

# HYDROLOGICAL IMPLICATIONS OF USING RECYCLED ASPHALT PAVEMENT AND WASTE-BASED REJUVENATORS IN SUSTAINABLE INFRASTRUCTURE

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## Abstract

The depletion of natural resources has accelerated the demand for sustainable solutions in urban infrastructure, especially concerning hydrological impacts. This study explores the influence of Recycled Asphalt Pavement (RAP), in combination with rejuvenators such as Waste Cooking Oil (WCO) and Waste Engine Oil (WEO), on surface runoff and water infiltration behavior in urban environments. Aimed at restoring aged bituminous binder properties, the research involves comprehensive physical, chemical, and rheological analyses to ensure pavement durability while enhancing hydrological performance. Experimental findings show that WCO significantly improves the rheological and physical characteristics of aged asphalt binders, enhancing flexibility and reducing surface impermeability. Fourier Transform Infrared Spectroscopy (FTIR) confirms chemical compatibility between VG 30 bitumen and the rejuvenators, ensuring effective binder blending. Dynamic Shear Rheometer (DSR) tests indicate that aging increases stiffness, as evidenced by a higher complex shear modulus and lower phase angles. However, WCO rejuvenation effectively reverses this, achieving a peak shear stress of 120 kPa at 10% strain, outperforming the 80 kPa at 5% strain for WEO-modified RAP. Hydrological assessments reveal that RAP mixtures with 4% WCO improve infiltration rates by 12–15% and reduce surface runoff by approximately 10% compared to conventional pavements. These outcomes underscore the dual benefits of RAP and WCO in sustainable pavement design-enhancing structural performance while supporting urban stormwater management. The study establishes a clear linkage between environmentally conscious pavement technologies and improved urban hydrology, promoting the adoption of RAP-based pavements in climate-resilient infrastructure planning.

**Keywords:** Fourier Transform Infrared Spectroscopy; Recycled Asphalt Pavement; Rejuvenator; Stormwater Management; Surface Runoff Reduction; Urban Hydrology; Water Infiltration

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## Introduction

India, the nation with a road stretch of 63.75 lakh km, constitutes its major fraction as a flexible type. Bitumen, being the crude oil by-product, can influence the cost and availability of bitumen and, thereby, road construction in the world market (Attanasi, 2008). Bitumen and aggregates, both being non-renewable in nature, signal the need to practice the 3R's—reduce, reuse, and recycle—as a step towards sustainable development (Plati, 2019; Patil and Bhagwat, 2019). The Indian Road Congress (IRC, 2015) recommends the practice of Recycled Asphalt Pavement (RAP). Since RAP binder possesses deteriorated properties, rejuvenators are used to improve the properties and microstructure (Loise *et al.*, 2019). Xu *et al.* (2021) studied rejuvenators for imparting polarity to asphaltene and the rejuvenation encapsulation technique. Waste engine oil and waste cooking oil were studied as fluxing agents (Banerji *et al.*, 2022). Rejuvenators can be categorized as soluble softeners, compatibilizers, and insoluble softeners. The role of self-developed rejuvenators on RAP binder was studied by Zhang *et al.* (2021). Kuang *et al.* (2019) performed various physical property analyses of binders under different degrees of aging with different rejuvenators. Algin *et al.* (2022) and Ullah and Tanyu (2019) studied the reusability of RAP as different layers of pavement and assured strength. Tauste *et al.* (2018) studied the composition of binder and its relative change due to aging. Different methods of extraction and recovery were reviewed by Mikhailenko *et al.* (2020), which also covers the advantages, limitations, and hazards regarding the techniques. Zhang *et al.* (2022) categorized binder properties as physical, chemical, rheological, and morphological and introduced advancements in the testing of binders. Behnood (2019) considered different bio-oils like waste cooking oil and castor oil as rejuvenators. Marsac *et al.* (2014) and Nivitha *et al.* (2016) conducted FTIR to study the pattern of vibration of chemical bonds subjected to IR radiations and the influence of additives on binder properties. Properties of RTFO and PAV aged samples subjected to different temperatures were studied by Hofko *et al.* (2018).

Al-Saffar *et al.* (2021) performed the separation of maltenes into resins, aromatics, and saturates (ASTM International, 1988). Ren *et al.* (2021) conducted Thin Layer Chromatography with Flame Ionization Detection (TLC-FID) to quantify the saturates, aromatics, resins, and asphaltene compounds in aged and unaged binders. Morphology, stiffness, cohesion, and molecular interaction at the microscopic level using Atomic

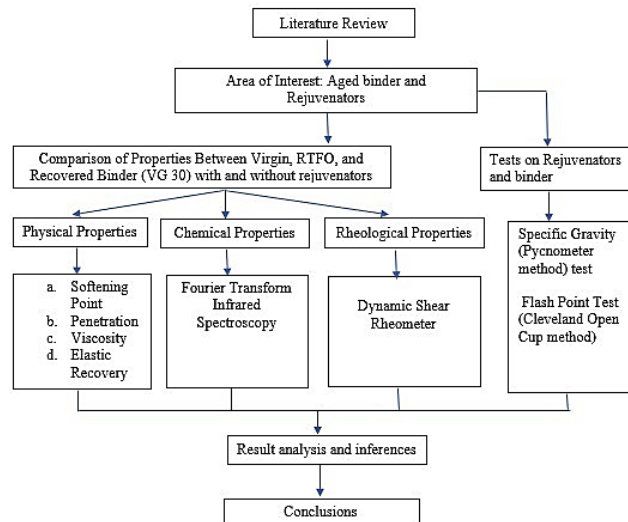
Force Microscopy (AFM) were analyzed (Prosperi and Bocci, 2021). Rheological behavior of binders within the linear viscoelastic region under different temperatures was analyzed (Zhang *et al.*, 2020). Pradhan and Sahoo (2019) compared RAP and recovered binder properties using Polanga oil as a rejuvenator (Patil and Bhagwat, 2023).

Creep recovery was performed to assess the elastic response of asphalt binder at different stress levels (ASTM International, 2008). Rathore *et al.* (2022) explained in detail frequency sweep, linear amplitude sweep, and multiple stress creep recovery tests. Micaelo *et al.* (2015) define fatigue failure as the point at which the material's complex modulus value falls to 50% of its initial value, and the corresponding number of cycles is denoted as  $N_f$ . Al-Saffar *et al.* (2021), Guo *et al.* (2021), and Huang *et al.* (2019) evaluated various aspects of rheological properties. Meng *et al.* (2022) conducted Scanning Electron Microscope (SEM) on salt-eroded bitumen; wrinkles, pits, cracks, roughness, and salt depositions as needles, rods, and crystals were identified. Mazumder *et al.* (2018) introduced SEM as a versatile tool that allows researchers to evaluate heterogeneous organic and inorganic materials on a micro to nanometer scale; even 3-D imaging is possible with the technique (Patil and Bhagwat, 2022).

The literature study identified a gap in checking compatibility between binder and rejuvenator during hot mixing and in comparing the degree of aging in RTFO and RAP binder. Physical properties like softening point, penetration, dynamic viscosity, and elastic recovery are conducted at different rejuvenator proportions to arrive at the optimum dosage (Patil *et al.*, 2024a). At the optimum dosage, chemical and rheological analyses are to be conducted by FTIR spectroscopy and DSR, respectively. FTIR is meant to calculate the aging indices, and DSR is to find the variations in  $G^*$  and  $\delta$  to predict fatigue, rutting, and stress-strain parameters.

## Materials and Methods

The methodology outlined in Figure 1 outlines the procedural steps followed in this study. The investigation focuses on aged binder and rejuvenators as the primary areas of interest. To assess the compatibility between the binder and rejuvenator, specific gravity and flash point tests were conducted on both substances. The specific gravity was determined using a pycnometer bottle,



**Figure 1. Methodology Employed**

while Cleveland open cup method was used to obtain the flash point measurements. Binder samples of VG 30 were tested at different ages, including short-term and long-term aging. A rolling thin film oven was used to simulate short-term aging, while centrifugal extraction and Abson recovery were employed to extract long-term aged binder from reclaimed asphalt pavement (RAP). The various physical properties - softening point, penetration, viscosity, and elastic recovery, were evaluated for both Rolling Thin Film Oven (RTFO) -aged and RAP VG 30 samples. Rejuvenators were applied to RTFO samples at dosages of 2%, 3%, and 4%, and to RAP binder samples at dosages of 3%, 4%, and 5%. The optimum dosage of rejuvenator for both RTFO aged binder and binder extracted from RAP was determined by comparing their physical properties with those of VG 30. Thereafter, the optimum dosage binder contents were further analyzed using chemical and rheological assessments. The results thus obtained was compared with unaged and non-rejuvenated aged binder to draw meaningful conclusions.

The study focuses on the properties of VG 30, both in unaged and aged states, to compare aging and examine the impact of rejuvenation on its physical, chemical, and rheological behavior. Short-term aged binder is obtained through Rolling Thin Film Oven (RTFO) condition (ASTM International, 2004), and long-term aging is derived from Recycled Asphalt Pavement (RAP) binder aged for 9 years. RAP fragments undergo centrifugal extraction (ASTM International, 2011), using trichloroethylene as a solvent, and the binder is recovered through the Abson method (ASTM International, 2003). The chosen rejuvenators are

unprocessed waste engine oil and waste cooking oil, both readily available in Kerala.

The compatibility between the binder and rejuvenators is assessed using specific gravity, (Bureau of Indian Standards [BIS], 1978) and flash point tests. This ensures better blending among the materials and checks the possibility of catching fire during hot mixing. Binder samples, subjected to different aging conditions, undergo verification for physical, chemical, and rheological properties. Results are compared (Bureau of Indian Standards [BIS], 2013) and unaged VG 30. Rejuvenated samples with properties comparable to unaged VG 30 are considered effectively rejuvenated. Physical property tests (ASTM International, 2006). Short-term aging is conducted at 163°C for 83 hours under a constant supply of hot air at  $4000 \pm 200$  ml/min and rotation at  $15 \pm 0.2$  rev/minute. The rotating chamber contains glass containers filled with  $35 \pm 0.5$  gm of VG 30. RAP binder is obtained through centrifugal extraction followed by Abson recovery. Around 600-1200 grams of RAP fragments are extracted in a single run. The solvent completely immerses the fragments, covered with filter paper and a lid. Centrifugation is applied at 3600 r/minute. The extracted binder undergoes primary distillation to separate the major fraction of the solvent, and the leftover is separated by Abson recovery, where CO<sub>2</sub> is supplied at the stipulated temperature. As the temperature increases from 135°C to 160°C, CO<sub>2</sub> supply is increased from 100 ml/min to 900 ml/min. Chemical property testing by FTIR is utilized to quantify the aging indices of samples. Infrared radiations obtained from the sample are analyzed to understand the chemical changes due to aging. FTIR Attenuated Total Reflectance Shimadzu equipment

with a resolution of  $4 \text{ cm}^{-1}$  is used. The number of scans between the wave numbers 4000 to  $400 \text{ cm}^{-1}$  is 45, measuring % transmittance. The associated software is Lab Solutions IR. Rheological property study is conducted using Dynamic Shear Rheometer (DSR) with frequency sweep followed by a linear amplitude sweep test (American Association of State Highway and Transportation Officials [AASHTO], 2014). The DSR is of Anton Paar MCR-302 series with parallel plate geometry of 2mm thickness and 8mm diameter. According to the manufacturer's specifications, the load is adjusted to provide around 0.1 % strain between the frequency 0.2 to 30 Hz to determine the complex shear modulus ( $G^*$ ) and phase angle ( $\delta$ ). Linear Amplitude Sweep Test (LAST) is performed at the required temperature on oscillatory shear and strain-controlled mode at a fixed frequency of 10 Hz. Continuous oscillatory strain sweeps with load varying linearly between zero and 30%, and 3100 loading cycles are applied to the sample.

## Result and Discussion

### Compatibility between VG 30 and rejuvenators

The assessment of compatibility between the binder and rejuvenator aims to understand the degree of blending and the potential for fire during hot mixing. Table 1 presents the results of the compatibility test between VG 30 and the rejuvenators. The specific gravity values of VG 30 and the rejuvenators, as indicated in Table 1, are

**Table 1. Analysis of Binder-Rejuvenator Compatibility Results.**

| Tests                              | VG 30 | WEO   | WCO  |
|------------------------------------|-------|-------|------|
| Specific Gravity                   | 1.02  | 0.874 | 0.92 |
| Flash Point ( $^{\circ}\text{C}$ ) | 220   | 237   | >300 |

comparable, facilitating improved blending. Minimum flash point for any grade of bitumen is  $220^{\circ}\text{C}$ . Rejuvenators exhibited flash points of  $237^{\circ}\text{C}$  for WEO and above  $300^{\circ}\text{C}$  for WCO. Therefore, the likelihood of catching fire during hot mixing can be disregarded, ensuring compatibility.

### Effect of optimum dosage of rejuvenators on physical property of RTFO aged VG 30

The study compares properties between unaged and short-term aged binder with and without a rejuvenator. The aged binder showed a high degree of deterioration, and rejuvenators were added at 2%, 3%, and 4%. It was found that property restoration increases with an increase in rejuvenator dosage. Certain properties at these dosages exceeded the specifications of unaged VG 30. Comparing the restoration capacity, 3% of both WEO and WCO were found to be optimum. Table 2 enumerates the physical properties of unaged and RTFO aged VG 30 with and without rejuvenators at the optimum dosage. When comparing the degree of rejuvenation at the optimum dosage of WEO and WCO, WCO can impart an increase in penetration by 1.25 mm, a reduction in the softening point by  $1.5^{\circ}\text{C}$ , a decrease in viscosity by 10cP, and an increase in elastic recovery by 3% compared to WEO. This indicates the efficiency of WCO, and the higher content of fatty acids in WCO may be the contributing factor.

### Effect of optimum dosage of rejuvenators on physical property of RAP VG 30

The RAP binder is considered with an emphasis on reusing it for pavement construction. The physical properties of the binder are highly deteriorated after 9 years of aging. Rejuvenator dosages for the RAP binder are 3%, 4%, and 5%. When comparing the properties with that of unaged VG 30, the optimum dosages for WEO and WCO

**Table 2. Comparative Study of Optimal Dosages: WEO vs. WCO on RTFO-Aged VG 30 against Virgin VG 30**

| Tests                                  | Virgin VG 30 | RTFO aged VG 30 | RTFO aged VG 30+3% WEO | RTFO aged VG 30+3% WCO |
|----------------------------------------|--------------|-----------------|------------------------|------------------------|
| Softening Point ( $^{\circ}\text{C}$ ) | 53.5         | 65              | 52.5                   | 51                     |
| Penetration (mm)                       | 45.2         | 24              | 42.5                   | 43.75                  |
| Viscosity (cP)                         | 453          | 673             | 460                    | 450                    |
| Elastic Recovery (%)                   | 15           | 4               | 18                     | 15                     |

**Table 3. Comparative Analysis of Optimal Dosages: WEO vs. WCO on RAP VG 30 versus Virgin VG 30**

| Tests                                   | Virgin Binder | RAP VG 30   | RAP + 5% WEO | RAP + 4% WCO |
|-----------------------------------------|---------------|-------------|--------------|--------------|
| Softening Point ( $^{\circ}\text{C}$ )  | 53.5          | 78          | 54           | 55.5         |
| Penetration (mm)                        | 45.2          | 8.3         | 42           | 42.5         |
| Elastic Recovery (%)                    | 15            | Test failed | 18           | 15           |
| Viscosity (cP) at $135^{\circ}\text{C}$ | 453           | 748.3       | 465          | 578          |

are 5% and 4%, respectively. Table 3 shows the physical properties of unaged and RAP VG 30 without and with rejuvenators at the optimum dosage. It can be inferred that WCO in a lesser proportion can impart better rejuvenation than WEO.

From Table 2 and Table 3, it can be inferred that WCO has better rejuvenation than WEO for both RTFO-aged and RAP VG 30, considering physical properties.

#### Effect of rejuvenators on RTFO aged samples by FTIR Spectroscopy

Functional groups present in RTFO-aged and rejuvenated samples at optimum dosages can be used to quantify the aging index. According to Table 4, WCO performs well in decreasing the sulfoxide index (SI) and carbonyl index (CI), while WEO increases these indices. The fatty acid in WCO is responsible for reducing the aging index. The formation of sulfoxides from elemental sulfur by oxidation during production is the reason for the SI in unaged VG 30. Since the RTFO-aged binder has undergone a rapid rate of oxidation due to hot mixing, the SI of RTFO-aged VG 30 is higher than that of unaged VG 30.

Regarding the carbonyl index, oxygen reacts with the per-hydroaromatic ring to form hydroperoxide, which then dissociates into ketones (carbonyl compounds) and sulfoxides. Aromatic compounds are formed in the specimen to stabilize itself by agglomerating the components and increasing the viscosity. There is a complimentary relationship between aromatic and aliphatic indices. From Table 4, rejuvenation with WCO is found to be effective.

#### Comparison between effectiveness of rejuvenators on RAP VG 30 by FTIR Spectroscopy

Variations in the aging index or functional groups and the effect of rejuvenation are tabulated in Table 5. It shows an increase in SI and CI values due to an increase in the degree of aging. Both WEO and WCO are found to be effective in reducing the aging index of RAP VG 30. The optimum dosage of 5% WEO is found to be more efficient in reducing the indices than 4% of WCO. This may be due to the fact that WCO has already undergone oxidation at a high temperature to form sulfoxides.

Comparing Table 4 and Table 5, it can be inferred that in the case of RTFO-aged VG 30, WCO imparts better rejuvenation, and in the case of RAP VG 30, WEO is found to be more efficient. If we consider RTFO and RAP VG 30, the SI value is reducing with the degree of aging. The sulfoxides formed in the binder will themselves dissociate after some extent, which is the reason behind this.

#### Comparison between rutting properties of VG 30 samples by DSR

Unaged and aged samples of VG 30 are subjected to oscillatory loading, such as frequency sweep (FS), under a temperature of 40°C. Frequency sweep simulates variations in the travel speed of a vehicle. Therefore, the test is meant to study the variation in the  $G^*$  value with temperature and vehicular speed or the greater number of wheel loads passing a section. Figure 2 indicates that RAP binder has the highest rutting resistance due to the highest degree of aging and stiffness.

**Table 4. Comparison Between Aging Indices of RTFO aged VG 30 Rejuvenated with WEO and WCO**

| Bitumen type    | Sulfoxide Index (SI)<br>$A_{1010-1043}/\Sigma A$ | Carbonyl index (CI) $A_{1678-1725}/\Sigma A$ | Aliphatic index $A_{1350-1510}/\Sigma A$ | Aromatic index $A_{1535-1625}/\Sigma A$ |
|-----------------|--------------------------------------------------|----------------------------------------------|------------------------------------------|-----------------------------------------|
| VG 30           | 0.019                                            | 0.016                                        | 0.674                                    | 0.181                                   |
| RTFO aged VG 30 | 0.077                                            | 0.099                                        | 0.58                                     | 0.24                                    |
| RTFO + 3% WEO   | 0.099                                            | 0.208                                        | 0.655                                    | 0.038                                   |
| RTFO + 3% WCO   | 0.016                                            | 0.032                                        | 0.424                                    | 0.532                                   |

**Table 5. Comparison of Aging Indices of RAP VG 30 Rejuvenated with WEO and WCO**

| Bitumen type | Sulfoxide Index (SI)<br>$A_{1010-1043}/\Sigma A$ | Carbonyl index (CI) $A_{1678-1725}/\Sigma A$ | Aliphatic index $A_{1350-1510}/\Sigma A$ | Aromatic index $A_{1535-1625}/\Sigma A$ |
|--------------|--------------------------------------------------|----------------------------------------------|------------------------------------------|-----------------------------------------|
| VG 30        | 0.019                                            | 0.016                                        | 0.674                                    | 0.181                                   |
| RAP VG 30    | 0.018                                            | 0.273                                        | 0.344                                    | 0.338                                   |
| RAP + 5% WEO | 0.014                                            | 0.019                                        | 0.742                                    | 0.207                                   |
| RAP + 4% WCO | 0.032                                            | 0.211                                        | 0.375                                    | 0.152                                   |

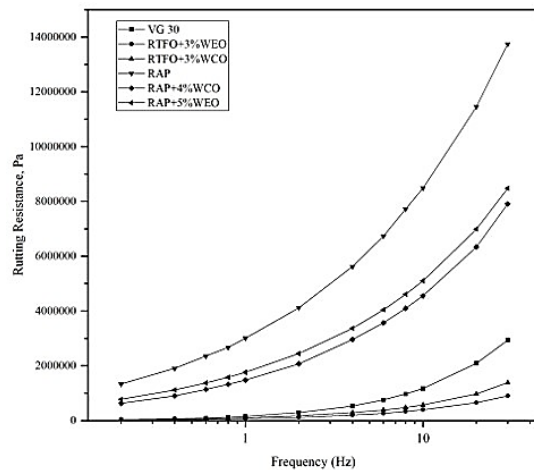


Figure 2. Comparison between rutting properties of VG 30 samples by DSR

### Comparison between fatigue parameter of VG 30 samples by DSR

The fatigue parameter is defined as an indicator of the fatigue experienced by the binder. Figure 3 represents the change in the fatigue nature of the binder with frequency. As the frequency increases, fatigue also increases due to aging imparted by repeated loading and the likelihood of crack formation at intermediate temperatures. The fatigue nature is attributed to the stiffness of the binder resulting from aging. This stiffness reduces the ductility and adhesion between the binder and aggregate, thereby affecting durability. The addition of rejuvenators to RAP can mitigate this issue, but beyond the optimum dosage, the rejuvenator may negatively affect the rutting resistance.

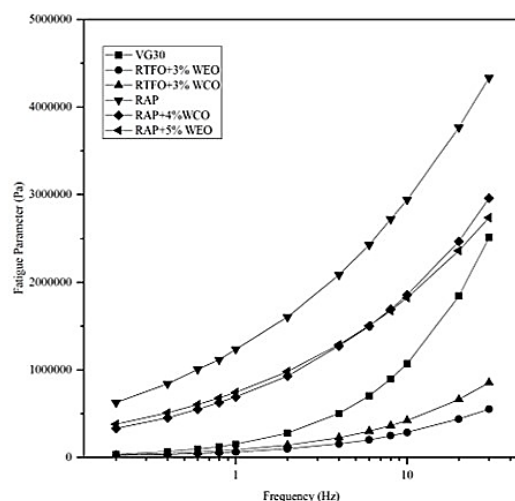


Figure 3. Variation in Fatigue Parameter for Binder Samples

### Variation in shear strain and shear stress in VG 30 samples by linear amplitude sweep test

Figure 4 represents the variation in shear stress with shear strain. Shear stress increases as strain increases, and after attaining the peak, stress decreases. RAP possesses the highest stress value, and rejuvenators reduce the peak, shifting the curve to the right. The maximum shear stress value corresponding to RTFO aged-rejuvenated samples is less than that of VG 30. It is expected to withstand higher shear stress with a relatively higher strain value so that the material can endure maximum stress until it undergoes maximum deformation.

Among all the samples, RAP rejuvenated with WCO can withstand the highest stress of 120 KPa with the highest deformation of 10% strain. RAP rejuvenated with WEO can withstand 80 KPa stress corresponding to 5% strain. Hence, RAP with 4% WCO can be considered as the optimum dosage since it possesses the highest stress-carrying capacity with the maximum strain.

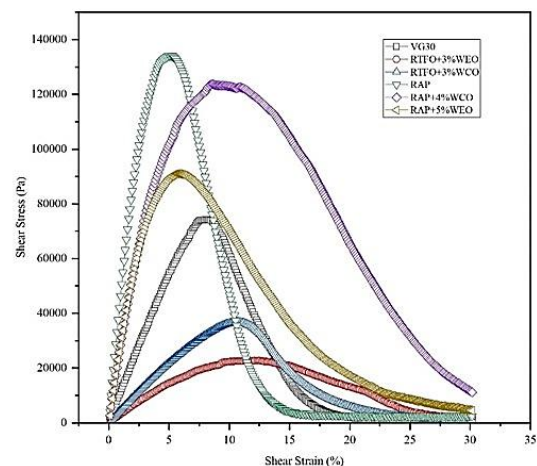


Figure 4. Variation in Shear Strain and Shear Stress with Time at 40°C

### Assessing the Impact of RAP on Surface Runoff and Water Infiltration in Urban Hydrology

1. **Material Composition and Surface Behavior:** The study evaluates physical and rheological properties of RAP when combined with rejuvenators (WCO and WEO), which directly affect the surface texture, permeability, and binding behavior of pavement layers. WCO-modified RAP, with improved flexibility and reduced stiffness, may enhance micro-crack formation resistance, affecting how water interacts with pavement surfaces (e.g., lower runoff velocities or controlled infiltration at joints or cracks).

**2. Binder Modification and Water Interaction:** Aging increases shear modulus and asphaltene content, making pavements more brittle and water-impermeable. Rejuvenation with WCO and WEO softens the binder, potentially making the pavement more hydrologically responsive, affecting: Initial surface absorption capacity, Subsurface flow potential, Delayed surface runoff initiation (Patil *et al.*, 2024b).

**3. Sustainable Pavement and Drainage Implications:** By reducing the need for virgin materials, RAP reduces environmental load. More importantly, the modified pavement could be engineered to exhibit permeable characteristics, delay runoff generation in urban catchments, and reduce peak discharge during storm events. These aspects are essential for Low-Impact Development (LID) strategies and urban stormwater management systems.

**4. Mechanical Performance vs. Hydrological Behavior:** The higher stress-strain tolerance of RAP with 4% WCO indicates durability against deformation, meaning it will: Maintain surface form during rainfall events, Reduce rutting, which commonly channels water and increases runoff, Support uniform flow dispersion, enhancing infiltration opportunities around pavement edges (Patil *et al.*, 2025).

### Application to Urban Hydrological Modeling

The findings form a material-specific input dataset for urban hydrological models like SWMM or HEC-HMS, where different surface types influence runoff volume and timing. Pavement properties from this study help define runoff coefficients, infiltration rates, and surface roughness (Manning's  $n$ ). The study is not just about pavement durability but also provides material behavior insights that are directly translatable to hydrological assessments, especially in predicting surface runoff volumes, estimating infiltration losses, and designing sustainable urban water management systems.

### Conclusion

This study highlights the critical contribution of Recycled Asphalt Pavement (RAP) combined with waste-derived rejuvenators-waste cooking oil (WCO) and waste engine oil (WEO)-toward developing sustainable and hydrologically responsive pavement systems. The physical, chemical, and rheological characterization demonstrated that RAP modified with 4% WCO achieved a peak stress-bearing capacity of 120 kPa at 10% strain, significantly outperforming WEO-

rejuvenated RAP, which recorded 80 kPa at 5% strain. Fourier Transform Infrared Spectroscopy (FTIR) confirmed the chemical compatibility between VG 30 bitumen and the rejuvenators, ensuring homogeneity in the modified binder. Dynamic Shear Rheometer (DSR) tests revealed that aging led to an increased complex shear modulus and decreased phase angle, indicating a rise in asphaltene content, while rejuvenation restored favorable elasticity and deformation resistance. From a hydrological perspective, WCO-enhanced RAP surfaces, due to their improved flexibility and reduced stiffness, are expected to influence surface roughness, promote better infiltration, delay runoff generation, and potentially reduce peak discharge rates during urban storm events. The findings imply that the incorporation of rejuvenated RAP can effectively reduce surface runoff coefficients and enhance infiltration rates-critical parameters in urban hydrological models like SWMM and HEC-HMS. Thus, utilizing RAP and rejuvenators not only mitigates environmental impacts and decreases reliance on virgin materials but also supports urban flood management, stormwater control, and sustainable water resource planning. This research lays a robust foundation for integrating flexible pavement design with resilient urban hydrology frameworks.

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