
Construction and Building Materials 234 (2020) 117323

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

Quantitative assessment of the parameters linked to the blending between reclaimed asphalt binder and recycling agent: A literature review

Marko Orešković [a,*], Gustavo Menegusso Pires [b], Sara Bressi [c], Kamilla Vasconcelos [d], Davide Lo Presti [b,e]

[a] University of Belgrade, Faculty of Civil Engineering, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia
[b] Nottingham Transportation Engineering Centre (NTEC), The University of Nottingham, Pavement Research Building, University Park, Nottingham NG7 2RD, United Kingdom
[c] Department of Civil, Industrial Engineering (DICI), University of Pisa, Largo Lucio Lazzarino 1, Pisa, Italy
[d] Department of Transportation Engineering, Polytechnic School, University of São Paulo, Av. Prof. Almeida Prado, Travessa 2, No 83, Cidade Universitária, São Paulo, SP, Brazil
[e] Department of Engineering, University of Palermo, Viale delle Scienze, Ed.8, Palermo 90128, Italy

H I G H L I G H T S

- Previously used methods for determining DoA, DoAv and DoB are shown.
- Investigation methods for determining DoA, DoAv and DoB are classified.
- Advantages and disadvantages of the investigation methods and techniques are shown.
- The literature review which may help in quantifying DoA, DoAv and DoB is given.

Citation: Marko Orešković, Gustavo Menegusso Pires, Sara Bressi, Kamilla Vasconcelos, Davide Lo Presti, Quantitative assessment of the parameters linked to the blending between reclaimed asphalt binder and recycling agent: A literature review, Construction and Building Materials, Volume 234, 2020, 117323, ISSN 0950-0618, https://doi.org/10.1016/j.conbuildmat.2019.117323

Original version of the manuscript:

http://www.sciencedirect.com/science/article/pii/S0950061819327758

50 days' free access link (expires on December 21st 2020)

https://authors.elsevier.com/a/1Z-7z3O1E1GNKE

Quantitative assessment of the parameters linked to the blending between reclaimed asphalt binder and recycling agent: A literature review

Marko Orešković[a] (corresponding author), Gustavo Menegusso Pires[b], Sara Bressi[c], Kamilla Vasconcelos[d], Davide Lo Presti[b,e]

[a] *University of Belgrade, Faculty of Civil Engineering. Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia. E-mail: moreskovic@grf.bg.ac.rs*

[b] *Nottingham Transportation Engineering Centre (NTEC), The University of Nottingham. Pavement Research Building, University Park, Nottingham, NG7 2RD, United Kingdom. E-mail: gmenegussopires@gmail.com*

[c] *Department of Civil, Industrial Engineering (DICI), University of Pisa. Largo Lucio Lazzarino 1, Pisa, Italy. E-mail: sara.bressi@ing.unipi.it*

[d] *Department of Transportation Engineering, Polytechnic School, University of São Paulo. Av. Prof. Almeida Prado, Travessa 2, No 83, Cidade Universitária, São Paulo, SP, Brazil. E-mail: kamilla.vasconcelos@usp.br*

[e] *Department of Engineering, University of Palermo, Viale delle Scienze, Ed.8, Palermo, 90128, Italy. E-mail: Davide.Lopresti@nottingham.ac.uk, davide.lopresti@unipa.it*

Abstract

The lack of understanding of the mechanisms governing the interaction between reclaimed asphalt binder (RAb)[1] and recycling agents is one of the technical issues that still need to be resolved when high amount of reclaimed asphalt (RA)[2] is used in a new recycled asphalt mixture (RAM). Due to important role of RAb in that interaction and increased used of RA, it becomes necessary to have a way to classify RA, as any other material used in asphalt mixture production. It is very important to determine how much RAb is active by itself (DoA)[3], but also to determine how much RAb can be considered available for a mix design of RAM (DoAv)[4], when a recycling agent is used. Finally, since that RAM's properties are strongly dependent on the degree of blending between RAb and recycling agent (DoB)[5], it should evaluate to what extent RAb contributes to the final properties of RAM. These parameters (DoA, DoAv and DoB) are so crucial that identifying suitable methodologies for their assessment would be extremely important in performing a proper mix design due to dangerous of having a lack of active bitumen in RAM. This paper presents a literature review of methods which have been used for the evaluation and assessment of mentioned parameters, grouped in four macro-areas: mechanistic, mechanical, chemical and visualization approaches. Furthermore, summarized review of used methods was prepared together with their critical review, all with aim to find appropriate methods for determining these parameters.

[1] RAb – Reclaimed Asphalt binder; [2] RA – Reclaimed Asphalt; [3] DoA – Degree of binder Activity; [4] DoAv – Degree of binder Availability; [5] DoB – Degree of Blending

Highlights

- Previously used methods for determining DoA, DoAv and DoB are shown.
- Investigation methods for determining DoA, DoAv and DoB are classified.
- Advantages and disadvantages of the investigation methods and techniques are shown.
- The literature review which may help in quantifying DoA, DoAv and DoB is given.

Keywords

Reclaimed Asphalt Pavement; Recycled Asphalt Mixture; Degree of Blending; Degree of binder Activity; Degree of binder Availability; Hot Mix Asphalt; Warm Mix Asphalt

1. Introduction

The construction of new roads requires huge amounts of virgin aggregate, filler and binder. Since these materials are available in limited quantities, it is inevitable to seek for alternative solutions in order to decrease/replace their usage. At the same time, reconstruction of existing roads brings an increased amount of stock-piled materials and a necessity for new materials as well. These issues can be overcome if Reclaimed Asphalt (RA), theoretically a 100% recyclable material, is used. Due to the presence of binder within RA, the total amount of virgin binder (VB) which should be added in an asphalt mixture will be decreased, so the highest potential of using RA is within hot mix asphalt (HMA) and warm mix asphalt (WMA), where it may even be used for the construction of unbound layers, embankments, etc.

However, the wider use of RA in asphalt mixtures is precluded by many limitations. Next to the lack of guidelines/policies, road agency specifications and technological issues (e.g. the capabilities of asphalt plants), the most common barriers are related to the RA as a component material. Copeland [1] reported that homogeneity, quality control, dust and moisture content of RA, as well as the aged binder grade and blending between the aged binder and recycling agent are concerns cited most often with regards to the quality of Recycled Asphalt Mixtures (RAM). The latter two barriers are strongly correlated to the performance of RAM, because increased amounts of aged binder within RAM mixtures significantly change their properties: rutting resistance [2–5], indirect tensile strength [6,7] and stiffness increase [4,6–9], while cracking resistance (both thermal and fatigue) decreases [5,9,10]. Due to these facts, it is necessary to estimate how much binder from RA is activated within the new asphalt concrete manufacturing process and how it is blended with a recycling agent. Generally, recycling agents are defined as family of additives or admixtures added within the RAM manufacturing process in order to restore the properties of RA binder (rejuvenators: virgin binder, different oils) or to facilitate the mixing production process by allowing lower manufacturing temperatures (lubricants: warm mix additives).

The quantity of activated/available RA binder (RAb) and the degree of blending between RAb and recycling agent (DoB) have been interchangeably used in previous studies due to the lack of a general consensus on these terms. The first term was, at times, identified as effective RAb [11], replaced VB [12,13], transferred binder [14], mobilized binder [15–18] or re-activated binder [19], whereas the second term was identified most often as DoB [20–27], but also as blending efficiency [28–30], blending status [31], blending ratio [32], rate of intermixing [33] or meso-blending [34]. In order to overcome this issue, Lo Presti et al. [35] provided a nomenclature and a theoretical framework of the blending phenomena. The aim of the study was to provide the scientific community with a theoretical explanation and nomenclature of key mechanisms linked with the blending phenomena for the sake of identifying and quantifying following parameters: Degree of binder Activity (DoA), Degree of Binder Availability (DoAv) and DoB. In the same study, DoA was defined as "the minimum amount of active RAb that a designer can consider for a selected RA and a selected asphalt manufacturing process". However, the binder available for blending is formed not only of the binder activated during the manufacturing process and the residual amount of a recycling agent, but also of the binder activated under the influence of the recycling agent, a new term was previously introduced – the Degree of binder Availability (DoAv) [11]. These two parameters are strongly correlated with properties of RAM, but due to the lack of precise definition, Lo Presti et al. [35] defined DoB as "an indicator describing to what extent the aged RA binder contributes to the final properties of the asphalt mixture's binder blend composed of aged binder and recycling agent".

Even though there have been many efforts in previous studies with the aim of assessing, estimating or simply describing DoA/DoAv/DoB, there are still no fully developed and standardized testing procedures on how to determine these amounts. Due to this fact, this paper provides a state of the art of testing methods used in previous research in order to help both the scientific and practitioner community in finding appropriate method(s). The used testing methods are explained in detail and divided into four groups: mechanical, chemical, visualization, and mechanistic approaches. Advantages and disadvantages of used methods are given together with recommendation for assessment of blending parameters, and at the end of paper, the methods that have been only used in evaluation of parameters considered are summarized.

2. Investigation methods for evaluation/assessment of DoA, DoAv and DoB

Even in an era in which 100% RA asphalt mixtures are used, some important questions remain to be answered: How much binder is actually activated from RA within the new asphalt concrete manufacturing process and how does it blend with the recycling agent? One possible reason why these questions are still un-answered is that assessing DoA and DoAv of RA and/or DoB of the blend are multi-variable problems with several factors influencing the outcome. However, these parameters are so crucial that identifying suitable methodologies for assessing them would be of key significance in controlling the contribution of aged binder in the recycled asphalt mixtures and in selecting the optimal amount of an appropriate recycling agent. This section presents the results of a critical literature review looking specifically at methodologies used so far for determining DoA, DoAv and DoB. The most relevant studies that quantify, or simply describe these parameters, are shown in this paper with the aim to motivate further research in finding unique testing method(s).

The investigation methods for determination of blending parameters (DoA, DoAv and DoB) from previous studies are grouped in four macro-areas related to their approach (mechanical, chemical, visualization and mechanistic). Mechanical approach includes mechanical blending, binder testing, asphalt mixture testing and nanoindentation technique. Chemical approach covers spectroscopy and chromatography techniques, visualization approach covers microscopy and computed tomography (CT), and finally, mechanistic approach includes numerical simulation techniques and modelling techniques. Figure 1 shows an overview of the macro-areas and methodologies found in the literature.

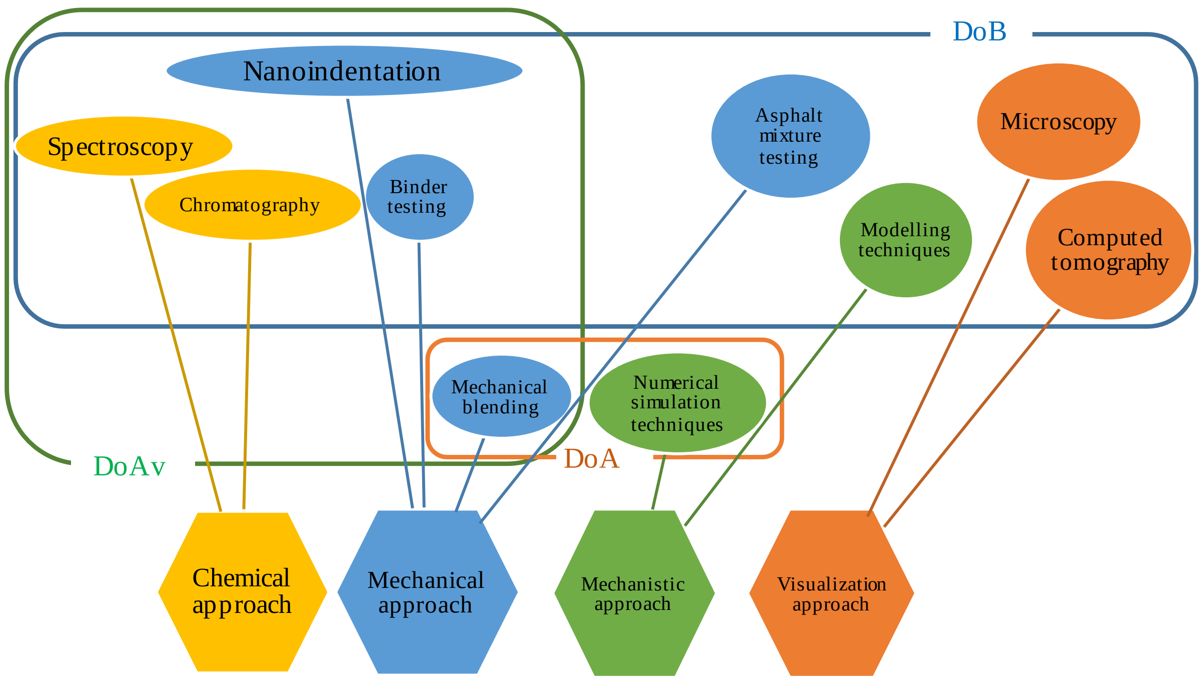

Figure 1. Methodologies used for the determination of DoA, DoAv and DoB

2.1 Mechanical approach

Testing methods where any mechanical act is applied on a testing sample/specimen during a test (i.e. mixing between RA, aggregate and/or recycling agent; asphalt mixture testing, etc.), belong to mechanical approach for determining blending parameters. This approach includes mechanical blending, binder testing, asphalt mixture testing and nanoindentation techniques. This approach has the highest potential to be used in assessment of all blending parameters.

2.1.1 Mechanical blending

Mechanical blending methods may be used for determining both DoA and DoAv. Within these methods, different fractions of the RA and virgin aggregate are blended, with or without the addition of recycling agents, for a certain period of time under certain conditions.

The coating study (Figure 2) presents the procedure where the RA fine particles are blended with virgin coarse aggregate particles, or opposite, without addition of a recycling agent and then separated using a “threshold” sieve. The aim of the coating study is to estimate DoA, i.e. the quantity of RAb mobilized from RA particles to virgin aggregate particles by only using mechanical action of mixing under different processing conditions, various RA content and fraction size.

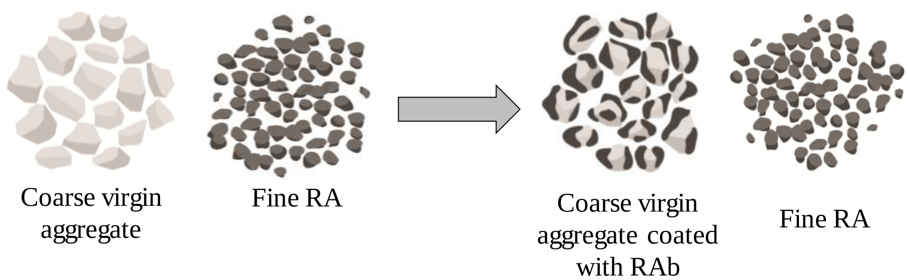

Figure 2. Coating study

Similar procedure with the addition of a recycling agent is called the blending study (Figure 3). It is typically the initial stage of further binder blend analysis used to determine DoAv [36,37], but may also be independently used to determine it [11,38]. The blending study may be also performed with the use of an artificial aggregate (i.e. round-shaped gravel, glass or steel beads) instead of a part of virgin aggregate to analyze DoAv [18], even though this kind of aggregate does not realistically simulate the situation in the asphalt plant.

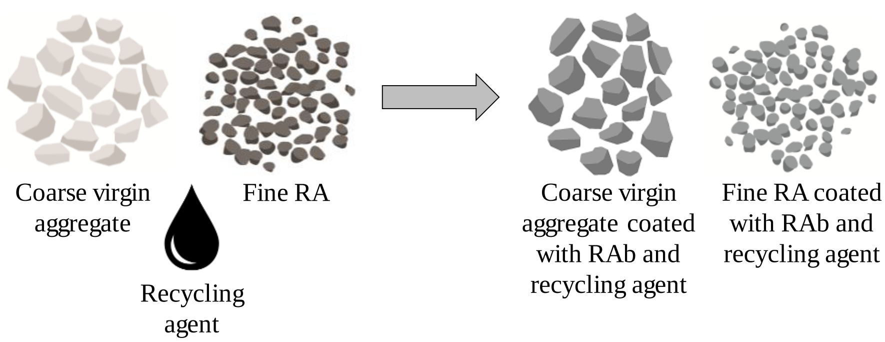

Figure 3. Blending study

Both procedures were developed by Huang et al. [36], and later explained by Shirodkar et al. [37]. The “threshold” sieve size, RA content, mixing and storage time, as well as mixing and storage temperatures are variables that may change considerably. These variables have not been defined by a standard procedure, so they typically depend on the researcher’s choice.

Huang et al. [36] conducted the coating study using 10%-30% RA at the mixing temperature of 190°C and the mixing time of 3 min. DoA was around 11%, regardless the RA content. Shirodkar et al. [37] used 25% and 35% RA, under different conditions (mixing temperature: 177 °C; mixing time: 10 min; storage time: 2 h and 30 min at mixing temperature) and obtained DoA of 24% and 15%, for 25% and 35% RA, respectively. Rinaldini et al. [39] conducted a coating study by blending 50% of previously preheated fine RA particles with 50% of coarse virgin aggregate also preheated at 185 °C obtaining very low values of DoA. Gottumukkala et al. [40] used20% and 35% RA within the coating study performed at the mixing temperature of 160 °C and obtained DoA of 12.4% and 10.4%, respectively.

Kaseer et al. [11] performed a modified blending study without any further testing to evaluate DoAv where a virgin mix, consisting of three distinct fractions (coarse, intermediate and fine), was mixed with VB. After blending, binder content of each fraction was determined. A RA mix was made the same way, but using RA of intermediate size, instead of virgin aggregate. The binder content of each fraction was also determined. The idea of this concept is that if there is no difference between the binder content of intermediate fractions of both mixes , DoAv is 100%. Four types of RAMs were made to verify this approach: soft RA (without aging), stiff RA (5 days aging at 110 °C), very stiff RA (10 days aging at 110 °C) and extremely stiff RA (10 days aging at 110 °C plus 3 days at 150 °C). Results showed that DoAv was 91.9%, 85.0%, 66.4% and 39.1% for these mixes, respectively. In the same study, a couple of different RA materials were analyzed together with the addition of a recycling agent, different conditioning times (2 and 4 h) and mixing temperatures (140 °C and 150 °C). It was concluded that extending the conditioning time did not significantly increase DoAv, that was going from 50% to 95%, and that the addition of recycling agents increased DoAv at the lower mixing temperature investigated.

In order to obtain binder from RA, RAM or materials from blending studies, it is first necessary to extract and then to recover it. The extraction procedure is usually single-staged. It is typically used for determining the asphalt mixture binder content or binder blend properties, whereas a staged (multistep, multiple) extraction procedure is a widely-used procedure for analyzing the different binder layers around the RA/aggregate particles. During the staged extraction procedure, particles coated with binder are firstly soaked into a solvent for the time required to obtain the solution of the binder and solvent. After the first soak, the process is repeated with clean solvent for as many times as necessary, depending on the number of layers that the researchers want to characterize (Figure 4).

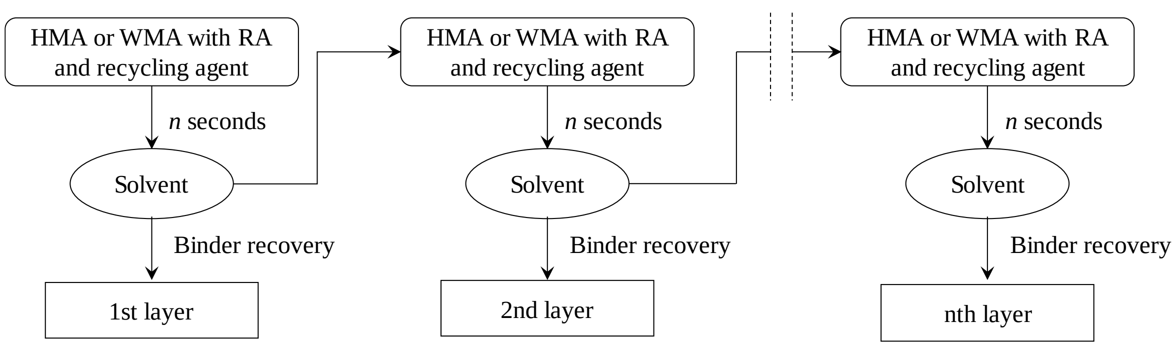

Figure 4. Scheme of the staged extraction procedure

During the extraction, standard or staged, both RAb and VB, are soaked in a solvent, that forces them to blend. This can cause a distortion in the determination of DoAv and DoB, but may also affect the binder due to the influence of the solvent used [30]. It is true that this method may provide important information in estimating DoAv and DoB [41]; however, it needs further investigation to overcome the technical issues mentioned.

After the extraction procedure, the Abson recovery method, rotary evaporator, fractionating column or leaching system can be used to recover the asphalt binder from the solution before subjecting it to any testing.

2.1.2 Binder testing

Rheological and physical properties of bituminous binder can provide significant contribution in the determination of DoAv and DoB, frequently in combination with other testing methods. The most commonly used equipment for performing rheological tests is (I) the Rotational Viscometer (RV) for binders at high service temperatures; (II) the Dynamic Shear Rheometer (DSR) at whole range of temperatures, and (III) the Bending Beam Rheometer (BBR) at low operation temperatures. Output data are expressed in terms of the dynamic shear modulus (|G*|), phase angle (δ), creep stiffness (S(t)) and/or rotational viscosity (η*).

Gottumukkala et al. [40] carried out a blending study on mixtures with 20% and 35% of fine RA particles blended with virgin aggregate at 160 °C and different virgin binder types. DoAv was evaluated on the binders recovered from both parts after determining the G*/sinα value, penetration and softening point, ranging from 16% to 87%, concluding that it depends on the VB type and RA content. Yu et al. [42] performed a blending study fine RA, coarse virgin aggregate and VB. Three mixtures were prepared, with 20%, 40% and 60 % RA. Rheological parameters (for rutting performance: G*/sinα, $J_{nr0.1}$ and $J_{nr3.2}$ and for fatigue performance: G*sinδ) were measured in order to assess DoAV which was found to be average 30%, 83% and 72% for mixtures with 20%, 40% and 60% RA, respectively.

Stephens et al. [43] used steel ball bearings to break RAMs with 15% and 25% RA into fine and coarse particles to investigate DoB. Tests were performed on binders recovered from both fractions using DSR and BBR. DoB was not quantified, but it was concluded that RA aggregate source does not have influence on DoB, whereas RA amount significantly influences it.

Shirodkar et al. [37] performed a blending study on mixtures with 25% and 35% of RA where fine RA and coarse virgin aggregate were blended with VB heated to mixing temperature. The amount of VB used in the blending study was determined as the difference between the appropriate designed binder content from the job mix formula and the estimated DoA obtained during the coating study from the same research. After blending, binders were recovered from both parts and their properties (|G*| and δ) were determined. At the same time, the specific surface area of fine RA aggregate was calculated using Bailey's method, to determine the proportion of VB and RAb that would coat the fine RA aggregates under zero-blending conditions. Those amounts of VB and RAb were blended and exposed to short-term aging, before determining their properties (|G*| and δ). DoAv was estimated by comparing rheological properties of the recovered and blended binders: 70% for the mixture with 25% RA and 96% for the mixture with 35% RA.

Gaitan et al. [26] carried out the same procedure comparing HMA and WMA with 25% RA, but using different testing conditions (mixing and conditioning time and mixing temperatures). It was concluded that DoAv of WMA is higher than that of HMA (82–85% compared to 59%, respectively) due to the presence of recycling agent. Also, it was observed that mixing time increases DoAv, whereas conditioning time and mixing temperature did not affect it.

Bressi et al. [15] carried out a blending study where 50% and 90% of fine RA were preheated for 1 h at 135 °C and coarse virgin aggregate for 3 h at 180 °C. After preheating, these fractions were blended with VB and left in the oven at 180 °C for 30 min. Binder was recovered from the coarse part that retained on the threshold sieve and it was assumed that the RAb of coarse part is blended with VB if the |G*| value of the blend is higher than the |G*| value of VB. Results showed only small amount of the RAb is mobilized during blending process.

Rinaldini et al. [39] performed a blending study using 50% of small RA particles in combination with coarse aggregate and 5% of VB. Also, two more mixtures were prepared: one containing a coarse virgin aggregate fraction and VB, and a second one containing only the fine RA. Rheological tests were performed on DSR on binder blends recovered from fine RA and coarse virgin aggregate, as well as on binders recovered from other two mixtures. DoAv was not quantified within this research, but the dynamic modulus master curves showed that a certain amount of RAb was additionally activated under the influence of the VB.

Liphardt et al. [27] went a step further from the assessment of DoAv and DoB based on the |G*| value and used the Multiple Stress Creep Recovery (MSCR) test. Binder tests were performed on the recovered binder after a staged extraction procedure from an asphalt mixture containing 100% RA and VB. Even though DoB and DoAv were not quantified, it was concluded that there was no full blending. Also, MSCR showed high potential in assessment of DoAv and DoB, especially if one of the binders is polymer-modified.

Gaspar et al. [44] used a staged extraction procedure to evaluate binder homogeneity of a plant-produced WMA with 25% RA. The obtained binder layers were analyzed using DSR, by means of the frequency-temperature sweep, MSCR, and linear amplitude sweep tests. The authors considered the procedure to be an option for determining binder homogeneity in RAMs, providing important qualitative information about DoB.

2.1.3 Asphalt mixture testing

The behavior of asphalt mixtures may be predicted by conducting mixture performance tests such as the wheel tracking test, the SUPERPAVE shear test, the indirect tension test, and the flexural beam fatigue test. Comparison of various mixtures using the same test conditions has been used in several studies to investigate the influence of RA on RAM's performance [9,23,45]. Since this approach may be useful in determining the influence of certain parameters (e.g. RA content, recycling agent type, etc.) on mixture performance, it has the highest potential to be used in estimating DoB.

Stephens et al. [43] used an unconfined compression test and indirect tension test to determine the influence of RA heating time, binder type and aggregate source on DoB of RAMs with 10-25% RA. It was concluded that more complete blending occurs in RAM if the RA reaches a temperature high enough to soften the aged binder and make it available for blending with the recycling agent.

Stimilli et al. [19] developed an analytical method combining the performance-based equivalence principle and specific surface area of aggregates from the mixture, by assuming that amount of activated RAb is proportional to the re-activated binder film thickness. The performance-based equivalence principle was based on the assumption that the "working" binder content in a virgin asphalt mixture and in RAM are the same, if mechanical performance of both mixtures is comparable. Four RAMs were prepared for the purposes of this research: one reference mixture with 25% of unfractionated RA (0/16 mm) and three mixtures with 40% RA (one with coarse RA fraction (8/16 mm), one with fine RA fraction (0/8 mm) and one with combined coarse and fine fractions). Results showed that the reference mixture and mixtures with fine and combined fractions had approximately the same DoAv (70%), whereas the mixture with coarse RA fraction had lower DoB (around 50%). Furthermore, it was concluded that the proposed methodology overestimates the real amount of re-activated binder in the mixture with high amount of fine RA particles. The explanation was found in the fact that a certain amount of RA particles possesses a lower surface area than the one calculated from the original RA aggregates obtained after binder extraction. The significant difference between real and calculated surface area may be a consequence of the applied surface area factors (Duriez, Hveem, Bailey's) which consider grains as a sphere or as a cube, whereas the RA particles have different shapes. Research results of this study were later confirmed by Bressi et al. [46], with recommendation to adjust these factors, considering the real shape of the aggregate.

Abd et al. [20] used specially prepared cylindrical specimens of a gap-graded hot rolled asphalt mixture containing 40% RA for testing in modified DSR equipment to estimate DoB. Even though it was not quantified, the results showed that there was no complete blending between RAb and VB, except in the case when a lubricant was used at higher mixing temperatures.

Abed et al. [47] prepared RAMs with 50% RA, varying the RA preheating temperature (95-135 °C) and mixing time (1-5 min) to assess their influence on DoB based on the ITS test. Results showed that DoB ranged from 37% to 95%, depending on the processing conditions.

2.1.4 Nanoindentation technique

Nanoindentation is a technique that can be used for assessing the mechanical properties of a material at nano/micro-scale. The indentation process consists of three phases: loading, holding and unloading of a diamond tip on the material surface. Based on a measured tip displacement, material properties (elastic modulus, stiffness, hardness, etc.) can be determined. It cannot be easily used for assessment of any of blending parameters, but it can help in measuring of binder film thickness, that is frequently correlated with DoB.

Mohajeri et al. [48] performed a nanoindentation test on a stone-binder-stone interface to determine DoAv and to investigate the blending zone between the soft and hard binder. Figure 5 shows the three zones recognized: two stone zones and one binder zone consisting of a soft and hard binder. The interface between two binders was not clearly identified and it was not possible to measure DoAv, although the binder film thickness between stones could be precisely measured.

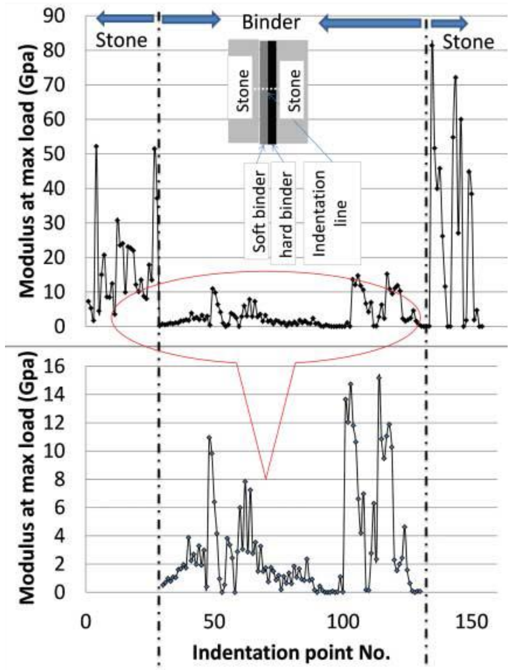

Figure 5. Nanoindentation test results from a stone-binder-stone interface, adapted from Mohajeri et al. [48]

Abd et al. [20] used a nanoindentation technique to determine DoV, concluding that the effect of the aggregate type on DoB can be neglected by using this technique, because measured mechanical properties of RA aggregate were almost the same as properties of the virgin aggregate. Obtained results confirmed the results from the same study obtained by binder testing: there was no complete blending between RAb and VB, except in the case when a lubricant was used.

2.2 Chemical approach

The chemical approach is based on the use of chemical techniques in order to analyze the chemical composition of a binder. Binder for testing may be recovered from RAM, RA or from mixtures obtained from blending study, but may also be analyzed without extraction, directly from a mixture. Having in mind that chemical properties of bitumen changes over the time under the influence external factors (oxidation, water, etc.), and also that recycling agents may help in recovering of chemical properties, this approach becomes inevitable in the assessment of blending parameters. It includes two techniques: chromatography and spectroscopy.

2.2.1 Chromatography

Gel Permeation Chromatography (GPC) is a type of Size Exclusion Chromatography (SEC) used to separate molecules of a solution into various sizes. Typically, the relative molecular weight of polymer samples and the distribution of molecular weights are determined within this technique. Using this technique may also help to distinguish between RAb from VB due to the higher amount of large molecules in aged binders when compared with VB. This is frequently achieved using the large molecular size percentage (LMSP) parameter.

The LMSP parameter presents the area of the first five slices over all the other 13 slices beneath the chromatogram derived from the GPC. Within previous research, LMSP has been correlated with the binder absolute viscosity and dynamic shear modulus, showing its potential for use in DoAv/DoB investigations [49].

Zhao et al. [18] used round-shaped gravel as a tracking material to isolate the binder blended during the mixing phase of RAMs with RA content from 10% to 80%. Results showed that DoB decreases with increasing of RA content, going from almost 100% for 10% RA to approximately 24% for 80% RA.

The same group of authors applied the GPC on the binders recovered from coarse virgin aggregate and fine RA aggregate obtained after a blending study [31]. DoAV was not quantified, but with conclusions that binder blend coating the virgin aggregate was more uniform than the binder blend surrounding RA aggregate due to the un-mobilized binder still attached to the RA.

Bowers et al. [50] were investigating the influence of mixing time, mixing temperature and recycling agents on DoAv by testing binders recovered from mixtures with 65% RA after a blending study. Results showed that 5 min mixing time should ensure 100% of DoAv, even though it is not a realistic time frame for mixing at a plant. Also, it was mentioned that increased mixing temperature increases DoAv, from 59% at 130 °C to 76% at 180 °C, and that lubricants may have a positive impact. Furthermore, it was noticed that the Black Rock phenomenon does not exist.

2.2.2 Spectroscopy

Fourier Transform Infrared Spectroscopy (FTIR) is a measurement technique that can be used to obtain an infrared absorption or emission spectrum of a solid, liquid or gas. The FTIR spectrometer simultaneously collects high-spectral-resolution data over a wide spectral range and determines functional groups within a medium.

Bowers et al. [28] tried to assume DoAv by preparing an artificially aged binder by aging a VB through a Rolling Thin Film Oven Test (RTFOT) followed by double Pressure Aging Vessel (PAV) aging. Further, 9.5 mm gravel had been mixed with VB and artificial RAb at 180 °C for 2 min and a staged extraction procedure was used (immersion time was 30 s or 1 min). FTIR was then applied on binder blends to compare the ratio of the carbonyls (C=O) and the saturated C-C vibration to evaluate oxidation, because an increase in the carbonyl is an indicator of the oxidation (aging) of the asphalt binder. Within the study, it was concluded that the carbonyl content is higher as the binder layer is closer to the aggregate bringing to the conclusion that the binder blending was not completely uniform. Also, the higher percent of carbonyl for the inner layer is a consequence of the aged binder presence. These results confirmed the findings from the same study obtained by using GPC.

A similar procedure, called the “leaching blending test”, was performed by Delfosse et al. [32]. The test is also based on a staged extraction procedure, where the Carboxyl index was determined through infrared spectrum analyses of the leachates. Test results showed that HMAs containing 20% and 35% RA, with PmB and straight-run asphalt binder, respectively, had high levels of DoB.

Ding et al. [29] investigated three plant-produced RA mixtures with 50% RA (one WMA, one HMA with recycling agent and one without) to characterize DoB. The FTIR procedure was applied on the binders recovered from different sizes of aggregate particles (passing No. 4 sieve; passing ¾ in. sieve and retained on No. 4 sieve; retained on ¾ in. sieve.). This study could not exactly assess DoB of every mixture, but it was possible to compare them using the so-called Aging Index (AI). AI was defined as the ratio between the area of the carbonyl ($C=O$) band and the area of the saturated C-C stretch band. Results showed that WMA had the highest DoB and that recycling agents slightly improved DoB of HMA.

Sreeram et al. [51] used FTIR to assess both DoAv and DoB of RAMs with 15%-50% RA. Borosilicate glass beads of different diameters were used to isolate the binder from RA and RAMs for further testing. Results showed that DoAv was dependent on the mixing temperature and RA content: it was around 5%, 15% and 20% at a mixing temperature of 135 °C and around 10%, 20% and 40% at a mixing temperature of 165 °C in mixtures with 15%, 30% and 50% RA, respectively. The measured DoB was more prone to the influence of temperature than to RA content. It was varying from 50% to 60% for the samples prepared at 165 °C and from 30% to 40% for the samples prepared at 135 °C.

Energy dispersive X-ray spectroscopy (EDXS, EDX, EDS or XEDS) is the technique that allows obtaining information concerning the chemical composition of a sample [52]. Since the EDS [21,53] and EDX [24] equipment have been used in electron microscopes (visualization approach) their application within the field of blending parameters assessment will be analyzed in the next section.

2.3 Visualization approach

Visualization methods at different scales have been used to investigate the uniformity of asphalt mixtures or to observe a certain place within a mixture rather than to quantify DoA, DoAv or DoB. These methods do not usually measure physical, mechanical or chemical properties of a material, buy may be used as auxiliary methods, mostly for describing DoB. However, some of the methods and equipment used to investigate DoB are microscopy technique (optical, electron, fluorescence and atomic force microscopy) and computed tomography (nano and micro level). Figure 6 illustrates an overview of the different scales investigated in the selected studies.

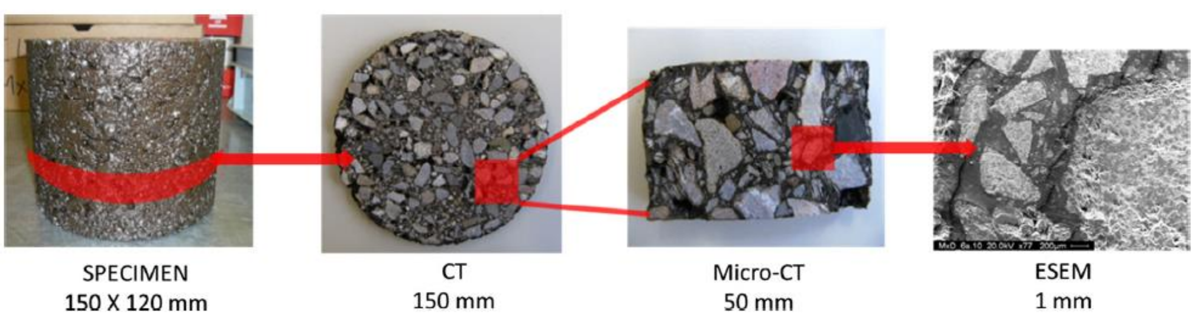

Figure 6. Overview of the different investigation scales, adapted from [39]

2.3.1 Microscopy

Scanning Electron Microcopy (SEM) can reveal information about the texture, chemical composition and crystalline structure of a sample, with magnification from 20 to 30000 times. In the field of pavement research, it has been used to determine the binder film thickness between aggregate particles [23,46] and to investigate if the VB and RAb could be homogenously identified [23]. This method is not typically suitable for quantifying DoB because it provides results based on singular spots, but it may help the observation of the binder blend homogeneity and it may be used as an additional method to verify the level of DoB.

In one research [54], an attempt was made to evaluate DoB process through the homogeneity of the binder blend under different mixing temperatures and times. The image analysis protocol was conducted on images taken under white light (WL) and ultraviolet light (UVL). The main conclusion was that the homogeneity of RAM depends on the mixing temperature more than on the mixing time, without precise determination of the DoB level.

A combination of the rheological tests, computed tomography and electron microscopy was found to be promising for investigating DoB within asphalt mixtures [39]. This research shows that blending of the VB and the RAb is commonly heterogeneous and that this technique cannot clearly quantify DoB, confirming the findings of Mohajeri et al. [48].

Energy dispersive X-ray spectroscopy was used to analyze DoB in the RAM with large clumps of adhered RA particles and in RAM with fractionated RA [21]. Titanium dioxide was used as a tracer to understand occurrence of blending between RAb and VB. It was concluded that the mixture containing pre-processed RA allowed lowering the formation of RA clusters and as a consequence it provided higher DoB. The same conclusions have been reported by Bressi et al. [15].

Furthermore, Jiang et al. [53] were first researchers who quantified DoB in RAMs using SEM and EDS, where the element mass ratio of titanium over sulfur was proposed as a quantitative indicator of DoB in compacted RAM. DoB was assessed to be around 100% in RAM with 15% RA, regardless the ageing conditions Additionally, it was concluded that DoB decreases with increasing RA content and increases with aging: in RAM with 30% RA, DoB ranged from 78% under normal conditions to 90% after long-term aging, whereas in RAM with 50% RA it ranged from 43% to 78%. In the same study it was also concluded that using recycling agents significantly improves DoB, bringing it almost to the complete blending.

Fluorescence microscopy is a technique that uses the emission of fluorescence to study properties of organic or inorganic substances. It was employed to estimate DoB of two plant-produced HMA, with and without a recycling agent, and one WMA with foaming technology, all containing 50% RA [16]. The binder recovered from the RA was blended with a VB at various contents and tested with a fluorescence microscopy to develop blending charts using a newly developed mean grey value (MGV) parameter. MGV presents the average fluorescence strength of a fluorescence image derived from image post-processing. DoB was measured on aggregates obtained after blending study, whereas overall DoB in the asphalt mixture was estimated by combining the MGV and the specific surface area of the RAM's aggregates. HMA mixtures with and without rejuvenator had DoB around 85%, whereas the WMA mixture had the DoB of around 92%, probably due to the positive impact of foaming technology on the RAb activation.

Atomic Force Microscopy (AFM) is a scanning probe technique that allows revealing the surface topography and heterogeneity of materials with high spatial resolution. It can be used to characterize RAb, VB and their blending zone. Nahar et al. [41] first observed the presence of the blending zone at the interface of the two binders of different grades by using AFM images. It was stated that DoB was 100% at the interface of RA and VB, but only in a transition area. Furthermore, the extent of the blending zone, d, will likely depend on parameters such as temperature, binder type and contact time (Figure 7).

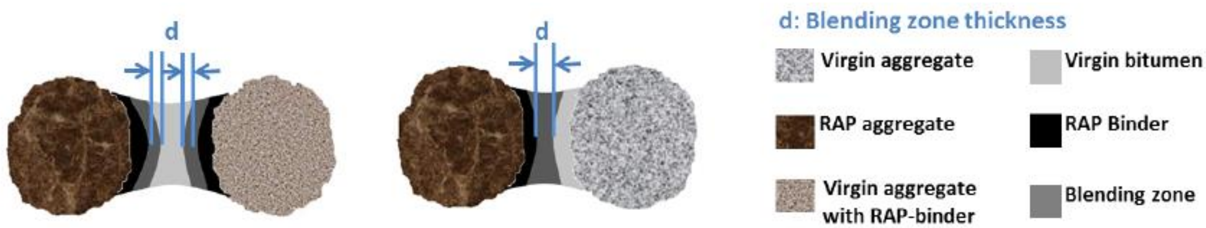

Figure 7. Possibilities for the formation of a blended zone between the RA and virgin aggregate, adapted from [41]

Xu et al. [30] used AFM on the binder obtained after staged extraction of RAM with 50% RA. Results confirmed previous studies [28,36] that non-homogeneous blending occurs between RAb and VB and that higher DoB was found in outside layers than in the inner. Also, it was found out that temperature and storage time have crucial impact on DoB in RAMs.

2.3.2 Computed tomography

Computed tomography (CT) uses many X-ray measurements, taken from various angles, to produce cross-sectional images of a scanned object or area without cutting the sample. There are several variations of CTs. The Environmental Scanning Electron Microscopy (ESEM) has been typically used for microscale characterization, and X-ray Computed Tomography (XCT) has been used for macro scale characterization. XCT inspects interior and exterior material structures, whereas micro computed tomography (micro-CT) enables achieving higher spatial resolution than XCT. These techniques have not helped in quantifying DoB in previous studies, but they have been successfully used to describe it.

Rinaldini et al. [39] concluded that using XCT allows observation of the virgin and RA materials grouped in homogenous, but distinct, clusters of RA and virgin materials. XCT results confirmed the ESEM micrographs, obtained in the same study, that DoB is locally dependent. Mohajeri et al. [48] did not differentiate binders in the RAM using nano-tomography scanning images, but succeed to determine the film thickness.

Cavalli et al. [55] used ESEM and XCT to investigate RAMs with 50% RA concluding that RAb thickness tended to decrease by increasing the mixing temperature, which is in agreement with the assumption that the decrease of RAb thickness is a consequence of the increased DoB level. It was also observed that increased local curvature of the aggregates may influence the RAb film thickness (Figure 8a) and the RAb reactivation (Figure 8b). Results of this research, regarding mixing temperature and micro geometrical inhomogeneity, were confirmed in a following research [24].

a) b)

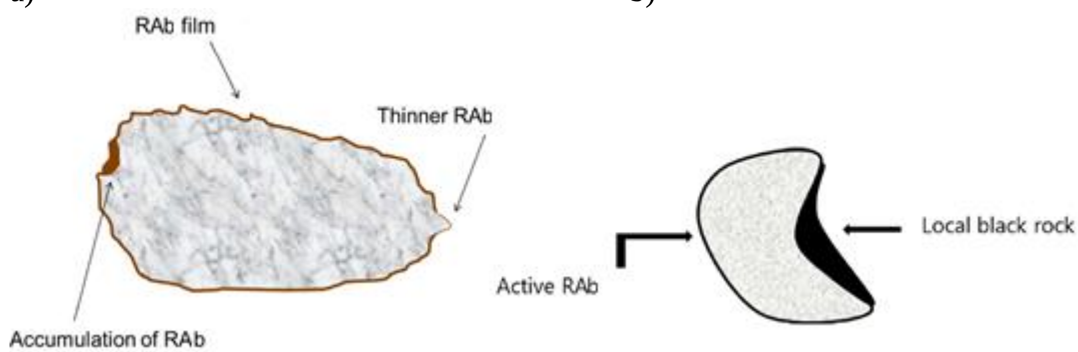

Figure 8. Influence of local curvature on (a) the RA binder thickness and (b) the RAb reactivation, adapted from Cavalli et al. [24]

2.4 Mechanistic approach

The mechanistic approach does not actually include any laboratory tests, but it combines results obtained by using other approaches to estimate DoA, DoAv or DoB. For example, an experimental procedure of the coating study may be simulated using the Finite Element Method (FEM) to predict DoA. This approach covers modelling and numerical simulation techniques.

2.4.1 Modelling techniques

This approach presents the combination of the smaller number of procedures: asphalt mixture testing, mastics or binder testing and adoption with different models. The aim of this approach is to evaluate DoB by comparing the measured dynamic modulus of asphalt mixtures (|E*|) with predicted dynamic modulus from testing of binder recovered from a RAM (Bonaquist approach[56]).

These techniques are usually consisted of following steps: first, asphalt mixture is tested to obtain |E*|; afterwards, the binder is recovered from the same mixture and |G*| is measured; the data are than applied to the Hirsch or any other model, together with volumetric properties of the mixture, to estimate the mixture's |E*| value; estimated |E*| values are compared with the measured |E*| value, where a high correlation of the data indicates a high DoB.

Mogawer et al. [9] investigated HMA's with 20-40% of RA, whereas Mogawer et al. [57] used mixtures with 40% RA. Then, the Bonaquist approach was applied showing that DoB may be affected by the production parameter (discharge temperature) and improved if recycling agents are used. Booshehrian et al. [22] explained how to carry out this procedure, step-by-step, testing mixtures with 20-40% of RA and obtained a good DoB. Results showed that both reheating process and the discharge temperature affects DoB. Delfosse et al. [32] tried to estimate DoB of the HMA mixtures with 20% and 35% RA and WMA with 20%, 40%, 50%, and 70% RA. The difference between measured and estimated values of |E*| was –4.5% and –3% for HMA mixtures, respectively, and –8.5%, 15%, –2.5% and –45% for WMA mixtures, respectively, suggesting that the estimation model should be improved, especially when DoA is poor.

The same conclusion was obtained by Al-Qadi et al. [23] who applied this method to estimate DoB. The results brought to the conclusion that the Hirsch model may not be appropriate to back-calculate |E*| from HMA with RA, and that DoB could not been accurately determined using this method. Ashtiani et al. [58] reached a similar conclusion, but with an estimation that DoB was between 40% and 60% in RAM with 15% RA.

The first attempt of using a micromechanical model to examine DoB was carried out by Gundla & Underwood [34]. Temperature and frequency sweep tests were conducted on mastics containing 10-100% RA that passed through a sieve opening of 0.075 mm. DoB was herein quantified as the amount of non-absorbed RAb combined into a meso-homogeneous mass with the recycling agent. DoB was estimated by a comparison of |G*| predicted using micromechanical modelling and measured |G*|. Predicted |G*| values were obtained using rheological results and the film shell assumption. Results show that DoB decreases as the RA content increases: 100%, 66%, 55% and 31% for the RA content of 10%, 30%, 50% and 100%, respectively.

2.4.2 Numerical simulation techniques

Discrete element methods (DEM) presents a numerical technique for modelling of a material behavior under different conditions by using a large number of independent particles.

Zhang et al. [14] conducted a coating study using different RA contents (10%-50%), virgin aggregate temperature (160-190 °C) and RA moisture content (0- 5%) to investigate their influence on DoA. Further, the particles movement and the applied forces (contact and the force of gravity) were simulated using the three-dimensional DEM. Simulations confirmed the laboratory results: DoA was dependent on RA content, mixing temperature, mixing time and moisture content. With increasing RA content and RA moisture content DoA decreases, while it increases as the virgin aggregate temperature increases. Regarding DoA, DEM results showed higher values compared with laboratory results (0.41%, 1.07% and 0.30% of RAb content for mixtures with 10%, 30% and 50% RA at mixing temperature of 190 °C compared with the laboratory results: 0.16%, 0.21% and 0.16% of RAb content), probably due to limitations of the method (single-sized RA particles were used during modelling). It was also concluded that the mixtures with higher RA content, more moisture and lower virgin aggregate temperature need a longer mixing time or higher virgin aggregate temperature to increase DoA. Overall, DEM has shown the potential for evaluating the qualitative effects of the RA content and virgin aggregate temperature on DoA.

3 Summary of DoA, DoAv and DoB determination approaches – Critical discussion

Despite the research efforts dedicated to investigate the behavior of aged binder in RAMs, there are no common and standardized procedure for quantifying the blending parameters. Due to this fact, a summary of the different methods used for these purposes is prepared, as presented in Table 1.The table shows the review of research which previously contributed to quantifying these parameters, whereas research where these phenomena were only described are not shown. Testing methods, levels of testing (index t), preparation (index p) or both (index p,t), RA content and whether recycling agents (excluding neat asphalt binder) were used or not, are shown as well. Furthermore, Table 1 shows the terms which were originally used in the cited papers and the terms according to the newly proposed definitions from the theoretical framework proposed by Lo Presti et al. [35]. Finally, estimated values of the parameters are also given.

From Table 1 can be seen that DoA was most often quantified by using mechanical blending methods, while DoAv was quantified most often by using both mechanical blending and binder testing methods. DoB has not often been quantified in previous studies, but asphalt mixture testing and microcopy testing methods are probably the most promising.

Table 2 was tailored for summarizing the main advantages and disadvantages of the procedures described in the paper. The same table also recommends which techniques and methods can be used for determining the individual values of each parameter.

Reference	Investigated parameter					Testing methods										Level					Addition of rejuvenator/lubricant	RA content [%]
						Mechanical approach				Chemical approach		Visualization approach		Mechanistic approach								
	Original term	DoA	DoAv	DoB	Estimated value [%]	Mechanical blending	Binder testing	Asphalt mixture testing	Nanoindentation	Chromatography	Spectroscopy	Microscopy	Computed tomography	Modelling techniques	Numerical simulation techniques	Binder (blend)	RA and aggregate	RA, aggregate and recycling agent	Mastics	Asphalt mixture		
[11]	RAb availability factor		✓		50-95	✓												✓$_{p,t}$				30
[14]	Binder transfer	✓			4-24	✓									✓		✓$_{p,t}$					10-50
[16]	Mobilization rate			✓	84-92							✓						✓$_{t}$		✓$_{p}$	✓	50
[18]	RAb mobilization rate			✓	24-100					✓						✓$_{t}$				✓$_{p}$		10-80
[19]	Reactivated RAb			✓	49-74			✓						✓						✓$_{p,t}$		25-40
[26]	Degree of blending		✓		59-85		✓									✓$_{t}$		✓$_{p}$			✓	25
[34]	Blending			✓	31-100		✓												✓$_{p,t}$			10-100

Reference	Investigated parameter					Testing methods										Level					Addition of rejuvenator/lubricant	RA content [%]
						Mechanical approach				Chemical approach		Visualization approach		Mechanistic approach								
	Original term	DoA	DoAv	DoB	Estimated value [%]	Mechanical blending	Binder testing	Asphalt mixture testing	Nanoindentation	Chromatography	Spectroscopy	Microscopy	Computed tomography	Modelling techniques	Numerical simulation techniques	Binder (blend)	RA and aggregate	RA, aggregate and recycling agent	Mastics	Asphalt mixture		
[36]	RAb loss	✓			11	✓											✓$_{p,t}$					10-30
	Blended binder		✓		40		✓									✓$_{t}$		✓$_{p}$				
[37]	RAb transfer	✓			15-24	✓											✓$_{p,t}$					25-35
	Degree of partial blending		✓		70-96	✓	✓									✓$_{t}$		✓$_{p}$				
[40]	Transferred binder	✓			10-12	✓											✓$_{p,t}$					20-35
	Blending ratio		✓		16-87	✓	✓									✓$_{t}$		✓$_{p}$				
[42]	Blending ratio		✓		21-83	✓	✓									✓$_{t}$		✓$_{p}$			✓	20-60
[47]	Degree of blending			✓	37-95			✓												✓$_{p,t}$		50
[50]	Blending ratio		✓		50-76					✓						✓$_{t}$		✓$_{p}$			✓	65

Reference	Investigated parameter					Testing methods										Level					Addition of rejuvenator/lubricant	RA content [%]
						Mechanical approach				Chemical approach		Visualization approach		Mechanistic approach								
	Original term	DoA	DoAv	DoB	Estimated value [%]	Mechanical blending	Binder testing	Asphalt mixture testing	Nanoindentation	Chromatography	Spectroscopy	Microscopy	Computed tomography	Modelling techniques	Numerical simulation techniques	Binder (blend)	RA and aggregate	RA, aggregate and recycling agent	Mastics	Asphalt mixture		
[51]	RAb mobilization		✓		5-40	✓					✓					✓$_{t}$		✓$_{p}$				15-50
	Blending efficiency			✓	30-60		✓				✓					✓$_{t}$				✓$_{p}$	✓	
[53]	Blending ratio			✓	43-100							✓								✓$_{p,t}$	✓	15-50

Table 1. Overview of the methodologies for the assessment of DoA, DoAv and DoB

<table>
<tr><th>Approach</th><th>Testing method/technique</th><th colspan="2">Advantages</th><th colspan="2">Disadvantages</th></tr>
<tr><td rowspan="4">Mechanical approach</td><td>Mechanical blending</td><td colspan="2">• Testing equipment is present in almost every pavement laboratory.
• Test are usually easy to perform and do not require a lot of time and resources.
• Results are easy and quick to analyze.
• Due to simplicity, it is easy to repeat tests under different conditions (mixing time, temperature, RA content, etc.).</td><td colspan="2">• It does not simulate realistic situation from an asphalt plant, as well as the use of an artificial aggregate (steel balls, round-shaped gravel, etc.).
• Cannot be performed on RAM obtained from an asphalt plant.
• Influence of a recycling agent on DoA/DoAv cannot be easily determined without further tests, which typically requires bitumen extraction.</td></tr>
<tr><td>Recommendation:</td><td>DoA: ✓</td><td colspan="2">DoAv: ✓</td><td>DoB: ✗</td></tr>
<tr><td>Binder testing</td><td colspan="2">• Testing equipment is present in almost every pavement laboratory.
• Test are usually easy to perform and do not require a lot of time and resources.
• High potential in analyzing of bitumen levels surrounding RA particles, that may help in determining DoAv.</td><td colspan="2">• Preparation of testing samples is time consuming if staged extraction procedure is applied.
• There is no standardized procedure for staged extraction.
• Bitumen should be recovered from solvent, whereas it may have a negative impact on chemical properties of bitumen.
• Forced blending between the RAb and VB during the extraction procedure might not always reflect what is happening during the mixing phase within a mixture.</td></tr>
<tr><td>Recommendation:</td><td>DoA: ✗</td><td colspan="2">DoAv: ✓</td><td>DoB: ✓</td></tr>
</table>

<table>
<tr><td rowspan="4"></td><td>Asphalt mixture testing</td><td colspan="2">• Testing equipment is present in almost every pavement laboratory.
• Test are usually daily routine in laboratories and do not require a lot of resources for performing.
• Highest potential in determining DoB due to fact that testing samples may be obtained by coring from the field or by compacting RAM obtained from a plant.</td><td colspan="2">• There is not yet proposed a property of RAM that will assess DoB.
• If asphalt samples are obtained from a plant, it is not easy to vary processing conditions (mixing temperature, mixing time, etc.).</td></tr>
<tr><td>Recommendation:</td><td>DoA: ✗</td><td colspan="2">DoAv: ✗</td><td>DoB: ✓</td></tr>
<tr><td>Nanoindentation</td><td colspan="2">• The bitumen film thickness, frequently correlated with DoB, can be precisely measured.</td><td colspan="2">• Testing equipment is not widely-spread in pavement laboratories.
• Not directly linked with any other parameter.
• Testing results are not simple for analyzing.
• Civil engineers have a lack of experience in this field of research.</td></tr>
<tr><td>Recommendation:</td><td>DoA: ✗</td><td colspan="2">DoAv: ✗</td><td>DoB: ✓</td></tr>
<tr><td rowspan="2">Chemical approach</td><td>Chromatography</td><td colspan="2" rowspan="2">• Testing time is relatively quick (up to 30 min) and do not require huge amount of material.
• Chemical characteristics of RAb can be determined and help in evaluation of DoAv or DoB.
• Presence of recycling agent, polymer or solvent in binder blend can be detected.
• Impact of recycling agent on chemical properties of bitumen can be determined.</td><td colspan="2" rowspan="2">• Key mixture's parameters are usually related to microstructure, so these types of tests are not yet typical for the pavement industry.
• Analysis of testing results may be complicated and time consuming.
• Tests are typically performed on binders obtained after extraction procedure, causing the same problem as with mechanical methods – forced blending and</td></tr>
<tr><td>Spectroscopy</td></tr>
</table>

				• negative influence of solvent. • Parameters used to evaluate DoAv and DoB are not yet widely established.
	Recommendation:	DoA: ✗	DoAv: ✓	DoB: ✓
Visualization approach	Microscopy	• Non-destructive methods. • There is a possibility to combine a couple of methods (e.g. with EDS) to determine DoB. • The use of tracer materials allows the determination of the distribution of RAb throughout RAMs, thus verifying the existence of the blending phenomenon and overall, at least describing DoB. • The interface between RAb and VB can be observed and cracks detected.		• The use of tracers is not reasonable during production of RAM at an asphalt plant. • Equipment is expensive and not widely spread in pavement laboratories. • Handling is complex and analysis of testing results is time consuming. • Requires additional knowledge from image analysis.
	Recommendation:	DoA: ✗	DoAv: ✗	DoB: ✓
	Computed tomography	• Analysis of samples is possible without their destruction. • The existence of the blending phenomenon and at least describing DoB are possible.		• Equipment is expensive, not widely spread in pavement laboratories. • Handling is complex and analysis of testing results is time consuming.
	Recommendation:	DoA: ✗	DoAv: ✗	DoB: ✓
Mechanistic approach	Modelling techniques	• Testing methods required for determination of |G*| and |E*| are usually carried out routinely in laboratories, on laboratory prepared or field cored specimens. • Back-calculation can be conducted very quickly.		• They are typically a combination of different testing methods, so it may be time consuming. • A wider knowledge of researchers/technicians for testing and interpretation of the results is required.

		• Obtained results strongly depend on the properties of material's components and testing conditions, which may be simulated using modelling techniques. • These techniques may able to quantify DoB, even though it has been typically used for description of DoB.	• Due to inhomogeneity of the RA, most of these methods are not reliable enough. For example, Bailey's method should be adjusted when RA is used due to the presence of irregular grains. Furthermore, due to the different behaviour of RAb, the Hirsch model might not provide an appropriate estimation of the mixture dynamic modulus.	
	Recommendation:	DoA: ✗	DoAv: ✗	DoB: ✓
	Numerical simulation techniques	• High potential to be used in assessment of blending parameters. • Processing conditions can be easily changed in simulations.	• There are many parameters which should be considered during simulation (contact forces between particles, behavior of binder blend, etc.). • Laboratory tests may be required in order to obtain input parameters. • High variability of RA may cause problems with models.	
	Recommendation:	DoA: ✓	DoAv: ✓	DoB: ✓

Table 2. Advantages and disadvantages of testing method summarized by recommended approaches

4 Conclusions

Common guidelines and protocols for determining blending parameters (DoA, DoAv and DoB) can contribute to support performance-based design practices and avoid problems with under or over dosage of recycling agent in RAMs, thus allowing a confident increase of reclaimed asphalt. However, there is still a challenge to develop methodologies which will help in determining these parameters.

Within this process, it is first necessary to work on characterizing RA and second to work on adapting methodology of mix design procedure what would allow for this new family of material to be considered as any other material in asphalt mixture production. This paper aims to provide scientific community with review of methodologies that would allow people to find the best methodologies to measure these parameters, which we do believe are vital to improve the current practices.

General conclusions, regarding methodologies for determining DoA, DoAv and DoB are the following:

- There are no overall accepted procedures for determining any of these parameters, thus new standard test method(s) should be developed, or one of the existing methods should be adopted, to make them measurable and quantitatively indicated for mixture design purposes;
- Measured values of these parameters were variable in previous studies due to various RA sources, different testing and processing conditions and various methodologies used.
- Some previous research, which quantified these parameters, should be repeated with other materials in order to validate these methods;

Correlation between testing methods should be established, since it is not always possible to conduct all the methods proposed.

During the development of new methodologies, it is necessary to consider influencing parameters, such as mixing time, temperature, and presence of recycling agents due to the fact that they are not unequivocally defined, so further studies should determine the correlations between them, and possibly establish models.

Newly developed methodologies should be further verified through the round robin or inter-laboratory tests due to the complex and heterogeneous nature of the RA. Methodologies should be further included in guidelines, protocols and mix design procedures, and possibly validated with a field trial section.

Acknowledgments

The authors want to acknowledge the asphalt technologists of the RILEM Technical Committee 264 RAP for the fruitful discussions and feedback that have significantly enriched the paper. The first author is supported by the Ministry of Education, Science and Technological Development of the Republic of Serbia through the research project TR 36017 “Utilization of by-products and recycled waste materials in concrete composites in the scope of sustainable construction development in Serbia: investigation and environmental assessment of possible applications” and bilateral project “Hot mix Asphalt with high Reclaimed Asphalt Content (HARAC)” and these supports are gratefully acknowledged. The second author is supported by Conselho Nacional de Desenvolvimento Científico e Tecnologico, CNPq – Brazil [grant number 200279/2014-9].

References

[1] A. Copeland, Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice, McLean, 2011. doi:10.1016/j.proeng.2016.06.119.

[2] B. Colbert, Z. You, The determination of mechanical performance of laboratory produced hot mix asphalt mixtures using controlled RAP and virgin aggregate size fractions, Constr. Build. Mater. 26 (2012) 655–662. doi:10.1016/j.conbuildmat.2011.06.068.

[3] H.M.R.D. Silva, J.R.M. Oliveira, C.M.G. Jesus, Are totally recycled hot mix asphalts a sustainable alternative for road paving?, Resour. Conserv. Recycl. 60 (2012) 38–48. doi:10.1016/j.resconrec.2011.11.013.

[4] P.C. Boriack, S.W. Katicha, G.W. Flintsch, C.R. Tomlinson, Laboratory Evaluation of Asphalt Concrete Mixtures Containing High Contents of Reclaimed Asphalt Pavement (RAP) and Binder, Virginia, 2014. http://www.virginiadot.org/vtrc/main/online_reports/pdf/15-r8.pdf.

[5] E.D. Anderson, J.S. Daniel, Long-Term Performance of Pavement with High Recycled Asphalt Content Case Studies, (2013) 1–12. doi:10.3141/2371-01.

[6] D. Vukosavljevic, Fatigue Characteristics of Field HMA Surface Mixtures Containing Recycled Asphalt Pavement (RAP), University of Tennessee - Knoxville, 2006. http://trace.tennessee.edu/utk_gradthes/1829.

[7] X. Shu, B. Huang, D. Vukosavljevic, Laboratory evaluation of fatigue characteristics of recycled asphalt mixture, 22 (2008) 1323–1330. doi:10.1016/j.conbuildmat.2007.04.019.

[8] G. Valdés, F. Pérez-jiménez, R. Miró, A. Martínez, R. Botella, Experimental study of recycled asphalt mixtures with high percentages of reclaimed asphalt pavement (RAP), 25 (2011) 1289–1297. doi:10.1016/j.conbuildmat.2010.09.016.

[9] W. Mogawer, T. Bennert, J.S. Daniel, R. Bonaquist, A. Austerman, A. Booshehrian, Performance characteristics of plant produced high RAP mixtures, Road Mater. Pavement Des. 13 (2012) 183–208. doi:10.1080/14680629.2012.657070.

[10] M. Sabouri, T. Bennert, J.S. Daniel, Y.R. Kim, A comprehensive evaluation of the fatigue behaviour of plant-produced RAP mixtures, Road Mater. Pavement Des. 16 (2015) 29–54. doi:10.1080/14680629.2015.1076997.

[11] F. Kaseer, E. Arámbula-Mercado, A.E. Martin, A Method to Quantify Reclaimed Asphalt Pavement Binder Availability (Effective RAP Binder) in Recycled Asphalt Mixes, Transp. Res. Rec. J. Transp. Res. Board. (2019) 036119811882136. doi:10.1177/0361198118821366.

[12] D. Lo Presti, A. Jimenez del Barco Carrion, G. Airey, E. Hajj, Towards 100% recycling of reclaimed asphalt in road surface courses: Binder design methodology and case studies, J. Clean. Prod. 131 (2016) 43–51. doi:10.1016/j.jclepro.2016.05.093.

[13] H. Ozer, I.L. Al-qadi, A.I. Kanaan, D.L. Lippert, Performance Characterization of Asphalt Mixtures at High Asphalt Binder Replacement with Recycled Asphalt Shingles, (n.d.). doi:10.3141/2371-12.

[14] K. Zhang, H. Wen, A. Hobbs, Laboratory Tests and Numerical Simulations of Mixing Superheated Virgin Aggregate with Reclaimed Asphalt Pavement Materials, Transp. Res. Rec. J. Transp. Res. Board. 2506 (2015) 62–71. doi:10.3141/2506-07.

[15] S. Bressi, M.C. Cavalli, M.N. Partl, G. Tebaldi, A.G. Dumont, L.D. Poulikakos, Particle clustering phenomena in hot asphalt mixtures with high content of reclaimed asphalt pavements, Constr. Build. Mater. 100 (2015) 207–217. doi:10.1016/j.conbuildmat.2015.09.052.

[16] Y. Ding, B. Huang, X. Shu, Blending efficiency evaluation of plant asphalt mixtures using fluorescence microscopy, Constr. Build. Mater. 161 (2018) 461–467. doi:10.1016/j.conbuildmat.2017.11.138.

[17] S. Vassaux, V. Gaudefroy, L. Boulangé, L.J. Soro, A. Pévère, A. Michelet, V. Barragan-Montero, V. Mouillet, Study of remobilization phenomena at reclaimed asphalt binder/virgin binder interphases for recycled asphalt mixtures using novel microscopic methodologies, Constr. Build. Mater. 165 (2018) 846–858. doi:10.1016/j.conbuildmat.2018.01.055.

[18] S. Zhao, B. Huang, X. Shu, M.E. Woods, Quantitative Characterization of Binder Blending: How Much Recycled Binder Is Mobilized During Mixing?, Transp. Res. Rec. J. Transp. Res. Board. 2506 (2015) 72–80. doi:10.3141/2506-08.

[19] A. Stimilli, A. Virgili, F. Canestrari, New method to estimate the “re-activated” binder amount in recycled hot-mix asphalt, Road Mater. Pavement Des. 16 (2015) 442–459. doi:10.1080/14680629.2015.1029678.

[20] D. Abd, H. Al-Khalid, R. Akhtar, Novel Methodology to Investigate and Obtain a Complete Blend between RAP and Virgin Materials, J. Mater. Civ. Eng. 30 (2018) 1–12. doi:10.1061/(ASCE)MT.1943-5533.0002230.

[21] C. Castorena, S. Pape, C. Mooney, Blending Measurements in Mixtures with Reclaimed Asphalt, Transp. Res. Rec. J. Transp. Res. Board. 2574 (2016) 57–63. doi:10.3141/2574-06.

[22] A. Booshehrian, W.S. Mogawer, R. Bonaquist, How to Construct an Asphalt Binder Master Curve and Assess the Degree of Blending between RAP and Virgin Binders, J. Mater. Civ. Eng. 25 (2013) 1813–1821. doi:10.1061/(ASCE)MT.1943-5533.0000726.

[23] I. Al-Qadi, S. Carpenter, G. Roberts, H. Ozer, Q. Aurangzeb, M. Elseifi, J. Trepanier, Determination of Usable Residual Asphalt Binder in RAP, 2009. http://hdl.handle.net/2142/13714.

[24] M.C. Cavalli, M.N. Partl, L.D. Poulikakos, Measuring the binder film residues on black rock in mixtures with high amounts of reclaimed asphalt, J. Clean. Prod. 149 (2017) 665–672. doi:10.1016/j.jclepro.2017.02.055.

[25] S. Coffey, E. Dubois, Y. Mehta, C. Purdy, Determine the Impact of Degree of Blending between Virgin and Reclaimed Asphalt Binder on Predicted Pavement Performance using Mechanistic-Empirical Design Guide (MEPDG), in: Transp. Res. Board 92nd Annu. Meet., Washington, D.C., 2013.

[26] L. Gaitan, Y. Mehta, A. Nolan, E. Dubois, S. Coffey, L. McCarthy, A. Welker, Evaluation of the Degree of Blending and Polymer Degradation of Reclaimed Asphalt Pavement (RAP) for Warm Mix Asphalt, J. Solid Waste Technol. Manag. 39 (2013) 101–113.

doi:10.5276/JSWTM.2013.101.

[27] A. Liphardt, P. Radziszewski, J. Król, Binder blending estimation method in hot mix asphalt with reclaimed asphalt, Procedia Eng. 111 (2015) 502–509. doi:10.1016/j.proeng.2015.07.123.

[28] B.F. Bowers, B. Huang, X. Shu, B.C. Miller, Investigation of Reclaimed Asphalt Pavement blending efficiency through GPC and FTIR, Constr. Build. Mater. 50 (2014) 517–523. doi:10.1016/j.conbuildmat.2013.10.003.

[29] Y. Ding, B. Huang, X. Shu, Characterizing blending efficiency of plant produced asphalt paving mixtures containing high RAP, Constr. Build. Mater. 126 (2016) 172–178. doi:10.1016/j.conbuildmat.2016.09.025.

[30] J. Xu, P. Hao, D. Zhang, G. Yuan, Investigation of reclaimed asphalt pavement blending efficiency based on micro-mechanical properties of layered asphalt binders, Constr. Build. Mater. 163 (2018) 390–401. doi:10.1016/j.conbuildmat.2017.12.030.

[31] S. Zhao, B. Huang, X. Shu, M.E. Woods, Quantitative evaluation of blending and diffusion in high RAP and RAS mixtures, Mater. Des. 89 (2016) 1161–1170. doi:10.1016/j.matdes.2015.10.086.

[32] F. Delfosse, I. Drouadaine, S. Largeaud, S.F. Dumont, Performance control of bituminous mixtures with a high RAP content, in: K. Suchý, J. Valentin, M. Southern, C. Karcher, H. Odelius, J.P. Michaut, F. Cointe (Eds.), 6th Eurasphalt Eurobitume Congr., Czech Technical University in Prague, Prague, Czech Republic, 2016. doi:dx.doi.org/10.14311/EE.2016.050.

[33] J.W.H. Oliver, The Influence of the Binder in RAP on Recycled Asphalt Properties, Road Mater. Pavement Des. 2 (2001) 311–325. doi:10.1080/14680629.2001.9689906.

[34] A. Gundla, S. Underwood, Evaluation of in situ RAP binder interaction in asphalt mastics using micromechanical models, Int. J. Pavement Eng. 18 (2015) 798–810. doi:10.1080/10298436.2015.1066003.

[35] D. Lo Presti, K. Vasconcelos, M. Orešković, M. Pires, S. Bressi, On the degree of binder activity of reclaimed asphalt and degree of blending with recycling agents, Road Mater. Pavement Des. (2019). doi:10.1080/14680629.2019.1607537.

[36] B. Huang, G. Li, D. Vukosavljevic, X. Shu, B.K. Egan, Laboratory Investigation of Mixing Hot-Mix Asphalt with Reclaimed Asphalt Pavement, Transp. Res. Rec. J. Transp. Res. Board. 1929 (2005) 37–45. doi:http://dx.doi.org/10.1080/14680629.2014.926625.

[37] P. Shirodkar, Y. Mehta, A. Nolan, K. Sonpal, A. Norton, C. Tomlinson, E. Dubois, P. Sullivan, R. Sauber, A study to determine the degree of partial blending of reclaimed asphalt pavement (RAP) binder for high RAP hot mix asphalt, Constr. Build. Mater. 25 (2011) 150–155. doi:10.1016/j.conbuildmat.2010.06.045.

[38] M. Orešković, S. Bressi, G. Di Mino, D. Lo Presti, Influence of bio-based additives on RAP clustering and asphalt binder rheology, in: A. Loizos, I. Al-Qadi, T. Scarpas (Eds.), Proc. Tenth Int. Conf. Bear. Capacit. Roads, Railw. Airfields, CRC-Taylor & Francis Group, Athens, Greece, 2017: pp. 1301–1306.

[39] E. Rinaldini, P. Schuetz, M.N. Partl, G. Tebaldi, L.D. Poulikakos, Investigating the blending of reclaimed asphalt with virgin materials using rheology, electron microscopy and computer tomography, Compos. Part B Eng. 67 (2014) 579–587. doi:10.1016/j.compositesb.2014.07.025.

[40] B. Gottumukkala, D. Ph, S.R. Kusam, V. Tandon, A.M. Asce, Estimation of Blending of Rap Binder in a Recycled Asphalt Pavement Mix, 30 (2018) 1–8. doi:10.1061/(ASCE)MT.1943-5533.0002403.

[41] S. Nahar, M. Mohajeri, A. Schmets, A. Scarpas, M. van de Ven, G. Schitter, First Observation of Blending-Zone Morphology at Interface of Reclaimed Asphalt Binder and Virgin Bitumen, Transp. Res. Rec. J. Transp. Res. Board. 2370 (2013) 1–9. doi:10.3141/2370-01.

[42] S. Yu, S. Shen, C. Zhang, W. Zhang, X. Jia, Evaluation of the blending effectiveness of reclaimed asphalt pavement binder, J. Mater. Civ. Eng. 29 (2017) 1–8. doi:10.1061/(ASCE)MT.1943-5533.0002095.

[43] J. Stephens, J. Mahoney, C. Dippold, Determination of the PG binder grade to use in a RAP mix, 2001. https://rosap.ntl.bts.gov/view/dot/14366.

[44] M. Gaspar, K. Vasconcelos, M. Lopes, L. Bernucci, Evaluation of Binder Blending on Hot and Warm Mix Recycling, in: ISAP 2018 Proc., Fortaleza, Brazil, 2018.

[45] R.S. McDaniel, H. Soleymani, R.M. Anderson, P. Turner, R. Peterson, Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method. NCHRP Web Document 30 (Project D9-12), 2000. http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w30-a.pdf.

[46] S. Bressi, A.G. Dumont, M.N. Partl, A new laboratory methodology for optimization of mixture design of asphalt concrete containing reclaimed asphalt pavement material, Mater. Struct. 49 (2016) 4975–4990. doi:10.1617/s11527-016-0837-1.

[47] A. Abed, N. Thom, D. Lo Presti, Design considerations of high RAP-content asphalt produced at reduced temperatures, Mater. Struct. Constr. 51 (2018) 1–16. doi:10.1617/s11527-018-1220-1.

[48] M. Mohajeri, A.A.A. Molenaar, M.F.C. Van de Ven, Experimental study into the fundamental understanding of blending between reclaimed asphalt binder and virgin bitumen using nanoindentation and nano-computed tomography, Road Mater. Pavement Des. 15 (2014) 372–384. doi:10.1080/14680629.2014.883322.

[49] S. Zhao, B. Bowers, B. Huang, X. Shu, Characterizing Rheological Properties of Binder and Blending Efficiency of Asphalt Paving Mixtures Containing RAS through GPC, J. Mater. Civ. Eng. 26 (2014) 941–946. doi:10.1061/(ASCE)MT.1943-5533.0000896.

[50] B.F. Bowers, J. Moore, B. Huang, X. Shu, Blending efficiency of reclaimed asphalt pavement: An approach utilizing rheological properties and molecular weight distributions, Fuel. 135 (2014) 63–68. doi:10.1016/j.fuel.2014.05.059.

[51] A. Sreeram, Z. Leng, Y. Zhang, R.K. Padhan, Evaluation of RAP binder mobilisation and blending efficiency in bituminous mixtures : An approach using ATR-FTIR and artificial

aggregate, Constr. Build. Mater. 179 (2018) 245–253. doi:10.1016/j.conbuildmat.2018.05.154.

[52] S.K. Sharma, ed., X-Ray Spectroscopy, InTech, 2012. http://www.issp.ac.ru/ebooks/books/open/X-Ray_Spectroscopy.pdf.

[53] Y. Jiang, X. Gu, Z. Zhou, F. Ni, Q. Dong, Laboratory Observation and Evaluation of Asphalt Blends of Reclaimed Asphalt Pavement Binder with Virgin Binder using SEM/EDS, Transp. Res. Rec. (2018) 1–10. doi:10.1177/0361198118782023.

[54] J. Navaro, D. Bruneau, I. Drouadaine, J. Colin, A. Dony, J. Cournet, Observation and evaluation of the degree of blending of reclaimed asphalt concretes using microscopy image analysis, Constr. Build. Mater. 37 (2012) 135–143. doi:10.1016/j.conbuildmat.2012.07.048.

[55] M.C. Cavalli, M. Griffa, S. Bressi, M.N. Partl, G. Tebaldi, L.D. Poulikakos, Multiscale imaging and characterization of the effect of mixing temperature on asphalt concrete containing recycled components, J. Microsc. 264 (2016) 22–33. doi:10.1111/jmi.12412.

[56] R. Bonaquist, Laboratory Evaluation of Hot Mix Asphalt (HMA) Mixtures Containing Recycled or Waste Product Materials Using Performance Testing, Publication FHWAPA-2005-006+98-32(19), 2005.

[57] W. Mogawer, A. Booshehrian, S. Vahidi, A.J. Austerman, Evaluating the effect of rejuvenators on the degree of blending and performance of high RAP, RAS, and RAP/RAS mixtures, Road Mater. Pavement Des. 14 (2013) 193–213. doi:10.1080/14680629.2013.812836.

[58] M.Z. Ashtiani, W.S. Mogawer, A.J. Austerman, A Mechanical Approach to Quantify Blending of Aged Binder from Recycled Materials in New Hot Mix Asphalt Mixtures, Transp. Res. Rec. J. Transp. Res. Board. 2672 (2018) 107–118. doi:10.1177/0361198118787634.