

# Rejuvenation of Hot Mix Asphalt Incorporating High RAP Content: Issues to Consider

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**Abstract:** The asphalt used to construct or rehabilitation roads often contains reclaimed asphalt pavement (RAP) in order to diminish not only the use of raw materials but also waste. However, when high level of RAP in hot mix asphalt (HMA) is used, the rejuvenating agents must be employed. A number of aspects must be taken into account to increase pavement service life as much as possible. Thus, the main issues related to the rejuvenation of asphalt mixtures with high levels of RAP are addressed in this paper. In particular, the focal points of this paper will focus on the use of reclaimed asphalt mixtures with maximum efficiency, special attention is paid to how the binder is structured and chemically composes, nature and dose selection of rejuvenator, as well as the diffusion, blending efficiency, homogeneity, time and temperature mixing. A review of the extant and related literature shows that RAP utilization holds promise for the sustainable pavements, provided that some issues were taken into consideration during the designing and application process.

## 1. Introduction

The first documented case of RAP utilization in constructing new asphalt roads dates back to 1915 [1]. However, it was not until the 1970s and the Arab oil embargo, during which the energy crisis triggered a substantial increase in asphalt binder prices, that RAP applications became widespread [2, 3]. Noteworthy, RAP utilization has increasingly been playing a prominent role over the past 20 years. Asphalt binder plays an indispensable role in asphaltic paving mixtures, as well as the degree to which these mixtures perform as required when applied in the form of pavements. The importance of asphalt binder is reflected in the fact that over 110 million tonnes of the material are used annually, while enormous sums of money are allocated to asphalt pavement construction, rejuvenation, and maintenance [4]. When a pavement's service life has elapsed, reclaiming aggregate and binder through recycling initiatives is worthwhile for several reasons [5], most notably due to economic and environmental advantages. In fact, there is no consensus in specifications available regarding the percentages of RAP that can be used in asphaltic mixtures. RAP are complex materials, and the literatures indicate that the manner in which RAP is utilized is informed by the degree to which the material is homogenous [6]. Although 100% HMA recycling was not uncommon throughout the 1970s [7], RAP percentages used in the materials was lower than 25% in the past decades [8, 9] due to the considerations related to the durability. Additionally, since the emergence of Superior Performing Asphalt Pavements, RAP levels

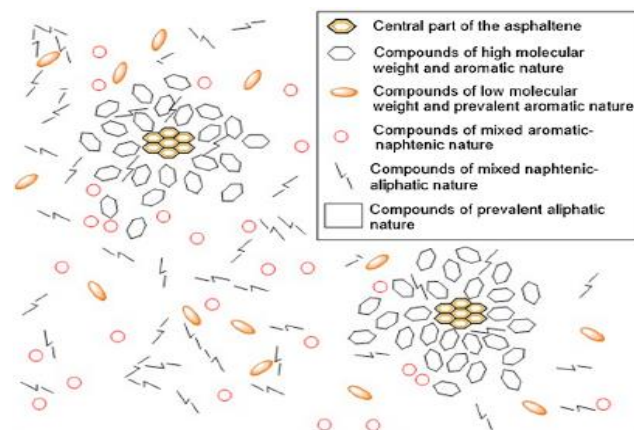


have consistently dropped substantially below 50% [10]. This has prompted many commentators, including the NCHRP Report 9-46, to claim that high RAP percentages should be employed, particularly with developing recycling techniques [8, 11]. Utilization of high RAP content is associated with numerous of economic and environmental benefits, but – at the same time – the associated obstacles cannot be overlooked. In general, a variety of factors have an impact on the use of high RAP content in HMA. Thus, the purpose of this paper is to explore some issues relevant to the rejuvenation of hot mix asphalt (HMA) incorporating high RAP content.

## 2. Using reclaimed HMA: factors to consider

### 2.1. Structure and chemical composition of binder

The hardening, durability, and viscoelastic characteristics of asphalt is informed by their chemical composition [12]. In terms of the chemical composition of asphalt, the material contains a variety of hydrocarbons with high molecular weights [13]. Additionally, asphalt contains nitrogen, sulfur, and oxygen in small quantities, as well as even smaller quantities of metals [14, 15]. The precise chemical composition of asphalt differs based on the crude oil's origin and the way of getting it. Significantly, understanding the RAP binder and the aging phenomenon is predicated on a clear knowledge of asphalt binder fractions. In general terms, asphalt binders consist of oily and non-oily phases [16]. Oily phase is composed of saturated hydrocarbons, aromatics, and resins [17]. In terms of their molecular weight, the hydrocarbon elements of the oil are the smallest components within the asphalt, and they determine its fluidity [13]. As for the resins, which can either be semi-solid or non-crystalline solid, these determine the material's ductility and adhesion. Contrastingly, the non-oily phase comprises asphaltenes [18, 19], which are fragile, non-crystalline, and solid materials [20]. The presence of asphaltenes in asphalt imposes an important effect on its physical properties [20]. It is also responsible for the strength and stiffness of asphalt. An asphalt binder's viscoelasticity depends on the ratio of asphaltenes to maltenes [17, 21]. Generally, asphalt binders are considered as a colloid, in which maltenes serve as the dispersion medium while asphaltenes serve as the dispersed phase [22]. Figure 1 shows the colloidal model of asphalt binder



**Figure 1.** Colloidal model of asphalt binder [17]

According to Pfeiffer et al. [23], asphaltene particles are considered to be the center of micelles, where a layer of aromatic resins surround this and serve as a stabilizing solvation medium. Due to asphalt's colloidal nature, it can be separated into the following categories: sol asphalt, gel asphalt, and sol-gel asphalt [24]. When the amount of resin is sufficiently aromatic and has suitable solvating power, asphaltene peptization takes place more effectively [14]. Additionally, the asphaltenes are mobile inside the asphalt, thus giving rise to sol asphalt. Furthermore, when the amount of resin is not enough with inadequate aromaticity, the mobility of the asphaltenes falls, and they associate together [14]. In practice,

sol-gel asphalt is commonly used in pavement construction [25], which exhibit elastic behavior only in the initial stages of deformation and have a colloidal structure with the presence of supermicelles and giant supermicelles [17]. Dissimilarly, gel asphalt has asphaltene content in excess of 20% and is characterized by reduced ductility, a high age-hardening rate, and limited temperature susceptibilities [17]. Although gel asphalt mixtures can withstand greater temperature deformation (rutting) when compared to sol asphalt mixtures, they suffer from brittleness and low crack resistance at lower temperatures [26].

A key feature of the asphalt binder aging process is the reduction of the maltene/asphaltene ratio. The asphalt binder aging process can be divided into the following stages: the short-term aging stage, which takes place over the construction period and is facilitated by high temperatures; and the long-term aging stage, which occurs in the course of the pavement's service life [27]. Asphalt binder aging takes place when the aromatic and resin asphalt fractions fall, and when the material has lost its solvation power to completely peptize the asphaltenes [24]. Furthermore, heating asphalt lead to leakage of oils out of the asphalt, some of which are volatilized and others of which are lost due to solubility in water. Lastly, the migration of oxygen takes place into the system, thereby forming a greater number of polar molecules, namely, asphaltenes[24].

In the study of Borghi et al. [28], it was mentioned that due to the aging, the RAP binder seems to exhibit greater brittleness and sensitivity to cracking compared to virgin asphalt. This affects how it performs and explains why restrictions are imposed on the maximum content of RAP. Furthermore, in the study performed by Cavalli et al.[29], it was found that the bio-based rejuvenators can be affected differently by ageing. So, the effect of aging on the rejuvenated binder is vital to identify how rejuvenators affect the mechanical and chemical properties of aged binder.

## *2.2. Rejuvenator types and dose selection*

There are more than 30 types of rejuvenating agents that were employed with HMA containing RAP. The selection of a rejuvenating agent depends on the degree to which it can improve the properties of the asphalt binder, and alongside this, reverse the RAP binder aging process. More specifically and as was mentioned by Zaumanis, Mallick [30], rejuvenating agents should satisfy "both short- and long-term criteria". Short-term criteria include the ability to diffuse quickly into the RAP asphalt binder and bring about the mobilization of the asphalt. Contrastingly, long-term criteria include the ability to modify the rheology of the binder, thereby limiting fatigue and improving low temperature cracking potential (without leading to softening and rutting issues) [27, 30]. Significantly, adhesion and cohesion must also be considered to safeguard against raveling and moisture damage.

In terms of dose selection for the rejuvenating agent, this should be based on the fresh binder properties, RAP binder's target grade, and rejuvenating agent properties. This is because such a selection process ensures enhanced cracking resistance, without negatively affecting rutting resistance[22].

Blending charts are usually formulated depending on the viscosity and/or penetration of the reclaimed binder blends with different recycling agent quantities. These charts facilitate dose selection of recycling agent [31]. The smallest dose required for rejuvenating recycled binder performance has been established by some researchers through assessment of the alterations in recycled binder stiffness occurring when the recycling agent is added, based on the performance grade (PG) system. In general, appropriate cracking resistance and rutting resistance are respectively ensured by setting a minimum and maximum dose [31, 32]. Usually, recycled binders differ in their performance according to the nature of softening and rejuvenating agents.

In 2014, various rejuvenators, including waste vegetable oil (WV oil), waste vegetable grease (WV grease), organic oil, distilled tall oil, aromatic extract and waste engine oil (WEO) (Table 1), have been extensively investigated by Zaumanis et al. [3] regarding their impact on the properties of aged binder. According to the findings obtained, all agents made the binder as viscous as a virgin binder at a moderate temperature. Furthermore, addition of 12% recycling agents made the RAP binder more workable. An optimal effect was induced by vegetable oil, with fatigue performance being almost identical to the performance of virgin binder. On the other hand, the aged binder was unaffected by petroleum products in terms of fatigue performance. In ascending order of the potency of their effect on performance were distilled tall oil, WV grease, and organic oil, whereas WEO had the poorest effect on performance. The

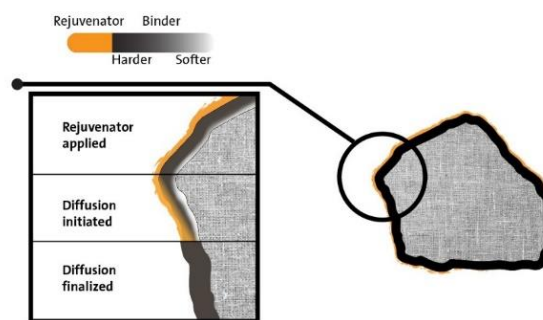
reason is that WEO can be considered as a softening agent, it doesn't contain any resin. Thus, it is not suitable to use in high temperature region.

**Table 1:** Recycling agents properties [3]

Recycling Agent	Visc. at 135 °C (Cst.)	Specific gravity	Petroleum or Organic	Refined or Waste
WV oil	5.17	0.924	Organic	Waste
WV grease	4.28	0.924	Organic	Waste
Organic oil	5.43	0.947	Organic	Refined
Distilled tall oil	5.60	0.950	Organic	Refined
WEO	3.86	0.872	Petroleum	Waste
Aromatic extract	9.20	0.995	Petroleum	Refined

*2.3. Diffusion, blending efficiency and homogeneity*

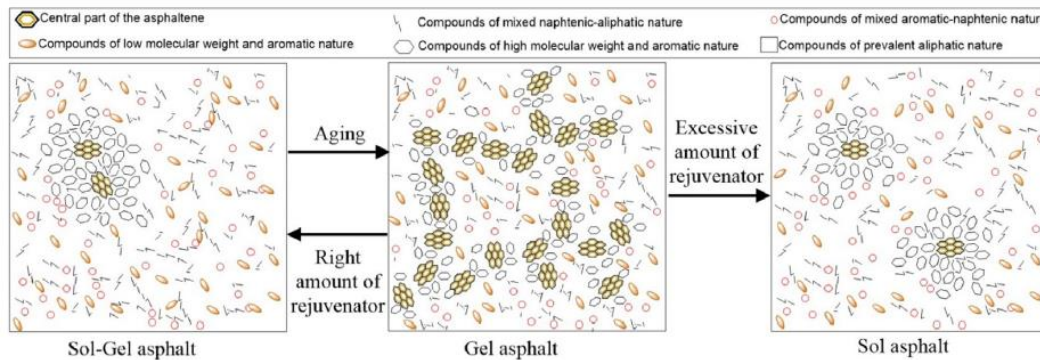
Excessive RAP utilization can lead to various disadvantages. For example, when this occurs, the aggregates pre-coated with an external thin-film of aged binder, which often operate as “black rock”, cannot be diffused into the mix [27]. “Diffusion” refers to the homogenization of the binder following the completion of the mixing process in the absence of the application of mechanical force [33]. Contrastingly, “blending” denotes the binder interaction which takes place in the course of mixing [33]. Significantly, diffusion has the greatest effect on RAP mixtures’ rheological characteristics, and it is informed by the binder thickness and production temperature [34]. As shown in figure 2, many steps of rejuvenating agent permeation into an aged binder that were distinguished by Carpenter and Wolosick [35]. The first step is formation of a minimally viscous layer by the rejuvenating agent around the aged binder coating the particles of recycled material. The second step is the onset of recycling agent permeation into the external layer of the aged binder, with the binder beginning to soften. As permeation and diffusion progress, there is less and less recycling agent around the recycled material particles. The third step is ongoing permeation of the recycling agent into the aged binder, which makes the internal layer of the reclaimed material particles less viscous and the external layer less viscous.



**Figure 2.** Recycling agent diffusion into binder film [30]

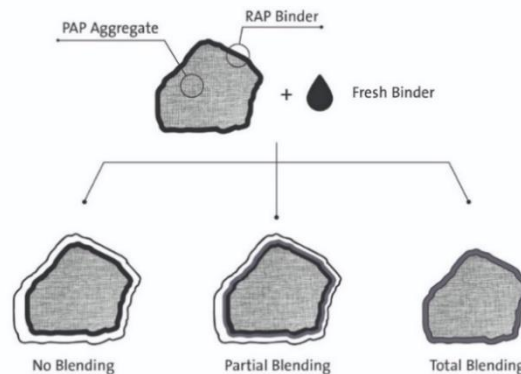
A research project focusing on the diffusion of rejuvenator in aged asphalt [24], it was referred to that a diffusion in asphalt is complex and the diffusion rates should not be like those in liquids or in solids. It remains a challenge to understand, predict and control the diffusion of rejuvenators in old asphalt. In order to estimate and manage the diffusion of rejuvenators within aged asphalt, asphaltene concentration and degree of swelling must be taken into consideration. Nevertheless, diffusion theories and physical models can be used to illuminate this issue. The colloidal structure and diffusion of rejuvenator within aged asphalt are illustrated in Figure 3. The same study argued that adequate diffusion was an as important property of an effective rejuvenator as optimal regeneration and antiaging

capability. Temperature, viscosity and time are the main determinants of diffusion, alongside material structure, dimensions, and form of molecules, and forces between molecules.



**Figure 3.** Asphalt’s colloidal structure and diffusion of rejuvenator [36]

According to Lopes et al. [6], homogeneity plays an important role in increasing recycling rates, when RAP’s homogeneity cannot be adequately controlled, so-called “heterogeneity” emerges, resulting in uncertain RAP performance. It is significant, therefore, that employing RAP content greater than 25% necessitates adequate homogeneity. Given that internal cohesion informs the level of performance for the new pavement, determining whether the RAP binder is “active” is critical. This can be achieved by checking the RAP’s color and properties [37]. In particular, when the RAP is a dark grey color, lacking brittleness and shining surfaces, it is regarded as inactive [38]. Evaluations can be conducted in the laboratory to determine whether RAP is active or inactive, principally by checking variables such as softening point, viscosity, and penetration. When the RAP binder is active, it significantly affects the adhesive property[37]. However, when the RAP is inactive, it is usually considered as black rocks. In the literature, perspectives differ on the manner in which RAP blending with virgin binder occurs (see Figure 4). One perspective is the “no blending” view, another is “complete blending”, and the final perspective is “partial blending. The first of these suggests that RAP behaves as a black rock in reclaimed HMA, thereby having no binder effect from the aged RAP. The second view, “complete blending”, involves combining 100% of the RAP binder with virgin binder, where the blending acts as a composite binder in reclaimed HMA. For the final view, “partial blending”, researchers have suggested that just a portion of RAP’s working binder reacts with the virgin binder [27, 39].



**Figure 4.** Blending cases for virgin binder and RAP binder [40]

If the assumption is made under reclaimed HMA’s mix design that the RAP binder blends completely with the virgin binder (that is, when RAP behaves as a black rock), then the amount of asphalt content used will not be enough [39]. Conversely, when no blending is expected between the virgin and RAP binders and instead react, asphalt content with greater than anticipated richness will be generated [39]. In each case, the design parameter cannot be accurately predicted, thus elevating the risk of poor HMA

pavement performance [41, 42]. In most cases, reclaimed-asphalt mixtures underperform given that virgin asphalt fails to blend with RAP content. This can be attributed to incompatibilities in their chemical and physical characteristics[43]. Several researchers have argued that in almost all cases involving high RAP content, the virgin binder and RAP binder blend partially [33, 44]. With these considerations in mind, improving the mix design for RAP is predicated upon identifying the blending efficiency between virgin binders and RAP [39].

#### 2.4 Time and temperature of mixing

Improving the bond between the aggregates and binder requires adequate time mixing. In addition, adequate time mixing brings about the breakup of RAP clusters, thereby alleviating the stiffening impacts of RAP, particularly in mixtures with high RAP content [34, 45]. In light of the existing findings in this area, it is clear that poor time and temperature mixing will lower adhesion between virgin material and RAP. In turn, this contributes to cracking, raveling, and various other forms of pavement distress [34]. Moreover, the usage of high RAP content also necessitates high mixing and compaction temperatures over the construction phase. However; but this lowers the intermediate temperature performance. This issue can be bypassed using softening and rejuvenating agents

An investigation was conducted to determine how the homogeneity of asphalt mixtures with high levels of RAP was affected by time and temperature. The lack of synchronicity of cluster breakdown was identified as having the most negative effect on the homogeneity of asphalt mixtures with RAP [46]. Furthermore, cluster sensitivity to breaking was found to depend mainly on the temperature of mixing; this sensitivity diminished the higher the temperature got. “Momentary homogeneity” was promoted by a brief duration of mixing, being characterized by lack of cluster breaking and poor extent of blending between the aged and fresh binder [46].

### 3. Summary

In addition to the environmental and economic advantages associated with RAP utilization, asphalt pavement recycling has become essential due to volatile oil prices. While 100% of RAP can be utilized, a range of considerations should be taken into account. An asphalt binder’s viscoelasticity depends on the ratio of asphaltenes to other components. A key feature of the asphalt binder aging process is the reduction of the maltene/asphaltene ratio. As a consequence of this, brittleness, and stiffness of the binder increase. The aging process can be divided into the short-term aging stage, which takes place over the construction period; and the long-term aging stage, which occurs in the course of the pavement’s service life. The type and dosage of a rejuvenating agent should be chosen according to the extent to which they can enhance asphalt binder properties. For a rejuvenator to be considered effective, it must demonstrate high regeneration and antiaging capacity, as well as suitable diffusion, whilst also meeting short- and long-term criteria. The rate of diffusion is significantly determined by temperature and time of mixing. Therefore, elevating the temperature or lengthening the time of mixing can enable deeper diffusion.

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