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Investigation of reclaimed asphalt pavement blending efficiency based on micro-mechanical properties of layered asphalt binders

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HIGHLIGHTS

- TCE alters the AFM topographic image of recovered asphalt binder.
- Non-homogeneous blending scenario for reclaimed HMA has been proposed.
- Micro-mechanical properties of various binder layers in reclaimed HMA are analyzed.
- Decrease of mixing temperature impairs blending between RAP-virgin binders.
- Complete blending between RAP-virgin binders occurs after sufficiently long time.

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ABSTRACT

The challenge in mix design and application of reclaimed hot mix asphalt (HMA) lies in the unknown blending efficiency between reclaimed asphalt pavement (RAP) binder and virgin binder. By using a combination of staged extraction method and Atomic Force Microscopy (AFM) imaging technique, this paper focused on the investigation of interaction and extent of blending between RAP-virgin binders under different mixing temperature and residence time, based on the micro-mechanical properties of layered binders in real reclaimed HMA. In addition, the impact of chemical solvent used in staged extraction, i.e. Trichloroethylene (TCE), on the AFM images of extracted asphalt binder was also explored. It was found that the topographic features of asphalt binder in terms of "bees" structure were obviously altered by TCE, which were not suitable for analysis on RAP blending. A possible blending scenario, indicating non-homogenous blending between RAP-virgin binders in the layered binder system, was put forward for the mixing stage of reclaimed HMA, in which increased DMT modulus and decreased adhesion force and energy dissipation were observed from the outermost towards to the innermost layers. Both mixing temperature and residence time have significant effects on the blending efficiency between RAP-virgin binders. With the decrease of mixing temperature, diffusion of the virgin binder into RAP binder is impaired, thus leading to less blending efficiency between the two binders. Besides the mixing process, the blending between RAP-virgin binders continues with the passing residence time, until a complete and homogeneous blending being reached after sufficiently long time.

1. Introduction

With the climbing cost of pavement materials and deterioration of the environment, in recent years the use of reclaimed asphalt pavement (RAP) in hot mix asphalt (HMA) pavement construction and maintenance has become more widespread. Through oxidation, volatilization and other mechanisms, asphalt binder progressively ages and hardens during the service time of asphalt pavement, which leads to an increased stiffness of the asphalt binder in RAP. So the addition of RAP has long been known to change the properties of HMA mixes. The magnitude of this change is dominated by the efficiency of blending that occurs between RAP and virgin binders in reclaimed HMA [1].

As to the combination of RAP and virgin binders, three controversial views are available. The first view is "Black Rock Theory", which considers RAP as black rock in reclaimed HMA with no binder effect from the aged RAP. The second is "Complete Blending Theory", which suggests that 100 percent of RAP binder combines with the virgin binder and their blending acts as composite binder

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in reclaimed HMA. The third is "Partial Blending Theory", which hypothesizes that only part of the working binder in RAP reacts with virgin binder. The actual level of blending between RAP and virgin binders affects the amount of effective binder in reclaimed HMA, so being critical to the performance of produced HMA and the economic competitiveness of the recycling process [2]. In the mix design of reclaimed HMA, if RAP binder is assumed to totally combine with virgin binder when RAP actually behaves as black rock, insufficient asphalt content will be used and the binder is characterized by lower stiffness. In contrast, if no blending are supposed between the two binders while they actually reactive with each other, rich asphalt content and stiffer asphalt binder than expected will be brought about. Both of the two cases will lead to wrong estimation of design parameter, in turn increasing the potential risk in terms of performance for reclaimed HMA pavement [2,3]. Therefore, it is imperative to determine the blending efficiency between RAP and virgin binders to establish improved mix design procedures for reclaimed asphalt pavement.

Given the significance of RAP-virgin binder blending, significant research efforts have been devoted to the interaction between the two binders. The most commonly used and simplest method is the indirect performance-based approach, which reveals the blending status between binders by exploring the mechanical and performance properties of reclaimed HMA. The research work in *NCHRP 9–12* [4] conducted performance related tests to compare four blending cases, i.e. black rock, total blending, partial blending and actual practice. Their findings disagreed with a full blending, but suggested a significant amount of blending does occur in the reclaimed HMA. By contrasting the laboratory fatigue and rutting performance of reclaimed HMA to new HMA, Oliver [5] attributed a partial blending of binders to the formation of agglomerates of aggregates and fillers, which were hard for the fresh binder to penetrate. Shirodkar et al. [6] used $G^*/\sin\delta$ of binders from dynamic shear rheometer (DSR) test to investigate the blending degree between RAP-virgin binders. Their studies implied that higher amount of RAP binder would be available to take part in the blending process with softer virgin binder added in reclaimed HMA. McDaniel et al. [7] and Mogower et al. [8] evaluated the blending extent with the "Bonaquist approach", which used mixture volumetrics and stiffness of recovered binder in the Hirsch Model to predict dynamic modulus of reclaimed mixes at complete blending status. By comparing the predicted values with those measured, the blending degree could be quantified. With this method, McDaniel et al. [9] claimed to find a complete blending of RAP-virgin binder in reclaimed HMA containing 15% RAP, while partial blending was found when more than 40% RAP was incorporated. To some extent, the performance-based approach can reflect the blending efficiency of RAP-virgin binder in reclaimed HMA. However, besides the combination status of the two binders, there are many other factors may affect the properties of mixtures. Therefore, a method needs to be developed to more directly reveal the RAP blending efficiency.

Due to the existence of temperature gradient between the core and the surface of RAP material, the blending between RAP-virgin binder is a gradual process [10]. Accordingly, analysis of different layers of binder film in reclaimed HMA is an effective way to determine the blending dynamics. Staged extraction has been widely adopted in recent years to strip the asphalt binders layer by layer, boosting the research regarding RAP blending. In 1979 Zearly [11] attempted to use two-stage extraction with Trichloroethylene (TCE) washing the mixture twice to recover two layers of asphalt binder. Penetration results for both layers were similar and in some cases the inner layer to the aggregate showed higher values. It was attributed to the selective absorption of the lighter asphalt fractions by a large amount of shale in the aggregates. A laboratory mixture was prepared using aggregates coated with 60 penetration grade asphalt as the inner layer, which was in turn coated by 200 penetration grade asphalt at the lowest possible temperature. Three layers of asphalt binder were stripped and their penetrations were determined as much less than 200, which indicated the occurrence of blending between the 60 and 200 penetration grade asphalt. Carpenter and Wolosick [12] also used two-stage extraction to strip the inner and outer layers of RAP binder by dipping the mixture of RAP and 20% rejuvenator for 3 min in TCE twice. Penetration test results were found different for the two layers with the outermost layer showing higher value than the innermost layers. However, they further found that the outer layer began to get stiffer while the inner layer softened with time until similar penetration value was reached between the two layers. The authors suggested that blending between rejuvenator and RAP binder is not confined to mixing time but continues to a more extended time.

Noureldin and Wood [13] stored a mixture of RAP and different rejuvenators for 15 h at 78 °C and then applied four-stage extraction method to study the diffusion between them. They achieved a profile of the consistency from the aggregate to the surface of the asphalt, which displayed the rheological property change in the different binder layers coating the RAP aggregate due to blending process. Based on the test results, they concluded that only the outermost layer binder of RAP blended with the rejuvenators. The conclusion was supported by Huang et al. [3], who used similar staged extraction method to explore blending between RAP-virgin binder. They reported that only a small portion (the outside 40% binders) of aged binders in RAP actually participated with the remixing process, while other portions (the inner 60% binders) coated around the RAP aggregates as a stiff film. Similarly, Zhao et al. [14] combined multi-layer staged extraction and GPC test and indicated that only part of the outermost RAP binder was remobilized and participated in the blending process with the virgin binder, while the other inner portions kept attaching on RAP aggregates. Bowers et al. [15] adopted four-layer staged extraction and GPC and FTIR tests to discuss the RAP-virgin binder blending process. By analyzing the percent of large molecule size (LMS) (%) of individual layer from GPC with 1 min washing time in each extraction cycle and the percent of Carbonyl (%) from FTIR at both 30 s and 1 min washing time in each cycle, the authors concluded that a non-uniform blending occurred within all layers around the aggregates in reclaimed HMA mixture.

Staged-extraction mainly uses chemical solvents to wash layers of asphalt binder off mixture to realize the analysis. There are concerns about the effectiveness of this technique to remove the asphalt binder layers from RAP aggregates. Cipione et al. [16] and Peterson [17] argued that some of the aged binders may still remain on aggregate after extraction, so the determined properties of extracted and recovered binders may not completely representative of the actual properties of binders in the mix. However, Zhao et al. [14] applied a steel ball model, in which steel balls were coated with an inner RAP binder layer and an outer virgin binder layer in same thickness of 50um for each, to prove the feasibility of staged extraction as a procedure to effectively obtain the original binder films coating the aggregates layer by layer. The GPC testing results showed that the composite binders coating the steel ball were washed out by the solvent layer by layer, which was in line with the pre-designed physical form of the composite binder system. Zhao et al. [18] and Bowers et al. [19] compared various kinds of solvents to see if there is sequential dissolution of asphalt fractions in the process of staged-extraction. Based on GPC and FTIR tests respectively, they reached the same conclusion that TCE was the most effective solvent to dissolve the asphalt binder without preferential dissolution, while other solvents were found more or less selectively dissolve the fractions of asphalt binder.

There are still concerns about the influences of chemical solvents on the properties of extracted and recovered asphalt binders. Burr