of 14 plant-produced asphalt mixtures were tested for their RAP/RAS binder mobilization rate using fluorescence microscopy and Gel Permeation Chromatography (GPC). Linear regression analyses were conducted to evaluate the influence of mixture design and production condition parameters on the mobilization rate.

3) In addition, a preliminary study was performed to investigate the influence of different rejuvenator incorporation methods on the rheological and aging properties of the recycled asphalt binders.

Based on the results of the study, the following conclusions can be drawn:

1) The mobilization rates were different for large and small aggregates because of different RAP/RAS contents. The overall mobilization rate of a mixture could be determined by considering the surface area of large and small aggregates.
2) The overall mobilization rates of 14 plant mixtures were in the range of 0.4 to 1.0 for the fluorescence microscopy method and 0.37 to 0.83 for the GPC method.
3) The sensitivity of MGV to the aged binder content was affected by the test conditions. An index, Differentiation Factor, was used to measure the sensitivity of MGV to aged binder content. Results indicated that the MGV measured at the wavelength of 450-490 nm and the exposure time of 0.5-1.5 s was most sensitive to the aged binder content.
4) For the construction of a blending chart, it was found that there existed a linear relationship between the MGV of a binder blend and its RAP binder content, and a quadratic relationship between the MGV of a binder blend and its RAS binder content. Therefore, the relationship between MGV and the aged binder content of a binder blend could be different for asphalt from diverse sources.
5) The mobilization rates from fluorescence microscopy and GPC method were different but showed a similar trend among the fourteen plant mixtures, which is due to the fact that the fluorescence microscopy method tests the aged asphalt content on the aggregate surface, whereas the GPC method tests the aged asphalt content of the outer layer of asphalt film.
6) According to the large molecules content (LMS (%)) results from the GPC tests, the mobilization rates for the inner layer and the outer layer were different,

indicating that only a part of the aged binder in the RAP/RAS was mobilized in the mixtures.

7) Among the production condition parameters of asphalt mixture plants, the mixing temperature and the percentage of RAP/RAS showed significant influences on the mobilization rate. In addition, the aging level of the RAP/RAS binder also had a significant influence on the mobilization rate. In general, a higher mixing temperature and less percentage of RAP/RAS may promote the mobilization rate, whereas a higher aging level of the RAP/RAS binder may decrease the mobilization rate.

8) By incorporating the rejuvenator with the aged binder first, the binder blends showed a more beneficial change in rheological properties compared to the one incorporating the rejuvenator with the virgin binder first, indicated by a lower complex modulus and a higher phase angle of the binder blends.

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Chapter 1 INTRODUCTION

1.1 Problem Statement

The Tennessee Department of Transportation (TDOT) has routinely incorporated recycled asphalt pavement (RAP) in its asphalt paving mixtures and is now starting to allow recycled asphalt shingles (RAS) in its construction. Use of RAP/RAS results in the following benefits:

(a) Conservation of natural resources including aggregates and asphalt binder

(b) Cost savings

(c) Environmental benefits by eliminating landfills

However, one disadvantage of using RAP/RAS is that the asphalt binder in RAP/RAS has experienced aging over its lifetime and become stiff and brittle. When RAP/RAS is added into new aggregate and virgin binder during plant mixing, the aged binder may not be able to be fully blended with virgin binder and thus negatively impacts the performance of recycled asphalt mixtures. If not fully blended, what proportion of the aged binder can be mobilized and blended into virgin binder? This is one critical question that has to be answered so that the benefits of using RAP/RAS can be realized and durable asphalt pavements can be ensured.

The research team of the University of Tennessee, Knoxville (UTK) led by Dr. Huang has been collaboratively working with TDOT and conducted five RAP/RAS-related studies since 2002. The team has determined the allowable percentages of RAP in different asphalt mixtures for TDOT based on laboratory performance test results and field surveys on test sections [1, 2]. They have conducted a comprehensive laboratory experiment and investigated the factors affecting the blending efficiency of RAP/RAS [3, 4]. They also developed a laboratory procedure to determine the proportion of aged asphalt binder in

RAP/RAS that can be mobilized and blended into virgin binder [5, 6].

This research project builds upon the previous TDOT-sponsored RAP/RAS studies, determines the blending efficiency of different asphalt mixing technologies used by the asphalt plants in Tennessee, and evaluates its impact on the performance of the resulting asphalt mixtures. The UT studies have shown that method of mixing, mix time, storage time, and additives can all affect blending efficiency, resulting in mixtures with different effective asphalt binder than designed [3, 5, 6]. In other words, some asphalt plants may be able to more efficiently recycle asphaltic materials into mixtures than others, or some asphalt plants may be able to utilize higher recycle percentages than others. At current, TDOT has 117 approved plants on its Approved Suppliers list, but minimal knowledge of any of these plants' ability to recycle materials. Consequently, TDOT specifications for maximum allowable percentages of recycled materials are conservative, ultimately limiting the ability of the more efficient facilities.

After the completion of the research project, a better understanding can be acquired about the role of RAP/RAS in asphalt mixtures. How is the aged binder mobilized and blended into the virgin binder? How does the aged binder interact with the virgin binder? The findings from the project will help maximize the use of RAP/RAS in asphalt mixtures and enhance the properties and performance of the mixtures containing RAP/RAS.

1.2 Objectives

The objectives of the research are:

(1) To evaluate the blending efficiency of typical plant mixtures containing RAP/RAS.

(2) To explore the factors affecting the blending efficiency of RAP/RAS mixtures.

(3) To provide recommendations for improving the blending efficiency of recycled mixtures.

1.3 Scope of Study

The scopes of the research work are:

- To complete a synthesis of literature review on RAP/RAS recycling technologies and a DOT survey on RAP/RAS recycling practices in the US, especially in the Southeastern region;
- To evaluate the blending efficiency of typical RAP/RAS recycling technologies used in Tennessee;
- To investigate the effects of plant mixing parameters on the blending efficiency of plant mixtures.

1.4 Overview of the Final Report

The whole report was organized as follows: Chapter 1 gives a brief background of the project. Chapter 2 performs a comprehensive literature review on recycling efficiency. Chapter 3 summarizes the surveys sent out to the DOTs in the U.S. Chapter 4 introduces the methodology for the fluorescence microscopy method. Chapter 5 validates the blending efficiency test. Chapter 6 measures the blending efficiency of plant mixtures in Tennessee. Chapters 7 performs a preliminary study on different rejuvenator incorporation methods. The report concludes by summarizing the findings from the laboratory studies.

Chapter 2 LITERATURE REVIEW

2.1 Introduction of Recycling Efficiency

With the ever-increasing cost of aggregate and asphalt binder, the incorporation of RAP/RAS into asphalt mixtures has become more and more popular [4, 7-9]. The use of RAP/RAS can produce significant economic and environmental benefits. RAP/RAS has experienced aging over its service life, and its binder has become highly stiff and brittle. In the production process, RAP/RAS is usually heated by the hot virgin aggregate instead of directly by fire to avoid further aging. Therefore, the stiff binder in RAP/RAS may not be able to flow freely and be blended with hot virgin binder to coat aggregates. The lack of a clear understanding of the recycling efficiency of recycled asphalt has been a major concern in determining the effective asphalt binder in asphalt mixtures containing RAP/RAS.

How much of the aged binder in the RAP/RAS that can be mobilized and blended into the virgin binder has been a critical question, and a rational solution to this question will considerably boost the benefits of using RAP/RAS and promote more durable asphalt pavements. The recycling efficiency was usually quantified through the blending efficiency developed in previous studies, and these previous studies have shown that partial blending may occur when RAP is mixed with virgin binder and aggregates [1, 10-13]. Soleymani et al. simulated three blending conditions by preparing three mixtures, which represent the scenarios of non-blending, true mixture, and total blending [14]. Their study concluded that at least partial blending occurs in the true mixture.

Recently, many researchers reported that the asphalt binder in the RAP/RAS was only partially blended into the virgin binder. In the NCHRP Project 9-12, for incorporating RAP into the Superpave system, McDaniel et al. stated that the partial blending does occur to a significant extent, and the insufficient blending affects the performance of mixtures containing a high percentage of RAP [15]. Therefore, the assumption of 100% blending may result in insufficient asphalt content in asphalt paving mixtures as the resulting coating film of virgin aggregate will be too thin to reach the target film thickness. Additionally, the binder on RAP aggregate will be stiffer than expected, reducing the resistance to fatigue and low temperature cracking. These changes will lead to poor pavement performance or a shorter pavement service life. Therefore, it is critical to accurately determine blending efficiency of RAP mixtures.

2.2 Recycling Efficiency for Asphalt Plants

Extensive laboratory studies have demonstrated that the blending efficiency of recycled mixtures is influenced by material properties and the mixture preparation process [3, 6, 16]. Factors such as mixing methods, mixing time, storage time, and additives all potentially affect the blending efficiency, resulting in mixtures with different effective asphalt binder than designed [3, 6, 16]. The production conditions are essential to the blending efficiency which typically vary among contractors and asphalt plants. Currently, there is limited knowledge on the influence of the production conditions on the blending efficiency of plant-produced mixtures containing RAP/RAS. Hence, it is highly desirable to investigate the effects of plant production conditions on the blending efficiency of the resulting asphalt mixtures.

Mogawer et al. investigated the influence of production process on the degree of blending between the RAP and virgin binders and the performance of the mixtures in 2012 [17]. Their study concluded that certain production parameters such as discharge temperature may have an impact on the blending efficiency. Recently, the mobilization rate, which quantifies the amount of aged binder mobilized into with the virgin binder, has been adopted to characterize the blending efficiency of mixture produced in laboratory [3, 4]. By using the mobilization rate as a target variable, it is also possible to evaluate the effect of production conditions on the blending efficiency of plant-produced mixtures.

Previous studies usually mixed RAP/RAS with virgin aggregates of particular sizes and shapes to prepare mixture samples, and the RAP/RAS particles could be visually detected and separated from the virgin aggregates for the mobilization rate testing. This approach is based on the fact that the virgin and RAP/RAS aggregates could be readily separated after the mixing process. However, this is not the same for plant-produced mixtures, especially when both types of particles have similar sizes and shapes. Therefore, improvements on the laboratory procedures are needed to adapt to the characteristics of plant mixtures, in which the virgin and RAP aggregates are difficult to be separated visually.

2.3 Methods for Determining Recycling Efficiency

The blending efficiency can be quantified using what is termed the mobilization rate, which is defined as the percentage of aged binder that can be mobilized and blended into virgin binder to coat aggregate particles. Analytical methods have been used to investigate the blending efficiency of virgin and aged binder, which can be classified into: 1) microscopy methods including atomic force microscopy (AFM) and environmental scanning electron microscopy (ESEM), 2) chemical dissolution methods including gel permeation chromatography (GPC) and Fourier transform infrared spectroscopy (FTIR), 3) mechanical property methods including dynamic shear rheometer (DSR) and bending beam rheometer (BBR), and other methods such as X-ray computer tomography (CT) [3, 18-25].

The chemical dissolution method is widely used to investigate the blending process of aged binder. It involves lixiviating binder blend using a chemical solvent, collecting the resulting solute gradually and using it to determine the mass fraction of the virgin and aged binder. This experimental technique is able to assess the extent to which the aged binder is blended into the virgin binder in the production process as well as the effects of different factors on blending, including processing temperature and mixing time [1, 3, 22, 26]. The most widely used test instrument in the dissolve method is GPC, which is used to test the molecular distribution of asphalt. The feasibility of utilizing GPC method for blending efficiency is due to the fact that the aged asphalt exhibits a higher molecular weight than the virgin asphalt. Karlsson et al. studied the influence of asphalt layer thickness, asphalt type, and temperature on the diffusion of rejuvenator by FTIR- Attenuated Total Reflection (ATR), and they also investigated the diffusion of rejuvenator by measuring the carbonyl content in asphalt [27]. Jia et al. utilized FTIR to analyze the blending degree of the aged and virgin asphalt in recycled asphalt mixtures, and the results showed that the recycled asphalt extracted from different layers had an uneven blend of aged and virgin asphalt [28].

In order to avoid the chemical dissolution process used in chemical dissolution methods, a mechanical property method has been developed to assess the blending efficiency by comparing the measured dynamic modulus of recycled mixtures with that predicted from binder testing of as-recovered binders [21, 23]. The degree of blending between RAP, RAS, and virgin binder can also be evaluated by comparing the dynamic modulus of mixtures to a dynamic modulus predicted using the complex modulus of the recovered binders and the Hirsch model [18, 29]. Another method has been developed to evaluate the blending efficiency by modifying the analysis procedure for estimating the low-temperature properties of RAP binder and binder blend [30, 31].

The optical microscopy methods have been proven to be effective in directly distinguishing between virgin and aged binders [24, 32]. AFM is used to probe the change of microstructural properties from a RAP [32], or RAS [12] binder and virgin bitumen to the blending zone of these two. With this visualization technique, the virgin binder could be differentiated from the aged binder qualitatively using grey level. Xu et al. used a combination of staged extraction method and AFM to investigate the interaction and extent of blending between RAP and virgin binders under different mixing temperature and residence time [33]. Elseifi et al. adopted optical microscopy and SEM to determine the effective asphalt film thickness [34].

These studies improved the understanding of the blending process of recycled asphalt materials. However, there are still no commonly accepted methods available to determine the blending efficiency. Among the above-mentioned chemical techniques, GPC and FTIR methods need to extract asphalt binder from aggregate particles to make samples for further testing. Therefore, the heterogeneity of binder on aggregate cannot be determined. In addition, the process of using a chemical solvent to dissolve asphalt binder makes the test time-consuming and complicated. The extraction and recovery process may also affect the accuracy of the test result. It is desired to develop a convenient method for determining the blending efficiency of RAP/RAS. A new visual observation tool without the tedious binder extraction process is desirable for distinguishing virgin from aged binders so that it would be much easier and more practical to quantify the blending efficiency of the recycled asphalt binder in an asphalt mixture.

Navaro et al. [35] utilizes fluorescence microscopy to investigate the degree of blending between virgin and aged binders. In the fluorescence photograph, the aged binder could be distinguished from the virgin binder due to their difference in fluorescence, which provides the basis for determining blending efficiency of RAP with fluorescence microscopy. However, the fluorescent intensity of binders is controlled by multiple factors such as their chemical composition and the experimental conditions. Therefore, to efficiently use this method in asphalt blending, the fluorescent characteristics of virgin and aged binders need to be further examined, and the quantitative relationship between the fluorescent intensity and the aged binder content also needs to be investigated. In addition, the test methods mentioned above are based on different properties of asphalt binders, so the comparability of different methods is still a concern.

2.4 Fluorescence of Asphalt

Fluorescence is a phenomenon in which ultraviolet or visible light is absorbed by an organic molecule, thus causing excitation of an electron from an initially occupied, low-energy orbital to a high-energy, previously unoccupied orbital (Khorasani 1987). Fluorescence in asphalt molecules is essentially related to electronic excitation of the conjugated π-systems (aromatic components) and of C=O groups [36-38]. Research indicates that the extractable C=O groups exhibit a weak fluorescence, whereas the aromatic hydrocarbon fractions show a moderate fluorescence. Highly condensed systems, such as those present in asphaltenes, are virtually non-fluorescent because many energy exchanges are possible through large conjugated π-systems, thus giving rise to nonradiative de-excitation [36-38].

Saturate fractions are expected to exhibit no fluorescence. Therefore, dilution in a saturated hydrocarbon matrix is the most favorable case for aromatics to emit fluorescence. The molecular environment, such as the proportion of saturates to aromatics, the polarity, and the intermolecular interactions, have a decisive effect on the fluorescence intensity of asphalt. The fluorescence intensity of asphalt is thus primarily controlled by the type and concentration of aromatic molecules relative to the concentration of saturate compounds [39, 40].

The fluorescence microscopy is an optical microscopy that uses the emission of fluorescence to study the properties of organic or inorganic substances [41]. Fluorescence microscopy has been used to visualize voids and cracking of asphalt mixtures, and to observe the state of asphalt binders when they are modified with polymers [42-44]. The polymer-rich phase that is swelled by the oily aromatic part of the asphalt appears to be yellow-colored, whereas the asphaltene phase is dark [19, 45, 46].

For the asphaltenes and maltenes fractions, the asphaltenes produce little to no fluorescence, but the maltenes exhibit strong fluorescence in the observed spectral region

[47]. For the saturated, aromatic, resin, and asphaltenic (SARA) fractions, the aromatics and resin phases are the only components capable of sufficiently intense fluorescent emission [47]. Research has also indicated that as bitumen ages, its fluorescence emission intensity decreases [48]. Therefore, the fluorescent intensity can be used to distinguish virgin binders from aged binders.

Chapter 3 DOTs SURVEY

3.1 DOT Survey

A survey was conducted to collect information from state and local highway agencies on the blending efficiency of RAP/RAS in the North America, including United States, Canada, and Puerto Rico. The purpose of this survey was to determine the current practices of state and local highway agencies regarding the blending efficiency of RAP/RAS and to seek advices and opinions in this area. The survey was sent to 52 state and local DOTs (including District of Columbia and Puerto Rico). Among them, as listed in **Table 3-1** and shown in Figure 3-1, 40 agencies responded to the survey, namely, 77% of surveys were responded.

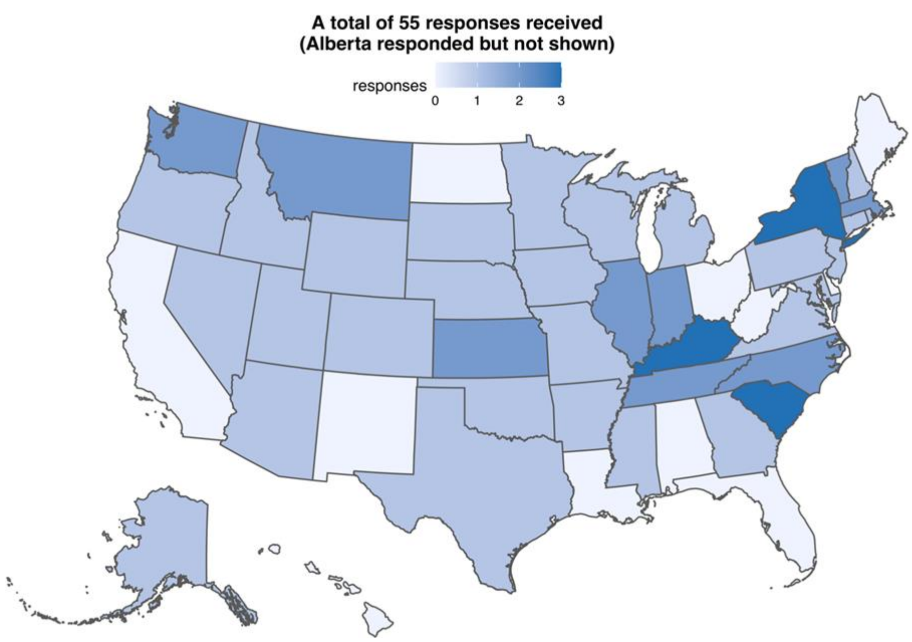


Figure 3-1 The distribution of respondents

Table 3-1. States response to the survey

No.	State Responded	No. of Respondents	No.	State Responded	No. of Respondents
1	Alaska	1	21	North Carolina	2
2	Alberta	1	22	Texas	1
3	Arizona	1	23	Nebraska	1
4	Arkansas	1	24	Nevada	1
5	Colorado	1	25	New Hampshire	1
6	Connecticut	1	26	New York State	3
7	Georgia	1	27	New Jersey	1
8	Idaho	1	28	Oklahoma	1
9	Illinois	2	29	Oregon	1
10	Indiana	2	30	Pennsylvania	1
11	Iowa	1	31	Rhode Island	1
12	Kansas	2	32	South Carolina	3
13	Kentucky	3	33	South Dakota	1
14	Maryland	1	34	Tennessee	2
15	Massachusetts	2	35	Utah	1
16	Michigan	1	36	Vermont	2
17	Minnesota	1	37	Virginia	1
18	Mississippi	1	38	Washington, D.C.	2
19	Missouri	1	39	Wisconsin	1
20	Montana	2	40	Wyoming	1
Total number of respondents		55			

Survey results were shared with industry and government agencies and officials to promote recycling and sustainable paving technologies. The collected information was analyzed, and the results are summarized below.

3.2 Responses to the Survey

3.2.1 Responses to the RAP application

Among the states and agencies that responded, 63% of the respondents indicated that they had specifications about how much of the aged asphalt binder on RAP can be used. Further, the respondents indicated the specified RAP recycling efficiency in their specification and the responses are shown in Figure 3-2. 20% of them considered RAP binder being fully used, and 25 %, 7 %, and 5 % of them believed that 0~30%, 30~60%, and 60~100% of RAP binder being used respectively. The rest of respondents replied that they had different recycling efficiency depending on the recycled material types (RAP or RAS), at what depth the recycled materials are obtained, and the mixture types.

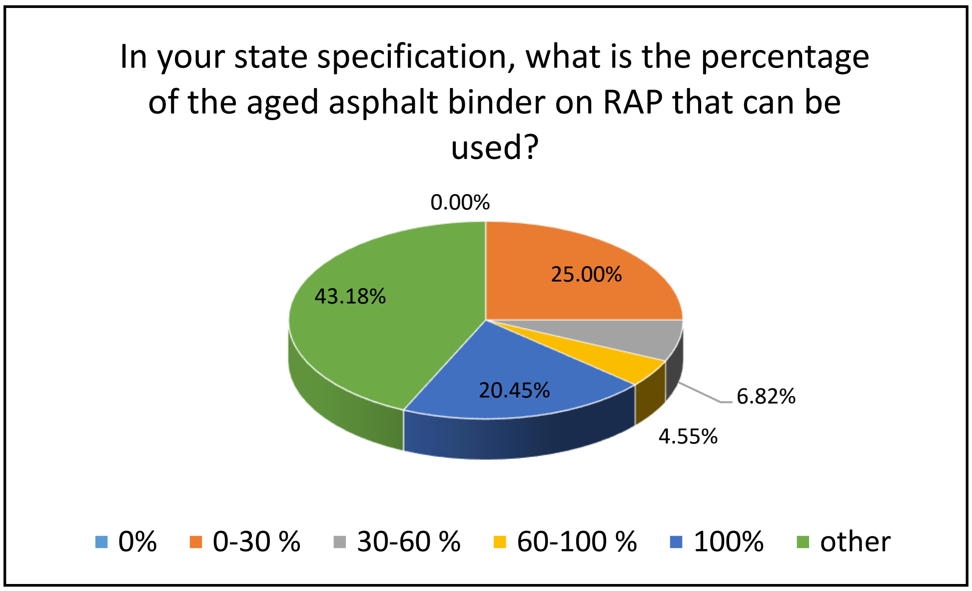


Figure 3-2 Percent of the aged asphalt binder on RAP that can be used

Figure 3-3 shows that among the respondents, 55% of them thought that the percentage in their state specification was reasonable, and 29% of them answered no.

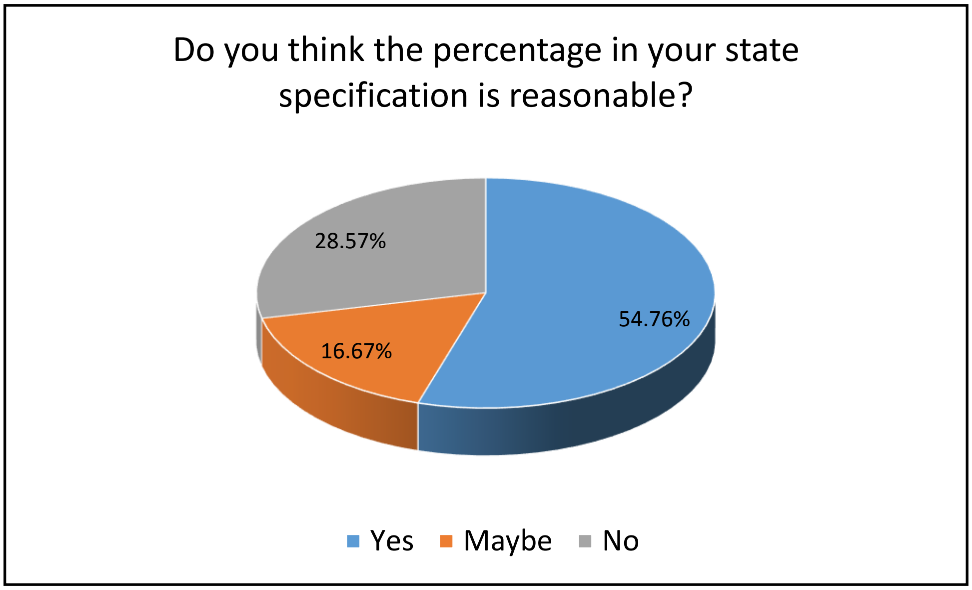


Figure 3-3 Percent in state specification

Among those that thought their specifications of recycling efficiency were unreasonable, the most common reason was due to the assumption of 100% aged binder being reusable. As the binder in the RAP has been considerably oxidized, it was unlikely that all of it will be released and available for use again. Some respondents also provided the recycling efficiency deemed as reasonable, which ranged from 15~40% depending on the mixture types and how the RAP was produced.

Figure 3-4 shows the results about what percentage of respondents think the aged asphalt binder on RAP can be used. More than 25% of the respondents believed the recycling efficiency was within the range of 0~30%, while more than 15% of them assumed that it was between 60% and 100%. More than 11% of the states thought the binder in the RAP could be fully reused, while one state used the RAP as black rock and thought none of the binder in RAP could be reused.

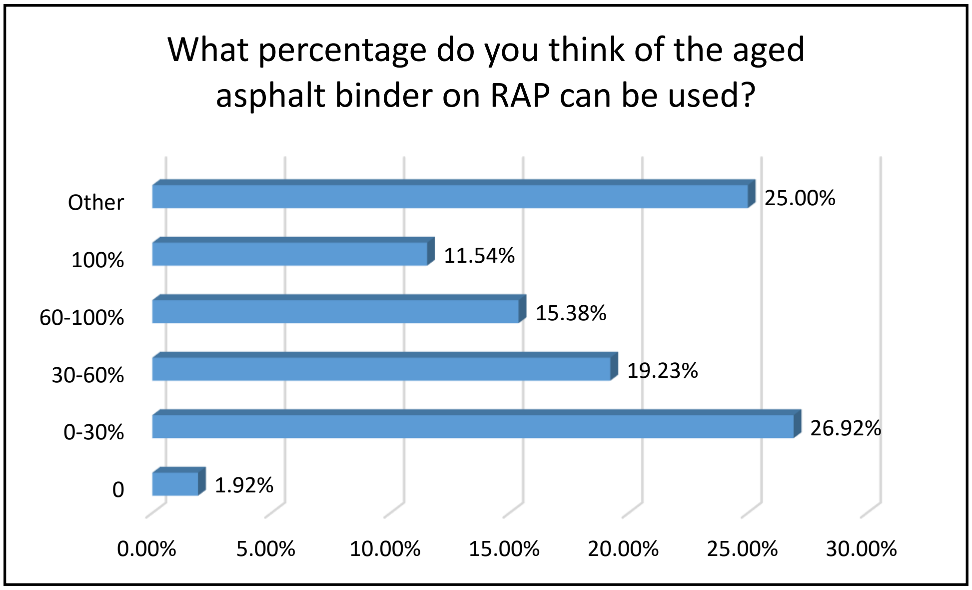


Figure 3-4 Percent of aged asphalt binder on RAP can be used

Up to 80% of respondents seemed to have no established method for testing the blending efficiency of RAP. For the respondents who knew the test methods, around 67% of them used DSR in this regard, and 34 % of them used fluorescence microscopy, GPC, or FTIR as shown in Figure 3-5. Among the 28% of respondents that selected "other", several indicated using bending beam rheometer (BBR) and tensile strength ratio (TSR) test, while some states used only mixture performance as indirect checking of the effects of RAP.

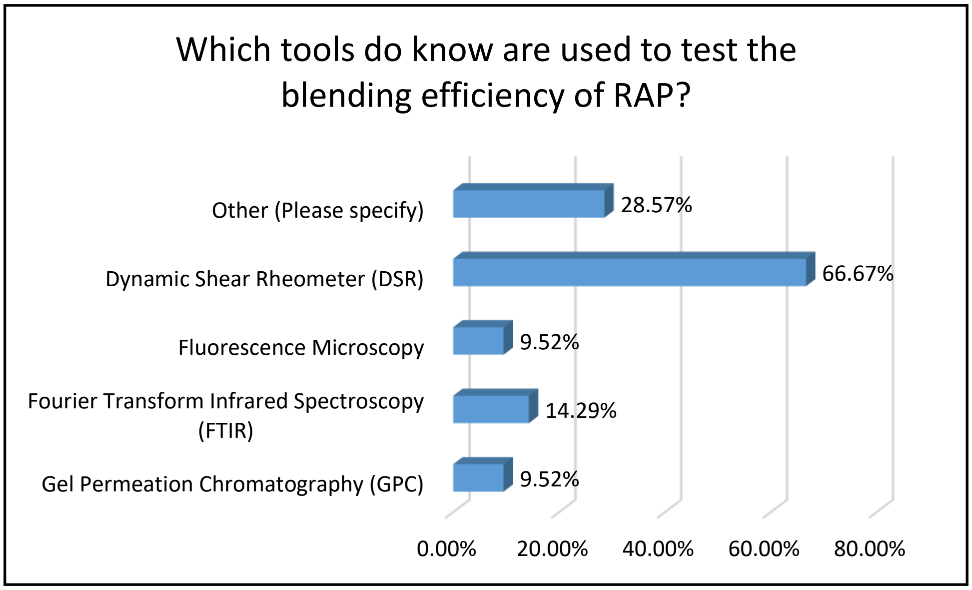


Figure 3-5 Tools used to test the blending efficiency

Only 16.3% of the respondents indicated using rejuvenator for asphalt mixture containing RAP. As shown in Figure 3-6, for the respondents using rejuvenator, less than 30% of them were confident in that adding rejuvenator would benefit the blending of RAP with new materials, while about 10% of them believed that the addition of rejuvenator had no connection to the blending efficiency.

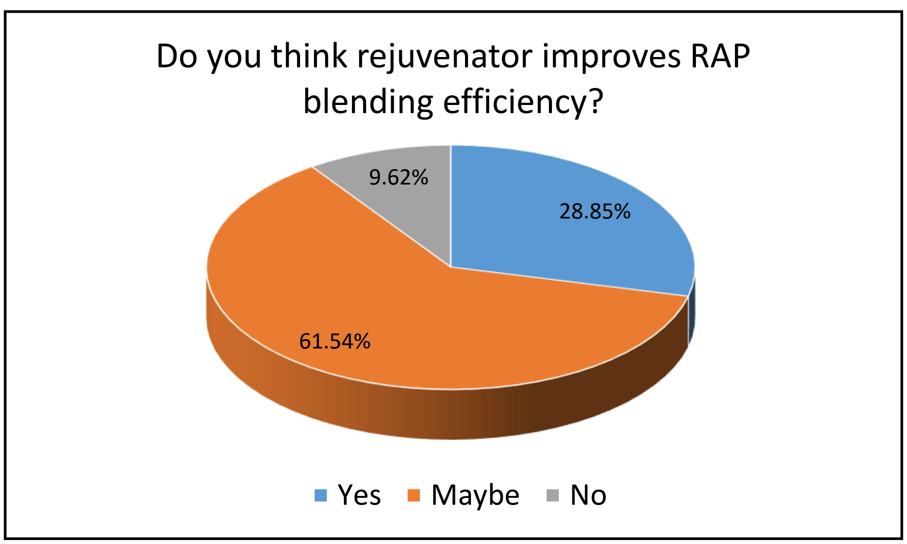


Figure 3-6 Efficacy of rejuvenator in RAP

3.2.2 Responses to the RAS application

63% of respondents showed they had specified allowable percentage of RAS binder replacement while up to 37% of them did not. This is similar to the situation for RAP. For respondents who had specifications, 15% of respondents believed RAS contributed no binder to the resulting mixture as shown in Figure 3-7. Most of them (around 40%) thought the percentage was less than 30%. Less than 9% of the responders thought the blending efficiency of RAS was in the range of 30~100%, and about 9% of them thought that all binder in the RAS could be reused.

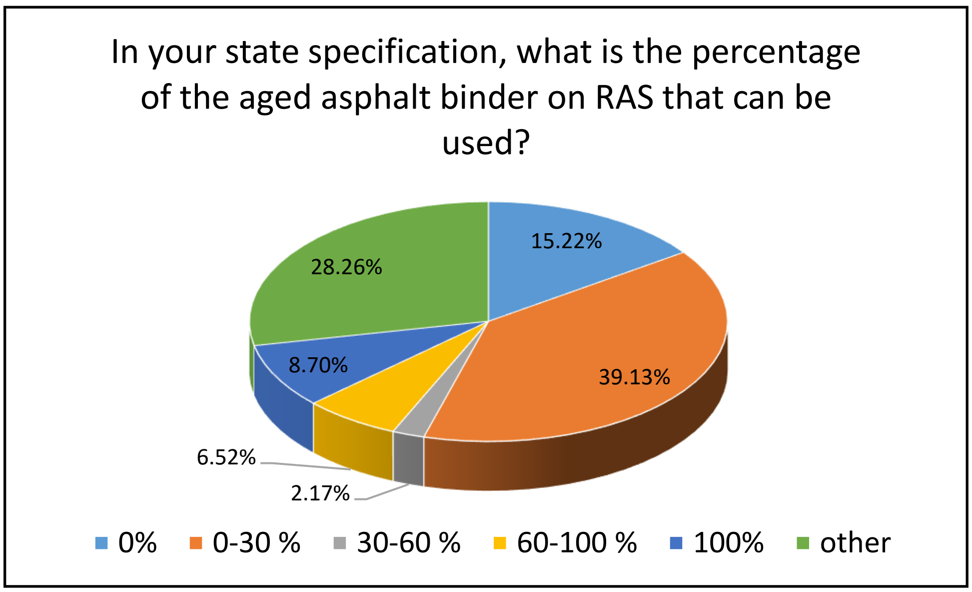


Figure 3-7 Percent of reusable RAS binder

Figure 3-8 shows that 49% of the respondents believed that the percentage in the state specification was reasonable. Four of the respondents answered “no” to this question, mainly because it is unlikely all binders in the RAS could be released under a regular mixing temperature.

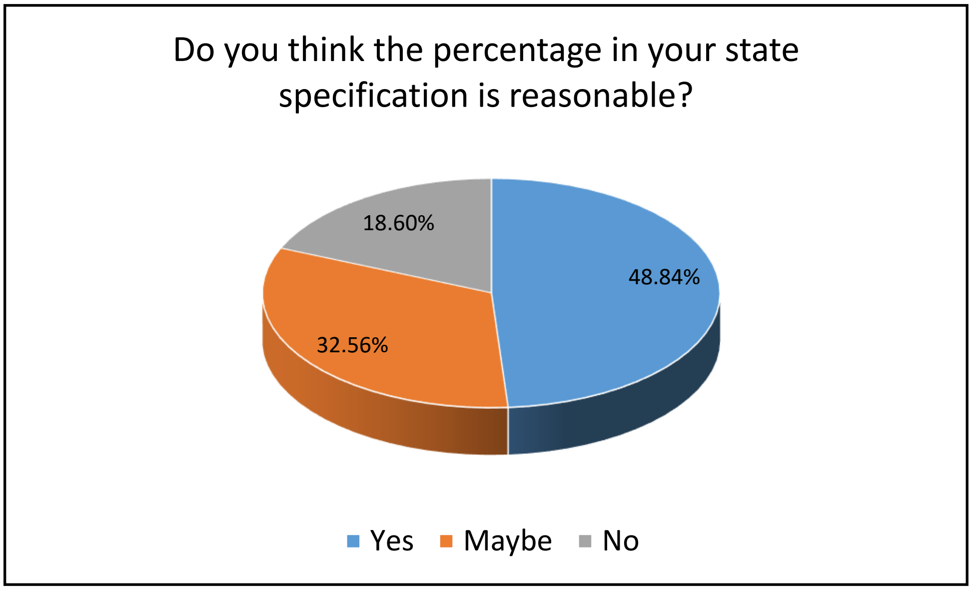


Figure 3-8 Rationality of state specification

There were 48 responses to the concerns about the current percentage in state specification. As shown in Figure 3-9, 35% of them had no concern about the current percentage in state specification.

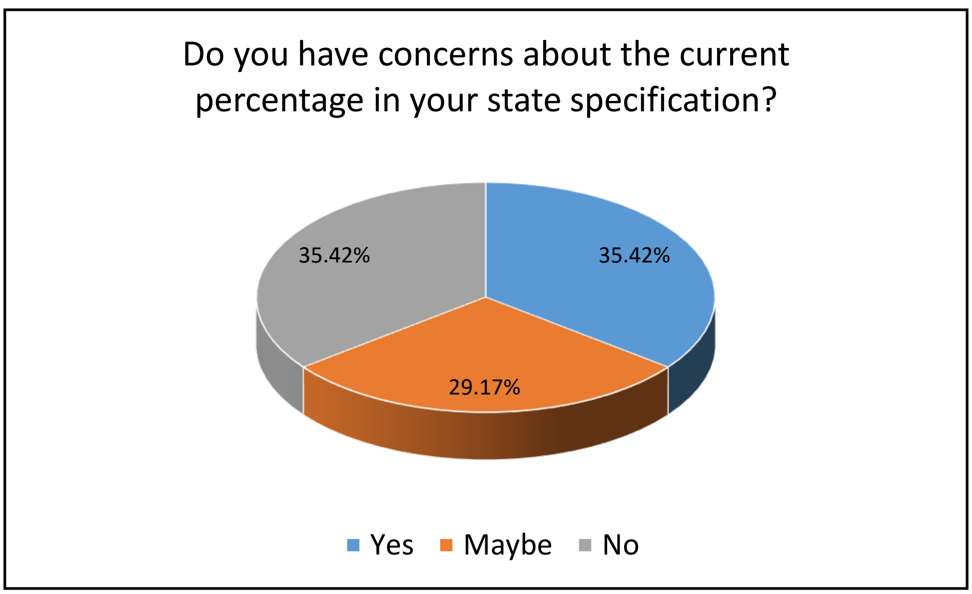


Figure 3-9 Concerns about the current percentage in state specification

Only about 15% of the respondents indicated they had established specific approach for testing the blending efficiency of asphalt mixture using RAS. Among them, 64% of respondents used DSR to test blending efficiency of RAS, and 35% of responders used fluorescence microscopy, GPC, or FTIR as shown in Figure 3-10. Of the 28% of respondents that selected "Other", most of them used the BBR test.

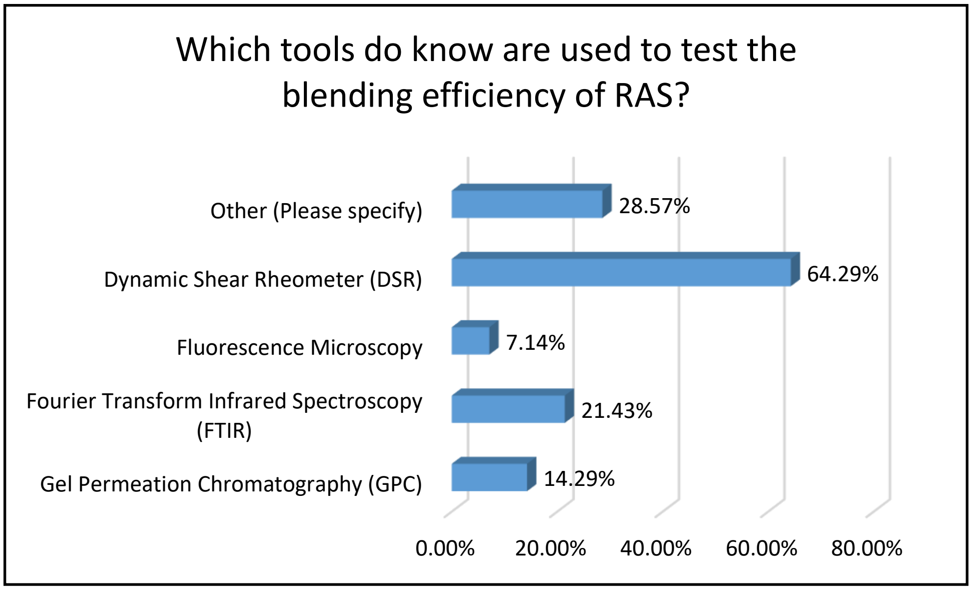


Figure 3-10 Tools used to test the blending efficiency

Less than 21% of the respondents reported using rejuvenator for asphalt mixtures containing RAS. Among them, about 48% of the respondents indicated they were unsure that the use of the rejuvenator would improve the blending efficiency of RAS in producing asphalt mixtures, while around 29% of them indicated they were certain about that the inclusion of rejuvenator would be beneficial in this regard as shown in Figure 3-11.

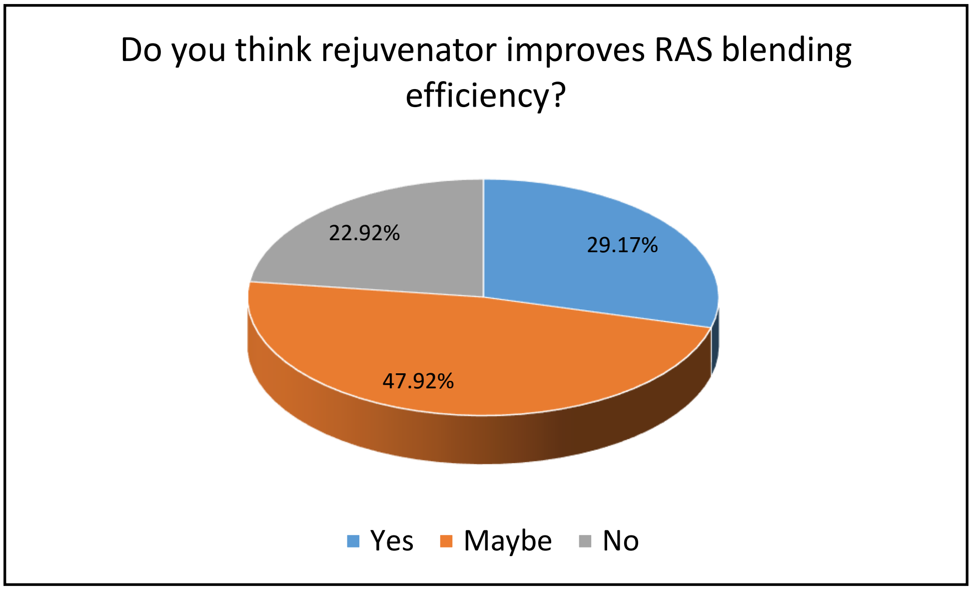


Figure 3-11 Efficacy of rejuvenator in RAS

3.2.3 Responses to the RAP/RAS blending efficiency

Figure 3-12 graphically summarizes the factors affecting the blending efficiency of RAP/RAS. As depicted, most of the respondents thought the mixing temperature, mixing time, the aging degree of the RAP/RAS, the use of rejuvenator, and the performance grade of the virgin binder were the most critical factors to the blending efficiency. About 13% of them also thought the aggregate size as an important factor. Other respondents also considered the influence of moisture content, the silo time, and the size of the RAP/RAS, while several states treated the RAP as pre-coated aggregates.

As shown in Figure 3-13, 47% of the respondents believed that a high percentage of RAP/RAS would shorten the service life of the pavement, and about 38% of the respondents thought it might be detrimental to long-term pavement performance, and less than 2% of the respondents thought it would not. Some respondents indicated that for RAP, if properly designed and controlled, the performance of mixtures using up to 40% of RAP could work equivalently well with those using new materials only.

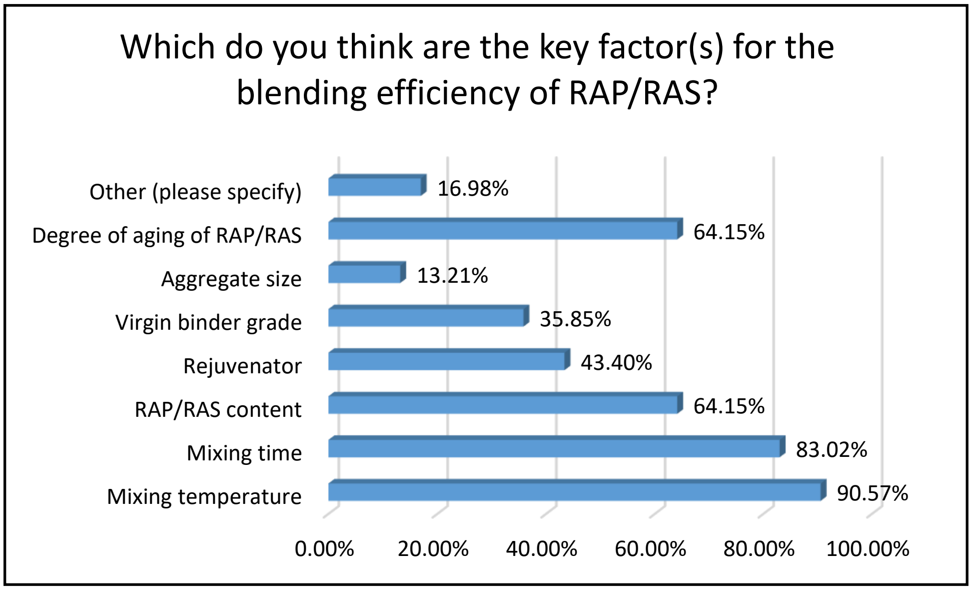


Figure 3-12 Key factors for the blending efficiency

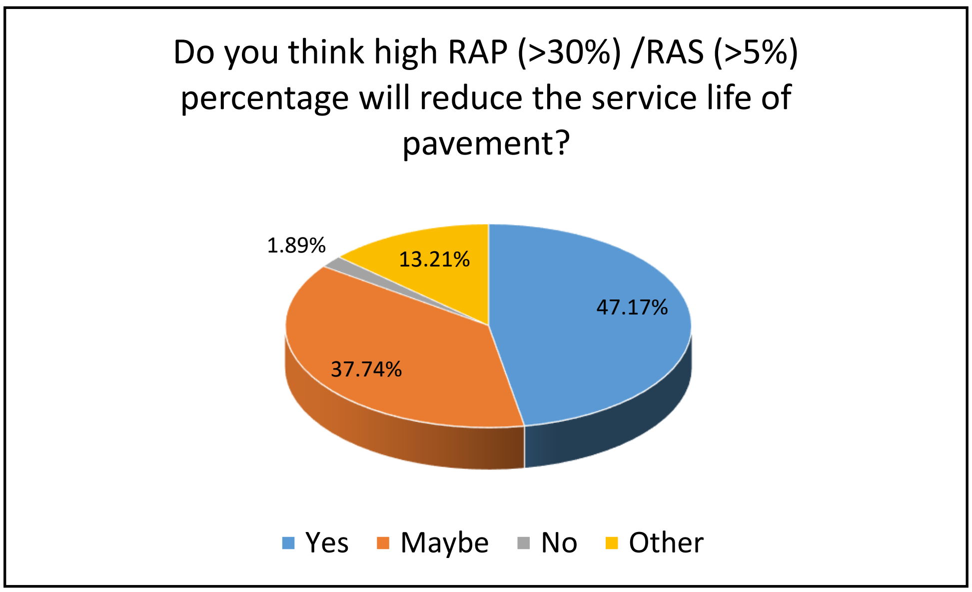


Figure 3-13 Influence of high percentage on service life of pavement

For the question about the linear blending charts (the relationship between the properties of mixed binders and the percentage of aged binder is linear) for RAP/RAS, Figure 3-14 shows that around 12% of the respondents thought the linear blending charts were reliable, and around 38% of them indicated the linear blending charts were invalid, whereas 44% of them were unsure.

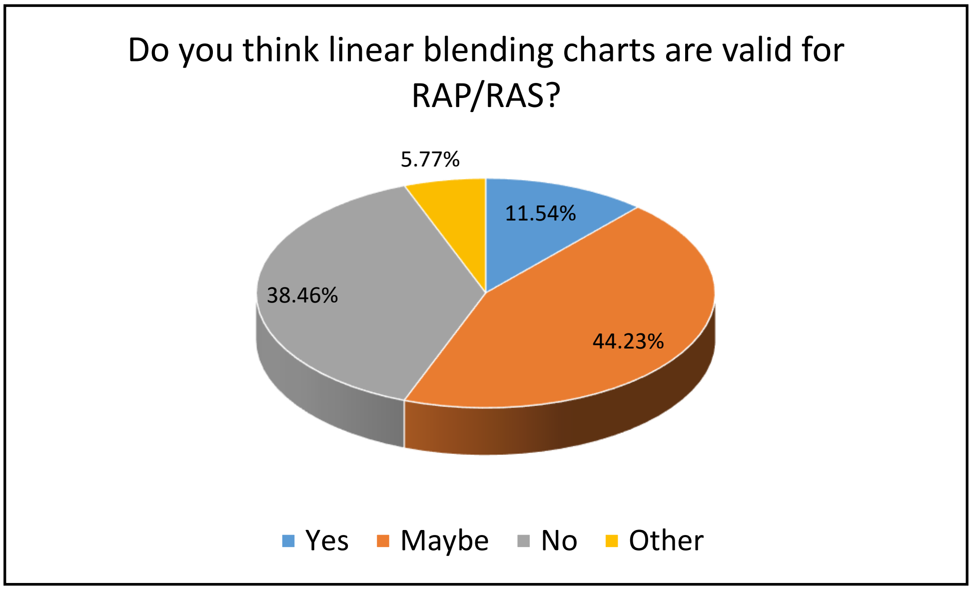


Figure 3-14 Linear blending charts

3.3 Conclusions

This chapter summarized the surveys sent out to state and local DOTs about the blending efficiency of RAP/RAS with 55 respondents. The survey contained questionnaires about the specification for allowable RAP/RAS percentages, the blending efficiency of RAP/RAS, the use of rejuvenator, and the established testing procedure for blending efficiency.

For the RAP, among the respondents 63% of them have specifications on the percentage of aged asphalt binder in the RAP that could be activated and reused, and more than half of the respondents thought their states' specifications were reasonable. For the states with specifications, 20% of them thought the RAP binder could be totally blended with the new binder, whereas 25% of them indicated that the portion of RAP binder reusable was in the range of 0~30%. Only 20% of respondents had procedures for testing blending efficiency, and most of them used the DSR as a tool. Based on the responses, it seemed not to be a typical practice to use rejuvenator for mixture containing RAP, as only around 16% of the respondents reported using a rejuvenator in tandem with RAP for producing asphalt mixtures.

For the RAS, 63% of respondents reported that their states specified the percentage of aged asphalt binder in RAS could be recycled into the new mixture. For the states had specifications on this, only 9% of them thought the RAS binder could be totally blended with the new materials, whereas 39% of them thought that less than 30% of the binder in RAS could be released and reused. Regarding the procedures for testing the blending efficiency of RAS with new binders, 85% of respondents reported that they had no method in this regard. Also, similar to RAP, more than 79% of the respondents indicated that they did not use rejuvenators when producing mixtures containing RAS.

For the critical factors influencing the blending efficiency of RAP/RAS with new materials, most of the respondents selected the mixing temperature, mixing time, the content of RAP/RAS, and the aging degree of RAP/RAS as critical factors. 47% of respondents believed that a high RAP (>30%) /RAS (>5%) percentage in binder would reduce the pavement service life. In summary, there currently exists no consensus among states about the blending efficiency of RAP/RAS and the standard testing procedure for this. The use of rejuvenator with RAP/RAS for producing asphalt mixtures is also questionable. Based on the survey, the test method for blending efficiency, the factors affecting blending efficiency and the usage of rejuvenators were further investigated in this study.

Chapter 4 METHODOLOGY FOR FLUORESCENCE MICROSCOPY METHOD

4.1 Introduction

The fluorescence microscopy is an optical microscopy that uses the emission of fluorescence to study properties of organic or inorganic substances [36, 49, 50]. Fluorescence microscopy has been used for the analysis of oil and petroleum products since the 1980s [51]. Navaro et al. utilized fluorescence microscopy first to investigate the degree of blending between virgin and aged binders [35]. They analyzed fluorescence microscope images by using a pair of photographs taken under white light (WL) and ultraviolet light (UVL) at the same position of recycled asphalt mixtures sample, and then utilized an image processing software to quantify the degree of blending between the virgin and RAP binders. To eliminate the influence of aggregate, two masks were used to hide the aggregate from the binder in an image. In the UVL photograph, the aged binder can be distinguished from the virgin binder, as the latter is fluorescent. However, the threshold value to distinguish between mastic and aggregate can only be chosen by experience in their study. There is not a quantified index available to determine whether all the aggregate have been hidden. In addition, the test procedure proposed by Navaro et al. [35] seems too complex to be used in the field.

In this study, a new method is proposed to determine the RAP/RAS binder mobilization rate based on the fluorescence effect, which is suitable for the plant mixtures with varied mixing condition. To achieve this, a fluorescent parameter is developed that is suitable for the study of virgin and RAP binder blending, and this new parameter is adopted to build a blending chart between the virgin and RAP binders. The detailed methodology of the new method is described below.

4.2 Methodology of Fluorescence Microscopy Method

The proposed fluorescence microscopy method for determining the blending efficiency of RAP/RAS mixtures is based on the differences in fluorescence between virgin and RAP binders. The procedure of this method includes three steps as shown in Figure 4-1.

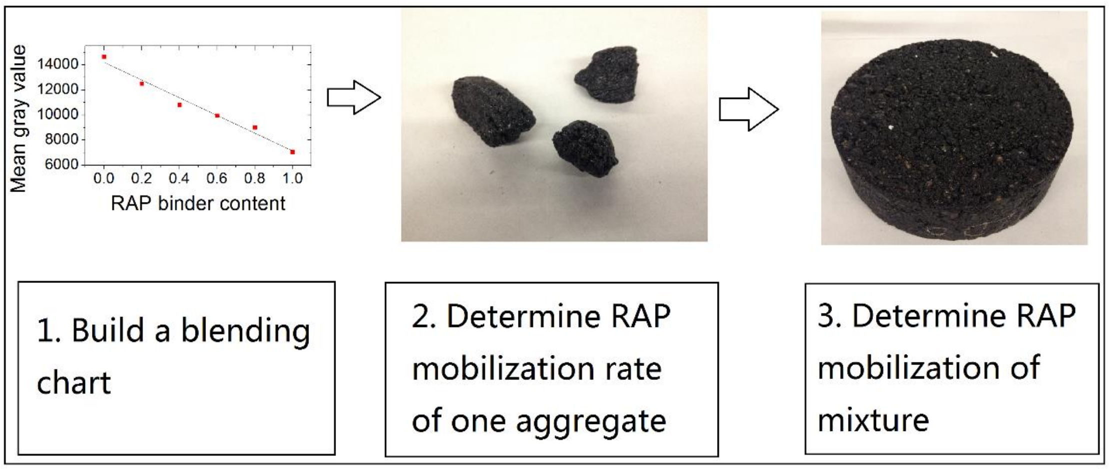


Figure 4-1 The main steps of the test method

4.2.1 Fluorescence intensity measurement

The fluorescence intensity was measured by a Nikon Y-IDP fluorescence microscope in this study. The specimen was illuminated with light of a specific wavelength to produce light of longer wavelengths. The illumination light was separated from the much weaker emitted fluorescence using a spectral emission filter. The filters were chosen to match the spectral excitation and emission characteristics of the fluorophore used to label the specimen. The distribution of a single fluorophore was imaged using a QImaging Micropublisher 3.3 RTV digital camera.

The charge coupled device (CCD) technology was used to produce quantitative digital images by fluorescence microscopy. The input light incident on the CCD creating output electronic charge is an intrinsically linear process. Each pixel is an independent linear photometer. The grey value of the pixel can be used to measure the brightness of the image which is linearly dependent on the input fluorescent intensity. In this study, the mean grey value (MGV) of the image was developed to characterize the fluorescence intensity of a material. MGV was defined as the mean of the grey value of a set area of the fluorescence image and can be easily obtained through post-processing of the image. The virgin binder exhibited a higher grey value than the aged binder as shown in Figure 4-2, so that the MGV of binder blend would decrease with the increasing of aged binder content. It can be expected that the MGV of one image would be affected by experimental conditions and material properties. Therefore, the variations of MGV with the factors such as exposure time, material properties were investigated in this study. The digital image collection process followed the procedure of ASTM F2998 [52].

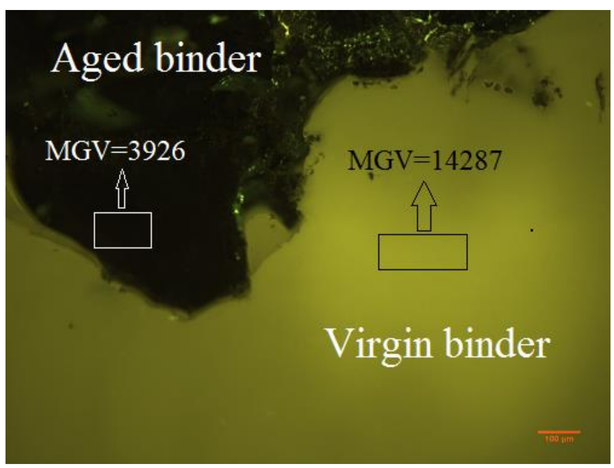


Figure 4-2 Fluorescence images of virgin and aged asphalt samples

4.2.2 Determination of rap binder blending efficiency

The blending process of virgin and aged binders is illustrated in Figure 4-3 and Figure 4-4. In Figure 4-3, the dark section is the aged binder, and the yellow background is the virgin binder. The binder blend was stirred at 150 °C for 30 seconds, 2 mins, and 5 mins, and the sample was observed under a fluorescence microscope. The results indicated that the aged binder was mobilized and blended into the virgin asphalt to form a homogeneous binder blend by stirring at 150 °C for 5 mins.

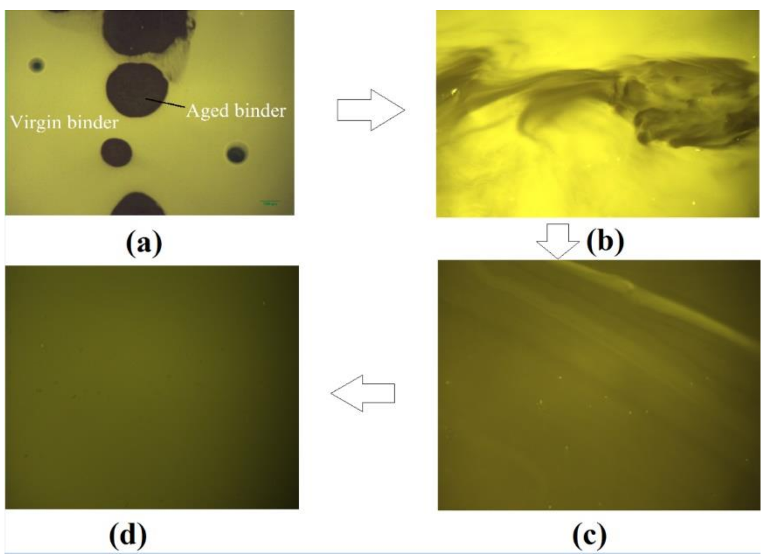


Figure 4-3 Blending process between virgin and aged binder (a) aged asphalt on the top of virgin asphalt; (b) binder blend stirred for 30 s; (c) binder blend stirred for 2 mins; (d) binder blend stirred for 5 mins

Figure 4-4 illustrates the partial blending scenario that may occur in a recycled asphalt mixture. Part of the aged binder film around RAP aggregate (the outmost layer) is mobilized and blended into the virgin binder to form a binder blend during the mixing process. The inner layer of RAP binder is not mobilized and does not contribute to binder blend. The mobilized RAP binder may also interact with the virgin binder, yielding a homogeneous binder blend that coats both virgin and RAP aggregates. If the RAP binder content can be determined in a binder blend, the percentage of mobilized RAP binder can be calculated based on the proportions of total virgin and RAP binder. If a particular property or parameter of asphalt blended is a function of the RAP binder content and can be measured in the laboratory, then RAP binder content in the blend can be quantitatively determined.

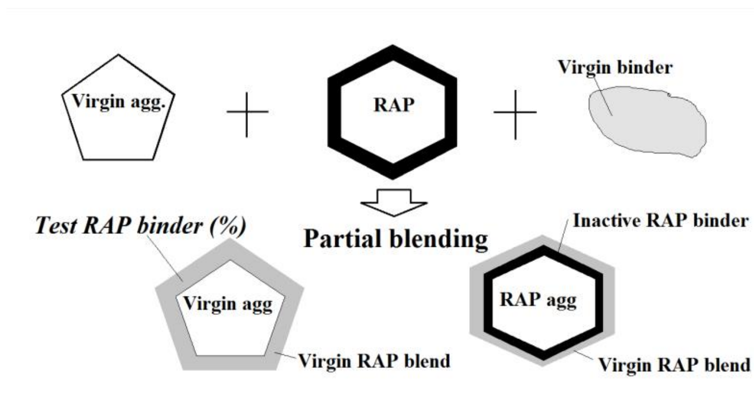


Figure 4-4 Partial blending scenario

In this study, a series of equations were proposed to calculate the mobilization rate of RAP binder on the basis of the research of Zhao et al. [6]. The RAP binder content of the binder blend is defined as active RAP binder divided by total binder blend, which can be expressed by the weight (W) of active RAP binder and virgin binder as shown in Equation (4.1).

$$\text{RAP binder (\%)} = \frac{W_{active\ RAP\ binder}}{W_{active\ RAP\ binder} + W_{virgin\ binder}} \tag{4.1}$$

Where, the percentage of RAP binder in binder blend is denoted as RAP binder (%). Then the weight of active RAP binder can be expressed by the RAP binder (%) as Equation (4.2).

$$W_{active\ RAP\ binder} = \frac{\text{RAP binder (\%)} \times W_{virgin\ binder}}{1-\text{RAP binder (\%)}} \tag{4.2}$$

Finally, the mobilization rate can be expressed as the active RAP binder divided by the total RAP binder as shown in Equation (4.3).

$$Mobilziartion\ rate = \frac{W_{active\ RAP\ binder}}{W_{total\ RAP\ binder}} = \frac{\text{RAP binder (\%)} \times W_{virgin\ binder}}{(1-\text{RAP binder (\%)}) \times W_{total\ RAP\ binder}} \tag{4.3}$$

Table 4-1 presents an example of the calculation of mobilization rate for an actual case. Assuming RAP binder (%) is determined in the laboratory as 30%, the weight (W) of RAP and virgin binder expressed as the percentage of total mixture. The mobilization rate can be calculated based on the weight of RAP and virgin binder and RAP binder (%). In the case in Table 4.1, mobilization rate is calculated as 45%, which means 45% of the RAP binder can be mobilized during mixing and contribute to coating the aggregates.

Table 4-1. Example of mobilization rate calculation

Parameter	Description	Value
RAP binder (%)	RAP binder percentage by binder blend	30%
$W_{total\ RAP\ binder}$	RAP binder percentage by total mixture	2.2%
$W_{virgin\ binder}$	Virgin binder percentage by total mixture	2.3%
$W_{active\ RAP\ binder}$	Active RAP binder percentage by total mixture	0.99%
$Blending\ rate$	Active RAP binder percentage by total RAP binder	45%

In this case, the key point in the calculation of mobilization rate is the determination of the RAP binder (%). A straightforward method to determine RAP binder (%) is to build a blending chart with one certain parameter and interpolating the laboratory-testing result of the sample. This study developed a blending chart for blending research using MGV derived from the fluorescence intensity of binder blend.

4.2.3 Building a blending chart in terms of MGV

If all the MGVs of a binder blend have a linear relationship with the aged binder content, the construction process of a blending chart only needs to test MGVs of virgin and aged binder and will be significantly simplified. To build a blending chart, samples with RAP/RAS binder content ranging from 0 to 100% in 10% increments should be enough to be tested for their MGV. The mixtures of virgin binder and recovered RAP/RAS binder are first heated to 170 °C (for RAP) and 190 °C (for RAS) and stirred for 30 minutes; then, they are placed into a vacuum oven (170 °C for RAP and 190 °C for RAS) for another 2 hours. Finally, the mixed binder is spread on a microscope slide and tested.

4.2.4 RAP binder mobilization of a mixture

In order to obtain an accurate overall blending efficiency for a RAP mixture, different aggregate sizes need to be taken into account. In this study, the overall mobilization rate of a mixture could be obtained based on the surface area proportions of aggregates with different sizes, such as large and small aggregates. The use of aggregate surface area instead of aggregate weight is due to the fact that the surface area is directly related to the asphalt film around aggregate particles. The mobilization rate of large and small aggregates is measured separately first, then the overall mobilization rate of a mixture could be calculated according to Equation 4.4.

$$Mobilization\ rate = Mobilization\ rate_{large\ aggregate} \times Surface\ area\ percentage_{large\ aggregate} + Mobilization\ rate_{small\ aggregate} \times Surface\ area\ percentage_{small\ aggregate} \tag{4.4}$$

Following the steps mentioned in this section, the mobilization rate of different lab and plant mixtures will be identified in the following chapters.

Chapter 5 VALIDATING THE BLENDING EFFICIENCY TEST BY USING LAB AND PLANT MIXTURES

To verify the proposed method, lab mixtures and three plant-produced asphalt mixtures were obtained. One RAP binder and one highly-aged asphalt binder from RAS were used to build an example blending chart and, thereby, determine the blending efficiency of mixtures in this study.

5.1 Lab and Plant Materials

5.1.1 Lab asphalt and mixtures

To investigate whether the fluorescence intensity can be used to distinguish virgin and aged binders, four Strategic Highway Research Program (SHRP) asphalt binders including AAD-1, AAG-1, AAK-1, AAM-1 were used in this study. The SHRP asphalt binders were aged by using the rolling thin-film oven (RTFO) [53] and pressurized aging vessel (PAV) methods [54]. The virgin binder used to build the blending chart was a typical PG 64-22 binder from Marathon Petroleum Company, located in Findlay, Ohio, which is commonly used in Tennessee. To investigate the influence of aging degree on the fluorescent property of the binder blend, in this study one RAP binder was extracted from RAP materials which contained 4.6% asphalt content, and one highly aged binder was extracted from tear-off RAS materials which contained 21% asphalt content. The extraction method followed ASTM D 6847–02 “Standard Test Method for Quantitative Extraction and Recovery of Asphalt Binder from Asphalt Mixtures” [55].

The blending efficiencies of a series of asphalt mixtures containing RAP/RAS were evaluated to verify the proposed method. The mixing time and temperature were considered as two key factors that affect the binder blending efficiency, as previous studies have indicated that the blending efficiency of an aged binder would increase with an increase in mixing time and temperature [56].

Figure 5-1 shows a detailed schematic for the asphalt mixture producing and testing procedure. To observe the binder using a fluorescence microscope, glass cullet (Figure 5-1(a)) was used as a special aggregate and added into the mixture, because it has two parallel planes and can be tested directly under a fluorescence microscope (Figure 5-1(f)). This study used a mixture containing 50 % RAP content and 2.19 % virgin asphalt binder content. Figure 5-2 shows the particle size distribution of the mixture. A mixture of 2,000g was produced for each batch, covering 10g of glass cullet. The aggregates were heated to 10°C higher than target mixing temperature for more than 2 hours before mixing. The RAP samples were heated to 110°C for 2 hours to avoid further aging. The virgin binder was heated to the target mixing temperature for 2 hours. The aggregates were pre-blended with the RAP samples for 10 seconds and then mixed with the virgin binder for a predetermined mixing time. Two mixing temperatures, 130°C and 160°C were selected to represent hot and warm mixing scenarios and three mixing times were used: 0.5, 3, and 6 minutes. The glass cullet was separated from the mixture after mixing and then tested under a fluorescence microscope (Figure 5-1(f)). For each batch of material, 10 samples were tested and the mean value of 10 samples was used as the result of the batch.

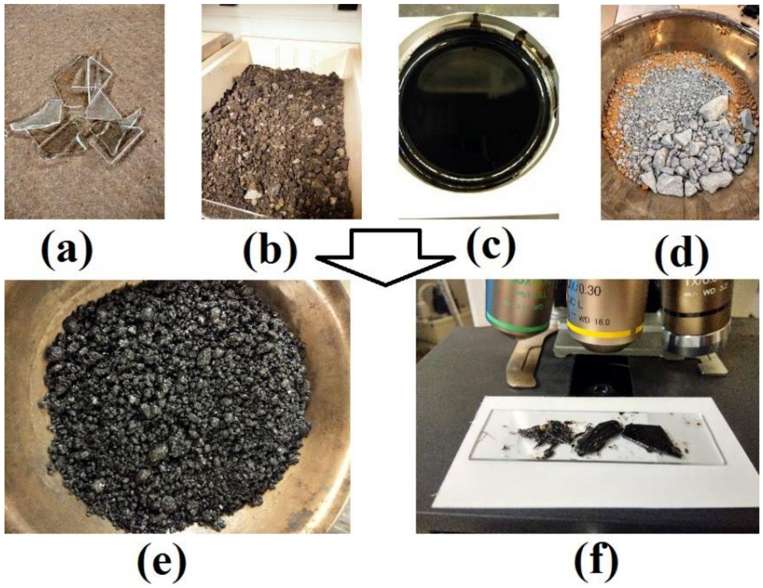


Figure 5-1 Asphalt mixture producing and test process (a) Glass cullet; (b) RAP; (c) Virgin asphalt; (d) Virgin aggregate; (e) Asphalt mixture; (f) Glass cullet tested by the fluorescence microscopy

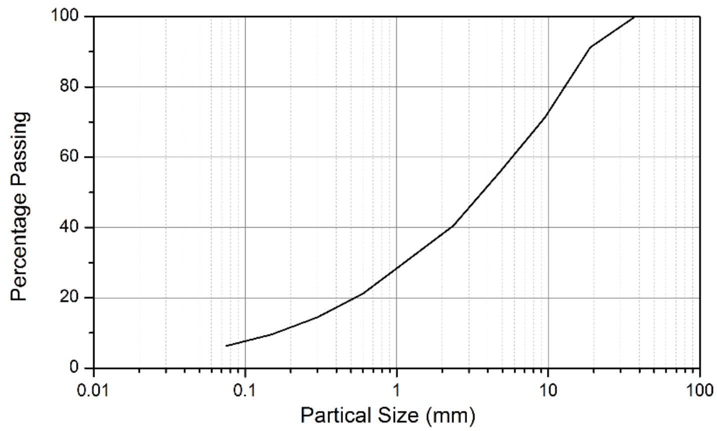


Figure 5-2 Particle size distribution curve of aggregate

5.1.2 Plant mixtures

The mixtures were produced in an asphalt plant in three different ways: hot mix with rejuvenator, hot mix without rejuvenator, and warm mix with foaming technology. The rejuvenator content was 0.4% by weight of asphalt binder. During the production process, the rejuvenator was first added into virgin binder and then mixed with aggregates. The mixing temperatures for warm mix and hot mix were 145 °C and 155 °C, respectively. After production, the mixtures were stocked in a silo for another two hours.

One performance grade asphalt binder, PG 64-22, was used in all three mixtures. The Marshall mix design procedure was employed design mixture. The asphalt content was 4.5% for all three mixtures, with 2.19% coming from virgin binder and 2.31% from RAP binder.

The same aggregate gradation was used for all three mixtures and is presented in **Table 5-1**. The virgin aggregates consisted of #5, #7 and #10 stones and natural sands. The RAP was processed and then sieved as RAP passing 3/4" and 5/16". The RAP content in the mixture was 50% for all three mixtures and its asphalt content was 4.61%.

Table 5-1. Gradation of the aggregates used in the mixtures

Sieve Size	Percentage Passing						
	# 5	# 7	# 10	Natural Sand	RAP Processed		Total
					Passing 3/4	Passing 5/16	
1.25"	100	100	100	100	100	100	100
3/4"	56	100	100	100	100	100	91
3/8"	8	54	100	100	68	100	71
No.4	2	5	86	95	35	95	56
No.8	1	3	56	82	22	72	40
No.30	0	0	23	50	14	37	21
No.50	0	0	16	28	10	27	14
No.100	0	0	12	12.7	6	20	9.6
No.200	0	0	9.5	4.6	4	13.5	6.3
Total	20	5	15	10	25	25	100

For the calculation of mobilization rate, the aggregate of the mixture could be divided into two aggregate sizes as shown in Figure 5-3. The large aggregate was the portion of aggregate retained on 3/4” sieve, and the rest was small aggregate. The mobilization rate of virgin aggregate could be determined from large aggregate because large aggregate was 100% virgin aggregate (Figure 5-3). The surface area was 28.4 ft^2/lb for small aggregate and 2.0 ft^2/lb for large aggregate [57]. The surface area proportions were 0.006 and 0.994 for the large and the small aggregates, respectively.

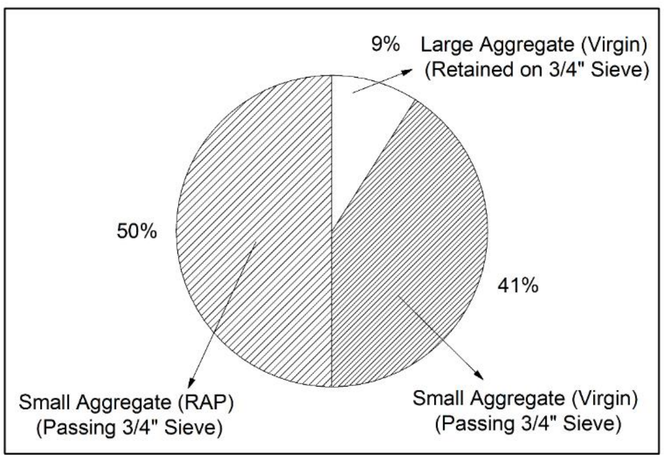


Figure 5-3 Proportions of large and small aggregates by mass

5.2 Results and Discussions

5.2.1 Influence of test conditions on MGV

It is expected that the MGV of an image is affected by experimental conditions. Figure 5-4 shows the MGVs of virgin and aged asphalt as a function of exposure time and wavelengths of excited light. It can be seen that the MGVs increased with an extended exposure time. In the low MGV range (<50000), there was a linear relationship between

MGV and exposure time, but the trend became quadratic gradually in high MGV region (>50000). The MGVs also varied under different excited lights. Therefore, the same excited light and exposure time are required to keep the MGVs of binder being comparable.

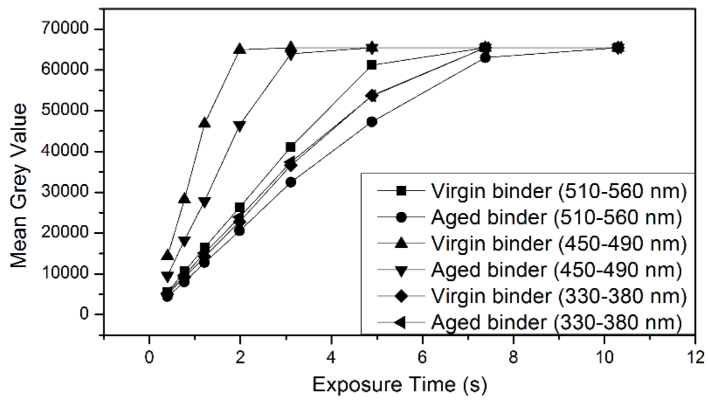


Figure 5-4 MGVs of virgin and aged asphalt as a function of exposure time

It was also noticed that the MGVs of virgin and aged binder were almost the same under excited wavelength of 330-380 nm, which indicates that the aged binder could not be distinguished from virgin binder under this test condition. To differentiate between virgin and aged binders as well as binder blends with varying aged binder content, it is desirable that MGV is sensitive to the aged binder ratio, which means that virgin and aged binders have a large MGV difference. Therefore, a differentiating factor (DF), which is defined as the ratio of the MGV of aged binder to that of the virgin binder (Equation (5.1)), was used to measure the sensitivity of MGV to the binders in this study. A lower DF means a large MGV difference between virgin and aged asphalt binders, indicating that MGV is more sensitive to the aged binder content in the binder blend.

$$\text{Differentiation Factor} = \frac{MGV_{aged\ binder}}{MGV_{virgin\ binder}} \tag{5.1}$$

Figure 5-5 shows the variations of DF with exposure time and wavelength of input light. It indicates that DF decreased first and then increased with exposure time. The exposure time range of 0.5-1.5 s showed a relatively lower DF, thus making DF more sensitive to the aged binder content. Among three wavelengths of input lights, 450-490 nm showed the lowest MGV ratios for the exposure time between 0.5 s and 1.5 s and thus was selected as input light in this study.

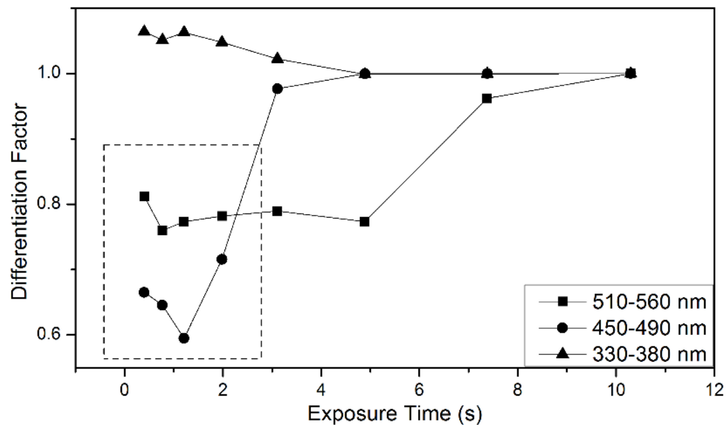


Figure 5-5 MGV ratios of aged and virgin binder at different conditions

5.2.2 MGV of virgin and aged asphalt

Figure 5-6 shows the MGVs of four SHRP asphalt binders before and after aging process (RTFO+PAV). The aged asphalt binders all exhibited lower MGV than the virgin asphalt, which indicates that the MGV method proposed in this study can differentiate between the virgin and aged asphalt. It was also noticed that the MGV of virgin asphalt is different when they are from diverse sources. One such example is that the MGV of virgin binder AAK-1 was much lower than that of AAG-1, which is due to the low content of resins and aromatics in AAK-1.

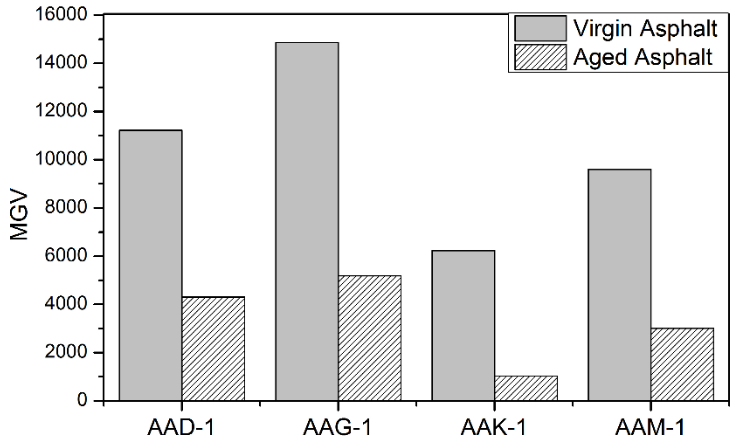


Figure 5-6 MGV of virgin and aged SHRP asphalt

5.2.3 Blending chart

The “blending chart” generated by blending one typical PG 64-22 binder with a RAP binder is presented in Figure 5-7. Linear correlations between RAP binder content and MGVs were revealed by a high R^2 value (0.976) for virgin-RAP blend. Accordingly, a linear regressive equation (Equation (5.2)) was obtained and can be used later to determine the active RAP binder once the blended binder is tested for MGV. It should be noted that Equation (5.2) was derived from the asphalt used in this study. For other asphalt, the complete process of building a blending chart needs to be repeated because the MGV of asphalt varies with its chemical composition.

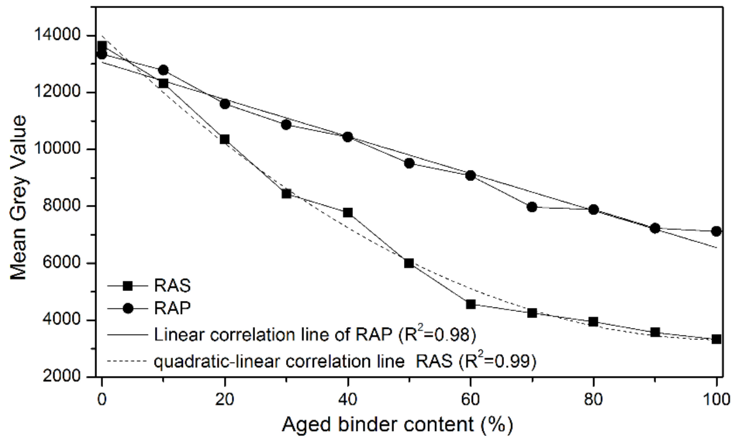


Figure 5-7 Blending chart generated with MGV

The MGV of the binder blend showed a strong linear relationship (R^2=0.91) but an even better quadratic relationship (R^2=0.992) with the RAS binder content. Therefore, the relationship between MGVs and aged RAS binder content should not be simplified as linear, and the construction of the blending chart should include as many data points as possible for a binder blend.

$$\text{RAP binder (\%)} = \frac{13056 - MGV_{binder\ blend}}{6508} \tag{5.2}$$

$$\text{RAS binder (\%)} = \sqrt{\frac{MGV_{binder\ blend}}{10309} - 0.33} + 1.015 \tag{5.3}$$

5.2.4 Determination of RAP binder blending efficiency for lab mixtures

Figure 5-8 shows the MGVs and RAP binder (%) of binder blend, and the mobilization rates of RAP binder for the lab mixtures. The RAP binder (%) was calculated based on the MGVs shown in Figure 5-8(a) and Equation (5.3). As stated before, the virgin asphalt content was 2.19%, and the RAP binder content was 4.6% × 50% = 2.3 % for the total mixture. The mobilization rate can be calculated by Equation (4.2) and (4.3). The MGVs (Figure 5-8(a)) showed a downward trend with the increase in both mixing temperature and mixing time. The decrease of MGVs of the binders can be attributed to the increase of RAP binder (%) (Figure 5-8(b)), indicating that more RAP binder was mobilized onto glass cullet with the increase in mixing time and temperature.

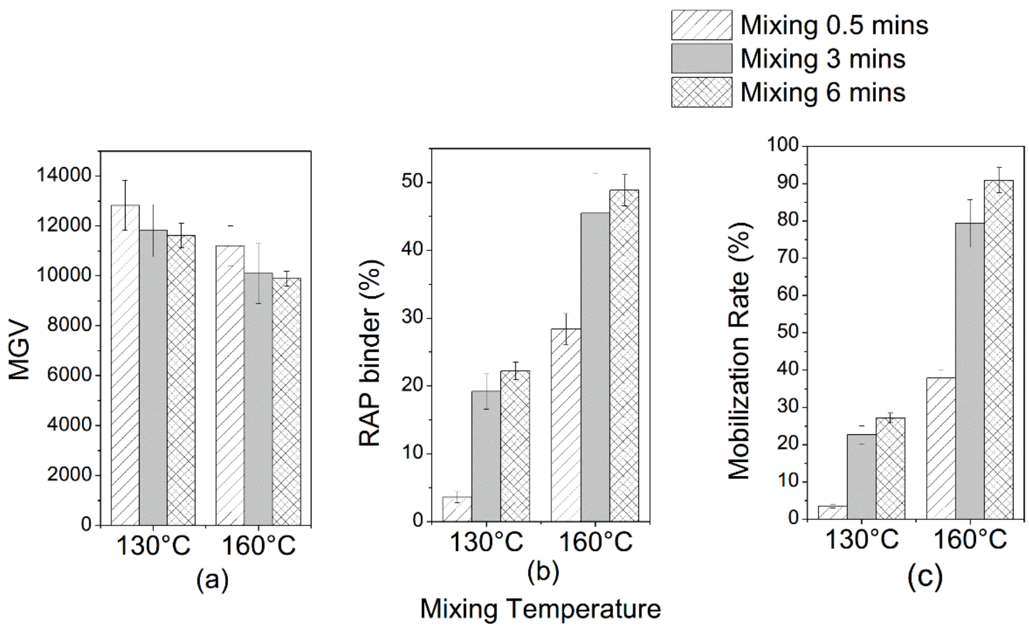


Figure 5-8 Test results of binder blends (a) Mean grey value (b) RAP binder content (c)Mobilization rate

As expected, the mobilization rate of RAP binder (Figure 5-8(c)) increased with the increase in mixing time and temperature, and it was consistent with previous results from numerous researchers [3, 32, 35, 58], which suggests that the method proposed in this study can evaluate the blending process of the aged binder more accurately.

5.2.5 Blending Efficiency of Plant Mixtures

Figure 5-9 and Figure 5-10 show the MGV and mobilization rates of large or small aggregates in different asphalt mixtures. As expected, the ranking of the mobilization rate is consistent with that of the MGV for the mixtures. The mobilization rate of three mixtures show no obvious differences. At the same time, it is noted that the large and small aggregates showed different mobilization rates. The reason for the different mobilization rate is due to the high RAP aggregate content on small aggregates. According to the definition of mobilization rate in this research, the mobilization rate of RAP aggregates was higher than that of virgin aggregates since the RAP aggregates contain more RAP binder. The mobilization rate of large aggregates was determined only from the virgin aggregates, whereas the mobilization rate of small aggregates was the combination of virgin and RAP aggregates.

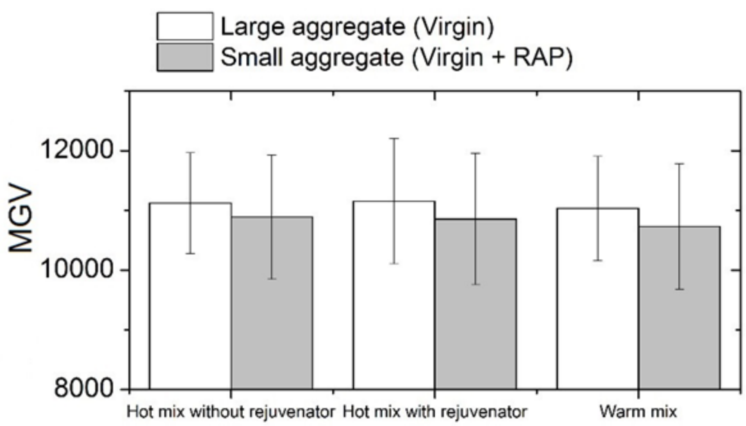


Figure 5-9 MGV for different mixing conditions

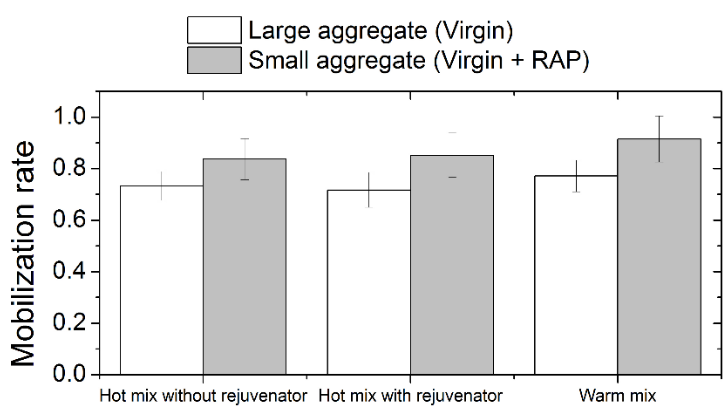


Figure 5-10 MGV for different mixing conditions

The overall mobilization rate of a mixture could be obtained based on the surface area (SA) proportion of large and small aggregates. The SA proportions calculated according to Equation 5.4 were 0.006 and 0.994 for the large and small aggregates, so the overall mobilization rate of a mixture could be calculated according to Equation 5.5. Figure 5-11 shows the overall mobilization rates of the mixtures. It can be seen that the overall mobilization rate of a mixture determined according to this method was close to that for small aggregates because of the low proportion of large aggregates.

$$SA\%_{large\ aggregate} = \frac{WT\%_{large\ aggregate} \times SA_{large\ aggregate}}{SA_{total\ mixture}} \tag{5.4}$$

$$Mobilization\ rate = Mobilization\ rate_{large\ aggregate} \times 0.006 + Mobilization\ rate_{small\ aggregate} \times 0.994 \tag{5.5}$$

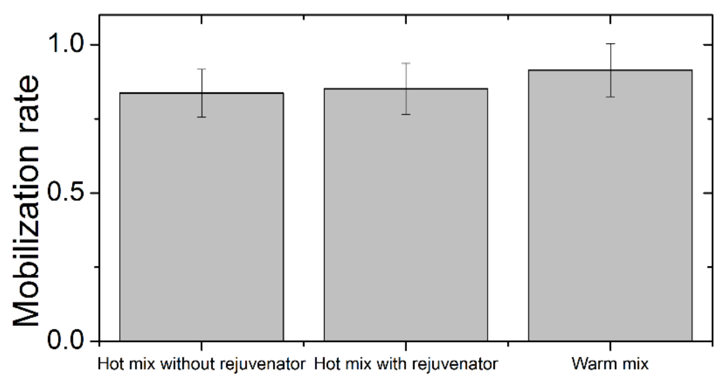


Figure 5-11 Overall mobilization rates of the mixtures

5.2.6 Discussions

In this study, a new procedure was developed by using fluorescence microscopy to differentiate between RAP/RAS and virgin binders as well as their blends. A new parameter, MGV, based on fluorescence image was utilized to quantitatively determine the mobilization rates of aged asphalt binder in RAP/RAS. A "Blending Chart" was generated, showing the change of MGV with RAP/RAS binder content. Ultimately, a new method was proposed to quantitatively determine the mobilization rate of aged binder in RAP/RAS by directly measuring the MGV of the binder blend. The test procedure is summarized as follows:

1) Test the MGV of virgin and RAP binder as well as binder blend with varying RAP binder contents to generate a "blending chart" in terms of MGV;
2) Test the binder blend on the surface of aggregate for its MGV;
3) Determine the RAP binder content of the binder blend;
4) Calculate the mobilization rate.

The sensitivity of MGV to aged binder content was affected by test conditions. One index, Differentiation Factor, was used to measure the sensitivity of MGV to aged binder content. Results indicate that the MGV measured at the wavelength of 450-490 nm and the exposure time of 0.5-1.5 s was most sensitive to aged binder content.

For the construction of a blending chart, it was found that there existed a linear relationship between the MGV of a binder blend and its RAP binder content, and a quadratic relationship between the MGV of a binder blend and its RAS binder content. Therefore, the relationship between MGV and the aged binder content of a binder blend could be different for asphalt from diverse sources.

For the lab mixtures, glass cullet was selected as a special aggregate and added into the mixtures because it could be separated from other aggregates easily after the blending process, and it has two parallel planes that can be tested by a fluorescence microscope directly. The results indicate that the mobilization rate increased with the increase of mixing time and temperature. It should be noted that the glass cullet used as tracking aggregates may not be able to fully represent the mixing scenario in the plant. The shape, size, absorption, surface texture, and other characteristics of aggregates could affect the mobilization rate of aged binder. Further research is needed to investigate the effects of these factors and to find more suitable tracking materials.

5.3 Conclusions

A method was proposed to determine the mobilization rate of RAP asphalt mixtures using fluorescence microscopy. By using this method, aggregate particles coated with asphalt binder can be directly tested by fluorescence microscopy to estimate binder content. There is no need to cut asphalt mixture samples and hide the aggregate as the method from Navaro et al. [35]. Therefore, fluorescence microscopy is potentially a simple, effective and efficient method for determining the RAP/RAS blending efficiency. To validate the proposed method, lab mixtures and three plant-produced asphalt mixtures were tested for their blending efficiency. The plant-produced mixtures included a hot mix with rejuvenator, a hot mix without rejuvenator, and a warm mix with foaming technology. Based on the results, the following conclusions can be drawn:

1) The new method was developed and validated for determining blending efficiency of RAP/RAS asphalt mixtures using fluorescence microscopy.
2) The MGV of fluorescence image could be used to determine the mobilization rate of RAP/RAS mixtures. There existed a linear relationship between the MGV of a binder blend and its RAP binder content, and a quadratic relationship between the MGV of a binder blend and its RAS binder content.
3) The mobilization rates were different for large and small aggregates because of different RAP/RAS contents. The overall mobilization rate of a mixture could be determined by considering the surface area of large and small aggregate.
4) Among the three plant-produced mixtures, the warm mix with foaming technology showed the highest mobilization rate, which should be further investigated in the future.

Chapter 6 BLENDING EFFICIENCY OF PLANT MIXTURES

In this chapter, to evaluate the blending efficiency of recycled asphalt mixtures from different types of asphalt plants and to achieve a better understanding of the effects of production conditions on the blending efficiency, the blending efficiencies of 14 recycled asphalt mixtures from different types of asphalt plants were evaluated by two methods, the fluorescence microscopy and GPC. The findings in the present study can help maximize the use of RAP/RAS in asphalt mixtures and improve the design of the mixtures containing RAP/RAS.

6.1 Plant Mixtures

14 recycled asphalt mixtures were collected in Tennessee and tested for their blending efficiency. **Table 6-1** presents the information about their mix design.

The mixtures were collected from three different types of plant in terms of mixing technologies including double barrel drum, regular drum, and batch mixing. Information on the production conditions is presented in **Table 6-2**. The double barrel plant can heat RAP/RAS aggregates and active RAP/RAS binders more efficiently because the inner barrel can heat aggregates continually during the mixing process. For the mixtures from the batch plants, RAP/RAS is weighed on its own separate scale or weigh hopper. The main difference between the batch plant and the drum plant is that the RAP/RAS can only be heated by virgin aggregates in the batch plant, which limits the amount of RAP/RAS that can be used in the mixture and may have an influence on the blending efficiency.

Table 6-1. Mix design information of mixtures

Mix No.	RAP content (%)	Virgin binder	Asphalt content in RAP (%)	Optimum AC (%)	Maximum Aggregate Size (in)	Mix types
1	10	70-22	5	5.7	3/8	Surface
2	20	70-22	5	4.5	3/4	Base
3	30	76-22	4.2	5	3/8	Shoulder
4	10	70-22	6	5.8	1/2	Surface
5	10	70-22	5.9	6	3/8	Surface
6	10 (3% RAS)	64-22	5.5	6	1/2	Surface
7	10	70-22	5.7	6	1/2	Surface
8	15	76-22	5.5	5.7	1/2	Surface
9	25	76-22	5.5	4.5	3/4	Base
10	25	76-22	5.5	5.1	3/8	Shoulder
11	30	76-22	5.5	4.9	3/4	Base
12	35	76-22	3.6	5.3	3/8	Shoulder
13	20	76-22	5.3	4.5	3/4	Base
14	25 (3% RAS)	70-22	1.63	5.7	1/2	Surface

Table 6-2. Information of mixture production

Mix No.	Mixing temperature (℉)	Production rate (TPH)	Storage time (hours)	Plant types
1	330	250	5	Double barrel
2	330	250	5	Double barrel
3	340	250	5	Double barrel
4	300	225	2	Drum
5	310	200	1	Drum
6	300	450	3.5	Drum
7	320	200	0.5	Drum
8	320	450	3.5	Drum
9	320	200	0.5	Drum
10	330	200	5	Drum
11	297	175	6	Drum
12	328	250	6	Drum
13	323	120	0.5	Batch
14	325	200	1	Batch

6.2 Laboratory Testing Procedures

6.2.1 Procedure for determining blending efficiency

For the mixture with a lower blending efficiency, only a part of the aged binder film around the RAP/RAS aggregate is mobilized and blended into the virgin binder to form a binder blend during the mixing process. The inner layer of the RAP/RAS binder is not mobilized and does not contribute to binder blend. The mobilized RAP/RAS binder may also interact with the virgin binder, yielding a homogeneous binder blend that coats both virgin and RAP/RAS aggregates. The mobilization rate, which was defined as the percentage of RAP/RAS binder that can be mobilized from RAP/RAS to virgin asphalt, has been used to evaluate the blending efficiency [59].

If the RAP/RAS binder content can be determined in a binder blend, similar to Equation (4.3), the percentage of mobilized RAP/RAS binder can be calculated based on the proportions of total virgin and RAP/RAS binder as shown in Equation 6.1.

$$\text{Mobilization rate} = \frac{P_{(b,\ \text{Virgin})} \cdot \ \text{RAP/RAS binder } (\%)_{\text{Blend}}}{P_{(b,\ \text{RAP})} \cdot (1 - \text{RAP/RAS binder } (\%)_{\text{Blend}})} \tag{6.1}$$

Where, $P_{(b,\ RAP)}$ means the percentage of RAP/RAS binder by total mixture, $P_{(b,\ virgin)}$ means the percentage of virgin binder by total mixture. RAP/RAS Binder $(\%)_{\text{Blend}}$ means the aged asphalt content in the binder blend. A straightforward method to determine RAP/RAS Binder $(\%)_{\text{Blend}}$ is to build a blending chart with one certain parameter and interpolate the laboratory-testing result of the sample.

As mentioned above, the virgin aggregates could not be separated from the RAP/RAS aggregates in plant mixtures. Therefore, the key of the test method is how to select the binder blend to best test blending efficiency. The aged asphalt content of a binder blend can be determined by both the fluorescence microscopy and GPC methods. The sketch of the two methods is illustrated in Figure 6-1. As indicated, the fluorescence microscopy method tests the aged asphalt content on the aggregate surface, whereas the GPC method tests the aged asphalt content of the outer layer of asphalt film.

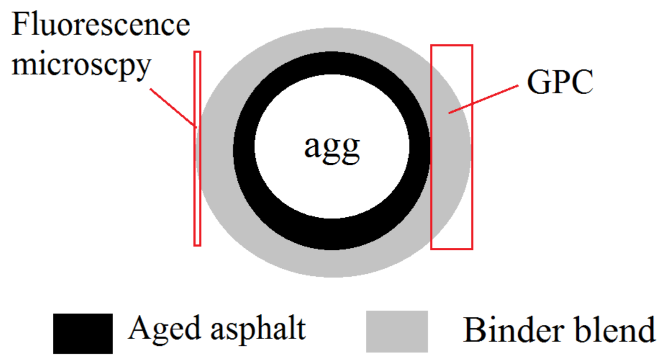


Figure 6-1 Contrast between the fluorescence microscopy and GPC method (in Figure, agg represents aggregate)

6.2.2 Fluorescence microscopy

The fluorescent intensity of the binder has proven to be an effective tool to distinguish the virgin and aged asphalt [60], which was measured by a Nikon Y-IDP fluorescence microscope in this study. The charge coupled device (CCD) technology was used to produce quantitative digital images by the fluorescence microscopy. The grey value of the pixel can be used to measure the brightness of the image, which has been found to be linearly dependent on the input fluorescent intensity. As first mentioned in Chapter 3, MGV of the image was used to characterize the fluorescence intensity of a material, which is defined as the mean of the grey value of a set of area in a fluorescence image and can be conveniently obtained through the post-processing of the image. The digital image collection process followed the procedure of ASTM F 2998 [52].

The virgin binder exhibits a higher grey value than the aged binder, and thus the

MGV of the binder blend decreases with the increasing of the aged binder content in a binder blend. The aged binder content in a binder blend can be determined by a blending chart as shown in Figure 6-2. A total of 20 aggregates were tested for each mixture. It can be seen that the mean gray value of mixtures can be used to calculate the aged asphalt content on the surface of each aggregate by using the blending chart.

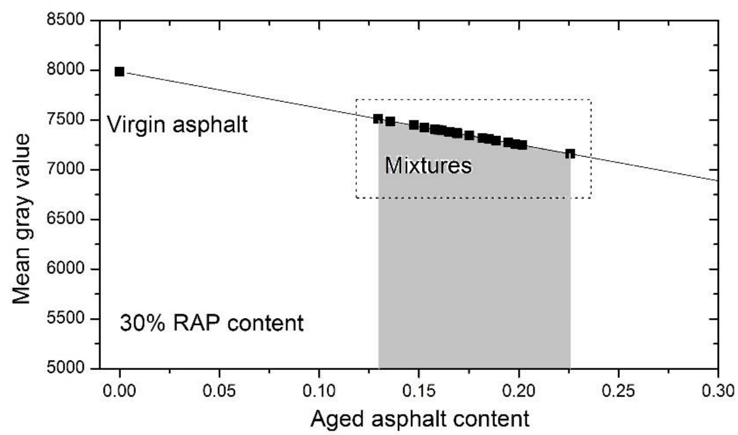


Figure 6-2 Blending chart built for the fluorescence microscopy method

6.2.3 Gel Permeation Chromatography (GPC)

The GPC method has been used to distinguish the virgin and aged asphalt due to the fact that the aged asphalt exhibits a high large molecules content (LMS (%)) than the virgin asphalt [6]. The GPC test procedure is as follows:

(1) Pick 500 grams of asphalt mixtures;

(2) Dissolve the outer and inner layers asphalt on mixtures using Trichloroethylene (TCE);

(3) Recover the dissolved binder in a 20 ml vial with a water bath of 70 °C in less than 15 min until the solvent is non-visible;

(4) Prepare the recovered asphalt binder for the GPC testing.

Typically, a larger LMS (%) indicates a higher aged binder content in the blend.

The aged binder content of a binder blend can be determined by a blending chart as shown in Figure 6-3. Two samples were tested for each mixture. As shown in Figure 6-3, the LMS (%) of mixtures can be used to find the aged asphalt content for the outer layer of the asphalt film by using the blending chart.

For comparison, the LMS (%) of the inner layer and outer layer were also tested in this study. The 500g of asphalt mixture sample contained both virgin and RAP aggregate. Both the outer layer of virgin and RAP/RAS aggregates were covered with the same virgin asphalt and the mobilized RAP/RAS binder. The ratio of RAP/RAS aggregate in the sample did not affect the test result as long as the outer layer was used to calculate the mobilization rate. However, the ratio of RAP/RAS aggregate would affect the test result if the inner layer was used to calculate the mobilization rate since the inner layer of RAP/RAS aggregate might contain more RAP/RAS binders which were actually not mobilized. Therefore, in this study the mobilization rate of outer layer was used to evaluate the blending efficiency of asphalt plant.

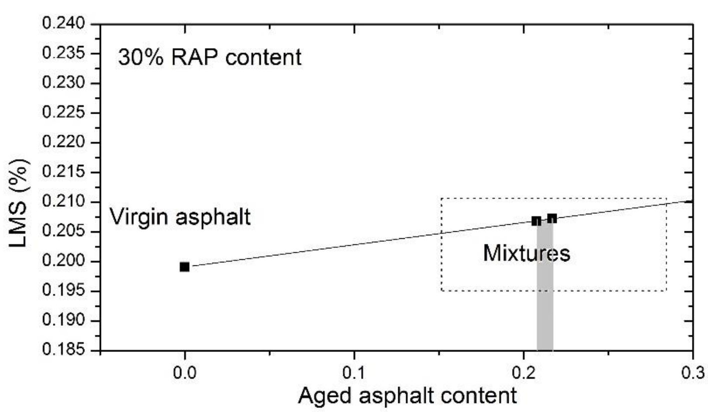


Figure 6-3 blending chart built for GPC method

6.2.4 Mobilization rate of a mixture

To obtain an accurate estimation of the overall blending efficiency for a RAP/RAS mixture, the aggregate size needs to be considered. For the fluorescence microscopy method, the requirement for the test sample is that the aggregate has a plane larger than 1 square millimeter. Therefore, the aggregates retained on No. 4 sieve was selected as the test sample. The overall mobilization rate of a mixture was obtained by the mean value of 20 aggregates considering both the test efficiency and accuracy. For the GPC method, 500 grams of mixtures were selected as one sample and the average of two samples served as the total mobilization rate of the mixture.

6.2.5 Multiple Regression

To gain insight into the factors affecting the binder mobilization rate of RAP/RAS, a multiple regression model was adopted to examine the potential correlations between the mobilization rate and the mix design parameters as well as the production conditions. The following factors were considered in the multiple regression model: the RAP/RAS content, the performance grade of the virgin binder (higher temperature), the virgin binder content, the mixing temperature, the production rate of asphalt plant, and the silo storage time.

6.3 Results and Discussions

6.3.1 Mobilization rate of fluorescence microscopy and GPC method

Figure 6-4 and Figure 6-5 show the overall mobilization rate of 14 mixtures by using the fluorescence microscopy and GPC. It was found that the overall mobilization rates of the mixtures were in the range of 0.4 to 1.0 for the fluorescence microscopy method and 0.37 to 0.83 for the GPC method. The difference between the fluorescence microscopy and GPC methods was probably due to the surface of asphalt being aged during the production process and thus increasing the mobilization rate of the fluorescence microscopy method, since the fluorescence method only tests the surface part of asphalt.

Although not completely consistent, the results of the GPC and the fluorescence microscopy still showed a similar trend for the mobilization rate among the 14 mixtures. For example, when compared with other mixtures, mixture No.6, which contained 3% RAS, showed a significantly lower mobilization rate in both methods, suggesting that the aged asphalt in the RAS was difficult to mobilize out during the production process.

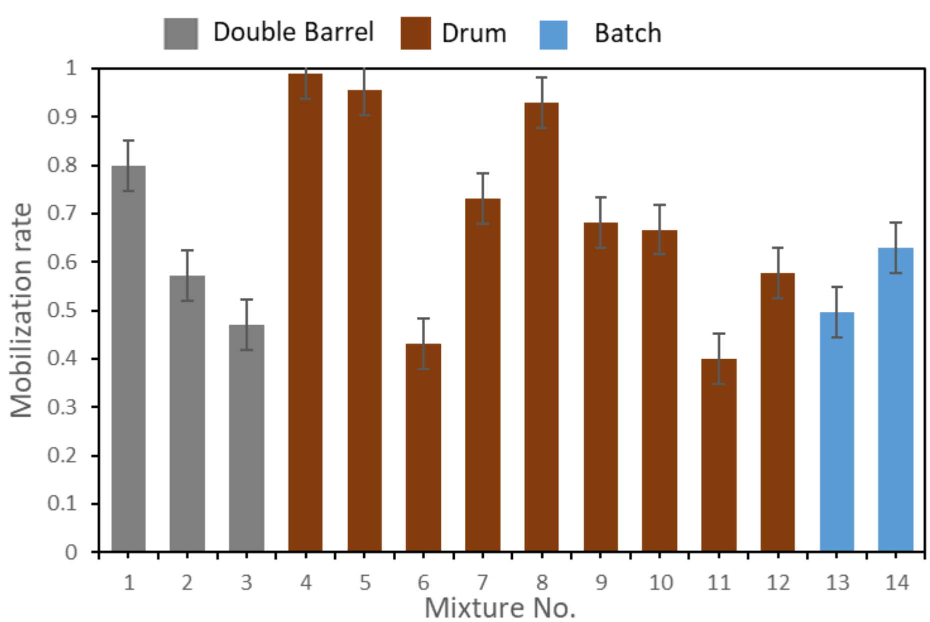


Figure 6-4 Mobilization rates of the mixtures from the fluorescence microscopy method

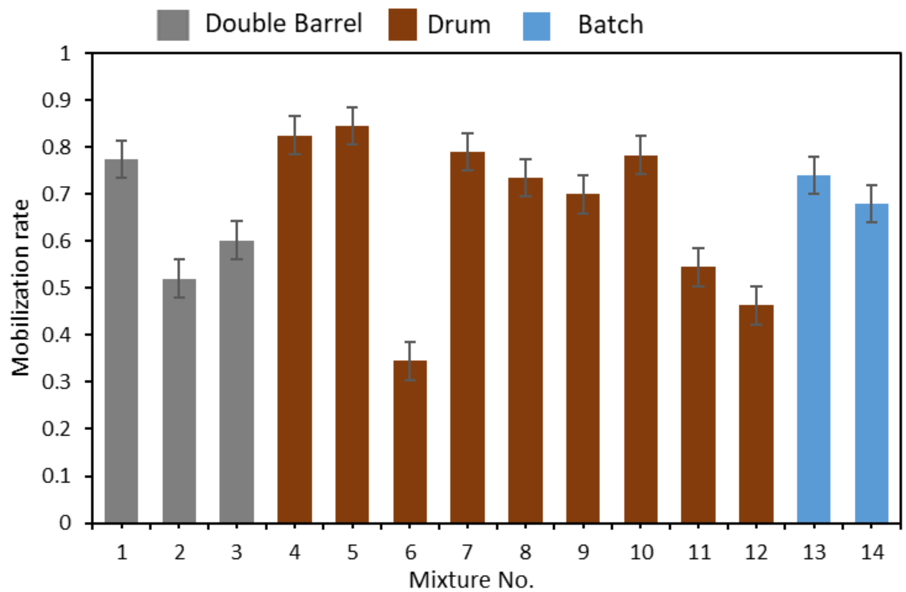


Figure 6-5 Mobilization rates of the mixtures from the GPC method

6.3.2 Mobilization rates for the inner and outer layers using GPC method

The outer layer of blend binders shows lower mobilization rates than the inner layers as shown in Figure 6-6. The mobilization rate is defined as the percentage of RAP/RAS binder that could be mobilized and blended with the virgin asphalt to coat virgin and RAP/RAS aggregate, which is suitable for the evaluation of virgin aggregate and the outer layer of RAP/RAS aggregate. However, it may not be appropriate to be used for the inner layer of RAP/RAS aggregate if the aged asphalt on RAP/RAS is not fully mobilized out. Since the samples contained a considerable amount of RAP/RAS aggregates, the calculated mobilization rate for the inner layer was larger than that of the outer layer, which seems contradictory. However, it only reveals that the percentage of aged binder in the inner layer was larger than that in the outer layer. On the other hand, the test to compare the outer layer and the inner layer is important since it can validate the appropriate procedure for the GPC test.

In summary, the reason for the different mobilization rates was due to the high content of RAP/RAS binder in the inner layer of the RAP/RAS aggregate. It can be predicted that the distributions of virgin and RAP/RAS binders were not homogeneous in the mixtures in this study.

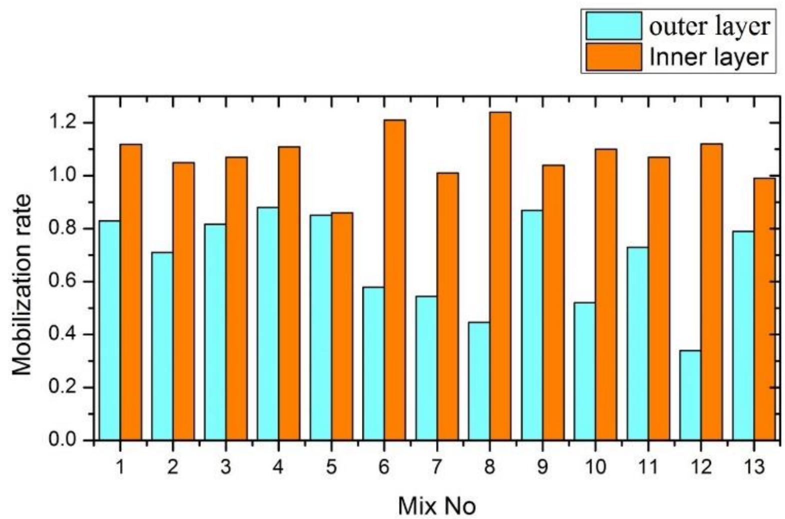


Figure 6-6 Mobilization rate of inner layer and outer layer

6.3.3 Correlation between GPC and fluorescence results

A linear regression and one-way analysis of variance (ANOVA) were conducted between the results from the fluorescence microscopy and the GPC method. The R^2 of the linear regression is 0.557 and the *p*-value of the ANOVA was 0.0022. As shown in Figure 6-7, the results of the fluorescence microscopy and the GPC method generally share the similar trend.

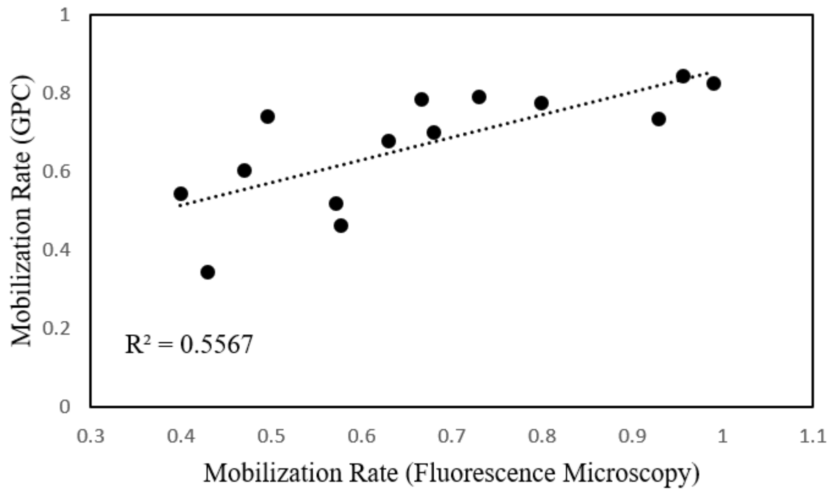


Figure 6-7 Linear regression between GPC and Fluorescence

6.3.4 Regression analysis on production condition

A linear regression model was adopted for the mobilization rate against the mixture design and production condition parameters. The mixture design parameters included the RAP/RAS content, the virgin asphalt high temperature grade, and the virgin asphalt content. The production condition parameters included the mixing temperature, the production rate, and the silo storage time.

The statistical significance of each of the independent variables was also tested. A significance level of α=0.05 was used in this study for this purpose. As displayed in **Table 6-3**, the *p*-values of the RAP/RAS content and the mixing temperature were less than 0.05, which indicates that the RAP/RAS content and the mixing temperature are the factors significantly affecting the mobilization rate. The results also suggested that the mixtures with the same RAP/RAS content and mixing temperature can be compared to illustrate the influence of other factors such as the plant types.

Table 6-3. Multiple regression of mobilization rate with design and production parameters

Parameters		Sig (fluorescence microscopy)	Sig (GPC)
Mix design	RAP content	0.008*	0.048*
	Virgin asphalt grade (High tem)	0.091	0.058
	Asphalt content	0.364	0.864
Production	Mixing temperature	0.004*	0.005*
	Production rate	0.000*	0.091
	Storage time in silo	0.293	0.281

6.3.5 Discussions

The mobilization rate of mixtures with a same RAP/RAS content were selected as a group and shown in Figure 6-8. As indicated, the mixtures from the double barrel plants, which have been reported to have a higher mixing ability, did not present significantly higher mobilization rates than those from the regular drum plants. There may be other important factors that affected the mobilization rates, but those were not included in this study.

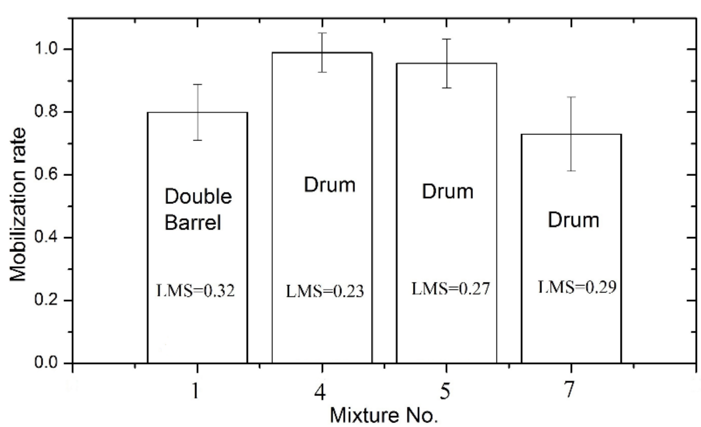


Figure 6-8 Mobilization rate of mixtures from double barrel and drum plant

The RAP/RAS used in this study came from different projects and the properties of the RAP/RAS may vary considerably. The large molecules content LMS (%) of the RAP/RAS binder in Figure 6-9 was used to evaluate the aging level of RAP/RAS, since previous studies indicated that there was a linear relationship between the LMS (%) and the viscosity of asphalt [5]. In Figure 6-9 the red lines indicate the maximum and minimum range. The linear regression results in **Table 6-4** indicate that both the LMS (%) and the RAP/RAS content had significant influences on the mobilization rate. Therefore, the higher mobilization rates of No.4 and 5 mixtures from the drum plants compared to the No.1 mixture from the double barrel plant were probably due to the fact that the RAP/RAS in the No.1 mixture was aged to a higher extent.

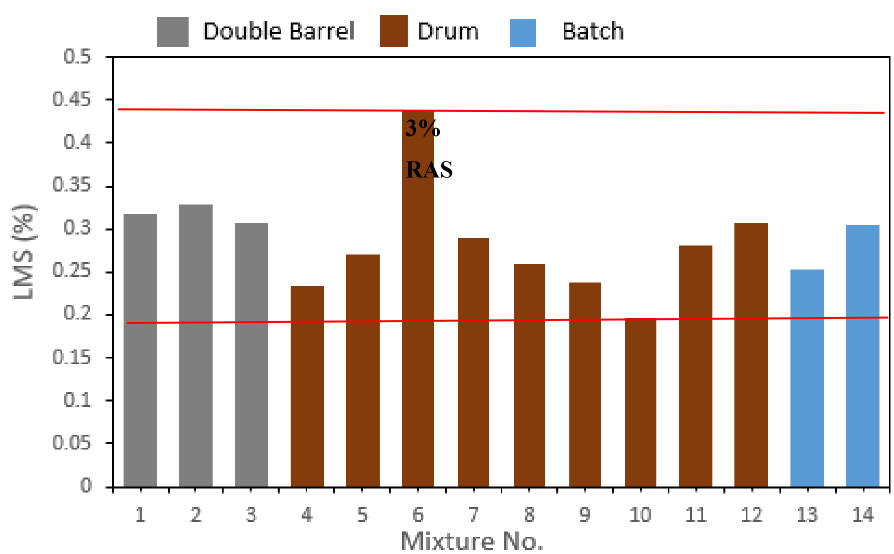


Figure 6-9 LMS (%) of RAP/RAS binders

Table 6-4. Linear regression of mobilization rate with LMS and RAP content

Aging properties of RAP	Significance
LMS %	0.023*
RAP content	0.009*

For a mixture not reaching a homogeneous blending, the aged asphalt content of inner layer is higher than that of outer layer for the RAP/RAS aggregate. Therefore, when using GPC method, the final calculated mobilization rate could vary based on the measuring depth of asphalt film as shown in Figure 6-6. Caution should be taken in lixiviating binder blend using a chemical solvent to reach a standard depth of asphalt film.

6.4 Conclusions

By using the fluorescence microscopy and GPC, this study tested a total of 14 plant-produced asphalt mixtures for their RAP/RAS binder mobilization rates. The purpose of the tests was to analyze the effects of production conditions on the blending efficiency of different types of mixture plant. A multiple regression model was adopted to evaluate the influence of the mixture design and the production condition parameters on the mobilization rates. Based on the results from the study, the following conclusions can be drawn:

1) The overall mobilization rates of 14 plant mixtures were in the range of 0.4 to 1.0 for the fluorescence microscopy method and 0.37 to 0.83 for the GPC method.
2) Although not the same, the mobilization rates obtained from the fluorescence microscopy and the GPC methods showed a similar trend in the mobilization rate among the 14 mixtures. The R^2 of the linear regression between GPC and fluorescence results is 0.557.
3) According to the LMS (%) results from the GPC tests, the mobilization rates for the inner layer and the outer layer are different, indicating that only a part of the aged binder in the RAP/RAS was mobilized in the mixtures.
4) Among the production condition parameters of asphalt mixture plants, the mixing temperature and the percentage of RAP/RAS showed significant influences on the mobilization rate. Other factors such as the virgin asphalt high temperature grade and the virgin asphalt content did not exhibit a significant influence on the

mobilization rate in this study, which should be further investigated with more samples.

5) According to the linear regression results, the aging level of the RAP/RAS binder also had a significant influence on the mobilization rate.

Chapter 7 UTILIZING MECHANICAL PROPERTY METHOD TO INVESTIGATE THE INFLUENCE OF REJUVENATOR

This chapter reviews a preliminary study that was performed to investigate the influence of different rejuvenator incorporation methods on the rheological and aging properties of the recycled asphalt binders. To achieve this, the extracted RAS/RAP binders were mixed with the virgin binder and the rejuvenator using different incorporation methods, and dynamic shear rheometer (DSR) tests were performed to identify the rheological properties of binder blends with various composition ratios. To analyze the aging properties, the binder blends were subjected to short-term and long-term aging were also tested by DSR. In addition, GPC tests and the mass loss tests were adopted in an attempt to clarify this aging phenomenon.

7.1 Introduction

During the last decades, both RAP and, less commonly, RAS have been used in the asphalt industry given their economic and environmental benefits [8, 61-63]. However, utilizing RAP or RAS solely will produce stiff mixtures and, consequently, be less workable for field compaction, which may lead to premature field failures [17]. One option to reduce the stiffness of RAP and RAS mixtures is to incorporate the rejuvenators. Generally, rejuvenators contain a high proportion of maltene components, which can balance the loss of maltenes in aged binders during construction [64].

There are serval types of rejuvenators, which can be classified as aromatic extracts, tall oils, fatty acids, paraffinic oils, napthenic oils based on National Center for Asphalt Technology (NCAT) [65]. Composite recycling agents including bio-based oils and modified vegetable oils are also currently available on the market. Previous studies concluded that different rejuvenators can cause a various effect on binder blends and asphalt mixtures [66]. Zaumanis et al. observed that the required amount of organic products including the tall oil and the waste vegetable oil to reduce the Superpave performance grading of recycled asphalt binders and mixtures is much lower than the petroleum-based products, such as the aromatic extract and waste engine oil [67, 68]. Nabizadhe et al. compared the rejuvenating effect of tall oil, soybean oil, and aromatic extract, summarizing that the aromatic extract was the most effective recycling agent to increase the crack resistance and reduce the stiffness of a recycled mixture with a high percentage of the RAP content [69].

The rejuvenation process is defined as the change of rheology and performance characteristics of the aged binder by using recycling agents [70]. Typically, there are three factors that can affect the rejuvenation mechanism: (a) dispersion of the virgin binder, aged binder and rejuvenator in the mixture; (b) diffusion of the rejuvenator into the recycled binder; and (c) compatibility between the rejuvenator and all the binder blends. Dispersion is a physical mixing process that recycling agents go through the asphalt mixtures to achieve a uniform blend with virgin and recycled binders, whereas diffusion is a process where the aged binder tries to absorb the hydrocarbon-type liquid in the rejuvenators [71]. The diffusion process consists of the following four steps suggested by Carpenter and Wolosick [22]:

1. The rejuvenator surrounds the highly aged binder layer coating the recycled aggregates.
2. The rejuvenator starts to diffuse and soften the aged binder.
3. As the diffusion process continues, the recycling agent decreases the viscosity of the aged binder, gradually mixed with the virgin binder.
4. An equilibrium is approached after a certain time.

The compatibility of the binder blends and rejuvenators is critical to create a uniform composite. Yang et al. investigated the compatibility between the bio-asphalt and petroleum asphalt by using an AFT test based on flocculation stability [72].

Aging is an important factor that leads to the degradation of road performance. Chen et al. confirmed that the aging effect of asphalt binder is a sluggish process by altering the content and microstructure of its internal components [73]. Regular binder tests including DSR and the bending beam rheometer test are usually used to evaluate the aging characteristics of the asphalt binders. When combining with rejuvenators, a different loss of rejuvenating effectiveness has been observed on the asphalt mixtures and binder blends based on the types and dosage of the rejuvenators [74]. It was also reported that aging can reduce the maltene phase of the rejuvenated binder blends, which results in a change in rheological properties [75].

Overall, the rejuvenation process is considered as a physical process, in which the diffusion of the rejuvenator is expected to mix with the aged asphalt directly. However, for most asphalt plants in the U.S., rejuvenators are usually mixed with the virgin binder first and then coated on the virgin aggregates and the recycled materials. Unlike the practice in the U.S., a new trial of recycled mixture production was reported in Japan that the rejuvenator is directly mixed with the heated aged materials in a small pugmill first, which allows the rejuvenator to quickly diffuse into the aged binder. Then the hot rejuvenated aged mixture is transferred to a surge bin for a longer condition time, which may result in varying dispersion and diffusion effects [76].

Aging of rejuvenated binder blends can also affect the recycling agent effectiveness. Studies observed that the changes of rheological properties caused by aging depend on the type and dosage of the rejuvenators [77, 78]. However, the effect of different incorporation methods on the properties of final products, including the short-term aging and the long-term aging has been rarely studied. In addition, the hot in-place recycling (HIR) technology for 100% recycled materials is becoming more and more popular in the U.S. HIR technology consists of in situ heating of the asphalt pavement, milling the surface layer, remixing the recycled materials with the addition of rejuvenators and repaving the combined mixtures. In this process, the rejuvenators are directly incorporated into the recycled materials during the remixing step. Such technology is similar to the rejuvenator incorporation method in Japan. Thus, in order to improve the utilization of RAP and RAS, it is necessary to characterize the properties of the rejuvenated blends using different incorporation methods.

7.2 Sample Preparation and Experiment Methods

7.2.1 Raw materials

One asphalt base binder, PG 64-22, was selected in this study. The raw RAP was collected from the Rogers Group and RAS materials used for aged binder extraction were collected from the Tennessee Shingle Recycling. One type of rejuvenator, which was formulated for high compatibility with the aged and oxidized asphalt, was selected for blending. The typical properties of the rejuvenator are summarized in **Table 7-1**.

Table 7-1. Typical properties of the rejuvenator used.

Typical properties	Value	Method
Appearance	Brown liquid	Visual
Color	14+	AOCS Td 1a-64
Density @ 20 °C, g/ml	0.92 – 0.95	ASTM D1475
Viscosity @ 40°C, cSt	45 – 60	AOCS Ja 10-87
Flash point °C, open cup	>290	AOCS Cc 9a-48

7.2.2 Sample preparation

The RAS and RAP binders were extracted following ASTM 2172 (test method A: centrifuge extraction) and then recovered according to the ASTM D5404 procedure. Two rejuvenator incorporation methods were used to prepare the binder blends (40g). One method, denoted as Incorporation Method A, was to combine the preheated base binder (PG 64-22) with the rejuvenator at the selected dosage first, and then manually mix it with the RAP/RAS at different ratios. The other method, named Incorporation Method B, was to blend the rejuvenator with the RAP/RAS binder first and then mix with the virgin binder at the selected temperature afterwards. The blending temperature for the virgin binder and rejuvenator was 150°C. Considering the different viscosity of the RAP and RAS binder, 165°C and 210°C were set as the blend temperature to mix the RAP/ RAS binder blends with rejuvenator, respectively.

In order to evaluate the aging properties of the binders, some selected binder blends were subjected to short-term and long-term aging. Rolling Thin Film Oven (RTFO) aging was used to simulate the short-term aging in accordance with the ASTM D2872 at 163°C for 85 min, while Pressure Aging Vessel (PAV) aging was performed on the RTFO aged binders for 20 h at 100 °C and 2.1 MPa pressure followed by the long-term aging procedure ASTM D6521. The work plan with varying blending ratios and blending methods is listed in **Table 7-2**. The content of the rejuvenator is indicated by the percentage of the total binder blends. The original (aging condition) in table means blends without any aging process.

Table 7-2. Binder blends and conditioning methods.

Binder/Blend label	Blend proportions	Rejuvenator (%)	Incorporation method	Aging condition
Virgin	PG 64-22	-	-	Original, RTFO, RTFO+ PAV
0.2 RAS	0.8 PG 64-22 0.2 RAS	-	-	Original, RTFO, RTFO+ PAV
0.2 RASR2B1		2	Method A	Original, RTFO, RTFO+ PAV
0.2 RASR2B2		2	Method B	Original, RTFO, RTFO+ PAV
0.2 RASR5B1		5	Method A	Original

0.2 RASR5B2		5	Method B	Original
0.2 RASR10B1		10	Method A	Original
0.2 RASR10B2		10	Method B	Original
0.2 RAP	0.8 PG 64-22 0.2 RAP	-	-	Original, RTFO, RTFO+ PAV
0.2 RAPR2B1		2	Method A	Original, RTFO, RTFO+ PAV
0.2 RAPR2B2		2	Method B	Original, RTFO, RTFO+ PAV
0.2 RAPR5B1		5	Method A	Original
0.2 RAPR5B2		5	Method B	Original

7.2.3 Experiment method

The DSR frequency sweep test was performed on all the binder blends to explore the rheological properties at three different temperatures of 10 °C, 25°C and 40°C and angular frequency of 0.1-100 rad/s for two replicates. The master curves were created at a reference temperature of 25 °C. The rheological properties are characterized by complex shear modulus (G*) and phase angle (δ) at a different reduced frequency. G* is considered as the sample's total resistance to deformation when repeatedly sheared. Larger complex modulus usually has better resistance to flow deformation. The phase angle, defined as the time lag between the applied shear stress and resulting shear strain, reflects the viscous response of the asphalt.

The GPC test was conducted to detect the change of molecular size distribution of the asphalt. The solution for GPC testing was prepared at a concentration of 1mg of asphalt per 1mL of tetrahydrofuran (THF), followed by being injected into a 2mL vial. The vial was inserted in an automatic sample injector, and the concentration of the components was recorded in the eluant during the testing. The chromatogram, which shows the relationship between the elution time and the refractive index was obtained from GPC testing.

7.3 Results and analysis

7.3.1 Master curves for the unaged binders

The time-temperature superposition principle is used to construct the master curves of the binder blends. Asphalt is considered as a viscoelastic material and is highly related to the temperature change. The shift factor (α_T) is defined as the ratio between the reduced frequency at the reference temperature (ω_r) and the frequency at the desired temperature (ω), which can be expressed as:

$$\alpha_T = \frac{\omega_r}{\omega} \tag{7.1}$$

A second-order polynomial relation mode is used to expresses $\log(\alpha_T)$ in terms of temperature [79]:

$$log(\alpha_T) = a_1T^2 + a_2T + a_3 \tag{7.2}$$

where a_1, a_2 and a_3 are regression coefficients.

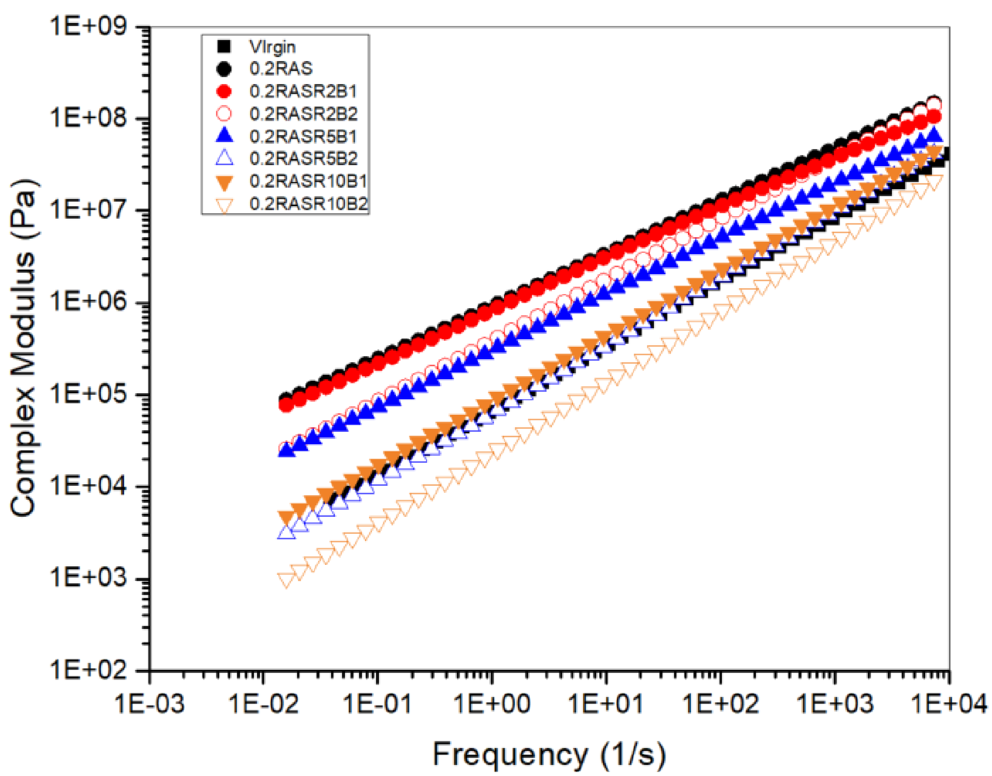
A sigmoidal model is utilized to construct the master curves:

$$log|G^*|) = \delta + \frac{\alpha}{1+e^{\beta+\gamma(log\, f)}} \tag{7.3}$$

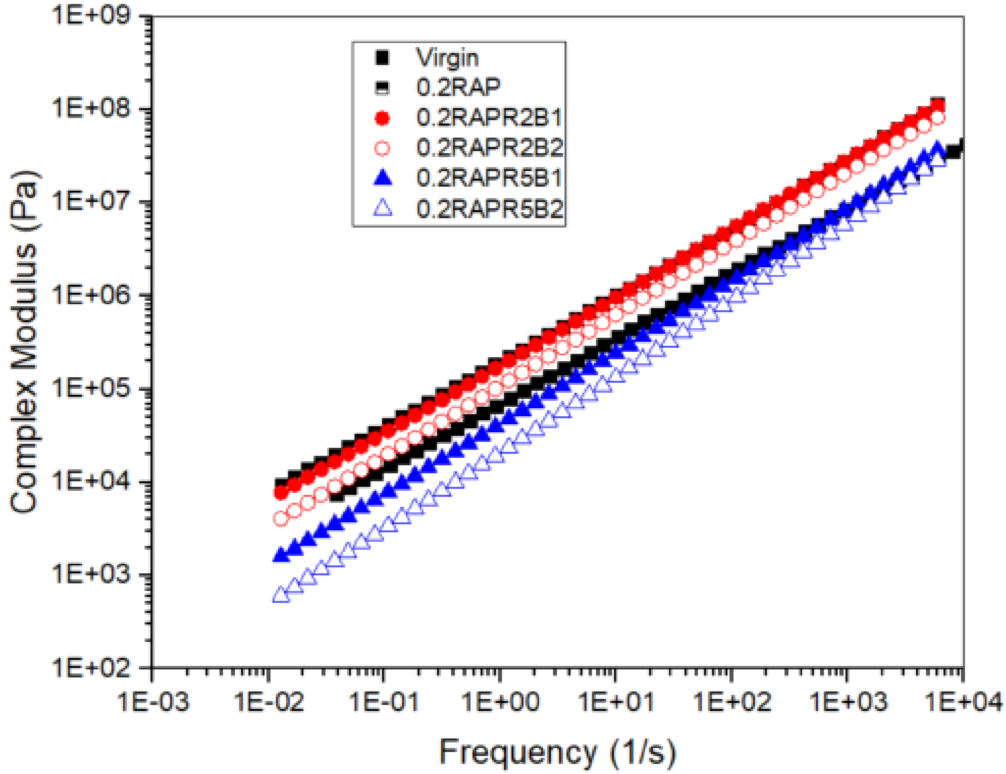
where G^* = dynamic modulus (Pa); f = reduced frequency (Hz); δ = the minimum value of G^*; $\delta + \alpha$ = the maximum value of G^*; β and γ = constants.

As the shift factors are calculated, a master curve of the binder is plotted at a reference temperature.

Figure 7-1 compares the complex modulus master curves at the reference temperature of 25 °C for different binder blends. It is obvious that adding rejuvenators will reduce the complex modulus of the binders. Basically, both incorporation methods can decrease the complex modulus especially at low frequency (high temperature). Using a high rejuvenator dosage in the binder blends resulted in a remarkable softening effect. For example, the complex moduli of the RAS binder with 10% rejuvenator and the RAP binder with 5% rejuvenator were even lower than that of the virgin binder, which indicated that the addition of such dosages of the rejuvenator may be overdosed. Thus, there existed an optimum dosage of the rejuvenator for each method to soften the aged binder to a target value. Compared to Method A, Method B led to a more significant reduction of complex modulus. In addition, it was observed that the gap of the complex modulus curves between Method A and Method B for the RAS binder was larger than that of the RAP binder, especially at low frequency. In other words, compared to Incorporation Method A, Incorporation Method B can have a more notable rejuvenation effect on the RAS binder than the RAP binder.



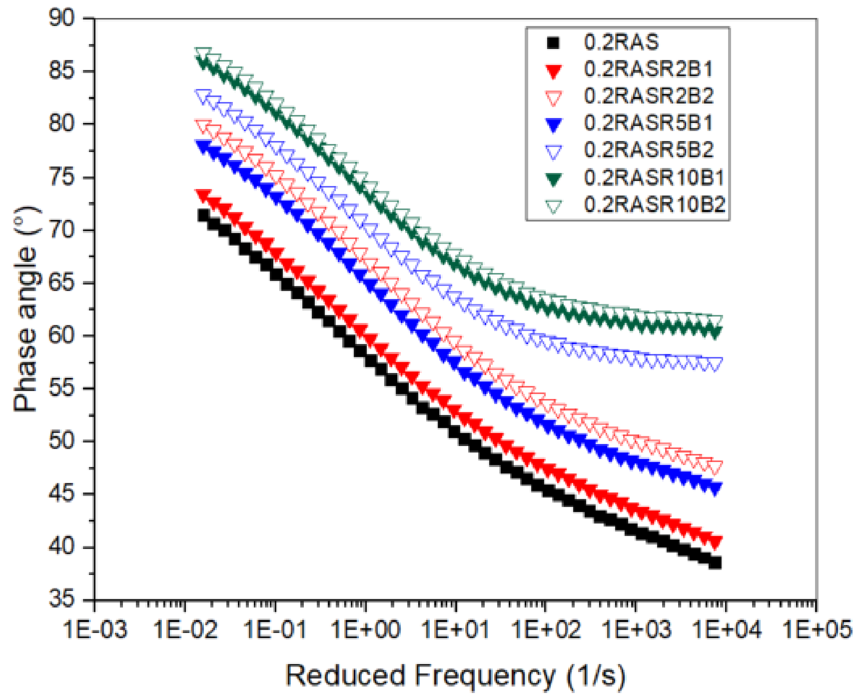
(a) 0.2 RAS



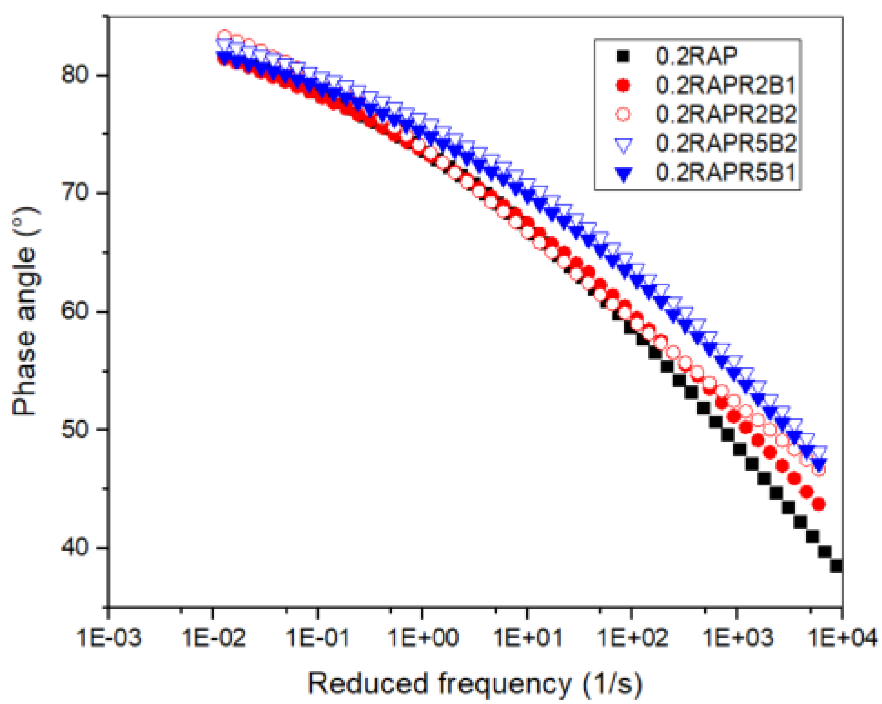
(b) 0.2 RAP

Figure 7-1 Complex modulus master curves of binder blends

Figure 7-2 shows the master curves of the binder blends in terms of the phase angle. A better viscous response of binders is usually indicated by a larger phase angle [80]. As shown in Figure 7-2, the phase angle is also affected by the amount of rejuvenator and different incorporation methods. Generally, a higher dosage of rejuvenator resulted in an increase of the phase angle in all cases. The binder blends using the incorporation method B presented a higher phase angle than incorporation method A, especially at the low frequency, which means that the viscous response of the binder blends using incorporation Method B was better than that of using Method A. That is to say, compared to Incorporation Method A, Incorporation Method B was more capable of softening the binder blends. Similar to the complex modulus master curves, the rejuvenation effect on the RAS binder blends was more pronounced than on the RAP binder blends.



(a) 0.2 RAS

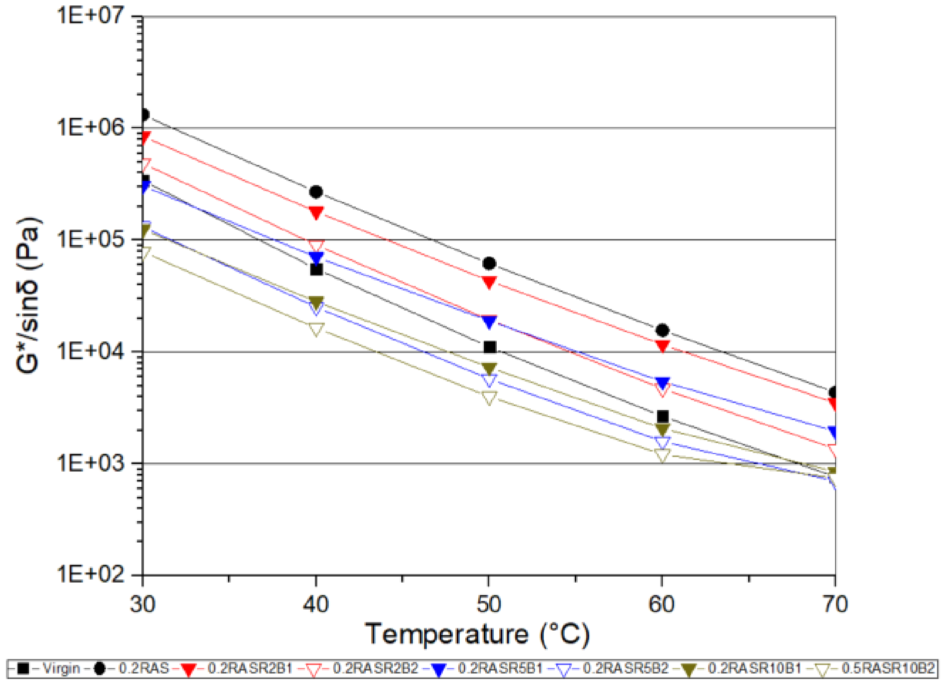


(b) 0.2 RAP

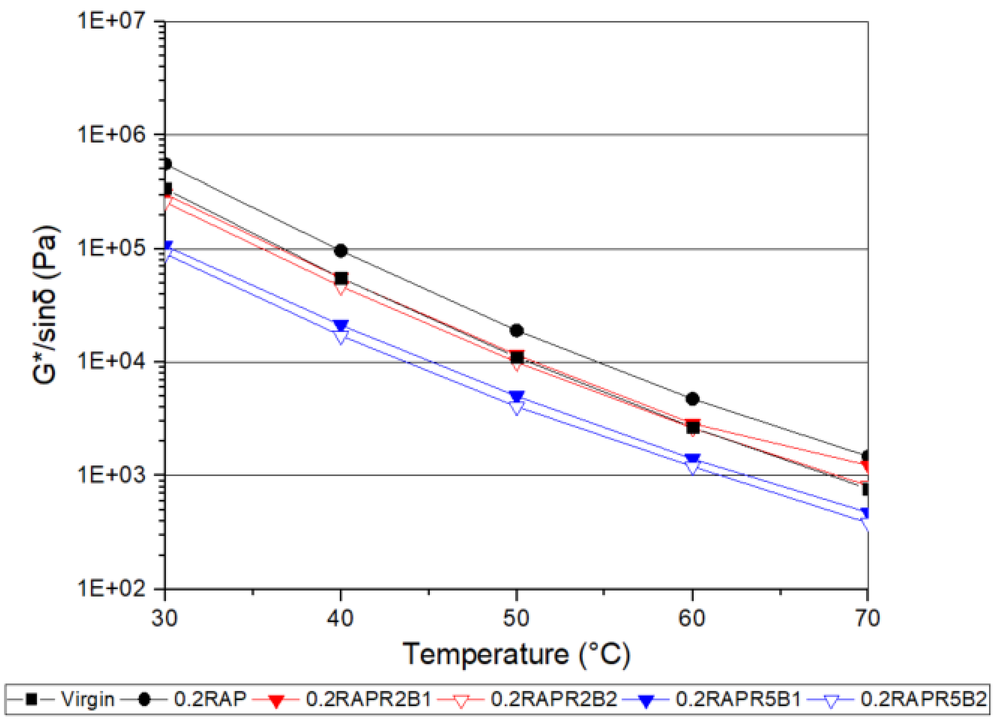
Figure 7-2 Phase angle master curves of binder blends

7.3.2 Rutting and fatigue resistance

The rutting and fatigue resistance of the binder blends was assessed according to AASHTO M320. The rutting parameter G*/sinδ, reflecting the irrecoverable deformation of asphalt during loading, was determined from the DSR test at a frequency of 10 rad/s. A higher value represents a higher rutting resistance of the asphalt. Figure 7-3 plots G*/sinδ parameter against the temperature of 0.2 RAS and 0.2 RAP binder blends with two different incorporation methods. As for the unaged binder, a rutting parameter (G*/sinδ > 1 kPa) is created to determine the critical high temperature of the asphalt according to AASHTO T315. It was obvious that the rutting parameter of the rejuvenated binder blends was strongly affected by the amount of rejuvenator and test temperatures. Generally, the rutting parameter decreased with the increase of rejuvenator concentrations and test temperatures. Compared with Incorporation Method A, using Incorporation Method B resulted in a larger difference of the rutting parameter between the rejuvenated binder blends and the unconditioned ones. Thus, there still exists an optimum dosage of rejuvenators for each incorporation method, which can minimize the rutting to an acceptable value.



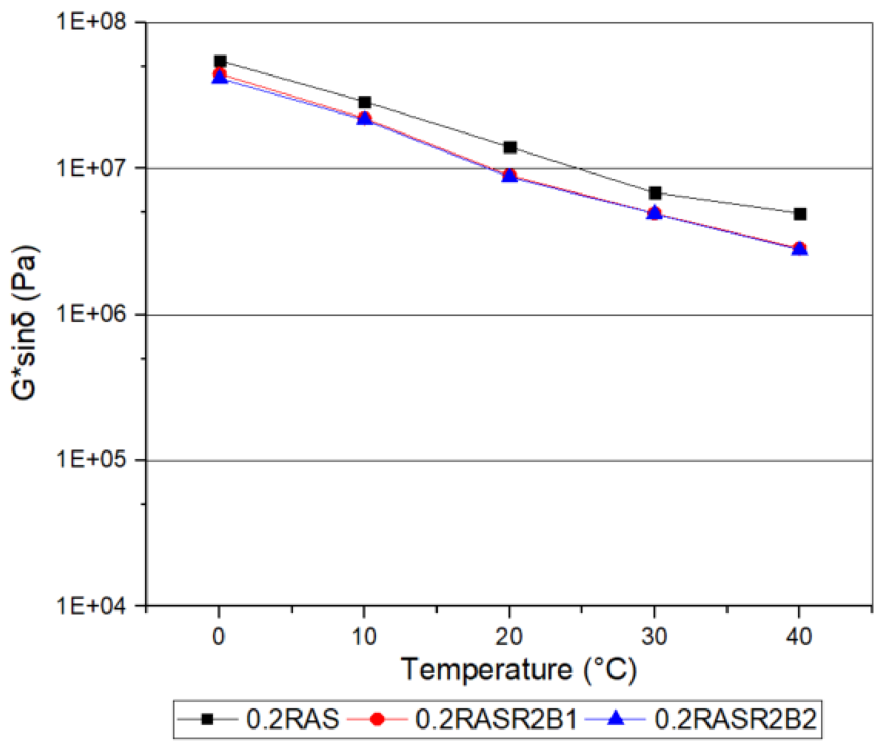
(a) 0.2 RAS



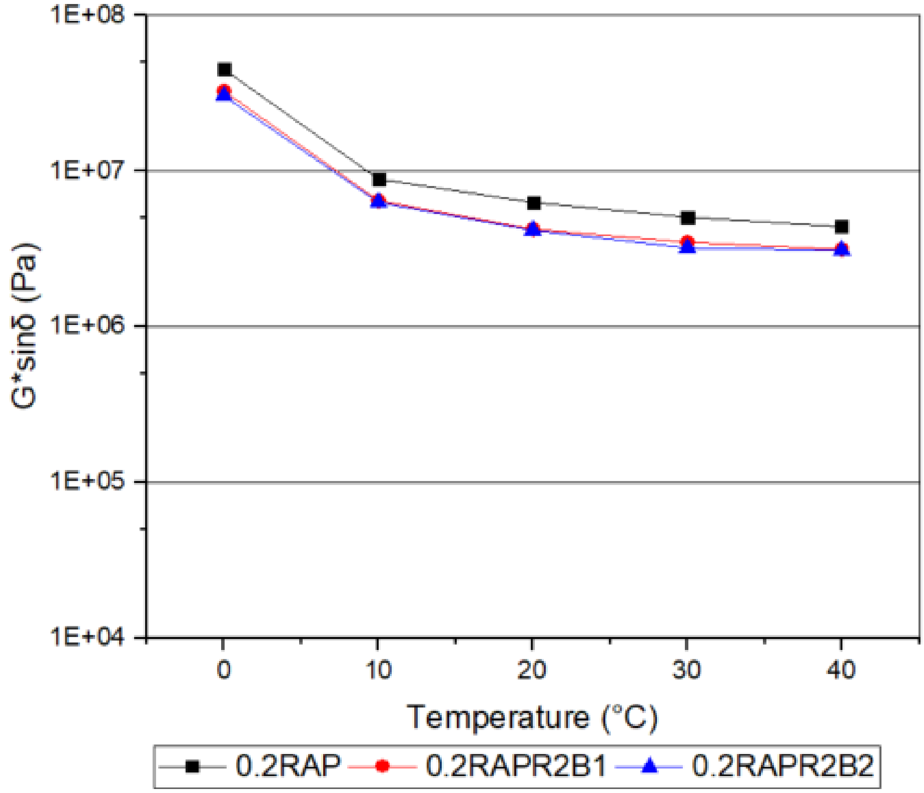
(b) 0.2 RAP

Figure 7-3 G*/sinδ parameter vs. temperature

The PAV-aged RAS and RAP binder blends were selected for the fatigue analysis. The fatigue potential of 0.2 RAS and 0.2 RAP binder blends, determined by G*sinδ, is plotted in Figure 7-4. The specification requirement for fatigue resistance is that the G*sinδ of the PAV-aged binder must be no more than 5MPa. Similar to rutting parameter, the fatigue parameter of the binder blends was highly related to temperature. Apparently, all the binder blends incorporated with rejuvenators presented a notable increase in fatigue resistance, indicated by a lower critical intermediate temperature. In addition, it was observed that the fatigue parameter patterns of the RAS and RAP binder blends using either incorporation method were close to each other after the long-term aging, meaning that the effects of rejuvenators on the fatigue resistance of the binder blends were similar regardless of the different incorporation methods.



(a) 0.2 RAS

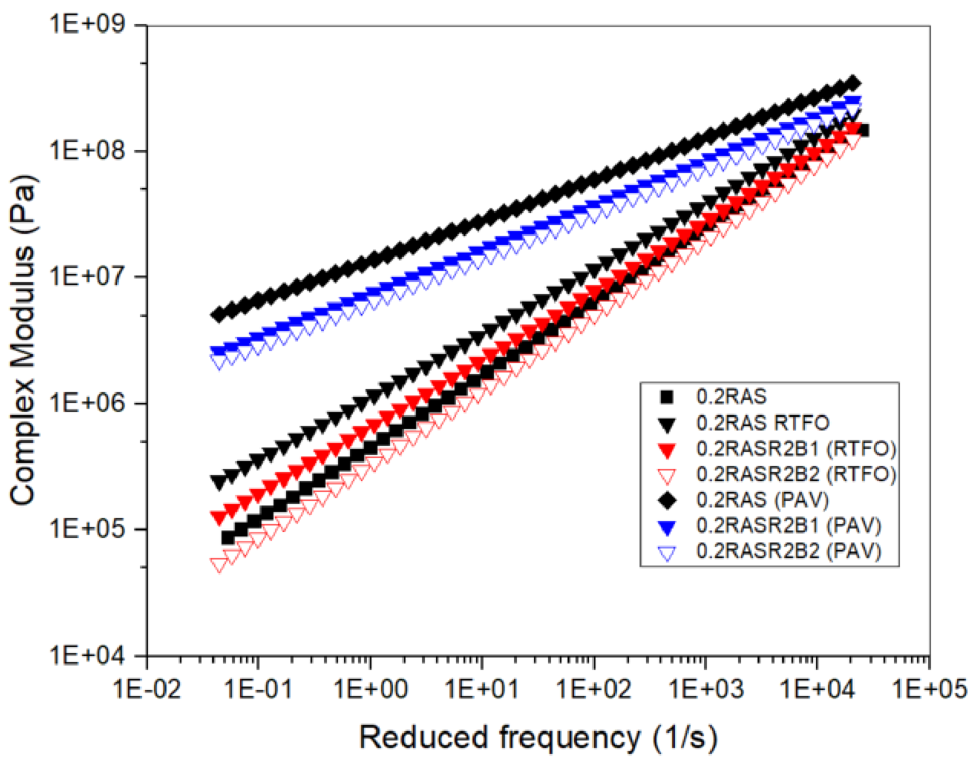


(b) 0.2 RAP

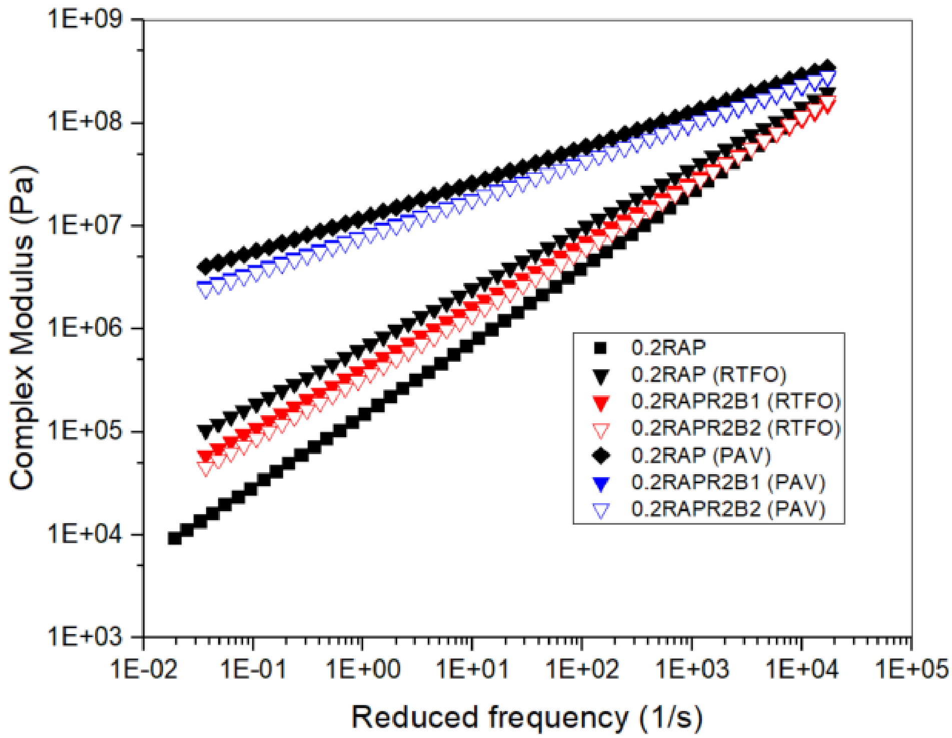
Figure 7-4 G*sinδ parameter vs. temperature.

7.3.3 Aging properties

The aging phenomenon of rejuvenated binders could result in the rheological and chemical changes of the binder blends. Several studies found that although the rejuvenating effectiveness of rejuvenators could be decreased due to long-term aging [78, 81], all the rejuvenated binders still presented different rheological properties (a lower complex modulus and a higher phase angle) compared to the binders without the addition of rejuvenators [82]. In this study, the binder blends subjected to RTFO and PAV was utilized to evaluate the aging effects of the binders the aforementioned incorporation methods. The DSR results are shown in Figure 7-5. The original stiffness of the RAS/RAP binder blends was selected for comparison. Both the RAS and RAP binder blends presented similar patterns of changing moduli. When the rejuvenator was added at a dosage of 2% regardless of the blending methods, the complex modulus decreased especially at low frequency, indicating that the rejuvenators were still able to soften the recycled binder blends over a certain service life. It should be noted that after the binder blends were subjected to RTFO aging, the complex modulus of the binder blends using Incorporation Method B was lower than that of using Method A, suggesting that the binder blends using Incorporation Method B had a less aging effect than using Method A after short-term aging. But as for the PAV aged binder blends, the complex modulus master curves, using both incorporation methods, nearly overlap each other indicating that the aging effects of using the two incorporation methods on the binder blends after the long-term aging were almost the same.



(a) 0.2 RAS



(b) 0.2 RAP

Figure 7-5 Aging properties of binder blends with two blending methods.

The altered rheological and aging properties of the rejuvenated binder blends may be due to the evaporation of rejuvenators or the change of molecule size. To clarify why there were such different behaviors of the binder blends, the mass loss was obtained by measuring the weight percentage reduction between the aged and unaged binder blends. Also, the GPC test was conducted to investigate the LMS(%) of the binder blends. An increase in the LMS percentage implies an increase in the viscosity of the binder blends, which is highly correlated to G* [83].

Table 7-3 shows the LMS(%) and mass loss of all the RAS binder blends. Generally, a longer aging time resulted in an increased LMS(%). As for the RTFO aging (blend 2, 4, and 6), both incorporation methods for blend 4 and 6 showed no mass loss, but a notable LMS(%) reduction for blend 2 indicating that the rejuvenator still played an important role in softening the short-term aged binders and that the rejuvenating effect of the RTFO aged binders can be attributed to a decrease of LMS(%). For the PAV aging (blend 3, 5 and 7), the two incorporation methods for blend 5 and 7 presented a slight decrease of LMS(%) and a more pronounced mass loss of the rejuvenated binder blends than blend 3, reflecting that the rejuvenating effect of the PAV aged binders may be mainly due to the evaporation of the rejuvenator. In accordance with the complex modulus master curves under different aging conditions, the RTFO aged binder blends using incorporation method B showed a more pronounced rejuvenating effect than using the method A because of the existing rejuvenator, whereas the PAV aged binder blends using both two incorporation methods presented the similar rejuvenating effect due to the evaporation of the rejuvenator. Therefore, consistent with the fatigue parameter curves of the PAV aged binder blends, using the different incorporation methods had a similar effect on the fatigue resistance of the rejuvenated binder blends.

Table 7-3. LMS (%) and mass changes during the aging process.

Blend number	Type	LMS (%)	Mass Loss (%)
1	0.2 RAS	22.08	0
2	0.2 RAS RTFO	27.01	0
3	0.2 RAS PAV	34.45	0.26
4	0.2 RASR2B1 RTFO	21.94	0
5	0.2 RASR2B1 PAV	32.37	0.70
6	0.2 RASR2B2 RTFO	21.31	0
7	0.2 RASR2B2 PAV	31.40	0.67

7.4 Discussions

Two incorporation methods were used to blend the virgin and aged binders with rejuvenators. The rheological and aging properties were investigated in this preliminary study. The test results showed that two rejuvenator incorporation methods perform different rheological and aging properties of the binder blends. Considering the factors that affect the rejuvenation mechanism, Incorporation Method B can probably better facilitate the diffusion of the rejuvenator into the recycled binders, ending in a more compatible blend between the rejuvenator and the binders. The loss of rejuvenating effectiveness was observed during the aging process by the altered LMS(%) of the binder blends, which is consistent with previous studies [73, 74]. In this study, mass loss of rejuvenator occurred because of evaporation during the long-term aging process, while a study by Ding et al found a change of mass both in the short-term and the long-term aging [63]. Such difference may due to the different types of rejuvenators used for blending. Thus, other types of rejuvenators, including the petroleum-based oil and aromatic extract, should be considered in future studies. To further explain the rejuvenating mechanism, SARA analysis can be used to investigate the chemical composition change of the rejuvenated asphalt binders during the different aging conditions. [84].

Both incorporation methods improved rejuvenating effectiveness on the highly aged binders. However, different rejuvenating effectiveness is expected in the recycled asphalt mixtures when incorporating the rejuvenators directly into the preheated aged binders. Further studies should be conducted for rejuvenated asphalt mixtures instead of the binders based on Incorporating Method B. Such incorporating methods may need more energy in the asphalt plant due to a higher temperature and longer mixing time required for the preheating process. A cost-effectiveness analysis would optimize the utilization of rejuvenators for recycled materials that provide adequate performance.

As mentioned above, rejuvenators are directly added into the recycled mixtures for remixing and compaction in HIR recycling technology, which is similar to Incorporation Method B. To improve the performance of the compacted recycled mixtures, several factors should be optimized including the amount of rejuvenator, the type of rejuvenator, and the mixing temperature. Efforts in such areas are necessary to achieve more sustainable pavements in the future.

7.5 Conclusions

In this chapter, the rheological and aging properties of RAS/RAP binder blends with rejuvenator using two different incorporated method were investigated. The RTFO and PAV methods were used to simulate the short-term and long-term aging. DSR and GPC test were performed to characterize the binder rheological properties and molecule size changes of the binder blends at different aging periods, respectively. Rutting and fatigue resistance parameters were also obtained by temperature sweep test. Based on the test results, the following conclusions can be drawn:

1) By incorporating the rejuvenator with the aged binder first, the binder blends showed a more pronounced change of rheological properties compared to the one incorporating the rejuvenator with the virgin binder first, indicated by a lower complex modulus and a higher phase angle of the binder blends.
2) By incorporating the rejuvenator with the aged binder first, the binder blends showed greater reduction in the rutting parameter, $G^*/\sin\delta$, than when using the other method.
3) The two incorporation methods presented a similar fatigue parameter, $G^*\sin\delta$, of the PAV aged binder blends.
4) By incorporating the rejuvenator with the aged binder first, the binder blends presented a lesser aging effect after the short-term aging, but a similar aging effect after the long-term aging, compared with the one using the other method.
5) Based on the binder rheological difference between the two incorporating procedures of rejuvenator, it is expected that the mixture's performance should be different for asphalt mixtures obtained through these two different procedures. A subsequent mixture study is necessary.
6) Due to the sample preparation procedure in which all binder components were dissolved into a stronger solvent (THF), GPC was not able to capture the

microstructural differences of binders prepared through the two rejuvenator incorporating procedures. Additional methods such as FTIR or AFM should be investigated in the future.

Chapter 8 CONCLUSIONS AND RECOMMENDATIONS

A series of studies were conducted to evaluate the recycling efficiency in asphalt plant mixtures containing RAP and RAS. A new method was developed using fluorescence microscopy to differentiate between RAP/RAS and virgin binders as well as their blends, in which a new parameter, MGV, based on fluorescence image, was utilized to quantitatively determine the mobilization rates of aged asphalt binder in RAP/RAS. By generating the "Blending Chart" to show the change of MGV with RAP/RAS binder content, the mobilization rate of aged binder in RAP/RAS can be directly measured. Fourteen plant-produced asphalt mixtures were tested for their RAP/RAS binder mobilization rates using fluorescence microscopy and GPC. Linear regression analyses were conducted to evaluate the influence of mixture design and production condition parameters on the mobilization rate. In addition, a preliminary study was performed to investigate the influence of different rejuvenator incorporation methods on the rheological and aging properties of the recycled asphalt binders. The findings from this study will help maximize the use of RAP/RAS in asphalt mixtures and enhance the properties and performance of the mixtures containing RAP/RAS. Based on the findings, the following conclusions can be drawn:

1) The mobilization rates were different for large and small aggregates because of different RAP/RAS contents. The overall mobilization rate of a mixture could be determined by considering the surface area of large and small aggregates.
2) The overall mobilization rates of 14 plant mixtures were in the range of 0.4 to 1.0 for the fluorescence microscopy method and 0.37 to 0.83 for the GPC method.
3) The sensitivity of MGV to the aged binder content was affected by the test conditions. An index, termed Differentiation Factor, was used to measure the sensitivity of MGV to aged binder content. Results indicated that the MGV

measured at the wavelength of 450-490 nm and the exposure time of 0.5-1.5 s was most sensitive to the aged binder content.

4) For the construction of a blending chart, it was found that there exists a linear relationship between the MGV of a binder blend and its RAP binder content, and a quadratic relationship between the MGV of a binder blend and its RAS binder content. Therefore, the relationship between MGV and the aged binder content of a binder blend could be different for asphalt from diverse sources.
5) The mobilization rates from fluorescence microscopy and GPC method were different but showed a similar trend among the fourteen plant mixtures, which is due to the fact that the fluorescence microscopy method tests the aged asphalt content on the aggregate surface, whereas the GPC method tests the aged asphalt content of the outer layer of asphalt film.
6) According to the LMS (%) results from the GPC tests, the mobilization rates for the inner layer and the outer layer are different, indicating that only a part of the aged binder in the RAP/RAS was mobilized in the mixtures.
7) Among the production condition parameters of asphalt mixture plants, the mixing temperature and the percentage of RAP/RAS showed significant influences on the mobilization rate. In addition, the aging level of the RAP/RAS binder also had a significant influence on the mobilization rate. In general, a higher mixing temperature and less percentage of RAP/RAS may promote the mobilization rate, whereas a higher aging level of the RAP/RAS binder may decrease the mobilization rate.
8) By incorporating the rejuvenator with the aged binder first, the binder blends showed a more beneficial change in rheological properties compared to the one incorporating the rejuvenator with the virgin binder first, indicated by a lower complex modulus and a higher phase angle of the binder blends.

Recommendations

On the basis of the conclusions obtained in this study, the following recommendations can be made:

1) Among mixture design and production parameters, the RAP content and the mixing temperature have a greater impact on the mobilization rate. It is recommended that these two parameters should be considered carefully in the mixture design and production process, especially for the mixtures with a high RAP/RAS content.
2) The aging properties of RAP/RAS asphalt have significant influence on the mobilization rate. It is recommended that more studies should be conducted to evaluate the aging properties of RAP/RAS binder.
3) The utilization of RAS could reduce the mobilization rate significantly, indicating that less asphalt can be used to cover new aggregates with RAS. Therefore, the designed asphalt content should be raised correspondingly for the mixture containing RAS.
4) The quadratic relationship between the MGV of a binder blend and its RAS binder content could relate to the highly aged properties of RAS binder. The aging process increases the polarity of molecules, which might cause some intermolecular interactions between the RAS binder and virgin asphalt. The interaction makes the blending chart deviate linear relationship.
5) This study indicates that the mobilization rate of aged asphalt varied with mixtures. The relationship between the mobilization rate and the performance of mixtures has not been addressed thoroughly. Therefore, the role of un-mobilized aged asphalt in mixture needs to be further investigated.
6) This study focuses on the mobilization rate of plant hot mix asphalt. The mobilization rate for the mixtures using different mixing approaches such as cold recycling could be varying. Therefore, the blending efficiency for other mixing methods need to be investigated in the future.

7) The test methods applied in this study are still time consuming and cannot directly reflect the mixture performance. More methods which can extrapolate blending efficiency based on the performance of recycling mixtures should be further investigated.
8) This study indicates that the production conditions vary among asphalt plants, which would affect both the blending efficiency and mixtures performance. It is recommended that more information on the production condition should be collected, and the influence of production conditions on the mixture performance should be further investigated.

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APPENDICES

APPENDIX A: Survey Questions

The University of Tennessee
RAP/RAS recycling technologies survey

The University of Tennessee (UT) is performing a research project entitled "Evaluating Recycling Efficiency of Asphalt Plants" along with the Tennessee Department of Transportation (TDOT). One of the research objectives is to determine the blending efficiency of recycled asphalt pavement (RAP) or recycled asphalt shingle (RAS) in asphalt mixtures. The blending efficiency is defined as the percentage of the aged asphalt binder in RAP/RAS that can be blended into virgin asphalt binder and thus is available to coat aggregate. If RAP/RAS is not 100% blended with virgin binder, the effective asphalt content would be lower than the design asphalt content and the performance of asphalt mixtures be compromised. The purpose of this survey is to determine the current practices of state DOTs regarding blending efficiency of RAP/RAS and to seek advice and opinion in this area. Survey results will be shared with industry and government agencies and official to promote recycling and sustainable paving technologies.
By completing this survey, you will be eligible to receive a complimentary copy of the final report. Your participation is greatly appreciated.

Please complete the following information on the RAP usage.

Q 1 Does your state have a specification about how much of the aged asphalt binder on RAP can be used? If so, please answer the next two questions.

(1) Yes
(2) No

Q 2 In your state specification, what is the percentage of the aged asphalt binder on RAP that can be used.

(1) 0
(2) 25%
(3) 50%
(4) 75%
(5) 100%
(6) Other (Please provide the percentage) ____________________

Q 3 Do you think the percentage in your state specification is reasonable? If no, please list your reasons.

(1) Yes

(2) Maybe
(3) No ____________________

Q 4 Do you have concerns about the current percentage in your state specification?
(1) Yes
(2) Maybe
(3) No

Q 5 What percentage do you think of the aged asphalt binder on RAP can be used?
(1) 0
(2) 25%
(3) 50%
(4) 75%
(5) 100%
(6) Other (Please provide the percentage) ____________________

Q 6 Are you aware of a method for testing the blending efficiency of RAP? If so, please answer the next question.
(1) Yes
(2) No

Q 7 Which tools do know are used to test the blending efficiency of RAP?
(1) Gel Permeation Chromatography (GPC)
(2) Fourier Transform Infrared Spectroscopy (FTIR)
(3) Fluorescence Microscopy
(4) Dynamic Shear Rheometer (DSR)
(5) Other (Please specify) ____________________

Q 8 Does your state use rejuvenator in RAP containing asphalt mixtures?
(1) Yes
(2) No

Q 9 Do you think rejuvenator improves RAP blending efficiency?
(1) Yes
(2) Maybe
(3) No

Please complete the following information on the RAS usage.

Q 10 Does your state have a specification about how much of the aged asphalt binder on

RAS can be used? If so, please answer the next two questions.

(1) Yes
(2) No

Q 11 In your state specification, what is the percentage of the aged asphalt binder on RAS that can be used.

(1) 0
(2) 25%
(3) 50%
(4) 75%
(5) 100%
(6) Other (Please provide the percentage) ____________________

Q 12 Do you think the percentage in your state specification is reasonable? If no, please list your reasons.

(1) Yes
(2) Maybe
(3) No ____________________

Q 13 Do you have concerns about the current percentage in your state specification?

(1) Yes
(2) Maybe
(3) No

Q 14 What percentage do you think of the aged asphalt binder on RAS can be used?

(1) 0
(2) 25%
(3) 50%
(4) 75%
(5) 100%
(6) Other (Please provide the percentage) ____________________

Q 15 Are you aware of a method for testing the blending efficiency of RAS? If so, please answer the next question.

(1) Yes
(2) No

Q 16 Which tools do know are used to test the blending efficiency of RAS?

(1) Gel Permeation Chromatography (GPC)
(2) Fourier Transform Infrared Spectroscopy (FTIR)

(3) Fluorescence Microscopy
(4) Dynamic Shear Rheometer (DSR)
(5) Other (Please specify) ____________________

Q 17 Does your state use rejuvenator in RAS containing asphalt mixtures?
(1) Yes
(2) No

Q 18 Do you think rejuvenator improves RAS blending efficiency?
(1) Yes
(2) Maybe
(3) No

Please provide the following information about blending efficiency between virgin and aged binders.

Q 19 Among the factors listed, which do you think are the key factor(s) for the blending efficiency of RAP/RAS. (You may choose more than one options)
(1) Mixing temperature
(2) Mixing time
(3) RAP/RAS content
(4) Rejuvenator
(5) Virgin binder grade
(6) Aggregate size
(7) Degree of aging of RAP/RAS
(8) Other (please specify) ____________________

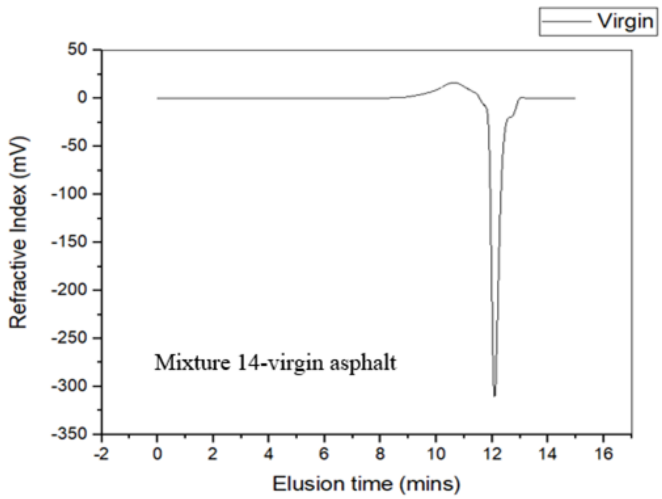
Q 20 Do you think high RAP (>30%) /RAS (>5%) percentage will reduce the service life of pavement?
(1) Yes
(2) Maybe
(3) No
(4) Other (please specify) ____________________

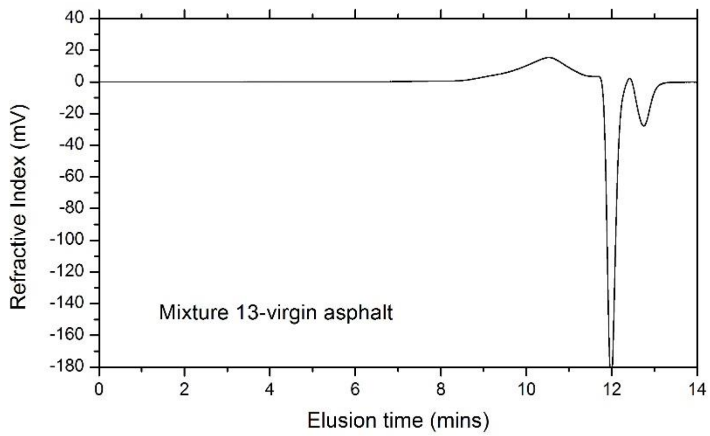
Q 21 Do you think linear blending charts (the relationship between the properties of mixed binders and the percentage of aged binder is linear) are valid for RAP/RAS?
(1) Yes
(2) Maybe
(3) No
(4) Other (please specify)

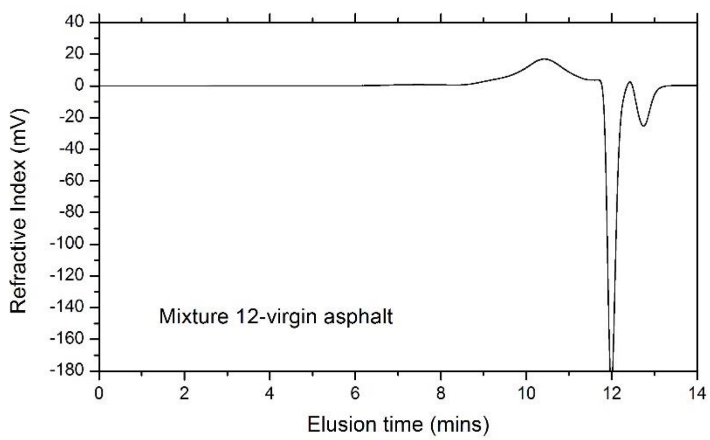
Q 22 Would you like a complimentary copy of the final report?

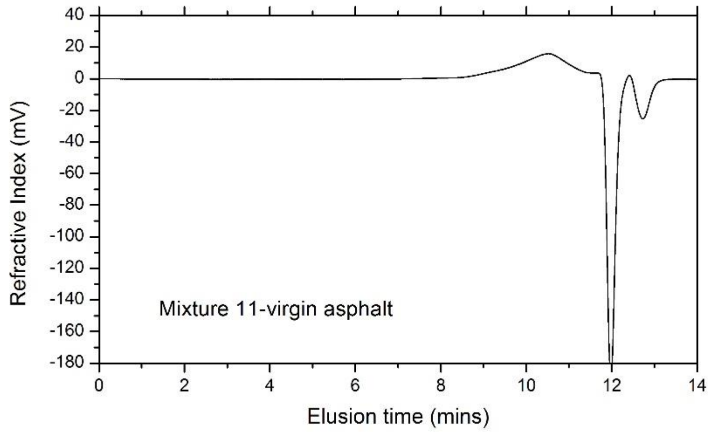
(1) Yes
(2) No

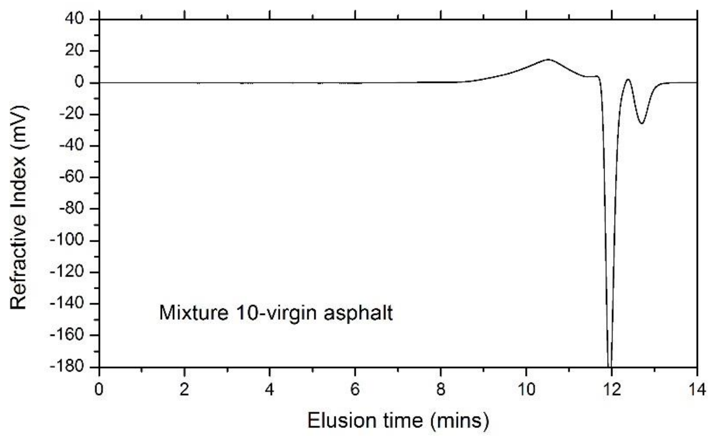
APPENDIX B: GPC Chromatograms of Test








Mixture 11-virgin asphalt
Refractive Index (mV)
Elusion time (mins)
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
0
2
4
6
8
10
12
14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Refractive Index (mV)
Elusion time (mins)
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20
0
-20
-40
-60
-80
-100
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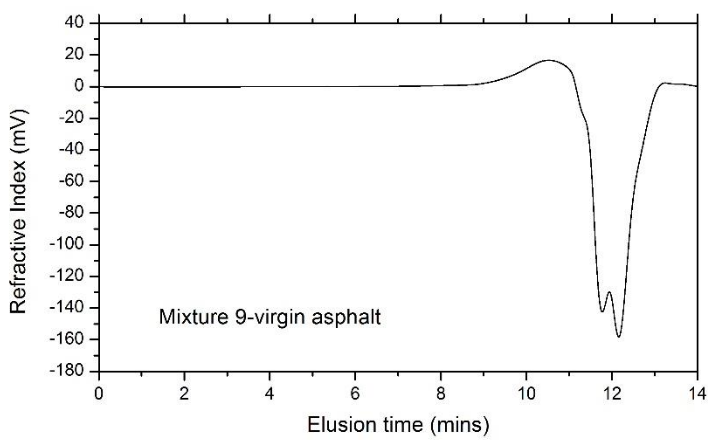
-140
-160
-180
0
2
4
6
8
10
12
14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Refractive Index (mV)
Elusion time (mins)
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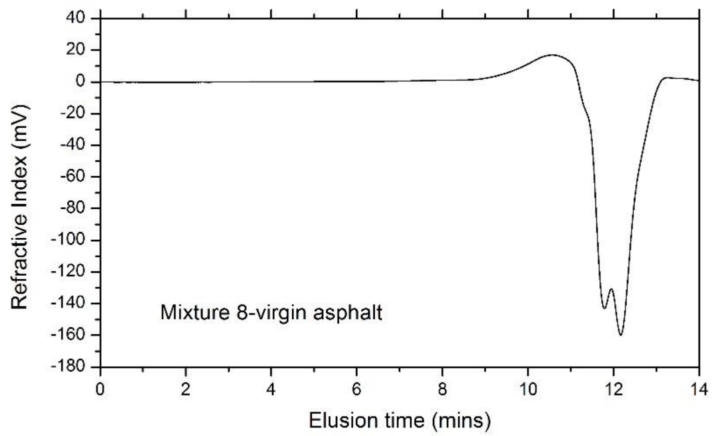
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
0
2
4
6
8
10
12
14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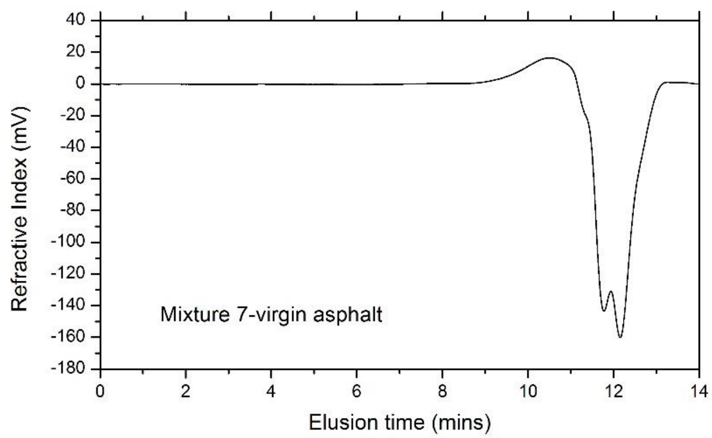
Elusion time (mins)
Mixture 8-virgin asphalt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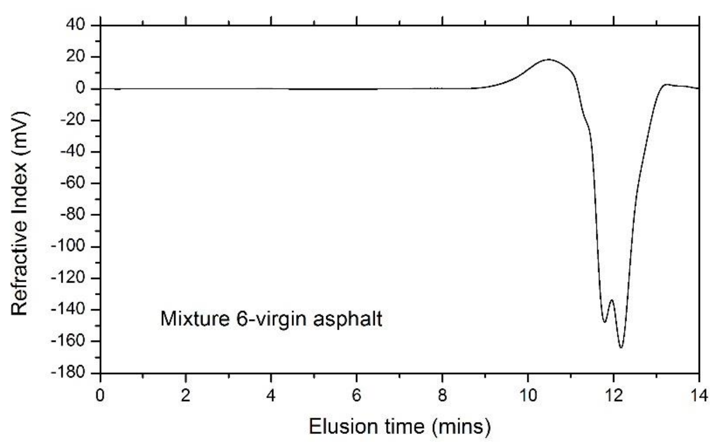
Mixture 7-virgin asphalt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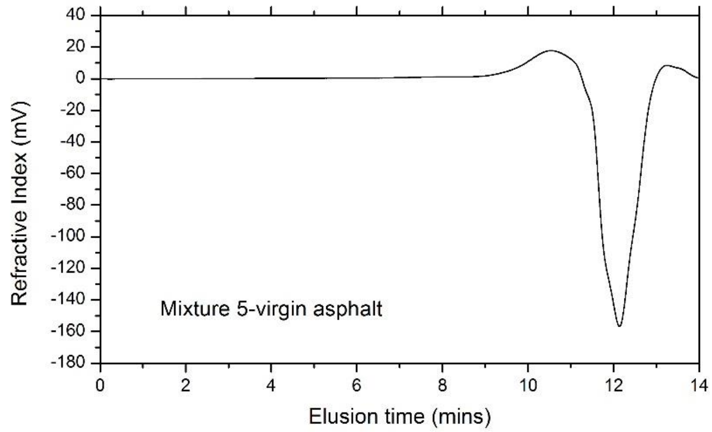
Elusion time (mins)
Mixture 6-virgin asphalt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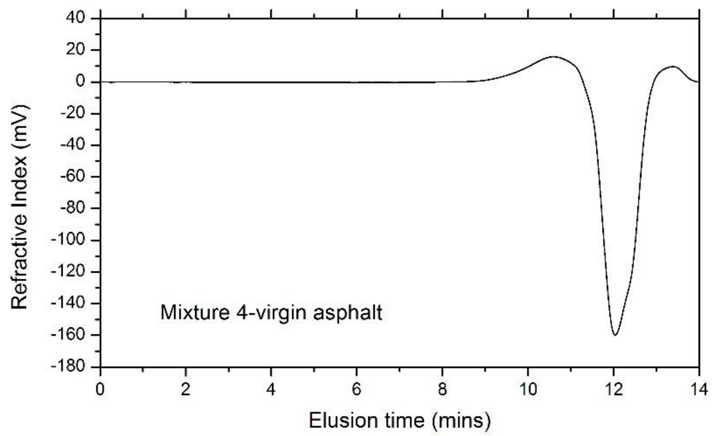
Elusion time (mins)
Mixture 5-virgin asphalt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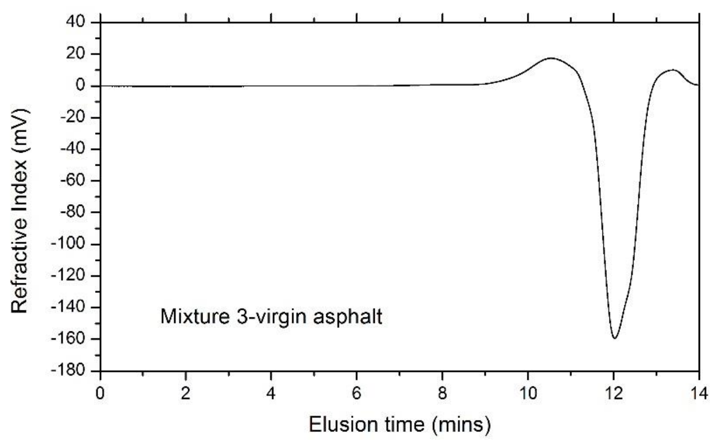
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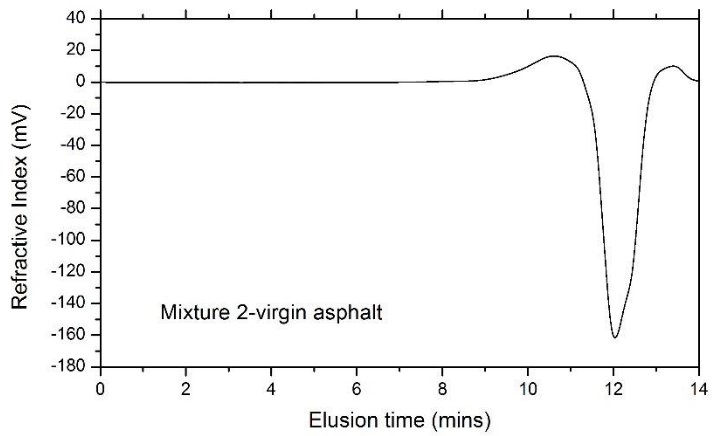
Elusion time (mins)
Mixture 3-virgin asphalt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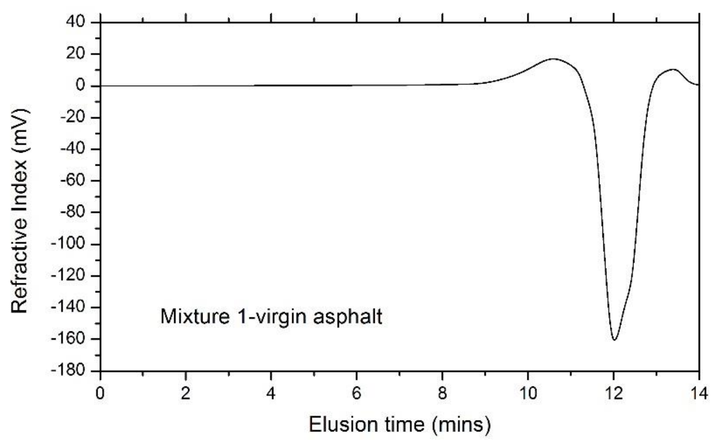
Refractive Index (mV)
Elusion time (mins)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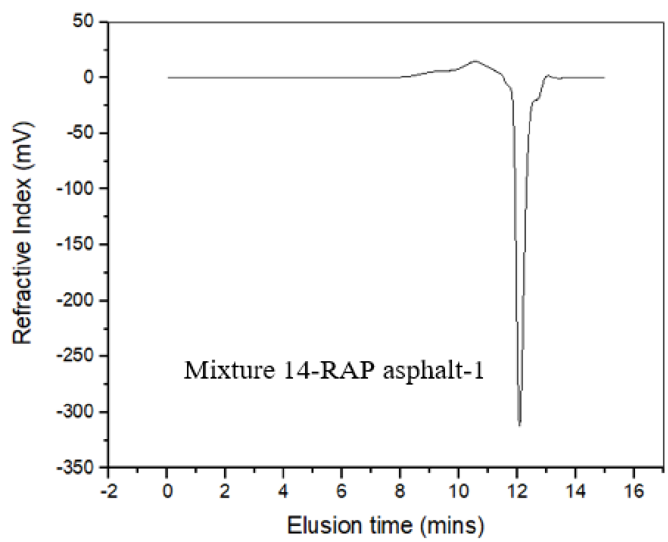
Refractive Index (mV)
Elusion time (mins)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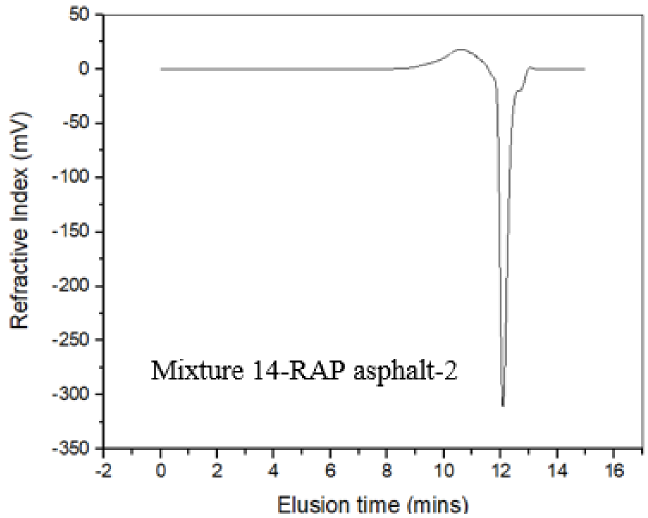
Refractive Index (mV)
Elusion time (mins)



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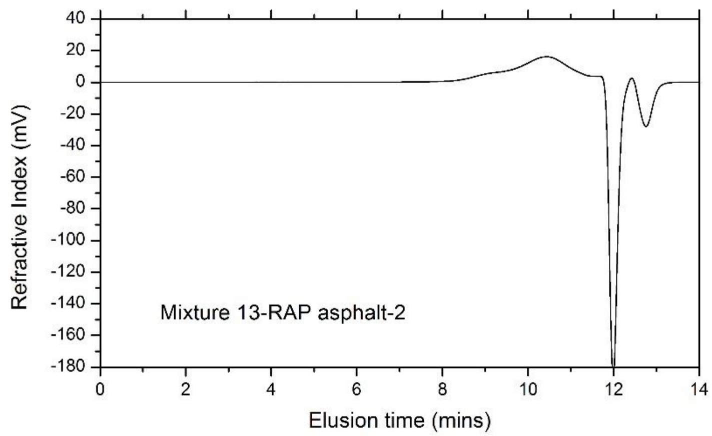
Elusion time (mins)



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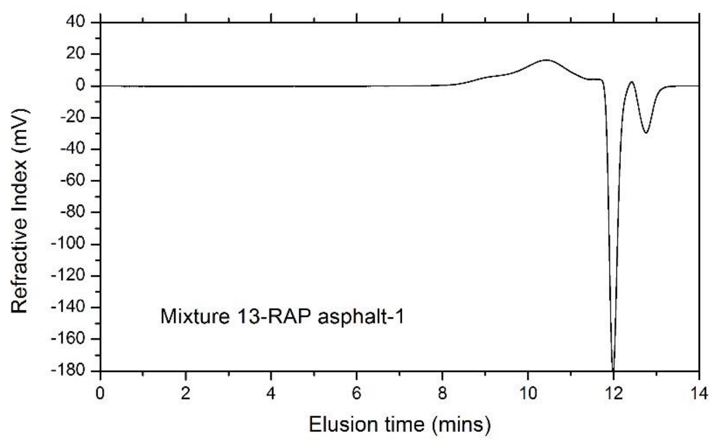

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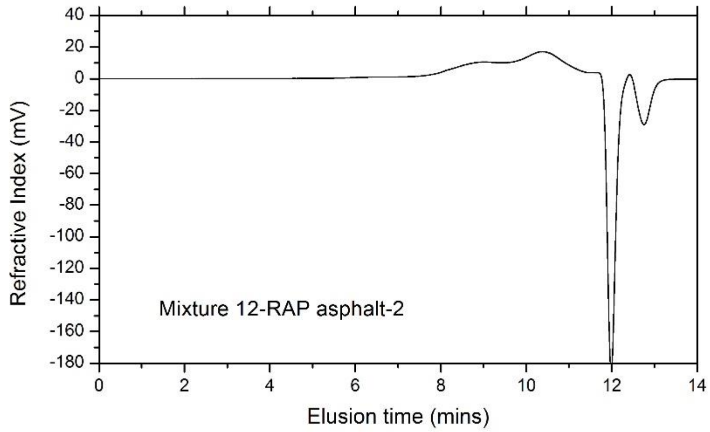
Refractive Index (mV)
Elusion time (mins)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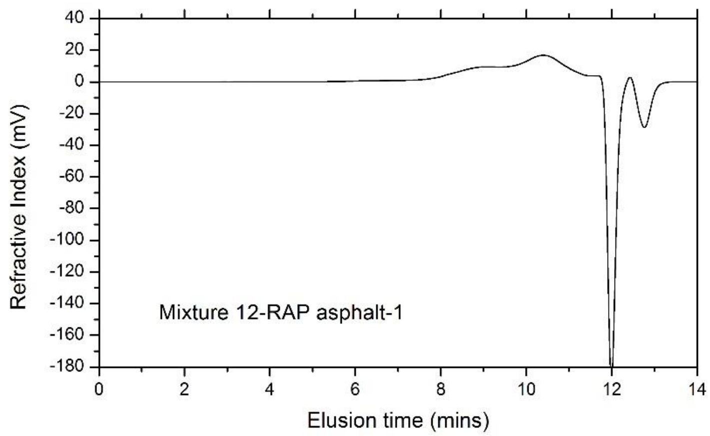
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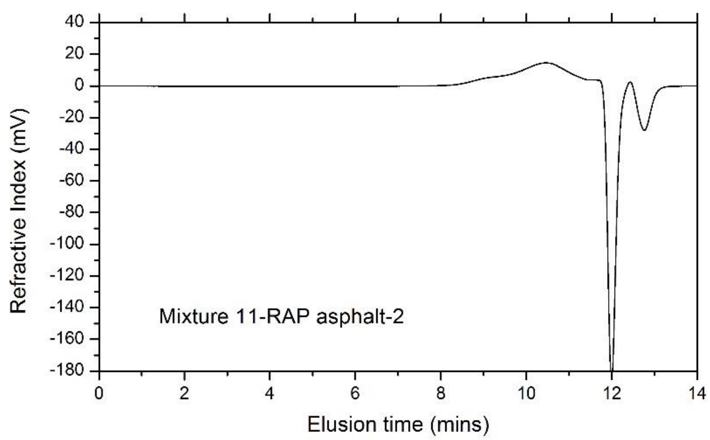
Elusion time (mins)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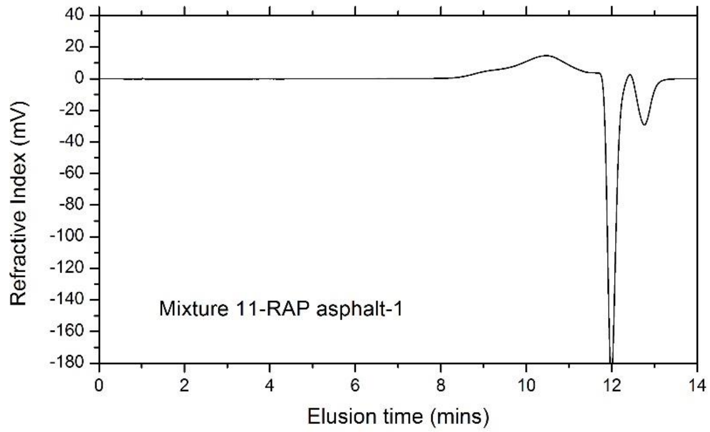
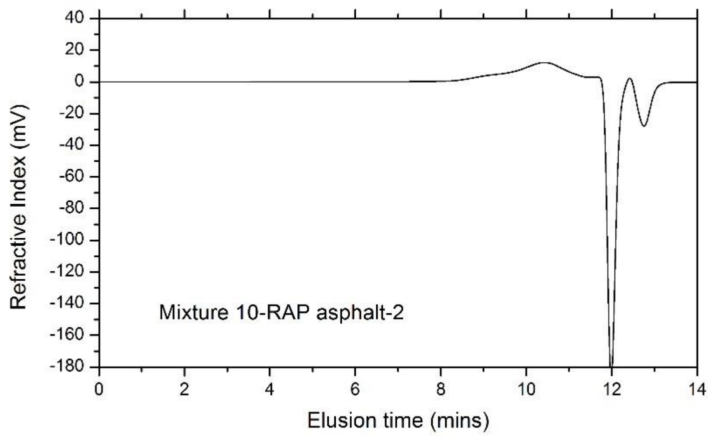
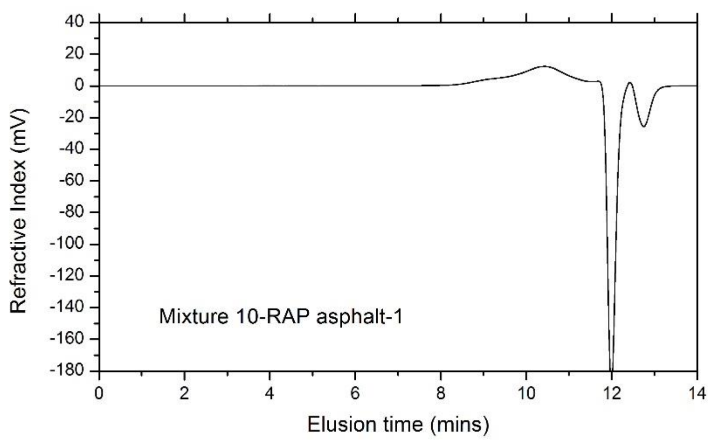
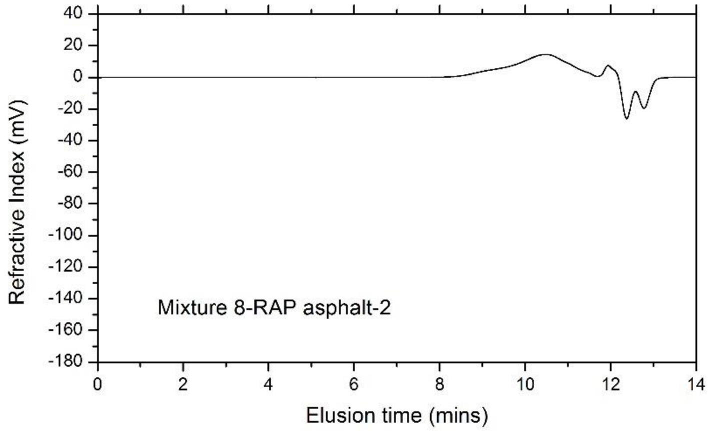
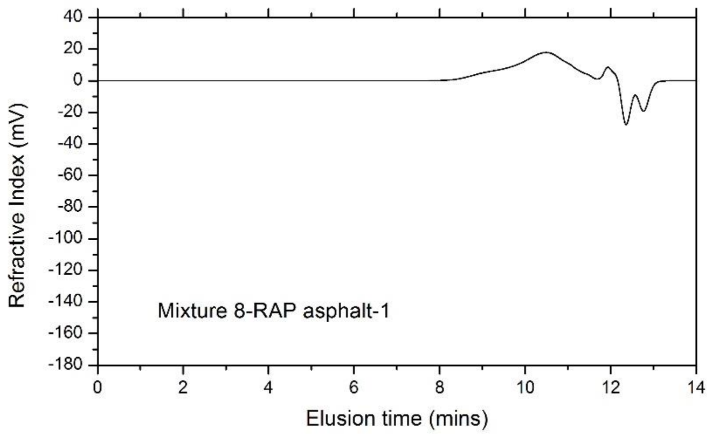
Refractive Index (mV)
Elusion time (mins)

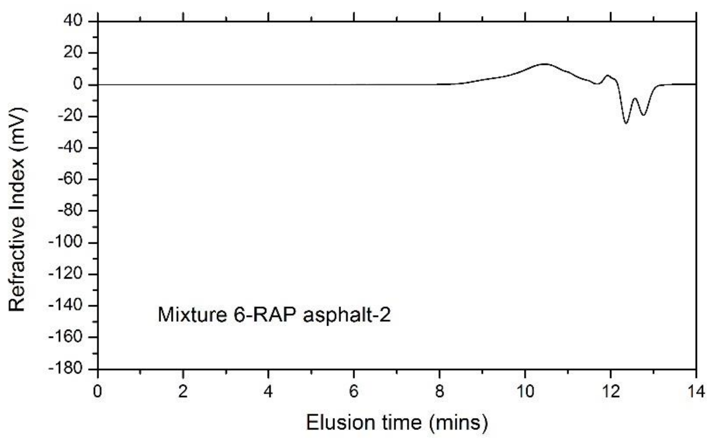

Mixture 11-RAP asphalt-1
Refractive Index (mV)
Elusion time (mins)

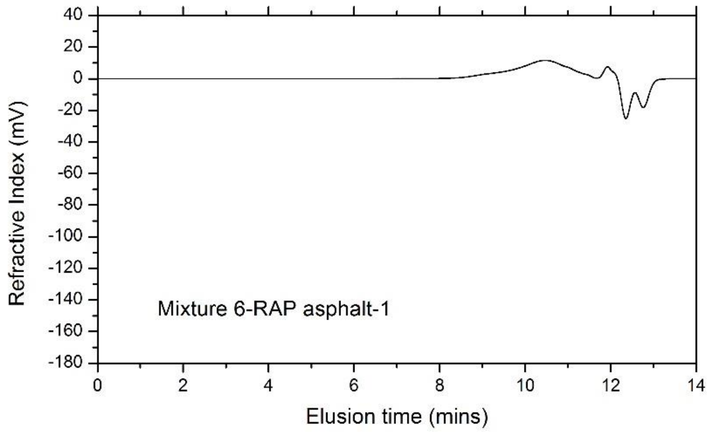

Mixture 10-RAP asphalt-2
Refractive Index (mV)
Elusion time (mins)

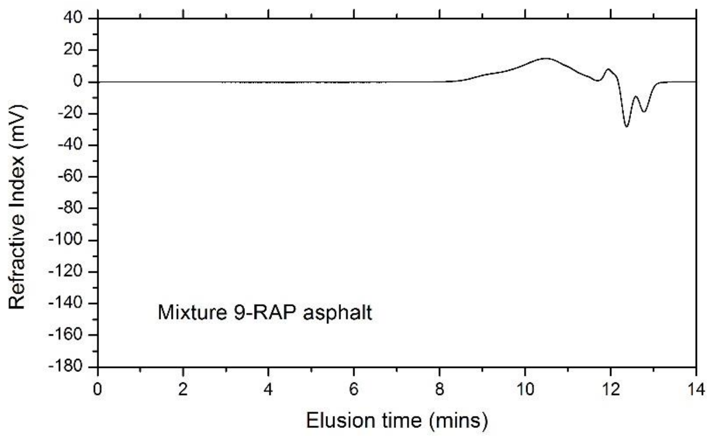

Mixture 10-RAP asphalt-1
Refractive Index (mV)
Elusion time (mins)

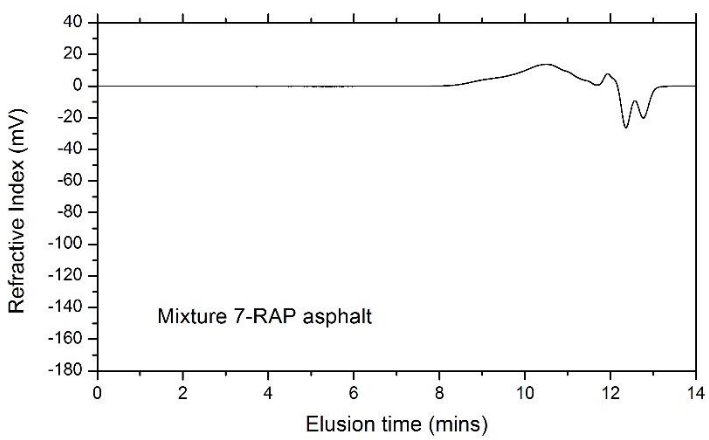

Refractive Index (mV)
Elusion time (mins)
Mixture 8-RAP asphalt-2

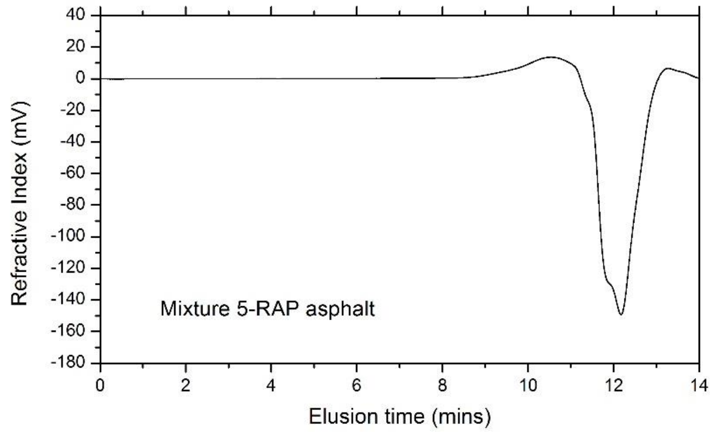

Refractive Index (mV)
Elusion time (mins)
Mixture 8-RAP asphalt-1

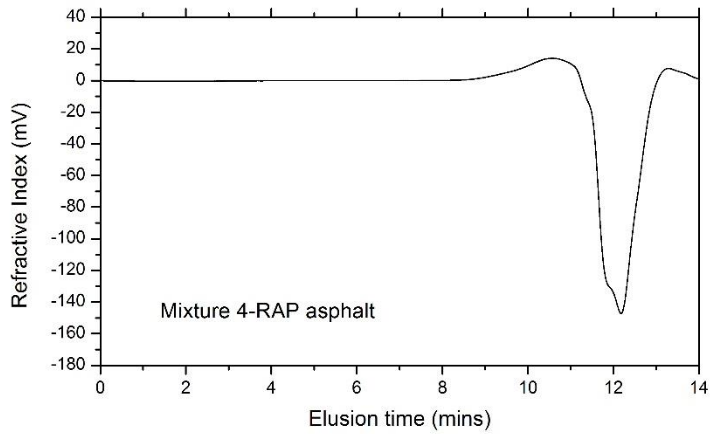

Refractive Index (mV)
Elusion time (mins)
Mixture 6-RAP asphalt-2

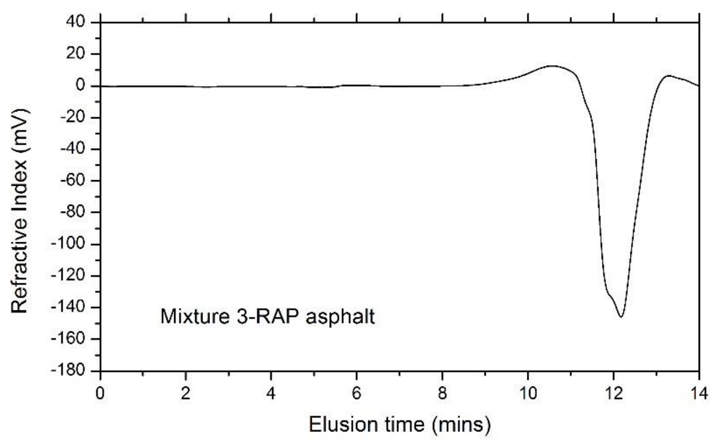

Refractive Index (mV)
Elusion time (mins)
Mixture 6-RAP asphalt-1

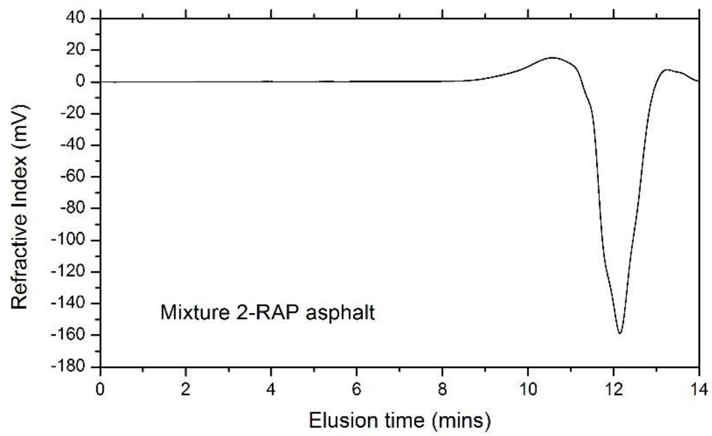

Refractive Index (mV)
Elusion time (mins)
Mixture 9-RAP asphalt


Refractive Index (mV)
Elusion time (mins)
Mixture 7-RAP asphalt

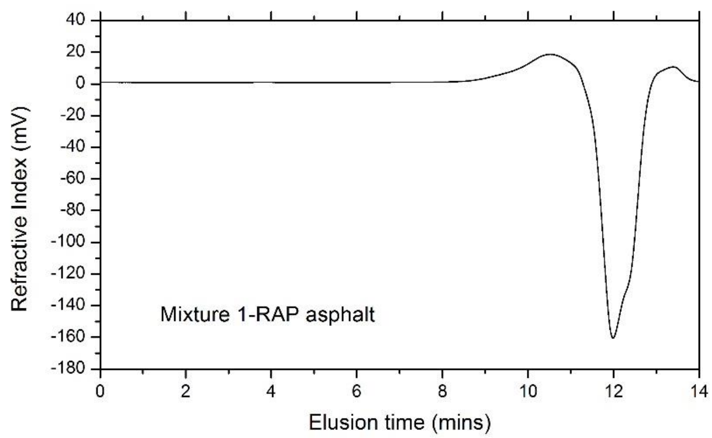

Refractive Index (mV)
Elusion time (mins)
Mixture 5-RAP asphalt


Refractive Index (mV)
Elusion time (mins)
Mixture 4-RAP asphalt

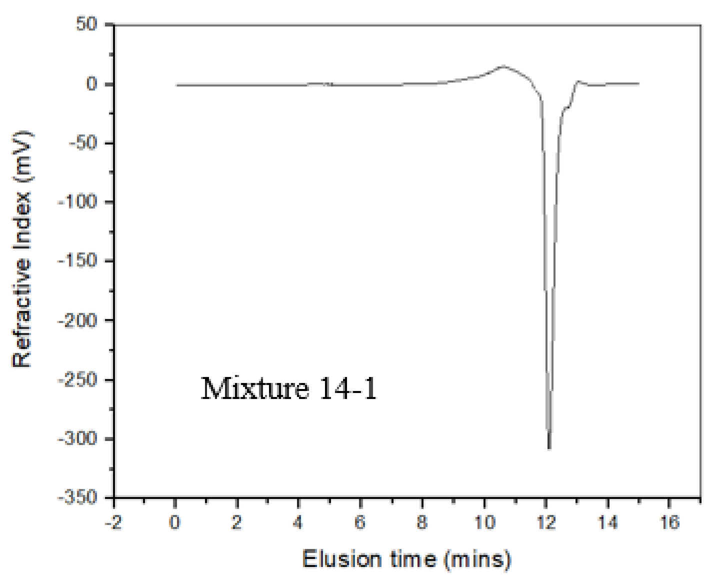

Refractive Index (mV)
Elusion time (mins)
Mixture 3-RAP asphalt



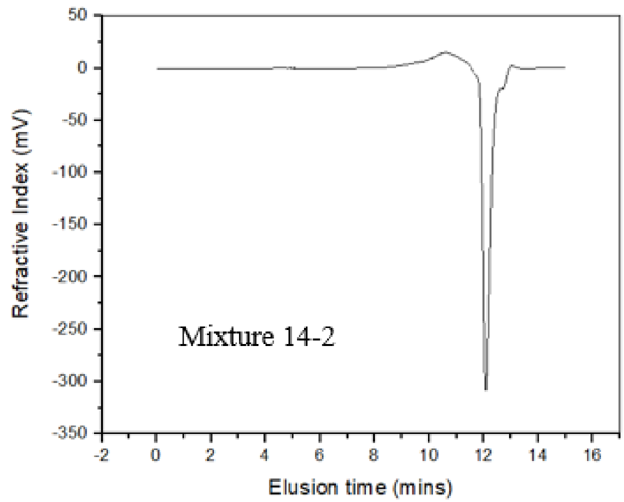
Mixture 2-RAP asphalt
Refractive Index (mV)
Elusion time (mins)

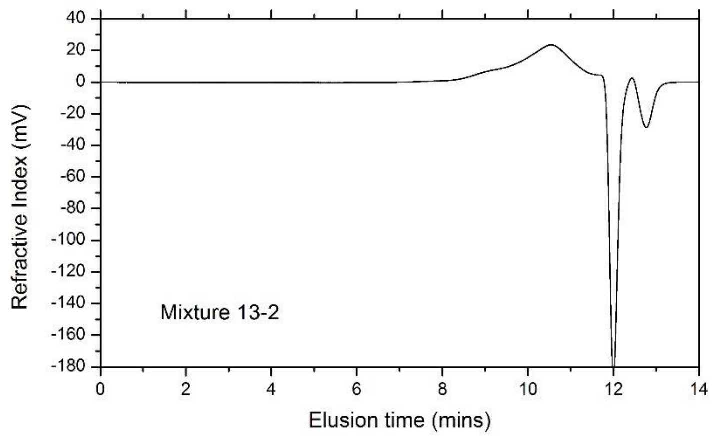


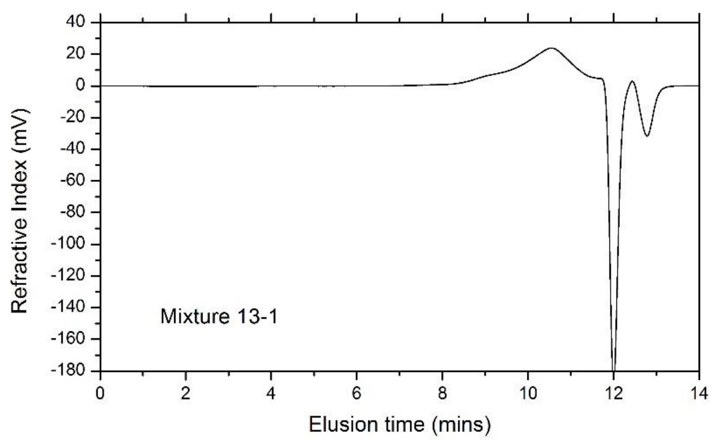
Mixture 1-RAP asphalt
Refractive Index (mV)
Elusion time (mins)

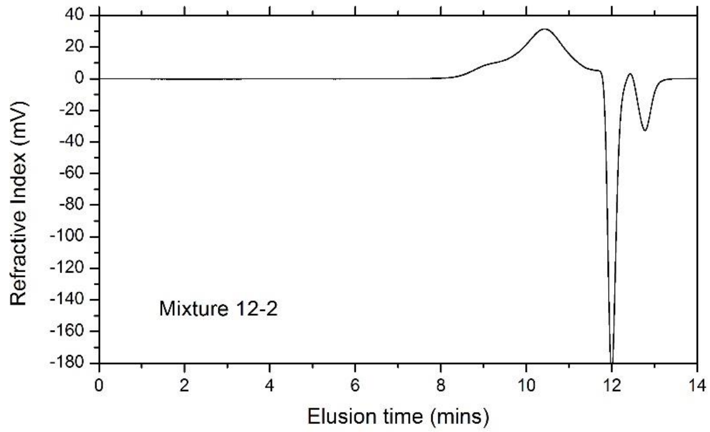


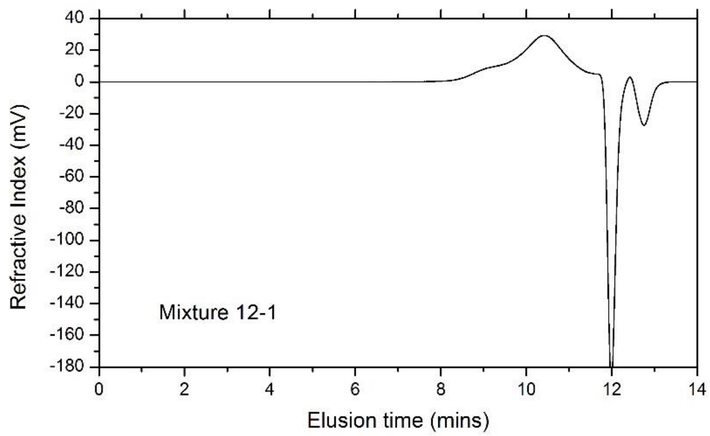
Mixture 14-1
Refractive Index (mV)
Elusion time (mins)

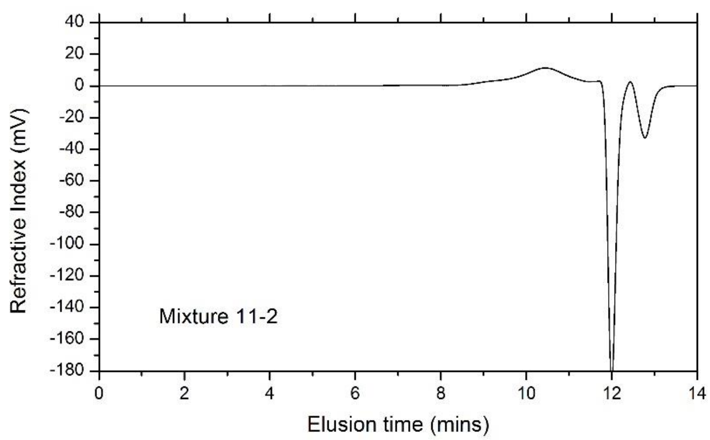

Mixture 14-2
Refractive Index (mV)
Elusion time (mins)
50
0
-50
-100
-150
-200
-250
-300
-350
-2
0
2
4
6
8
10
12
14
16

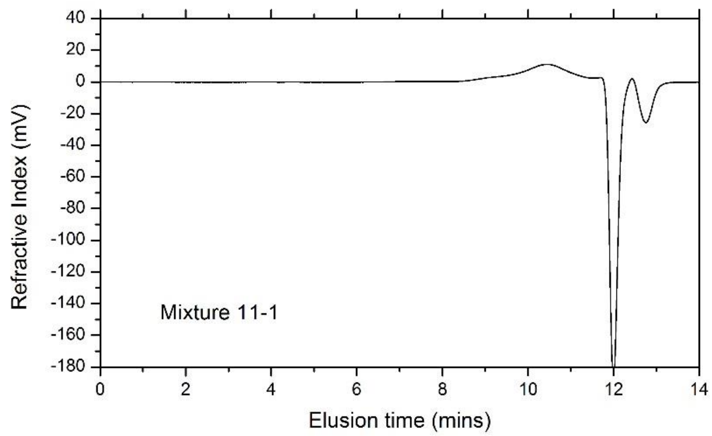

Mixture 13-2
Refractive Index (mV)
Elusion time (mins)
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
0
2
4
6
8
10
12
14

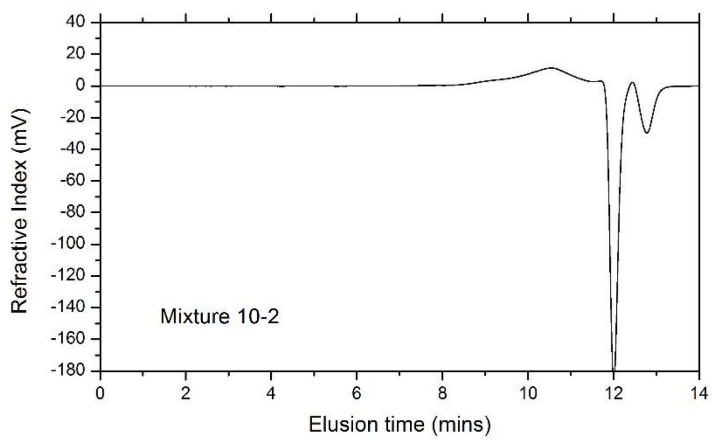

Mixture 13-1
Refractive Index (mV)
Elusion time (mins)
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
0
2
4
6
8
10
12
14

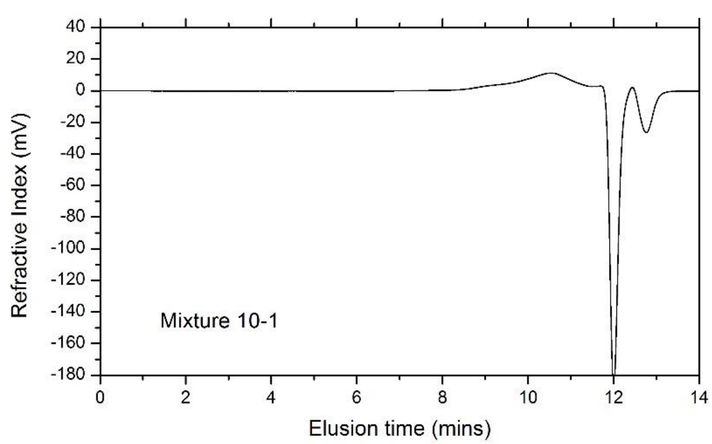

Mixture 12-2
Refractive Index (mV)
Elusion time (mins)

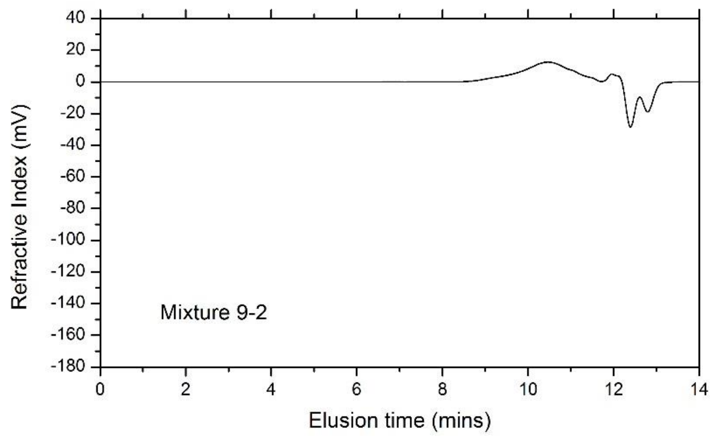

Mixture 12-1
Refractive Index (mV)
Elusion time (mins)

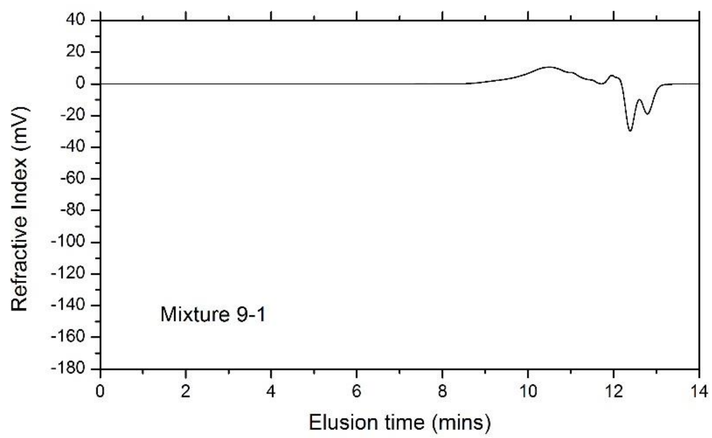

Mixture 11-2
Refractive Index (mV)
Elusion time (mins)

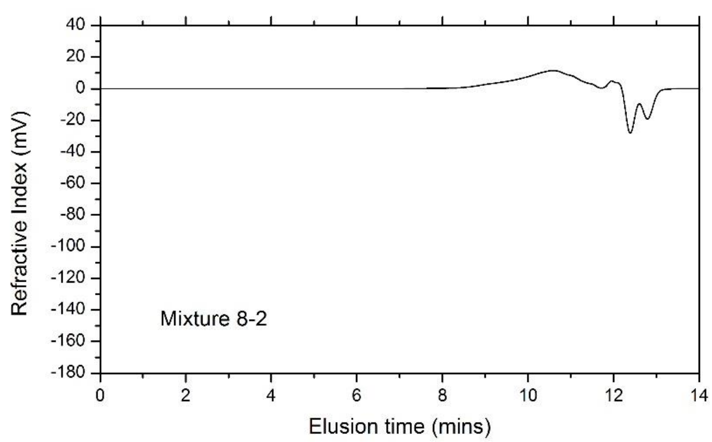

Refractive Index (mV)
Elusion time (mins)
Mixture 11-1
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
0
2
4
6
8
10
12
14

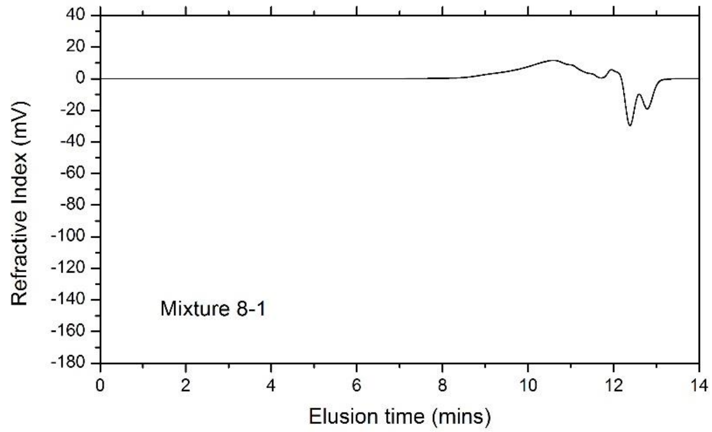

Refractive Index (mV)
Elusion time (mins)
Mixture 10-2
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
0
2
4
6
8
10
12
14

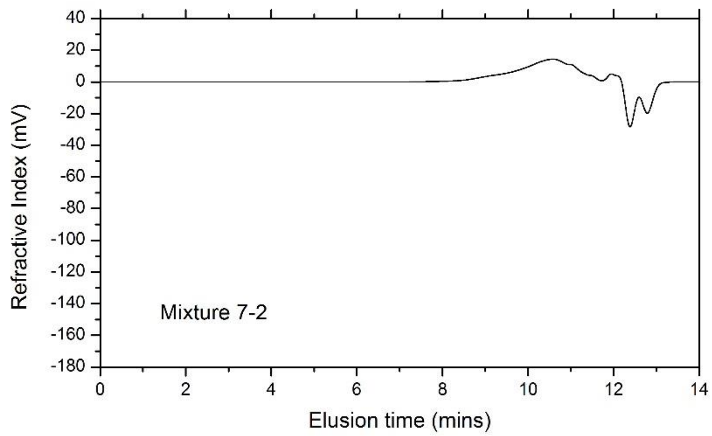

Refractive Index (mV)
Elusion time (mins)
Mixture 10-1
40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
0
2
4
6
8
10
12
14

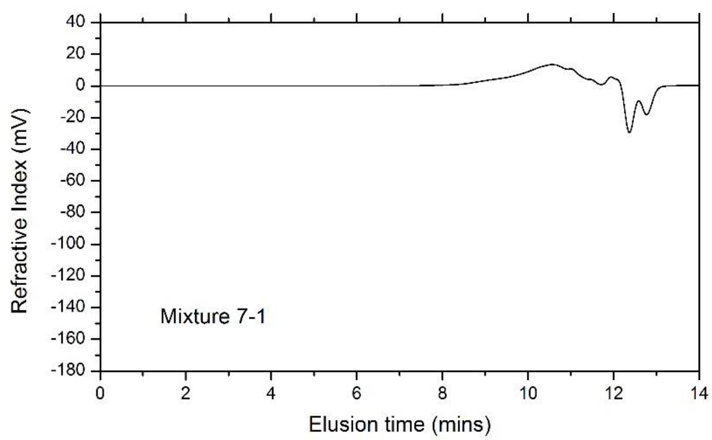

Refractive Index (mV)
Elusion time (mins)
Mixture 9-2

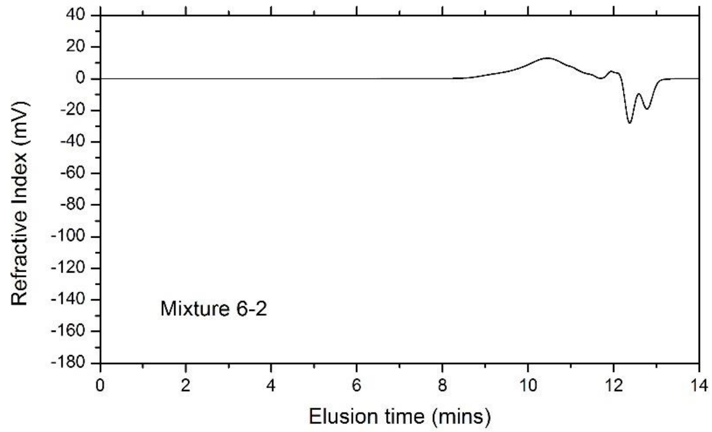

Refractive Index (mV)
Elusion time (mins)
Mixture 9-1

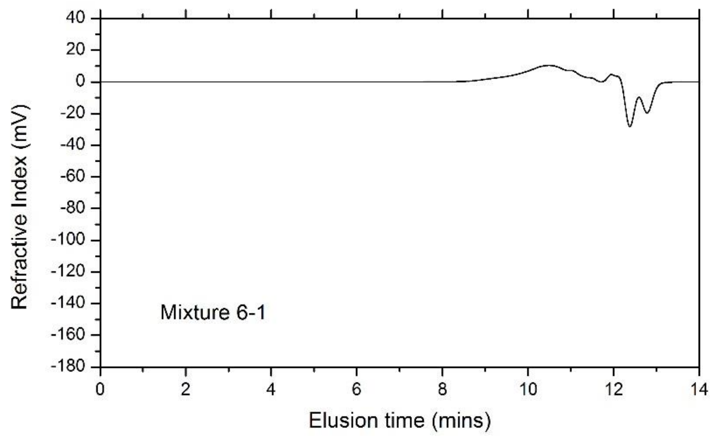

Refractive Index (mV)
Elusion time (mins)
Mixture 8-2

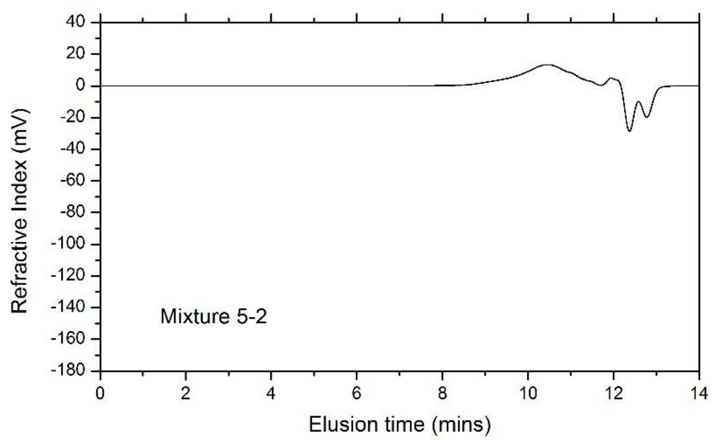

Refractive Index (mV)
Elusion time (mins)
Mixture 8-1

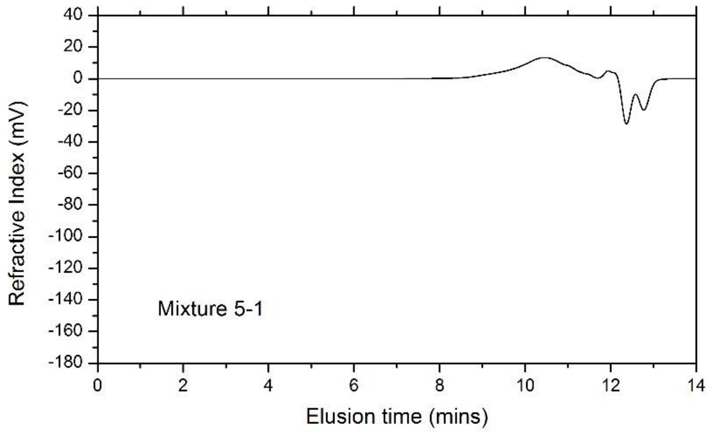

Refractive Index (mV)
Elusion time (mins)
Mixture 7-2

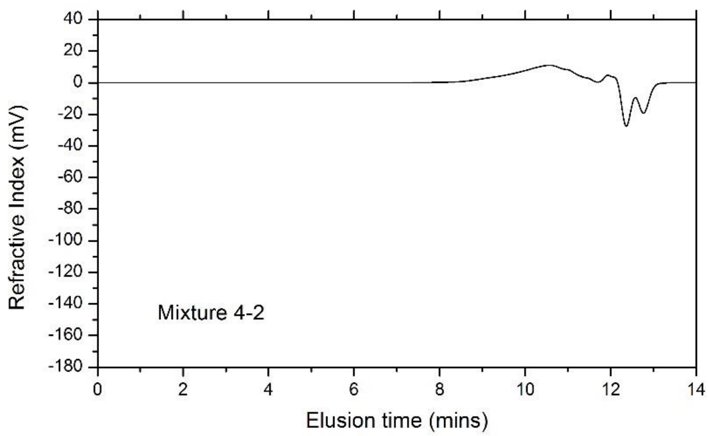

Refractive Index (mV)
Elusion time (mins)
Mixture 7-1

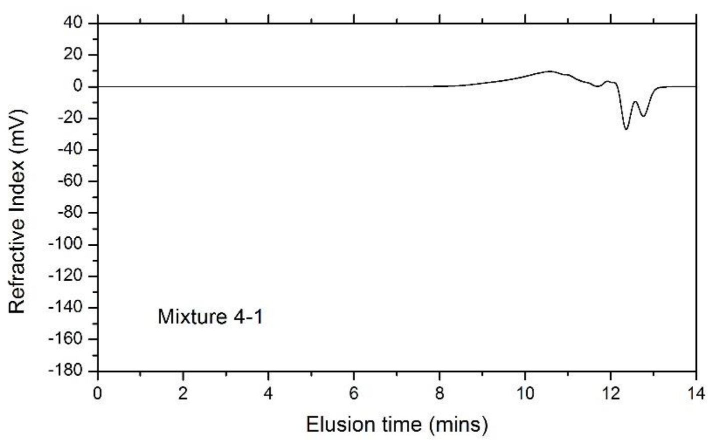

Refractive Index (mV)
Mixture 6-2
Elusion time (mins)

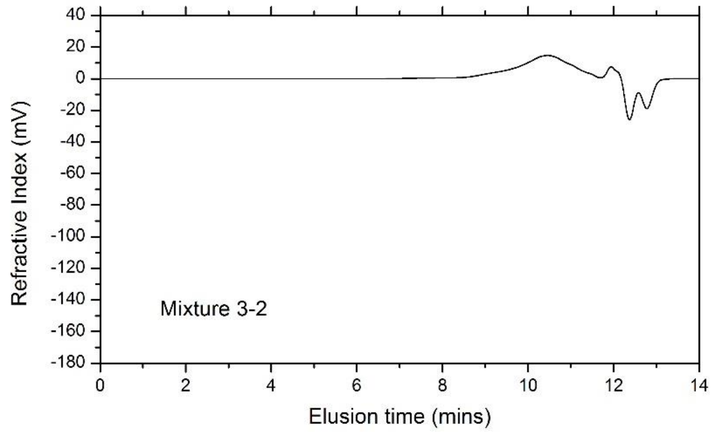

Refractive Index (mV)
Mixture 6-1
Elusion time (mins)

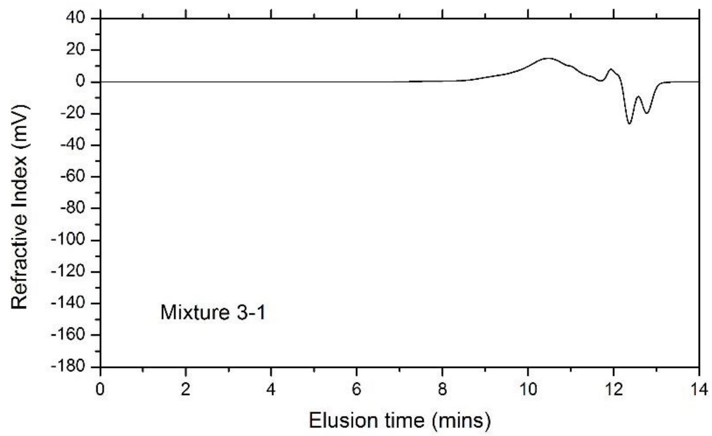

Refractive Index (mV)
Mixture 5-2
Elusion time (mins)

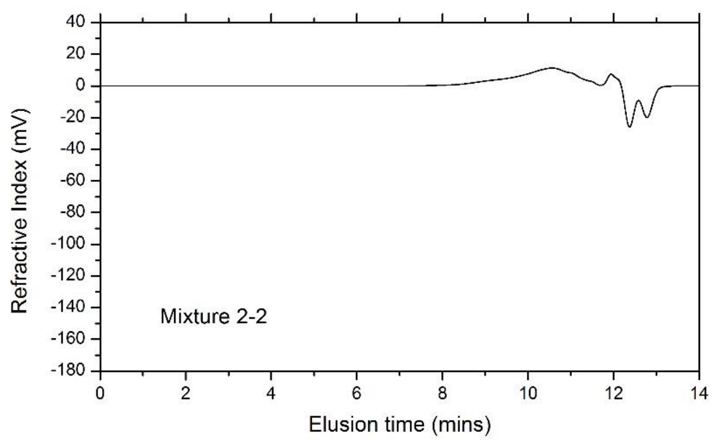

40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Refractive Index (mV)
Mixture 5-1
0
2
4
6
8
10
12
14
Elusion time (mins)

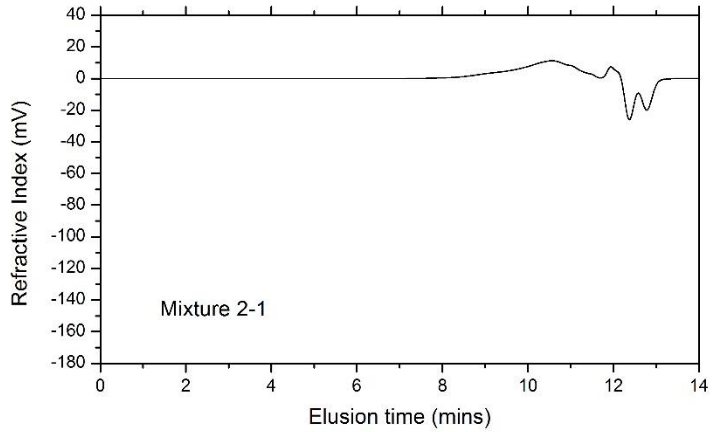

40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Refractive Index (mV)
Mixture 4-2
0
2
4
6
8
10
12
14
Elusion time (mins)

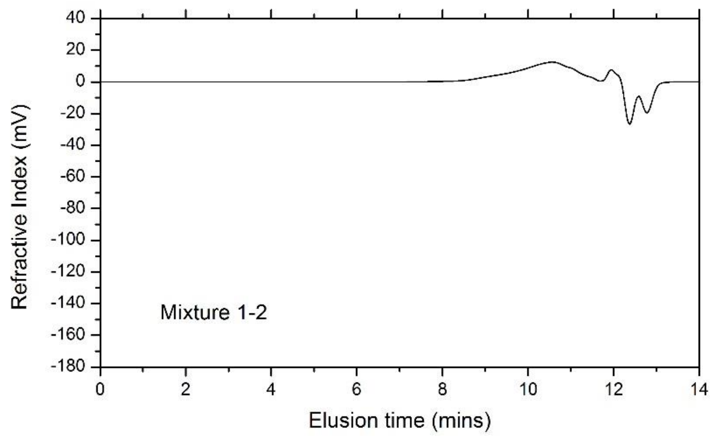

40
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
Refractive Index (mV)
Mixture 4-1
0
2
4
6
8
10
12
14
Elusion time (mins)

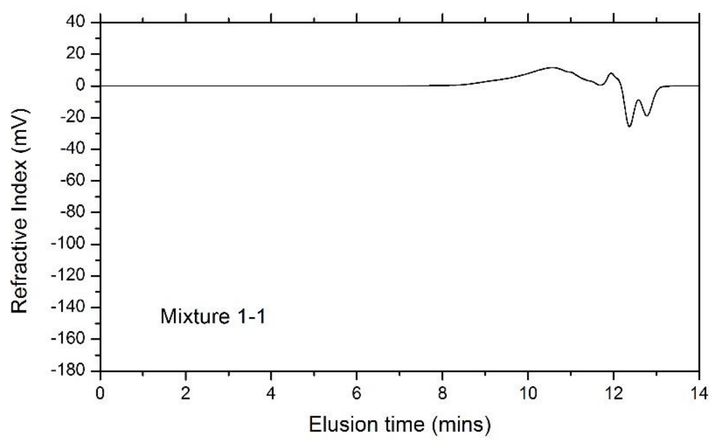

Refractive Index (mV)
Elusion time (mins)
Mixture 3-2


Refractive Index (mV)
Elusion time (mins)
Mixture 3-1

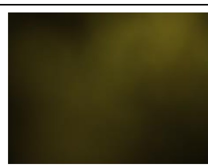
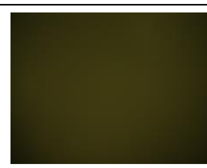
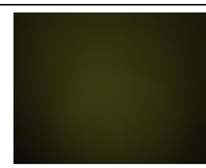
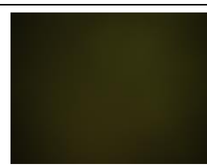
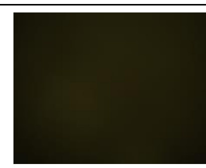

Refractive Index (mV)
Elusion time (mins)
Mixture 2-2

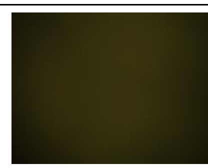
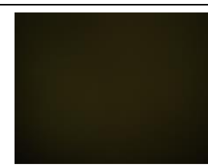

Mixture 2-1
Refractive Index (mV)
Elusion time (mins)


Mixture 1-2
Refractive Index (mV)
Elusion time (mins)


Mixture 1-1
Refractive Index (mV)
Elusion time (mins)

APPENDIX C: Fluorescent image of Test

Mixture	Virgin asphalt	RAP1	RAP2
1			
2			
3			
4			
5			
6			
7			
8			

9			
10			
11			
12			
13			
14