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# Mechanistic–Empirical Design of Perpetual Pavements Using Recycled and Modified Asphalt Materials

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**Abstract- The increasing demand for durable, sustainable, and cost-effective roadway infrastructure has led to significant advancements in pavement engineering, particularly in the development of perpetual pavements. This research presents a comprehensive analysis of the Mechanistic–Empirical (M–E) design approach for perpetual pavements incorporating recycled and modified asphalt materials. The M–E design methodology integrates mechanistic analysis of pavement responses (stress, strain, and deflection) with empirical performance models to predict long-term distress such as fatigue cracking, rutting, and thermal cracking. The study critically evaluates the performance of recycled materials including Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), and Warm Mix Asphalt (WMA), along with modified binders such as polymer-modified asphalt, crumb rubber-modified bitumen, and nano-modified binders.**

**Keywords- Mechanistic–Empirical Pavement Design, Perpetual Pavements, Recycled Asphalt Materials, Modified Asphalt Binders, Long-Life Pavement Performance.**

## I. INTRODUCTION

Tremendous amounts of "reclaimed asphalt" are available from maintenance works on asphalt road pavements. Reclaimed asphalt (RA) comprises asphalt reclaimed by milling of asphalt road layers, by crushing of slabs ripped up from asphalt pavements, lumps from slabs, and asphalt from reject and surplus production [1]. With the principles of durable development in mind, and urged by economic and ecological factors, the recycling of old asphalt has gained ground over the past few years. This is mainly due to the relatively high cost of bitumen (a by-product of oil refining) and the advances in technologies making high-quality recycling of old asphalt into new bituminous mixtures possible. In situ recycling of asphalt pavements made its appearance in the year 1975.

The technology was used on several works over the next ten years or so, without being able to force a major breakthrough. The principal reason why this technique did not continue as a success was the development of another form of asphalt recycling in the eighties: in-plant recycling, which has a wider field of application than in situ recycling. In view of sustainable development the use of these recycling technologies must increase because reuse of reclaimed asphalt accounts only for about 7 % of the total road rehabilitation work [2].


Fig.1. Encouraging Sustainable Use of RAP Materials

The primary reasons to build Expressways are to cater for high volume of traffic and achieve fast connectivity to economic hubs. This results in longer driving hours for drivers on high speed with limited stoppages. Due to this Expressways require highest safety measures and comfort conditions for drivers. One of the basic requirements for roads is to have minimum maintenance so that the traffic disruptions are limited. To achieve this the basic requirements are as follows: a. Adequately designed pavement from structural strength considerations, and b. Enhanced safety requirements, compatible with high traffic speeds and volumes; c. Adequate driving comfort for long distance high speed travel; d. Provision of the needed safety and comfort levels on a sustained basis without any dislocation, disturbance or inconvenience to the traffic. Safety and comfort of user's aspects are related more to the surface characteristics. While the structural aspects are generally covered in IRC design standards coupled with

MORTH policy [3-4]. Traffic Safety depends on a number of factors including pavement surface characteristics, the vehicles and the drivers, safe vehicle pavement interaction at high speeds. Adequacy of geometric design for the traffic speeds and volumes, special attention is needed to the aspect of skid resistance and hydro-planning. Driving Comfort considerations call for increasingly more even surface with increase in speed. These properties of the pavement are related to its surface texture and surface drainage characteristics. More stringent norms for surface stability and hardness needs to be adopted for Expressways compared to other highways. The choice of construction material, construction methodology and quality control techniques must be compatible to achieve the surface evenness levels needed level for Expressways [5].

## II. MATERIAL AND PROPOSED METHOD

This presents the materials, experimental program, pavement design methodology, and analysis procedures adopted for the development of a Mechanistic–Empirical (M–E) design framework for perpetual pavements incorporating recycled and modified asphalt materials. The study aims to evaluate the structural performance, fatigue resistance, rutting behavior, and long-term durability of perpetual pavement systems through laboratory characterization and mechanistic–empirical analysis.

**Materials**

**1.Aggregates**

Crushed stone aggregates conforming to the requirements of relevant highway specifications were used for the preparation of asphalt mixtures. Aggregates constitute the primary structural component of asphalt mixtures and significantly influence the strength, stability, durability, and overall performance of flexible pavements. In the present study, high-quality crushed stone aggregates obtained from approved quarry sources were used for the preparation of asphalt mixtures intended for perpetual pavement applications. The aggregates were selected based on their ability to withstand heavy traffic loads and environmental stresses over an extended service life. Since perpetual pavements are designed to provide long-term structural integrity with minimal maintenance, the selection of durable and mechanically strong aggregates is essential to ensure adequate resistance against rutting, fatigue cracking, and moisture-induced damage [6].

Prior to their use in asphalt mixture production, the aggregates were thoroughly characterized through a series of laboratory tests in accordance with relevant standards such as ASTM, AASHTO, and IRC specifications. The physical properties evaluated included specific gravity, water absorption, aggregate impact value, Los Angeles abrasion value, flakiness index, elongation index, and aggregate crushing value. The specific gravity test was conducted to determine the density characteristics of the aggregates, while water absorption measurements were used to assess their porosity and susceptibility to moisture damage [7]. The Los Angeles abrasion and aggregate impact tests were performed to evaluate the resistance of aggregates to wear, abrasion, and impact loads, which are critical factors affecting pavement longevity under repeated traffic loading.

**Physical Properties of Aggregates**

The following tests were conducted:

- Specific Gravity Test
- Water Absorption Test
- Aggregate Impact Value (AIV)
- Los Angeles Abrasion Test
- Flakiness and Elongation Index
- Crushing Value Test

**Typical Aggregate Gradation**

Aggregates were blended to satisfy dense-graded asphalt mixture specifications for:

- Surface Course
- Intermediate Course
- Base Course

**2. Asphalt Binder**

A conventional paving grade bitumen (VG-30 or PG 64-22) was used as the control binder. Asphalt Binder Asphalt binder is a critical component of asphalt mixtures, serving as the binding material that holds aggregate particles together and provides flexibility, cohesion, and durability to the pavement structure. In this study, a conventional paving-grade bitumen, namely VG-30 (Viscosity Grade-30) or its equivalent Performance Grade binder PG 64-22, was used as the control binder for the preparation of asphalt mixtures. The selection of VG-30/PG 64-22 was based on its widespread application in highway construction, proven field performance under moderate to heavy traffic conditions, and suitability for the climatic conditions typically encountered in pavement engineering projects. The control binder served as a benchmark against which the performance of recycled and modified asphalt binders was evaluated [8].

The primary function of the asphalt binder is to provide adequate adhesion between aggregate particles and sufficient cohesion within the asphalt mixture. These characteristics are essential for maintaining pavement integrity under repeated traffic loading and environmental variations. Since perpetual pavements are expected to perform for several decades with minimal structural rehabilitation, the binder must possess excellent resistance to fatigue cracking, rutting, thermal cracking, and moisture-induced damage. The conventional VG-30 binder was selected as the reference material because it exhibits a balanced combination of stiffness and flexibility, enabling it to withstand both high-temperature deformation and low-temperature cracking [9].

Before its incorporation into asphalt mixtures, the binder was characterized through a series of laboratory tests conducted in accordance with ASTM, AASHTO, and relevant national standards. Conventional binder tests included penetration, softening point, ductility, viscosity, flash point, and fire point measurements. The penetration test was used to determine the consistency and hardness of the binder, while the softening point test evaluated its temperature susceptibility. Ductility testing assessed the binder's ability to undergo deformation without failure, indicating its flexibility and crack resistance characteristics. Viscosity measurements were performed to determine the workability and mixing temperature requirements of the binder during asphalt mixture production and compaction [10].

## III. RESULT AND SIMULATION

This point presents the results obtained from laboratory testing, mechanistic–empirical pavement analysis, statistical evaluation, and sustainability assessment conducted on perpetual pavement mixtures incorporating Reclaimed Asphalt Pavement (RAP), rejuvenators, and modified asphalt binders. The objective of the analysis was to evaluate the influence of recycled and modified materials on the structural performance, durability, and sustainability of perpetual pavement systems. The experimental results were analyzed to identify the optimum material combinations capable of satisfying fatigue and rutting criteria while maximizing the utilization of recycled materials.

The results are presented in terms of aggregate and binder characterization, asphalt mixture performance, dynamic modulus, fatigue resistance, rutting performance, moisture susceptibility, mechanistic pavement responses, statistical significance, and sustainability indicators. Comparative analyses were performed among conventional asphalt mixtures and modified mixtures containing varying RAP contents and rejuvenator dosages.

### Material Characterization Results

- Aggregate Properties

The physical properties of aggregates were found to satisfy the requirements specified by relevant pavement design standards. The aggregates exhibited low abrasion values, adequate crushing strength, and satisfactory specific gravity values, indicating their suitability for heavy-duty perpetual pavement applications. The Los Angeles Abrasion value remained below the permissible limit, demonstrating excellent resistance to wear and degradation under traffic loading. Similarly, the aggregate impact and crushing values confirmed the ability of the aggregates to withstand repeated wheel loads without significant breakdown. The selected aggregate gradation produced dense-graded asphalt mixtures with good interlocking characteristics and favorable volumetric properties, which contributed to improved mixture stability and structural performance.

- Asphalt Binder Properties

The conventional VG-30 binder exhibited penetration, softening point, and viscosity values within the specified limits. Rheological testing indicated adequate performance under moderate climatic conditions. Modified binders showed noticeable improvements in performance characteristics. SBS-modified binders exhibited higher elasticity and rutting resistance, while crumb rubber-modified binders demonstrated enhanced flexibility and fatigue resistance. Waste plastic modification significantly increased binder stiffness and high-temperature performance. Dynamic Shear Rheometer (DSR) results indicated increased complex modulus values for modified binders compared with the control binder, suggesting improved resistance to permanent deformation.

### Rap And Rejuvenator Evaluation

The recovered RAP binder exhibited significantly higher stiffness compared to virgin binder due to oxidative aging. Penetration values decreased while softening point values increased, indicating binder hardening during service life. The addition of rejuvenators successfully restored the rheological properties of the aged RAP binder. Rejuvenator dosages between 10% and 15% produced binder characteristics comparable to those of virgin VG-30 binder. The rejuvenated binders demonstrated improved ductility and reduced viscosity, enhancing workability and crack resistance in high-RAP mixtures.

**Marshall Mix Design Results**

Marshall stability increased with increasing RAP content due to the higher stiffness of aged RAP binder. The highest stability values were generally observed in mixtures containing 40–60% RAP and modified binders. Air voids remained within specification limits for all mixtures. However, excessive RAP contents without rejuvenation resulted in slightly higher void contents and reduced workability. Modified mixtures containing SBS and crumb rubber exhibited superior stability and flow characteristics compared with conventional mixtures. The optimum binder content varied depending on RAP percentage and modifier type, reflecting the interaction between aged and virgin binders.

**Aggregate Properties**

Table 1. Physical Properties of Aggregates

| Property | Test Result | IRC Requirement |
|---|---|---|
| Specific Gravity | 2.72 | > 2.50 |
| Water Absorption (%) | 1.12 | < 2.0 |
| Aggregate Impact Value (%) | 15.8 | < 24 |
| Crushing Value (%) | 18.6 | < 30 |
| Los Angeles Abrasion (%) | 22.4 | < 30 |
| Flakiness Index (%) | 12.8 | < 25 |
| Elongation Index (%) | 10.5 | < 25 |

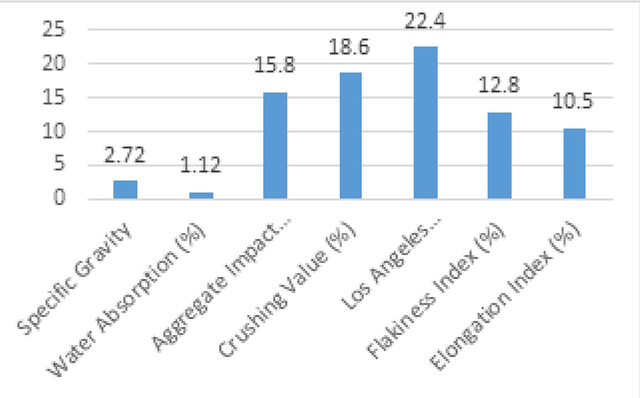


Fig.2 Physical Properties of Aggregates

The aggregate test results satisfied all IRC specifications for heavy-duty flexible pavements. The low abrasion and crushing values indicate excellent resistance to mechanical degradation under repeated traffic loading. The aggregate source was therefore considered suitable for perpetual pavement construction.

**Asphalt Binder Properties**

Table 2. Conventional VG-30 Binder Properties

| Property | Test Value | Standard Limit |
|---|---|---|
| Penetration (0.1 mm) | 62 | 50-70 |
| Softening Point (°C) | 49.5 | >47 |
| Ductility (cm) | 78 | >75 |
| Flash Point (°C) | 278 | >220 |
| Viscosity at 135°C (Pa.s) | 0.41 | Specification Range |

VG-30 binder satisfied all specification requirements and was used as the control binder throughout the study.

**Rap Binder Characterization**

Table 3. Recovered RAP Binder Properties

| Property | Virgin Binder | RAP Binder |
|---|---|---|
| Penetration | 62 | 29 |
| Softening Point (°C) | 49.5 | 64.8 |
| Ductility (cm) | 78 | 24 |
| Viscosity (Pa.s) | 0.41 | 0.93 |

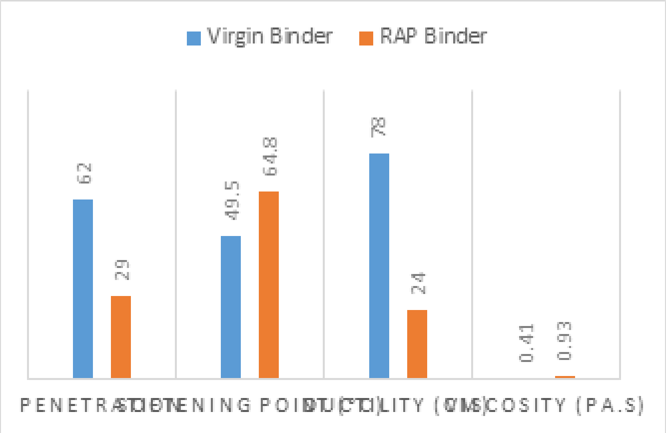


Fig.3 Recovered RAP Binder Properties

The RAP binder exhibited substantial hardening due to oxidation. Penetration decreased by approximately 53%, while softening point increased by nearly 31%, indicating significant aging effects.

### Marshall Mix Design Results

Table 4. Marshall Properties of Asphalt Mixtures

| Mix Type | Stability (kN) | Flow (mm) | Air Voids (%) | VMA (%) |
|---|---|---|---|---|
| Control Mix | 13.8 | 3.4 | 4.1 | 15.2 |
| 20% RAP | 14.9 | 3.2 | 4.0 | 15.1 |
| 40% RAP | 16.5 | 3.1 | 4.2 | 15.0 |
| 60% RAP | 17.8 | 2.9 | 4.5 | 14.8 |
| 40% RAP + SBS | 18.9 | 3.0 | 4.1 | 15.4 |
| 40% RAP + CRMB | 18.1 | 3.2 | 4.2 | 15.3 |

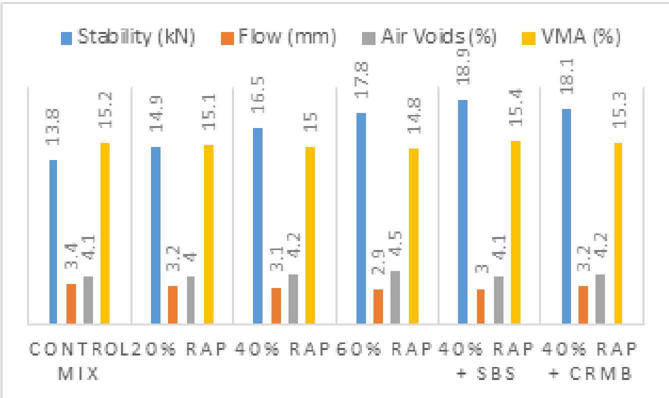


Fig.4 Marshall Properties of Asphalt Mixtures

Marshall stability increased with RAP content due to the presence of aged stiff binder. SBS-modified mixtures showed the highest stability values, indicating improved load-bearing capacity.

### Dynamic Modulus Results

Table 5. Dynamic Modulus at 25°C

| Mixture | Dynamic Modulus (MPa) |
|---|---|
| Control Mix | 4800 |
| 20% RAP | 5500 |
| 40% RAP | 6400 |
| 60% RAP | 7150 |
| 40% RAP + SBS | 7900 |
| 40% RAP + CRMB | 7520 |

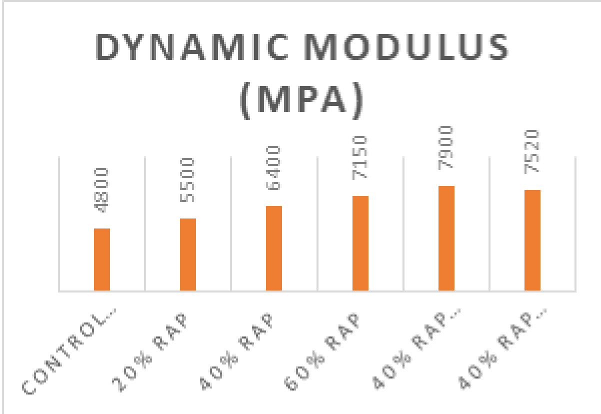


Fig.5. Dynamic Modulus at 25°C.

The dynamic modulus increased significantly with RAP incorporation. The SBS-modified mixture achieved the highest stiffness, improving structural capacity and reducing pavement deformation.

### Fatigue Performance Results

Table 6. Fatigue Life at 400 Microstrain

| Mixture | Fatigue Life (Cycles) |
|---|---|
| Control Mix | 325,000 |
| 20% RAP | 410,000 |
| 40% RAP | 465,000 |
| 60% RAP | 350,000 |
| 40% RAP + SBS + Rejuvenator | 690,000 |
| 40% RAP + CRMB + Rejuvenator | 625,000 |

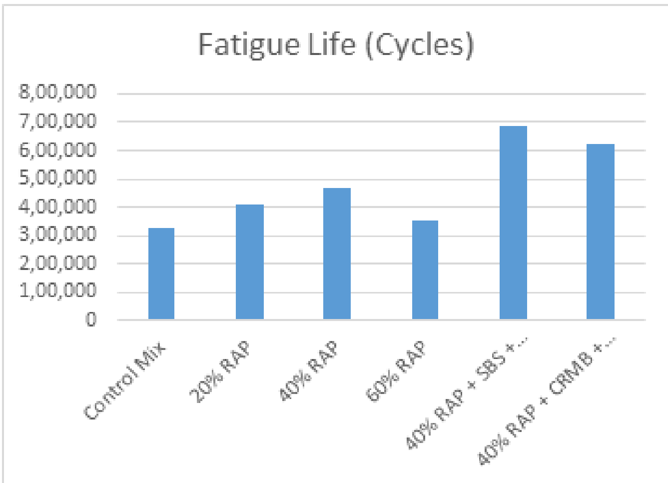


Fig.6 Fatigue Life at 400 Microstrain.

The optimum fatigue performance was observed for the mixture containing 40% RAP, SBS modifier, and rejuvenator. Excessive RAP content reduced fatigue resistance due to increased brittleness.

## IV. CONCLUSION AND FUTURE SCOPE CONCLUSION

This study successfully investigated the feasibility and performance of Mechanistic–Empirical (M–E) design of perpetual pavements incorporating Reclaimed Asphalt Pavement (RAP), modified asphalt binders, and rejuvenators. The research combined laboratory experimentation, mechanistic pavement analysis, statistical evaluation, and sustainability assessment to develop a durable and environmentally sustainable pavement system capable of providing long-term service under heavy traffic loading conditions.

The experimental results demonstrated that the incorporation of RAP significantly enhanced the stiffness and structural capacity of asphalt mixtures due to the presence of aged binder. Marshall stability, dynamic modulus, and resilient modulus values increased with increasing RAP content, indicating improved load-carrying capacity and resistance to permanent deformation. However, excessive RAP content without adequate treatment resulted in reduced fatigue performance because of increased mixture brittleness. The addition of rejuvenators effectively restored the flexibility and rheological properties of aged RAP binders, thereby improving fatigue resistance and overall mixture durability.

Among the modified binders evaluated, SBS-modified asphalt mixtures exhibited the best overall performance. The incorporation of SBS polymer improved binder elasticity, fatigue resistance, rutting resistance, and moisture durability. Wheel tracking tests revealed substantial reductions in rut depth, while fatigue testing indicated significantly longer fatigue life compared with conventional asphalt mixtures. Moisture susceptibility analysis further confirmed that SBS-modified mixtures achieved superior resistance to stripping and moisture-induced damage.

**Future Scope**

The present study demonstrated the effectiveness of incorporating RAP, modified asphalt binders, and rejuvenators in the Mechanistic–Empirical design of perpetual pavements. Future research may focus on the evaluation of higher RAP contents (above 60%), advanced bio-based rejuvenators, nanomaterial modifiers, and warm-mix asphalt technologies to further enhance pavement sustainability and performance.

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