Assessing repeated recycling capacity of 100% RAPM binder using mustard oil

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ABSTRACT: This study evaluates the effectiveness of mustard oil (MO) in restoring the properties of a 60 h aged binder across multiple recycling cycles. Two recycling cycles were conducted with 100% aged binder, and the changes in rheological and performance characteristics were assessed using Dynamic Shear Rheometer (DSR). Results indicated that MO effectively restores binder properties in the first recycling cycle; however, complete restoration in the second recycling cycle is not achievable with the same dosage. This indicates a diminishing effectiveness of MO with successive recycling cycles. Additionally, MO-rejuvenated binders demonstrated reduced sensitivity to re-aging and subsequent re-rejuvenation. Linear amplitude sweep (LAS) test results confirmed that fatigue resistance can be sustained even after multiple aging and recycling cycles. Overall, the findings suggest that while reclaimed asphalt pavement materials (RAPM) can be recycled multiple times, selecting an appropriate rejuvenator is essential for restoring and maintaining binder performance across successive cycles to ensure sustainable pavement solutions.

1 INTRODUCTION

Asphalt mixtures used in road construction have a limited lifespan, primarily influenced by factors like traffic, environmental conditions, oxidative aging, etc. (Rai et al. 2024a; b). Consequently, it becomes necessary to replace or rehabilitate these mixtures after a certain period, leading to the generation of large quantities of reclaimed asphalt pavement materials (RAPM). Since this material is produced after its first use, it is referred to as first-generation RAPM. Many pavements have been and are still being constructed using this first-generation RAPM, either with or without the addition of rejuvenating agents (RAs). As these pavements approach the end of their service lives, their maintenance and rehabilitation will result in the large quantity of waste materials termed as second generation RAPM. Recycling these second-generation RAPM and furthermore generations is known as re-recycling or repeated recycling. It supports environmental and economic sustainability by reducing land pollution, carbon footprint, conserving natural resources (virgin aggregates and bitumen), and lowering construction and maintenance costs.

Although re-recycling is essential for sustainable pavement practices, re-recycled pavements (constructed with second-generation RAPM) must demonstrate performance equal to or better than conventional pavements to justify widespread adoption. The primary concern with the re-recycled RAPM is the cumulative aging process, which leads to increased stiffness and greater susceptibility to cracking. This increased stiffness limits the interaction between aged binders and RA, making it difficult for RA to fully restore the binder's original properties, thereby making it unsuitable for repeated recycling processes. To address these concerns, efforts have been made to evaluate the feasibility of repeated recycling and its impact on RAPM performance.

In 1995, Yoshikane introduced the use of second-generation RAPM and evaluated the performance of re-recycled RAPM through 15-year field investigation. The study found that re-recycled RAPM performed satisfactorily compared to single-recycled RAPM and conventional HMA, demonstrating that re-recycling of RAPM is a feasible and effective option. Similarly, Petho and Denneman (2016) concluded that RAPM can be recycled multiple times without compromising the performance. However, Kriz et al. (2017) concluded that the virgin binder type, a high recycling rate, and type of RAs might reduce the number of viable cycles significantly and thus make recycling unsustainable in the future. Further, Koudelka et al. (2019) used a variety of rejuvenators to restore the properties of first and second generation RAPM and found that most rejuvenated asphalt blends in the second cycle of rejuvenation did not meet the performance requirements. Additionally, Rodrigues et al. (2024) investigated the effects of repeated recycling on the fatigue and rutting resistance of asphalt binders, focusing on how multiple cycles influence their performance characteristics. The findings indicated that asphalt binders could be effectively re-recycled up to three cycles while maintaining satisfactory performance.

Most of the previous studies have primarily focused on the single recycling of RAPM in HMA, with or without recycling agents. These studies concluded that some RAs are effective in preserving the performance of recycled asphalt binder after a single reuse (Koudelka et al. 2019, Rai et al. 2024a). However, there is still the issue of the effectiveness of RAs in allowing repeated recycling processes without compromising the performance. Repeated recycling of RAPM is not common, and limited research and information are available on this topic. Therefore, the role of RAs in restoring the characteristics of RAPM over multiple recycling cycles must be evaluated.

The objective of this study was to evaluate the effectiveness of mustard oil (MO) as a RA in restoring the properties of RAPM across multiple recycling cycles.

2 MATERIALS AND METHODS

2.1 *Materials*

The asphalt binder used in this study was VG30 with penetration of 45 dmm and softening point of 52.3 °C. Its performance grade was PG 70-XX. Mustard oil (MO), derived from mustard seeds, was used as the RA. MO used in this study was obtained locally from a grocery store. The density and viscosity (at 60 °C) of MO was found to be 0.92 g/cm³ and 40.12 cP, respectively.

2.2 *Methods*

2.2.1 *Experimental process design*

Asphalt binder was aged in the laboratory and then rejuvenated using MO. The rejuvenated asphalt binder was then re-aged and re-rejuvenated again. This process continued for two cycles of aging and rejuvenation, as shown in the flow diagram in Figure 1. Comprehensive rheological tests, including frequency sweep (FS), true high fail temperature (TFT), multiple stress creep and recovery (MSCR), and linear amplitude sweep (LAS) were conducted using a DSR to thoroughly assess the performance of asphalt binder after each aging and rejuvenation cycle. The temperature at which G*/sin δ of an asphalt binder equals 1 kPa is termed as TFT. FS test was conducted at 10 rad/s frequency over a temperature range of 10-80 °C and master curves were plotted using time temperature superposition principle. The results were then analyzed to evaluate the changes in the rheological and performance characteristics at all the selected MO dosages.

2.2.2 *Aging and rejuvenation procedure*

The asphalt binder was short-term aged in the laboratory using universal simple aging test (USAT) at 150 °C for 50 mins. The residue was subsequently subjected to pressure aging vessel (PAV) at 110 °C and 2.1 MPa for 60 h. For long-term aging, instead of standard aging time of 20 h, 60 h was adopted to replicate severely aged binder in tropical countries (Rai et al. 2024a). The binder obtained after the first aging cycle (FAC) is called as the first generation of RAPM binder, labelled as RAP^1. The first recycling cycle (FRC) involved mixing of RAP^1 with MO at three dosages: 10%, 20%, and 30% by weight of the aged binder. The mixture was blended for 15 minutes at a speed of 700-1000 rpm. The resulting binders were labelled RAP^1 + 10%, RAP^1 + 20%, and RAP^1 + 30%, respectively. Following this, the optimal MO dosage (30%) was determined using a rational procedure, the details of which can be found elsewhere (Rai et al. 2024a). The first rejuvenated binder (FRB) was prepared by incorporating the optimal MO dosage in RAP^1. The FRB underwent second aging cycles (SAC) to generate the second generation of RAPM (RAP^2). Subsequently, it was subjected to second recycling cycles (SRC) to produce the second rejuvenated binder (SRB). The aging and rejuvenation process in the second cycle was kept similar to the first cycle.

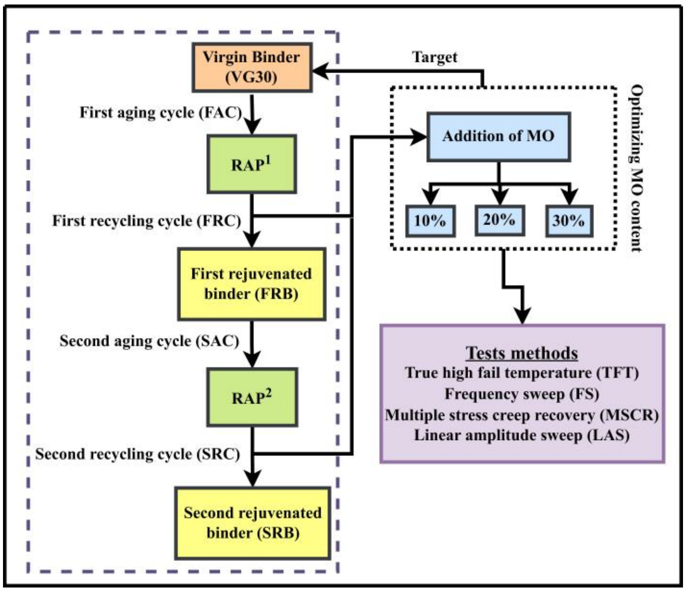

Figure 1. Design methodology and experimental plan

3 RESULTS AND DISCUSSIONS

3.1 *True high fail temperature (TFT)*

Figure 2 illustrates the TFT of aged and rejuvenated asphalt binders obtained for FRC and SRC. In the first cycle (FAC + FRC), Figure 2(a) shows that the TFT of VG30 increased by approximately 51% after aging, indicating significant stiffening of asphalt binder. Following rejuvenation, the binder softened, and the TFT decreased. At MO dosage of around 30%, the TFT of rejuvenated binder closely aligned with that of VG30, suggesting effective restoration during FRC.

In the second cycle (SAC + SRC), a similar trend was observed: aging increased the TFT, while rejuvenation reduced it. However, during SAC, a 42.3% increase in the TFT was observed, which is notably lower than the increase observed in the FAC. This indicates that the stiffness of RAP^2 was significantly lower than that of RAP^1, demonstrating that the presence of MO slowed down the aging process.

Although RAP^2 exhibited lower stiffness than RAP^1, the 30% dosage of MO used in the SRC was insufficient to fully restore the binder property of RAP^2 (to match with VG30). This suggests that higher dosages or alternative rejuvenators may be required for further recycling cycles. Therefore, the concept that less stiffened binder required low rejuvenator dosages is not valid for repeated aging and recycling process. This conclusion is based on the selected RA and the aged binder used in this study. However, further research is necessary to validate these findings and explore their applicability across a broader range of aging conditions, binder types, and RA types.

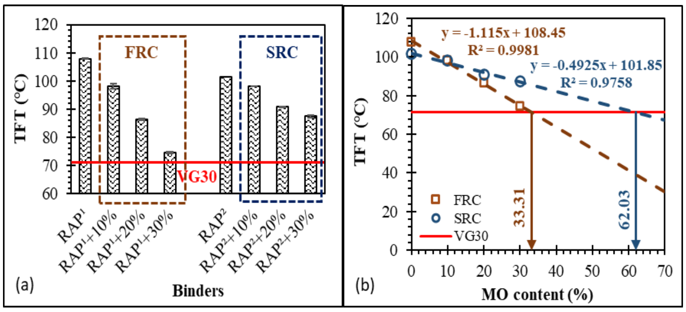

Figure 2. (a) TFT of aged and rejuvenated binder, (b) Linear regression of TFT versus MO dosage for FRC and SRC.

To determine the exact dosages required to achieve comparable properties, a plot of TFT versus MO content was generated as shown in Figure 2(b) for both recycling cycles. The linear regression equations, shown in the graphs for each cycle, were then used to calculate the required dosage. The results indicate that during the FRC, a dosage of approximately 33% MO was sufficient to restore the TFT similar to VG30. However, in the SRC, a substantially higher dosage of around 62% was necessary to achieve similar TFT. This significant increase in the required dosage highlights either the limited ability of MO to diffuse and soften RAP^2 or the reduced reactivity of RAP^2.

3.2 *Complex modulus (G*) master curve*

For the first cycle, as shown in Figure 3, it was observed that after aging, the G* of asphalt binder increased significantly. After rejuvenation, the binder softened, and the value of G* reduced in the entire domain of reduced frequency. However, the reduction in G* due to rejuvenation was found to be more prominent at lower reduced frequencies. It can also be observed that none of the rejuvenated binder master curves exactly match the virgin binder master curve. As observed, aligning the G* curve of rejuvenated binders in the low-frequencies range (corresponding to high temperatures) can result in a lower G* value compared to virgin binders in the high-frequencies range (corresponding to lower temperatures). This indicates that rejuvenated binders exhibit reduced stiffness at lower temperatures while maintaining comparable or improved stiffness at higher temperatures. In other words, the rejuvenation process enhances the low-temperature performance of the aged asphalt binder. Similar trends have been reported in a previous study (Hugener and Kawakami 2017).

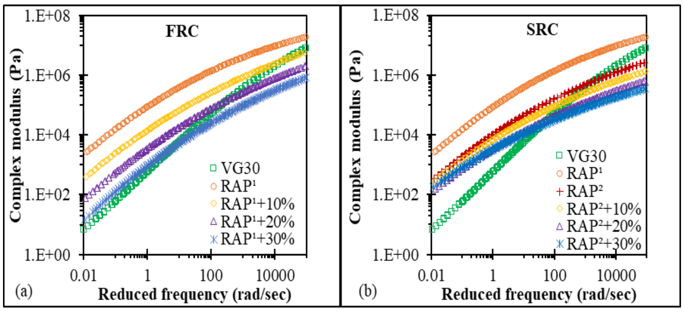

Figure 3. G* master curve at 60 °C for (a) FRC (b) SRC

In the second cycle, as shown in Figure 3, complex modulus (G*) increased after aging and reduced after rejuvenation, following trends similar to the first cycle. The increase in stiffness due to aging was lower in the second cycle compared to the first, suggesting that the binder became more resistant to aging-induced stiffening. Additionally, RAP^2 had lower stiffness than VG30 at higher reduced frequencies because FRB initially had much lower stiffness than VG30, and even after secondary aging, it remained lower. Further, MO effectively softens RAP^2, as evidenced by the reduction in G* with increase in dosage. However, the differences in the G* master curves across various rejuvenator dosages were less pronounced, particularly in the lower frequencies range, indicating reduced sensitivity of the asphalt binder to rejuvenation. Furthermore, rejuvenated binders exhibit lower values of G* at higher frequencies and higher values at lower frequencies, compared to VG30. This indicates that MO (up to 30%) was unable to fully restore the stiffness characteristics of the rejuvenated binder, particularly in the low-frequencies domain.

3.3 *Rutting and fatigue performances*

The MSCR test was conducted at 60 °C to evaluate the rutting performance, while the LAS test was performed at 20 °C to assess the fatigue characteristics of the asphalt binders. Non-recoverable creep compliance (J_{nr}) and fatigue life (N_f) were the primary parameters obtained from these tests. Lower J_{nr} and higher N_f values indicate better rutting and fatigue resistance in the binder. Previous studies have suggested that Jnr at a stress level of 3.2 kPa ($J_{nr,3.2}$) and fatigue life at 5% strain ($N_{f,5}$) may be used to study the effects of aging and rejuvenation process. The results obtained in this study are shown in Figure 4.

Figure 4 (a) shows the $J_{nr,3.2}$ values for the virgin binder and rejuvenated binder after each aging and rejuvenation cycle. Aging reduces $J_{nr,3.2}$, indicating improvement in the resistance to rutting. Conversely, adding MO increases $J_{nr,3.2}$, thus softening the binder. The increase in $J_{nr,3.2}$ with the increase in MO content in FRC was more prominent than SRC. In FRC, MO successfully restored $J_{nr,3.2}$ of aged binder to similar level of VG30 at 30% MO dosage. However, in the SRC, the same dosage was insufficient to achieve a comparable $J_{nr,3.2}$ indicating a diminished rejuvenation effect in subsequent cycles. This reduction in effectiveness could be attributed to MO's inability to significantly reduce the G* of RAP^2 up to the 30% dosage, as discussed in the previous section.

Figure 4 (b) shows that the fatigue life of the binder decreased after aging but improved with the incorporation of MO in both recycling cycles. All rejuvenated binders exhibited greater fatigue resistance than the virgin binder in both cycles. However, the reduction in fatigue life during FAC was more significant compared to SAC, indicating that MO also acts as an anti-aging agent. Additionally, the fatigue life of the binders increased progressively with successive recycling cycle. The improvement was attributed to the lower G* of rejuvenated binder compared to VG30 at lower temperatures, as discussed in section 3.2.

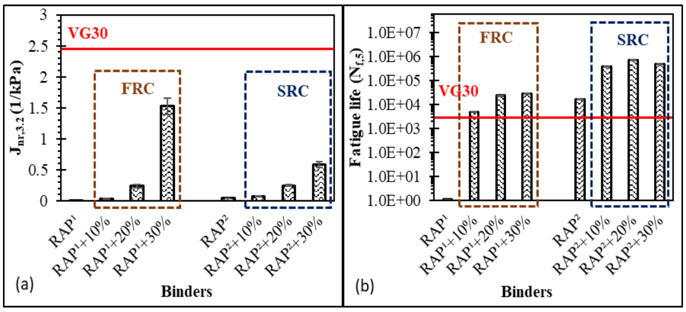

Figure 4. (a) Rutting resistance and (b) fatigue life of asphalt binders during repeated aging and recycling cycles

4 CONCLUSIONS

Based on the test results, the following conclusions can be drawn.

- MO is effective in restoring the original properties of the aged binder during the FRC, its effectiveness significantly diminishes with subsequent aging and recycling, requiring higher MO dosages in SRC.
- High temperature performances can be recovered during FRC but recovery during SRC using similar dosage is not achievable.
- The MO rejuvenated binder appeared to be less sensitive to both re-aging and the subsequent re-rejuvenation process, as seen by the lesser increase and decrease in stiffness caused by aging and rejuvenation in the second cycle compared to the first cycle.
- The LAS test result indicates that fatigue resistance can be maintained even after multiple aging and recycling cycles. Moreover, the fatigue life of the binders progressively improved with each successive recycling cycle.
- Overall, RAPM can be recycled multiple times, but selecting the right rejuvenator is essential for restoring and maintaining its performance.

5 REFERENCES

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