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A CRITICAL REVIEW ON MIXING PARAMETERS FOR HIGH CONTENT RECLAIMED ASPHALT MIXTURES

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Abstract. High content reclaimed asphalt (RA) mixtures have been identified as one of the options to reduce the environmental and economic impacts of pavements construction. However, the process of designing and producing high content RA mixtures is challenging and the asphalt industry have serious concerns towards quality and long-term performance these mixtures. In laboratory, several parameters affect mixture characteristic, and if not controlled, may results into inaccurate estimation of performance. This state-of-the-art study aims to identify critical parameters for high content RA mixture production and highlight the effects of these parameters on mixture performance. The mixing parameters adopted in several laboratory studies have been highlighted and compared. The best practices to mix recycled asphalt in laboratory are reviewed in order to optimize the laboratory mixing. Based on review, important considerations for evaluating laboratory performance have been discussed.

Keywords: reclaimed asphalt pavement; high RAP; laboratory mixing, plant production

1. Introduction

Recycling of asphalt pavements is not a new concept. Although the use of reclaimed asphalt (RA) from old pavement for building and maintaining new roads is now considered as an environment friendly alternative to conventional hot mix asphalt (HMA). It originated in 1970s primarily to improve the economics of pavement construction after the Arab oil embargo when the cost of asphalt was increasing significantly (Kandhal and Mallick, 1997). Until this time, the cost of virgin asphalt was lower than the cost for processing RA, which provided no incentive for using RA materials (J. Don Brock, and Jeff L. Richmond, 2010). During the past few years, there has been a major breakthrough in recycling of pavements and increasingly large amount of reclaimed asphalt (RA) material is being re-used in production of new asphalt. The use of RA material in new pavements not only reduces the consumption of natural resources but also addresses problems like disposal of milled RA. It truly creates a cycle that sustains the asphalt pavement industry (Copeland, 2011).

A logical approach to enhance the cost-effectiveness and mitigate the environmental impact of pavement construction is to use larger amounts of reclaimed asphalt (Mogawer Walaa S. et al., 2015). This can only be possible when asphalt mixtures are designed with high content of RA material. Although possible, but the use of reclaimed asphalt (RA) in base layers or shoulder material may not be the most economical available option (Willis et al., 2012). A recent life cycle cost assessment study shows that agency cost was reduced by about 18% when 40% RA material was used in HMA (Qiao et al. 2019). Several other studies have also shown that the amount of savings can increase exponentially when a greater percentage of RA material is incorporated in the asphalt mixtures (Franke et al. 2014; Hong et al. 2016). However, the process of designing and manufacturing high RA mixtures is challenging compared to conventional asphalt and requires much more experience (Zaumanis and Mallick, 2015). Moreover, the asphalt industry has some serious concerns about the quality and long-term performance of pavements with high content RA materials.

The binder available in reclaimed asphalt is excessively stiff as a result of oxidation of bitumen during its lifetime. Hence, the resultant mixture with high content RA may be “overly stiff” and experience issues such as low-temperature cracking failure (Copeland, 2011). Therefore, for high RA content, it becomes necessary to change the mix design by using rejuvenators, additives, or softer binder, etc (Rathore et. al., 2019; Izaks et. al. 2020). AASHTO M323, 2012 guidelines suggest no change in binder when RA content is less than 15%, one grade softer binder to be used for 15-25% RA and using blending charts for more than 25% RA mixtures. However, these guidelines assume complete blending of oxidized RA binder with the virgin binder. As observed by from different studies, 100% blending does not happen (Bowers et al., 2014; Gottumukkala et al., 2018; W. S. Mogawer et al., 2013). Assuming complete blending can cause problems in predicting the pavement performance in laboratory, especially for long-term properties, such as fatigue (Carpenter and Wolosick, 1980). On the other hand, assuming lower blending than actual may overrate the binder quantity requirement and can ultimately lead to plastic deformation of the mix (Al-Qadi et al., 2007). Therefore, it is important to conduct extensive blending characterisation study of RA binder and develop mix design for high content RA mixtures.

As RA percentage is increased (>50%), incorporating recycling agents, commonly known as "rejuvenators" into the mix offer many unique benefits as compared to the use of softer binders (Zaumanis and Mallick, 2013). These recycling agents replace the oils lost during aging process and balance the bitumen proportions such that it is no longer brittle. Some studies also show that oxidation effect can be less severe on the rejuvenated bitumen than on the virgin one as rejuvenators have the ability to mechanically restore the aged binder (Bocci et al., 2019; Cavalli et al., 2018). But it is important to determine the quantity of rejuvenator required for a particular RA mixture as incorrect design may lead to premature distresses in pavement. A rational procedure should be developed to determine dosage of rejuvenator in order to balance the softening effect of rejuvenator (W. Mogawer et al., 2013). Some studies have developed the methods for determination of rejuvenator dosage for RA mixtures (Im et al., 2016; Zaumanis et al., 2014).

There has been wide research showing that these mixes can perform equal to or sometimes even better than conventional hot mix asphalt (Mhlongo et al., 2014; Zaumanis et al., 2018a). However, the performance of mixtures in the laboratory depends upon various parameter that must be carefully controlled for accurate estimation (Rathore et al. 2020). For example, the parameters: plant type, production temperature, mixing time, discharge temperature, storage time, RA source, RA properties, and virgin binder grade etc. can impact the properties of high content RA mixtures (Mogawer et al., 2012). It is clear that the mix results obtained in laboratory cannot be directly applied to predict the performance of mixture in field. The studies should focus on simulating the plant mixing conditions in the laboratory for an accurate evaluation of performance.

2. Objective and Scope

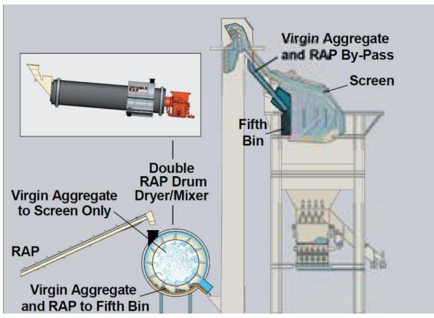
The main objective of this paper is to present a critical review highlighting the importance of laboratory mixing parameters in performance evaluation for high content RA mixture. This study will identify the parameters involved in plant production of high content RA mixtures and form a comparison with mixing process adopted in the laboratory. In the first section, several parameters linked with plant production of high content RA mixture were highlighted and their impact on mixture properties were summarized from available literature. In the next section, the effect of laboratory mixing parameters on performance of high content RA mixtures is presented. Finally, a conclusion is made recommending the important consideration to be taken for mixing high content RA mixtures in the laboratory.

3. Plant production parameters

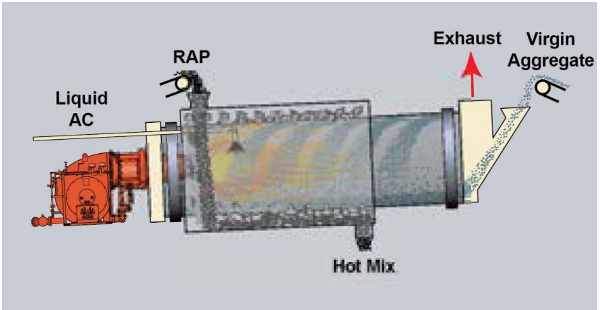
The plant production parameters of conventional hot mixing are generally not affected when low amount of RA is added to asphalt mixtures. Since, at low RA content (10-20%), there is not enough aged binder present in mixture to change the total binder properties (NCHRP Report 452). However, at high RA content (>25%), various considerations and/or modifications are required to the asphalt plant (Stroup-Gardiner, 2016). Some of these production parameters for high RA content mixtures are described in this section.

3.1. RA heating process during production

The aggregates are required to be heated at high temperature to allow complete drying and to reach uniform temperature throughout the aggregate structure for mixing. For hot mix asphalt production, all the constituent materials are heated at their desired production temperature typically around 150°-190°C (Rubio et al. 2012). The recycling of asphalt can be categorized as warm/hot recycling and cold recycling depending upon the heating temperature of RA material. The warm/hot recycling uses a dual-drum system to dry and preheat RA materials at temperatures range of 110–160°C and virgin aggregates at the temperature range of 190–250°C simultaneously before mixing them together (Zhang et. al., 2019). On the other hand, cold feed recycling uses RA material to be added at ambient temperature using a double drier drum to avoid direct contact of RA material to the flame. In asphalt plants when low RA contents are used, RA is either used as unheated aggregates or heated at very low temperature to remove the moisture. Though, using unheated RA has shown lower stiffness and poor blending of oxidized and virgin binder (Pérez Madrigal et al., 2016). On the contrary, it is also recommended not to heat RA to very high temperatures in order to avoid extra oxidation of binder as well as emissions from RA (Rathore et al. 2019). The batch plant and drum plant can incorporate up to 35% RA and 50% RA into asphalt mixtures, respectively depending on the superheating capacity and emission regulations (Brock 2007; Liu et. al. 2017). Figure 1 shows the batch plant with double drum dryer and Double Barrel® combination dryer/mixer.



(a)



(b)

Figure 1. (a) Batch plant with double RA dryer; (b) Double Barrel® combination dryer/mixer (Brock and Richmond 2007)

3.2. RA mixing process during production

In a conventional drum plant, a center entry is used to introduce RA material to the superheated virgin aggregates. It is expected that the superheated aggregates will heat the RA material and melt its binder. However, due to short mixing time available, complete melting of binder may not be possible (Dedene et al., 2014). Moreover, overheating of RA material may result into excessive gases and sticking of RA on preheating facilities. The above technical and environmental concerns led to the development of new drying and processing technologies, such as the counterflow drum mixer, (NAPA, 1996). Most modern plants now are designed to handle higher percentages of RA by adding the RA downstream of the burner in a counter-flow dryer arrangement thus providing longer mixing time (West, 2015). Further, double and triple drum mix plants were developed to prevent the virgin and RA materials from being exposed to hot gases or steam of the drying process (FHWA, 2019).

In asphalt plants, the RA material mixing with the virgin aggregates and binder takes places in two stages that are known as “dry mixing” and “wet mixing” process. In the first stage, RA material at ambient temperature is introduced with superheated virgin aggregates, and later the combination of RA and virgin aggregate is mixed with virgin binder (Brock and Richmond 2005). The dry mixing stage enhances the RA binder activation, and the wet mixing process distributes the binder uniformly and increases the diffusion between virgin binder and RA binder. The above two mixing process can take place either in a single drum of parallel/counterflow mixer or in a mixer accompanied with an outer coating chamber. The total mixing time in a pugmill is typically around 30–60 s and longer in the outer mixing chamber of the drum mixers approximately 40–90 s (Zhang et al. 2019). Depending on the plant type the total production cycle varies between 60 s, for both batch and drum plants, and 90 s for double barrel drum plants (Antunes et. al. 2019).

3.3. RA mixing temperature during production

Mixing of aggregates and asphalt has to be done at an appropriately selected temperature. The mixing temperature controls the dryness of the aggregates, the quality of the mixture, the time it takes for the mix to cool down during laying and the ease of compaction during paving (Shenoy, 2001). It will not be possible to have a uniform coating of bitumen over aggregates at lower mixing temperature. On the contrary, mixing temperature that is too high will make the bitumen to rapidly age and increase the cracking susceptibility of mix. There are several methods for determination of mixing temperatures including equiviscous method, phase angle procedure, and steady shear flow procedure (Asphalt Institute, 2014a, West C. Randy, Donald E. Watson, , Pamela A. Turner, 2010). It was observed that the linear temperature-viscosity relationship assumed for unmodified binders may not be valid for modified asphalt binders (Gayle E. Albritton, PE William F. Barstis, PE Alfred B. Crawley, 1999). The researchers hypothesized that this was due to the fact that most of the modified binders were sensitive to shear rate and therefore did not meet the current assumption of all binders as Newtonian fluids (Asphalt Institute, 2014b)

When high RA content is used, generally a higher virgin aggregates temperature is required to attain sufficient mix temperature in order to compensate the lower heating temperatures of RA. A laboratory study showed that for 50% RA mixtures, it was required to heat the virgin aggregates at 220°C to reach a mix temperature of 150°C where RA was heated at 120°C (Yu et al., 2017). The required superheating temperatures of virgin aggregates for 50% RA mixture production for different moisture contents of RA are given in Table 1. The shaded region shows excessively high temperatures that are not realistically achievable.

Table 1. Virgin Aggregates temperature requirement at asphalt plant corresponding to discharge mix temperature for 50% RA: 50% aggregate mix* (NAPA, 1996).

RA Moisture Content	Recycled mix discharges temperature, °C			
	104°C	116°C	127°C	137°C
	Virgin aggregates temperature requirement, °C			
0	210	235	257	282
1	241	268	288	310
2	271	293	318	343
3	302	327	349	374
4	338	360	377	404
5	366	391	413	438

*20˚F loss between dryer and pugmill assumed in these calculations

3.4. Rejuvenator application during production

®A method is widely used in Japan, where rejuvenators are mixed with heated RA in a small pugmill and then transferred to a surge bin to give additional conditioning time (2–3 hours) (West and Copeland, 2015). The finished mix with typical temperature of 160°C is very well coated and uniform even before it is transferred to the silo (West and Copeland, 2015). In a study by Zaumanis et al., 2018b, a conventional approach of adding rejuvenator on hot RAP into mixer was compared to a rather innovative approach- spraying rejuvenator on cold RA at conveyer belt. No significant difference was observed from extracted binder properties in both the cases (Zaumanis et al., 2018b). However, the mixture test results demonstrated potentially improved fatigue life in sprayed rejuvenator mix due to improved blending of the materials (Zaumanis et al., 2019).

4. Laboratory mixing parameters

The key elements in mixing process of high content RA mixtures are similar to conventional hot mix asphalt which includes the mixture design (selection of aggregate gradation, asphalt content, additive dosage etc.), heating and mixing of raw materials, conditioning, and compaction of mixtures. However, when high content of RA material is used in mixture, the mixing parameters can have an important effect on mixture properties (Rathore & Zaumanis 2020). The important parameters of mixing in the laboratory have been described in the sections below.

Table 2 summarizes the information mixing parameters adopted in the laboratory studies for high content RA mixtures. The RA content considered in these studies was from 40% and upto 100%. Based on these studies, the most commonly used RA material heating temperature was 110°C and heating time was 2 h. However, when high content upto 100% RA was considered, the heating temperature of RA material was increased even above 155°C (Moniri et. al. 2019; Daryaee et. al., 2020). The mixing temperature for HMA mixtures was around 155-165°C and for WMA mixtures was around 120-130°C. The information about the mixing time was not reported in most of the studies. Another important information that was not reported by most of the authors was the rejuvenator/ additive application method. One study considered two mixing methods i.e. adding rejuvenator directly to RA material vs adding rejuvenator. It was found for 50% RA mixtures; moisture resistance was enhanced when rejuvenator was added directly to the RA material.

Table 2. Laboratory mixing parameters adopted in recent high RA content studies

Reference	RA % upto	RA material heating temperature	RA material heating time	Mixing temperature	Mixing time	Rejuvenator/ additive
Colbert et. al., 2012	50%	135°C	2 h	155°C	No information	No information
Lopes etl al. 2014	50%	110°C	No information	HMA: 160°C WMA: 130°C	2.5 min	No information
Dinis-Almeida et. al. 2016	100%	130°C	No information	100-120°C	No information	Added to RA material
Lu et. al. 2016	70%	No information	No information	110°C	No information	Added to virgin binder
Fakhri et. al., 2017a	50%	125°C	2 h	125°C	No information	Added to mixture
Fakhri et. al., 2017b	40%	110°C	2 h	135°C	No information	Added to mixture
Kumari et. al. 2018	100%	110°C	1.5 h	156-159°C	No information	No information
Song et. al. 2018	50%	No information	No information	HMA: 150°C WMA: 125°C	No information	No information
Lizzarga et. al. 2018	100%	95-100°C	No information	No information	No information	No information
Kumari et. al. 2019	70%	110°C	No information	HMA: 163°C WMA: 130-140°C	No information	No information
Lu et. al. 2019	50%	No information	No information	115°C	No information	Two cases: Added to virgin binder; added to RA material
Moniri et. al. 2019	100%	163°C	2 h	163°C	5 min	Added to RA material
Daryaee et. al., 2020	100%	155°C	2 h	155°C	No information	Added to virgin binder

4.1. RA heating in laboratory

In laboratory, heating temperature of 110°C (230°F) for a time of no more than 2 h is recommended for sample sizes of 1 to 2 kg as higher temperatures and longer heating times have been shown to change the properties of RA (Rebecca Mcdaniel; R. Michael Anderson, 2001). Mogawer et al. [2013] observed when RA material was heated for 2 hours prior to mixing, it resulted into lower air voids and heating time had to be increased to 4 hours to reach the desired air voids. The reason stated was that the heating time was not enough for commingling of binders. Results of another heating experiments showed that an appropriate method is to heat RA in oven at the mixing temperature for 1½ to 3 hours. Heating RA samples for more than 3 hours may cause excessive aging of the RA binder (Willis et. al. 2013).

In a study, four different RA heating process (cold, heated in a microwave, heated in an oven in covered pan, and heated in an oven in a non-covered pan) were adopted to prepare 25% RA mix in a laboratory and results shown no difference in stiffness and thermal cracking resistance (Basueny et al., 2014). A heating temperature of 110°C for 3 hours in an oven was recommended as the best option. It may be possible that the effect of conditioning process was not captured due to low content of RA. Microwave heating could also be used while heating RA at higher temperatures as microwave heat is more easily absorbed by the aggregates as compared to the binder, thus reducing its susceptibility to aging during production (Al-Qadi et al., 2007). In a study, to simulate the plant heating conditions, RA was not heated in an oven, but rather heated only by contact (conduction) from the superheated virgin aggregate. It was observed that the high conductive heat was sufficient to significantly age the binder (Willis et. al. 2013).

4.2. RA mixing time in laboratory

A sufficient mixing time is required for the aggregate-bitumen mix to form a uniform coating over the aggregates. AASHTO, (2008) has set down procedures to establish the accurate mixing time in laboratory which involves separating coarse aggregate particles from the mix on a selected sieve size and examining 200 to 300 particles are under a strong light. Usually, the minimum coating percentage required is around 90 and 95% for base and surface course respectively (Shenoy, 2001) The least time needed for the pugmill to achieve these minimums is taken as the most desirable mixing time.

When softer binder is used in high RA mix, diffusion between the two binders is better at higher mixing time, and that changes the properties of the mix (Abed et al., 2018). Results from the optical microscopy showed that by increasing the mixing time to double the normal time for 15% RA mixes, improves blending of RA and virgin binder (Hassan et al., 2015). Increased mixing time also has an impact on the physical and mechanical properties of laboratory mixtures. Longer mixing times tend to reduce the air voids in mixtures containing high RA material (Hassan et al., 2015; Pérez Madrigal et al., 2016). This is attributed to increase in blending between virgin and oxidized binder and thus having a better compactibility.

4.3. RA mixing temperature in laboratory

With the increase in mixing temperatures, the air voids in RA mixes were found to be reduced (Abed et al., 2018). This is due to the fact that at higher temperature, the particle clustering is lowered which in turn leads to increased compaction. Increasing mixing temperature improves the blending which leads to greater modulus. This change is more significant when RA percentage is increased (Pérez Madrigal et al., 2016). (Navaro et al., 2012) observed if the mixing temperature is reduced by 30°C then, generally to obtain a recycled asphalt concrete with a binder of the same homogeneity, the mixing time has to be multiplied by factor of 2.5–3. Therefore, in some cases where high mixing temperatures are not possible, a longer mixing time will be required. Warm mix additives are also used to reduce the mixing temperature while maintaining the same workability of mix. The use of WMA technologies- foaming, organic or wax usually allows the incorporation of higher RA amounts than for HMA and appears to provide a synergetic effect on improving both the WMA and high RA mix performance (Zaumanis and Mallick, 2015). Xie et al. (2016) observed that WMA with 20% and 30% RA mixes showed similar compactibility as corresponding HMA mixes with the production temperature being approximately 30°F higher. Warm mixes are generally more susceptible to moisture damage due to lower mixing temperature.

Overheating the aggregates without preheating RA and extending mixing time has also proven to be good expedients to improve the cracking resistance of the mixtures (Pérez Madrigal et al., 2016). But this is not always possible with higher RA contents and to heat the aggregates at very high superheated temperatures becomes practically difficult in plant. Where high mixing temperatures cannot be attained, mixing time can be increased upto a certain level to achieve desired air voids. For example, in a study on mix containing 50% RA, mixing at 135°C for 3 min was sufficient to achieve the target air voids of 5%, whereas at 115°C, a longer mixing time was required and the target air voids were barely obtained after 5 min of mixing. At 95°C, the target air voids were never achieved, even after 5 min of mixing (Abed et al., 2018).

4.4. Rejuvenator incorporation method in laboratory

Conventionally, for production of HMA in laboratory, all mineral aggregates are mixed together (dry mixing), followed by pouring the bitumen on this aggregate mixture (wet mixing) which is continued till the desired mixing time (Roberts et al., 1996). When high content of RA is being used in the mix, the incorporation of rejuvenators is also required in the process. Recycling agents offer many unique benefits as compared to the use of softer binders (Zaumanis and Mallick, 2013). In laboratory, the rejuvenators are generally incorporated by blending rejuvenator with virgin bitumen. This is the most convenient and widely used rejuvenator application method in laboratory. The rejuvenator is pre-blended into bitumen with the required dosage and then added directly to the mix. Though, this method simulates the plant operation of adding rejuvenator, it could be less efficient than other methods discussed below as some part of added rejuvenator may not be available to RA due to lower blending between virgin bitumen and RA bitumen.

Another method is to add rejuvenator directly to RA material. In this method, the rejuvenator is added directly to RA material (with or without preheating the RA material) in order to activate the stiff binder. This method facilitates the diffusion of the rejuvenator as rejuvenator is in direct contact with the RA binder maximizing the binder activation. However, in the previous method of blending with binder, the rejuvenator is diluted by virgin bitumen and therefore weakens the modifying effect (Yu et al., 2017). A sufficient rest period is likely to cause some diffusion of rejuvenator into RA binder and ultimately restore the original properties of binder.

4.5. Mixture conditioning in laboratory

To have an accurate assessment of performance of asphalt mixes, conditioning in laboratory should be able to simulate the field conditions. Therefore, it is important to quantify the effect of short term and long-term ageing on mixes and compare it with plant produced mixes. Ageing during mixing and construction is referred as short-term ageing and ageing during the service life of the pavement is referred to as long-term ageing. The short-term conditioning of asphalt mixtures also affects the long-term ageing, and the effect is more significant for some mixtures than the others (Azari 2013). For mixes containing RA, it becomes much more important as RA binders often age differently than the virgin binder. Two ageing methods have been described in a technical specification released by the CEN recently: (CEN/TS 12697-52, 2017) one with the loose sample and other with the compacted specimen. The short-term ageing is done at 135°C for 4h and long-term aging is done at 85°C for 216 h. AASHTO R30 specifies mixture to be conditioned for 2 hours at compaction temperature for volumetric mix design. Short term ageing is carried out at a temperature of 135°C for 4 h and long-term ageing is done at 85°C for 5 days.

5. Summary and discussion

This paper highlights the current scenario for production of high content reclaimed asphalt mixtures and identifies the important associated parameters. The current scenarios of high RA content mixture production at plant shows that most of modern plants are now designed to handle higher percentages of RA material by having RA material drying mechanism. The main reason of limiting the heating temperatures of RA material was to avoid the oxidation of binder and sticking of binder to heating facility. However, to produce mixes with high RA content, it will become necessary to heat the RA material to a higher temperature so as to allow higher activation of RA binder and avoid heating virgin aggregates at unrealistically high temperature. Recently, double and triple drum mix plants were developed which prevent the RA binder exposure to hot gases and thus prevents “blue smoke”. This indirect heating principle allows heating RA without direct contact with the flame, to a conventional hot-mix asphalt production temperature of 160 °C.

It was observed that laboratory mixing parameters are often not reported which makes it difficult to compare various studies. As laboratory mixing parameters were found to significantly affect the performance of mixtures. For example, very high mixing temperature will cause oxidation of bitumen hard and will increase the cracking susceptibility of mix. However, it might not be possible to have a uniform coating of bitumen over aggregates at lower mixing temperature. In some cases where high mixing temperatures are not possible to achieve, a longer mixing time will be required or warm mix asphalt (WMA) technology can be incorporated. Providing longer mixing times tend to reduce the air voids in mixtures containing high RA material until a minimum mixing temperature below which the target air voids cannot be achieved. Microwave heating was also given as one of the options to heat RA material as at higher temperatures as microwave heat is more easily absorbed by the aggregates comparing to the binder, thus reducing its susceptibility to aging during production. The sequence of mixing material can be another important mixing parameter in the laboratory as it can affect the workability and compactibility of mix. This has not been much explored and thus future studies must investigate the effect of sequencing the materials while mixing. The method of addition of rejuvenator is another important parameter that affects the degree of binder activation and blending with virgin bitumen. Ideally, rejuvenator should be added directly to RA material to increase the binder activation. However, more studies are required in this direction to determine the optimized procedure for rejuvenator application so that this can be extended to asphalt plants. Finally, the laboratory conditioning is very important to predict the actual performance of high RA mixes in field. Therefore, there is a need to develop laboratory aging procedure for high RA mixtures (upto 100%) to simulate the plant aging of materials.

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