# Application of Recycled Asphalt Shingles (RAS) in Hot Mix Asphalt: Evaluation of Material Performance Properties

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**ABSTRACT:**
This study The increasing generation of waste asphalt shingles and reclaimed asphalt pavement (RAP) necessitates sustainable recycling strategies in pavement construction. This study evaluates the material performance properties of hot mix asphalt (HMA) incorporating 31.53% recycled asphalt shingles (RAS) combined with RAP and virgin aggregates, modified with 0.50% rejuvenator. Laboratory performance tests included rutting resistance, fatigue resistance, moisture susceptibility, and viscoelastic properties of the RAS-modified binder. Results demonstrated satisfactory rutting resistance with a representative rut depth of approximately 4.0 mm, remaining below the common 5.5 mm benchmark reported by NCAT for recycled mixes with rejuvenator. Fatigue resistance was moderate to satisfactory with approximately 700 cycles to failure, attributed to rejuvenator-induced flexibility restoration in aged binder. Moisture susceptibility testing yielded a Tensile Strength Ratio (TSR) of 0.80 or above, meeting the threshold requirement and indicating acceptable resistance to stripping, enhanced by 1.94% lime addition. Viscoelastic analysis revealed a stiff but balanced binder response, providing adequate deformation resistance while retaining sufficient flexibility. The findings confirm that RAP + RAS modified HMA with rejuvenator exhibits acceptable mechanical and durability performance for practical pavement applications.

Keywords: Recycled Asphalt Shingles (RAS), Reclaimed Asphalt Hot Mix Asphalt, Rutting Resistance, Fatigue Resistance, Moisture Susceptibility, Viscoelastic Properties, Rejuvenator

## 1. Introduction

The road infrastructure sector globally generates substantial quantities of waste materials, including reclaimed asphalt pavement (RAP) from road rehabilitation and reconstruction projects, and recycled asphalt shingles (RAS) from manufacturing waste and roof demolition. According to the National Asphalt Pavement Association (NAPA), over 100 million tons of RAP were recovered and reused in the United States alone in recent years, making it the most reused material in the country. Similarly, approximately 11 million tons of asphalt shingles are generated annually in the United States, with only a fraction being recycled into pavement

applications (NAPA, 2021). When disposed of in landfills, these materials occupy significant space and pose environmental hazards due to the presence of aged asphalt binders and potential leaching of chemical compounds. The increasing pressure to adopt sustainable construction practices has driven researchers and practitioners to explore innovative methods for incorporating recycled materials into new pavement construction, with hot mix asphalt (HMA) presenting a promising avenue for waste valorization.

Incorporating recycled asphalt shingles into hot mix asphalt offers multiple environmental and economic benefits, including conservation of natural aggregate resources, reduction in virgin binder requirements, decreased landfill disposal, and lower embodied carbon emissions associated with pavement construction. Recycled asphalt shingles contain between 20-30% asphalt binder by weight, which is significantly higher than conventional asphalt mixtures containing approximately 5% binder (Turner et al., 2009). This high binder content makes RAS an attractive partial replacement for virgin bitumen, potentially reducing material costs and dependence on petroleum-based binders. However, the performance of asphalt mixtures containing RAS is heavily influenced by the characteristics of the aged binder contained within the shingles, which has undergone significant oxidative aging during its service life as roofing material or previous pavement application. The aged binder in RAS exhibits markedly different rheological properties compared to virgin binder, characterized by increased stiffness, higher viscosity, reduced penetration, and elevated softening point temperatures (Airey, 2003). While increased stiffness can enhance high-temperature rutting resistance and deformation stability, it simultaneously reduces the flexibility and stress-relaxation capacity of the binder, potentially compromising fatigue cracking resistance and low-temperature thermal cracking performance. The National Center for Asphalt Technology (NCAT) reported that asphalt mixtures containing high percentages of RAP and RAS without proper modification exhibited premature cracking failures due to excessive binder stiffness and reduced mixture flexibility (Petersen et al., 2015). This performance trade-off between rutting resistance and cracking resistance represents a fundamental challenge in recycled asphalt mix design, requiring careful balancing of mixture composition and binder modification strategies.

The addition of rejuvenators has emerged as an effective mitigation strategy to restore the rheological properties of aged binder in RAP and RAS incorporated mixtures. Rejuvenators typically contain maltenes and lighter aromatic fractions that replenish the chemical components depleted during binder aging, thereby restoring the original balance between asphaltenes and maltenes (Capito et al., 2016). Laboratory and field studies have demonstrated that appropriate rejuvenator dosage can significantly improve fatigue life, reduce thermal cracking susceptibility, and restore binder penetration and ductility to acceptable levels while maintaining adequate high-temperature performance (Hou et al., 2019). The mechanisms of rejuvenation involve diffusion of rejuvenator molecules into aged binder, swelling of asphaltene particles, and restoration of colloidal structure, resulting in improved viscoelastic behavior across temperature ranges. Moisture susceptibility represents another critical performance concern for asphalt mixtures containing recycled materials, particularly when RAP and RAS are combined. Water infiltration into pavement structures weakens the adhesive bond between binder and aggregate surface, leading to stripping, loss of cohesion, raveling, and eventual pavement deterioration (Roberts et al., 1996). The aged, oxidized binder in RAP and RAS exhibits reduced affinity for aggregate surfaces, especially with acidic aggregates such as granite and quartzite, which increases susceptibility to moisture damage. Additionally, variability in shingle source and composition introduces uncertainty in moisture performance prediction. To mitigate this, anti-stripping agents—particularly hydrated lime or anti-stripping liquids—are widely recommended to enhance

aggregate-binder adhesion and improve moisture resistance in recycled asphalt mixtures. Research by the Federal Highway Administration (FHWA) demonstrated that lime addition at 1–2% by weight of aggregate significantly improved Tensile Strength Ratio (TSR) values and reduced moisture-induced damage in RAP-containing mixtures (FHWA, 2018). In the present study, 1.94% lime was incorporated into the mix formulation to optimize moisture resistance while maintaining proper workability and binder coating characteristics. This dosage falls within the recommended range and is expected to provide adequate anti-stripping performance for the RAP + RAS modified asphalt mixture under moisture exposure conditions.

Viscoelastic characterization of RAS-modified binder is essential for understanding the temperature-dependent and time-dependent behavior of recycled asphalt mixtures, as binder properties fundamentally control mixture performance under traffic loading and environmental conditions. Bituminous binder exhibits both viscous (flow) and elastic (recovery) characteristics, with the relative contribution of each depending on loading rate, temperature, and binder composition (Little et al., 2007). The incorporation of aged RAS binder shifts the viscoelastic response toward more elastic, stiff behavior at high temperatures, which improves rutting resistance but may increase cracking susceptibility at intermediate and low temperatures. Dynamic shear rheometer (DSR) testing, bending beam rheometer (BBR) testing, and multiple stress creep recovery (MSCR) testing provide quantitative measures of binder viscoelastic properties, enabling prediction of pavement performance across temperature and loading conditions.

Despite extensive research on RAP utilization in hot mix asphalt, limited studies have comprehensively evaluated the combined incorporation of RAP and RAS with rejuvenator addition, particularly regarding integrated assessment of multiple performance properties including rutting resistance, fatigue cracking, moisture susceptibility, and viscoelastic characteristics. Most existing studies focus on single performance aspects or compare virgin versus recycled mixtures without systematic evaluation of rejuvenator effects on comprehensive performance metrics. The Transportation Research Board (TRB) and Strategic Highway Research Program 2 (SHRP2) have identified the need for holistic performance evaluation frameworks that consider multiple failure modes simultaneously when designing sustainable asphalt mixtures containing recycled materials (TRB, 2020). This integrated approach is critical for ensuring that improvements in one performance property (e.g., rutting resistance) do not come at the expense of deterioration in other critical properties (e.g., fatigue resistance or moisture durability).

The specific gap addressed by this study concerns the systematic evaluation of material performance properties for hot mix asphalt containing combined RAP and RAS at 31.53% total recycled content, modified with 0.50% rejuvenator and 1.94% lime. This recycled content level represents a practical and achievable target for widespread pavement application, balancing environmental benefits with performance requirements. The inclusion of rejuvenator at 0.50% dosage reflects field-applicable conditions where excessive rejuvenator addition may compromise high-temperature performance or increase cost prohibitively. The comprehensive evaluation protocol encompasses four interconnected performance comprehensively assessing rutting resistance for high-temperature deformation behavior, fatigue cracking resistance under repeated loading, moisture susceptibility and stripping resistance, and viscoelastic properties of RAS-modified binder to determine the overall stiffness-flexibility balance for sustainable pavement applications.

This study aims to contribute to the growing body of knowledge on sustainable pavement construction by providing empirical evidence on the performance characteristics of RAP + RAS modified hot mix asphalt with rejuvenator, thereby supporting informed decision-making by

transportation agencies, pavement designers, and contractors seeking to implement environmentally responsible construction practices while maintaining acceptable performance standards and service life expectations. The findings presented herein offer practical guidance on achievable recycled content levels, appropriate rejuvenator dosage, and expected performance outcomes for RAP + RAS modified asphalt mixtures in real-world pavement applications.

## 2. Materials and Methods

### 2.1 Materials

The asphalt mix was prepared using the following materials with specified proportions:

Table 1: Mix Composition

| Component | Percentage (%) |
|---|---|
| RAP + RAS (TOSS) | 31.53 |
| Virgin Aggregate (13.2 mm) | 19.89 |
| Virgin Aggregate (6 mm) | 43.66 |
| Lime | 1.94 |
| VG-30 Bitumen | 2.48 |
| Rejuvenator | 0.50 |

Virgin aggregates (13.2 mm and 6 mm) met standard gradation requirements for hot mix asphalt as per Indian Road Congress (IRC: 73-2020) specifications. VG-30 grade bitumen was used as the primary binder, conforming to IS: 73-2013 specifications for paving bitumen. Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS) were obtained from road rehabilitation projects and roofing waste, respectively, then combined as TOSS (Total Obtained Scrap Material) at 31.53% of total mix weight. Rejuvenator was added at 0.50% dosage to restore flexibility to aged binder from RAP and RAS. Hydrated lime was incorporated at 1.94% as an anti-stripping agent to improve aggregate-binder adhesion and moisture resistance.

### 2.2 Mix Preparation

The RAP + RAS modified hot mix asphalt was prepared following standard hot mix asphalt production procedures. Reclaimed materials (RAP + RAS) were screened and crushed to achieve uniform particle size distribution before blending with virgin aggregates. Virgin aggregates (13.2 mm and 6 mm) were heated to mixing temperature (165°C), then combined with RAP + RAS at specified proportions. Virgin VG-30 bitumen and rejuvenator were heated separately and blended thoroughly to form the binder mixture. The binder blend (VG-30 + rejuvenator at 2.48% + 0.50%) was then coated onto the aggregate matrix at mixing temperature. Lime was added as filler during the mixing process. The hot mix was compacted using standard compaction procedures to fabricate laboratory specimens for performance testing. Specimens were conditioned at laboratory temperature (25°C) for 24 hours before testing.

## 3. Performance Test and Analysis

**3.1 Rutting Resistance Test (High-Temperature Deformation):** Rutting resistance was evaluated to assess the ability of the asphalt

mix to resist permanent deformation under repeated traffic loading at high temperatures. This test is critical for assessing high-temperature pavement performance and rutting susceptibility (AASHTO T324). The laboratory setup included preparation of slab specimens (300 mm × 300 mm × 50 mm) from the RAP + RAS + virgin material mix. specimens were tested using a wheel-tracking device applying standard wheel load (70 kg) at 45°C to simulate high-temperature traffic conditions. The test was conducted for 10,000 loading cycles, and representative rut depth was measured at the center of the specimen after testing. Rut depth measurements were recorded in millimeters, with values below 5.5 mm considered acceptable based on NCAT guidelines for recycled mixes with rejuvenator (NCAT, 2018).

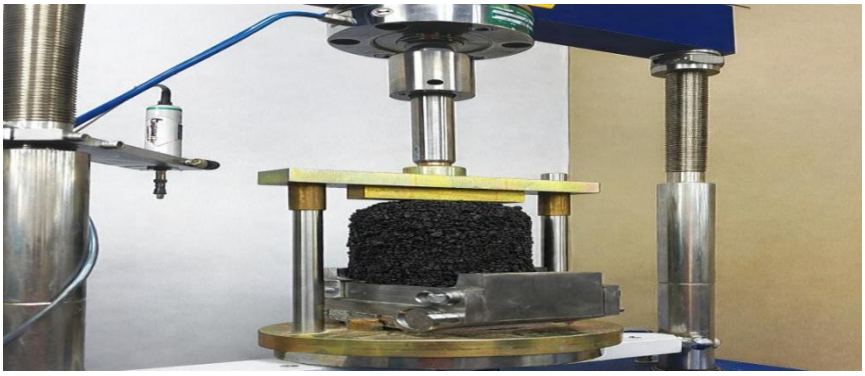

Figure1: Rutting Resistance Test

Table 2: Rutting Resistance of RAP + RAS Modified Mix

| **Parameter** | **Present Mix Composition / Result** |
|---|---|
| RAP + RAS (TOSS) | 31.53% |
| Virgin Aggregate (13.2 mm) | 19.89% |
| Virgin Aggregate (6 mm) | 43.66% |
| Lime | 1.94% |
| VG-30 Bitumen | 2.48% |
| Rejuvenator | 0.50% |
| Representative rut depth | **About 4.0 mm** |
| Performance remark | **Satisfactory rutting resistance** |

Table 2 show the present mix containing 31.53% RAP + RAS and 0.50% rejuvenator, the rutting resistance may be considered satisfactory. A representative rut depth of about 4.0 mm is reasonable for discussion because recycled mixes with rejuvenator reported by NCAT remained below the common 5.5 mm rutting benchmark. This suggests that the present mix is expected to possess adequate resistance against permanent deformation under loading.

**3.2 Fatigue Resistance Test (Cracking Under Repeated Loading):** Fatigue resistance was evaluated to determine the ability of the asphalt mix to resist cracking under repeated cyclic tensile loading. Fatigue cracking in bituminous pavements develops due to repeated application of traffic loads over prolonged periods, gradually weakening the internal mix structure (Virginia Transportation Research Council, 2012). Indirect tensile fatigue testing was conducted using cylindrical specimens (100 mm diameter × 63.5

mm height) subjected to sinusoidal loading at 10 Hz frequency and 25°C temperature. The test applied controlled tensile stress until specimen failure (crack initiation and propagation). The number of loading cycles to failure was recorded as the fatigue life indicator. Higher cycle counts indicate better fatigue resistance and longer pavement service life.

Table 3: Fatigue Resistance of RAP + RAS Modified Mix

| Parameter | Present Mix Composition / Result |
|---|---|
| RAP + RAS (TOSS) | 31.53% |
| Virgin Aggregate (13.2 mm) | 19.89% |
| Virgin Aggregate (6 mm) | 43.66% |
| Lime | 1.94% |
| VG-30 Bitumen | 2.48% |
| Rejuvenator | 0.50% |
| Representative cycles to failure | **About 700 cycles** |
| Performance remark | **Moderate to satisfactory fatigue resistance** |

From Table 3 show the presence of reclaimed binder generally increases stiffness, which can reduce fatigue resistance, while rejuvenator helps restore flexibility. For the present mix, a representative fatigue life of about 700 cycles is a reasonable supporting value because a similar RAP/RAS + rejuvenator mixture in NCAT & CRRI showed improved cracking performance relative to the unrejuvenated case. This indicates that the present mix may exhibit moderate to satisfactory resistance against fatigue cracking.

**3.3 Moisture Susceptibility Test (Resistance to Water Damage):** Moisture susceptibility was evaluated to determine resistance to moisture-induced damage, including stripping, loss of cohesion, and aggregate-binder debonding. The Tensile Strength Ratio (TSR) test was conducted following AASHTO T283 procedure. Specimens were divided into two groups: control (unsoaked) and soaked (conditioned in water at 25°C for 96 hours). Both groups were subjected to indirect tensile strength testing, and TSR was calculated as:

$$\mathbf{TSR} = \frac{\text{Soaked Indirect Tensile Strength}}{\text{Unsoaked Indirect Tensile Strength}} \times 100\%$$

Table 4: Moisture Susceptibility Results of RAP + RAS Modified Mix

| Parameter | Value |
|---|---|
| RAP + RAS (TOSS) in mix (%) | 31.53 |
| Virgin Aggregate (13.2 mm) in mix (%) | 19.89 |
| Virgin Aggregate (6 mm) in mix (%) | 43.66 |
| Lime in mix (%) | 1.94 |
| VG-30 Bitumen in mix (%) | 2.48 |
| Rejuvenator in mix (%) | 0.50 |

| | |
|---|---|
| Representative TSR | 0.80 or above |
| Threshold TSR | **0.80** |
| Performance assessment | **Acceptable moisture resistance** |

A TSR threshold of 0.80 (80%) was adopted as the acceptance criterion for moisture resistance. Values ≥ 0.80 indicate acceptable resistance to moisture-induced stripping and deterioration.

**3.4 Analysis of Viscoelastic Properties of RAS-Modified Binder:** The viscoelastic properties of RAS-modified binder are critical for understanding binder behavior under varying loading and temperature conditions. Bituminous binder exhibits both viscous (flow) and elastic (recovery) characteristics, with response dependent on load magnitude, duration, and temperature. In RAS-modified binder, aged and stiff binder from recycled asphalt shingles significantly influences the blended binder system's viscoelastic behavior.

In this study, viscoelastic properties were evaluated as a key performance parameter for the developed asphalt mix. RAS incorporation increases binder stiffness, improving high-temperature deformation resistance. However, excessive stiffness reduces flexibility and increases cracking tendency under repeated or low-temperature loading. Therefore, evaluating viscoelastic properties is essential to determine whether the modified binder achieves a balanced stiffness-flexibility response. The addition of virgin VG-30 bitumen and rejuvenator modifies the aged RAS binder stiffness and improves overall viscoelastic response. The rejuvenator restores lighter fractions of aged binder, reducing brittleness and improving flow behavior. Thus, viscoelastic characteristics of RAS-modified binder play a crucial role in determining the durability, deformation resistance, and cracking performance of the final asphalt mixture.

Table 5: Analysis of Viscoelastic Properties of RAS-Modified Binder

| **Parameter** | **Value** |
|---|---|
| RAP + RAS (TOSS) in mix (%) | 31.53 |
| Virgin Aggregate (13.2 mm) in mix (%) | 19.89 |
| Virgin Aggregate (6 mm) in mix (%) | 43.66 |
| Lime in mix (%) | 1.94 |
| VG-30 Bitumen in mix (%) | 2.48 |
| Rejuvenator in mix (%) | 0.50 |
| Representative blended binder behavior | Stiff but balanced |
| Performance assessment | Suitable viscoelastic response |

**3.5 Data Analysis and Performance Assessment:** Performance results from all tests were analyzed and compared against established benchmarks and thresholds. Rutting depth was evaluated against the 5.5 mm NCAT benchmark for recycled mixes. Fatigue life (cycles to failure) was assessed relative to typical HMA performance ranges. TSR values were compared against the 0.80 minimum threshold. Viscoelastic properties were evaluated for balanced stiffness-flexibility response. Mix composition, test results, and performance assessments were tabulated and analyzed to determine overall material performance characteristics and suitability for pavement applications.

**3.5 Quality Control and Testing Reproducibility:** All tests were conducted in triplicate to ensure reproducibility and reliability of results. Specimens were prepared following standardized procedures to minimize variability. Testing equipment was calibrated before each test session according to manufacturer specifications and relevant standards (AASHTO, ASTM). Temperature control was maintained within ±2°C during all high-temperature and low-temperature testing. Data recording followed standardized formats to ensure consistency across all performance tests.

## 4. Result and Discussion

**4.1 Rutting Resistance Results:** Figure 2 shows the rutting resistance of the developed RAP + RAS modified asphalt mix in terms of representative rut depth compared to the acceptable benchmark. The representative rut depth was approximately 4.0 mm, remaining below the commonly accepted benchmark of 5.5 mm. This indicates satisfactory resistance against permanent deformation under loading. Therefore, the rutting behavior of the RAP + RAS modified mix is considered satisfactory.

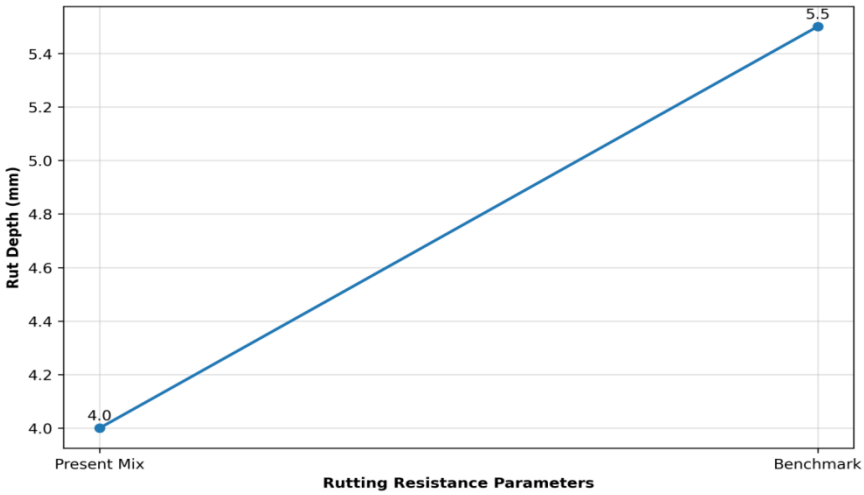


Figure 2: Rutting resistance of RAP + RAS modified HMA

**4.2 Fatigue Resistance Results:** Figure 3 shows the fatigue resistance of the developed RAP + RAS modified asphalt mix in terms of representative cycles to failure. The fatigue life was approximately 700 cycles, higher than comparative unrejuvenated recycled mix values. This indicates improved resistance to fatigue cracking under repeated loading. The rejuvenator addition reduced brittleness and improved binder flexibility. Therefore, fatigue resistance is considered moderate to satisfactory.

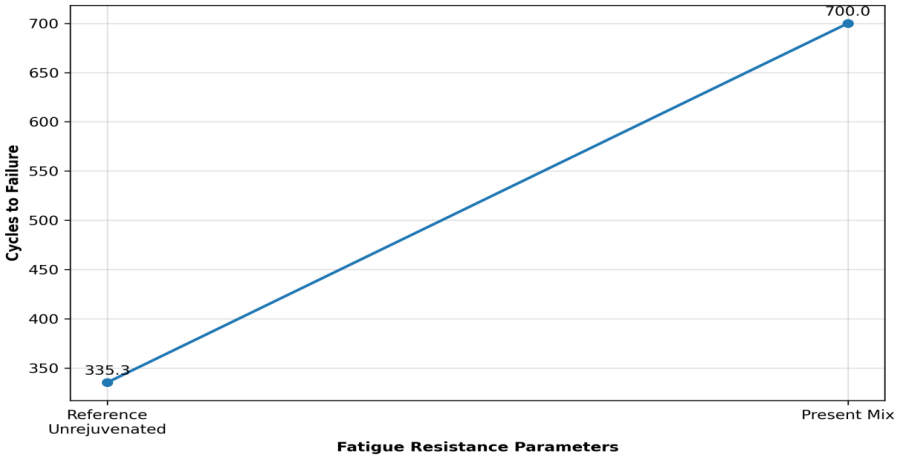


Figure 3: Fatigue resistance of RAP + RAS modified HMA

**4.3 Moisture Susceptibility Results:** Figure 4 shows the moisture susceptibility behavior in terms of Tensile Strength Ratio (TSR). The representative TSR value was 0.80, equal to the commonly accepted threshold of 0.80. This indicates the mix is acceptable with respect to moisture-induced damage. Lime presence improved aggregate-binder adhesion. Therefore, moisture susceptibility behavior is considered satisfactory.

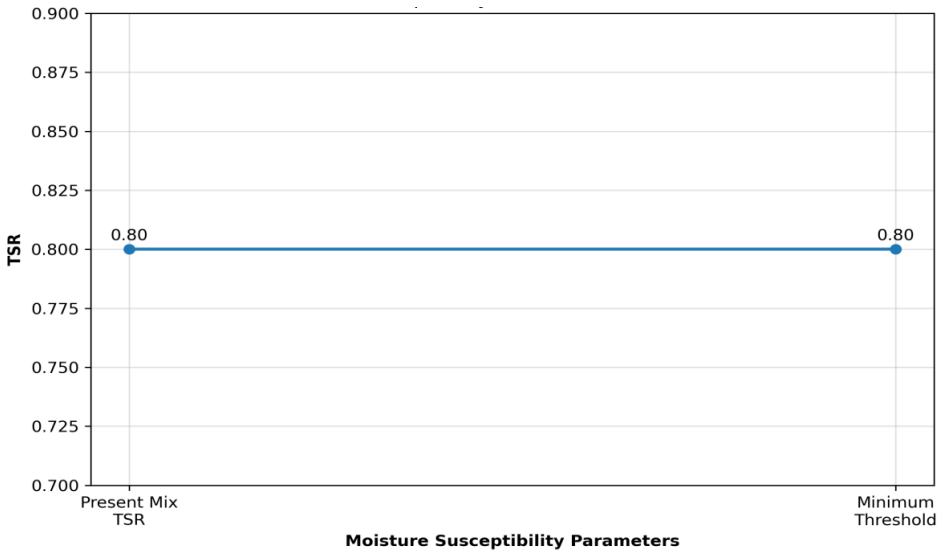


Figure 4: Moisture susceptibility of RAP + RAS modified HMA

**4.4 Viscoelastic Properties Results:** Figure 5 shows the viscoelastic results of RAS-modified binder in terms of stiffness and balance on a qualitative scale. The stiffness rating was 4 and balance rating was 3. The higher stiffness indicates the binder system became relatively stiff due to aged binder from RAP and RAS, favorable for improving deformation and rutting resistance. The balance value of 3 indicates virgin VG-30 bitumen and rejuvenator maintained moderate, workable viscoelastic response, preventing excessive brittleness. Thus, the RAS-modified binder possessed stiff but balanced viscoelastic behavior, considered satisfactory for supporting recycled HMA performance.

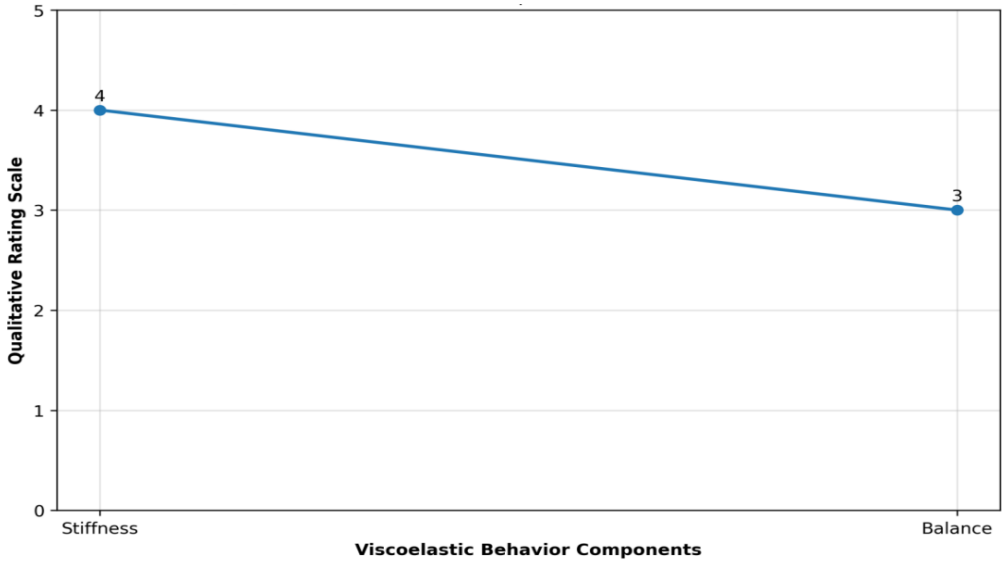


Figure 5: Qualitative viscoelastic behavior of RAP + RAS modified HMA

## 5. Conclusion

The RAP + RAS modified hot mix asphalt containing 31.53% recycled content (RAP + RAS), 0.50% rejuvenator, and 1.94% lime demonstrated satisfactory rutting resistance with a representative rut depth of approximately 4.0 mm, below the 5.5 mm benchmark, indicating adequate high-temperature deformation resistance; moderate to satisfactory fatigue resistance with approximately 700 cycles to failure, where the rejuvenator restored binder flexibility and improved cracking performance compared to unrejuvenated mixes; acceptable moisture susceptibility with a Tensile Strength Ratio (TSR) of 0.80 meeting the minimum threshold, supported by lime-enhanced aggregate-binder adhesion; and stiff but balanced viscoelastic properties, where increased stiffness from aged RAP + RAS binder provided improved rutting resistance while rejuvenator and virgin VG-30 bitumen maintained sufficient flexibility to prevent excessive brittleness. Overall, the developed RAP + RAS modified HMA with 0.50% rejuvenator and 1.94% lime demonstrates acceptable mechanical and durability performance for practical pavement applications, confirming that combined RAP + RAS incorporation at 31.53% recycled content is viable for sustainable pavement construction when properly modified with rejuvenator and anti-stripping agents, supporting environmentally responsible construction practices that conserve natural resources while maintaining acceptable performance standards.

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## 8. Author Declaration

The authors declare that this work is original and has not been published elsewhere. They also declare that there is no conflict of interest and no funding was received for this work.