

Strength and Durability Enhancement of Sustainable Flexible Pavements Using Waste Tires, PET Plastics, Polythene Sheets, and Bituminous Concrete

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ABSTRACT

The present study investigates sustainable rehabilitation techniques for flexible pavements that utilize waste materials, including scrap tires, polyethylene sheets, and Polyethylene Terephthalate (PET) plastics. It evaluates various innovative techniques such as geo-tire confinement systems to enhance subgrade stability, polyethylene moisture barriers to reduce water penetration, and Thermo-Geo-Plastic (TGP) composites for pothole repair. Laboratory tests reveal that these methods significantly outperform traditional systems, showing increased Marshall stability and flow rates, which enhance load-bearing capacity and flexibility of the pavement. Modified mixtures show approximately 20% improvement in indirect tensile strength and reduced moisture susceptibility. Rutting tests demonstrate reduced permanent deformation and improved fatigue resistance, while permeability tests indicate that the polyethylene interlayers effectively reduce moisture infiltration by 21–60%. The TGP composite achieves compressive strengths of up to 18.81 MPa in field tests, indicating high durability. Microstructural analysis indicates stronger interactions between the aggregate and the binder, thereby improving mechanical properties. Field evaluations validate laboratory results, with noticeable improvements in pavement stability and reduced distress. These sustainable techniques not only improve pavement performance but also reduce waste materials for landfills, decrease embodied carbon emissions, and promote circular economy practices. The study demonstrates that integrating waste materials into pavement rehabilitation can enhance structural reliability, extend service life, and yield substantial environmental benefits.

Keywords-flexible pavements; rehabilitation; solid waste; geo-tires, and thermo-geo-plastic

I. INTRODUCTION

Flexible pavements, which dominate road infrastructure in industrialized countries, are experiencing rapid degradation due to increased vehicle traffic [1, 2]. The Saudi Roads Authority (SRA) identifies flexible pavements as the most prevalent pavement type [3]. While flexible pavements experience issues, such as rutting, potholes, and premature distress, these challenges also present opportunities to improve subgrade performance, drainage efficiency, and maintenance practices. Enhancing these parameters can significantly improve pavement durability, service life, and overall performance, promoting the adoption of sustainable materials and methods in pavement rehabilitation efforts [4].

Materials such as geosynthetics, recycled plastics, and discarded tires are used to strengthen and stabilize pavement layers. These materials contribute to long-term durability, moisture resistance, and overall structural integrity. The effects of repetitive traffic loading, environmental exposure, and

subgrade deformation significantly influence pavement performance [5, 6], underscoring the need for improved subgrade enhancement techniques, particularly those that utilize confinement systems such as geocells and recycled tire structures [3]. Implementing recycled tire cells within 3D confinement systems, along with polyethylene films between bituminous layers, can significantly mitigate moisture-induced damage and extend pavement service life [7]. Geosynthetics have been crucial to road construction since the 20th century, aiding soil stabilization, reducing layer thickness, and improving drainage [8]. They play an important role in pavement rehabilitation efforts, including repair, restoration, and reconstruction [9]. Fatigue cracking, rutting, and moisture intrusion are frequently identified as the primary failure mechanisms [3]. Insufficient material quality, drainage issues, and poor design are key factors in pavement failures [10]. In contrast, cracking and deformation are the primary concerns that require maintenance and overlay treatments [11].

The formation of potholes can be attributed to inadequate binder distribution and heavy rainfall [12]. To assess pavement degradation, modern deterioration models utilize performance indicators such as the International Roughness Index (IRI) and Equivalent Single Axle Load (ESAL). Rehabilitation strategies aim to restore both the functional condition and structural integrity of pavements through overlays, material recycling, and subgrade improvements. For instance, the geo-tire technique employs scrap tires in cellular confinement systems, providing an environmentally friendly and effective rehabilitation method [13, 14]. This approach not only enhances subgrade stability but also aligns with circular economy principles, thereby reducing waste and mitigating carbon emissions, supporting the United Nations Sustainable Development Goals (SDGs). Using confinement systems and reinforcement materials significantly improves load-bearing capacity and extends long-term pavement performance [1]. It has been shown that geocell reinforcement can reduce rutting by 13 to 71% and increase service life by 16 to 35% [15]. Additionally, waste-derived stabilizers, particularly rubber and plastics, are efficient solutions for repairing expansive soils, offering both economical and environmentally sustainable options [16]. Incorporating geo-tire rubber into bitumen significantly enhances several key performance characteristics, such as elasticity, skid resistance, and overall service life, while concurrently reducing the need for ongoing maintenance. Specifically, the addition of 10-15% rubber to bitumen improves significant engineering properties such as viscosity, softening point, and penetration resistance [17], thereby extending the lifespan of pavements through enhanced load distribution within cement-stabilized layers.

Moreover, confinement systems that use waste tire cells, geocells, and geogrids have demonstrated improved pavement structural performance. These systems contribute to enhancing the subgrade's responsive modulus and assist in controlling transverse displacement in soil [18]. Consistent with prior research, geocell confinement can improve stress distribution and reduce the required thickness of granular subsurface layers by 27-33% [19]. Geo-tire confinement offers comparable advantages, including improved interlocking, reduced settlement, and greater resistance to moisture-induced deformation, thereby contributing to a more robust pavement.

Recycling waste materials provides environmental benefits, with various tests—including triaxial traction, falling-head permeability, California Bearing Ratio (CBR), and plate load testing—employed to assess the performance of both confined and free-standing subgrades. To ensure the reliability of confinement-based pavement systems, field research and laboratory trials are essential in validating mathematical and computational models [1, 20]. Authors in [21, 22] demonstrated that confinement enhances load-bearing capacity, increases modulus, and decreases rut depth, thus directly influencing the design of moisture barriers and tire-based confinement systems. Despite improvements in pavement design, issues such as inadequate subgrade strength, moisture infiltration, and ineffective rehabilitation practices constitute significant challenges in pavement performance [23-25]. Weak subgrades and water penetration are exacerbated by reactive maintenance strategies rather than preventive measures.

Authors in [26] incorporated life cycle evaluation to assess the environmental benefits of integrating recycled materials into Iraqi asphalt pavements, demonstrating that mixtures containing crumb rubber and recycled asphalt can significantly reduce emissions, resource consumption, and maintenance costs, thereby presenting recycled pavements as a viable option for road construction in underdeveloped regions [26].

The effectiveness of fly ash and Ground Granulated Blast Furnace Slag (GGBFS) as sustainable binders in self-compacting geopolymer concrete has been investigated. It has been indicated that under standard curing conditions, substituting fly ash with up to 30% GGBFS and 12M NaOH significantly enhances the strength and durability of concrete. Similarly, microstructural analyses reveal that this combination yields denser, stronger concrete. However, prolonged exposure to saltwater has a detrimental effect on concrete's strength. Authors in [27] examined the potential use of gold mine tailings as a partial cement replacement, promoting sustainable waste management; the optimal strength was achieved with a 10% substitution, though higher replacements still met structural specifications despite diminishing workability and strength [27].

A gap in the existing literature is the lack of studies that combine 3D confinement using waste tires of 550-650 mm diameter and a width of 150-200 mm, in moisture-arresting membranes, and sustainable pothole-filling materials. This research addresses that gap by proposing a composite approach that enhances structural stability, reduces moisture ingress, and contributes to environmental sustainability.

II. METHODOLOGY

The design of field tests for moisture barriers and tire-based confinement systems is influenced by insights gained from laboratory investigations. Flexible pavements often fail due to inadequate subgrade strength, moisture infiltration, and ineffective rehabilitation practices [23]. Despite enhancements in pavement design, these issues persist because of existing challenges, namely weak subgrades, water penetration, and reactive (rather than preventive) maintenance [24]. In addition, the study examines the effects of an impermeable polyethylene film placed at the bituminous interface to reduce moisture infiltration and of the geo-tire technique on pavement stability. The main objective of the present study is to improve the performance of pavement structures in high-traffic roads. However, government clearance and funding are necessary to implement large-scale rehabilitation using geo-tire systems due to the substantial financial expenditure required. A framework for applying the geo-tire technique in real-world traffic conditions is also presented.

A. Preparation of Rehabilitation Pavement

To prepare a geo-tire, tires were cut and placed horizontally, then joined using a nut-and-bolt system. Granular Subbase (GSB) on natural or artificial subgrade requires the geo-tire to be perforated with holes for subsurface drainage. This is achieved using a high-tension wire. Rubber strips were used to fix tires at pavement margins to prevent direct subsurface drainage. A honeycomb grid structure was created by drilling holes in tires, as shown in Figure 1.



Fig. 1. Honeycomb grid structures of geo-tires.

B. Impervious Polyethylene Layer Installation

Water seepage is the main contributor to pavement failure. It reduces shear resistance and increases the risk of ruts and depressions. To prevent water seepage, an impermeable layer was installed to improve the pavement's flexibility and imperviousness. This layer also enhances pavement sustainability and longevity. The study employed a 150-micron polyethylene sheet in a 6000-mm stretch as an impervious layer. After an impervious layer, a Bituminous concrete (BC) was laid over Dense Bituminous Macadam (DBM). A bituminous tack coat was applied to the DBM surface. A polyethylene sheet was stretched on the DBM. The polyethylene sheet sticks to the DBM layer and forms a uniform layer. A thin BC layer was applied to the sheet to prevent adhesion to the roller wheels. Another BC layer was then placed on the sheet by a mechanical paver and compacted by a roller from the edge toward the center of the road. Finally, the road surface was compacted using an appropriate number of roller passes. Precautions were taken during the entire process, including maintaining a lay temperature between 118 °C and 125 °C, avoiding folding on the sheet, applying a VG-40 tack coat before and after laying the polyethylene sheet, manually spreading a small quantity of BC over the sheet, and ensuring proper compaction with a minimum of 10 passes of pneumatic roller and at 600 mm gap between consecutive sheets. The camber of the BC layer was set at 2.5%, in accordance with the standard camber. The road was observed for one year after its execution and subjected to monsoon with moderate rainfall. One year after construction, a non-destructive falling-head permeability test was conducted using both the falling-head and vessel permeability tests.

C. Development of TGP

To turn waste Polyethylene Terephthalate (PET) plastic into usable material for road repairs, TGP was created, as depicted in Figure 3. To find the ideal compressive strength and water absorption, shredded PET was mixed with granular materials such as M-sand, sea sand, BC soil, and gravel. An ideal blend with a density of 21.45 kN/m³ and a compressive strength of approximately 15.94 MPa was produced using TGP. After TGP preparation, shredded PET waste bottles were mixed with pre-graded gravel after heating to 270 °C. The potholes were

cleaned and filled with this composite material. Potholes were manually compacted and observed for four years. Pavement permeability was measured using two test methods, as described above.



Fig. 2. Preparation of road with waste geo-tires, 125 µm polyethylene sheet as interlayer, and potholes filled up with Thermo-Geo-Plastic (TGP) material between BC.

The experiments were conducted using shredded plastic and gravel (1:3.5 by weight) at 260 °C. The mix was stirred until a homogeneous material was achieved. The prepared molten TGP was poured into clean rectangular potholes and manually compacted. Six months later, a BC overlay was applied. The site was monitored for more than a year.



Fig. 3. TGP composite for filling the potholes.

D. Non-Destructive Permeability Test (NDPT)

After one year of field exposure, permeability was assessed using the falling-head and vessel permeability tests. Falling-head permeability test, as portrayed in Figure 4, employed a 600 mm standpipe with an 8 mm ID, 250 mL of distilled water, and an aluminum base plate with watertight seams. In contrast, the vessel permeability test uses a measuring jar to quantify vertical seepage over a specified volume change. Three sites—

covering edge, wheel-track, and crown positions—were tested both with and without polyethylene sheets. The coefficient of permeability was calculated for falling heads of 500–200 mm and 400–200 mm. Key assumptions in the falling head method include homogeneous subgrade, steady-state seepage flow, controlled head condition, boundary conditions during field testing, and limitations related to edge flow and heterogeneity.

The coefficient of permeability (K) was computed using:

$$K = 2.30 aL \log \frac{h_1}{h_2} / At \quad (1)$$

where a is the area of the standpipe, A is the area of the test section, L is the pavement thickness, t is the time, and h_1 , h_2 are the initial and final heads.

E. Durability and Performance Assessment of Rehabilitated Pavement

In the initial phase of the study, materials were gathered and characterized, including 125-micron low-density polythene sheets, cleaned and shredded PET plastic bottles, and geo-tire honeycomb from discarded tires, sourced from local recycling facilities. Bituminous cement and conventional aggregates were obtained in accordance with relevant guidelines. To evaluate the longevity and effectiveness of sustainable flexible pavements, a rigorous series of laboratory tests, pilot-scale construction, and performance evaluations was conducted. The approach aimed to enhance mechanical strength, moisture resistance, deformation behavior, and environmental sustainability by employing confinement techniques, such as geogrids and geocells, and by using recycled tire rubber, PET plastics, and polythene sheets as partial substitutes for traditional materials.



Fig. 4. Field permeability test setup.

During material collection and characterization, specific gravity, gradation, elemental composition, and rheology were assessed for the rubber-treated bitumen. Tests of polythene sheets included tensile strength and permeability measurements, whereas confinement systems were analyzed for stiffness, aperture size, and tensile strength. Bitumen mixes were designed using the Marshall design method, incorporating honeycomb geotextiles (5–10% of binder weight), PET fibers (0.3–0.5% of mix weight), and PET-aggregate replacements

(3–5%), with control mixes without recycled materials. Compacted specimens of 100 mm × 63.5 mm were evaluated for moisture permeability in accordance with ASTM D5084, while rutting and indirect tensile strength were determined as per AASHTO T324 and ASTM D693, respectively. In addition to these tests, a fatigue test was conducted under cyclic loads.

In total, seven pavement sections (six modified and one control), measuring six to eight meters in length, were constructed during the pilot-scale testing phase. The study encompasses contemporary asphalt materials and techniques, including polyethylene Stress-Absorbing Membrane Interlayers (SAMI), geocell confined bases, PET aggregate substitutions, Geo-Tire-Modified Asphalt (GTMA), and PET-reinforced asphalt. Performance monitoring focused on field density, surface evenness, rut depth, and interlayer bond strength, with observations taken monthly for the first six months and subsequently every three months to track features such as rutting development, fatigue cracking, moisture damage, surface roughness (using the IRI), and temperature effects. Core samples were collected periodically to assess changes in material stiffness and aging.

F. Difficulties Faced in the Field Testing

Significant difficulties were encountered during field testing, including unregulated traffic movement, adverse weather conditions, and uncontrolled lateral water movement of the BC surface outside the test area. In addition, density variations and voids of compacted bitumen were also observed within the same sections of the road. The road authorities prohibited bituminous course core cutting, preventing the conduct of a falling-head permeability test.

III. RESULTS AND DISCUSSION

A. Impervious Polyethylene Layer Performance

A 125-micron polyethylene layer was placed between the BC wearing course and the DBM binding course, and its performance was evaluated to check effectiveness. Field experiments were conducted on a stretch of the highway, where a 6-m trial pavement was built and monitored over a year. The objective was to compare the permeability properties of test sections with and without the polyethylene covering using an NDPT with three measurement locations per test stretch to ensure reliability.

The test results, presented in Table I, indicate that the introduction of the polyethylene barrier significantly decreased water infiltration. For a head drop of 300 mm, the infiltration time increased from 2.74 s without the sheet to 3.09 s with it. Similarly, for a 200 mm head drop, it increased from 2.53 s to 3.69 s. The vessel permeability test showed that 50 mL required 32.95 s without the sheet and 52.22 s with it, highlighting the effectiveness of the polyethylene layer in reducing permeability.

The coefficient of permeability (K) was calculated utilizing the falling-head permeability test. The results showed a consistent decrease in K with the polyethylene layer: from 2.82×10^{-2} mm/s (without sheet) to 2.52×10^{-2} mm/s (with sheet) for the 500–200 mm head range; and from 2.31×10^{-2} mm/s to 1.58×10^{-2} mm/s in the 400–200 mm range. For the vessel

permeability test, K decreased from 0.40 mm/s to 0.25 mm/s. Overall, permeability decreased by an average of 21.47% in the falling-head approach and 59.99% in the vessel permeability test. This reduction is attributed to changes in air-void

distribution and lateral water flow. However, some lateral leakage persisted under unconfined conditions despite the polyethylene film's efficacy in reducing vertical penetration.

TABLE I. RESULTS OF PERMEABILITY RESULTS

Test	Head drop	Average time (with sheet)	Average time (without sheet)	Reduction in flow rate (%)
Falling-head permeability test	500–200 mm	3.45 s	2.48 s	14.1
Falling-head permeability test	400–200 mm	4.02 s	2.86 s	28.9
Vessel permeability	250–200 ml	61.8 s	37.5 s	64.2

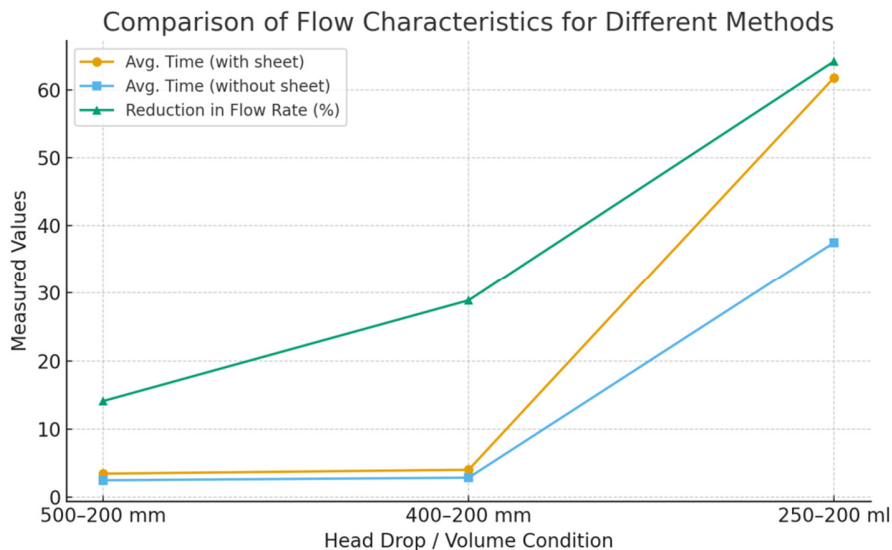


Fig. 5. Permeability versus head drop.

B. Pothole Repair Performance

One objective of the study is to optimize the PET-to-aggregate ratio to achieve high strength, low permeability, and durability. For this reason, various combinations of shredded PET with materials such as sea sand, gravel, M-sand, and BC soil were examined. Laboratory tests indicate that the PET-gravel mixture outperformed other combinations. The highest performance was achieved at a 1:3.5 PET-to-gravel ratio, yielding a dry density of 25.31 kN/m³, a water absorption rate of 1.66%, and a compressive strength of 18.81 MPa, indicating a cohesive and dense structure. In contrast, other combinations showed lower compressive strengths ranging from 11.8 to 12.74 MPa. The superior performance of the PET-gravel mixture can be attributed to the interlocking mechanism between molten plastic and angular gravel particles, which forms a robust, monolithic mass capable of withstanding mechanical stress.

Based on laboratory findings, the 1:3.5 PET-gravel mixture was chosen for field implementation due to its favorable properties. The pothole repair was carried out systematically, involving several key stages: first, the pothole was cleaned to eliminate debris and loose materials; second, shredded PET plastic was heated to around 260 °C until it is fully molten; third, this molten plastic was mixed with gravel to create a uniform composite; fourth, the mixture was poured into the pothole and compacted manually to ensure proper bonding and leveling of the surface. Subsequently, the composite cooled and

solidified. The area was left to stabilize, and after six months, a thin BC soil overlay was applied as a finishing layer.

For more than a year, the TGP repair's field performance was assessed under actual traffic conditions, especially on a pavement utilized by lorries delivering metal goods to a neighboring industry. Inspections conducted throughout this monitoring period revealed no evidence of surface deformation, rutting, delamination, or cracking. This stability indicates that the TGP filler exhibits high impermeability, outstanding structural integrity, and resistance to environmental damage.

To form a dense composite structure that efficiently distributes traffic stresses and prevents moisture intrusion, the molten PET bonded and enclosed the gravel particles. As a consequence, despite constant exposure to heavy vehicle loads and variable weather conditions, the rebuilt pavement segment remained structurally sound and functional, yielding significant environmental and economic benefits. Using waste PET reduces solid waste and promotes environmental sustainability. By reducing maintenance and long-term repair costs, it also serves as an affordable alternative to traditional repair materials. The TGP filler's impermeability decreases water intrusion into the subgrade, thereby reducing the likelihood of further failures and increasing pavement longevity. A quantitative analysis further demonstrates its sustainability: it requires approximately 32 m³ of TGP composite to repair 1 km of a single-lane road with 35% pothole coverage and 35 mm

depth, equivalent to 3,250 km of gravel and 980 kg of PET plastic, or about 49,000 used water bottles. This illustrates how the TGP technique may both reduce plastic pollution and offer a long-lasting, affordable pavement repair option. Table II summarizes the mechanical properties of PET-aggregate mixtures, showing the relationship between composition, density, compressive strength, and water absorption.

Figure 6 displays the density, compressive strength, and water absorption performance of four plastic-soil types: M-sand, gravel, sea sand, and BC soil used in geotechnical and pavement applications. The sea sand achieved the highest density (32.63 kN/m³), indicating higher packing and compaction. In contrast, due to its lower density, BC soil had less structural stability. Similarly, gravel-type plastic-soil achieved the highest compressive strength (18.81 MPa), making it suitable for load-bearing applications. At the same time, M-sand and sea sand exhibited intermediate strengths, whereas BC soil consistently showed lower compressive strengths.

TABLE II. MECHANICAL PROPERTIES OF PET-AGGREGATE MIXTURES

Plastic-soil type	Optimum ratio	Density (kN/m ³)	Compressive strength (MPa)	Water absorption (%)
M-Sand	1:1	24.839	11.8	0.274
Gravel	1:3.5	25.311	18.81	1.66
Sea Sand	1:3.5	32.627	12.74	0.34
BC Soil	1:3.5	20.827	12.75	0.34

All soil types demonstrated varying water absorption performance, with M-Sand achieving the lowest absorption rates (0.27-0.34%). Other soil types, except gravel, showed significantly lower water absorption, indicating their durability and resistance to moisture damage. Gravel achieved a water absorption rate of 1.66%, indicating susceptibility to weathering and disintegration despite its strength.

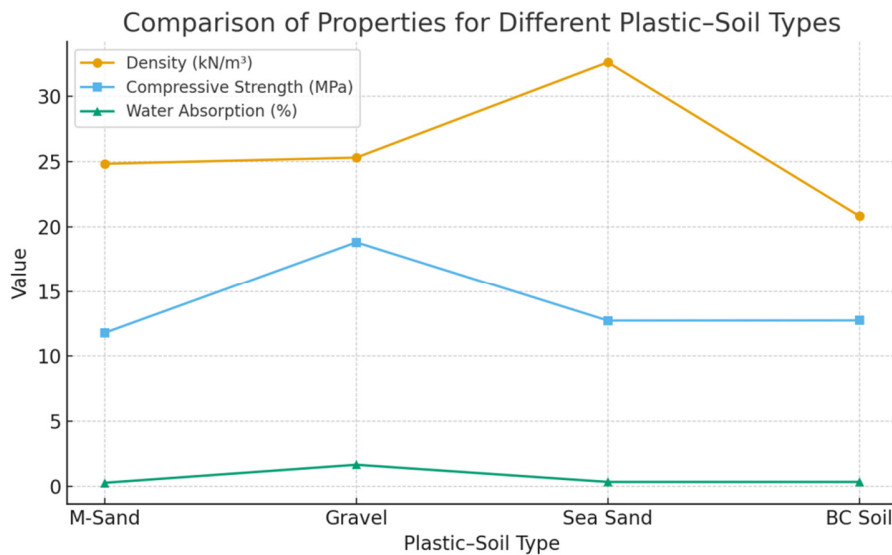


Fig. 6. Density, compressive strength, and water absorption performance of plastic-soil types.

The results indicate the 1:3.5 PET-gravel blend is the optimal choice for field applications, featuring the highest compressive strength and appropriate density among all tested combinations. These findings suggest that TGP composite materials have the potential to be a sustainable material for road infrastructure. These materials are environmentally friendly and extremely durable for repairing flexible pavements.

C. Result Interpretation

The number of air voids, compaction quality, and aggregate gradation all significantly affect the permeability of the bituminous layer. When air-void is maintained below 6%, densely graded composites usually perform almost impermeably. Despite the application of a polyethylene barrier, some seepage was observed, indicating gaps between DBM and base course, primarily due to inadequate sealing at this

junction. Nonetheless, the polyethylene sheet remains a cost-effective solution for reducing moisture infiltration, which often leads to the deterioration of the foundational/core elements of road structures. The impermeable nature of these sheets limits water movement, with enhanced bonding between layers achieved through the use of tack coats. This integration enhances layer adhesion, reduces slippage, and increases stability without complicating application processes.

Despite signs of surface-level resilience, resulting in reduced moisture causing delamination or warping, the field test results confirmed sustained strength over time, outlasting lab-based predictions. Fewer repairs were needed because pavements last longer as their strength increases gradually. An increase in durability results in improved long-term performance over the service life of the roads.

D. Comparative Analysis

Developing alternative methods to repair pavements requires detailed testing of new materials. One such innovative approach involves the use of polyethylene sheets. Polyethylene sheets placed between BC and DBM improve seepage protection. Reduced seepage enhances material strength and minimizes crack development. The findings also indicate that TGP, prepared with molten recycled plastic and sand, can be

effectively used for pavement repair. TGP-sand blend flows into cracks and hardens the cracked region. High temperature of molten plastic reshapes the material, resulting in a binding element that locks minerals together. This binding material then stabilizes the pothole and prevents it from further cracking under vehicular load. Table III outlines the key characteristics and conceptual basis of sustainable paving techniques.

TABLE III. KEY CHARACTERISTICS AND CONCEPTUAL BASIS OF SUSTAINABLE PAVEMENT TECHNIQUES

Technique	Application	Advantage	Mechanism
Polyethylene sheet	Moisture barrier between DBM-BC 21-60 %	Lower permeability	Reuses plastic film and extends pavement life
TGP	Pothole rehabilitation	Excellent performance	Converts waste PET into a structural material

E. Results of the Pilot Study

The pilot study provided detailed insights into how waste materials, specifically geo-tire rubber, recycled PET, polythene interlayers, and geocell/geogrid confinement, can improve flexible pavement.

1) Strengthening Mechanical Properties

While PET fibers improved tensile strength by 8–15%, the addition of crushed rubber enhanced elasticity and fracture resistance by increasing indirect tensile strength by 12–25%. Polythene SAMI reduced shear stress and reflective cracking, whereas geocell confinement enhanced load distribution, increasing the modulus of resilience by 18–35%.

2) Rutting and Deformation Behavior

At high temperatures, rubber-modified binders exhibited a 20–40% decrease in rutting depth. Similarly, the rutting was reduced by more than 45% in hybrid systems that combined rubberized mixes with geocell confinement. Parts repaired with geo-tire confinement, polyethylene interlayer, and TGP filler exhibited an average rut depth of 6.1 mm, representing a 45.5% reduction relative to the traditional flexible pavement control section, which had an average rut depth of 11.2 mm. These results were validated by laboratory testing, which showed that the modified system's rut depth was 4.9 mm, whereas the control mix's rut depth was 8.8 mm. This resulted in a 44.3% increase in rutting resistance. Overall, the trial results indicate that rutting resistance increased by approximately 45%.

3) Moisture Damage Resistance

This study also evaluated the suitability of recovered PET polymers, waste tire rubber, polythene interlayers, and confinement techniques, such as geocells/geogrids, for improving flexible pavement design. The results indicate that PET fibers and polythene SAMI significantly enhanced moisture-damage resistance. The control mix achieved a Tensile Strength Ratio (TSR) of 78%, while the GTMA and hybrid mixes achieved TSR values of approximately 88% and 92%, respectively. This indicates a substantial improvement in moisture resistance. Polythene sheets significantly improved durability in dampness by effectively blocking water ingress. Additionally, rubberized binders maintained their elasticity at lower temperatures, increasing the estimated service life for

pavement. At the same time, PET fibers were crucial in stopping the spread of microcracks during freeze-thaw cycles.

4) Environmental Performance

Recycled PET, polythene sheets, and used geo-tires significantly decreased the amount of waste that often ends up in landfills. Leachate studies indicated that polymer-modified mixtures did not exceed regulatory limits for microplastics or heavy metals. Carbon emissions and embodied energy decreased due to reduced use of virgin binders and aggregates. GTMA and PET-based materials showed significant environmental benefits without affecting structural performance. Field monitoring indicates that the hybrid section (GTMA + PET fibers + geocell confinement + SAMI) performed significantly better than in previous studies, with rut depths remaining below 4 mm after 1 year of vehicular loading. In the control section, the rut depth ranged from 7 to 9 mm, with a consistent decrease in surface roughness and improved ride quality.

F. Limitations and Future Work

Despite these favorable results, the current study has some limitations. The road performance was affected by uneven compaction, primarily due to real-world implementation, resulting in frequent traffic disruptions. The field conditions introduced variability that undermined consistent results. In addition, the absence of direct measurements of field permeability via core cutting reduced the reliability of the results. To address these limitations, future studies should test pavement materials in laboratory settings to improve reliability. A field test should be conducted to validate road performance under real-world environments. Further studies are required to evaluate the road performance under various climatic conditions, i.e., long-term studies incorporating thermal aging, cyclic loading, and freeze-thaw cycles.

IV. CONCLUSIONS

This study investigated sustainable rehabilitation techniques for flexible pavements. Waste materials, such as scrap tires, polyethylene sheets, and Polyethylene Terephthalate (PET) plastic, were used to stabilize soil and repair potholes. The study examined various techniques, including geo-tire confinement systems to enhance subgrade stability, polyethylene moisture barriers to reduce water penetration, and Thermo-Geo-Plastic (TGP) composites for pothole repair.

The results indicate that sustainable pavement rehabilitation can maintain structural integrity and enhance long-term performance by employing these innovative materials and techniques. The use of geo-tire confinement systems, a 125 µm polyethylene moisture barrier, and TGP composites for pothole repair significantly improves mechanical durability and addresses plastic and tire waste management issues. Key findings indicate that the polyethylene interlayer effectively reduces water intrusion, with falling-head permeability tests showing a 21% reduction and vessel permeability tests showing a 60% reduction. The permeability also decreased from 0.40 mm/s to 0.25 mm/s in the vessel permeability test and from 0.028 mm/s to 0.025 mm/s in the falling-head permeability test. The TGP plastic-gravel composite, used at a 1:3.5 mixing ratio, exhibited a compressive strength of 18.81 MPa after four years, demonstrating its effectiveness in pothole rehabilitation while recycling around 49,000 PET bottles per lane with 3.5% pothole coverage, thereby supporting circular economy objectives.

The laboratory test results indicate that the geo-tire system significantly enhanced subgrade performance, reducing the required subgrade thickness from the traditional 500 mm to approximately 195-200 mm while increasing rutting resistance. This confinement mechanism improves shear resistance and minimizes lateral deformation, which is particularly advantageous in weaker soil conditions.

Overall, these integrated techniques present a viable, cost-effective, and environmentally sustainable solution for pavement rehabilitation. Although additional long-term lifecycle assessments and further permeability testing are proposed, the findings confirm the structural integrity, enhanced durability, and sustainability potential inherent in these techniques.

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REFERENCES

- [1] V. H. Jadhav, "Geo Tyre Technology in Pavement Stabilization," *International Journal of Engineering Applied Sciences and Technology*, vol. 4, no. 2, pp. 67–71, Jun. 2019, <https://doi.org/10.33564/IJEAST.2019.v04i02.011>.
- [2] A. Grinys, H. Sivilevičius, and M. Daukšys, "Tyre Rubber Additive Effect on Concrete Mixture Strength," *Journal of Civil Engineering and Management*, vol. 18, no. 3, pp. 393–401, Jun. 2012, <https://doi.org/10.3846/13923730.2012.693536>.
- [3] *Geometric Design Standards for National Highways*, SHC 301, Saudi Roads Authority, Riyadh, Saudi Arabia, 2023.
- [4] A. Banerjee, N. Biswas, A. Khan, and A. Puppala, "Advances in Transportation Geotechnics IV," I. L. Al-Qadi, S. Nazarian, and I. I. A. Qamhia, Eds. Cham, Switzerland: Springer, 2022.
- [5] *Test Methods for Vulcanized Rubber and Thermoplastic Elastomers Tension*, ASTM D412-16, ASTM International, West Conshohocken, PA, USA, 2016, <https://doi.org/10.1520/D0412-16R21>.
- [6] B. Leshchinsky and H. Ling, "Effects of Geocell Confinement on Strength and Deformation Behavior of Gravel," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 139, no. 2, pp. 340–352, Feb. 2013, [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0000757](https://doi.org/10.1061/(ASCE)GT.1943-5606.0000757).
- [7] J. Han *et al.*, "Performance of Geocell-Reinforced RAP Bases over Weak Subgrade under Full-Scale Moving Wheel Loads," *Journal of Materials in Civil Engineering*, vol. 23, no. 11, pp. 1525–1534, Nov. 2011, [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0000286](https://doi.org/10.1061/(ASCE)MT.1943-5533.0000286).
- [8] S. K. Khanna and C. E. G. Justo, *Highway Engineering*, 8th ed. Uttarakhand, India: Nem Chand & Bros., 2001.
- [9] P. V. Ivanov, N. N. Belyaev, and A. V. Petryaev, "Design Characteristics of Road Structure Reinforced with Cell Geosynthetic Materials with Account of Dynamic Load Impact," *Procedia Engineering*, vol. 189, pp. 338–345, 2017, <https://doi.org/10.1016/j.proeng.2017.05.054>.
- [10] M. M. E. Zumrawi, "Survey and Evaluation of flexible Pavement Failures," *International Journal of Science and Research*, vol. 4, no. 1, pp. 1602–1607, Jan. 2015.
- [11] H. Khaing and T. Htwe, "Study on Failures and Maintenance of Flexible Pavement (Pyay-Aunglan –Koepin Portion)," *International Journal of Engineering and Technology*, vol. 3, no. 14, pp. 267–275, 2014.
- [12] N. G. Sorum, T. Guite, and Martin, "Pavement Distress: A Case Study," *International Journal of Innovative Research in Science, Engineering and Technology*, vol. 3, no. 4, pp. 274–284, Mar. 2014.
- [13] K. Rajagopal, N. R. Krishnaswamy, and G. Madhavi Latha, "Behaviour of Sand Confined with Single and Multiple Geocells," *Geotextiles and Geomembranes*, vol. 17, no. 3, pp. 171–184, Jun. 1999, [https://doi.org/10.1016/S0266-1144\(98\)00034-X](https://doi.org/10.1016/S0266-1144(98)00034-X).
- [14] K. Rajagopal, A. Veeragavan, and A. Chandramouli, "Studies on Geocell Reinforced Road Pavement Structures," in *5th Asian Regional Conference on Geosynthetics*, Bangkok, Thailand, Dec. 2012, pp. 497–502.
- [15] S. K. Pokharel, J. Han, D. Leshchinsky, and R. L. Parsons, "Experimental Evaluation of Geocell-Reinforced Bases Under Repeated Loading," *International Journal of Pavement Research and Technology*, vol. 11, no. 2, pp. 114–127, Mar. 2018, <https://doi.org/10.1016/j.ijprt.2017.03.007>.
- [16] S. Chandra, M. N. Viladkar, and P. P. Nagrale, "Mechanistic Approach for Fiber-Reinforced Flexible Pavements," *Journal of Transportation Engineering*, vol. 134, no. 1, pp. 15–23, Jan. 2008, [https://doi.org/10.1061/\(ASCE\)0733-947X\(2008\)134:1\(15\)](https://doi.org/10.1061/(ASCE)0733-947X(2008)134:1(15)).
- [17] D. Gardete, R. Luzia, M. Sousa, S. Carronda, and A. Simão, "Soil Stabilization with Waste Plastic and Waste Tyre Fibres," *Proceedings of the XVII European Conference on Soil Mechanics and Geotechnical Engineering*, no. Geotechnical Engineering, foundation of the future, pp. 4315–4320, 2019, <https://doi.org/10.32075/17ECMGE-2019-0894>.
- [18] T. Kumar, S. Panda, and S. Hameed, "Behaviour of Soil by Mixing of Plastic Strips," *International Research Journal of Engineering and Technology*, vol. 5, no. 5, pp. 2578–2581, May 2018.
- [19] L. Suku, S. S. Prabhu, P. Ramesh, and G. L. S. Babu, "Behavior of Geocell-Reinforced Granular Base Under Repeated Loading," *Transportation Geotechnics*, vol. 9, pp. 17–30, Dec. 2016, <https://doi.org/10.1016/j.trgeo.2016.06.002>.
- [20] J. Singh, V. Sonthwal, and J. Rattan, "Review on Improvement of Engineering Properties of soil Using Waste Plastic Bottles Strips (Polyethylene Terephthalate)," *International Journal on Emerging Technologies*, vol. 8, no. 1, pp. 1–4, Apr. 2017.
- [21] D. V. A. M. Bharathi, E. Dhanalakshmi, R. S. Begum, and K. Muthu Kumar, "Design of Flexible Pavement Using Geocell," *International Journal of Creative Research Thoughts*, vol. 6, no. 2, pp. 1334–1340, Apr. 2018.
- [22] K. H. Mamatha and S. V. Dinesh, "Performance Evaluation of Geocell-Reinforced Pavements," *International Journal of Geotechnical Engineering*, vol. 13, no. 3, pp. 277–286, May 2019, <https://doi.org/10.1080/19386362.2017.1343988>.

- [23] S. Peddaiah, A. Burman, and S. Sreedeeep, "Experimental Study on Effect of Waste Plastic Bottle Strips in Soil Improvement," *Geotechnical and Geological Engineering*, vol. 36, no. 5, pp. 2907–2920, Oct. 2018, <https://doi.org/10.1007/s10706-018-0512-0>.
- [24] D. Landi, S. Gigli, M. Germani, and M. Marconi, "Investigating the Feasibility of a Reuse Scenario for Textile Fibres Recovered from End-of-Life Tyres," *Waste Management*, vol. 75, pp. 187–204, May 2018, <https://doi.org/10.1016/j.wasman.2018.02.018>.
- [25] M. Abbaspour, E. Aflaki, and F. Moghadas Nejad, "Reuse of Waste Tire Textile Fibers as Soil Reinforcement," *Journal of Cleaner Production*, vol. 207, pp. 1059–1071, Jan. 2019, <https://doi.org/10.1016/j.jclepro.2018.09.253>.
- [26] I. F. Al-Saadi, A. F. Jasim, S. A. Tayh, and R. A. Yousif, "A Case Study of Life Cycle Eco-Assessment of Recycled Asphalt Materials in Iraq Using OpenLCA and SimaPro," *Engineering, Technology & Applied Science Research*, vol. 15, no. 6, pp. 28569–28575, Dec. 2025, <https://doi.org/10.48084/etasr.13720>.
- [27] M. Alyamani, "Performance Evaluation of Self-Compacted Geopolymer Concrete with Fly Ash Partially Replaced with Blast Furnace Slag," *Engineering, Technology & Applied Science Research*, vol. 15, no. 6, pp. 28646–28659, Dec. 2025, <https://doi.org/10.48084/etasr.13914>.