https://doi.org/10.1016/j.conbuildmat.2018.05.154

Evaluation of RAP Binder Mobilisation and Blending Efficiency in Bituminous Mixtures: An Approach Using ATR-FTIR and Artificial Aggregate

[1] Anand SREERAM, [1*] Zhen LENG, [1] Yuan ZHANG, [1] Rabindra Kumar PADHAN
[1] Department of Civil and Environmental Engineering
Hong Kong Polytechnic University, Hong Kong
*Corresponding Author. Tel: +852-27666007, Fax: +852-23346389
Email: zhen.leng@polyu.edu.hk

Abstract

The undetermined extent of reclaimed asphalt pavement (RAP) binder mobilisation is a major apprehension in the design and construction of bituminous mixtures with RAP. This study proposes a new method to quantify the degree of mobilisation of RAP binder and subsequent blending efficiency of RAP mixtures by utilising attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy as an assessment tool. Binders were recovered from laboratory bituminous mixtures with different percentages of RAP prepared under different mixing conditions using glass-based aggregates as tracers. Parameters for assessing the relevant properties were then developed and validated through the means of dynamic shear rheometer (DSR) and gel permeation chromatography (GPC) tests. Lastly, the study was extended to the use of various warm mix additives (WMA) in RAP mixtures. The results indicated that RAP binder mobilisation is highly dependent on temperature and the usage of WMA additives can enhance the mobilisation at lower mixing temperatures. It was also observed that certain chemical additives increased RAP binder mobilisation and blending efficiency to comparable levels of that in hot mix asphalt (HMA) mixtures.

Keywords: RAP, Blending Efficiency, ATR-FTIR, Warm Mix Additives

1. Introduction

The use of reclaimed asphalt pavement (RAP) in pavement mixtures has been widely encouraged around the word due to economic and environmental benefits [1]. Nevertheless, the field implementation of RAP is a challenge for practitioners as the nature of aged binder in RAP introduces several difficulties such as decreased workability of mixtures and increased stiffness of binders. It is now increasingly common that mixtures with RAP are used in combination with warm mix asphalt (WMA) technologies to better address these concerns and help reduce construction temperatures [2] [3]. However, one of the main limitations that still lingers in mix design is the limited understanding on the mobilisation of the aged RAP binder and the subsequent blending efficiency of the aged and new binders with or without WMA additives. Quantitative information of mobilised RAP binder is critically important, as the extent of the RAP binder that blends with the new binder can substantially alter the design criteria and overall mixture performance. The initial research on RAP mobilisation assumed that the RAP binder completely mixes with the virgin binder or rejuvenator to form a new mixture with intended properties [1]. Thereafter, the degree of this blending between the binders has been a matter of much deliberation and debate [4] [5]. Another effect considered earlier was the “black rock” effect which suggests the likelihood of a binary coat of aged and virgin binder when RAP is used [6]. Due to these uncertainties, many regulatory frameworks specify caution when defining targets for RAP mixing and blending [7]. Specifically, the extent of RAP binder mobilisation and blending of RAP mixtures have been studied by many researchers in the past using various rheological and chemical techniques [8] [9] [10] [11]. Some rheological approaches involved using models, such as the Hirsch model to predict the effective dynamic modulus (E*) of blended binders using the master curves of plant produced mixtures [12] [13]. Regarding the chemical methods, gel permeation chromatography (GPC) and Fourier transform infra-red (FTIR) spectroscopy have been the main tools used to assess the extent of blending and RAP mobilisation. Several studies have been conducted using GPC which has consistently showed a near linear relationship between the percentage of LMS (large molecular size) and percentage of RAP mobilised [9]. FTIR on the other hand, has been used to a lesser extent but also proven to be effective in determining the blending efficiency of recycled asphalt mixtures [14]. Most of these studies have indicated that full mobilisation and blending of RAP binder is unlikely, although it occurs to a substantial level. For RAP mixtures with WMA additives, it is unclear whether RAP and virgin binders blend completely during WMA production. On one hand, the level of blending and mobilisation occurring during production might be lower due to the reduced production temperature. But on the other hand, the increase in workability brought about by using WMA additives might increase binder mobilisation during mixing, as reported by some previous studies [14] [15]. One of these studies, which specifically looked at the effect of WMA using GPC as an analysis tool, showed that WMA additives yielded higher blending ratios as compared to the virgin mixes [15]. But in many of these previous studies, characterizing the extracted binder required the separation of RAP and virgin aggregate. Hence, a gap gradation or certain aggregate type was usually used. This represented the best-case scenario as the gradation of the mixtures might also impact RAP mobilisation. Most significantly, there is no tangible consensus regarding RAP mobilisation and exists an imperative need to validate prior results using various methods under different laboratory conditions. To address this need, this study aims to investigate the effect of temperature and WMA usage on RAP mobilisation and blending efficiency by using attenuated total reflectance FTIR (ATR-FTIR) and artificial aggregates as suitable methods of evaluation.

2. Experimental Mix Design and Materials

The Marshall mix design was used to prepare the mixtures in this study. The virgin binder used was of penetration grade 60/70 (PEN 60/70) which is a common type of bitumen used locally.

The specific gradation of the mixture is presented in Table 1. The coarse aggregates (greater than 5mm) and fine aggregates (smaller than 5mm) were local granite rocks. The RAP was obtained locally from wearing course milling. The RAP binder was extracted as per AASHTO T164 and analysed through Saturate, Aromatic, Resin and Asphaltene (SARA) fractionation as represented in Table 2. The SARA fractionation was conducted as per ASTM D2007. The softening point and penetration tests were conducted as per ASTM D5 and ASTM D36, and the obtained values are presented in Table 3. A mechanical mixer was used to mix all the samples for a period of 2 min to reduce variability and discrepancies between samples with regards to preparation [16]. As RAP contains aged binder, the mixtures prepared in this study were designed with consideration of the total contribution of the recycled binder. The binder content of the RAP was determined as per AASHTO T308 and found to be to 5%. For all the mixtures with 0%, 15%, 30% and 50% RAP materials, a total binder content of 5% was chosen.

Four different types of commercially available WMA additives were chosen in this study including wax based, foaming and chemical additives. The details of the additives used are presented in Table 4 and Figure 1.

Table 1. Mixture Composition

	Mixture Gradation	RAP gradation
Sieve Size (mm)	Pass ratio (%)	
14	100	100
10	85.0	94.1
5	58.0	87.8
2.36	38.0	70.0
1.18	26.0	50.2
0.6	17.9	32.7
0.3	11.0	19.2
0.15	3.4	9.7

0.075	3.0	3.4

Table 2. SARA Fraction of RAP

RAP	Composition%
Asphaltene	15.80
Saturate	24.23
Aromatics	19.53
Resin	40.45

Table 3. Softening Point and Penetration of RAP

Softening Point (^oC)	Penetration (0.1mm)
75.5	29

Table 4. Warm Mix Additives Used

Additive Type	Name	Dosage	Legend
Wax Based	Sasobit	1.5% by weight of binder	Saso
Foaming	Asphamin	0.3% by mixture weight	Aspha
Chemical	Evotherm DAT	5% by weight of Binder	DAT
	Evotherm 3G	0.5% by weight of Binder	3G

a) Saso b) Aspha c) DAT d) 3G

Figure 1. Pictures of the warm mix additives

As the primary objective of this study is to examine the amount of RAP binder mobilisation, the blend of mobilised RAP binder and virgin binder coating the fresh aggregates is of specific interest. In a real blending scenario, it is visually impossible to distinguish between RAP aggregate and virgin aggregates after mixing. Thus, in this study artificial aggregates in the form of borosilicate glass beads were employed. Beads of diameter 12 mm, 10 mm and 7.5 mm were used to make up approximately a 2% fraction of the overall gradation of the mixes by weight by adjusting the original fresh aggregates. Such a small fraction was chosen so that the effect of the glass beads in the mixing process and aggregate interaction would be negligible. The chemical composition and the proportion of glass beads used are shown in Table 5 and Table 6, respectively. Figure 2 shows illustrative images of the glass beads and glass beads dry blended with RAP. Prior studies have successfully used similar types of glass beads to characterise the mobilisation of RAP binder to virgin aggregates [17]. The consistent dimensions of glass beads make them useful for such studies. However, it does have the drawback of its relatively smooth surface as compared to the naturally rough surface of normal aggregates. To minimise this, the glass beads were initially blended with fresh aggregates to roughen the surface.

Table 5. Chemical Composition of Glass Beads

Chemical Composition	SiO_2-82% B_2O_3-12.4% Na_2O-3% Sb_2O_3/As_2O_3 - <0.01%
Density	2230 Kg/m^3
Melting Point	1500°C

Table 6. Weight of Glass beads Used in Each Mixture

Glass Bead Types (*Number)	Weight (in gms)
12mm (*2)	7.17
10mm (*4)	8.88
7.5mm (*6)	7.08
Sum	23.13

a) Original glass beads

b) Glass beads after dry blending with RAP.

Figure 2. Pictures of the glass beads used

3. ATR-FTIR to Evaluate RAP Mobilisation and Blending

Previously, chemical methods such as GPC and FTIR have been used to characterise oxidative ageing and its significance on the chemical composition of bituminous binders. FTIR is particularly interesting for researchers and engineers because of its accuracy and the fact that it does not require a large or controlled lab space in comparison to GPC. There is a prospect that with advancing FTIR research, parameters for mix design and optimisation could be derived from the FTIR results of bituminous binders. FTIR using attenuated total reflectance (ATR) is generally the most preferred method of characterisation as if offers faster sampling with limited preparation and also excellent sample-to-sample reproducibility. In ATR, evanescent light located in the region of contact between the sample specimen and a crystal of high refractive index is attenuated as a result of molecular vibrations. The study of the natural oxidative ageing exposed by bituminous binders has been the prime focus of attention for asphalt researchers using FTIR. The variations in this level of oxidation has been used to correlate changes in rheological and chemical property of mixes in the past [8] [14]. For the analysis of the obtained FTIR spectra of bituminous binders, many different approaches can be used. The spectra can be examined in its original form or be normalised prior to analysis. Unique values from absorbance bands may be used or a variety of wavenumbers could be considered by integrating the area underneath an absorbance spectrum in between a defined wave number. Lastly, the foundation for finding the area can be either using a tangential or an absolute baseline. One recent study used a statistical approach to study the repeatability and sensitivity of various FTIR analysis methods [18]. From the conclusions, it was advocated to work with a normalised spectra, utilise an absolute baseline and integration of areas in favour of other approaches as it offers the most consistent results with regard to sample repeatability and sensitivity. As it is the most comprehensive work in recent times regarding FTIR analysis of asphalt binders, this study also employs the use of those recommendations as the basis of its analysis approach.

In asphalt binder chemistry, the carbonyl band (C=O) exhibited at around 1700 cm^{-1} and the sulphoxide band (S=O) exhibited around 1000 cm^{-1} of a bitumen spectrum are the major functional groups used to gage the level of oxidation. However, the carbonyl band has been more commonly used and known to better correlate the level of long term ageing [8]. Binders extracted from RAP materials exhibit significantly higher levels of C=O bonds due to the natural oxidation of asphalt binder during the producing process and service period on pavement whereas virgin binders exhibit little or no C=O bond at this wavelength. This difference in oxidation can be utilised to approximate the amount of RAP mobilisation and blending in mixtures [14]. Figure 3 shows the FTIR spectrum of the RAP binder and the virgin binder, which shows the clear oxidation peak at the wavelength of around 1700 cm^{-1} for the RAP binder. Also indicated in Figure 3 is the analysis area of the FTIR spectra.

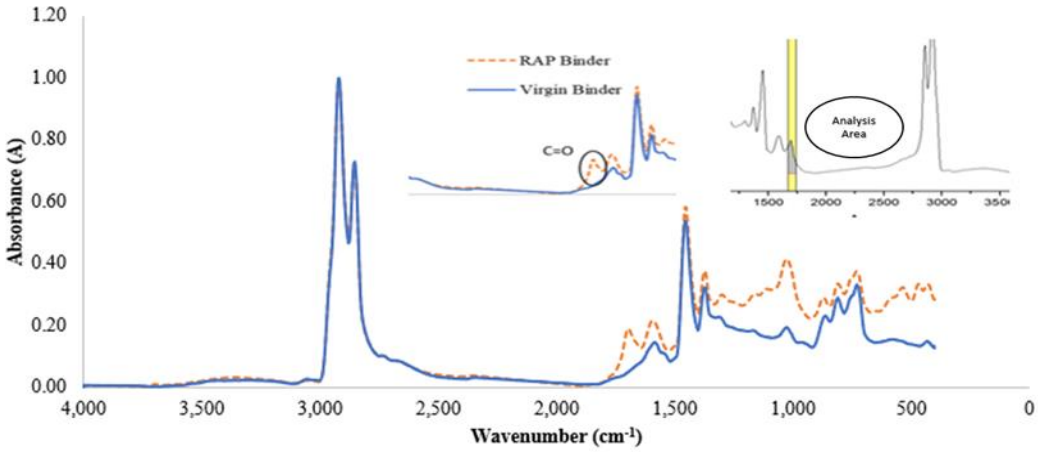

Figure 3. FTIR spectra of the virgin binder and RAP binder

The analysis approach of the various FTIR spectra involved the integration of areas, normalised spectra and absolute baseline. Hence, the parameter for one spectrum can be defined as

$$IA=\int_{w_{l,oa}}^{w_{u,oa}} VA_{norm}(w)\, dw \qquad (1)$$

where IA is the normalised integrated area using an absolute baseline at an absorbance value of 0; $w_{u,oa}$ is the upper wavenumber limit for the structural group; $w_{l,oa}$ is the lower wavenumber limit for the structural group and $VA_{norm}(w)$ is the normalised absorbance at wavenumber w. The lower and upper wave numbers for the carbonyl structural group was defined from 1666 to 1746 cm^{-1} [18].

Using Equation (1) as the basis, the parameters for characterising RAP mobilisation and blending efficiency were established. The binder recovered from the glass beads is expected to have a considerable amount of RAP binder mobilised as a result of the mixing process. In this study, a concept that the RAP binder is considered at 100% RAP character whereas virgin binder has 0% of RAP character was used. Based on this, a parameter to estimate the percentage of RAP binder in the recovered binders was developed. This parameter is used to represent the RAP mobilisation and can be described as follows:

$$\text{Percentage of RAP Binder Recovered (\%)} = \frac{IA_{BS}-IA_{VB}}{IA_{RAP}-IA_{VB}}*100 \qquad (2)$$

where,

IA_{BS} is the IA of the recovered binder from the respective sample;

IA_{VB} is the IA of the virgin binder;

IA_{RAP} is the IA of the RAP binder.

The term "blending efficiency" has been defined differently in many studies, and it has been previously used to describe various types of RAP binder mobilisation through the development of special parameters [14] [15] [19]. In this study, the idea of using artificially blended RAP binder and virgin binder to create an efficiency baseline was used. For example, when RAP binder and virgin binder are artificially mixed in the laboratory and then used to prepare asphalt mixtures, it is reasonable to conclude that the asphalt mixture with such kind of blended binder has full blending efficiency, whereas the asphalt mixture prepared with RAP, fresh aggregates and binder can be considered to have a blending efficiency of less than 100%. The FTIR index i.e. the IA produced from the binders with full blending efficiency can be employed to create the baseline for calculating the blending efficiency of the binders in the asphalt mixtures with RAP materials assuming homogeneity of mixing [20].

$$\text{Average Blending Efficiency (\%)} = \frac{IA_{BS}-IA_{VB}}{IA_{AB-i}-IA_{VB}}*100 \qquad (3)$$

where

IA_{AB-i} is the IA of the artificially blended binders; and i is the percentage of RAP binder.

4. Experimental Procedure and Methods

The results of the proposed parameters from the FTIR tests were validated through rheological and chemical evaluation using Dynamic Shear Rheometer (DSR) and GPC tests, respectively.

Control mixtures with 15%, 30% and 50% RAP percentages were prepared at the temperatures of 135°C and 165°C as illustrated in Table 7. In addition, mixtures with the same proportion of RAP were prepared using the warm mix additives at the temperature of 135°C. Regarding the mixing process, the glass beads were heated with the virgin aggregates at approximately 10°C higher than the sample mixing temperature before adding the pre-heated RAP [15]. The WMA was first added to the virgin binder before subsequent mixing with aggregates [21]. Three replicates for each type of samples were prepared. Lastly, artificially blended binders with 15%, 30% and 50% RAP binder to virgin binder content referred to as AB-15, AB-30 and AB-50 in this study were also prepared. After mixing, the glass beads were collected as shown in Figure 4 and the binder was recovered using Trichloroethylene (TCE) solvent [14]. Minimal temperature was used in the extraction process to negate any additional aging effects. The recovered binders were characterized through ATR-FTIR analysis using a Bruker Vertex 70 Hyperion 1000 spectrometer with a diamond ATR module. A resolution of 4 cm^{-1} was used to record the spectra from 4000 to 400 cm^{-1} in a reflective mode. 3 samples were analysed for each mixture. Following each test, the optics were thoroughly cleaned using solvent and acetone. The DSR tests were conducted using an Anton Paar DSR machine at the frequency range of 0 to 30 Hz at 30°C. The GPC studies of the recovered binder samples were tested using a Shimadzu Prominence GPC system using two styragel columns. Tetrahydrofuran (THF) was used to dissolve the binders to the required concentration and subsequently filtered through a 0.2 µm filter for testing. Subsequently, the large molecular size (LMS) percentages were calculated for the recovered binder as follows [22] [23]:

$$\text{LMS\%} = \frac{\text{Area of first } \frac{5}{13}\, of\ chromatogram}{\text{Toal Area below the chromatogram}} * 100 \qquad (4)$$

Table 7. Control Samples Prepared

Temperature	RAP Content	Legend

135^{o}C	15% RAP	15% RAP-135
	30% RAP	30% RAP-135
	50% RAP	50% RAP-135
165^{o}C	15% RAP	15% RAP-165
	30% RAP	30% RAP-165
	50% RAP	50% RAP-165

Figure 4. Glass beads recovered after mixing

5. Results and Discussion

5.1 Temperature Effect on RAP Mobilisation and Blending Efficiency

Initially, the recovered binders from the control samples were analysed using Eq (2) as represented in Figure 5. It was observed that at all percentages of RAP added, there was significantly more RAP mobilised at higher temperature than at lower temperature. The results obtained are in accordance with other reported studies in which it was ascertained that in a mixing process, the RAP mobilisation is highly conditional on temperature [15] [22]. The increase in mobilisation with temperature was more obvious at higher RAP content as compared to lower RAP content. It is likely that the additional availability of RAP aggregates will promote added interaction and mobilisation of RAP binder with the increase in temperature during the mixing process.

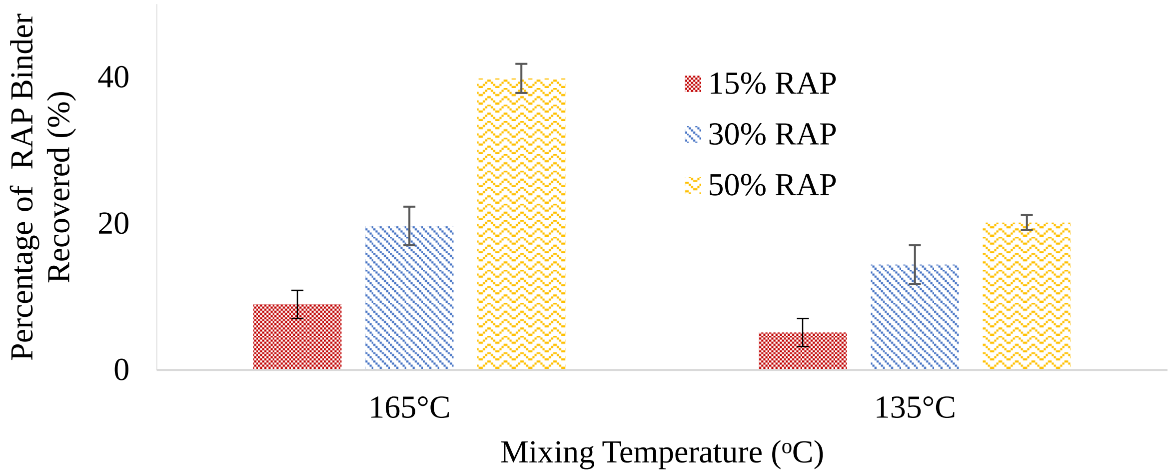

Figure 5. Percentage of RAP binder recovered for control samples

The blending efficiency was calculated using Eq (3) and represented in Figure 6. It was observed that the samples mixed at the temperatures of 165°C showed higher efficiency of blending as compared to the samples mixed at 135°C. The samples with 50% RAP showed the highest average efficiency of blending as compared to the samples with 15% and 30% RAP contents. Approximately, the blending efficiencies ranged from 50% to 60% for the samples prepared at 165°C and from 30% to 40% for the samples prepared at 135°C. Among the samples with different percentages of RAP, those with 50% RAP showed the highest difference in blending efficiency with the change in mixing temperature. A previous study reported that the highest RAP mobilisation rates and subsequent blending efficiencies were obtained at lower RAP content as opposed to higher content [19]. In this study, however, the blending efficiency was seen to be in a similar range for all RAP mixtures and mainly dependant on the temperature of mixing. This could be mainly attributed to the level of ageing and chemical nature of the RAP material. However, the exact influence of these factors is still unknown and should be assessed in future studies.

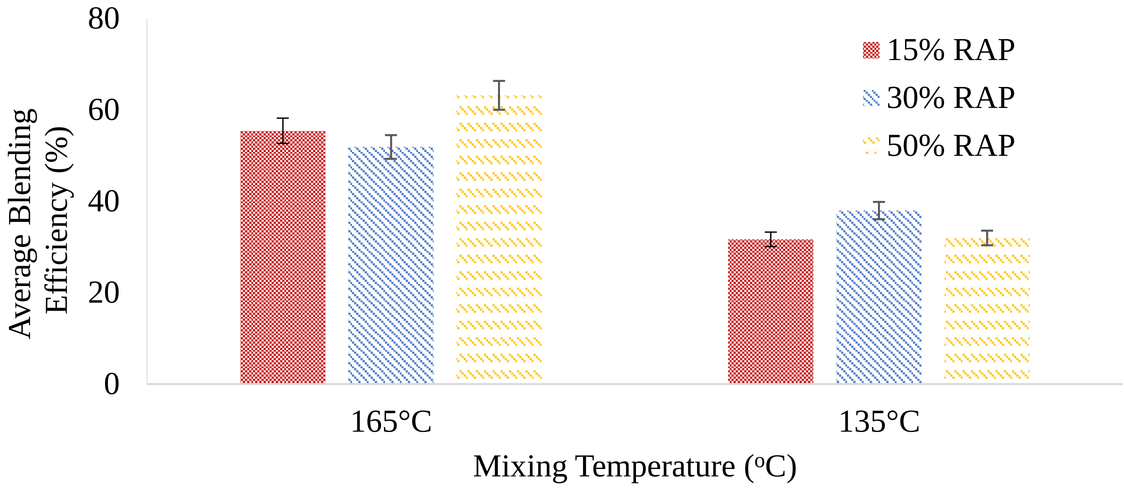

Figure 6. Blending efficiency of the control samples

5.2 Validation of the Proposed Parameters

To validate the results attained from the proposed ATR-FTIR method, the rheological and chemical properties of the recovered binders were tested [22]. The binders recovered from the warm mixtures were not used in the validation part of the study as the additives might influence the rheological and chemical properties of the binder [24]. Frequency sweep tests were firstly conducted to evaluate rheological properties of the binders using DSR. The rationale for using such tests is that if higher temperature can mobilise more RAP binder, then the resultant extracted mixture of RAP and virgin binder should be considerably more harder and exhibit higher complex shear modulus (G*) especially at lower frequency ranges [22]. Figure 7 shows the G* values exhibited by RAP binder in comparison to the virgin binder and the artificially blended binders at 15%, 30% and 50% RAP binder contents. It was observed that even 15% RAP binder could have one log increment for the value of G*. When the amount of RAP binder was increased to 30% and 50%, their G* values did not change to a comparable extent. It is worth noticing that this result was acquired from the artificially blended binders. Hence, when considering the lesser blending efficiencies of asphalt mixtures with RAP, the expected differences in G* between the extracted binders are less. Figures 8, 9 and 10 show the frequency sweep tests of the various binder samples prepared at different temperatures and in comparison, to the artificially blended binder of the equivalent RAP proportion. It was observed that for all tests, the samples prepared at higher mixing temperature indubitably showed higher G* values which indicates that those respective binders contain significantly more RAP binder as compared to the samples prepared at lower temperature. However, the artificially blended binders showed even higher G* values which demonstrates that a normal mixing process cannot obtain the same level of RAP binder mobilisation as artificial mixing. Although these tests cannot quantitatively confirm the results of the FTIR tests, they verified that the approach using the proposed method is representative of the actual mixing that occurs.

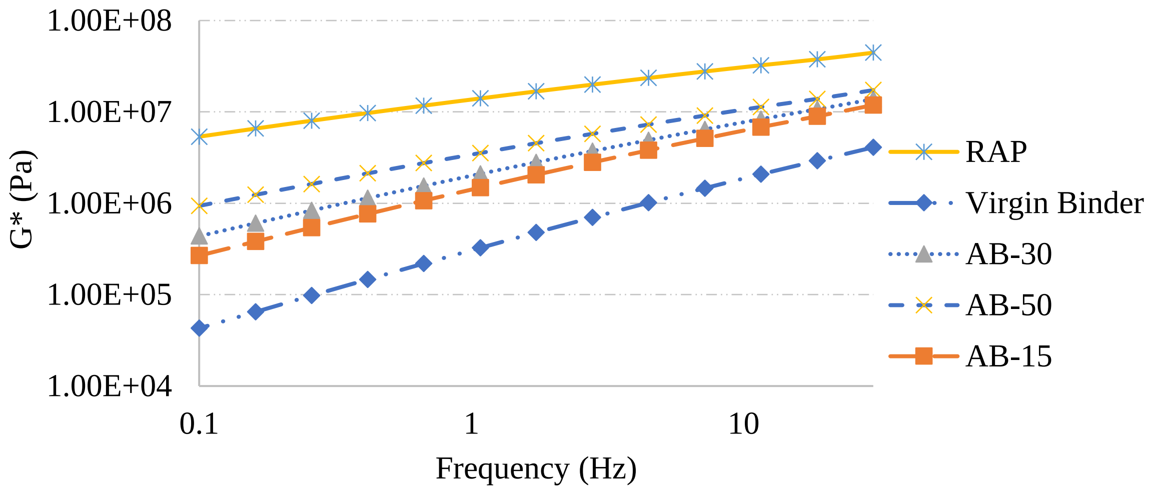

Figure 7. Frequency sweep test at 30°C

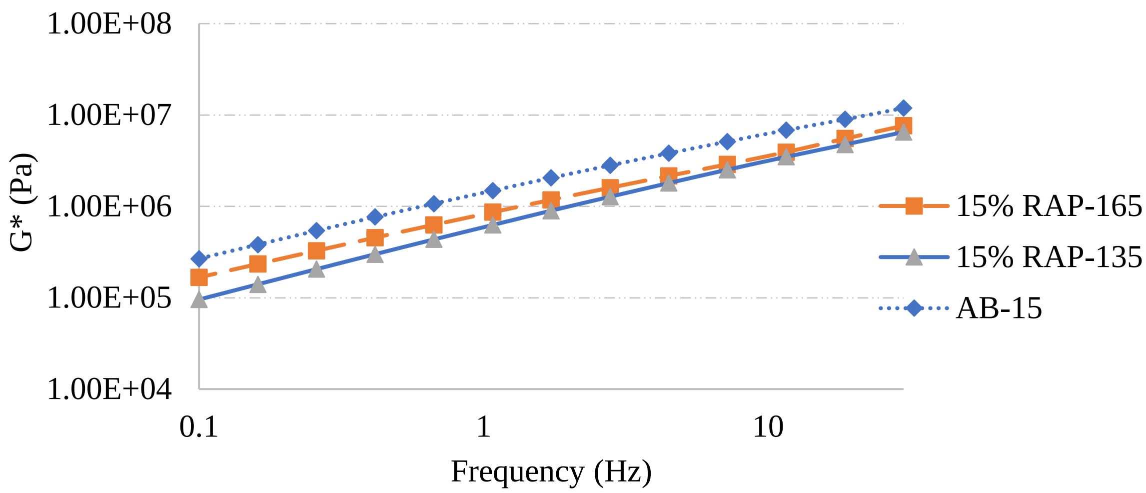

Figure 8. Frequency sweep test at 30^{o}C at 15% RAP content

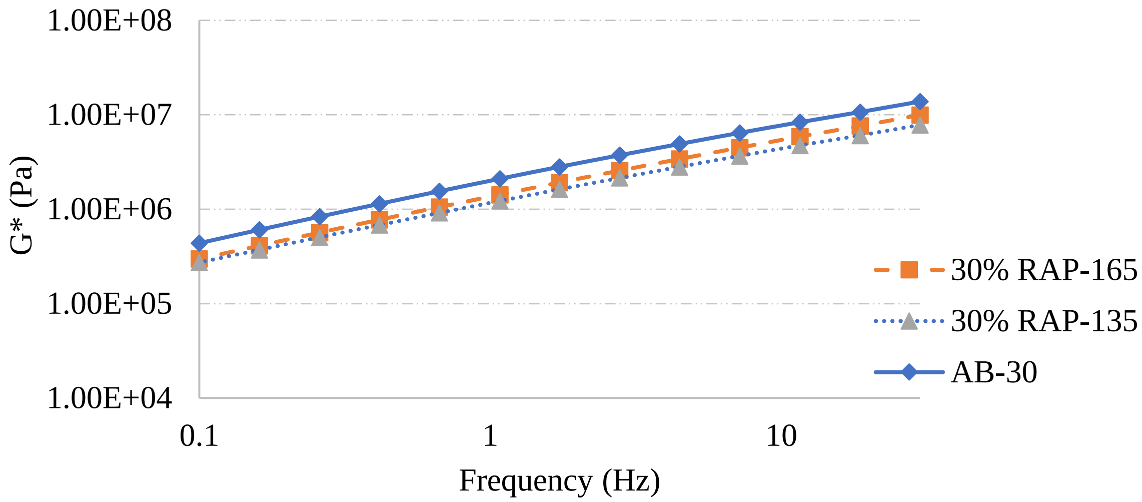

Figure 9. Frequency sweep test at 30^{o}C at 30% RAP content

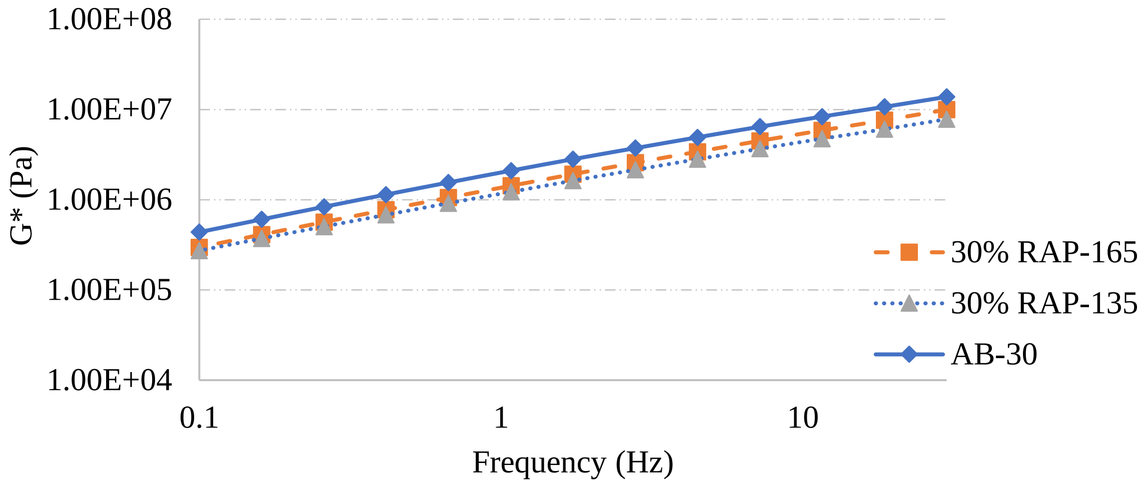

Figure 10. Frequency sweep test at 30°C at 50% RAP content

GPC, widely referred to as size exclusion chromatography, is regarded as the most convenient technique to separate molecules into various sizes and characterise the complete weight distribution of polymeric materials. GPC analysis has been extensively utilised in asphalt research in the past and found to be suitable to correlate ageing behaviour of binders. The LMS percentages obtained from the tests have been successfully correlated with the extent of oxidation and ageing by various studies in the past [22] [23]. The chromatogram of the virgin binder and RAP binder is presented in Figure 11 and the results obtained using Eq (4) for the LMS percentages of the various binders are presented in Figure 12. The LMS percentage attained from the RAP binder was 12.5%, which is significantly higher than the value of 5.9% for the virgin binder. For the artificially blended binder with 50% RAP binder, the LMS percentage was 10.9% which is higher than the LMS percentage of 50% RAP-165 sample (10.4%), while the LMS percentage of 50% RAP-135 sample was only 9.8%. The same tendency was found in the LMS percentages of the binders with RAP contents of 15% and 30%. The samples prepared at a higher temperature of 165°C in general showed a higher percentage of LMS, which indicates that more RAP binder has been mobilised in those mixtures as compared to the samples prepared at 135°C. But even those samples do not reach the LMS percentage exhibited by the artificially blended samples which suggests that the mixtures prepared cannot reach full efficiency. Future studies may be conducted to quantify the results attained from the DSR and GPC in comparison to the FTIR using other reported methods.

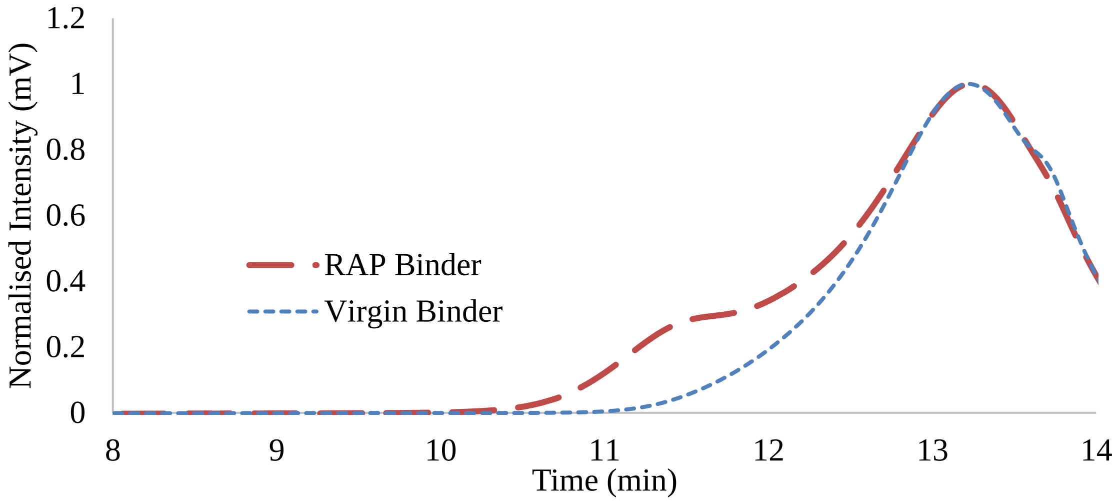

Figure 11. Illustrative chromatogram of the RAP binder and virgin binder

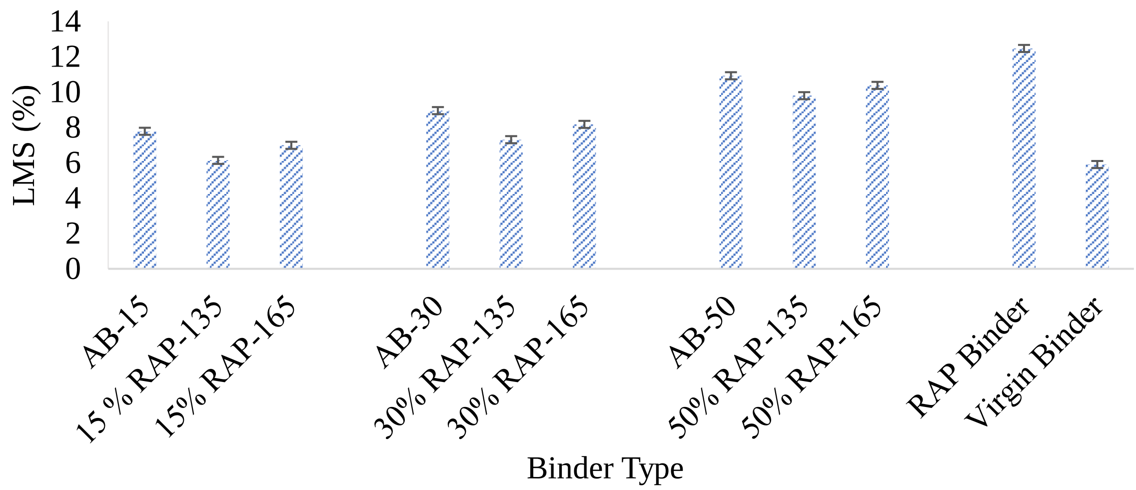

Figure 12. LMS (%) obtained from GPC testing

5.3 Effects of WMA

Through the DSR and GPC tests, it was validated that the proposed method is representative for studying the extent of RAP mobilisation and blending efficiency in mixtures. Therefore, the study was extended to investigate the influence of WMA on RAP binder mobilisation. Four different types of commonly used additives were chosen including wax-based, foaming and chemical additives. Warm mix additives are generally expected to reduce the viscosity and improve flow characteristics of the asphalt binders at lower temperatures, most early WMA literature revolved this idea and the subsequently reduced production temperature as a result [25]. Before testing for the blending parameters, the viscosities of various binders were measured as per ASTM D4402 using a Brookfield viscometer at the warm mixing temperature of 135^{o}C and at a higher temperature of 165^{o}C as presented in Figure 13. It was observed that at 135^{o}C, the warm binders have considerably lower viscosities than the virgin binder. But at 165^{o}C, this difference is less significant. Therefore, the warm binders offer better workability at lower temperatures but as the mixing temperature increases, this effect is less obvious specifically with regard to the virgin binder used in this study. The foaming additive Asphamin was not used in the viscosity study, because its working nature makes it unsuitable for this test.

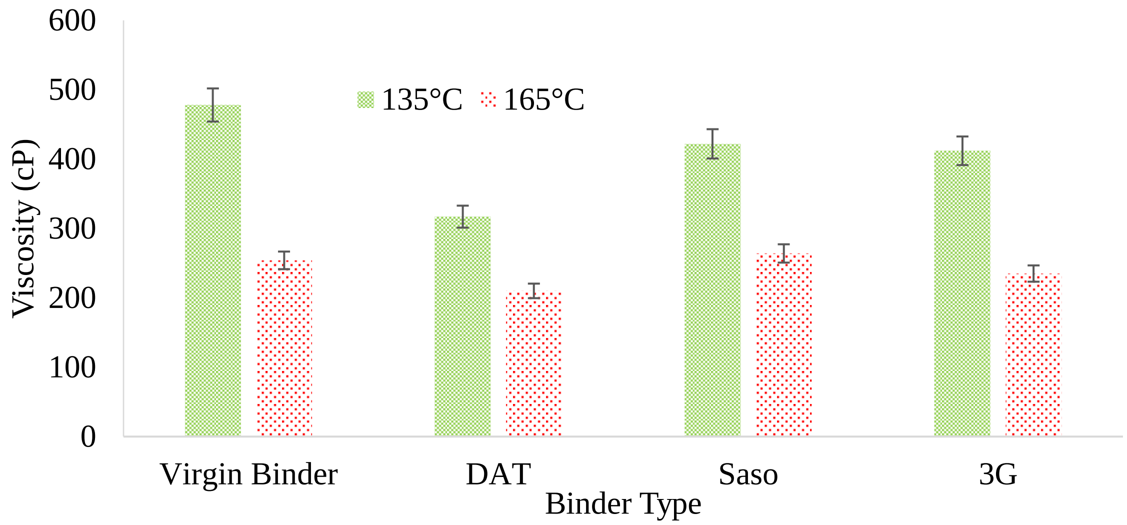

Figure 13. Viscosities of the warm binders

The recovered binders were tested according to the parameters developed to assess the percentage of RAP binder recovered and its blending efficiency. As illustrated in Figure 14, all recovered warm binders exhibited higher percentage of RAP binder than the control sample prepared at 135^{o}C. Among different warm mix additives, the chemical additive DAT showed the highest capability to mobilise RAP binder. At 30% RAP content, Asphamin additive also showed higher mobilisation capability than the control sample prepared at 165°C. Asphamin is a synthetic zeolite based foaming additive which temporarily causes the binder to be smoother and more workable [24] [26]. This effect could have instigated the increased mobilisation of RAP binder. Prior studies have also reported similar effects of foaming-based additives on RAP binder mobilisation and blending [15]. As the warm mix additives were seen to have lower viscosities at the mixing temperature, the influence of viscosity on binder mobilisation is also likely.

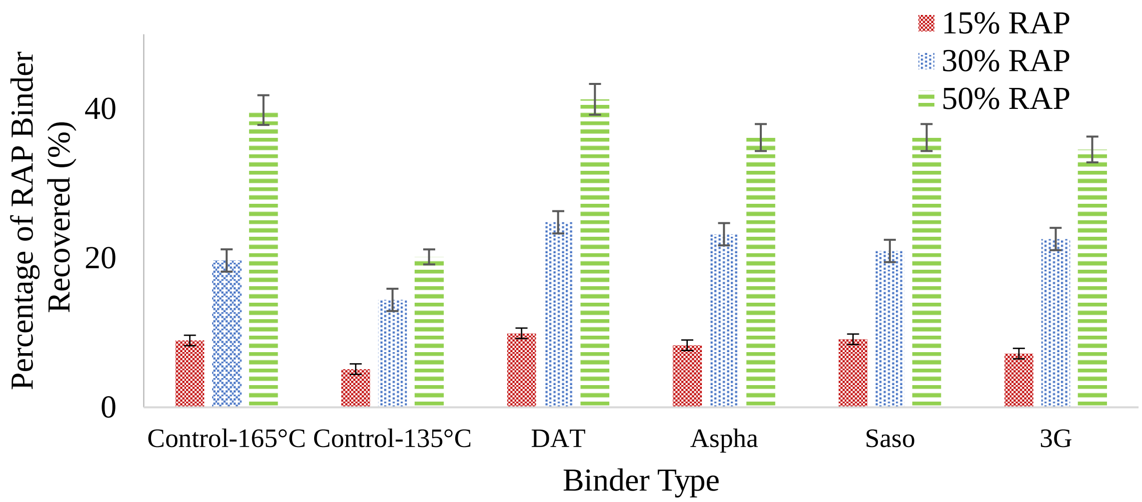

Figure 14. Percentage of RAP binder recovered for warm mix samples

In terms of the blending efficiency parameter, the ensuing results were obtained as presented in Figure 15. As more RAP is mobilised by the addition of the WMA, the warm binders showed higher blending efficiencies as compared to the control mixtures prepared at 135°C. The efficiency of blending calculated increased with the percentage of RAP and ranged from 40% to 65%. A conclusion that can be obtained from these results is that there seems to exist a threshold level of blending efficiency above which more RAP binder cannot be further mobilised. Such a premise should be evaluated in future studies as it could be an important consideration in RAP mixture design. The mixtures prepared with the DAT additive at 15%

and 30% RAP content exhibited the highest blending efficiency of 60% to 65%, which was greater than the control sample prepared at 165°C. The Evotherm based additives such as DAT and 3G has been reported to effectually reduce binder viscosity through an emulsification platform and subsequent interaction between water and surfactant [27]. This excess emulsification could have aided the additional mobilisation of RAP binder. However, the mechanism of mobilisation is still theoretical at this stage and possibly unique to each additive chemistry.

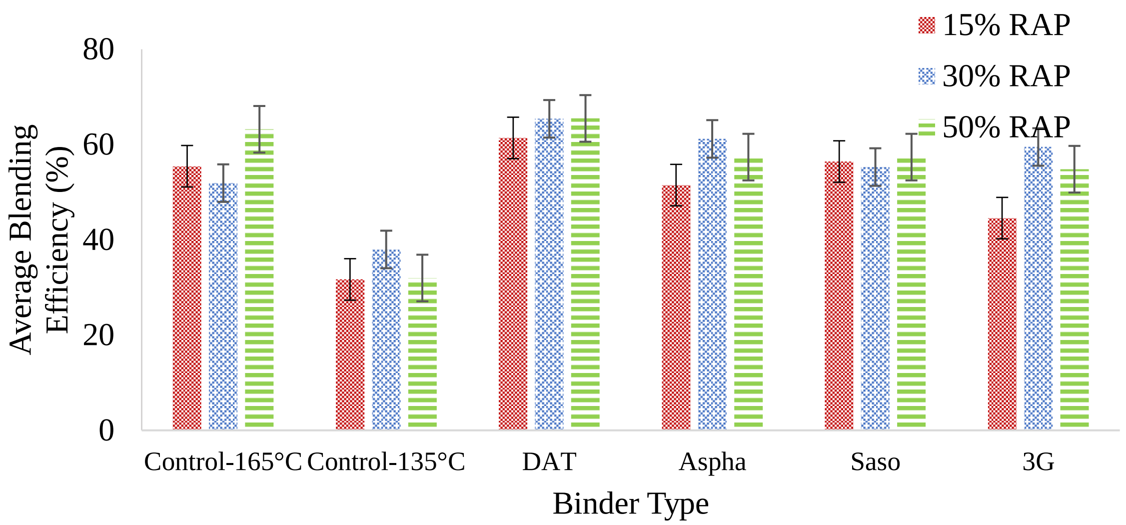

Figure 15. Blending efficiency of the warm mix samples

6. Conclusions

In this study, the influence of temperature and warm mix additives on RAP mobilisation and blending efficiency was investigated. Artificial aggregates in the form of glass beads were used as tracers in mixtures to separate RAP aggregates and virgin aggregates after mixing. New parameters for assessing RAP mobilisation and blending were derived using the latest developments in the characterisation of bituminous binders using ATR- FTIR. The following conclusions were drawn after the laboratory tests:

- ATR-FTIR is an effective semi quantitative tool to study the mobilisation and blending of RAP-virgin mixes.
- The RAP mobilisation is highly dependent on temperature, the mixtures prepared at 165°C showed on average close to 30% higher RAP mobilisation than mixtures prepared at 135°C.
- Warm mix additives can help to increase the mobilisation of RAP and its subsequent blending efficiency than mixtures prepared at the same temperature.
- The RAP mixtures prepared with the chemical additive Evotherm-DAT showed the highest percentages of blending efficiency. It is probable that the emulsification and increased workability induced in the mixtures by the addition of Evotherm-DAT could have contributed to increased RAP binder mobilisation.
- It is essential that WMA mixtures with RAP account for the increased mobilisation of RAP into consideration when designing mixes.

It is worth noting, though, that the glass beads used in this study do not exactly represent the identical nature and texture of the real aggregates used in bituminous mixtures. Additionally, the binders recovered were treated and assumed to be fully blended. But this only represents the ideal case, as the mixtures could be heterogeneous rather than completely homogenous mixtures. Future studies should be conducted to further understand the RAP binder mobilisation mechanism and how it is affected by different parameters, such as RAP type, binder viscosity and WMA dosages.

7. Acknowledgement

The authors would like to thank the Hong Kong Research Grant Council for the financial support for the study presented in this paper (Project Number: 15214615). Trademark or

manufacturers names appear in this paper only because they are considered essential to the objective of this paper.

8. References

[1] Al-Qadi, I, Elseifi, M & Carpenter, S, Reclaimed asphalt pavement: a literature review, Illinois Center for Transportation, Urbana, IL, USA (2007).

[2] Dinis-Almeida, M & Afonso, M.L, Warm Mix Recycled Asphalt as a sustainable solution, Journal of Cleaner Production, 107, 310-316 (2015).

[3] Zhou, F, RAP Stockpile Management and Processing in Texas: State of the Practice and Proposed Guidelines, FHWA/TX-10/0 - 6092-1 (2010).

[4] McDaniel, R.S, Soleymani, H.A.R, Anderson, R.M, Turner, P & Peterson, R, Recommended use of reclaimed asphalt pavement in the Superpave mixture design method, NCHRP final report no. 9-12, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, USA (2000).

[5] McDaniel, R.S, Kowalski, K.J & Shah, A, Evaluation of reclaimed asphalt pavements for surface mixtures, JTRP technical report, Joint Transportation Research Program, Purdue University, West Lafayette, Indiana, USA (2012).

[6] Mollenhauer, K & Gaspar, L, Synthesis of European knowledge on asphalt recycling: options, best practices and research needs, Eurasphalt & Eurobitumen congress, 5th, Istanbul, Turkey, European Bitumen Association, Brussels, Belgium (2012).

[7] Austroads, Maximising the Use of Reclaimed Asphalt Pavement in Asphalt Mix Design: Field Validation (2016).

[8] Bowers, B.F, Huang, B, Shu, X & Miller, B.C, Investigation of reclaimed asphalt pavement blending efficiency through GPC and FTIR, Constr. Build. Mater. 50, 517–523 (2014).

[9] Zhao, S, Bowers, B, Huang, B & Shu, X, Characterizing rheological properties of binder and blending efficiency of asphalt paving mixtures containing RAS through GPC, J. Mater. Civ. Eng., 26 (5), 941–946 (2013).

[10] Stimilli, A, Virgili, A & Canestrari, F, New method to estimate the “re-activated” binder amount in recycled hot-mix asphalt. Road Mater. Pavement Des. 16, 442–459 (2015).

[11] Rinaldini, E, Schuetz, P, Partl, M.N, Tebaldi, G & Poulikakos, L.D, Investigating the blending of reclaimed asphalt with virgin materials using rheology, electron microscopy and computer tomography. Compos.Part B Eng. 67, 579–587 (2014).

[12] Bonaquist, R, Can I run more RAP?, HMAT: Hot Mix Asphalt Technol, 12 (5), (2007).

[13] Mogawer, W, Bennert, T, Daniel, J.S, Bonaquist, R, Austerman, A & Boosherian, A, Performance characteristics of plant-produced high RAP mixtures. Road Mater Pavement Des.13(S1), 183–208 (2012).

[14] Ding, Y, Huang, B & Shu, X, Characterizing blending efficiency of plant produced asphalt paving mixtures containing high RAP. Construction and Building Materials, 126, 172–178 (2016).

[15] Zhao, S, Huang, B, Shu, X & Moore, J, Effects of WMA Technologies on Asphalt Binder Blending, Journal of Materials in Civil Engineering, 28 (2): 04015106, (2016).

[16] Asphalt Institute. Mix Design Methods for Asphalt Concrete and Other Hot Mix Types. MS-2, Sixth Edition, Lexington, KY. (1993).

[17] Mohajeri, M, Molenaar, A.A.A & Van de Ven, M.F.C. (promotor), Hot Mix Asphalt Recycling: Practices and Principles, doi: 10.4233/uuid:75ea46bc-deab-4259-9a73-0ca420cb94f6 (2015).

[18] Hofko, B, Alavi, M.Z, Grothe, H, Jones, D & Harvey, J, Repeatability and sensitivity of FTIR ATR spectral analysis methods for bituminous binders, Materials and Structures 50:187 (2017).

[19] Zhao, S, Huang, B, Shu, X, & Woods, M.E, Quantitative Characterization of Binder Blending: How Much Recycled Binder Is Mobilized During Mixing?, Transportation Research Record: Journal of the Transportation Research Board, doi: 10.3141/2506-08 (2015).

[20] Zhao, S, Huang, B, Shu, X, & Woods, M.E, Quantitative evaluation of blending and diffusion in high RAP and RAS mixtures, Materials and Design 89, 1161–1170 (2016).

[21] Yu, H, Leng, Z, Zhou, Z, Shih, K, Xiao, F & Gao, Z, Optimization of preparation procedure of liquid warm mix additive modified asphalt rubber. Journal of Cleaner Production. 141, 336-345 (2017).

[22] Bowers, B.F, Moore, J, Huang, B & Shu, X, Blending efficiency of Reclaimed Asphalt Pavement: An approach utilizing rheological properties and molecular weight distributions Fuel 135, 63–68 (2014).

[23] Kim, K.W, Kim, K, Doh, Y.S & Amirkhanian, S.N, Estimation of RAP's Binder Viscosity Using GPC Without Binder Recovery. Journal of Materials in Civil Engineering, 18 (4), 61–567 (2006).

[24] Xu, S, Xiao, F, Amirkhanian S & Singh, D, Moisture characteristics of mixtures with warm mix asphalt technologies – A review, Construction and Building Materials 142, 148–161 (2017).

[25] Button, J.W, Estakhri, C & Wimsatt, A, A Synthesis of Warm-Mix Asphalt, Texas Transportation Institute, Report No. TX-07/0-5597-1 (2007).

[26] Zhang, Y, Leng, Z, Zou, F, Wang, L, Chen, S.S & Tsang, D.C.W, Synthesis of zeolite A using sewage sludge ash for application in warm mix asphalt, Journal of Cleaner Production 172, 686-695 (2018).

[27] Yu, X, Leng, Z & Wei, T, Investigation of the Rheological Modification Mechanism of Warm-Mix Additives on Crumb-Rubber-Modified Asphalt, Journal of Materials in Civil Engineering, 26 (2), 312-319 (2014).