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Sustainable Utilization of Shredded Polypropylene Fibers in Pavement Subgrade and Binder Course Applications

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ABSTRACT: This study investigates the use of randomly distributed shredded polypropylene fibers to strengthen both flexible pavement subgrade soils and asphalt course. For subgrade stabilization, fiber dosages from 0% to 2.0% by dry weight of soil were evaluated. For binder course modification, polypropylene fibers were added at 0% to 12% by weight of bitumen to assess improvements in mix performance. Incorporating polypropylene fibers increased the unconfined compressive strength of the soil, with peak performance at 1.25% by dry weight. At this optimum dosage, the 28-day UCS was 78% higher than that of the unreinforced control. Soaked CBR peaked at 9.9% with 1.25% polypropylene fiber, a 209% increase over the control. The fibers improve performance through tensile reinforcement and lateral confinement, reducing deformation and effectively controlling swell in expansive soils. After 12 wet–dry cycles, UCS retention peaked at 88% with 1.25% polypropylene fiber, versus 52% for unreinforced soil. Marshall Stability increased up to 10% polypropylene fiber, as the 3D fiber network bridged micro cracks and improved tensile resistance. This dosage gave optimum performance by bitumen weight, achieving peak stability while maintaining acceptable flow and favorable volumetric properties. Both dry and wet Indirect Tensile Strength peaked at 10% polypropylene fibers, rising from 950 to 1180 kPa and 741 to 1050 kPa, respectively. TSR also increased from 78.0% to 89.0%, confirming improved moisture resistance. Using shredded polypropylene fibers at layer-specific optimum dosages, 1.25% for subgrade soil and 10% for the asphalt binder course offers a technically viable and sustainable strategy for pavement upgrade. The utilization of shredded polypropylene fibers promotes sustainable pavement construction by converting plastic waste into a value-added resource while reducing dependence on conventional pavement materials and contributing to improved resource efficiency.

1. INTRODUCTION

Soil improvement and reinforcement are critical in civil engineering because natural ground conditions frequently fail to satisfy the strength, stability, and durability requirements of modern infrastructure. The need arises primarily from poor natural soil conditions, as many construction sites consist of weak, compressible, expansive, or low-bearing-capacity soils such as soft clay, loose sand, or black cotton soil, which cannot safely support structures without treatment. In pavement applications, weak subgrades lead to rutting, fatigue cracking, and premature failure. Urbanization and infrastructure expansion further drive the need for ground improvement by forcing construction on previously “unbuildable” marginal lands, including compressible ground for high-speed rail lines, port warehouses on coastal soils, and airports on artificial islands, where soil reinforcement makes such projects technically and economically feasible. From a safety and performance

standpoint, inadequate soils can cause excessive settlement, bearing capacity failure, or liquefaction during seismic events. Ground improvement techniques increase shear strength and bearing capacity while controlling deformations, thereby ensuring structural stability and long-term serviceability. Pavement deterioration continues to be a major challenge in global infrastructure development, with subgrade soil properties and binder course characteristics playing a fundamental role in ensuring long-lasting road structures [1]. The use of synthetic fibers, particularly polypropylene, has emerged as a sustainable approach to improve both pavement durability and subgrade performance [2]. Shredded polypropylene fibers sourced from waste plastic materials provide economic and environmental advantages while significantly enhancing the mechanical properties of asphalt mixtures and soil layers [3]. The design and construction of pavements are constrained by subgrade strength, long-term durability, and sustainability concerns. Traditional stabilization of subgrade and binder layers using cement and lime contributes substantially to carbon emissions and environmental impact. The use of shredded polypropylene fibers provides a sustainable solution that enhances pavement performance while utilizing waste materials [4]. Polypropylene fibers are attractive for reinforcement owing to their cost-effectiveness, availability, and capacity to improve strength, reduce volume change, and increase durability under severe environmental conditions, as demonstrated in recent research. These characteristics make shredded polypropylene fibers particularly viable for pavement systems across diverse geographic and economic contexts [5].

The use of waste polypropylene in pavement construction supports circular economy principles and aligns with global sustainability goals. With polypropylene accounting for nearly 19.1% of global plastic waste, incorporating shredded waste material into pavement layers provides the dual advantage of waste valorization and enhanced engineering performance [6]. Recent investigations of plastic materials in environmental and geological settings have also identified polypropylene among commonly detected polymer types, emphasizing the importance of effective plastic-waste management and reuse strategies [7]. The adaptability of polypropylene fibers further extends their application across various pavement components, from subgrade stabilization to asphalt binder modification, offering integrated solutions for improving infrastructure durability [8]. Conventional pavement construction relies on traditional materials and stabilization techniques that often perform poorly against rutting, cracking, and moisture-induced damage [9]. Incorporating waste polypropylene materials addresses environmental concerns while providing technical solutions that enhance overall pavement resilience [10]. Polypropylene fiber use in asphalt is expanding rapidly. Polymer-modified bitumen improves pavement performance, and polymer-modified binders have become standard for high-performance pavements in many developed and developing countries [11]. Adding polymers increases bitumen stiffness, reduces temperature susceptibility, and enhances rutting resistance. It also permits use of softer base bitumen's for better low-temperature performance. Polymer-modified binders further improve adhesion and cohesion [12]. Polymers also improve aggregate coating, increasing surface roughness to produce superior asphalt mixtures [13]. Despite their enhanced performance, polymer-modified mixes face adoption barriers due to high cost. With rising material and energy costs and dwindling natural resources, affordable polymer-modified mixtures are increasingly needed [14].

Using inexpensive polymers offers a cost-effective path to high-performance road materials. Waste materials are one promising option, and recent research has focused heavily on incorporating solid waste into road construction [15]. Incorporating polymers into bituminous binders improves pavement quality and performance [16]. Polymers are attractive for their enhanced mechanical strength, heat resistance, gas barrier properties, and reduced flammability compared to pure bitumen [17]. Using plastic waste in road pavements helps address disposal issues while potentially improving performance. Recycled PET, for example, lowers construction costs, resists distress, and extends service life, making it a viable alternative to conventional asphalt [18]. Optimizing resource use, cutting fuel consumption, and minimizing environmental impact are critical in road construction to reduce greenhouse gas emissions and advance sustainability [19]. Plastic additives up to 8% significantly improve asphalt mixture performance by increasing stability, strength, durability, and deformation resistance [20]. Post-earthquake debris can be screened to recover recyclable plastics. Processing these into new building products reduces environmental harm, conserves raw materials, and enables cheaper, faster, more sustainable reconstruction [21]. Converting plastic waste to bio-oil is another sustainable option for waste management and energy production [22, 23]. Sustainable management of waste materials is also important from an environmental perspective, particularly where waste disposal can affect land and surrounding environmental systems. Effective stabilization and management of waste materials can therefore support broader sustainable construction practices [24]. There is a clear need for techno-environmentally sound alternatives in pavement-grade concrete. Plastic fibers also show promise in civil engineering as a bulk waste disposal solution that mitigates

environmental issues [25]. This study aims to evaluate the dual application of polypropylene fibers in both asphalt binder courses and subgrade soils as an innovative approach to mitigating pavement distresses.

2. EXPERIMENTAL TESTING METHODOLOGIES AND QUALITY CONTROL

The experimental program was designed to evaluate the performance of polypropylene fiber-reinforced materials in both subgrade soils and asphalt binder courses. All tests were conducted in accordance with relevant ASTM, AASHTO, and IS standards to ensure consistency and reproducibility. Quality control measures were implemented during specimen preparation, curing, and testing to minimize experimental variability. Baseline properties were established for subgrade soil, asphalt binder, and shredded waste polypropylene fiber. Test details are given in Table 1. Triplicate specimens were tested for reliability. Fiber dispersion was checked visually and by density uniformity. Mixing and compaction used controlled temperature and humidity. Equipment was calibrated before each series, and outliers were removed statistically. For subgrade stabilization, polypropylene fiber dosages of 0%, 0.25%, 0.5%, 0.75%, 1%, 1.25%, 1.50%, 1.75%, and 2.0% by dry weight of soil were evaluated. For the binder course, fiber dosages of 0%, 6%, 8%, 10%, and 12% by weight of bitumen were used.

2.1. Polypropylene Fibers

Waste polythene was collected from the municipal collection point. Plastic waste involves three preparation steps: segregation, cleaning, and shredding prior to mixing into subgrade, as shown in Figure 1. The length of shredded polythene fiber was 12 mm. The melting point and density of polypropylene fiber was 115°C and 0.92 g/cm³.



Figure 1. Shredded polypropylene fiber

2.2 Binder Course Preparati

Coated coarse aggregate was prepared in the lab using the dry process. Clean, oven-dried 10–12.5 mm aggregates were heated to 160–170°C, then mixed with shredded polypropylene fiber at 6–12% by weight of bitumen until the plastic melted and uniformly coated the aggregate as shown in Figure 2. Bitumen at 5.4% by weight of aggregate was then added and mixed for 5–10 minutes. The coated aggregate was spread and cooled to room temperature before testing for specific gravity, impact, crushing, abrasion values, and other properties. Figure 3 shows the uncoated and coated aggregate samples to use in binder course in asphalt pavement. The fine aggregate were also used in binder course with specific gravity 2.62 and 1.45% water absorption.



Figure 2. Plastics mixing with aggregates



Figure 3. Uncoated and Coated aggregate for Binder Course

Test details on subgrade soil, bitumen and binder course with varying percentage of polypropylene fiber are given in Table 1.

Table 1. Experimental Test, Standards, and Key Parameters

Material Layer	Test	Standard	Key Parameters Measured
Subgrade Soil	Atterberg Limits	ASTM D4318 / IS 2720-5	Liquid Limit, Plastic Limit, Plasticity Index
	Standard Proctor Compaction	ASTM D698 / IS 2720-7	Optimum Moisture Content, Max Dry Density
	Unconfined Compressive Strength (UCS)	ASTM D2166 / IS 2720-10	UCS at 7, 14, 28 days
	California Bearing Ratio (CBR)	ASTM D1883 / IS 2720-16	Soaked & Unsoaked CBR
	Free Swell Index	IS 2720-40	Free Swell Index, Swelling Pressure
	Durability - Wet/Dry Cycle	ASTM D559 / D560	Strength loss after cycles
Coarse Aggregate	Specific Gravity	IS 2366	Specific Gravity
	Water Absorption	Part III	% Water Absorption

	Impact Test	IS 2366 Part IV	Aggregate Impact Value
	Crushing Test		Aggregate Crushing Value
	Abrasion Test		Los Angeles Abrasion Value
Bitumen	Penetration Test	ASTM D5 / IS 1203	Penetration value at 25°C
	Softening Point	ASTM D36 / IS 1205	Ring & Ball temperature
Binder Course	Marshall Stability & Flow	ASTM D6927 / MS-2	Stability, Flow, Air Voids, VMA, VFB
	Indirect Tensile Strength (ITS)	ASTM D6931	ITS dry, ITS wet, TSR

3. RESULTS AND DISCUSSION

This Results and Discussion section is organized into two parts. The first evaluates the influence of shredded polypropylene fibers on subgrade soil properties and soil stability, which is the critical for long-term pavement performance. The second examines their effects on the asphalt pavement binder course, with particular attention to sustainability and environmental performance.

3.1 Subgrade Soil Reinforced with Polypropylene Fibers

3.1.1 Effect of Polypropylene Fiber Content on Index and Compaction Properties

The addition of polypropylene fiber significantly modified the soil's consistency and compaction characteristics. The plasticity index (PI) decreased progressively from 32% to 18% as polypropylene fiber content increased to 2.0%, primarily driven by a substantial reduction in the liquid limit from 68% to 49%. Notably, the most pronounced reduction in PI occurred up to 1.25% fiber content, after which the rate of change diminished, indicating a threshold of diminishing returns for plasticity modification. Regarding compaction behavior, the maximum dry density (MDD) declined from 1.72 g/cm³ to 1.61 g/cm³, while the optimum moisture content (OMC) rose from 18.2% to 21.8%. This reduction in MDD is attributed to the low specific gravity of the fibers displacing heavier soil solids and the increased water demand required for fiber lubrication. While specimens remained stable and free of segregation up to 1.5% polypropylene fiber, dosages at or above 1.75% resulted in surface hairiness and a degraded surface finish. These findings suggest that while higher fiber contents continue to alter soil properties, a practical limit of 1.25% polypropylene fiber is necessary to maintain workability and optimize engineering benefits. Based on the results, the polypropylene fiber stabilized soil is recommended for pavement subgrade modification and slope stabilization in high-plasticity clay regions. Utilizing a dose of 1.25% provides the best balance between reducing the plasticity index and maintaining structural integrity. This modification is particularly effective for low-volume road construction.

3.1.2 Effect of Polypropylene Fiber Content on Unconfined Compressive Strength (UCS)

The unconfined compressive strength of subgrade soil showed a strong dependence on polypropylene fiber content, with peak values observed at intermediate dosages before declining due to workability and dispersion effects. Figure 4 showed the UCS results with varying percentage of fiber content. The Unconfined Compressive Strength of the stabilized soil showed significant enhancement with the addition of polypropylene fibers, peaking at a 1.25% dosage. At this optimum content, the 28-day UCS exhibited a 78% strength increase compared to the untreated control. This substantial gain is attributed to the bridging effect, where fibers intercept potential failure planes and provide lateral confinement, effectively increasing the soil's internal resistance to axial loads [26, 27].

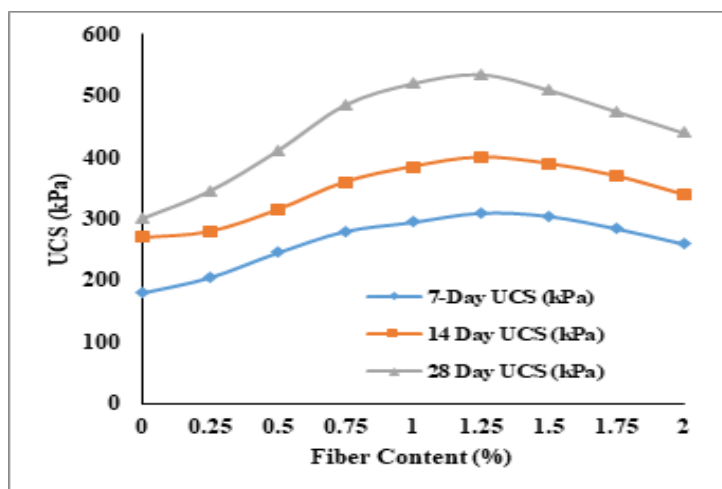


Figure 4. UCS results with varying percentage of polypropylene fibers

However, beyond the 1.25% threshold, a decline in UCS was observed. At dosages of 1.75% and 2.0%, the formation of fiber clusters created localized weak zones and reduced the effective contact area between the soil particles and the fiber surface [28]. Furthermore, a fundamental shift in failure mode was recorded; while the untreated soil exhibited sudden, brittle failure, all Polypropylene Fibers reinforced specimens demonstrated increased ductility and significant post-peak load retention [29]. This suggests that the optimal dosage for maximizing structural strength lies between 0.75% and 1.25%. Integrating 1.25% Polypropylene Fiber into heavy-duty pavement subgrades delivers major structural benefits. It increases strength, boosts axle load capacity, and shifts failure to a ductile mode. This enhances energy absorption and prevents rapid fatigue crack propagation to the surface.

3.1.3 Effect of Polypropylene Fiber Content on California Bearing Ratio (CBR)

CBR results directly govern pavement thickness design. Incorporating discrete Polypropylene Fiber altered load-penetration behavior, with fiber content influencing both the peak CBR value and strength retention under soaked and unsoaked conditions as shown in Figure 5. The inclusion of polypropylene fibers substantially enhanced the soaked CBR of the soil, with a peak value of 9.9% achieved at a 1.25% dosage. This represents a remarkable 209% increase over the untreated soil's baseline strength. This improvement is primarily attributed to the fiber reinforcement's ability to act as a tension-resisting element, providing lateral confinement and resisting soil deformation under concentrated axial loads. Moreover, the strength retention after soaking remained above 70% for dosages ranging from 0.75% to 1.5%, confirming that the fiber matrix significantly reduces moisture susceptibility and maintains structural stability in saturated conditions.

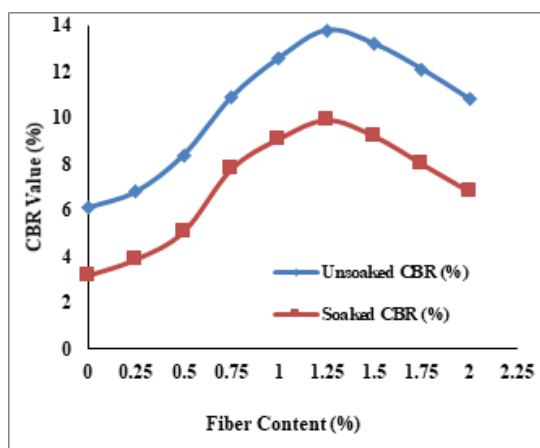


Figure 5. Polypropylene fibers content and CBR values of Subgrade Soil

On the other hand, at higher dosages (1.75%–2.0%), the CBR values declined due to poor fiber dispersion and clumping, which increased the void ratio and weakened the soil-fiber interlock. Polypropylene fibers stabilization's with soaked CBR gain enables thinner pavements in flood-prone areas, all-weather rural roads, and settlement-resistant foundations for hydraulic structures. Aneke, F. at al. [30] also explored that the dry soil achieved CBR values higher than soaked soil, reducing the likelihood of deformation under traffic loading. So to avoid this condition the addition of polypropylene fiber to the subgrade soil will improves CBR and limits deformation by reinforcing the soil matrix. In the field, this is applied in low-volume rural roads to reduce pavement thickness and cost, in highway and expressway subgrades to improve load-bearing capacity in weak or wet soils, in pavement shoulders and widening projects to prevent differential settlement, in airfield taxiways and aprons to withstand heavy repetitive loads, and in embankments and bridge approaches to control settlement and slope instability.

3.1.4 Effect of Fiber Content on Swelling Characteristics

Free swell index decreased from 95% at 0% polypropylene fibers to 22% at 2.0% polypropylene fibers, while swelling pressure reduced from 220 kPa to 48 kPa. The reduction was substantial up to 1.25% polypropylene fibers, beyond which improvements were marginal due to fiber network saturation. Therefore, a 1.25% polypropylene fiber is optimal for swell control in expansive soils. In field applications, this dosage is effective for subgrades under pavements and canal linings in expansive soil regions, where it limits heave, prevents differential settlement, and reduces maintenance from shrink-swell cycles. The fiber-soil matrix maintains integrity during wet-dry fluctuations, making it suitable for irrigation channels and low-volume roads in black cotton soil areas.

3.1.5 Effect of Fiber Content on Durability under Wet-Dry Cycles

After 12 wet–dry cycles, UCS retention peaked at 88% for 1.25% polypropylene fibers, compared to 52% for unreinforced soil. Retention improved from 0.5% to 1.25% polypropylene fibers but declined at higher dosages due to fiber pull-out and surface erosion during wetting, which increased moisture ingress. Considering strength, soaked CBR, swell, and durability together, 1.25% polypropylene fibers is the optimum range. Beyond 1.5% polypropylene fibers, performance dropped from fiber agglomeration, higher void content, and reduced soil–fiber interface friction. Fibers function as discrete tensile reinforcements that limit tensile strain, bridge micro cracks, and preserve fabric integrity under moisture fluctuation. This durability makes 1.0%–1.25% polypropylene fibers suitable for road subgrades in monsoon-prone regions and for canal embankments subjected to repeat wetting–drying, where it maintains bearing capacity and reduces erosion and maintenance. Field compaction and mixing become difficult beyond 1.5% polypropylene fibers due to fiber balling and poor workability, consistent with lab results. The Texas subgrade stabilization project showed that fibrillated fiber can be easily mixed and compacted using standard equipment, and is commercially available according to Fletcher and Humphries [31]. According to Hassan et al. [32] adding up to 4% polypropylene fiber by weight improves soil strength and deformation behavior. Dry-mixing polypropylene at this dosage into subgrade soil during road construction reduces rutting and allows thinner pavement layers in low-volume roads, embankments, and shoulders.

3.2 Results and Discussion on Asphalt Binder Course with Polypropylene Fibers

3.2.1 Effect of Polypropylene Fibers on Bitumen Properties

This section presents the effect of polypropylene fiber content on the performance of the bitumen used in asphalt binder course under varying dosages. Table 2 shows the influence of polypropylene fiber content on basic bitumen properties. With increasing polypropylene fiber from 0% to 12% by weight of bitumen, penetration at 25°C consistently decreased from 67 mm to 51 mm, indicating higher stiffness. Softening point increased from 48.0°C to 57.1°C, while rotational viscosity at 135°C rose from 0.42 Pa·s to 0.92 Pa·s.

Table 2. Effect of Polypropylene Fibers on Bitumen Properties

Fiber Content (% by wt of bitumen)	Penetration @ 25°C (mm)	Softening Point (°C)	Viscosity @ 135°C (Pa·s)
0	67	48.0	0.42

6	63	52.2	0.51
8	58	53.8	0.64
10	54	55.5	0.78
12	51	57.1	0.92

The rate of change was nearly linear for all three parameters, with no sudden plateau observed within the tested range. The reduction in penetration and increase in softening point confirm that polypropylene fiber addition stiffens the bitumen matrix and enhances its temperature susceptibility. A 23.9% drop in penetration and 9.1°C rise in softening point at 12% polypropylene fiber suggest improved rutting resistance under high service temperatures. The increase in viscosity to 0.92 Pa·s at 135°C indicates higher mixing and compaction temperatures would be required to achieve adequate workability. While this improves resistance to permanent deformation, viscosity above 0.5–0.6 Pa·s often complicates plant mixing and field compaction due to poor fiber dispersion and balling. From a practical standpoint, 10%–12% polypropylene fiber provides a balance between stiffness gain and workability. At this range, softening point increased and viscosity remained low, which is within typical handling limits for VG-30 bitumen. Beyond 10% polypropylene fiber, the doubling of viscosity relative to neat bitumen may lead to heterogeneous mixes and lower coating efficiency, offsetting performance gains. The stiffening effect makes polypropylene fiber modified bitumen suitable for binder courses in high-temperature, heavy-axle regions to limit rutting. However, the dosages above 8% would require elevated mixing temperatures or warm-mix additives to maintain workability and ensure uniform fiber distribution during construction. This method is classified as a wet method, but the results are intended for trend observation only.

3.2.2 Effect of Polypropylene Fibers on Coated Aggregate Properties

The incorporation of polypropylene fibers into bitumen-coated aggregates alters their physical and mechanical characteristics by modifying surface texture, bonding, and resistance to degradation. This section evaluates the effect of varying fiber content on specific gravity, water absorption, and aggregate strength parameters including impact, crushing, and abrasion values.

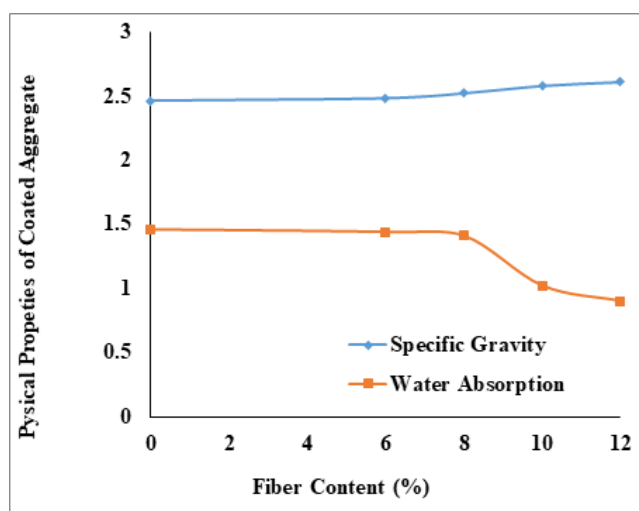


Figure 6. Physical properties of polypropylene fibers coated aggregate

Figure 6 shows that the specific gravity increased steadily with fiber content, from 2.46 at 0% to 2.61 at 12%. Water absorption decreased as fiber content rose, dropping from 1.46% at 0% to 0.90% at 12%. The most notable reduction occurred between 8% and 10% fiber, where water absorption fell from 1.41% to 1.02%. The rise in specific gravity indicates a denser, more compact mixture with polypropylene fiber addition. This suggests improved packing and reduced air voids, which typically enhances stability and load-bearing capacity. The concurrent drop in water absorption reflects lower permeability and better moisture resistance. Reduced water ingress helps prevent stripping, raveling, and freeze-thaw damage in asphalt layers. Overall, 10% polypropylene fiber by weight of bitumen showed the best combination of high specific gravity and low water absorption, implying superior durability and moisture resistance compared to unmodified mix. For field

application, mixtures with 10% polypropylene fiber are suitable for moisture-prone areas with high rainfall, poor drainage, or high water tables due to their low water absorption. The higher specific gravity at 10% fiber indicates a denser mix with improved rutting resistance, making it appropriate for heavy traffic pavements such as highways and truck lanes. Although 12% fiber yields the lowest water absorption, 10% provides substantial improvement over 8% while using less material, offering a better cost-performance balance; however, field trials are needed to verify workability and optimum dosage since excessive fiber can reduce compaction. Overall, polypropylene fiber modified binder courses can enhance durability and extend pavement service life, particularly in expansive soil areas or regions where moisture-induced distress is common.

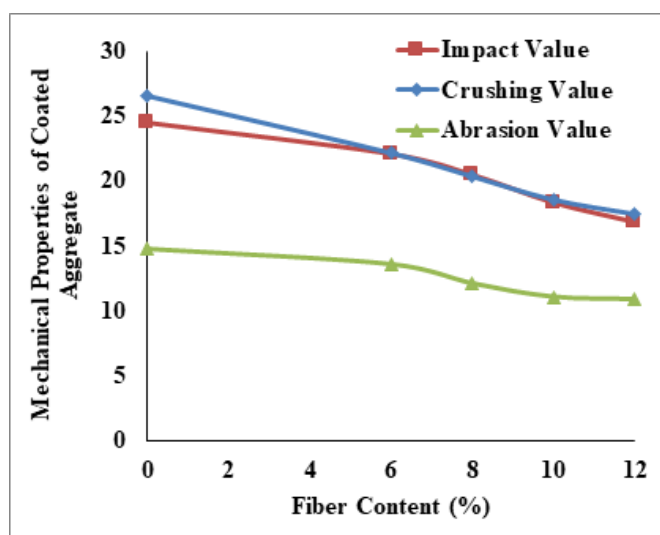


Figure 7. Mechanical properties of polypropylene fibers coated aggregate

Figure 7 shows that the Impact value, crushing value, and abrasion value all decreased progressively as polypropylene fiber content increased from 0% to 12%. Impact value dropped from 24.50% to 16.85%, crushing value from 26.60% to 17.50%, and abrasion value from 14.85% to 10.90%. The most significant improvements occurred at 10–12% fiber content. Lower impact and crushing values indicate higher toughness and greater resistance to sudden loads and crushing under traffic. The reduced abrasion value reflects improved wear resistance and durability against surface disintegration. These trends suggest that polypropylene fiber addition enhances the mechanical integrity of the asphalt mixture by reinforcing the binder matrix and improving aggregate interlock. Based on IS 2386 limits, all modified mixes meet standard requirements, with 10–12% polypropylene fiber showing the best performance. Mixtures with 10–12% polypropylene fiber are well suited for high-stress pavements due to their low impact and crushing values, indicating superior load resistance for highways, intersections, and heavy truck routes. The low abrasion values of 10.90–11.10% make these mixes appropriate for wearing courses in areas with high tire abrasion or frequent braking. For cost-effective application, 10% polypropylene fiber provides a substantial gain over 8% with lower fiber use than 12%, but field compaction trials are essential to confirm workability at higher dosages. Overall, polypropylene fiber modified mixes can reduce aggregate degradation, extend pavement life, and lower maintenance needs in demanding traffic and environmental conditions.

3.2.3 Marshall Properties of Polypropylene Fiber Modified Asphalt Mixtures

The Marshall properties of the asphalt mixture were evaluated to assess the effect of polypropylene fiber content on stability, flow, volumetric parameters, and overall mix performance relative to the control mix as shown in Table 3, which shows the effect of polypropylene fiber content on Marshall Properties of the asphalt binder course.

Table 3. Marshal Properties of Modified Asphalt Mixtures

Fiber Content (% by wt of bitumen)	Stability (kN)	Flow (mm)	Air Voids (%)	VMA (%)	VFB (%)
0	11.2	3.1	4.1	15.2	73

6	12.5	3.3	3.9	15.0	74
8	13.9	3.5	3.7	14.9	75.2
10	14.8	3.6	3.5	14.8	76.4
12	14.2	3.9	3.6	15.1	74.8

As fiber content increased from 0% to 12% by the mix of bitumen weight, Marshall Stability improved from 11.2 kN to a peak of 14.8 kN, a 32.1% increase. Flow value increased gradually from 3.1 mm to 3.6 mm. Air voids decreased from 4.1% to 3.5%, while VMA reduced from 15.2% to 14.8%. VFB increased from 73% to 76.4% at 10% polypropylene fiber. At 12% polypropylene fiber, stability declined to 14.2 kN, flow increased to 3.9 mm, and air voids/VMA both rose to 3.6% and 15.1%, with VFB dropping to 74.8%. The increase in stability up to 10% polypropylene fiber is attributed to the 3D reinforcing effect of fibers, which bridge micro cracks in the mastic and improve tensile resistance under loading. The marginal rise in flow indicates that the mix retained adequate flexibility, with all values staying within MoRTH limits of 2–4 mm. The decrease in air voids and VMA up to 10% polypropylene fiber suggests improved compaction and denser aggregate packing due to fiber-mastic stiffening, which also raised VFB and improved durability against moisture intrusion. At 12% polypropylene fiber, the reversal in trends reflects fiber agglomeration and higher mix viscosity. Clumped fibers create localized voids, reduce effective binder coating, and resist compaction, leading to higher air voids, increased VMA, and lower stability. The flow value of 3.9 mm approaches the upper MoRTH limit, indicating reduced stiffness and higher deformation potential. 10% polypropylene fiber by mix weight gives optimum Marshall Performance, balancing peak stability, acceptable flow, and favorable volumetric properties. Beyond this dosage, workability issues and fiber clustering offset strength gains. For field use, this dosage would improve rutting resistance in binder courses but requires strict control on mixing temperature and fiber dispersion to avoid heterogeneity. This trend is driven by the need for sustainable practices and environmental conservation [33]. Sustainable engineering approaches also emphasize the need to manage infrastructure development in relation to environmental conditions and long-term resource conservation [34].

3.2.4 Indirect Tensile Strength and Moisture Susceptibility

Indirect tensile strength and tensile strength ratio were measured to evaluate the effect of polypropylene fiber on the cohesive and adhesive properties of the asphalt mixture under dry and moisture-conditioned states as shown in Table 4.

Table 4. Indirect Tensile Strength Results

Fiber Content (% by wt of bitumen)	ITS Dry (kPa)	ITS Wet (kPa)	TSR (%)
0	950	741	78.0
6	1040	853	82.0
8	1125	957	85.1
10	1180	1050	89.0
12	1140	991	86.9

Table 4 shows the effect of polypropylene fiber content on indirect tensile strength and moisture susceptibility. Both ITS Dry and ITS Wet increased with fiber content up to 10%, from 950 kPa to 1180 kPa dry and 741 kPa to 1050 kPa wet. TSR improved from 78.0% for the control mix to a maximum of 89.0% at 10% polypropylene fiber. At 12% polypropylene fiber, ITS Dry and ITS Wet declined to 1140 kPa and 991 kPa, with TSR reducing to 86.9%. The rise in ITS up to 10% polypropylene fiber indicates enhanced cohesive and tensile strength due to fibers forming a 3D network within the mastic. Fibers bridge micro cracks and increase fracture energy, delaying crack initiation and propagation under diametric loading. The improvement in TSR to 89.0% shows better moisture resistance, as fibers reduce permeability and limit stripping by maintaining aggregate-binder adhesion during conditioning. The drop at 12% polypropylene fiber is due to fiber agglomeration and poor dispersion. Clumped fibers create weak planes and localized voids that act as moisture pathways, reducing both dry strength and wet strength retention. Higher mix viscosity at this dosage also lowers coating efficiency, leaving more uncoated aggregate surfaces vulnerable to water. All polypropylene fiber -modified mixes exceeded the MoRTH

minimum TSR of 80%, while the control mix was marginal at 78.0%. The 10% polypropylene fiber mix showed the highest strength retention, indicating optimum fiber-binder interaction. The improved ITS and TSR at 6%–10% polypropylene fiber make the modified binder course suitable for high-rainfall regions and flood-prone subgrades, such as highway stretches in the Western Ghats and coastal Maharashtra. Higher tensile strength reduces top-down and bottom-up cracking, while TSR greater than 85% ensures durability against monsoon-induced stripping and raveling. For field implementation, 10% polypropylene fiber provides the best balance of crack resistance and moisture durability without severe workability penalties. Mixing temperature should be increased by 10–15°C to ensure uniform fiber dispersion and full coating at these dosages. Integrating polypropylene fiber into soil stabilization and pavement projects delivers strong cost-benefit advantages. Gains in California Bearing Ratio often exceed 250%, allowing thinner base and sub-base layers and reducing initial construction costs. Identical result declare by Mosa et al. [35], adding Polyethylene terephthalate improved mixture stability, stiffness, indirect tensile strength, and moisture resistance while lowering rutting susceptibility, with no adverse effects on other properties. The fibers provide tensile reinforcement that bridges micro cracks and slows crack propagation, extending pavement service life and lowering long-term maintenance and rehabilitation expenses. These life-cycle savings offset the upfront cost of fiber addition. Using recycled polypropylene fiber from up cycled plastics converts non-biodegradable waste into a structural pavement material, reducing disposal costs while advancing sustainable construction [36,37]. The polypropylene fiber stabilization approach presents a viable method for improving the load-bearing capacity of subgrade soils. Utilizing waste materials further offers a sustainable solution for subgrade stabilization [38, 39].

4. CONCLUSION

1. Polypropylene fiber addition reduced soil plasticity and altered compaction behavior. PI dropped from 32% to 18% and MDD from 1.72 to 1.61 g/cm³ as fiber increased to 2.0%, while OMC rose from 18.2% to 21.8%. The greatest improvement occurred up to 1.25% fiber, beyond which benefits diminished and workability issues appeared at 1.75%. Thus, 1.25% Polypropylene fiber is the optimal dosage for practical subgrade stabilization.
2. The unconfined compressive strength (UCS) of stabilized soil increased significantly with polypropylene fiber addition, reaching a maximum at 1.25% dosage. At 28 days, UCS showed a 78% strength gain over the untreated control. This improvement is attributed to the fiber bridging effect, which intercepts failure planes and provides lateral confinement, thereby enhancing internal resistance to axial loads.
3. The inclusion of polypropylene fibers substantially improved the soaked CBR of the soil, peaking at 9.9% with a 1.25% dosage. This reflects a 209% increase over the untreated baseline. The improvement is mainly due to fiber reinforcement acting as a tension-resisting element, providing lateral confinement and reducing deformation under axial loads.
4. Adding polypropylene fibers reduced free swell index from 95% to 22% and swelling pressure from 220 kPa to 48 kPa. Gains were significant up to 1.25% polypropylene fibers, with minimal benefit beyond that point. Hence, 1.25% polypropylene fibers is the optimum dosage for controlling swell in expansive soils.
5. Fiber addition from 0% to 12% decreased penetration and increased both softening point and viscosity, showing improved stiffness and high-temperature performance at the expense of workability.
6. Fiber-coated aggregates showed higher specific gravity and lower water absorption, impact, crushing, and abrasion values as fiber content increased to 12%. The results confirm enhanced aggregate quality and durability with higher fiber dosage.
7. Fiber addition enhanced Marshall Stability up to 14.8 kN at 10% dosage with acceptable flow and air voids. Beyond 10%, stability declined and flow exceeded desirable limits. Therefore, 10% fiber by weight of bitumen is the optimum content for balanced strength and durability.
8. Fiber addition increased ITS and TSR, with peak values at 10% dosage — ITS Dry 1180 kPa, ITS Wet 1050 kPa, and TSR 89.0%. Performance dropped at 12% fiber. Thus, 10% fiber is optimum for improved strength and moisture resistance.

The dual application of shredded polypropylene fibers at layer-specific optimum dosages 1.25% for subgrade soil and 10% w.r.t.bitumen for asphalt binder course provides a technically viable and sustainable pavement upgrade strategy. The subgrade reinforcement primarily enhances bearing capacity and dimensional stability through mechanical restraint and cracks bridging, while the asphalt modification improves stiffness, moisture resistance, and fatigue life via fiber-mastic reinforcement.

Future studies should develop eco-friendly asphalt pavements by recycling polypropylene fibers from plastic waste. This can be done by modifying asphalt binder and mixtures, using pulverized plastic as a partial or full filler substitute, and replacing aggregates with polypropylene fibers of varying sizes and proportions to optimize performance and cost. Since these findings are limited to lab tests, further research is needed to evaluate fatigue behavior and rutting resistance under field conditions.

REFERENCES

- [1] N.S.Mashaan, M.R.Karim, F.Khodary, N.Saboo, A.Milad, Bituminous Pavement Reinforcement with Fiber: A Review, Civil Engineering, (2021). <https://doi.org/https://doi.org/10.3390/civileng2030033>
- [2] H.Akram, H.A.Hozayen, A. Abdelfatah, F.Khodary, Fiber Showdown: A Comparative Analysis of Glass vs. Polypropylene Fibers in Hot-Mix Asphalt Fracture Resistance, Buildings, (2024). <https://doi.org/10.3390/buildings14092732>
- [3] I.Nteyoho, S.Balogun, P.Akinteye, The Effect of Polypropylene Fibre Waste As Reinforcement In Asphaltic Binder Course, Nile Journal of Engineering and Applied Science, (2024). <https://doi.org/10.5455/njeas.194804>
- [4] M. Miturski, Influence of curing time on the effectiveness of polypropylene fibers in cement-stabilized soil improvement, Inżynieria Bezpieczeństwa Obiektów Antropogenicznych, (2025). <https://doi.org/10.37105/iboa.2>
- [5] N. Tiwari, N. Satyam N, An experimental study on strength improvement of expansive subgrades by polypropylene fibers and geogrid reinforcement, Scientific Reports, (2022). <https://doi.org/10.1038/s41598-022-10773-0>
- [6] N, Yang, C, Du, Y, Tang, Z, Li, S, Xu, X, Xu, Waste Polypropylene in Asphalt Pavements: A State-of-the-Art Review Toward Circular Economy, Sustainability, (2025). <https://doi.org/10.3390/su172410954>
- [7] Darshan MS, Siddaraju K, Madhu R. Assessing microplastic contamination in Gurupura Estuarine Sediments, Mangalore, India. Bull Pure Appl Sci Geol. 2024;43F(1). Available from: <https://bpasjournals.com/geology/index.php/journal/article/view/3>
- [8] J.M. Nathen, A.K. Arshad, N.M. Rais, E. Shaffie, E. Ismail, N.A. Kamaluddin, A. Malek, Review of Subgrade Soil Stabilised with Natural and Synthetic Fibres, IOP Conference Series: Earth and Environment, (2024). <https://doi.org/10.1088/1755-1315/1296/1/012005>
- [9] M. Ahmeti, B. Selimi, Aramid Fiber Reinforcement in Asphalt Mixtures: A Holistic Study on Mechanical Enhancement, Life-Cycle Economics, and Sustainable Pavement Solutions, Engineering Perspective, (2026). <https://doi.org/10.64808/engineeringperspective.1864762>
- [10] C. Abdy, Y. Zhang, J. Wang, Y. Yang, I. Artamendi, B. Allen, Pyrolysis of polyolefin plastic waste and potential applications in asphalt road construction: A technical review, Resources Conservation and Recycling, (2022). <https://doi.org/https://doi.org/10.1016/j.resconrec.2022.106213>
- [11] P. Ahmedzade, M. Yilmaz, Effect of polyester resin additive on the properties of asphalt binders and mixtures, Construction and Building Material, 22(4), (2008), 481–486. <https://doi.org/10.1016/j.conbuildmat.2006.11.015>
- [12] Y. Yildirim, Polymer modified asphalt binders, Construction and Building Material, 21(1), (2007), 66–72. <https://doi.org/10.1016/j.conbuildmat.2005.07.007>
- [13] M.T.Awwad, L. Shbeeb, The use of polyethylene in hot asphalt mixtures, American Journal of Applied Science, 4(6), (2007), 390–396. <https://doi.org/10.3844/ajassp.2007.390.396>
- [14] L.A. Ahmed, Improvement of Marshall properties of the asphalt concrete mixtures using the polyethylene as additive, Engineering Technology, 25(3), (2007), 383–394. <https://doi.org/10.30684/etj.25.3.9>
- [15] Y. Xue, H.Hou, Sh.Zhu, J. Zha, Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: pavement performance and environmental impact, Construction and Building Material, 23(2), (2009), 989–996. <https://doi.org/10.1016/j.conbuildmat.2008.05.009>

- [16] Q. Yang, J. Lin, X.Wang, D.Wang, N.Xie, X. Xianming, A review of polymer-modified asphalt binder: Modification mechanisms and mechanical properties, *Cleaner Materials*, 12, (2024), 100255. <https://doi.org/10.1016/j.clema.2024.100255>
- [17] J. Cardoso, A. Ferreira, A. Arminda Almeida, J. Santos, Incorporation of plastic waste into road pavements: A systematic literature review on the fatigue and rutting performances, *Construction and Building Material*, 407,(2023), 133441. <https://doi.org/10.1016/j.conbuildmat.2023.133441>
- [18] B. Rath, Effect of asphalt pavement construction on the environment of Ethiopia, *Research on Engineering Structures and Materials*, . 8(3), (2022), 615-632. <http://dx.doi.org/10.17515/resm2022.352ma1010>
- [19] W.M.N.W. Rahman, A.F.A.W. Wahab, Green Pavement using Recycled Polyethylene Terephthalate (PET) as Partial Fine Aggregate Replacement in Modified Asphalt, *Procedia Engineering*. 53, (2013), 124-128. <https://doi.org/10.1016/j.proeng.2013.02.018>
- [20] F. Khurshid, A.Y. Gunal, Harnessing earthquake generated glass and plastic waste for sustainable construction, *Turkish Journal of Engineering*, 8(2), (2024), 394-402. <https://doi.org/10.31127/tuje.1405272>
- [21] R. Thamizhvel, S. Naveen, S. Krishna, Production of Oil from Plastic Waste through Thermal Degradation Process, *Turkish Journal of Engineering*, 9(3), (2025), 409-416. <https://doi.org/10.31127/tuje.1535115>
- [22] M. Yılmaz, S. Öztürk, Thermal Degradation of Plastic Waste and its Potential as an Alternative Fuel Source, *Turkish Journal of Engineering*, 8(2), (2024), 289-297. <https://doi.org/10.31127/tuje.1535115>
- [23] F. Kdous, S. El Euch Khay, A. Loulizi, Eco-efficient concrete containing coarse reclaimed asphalt pavement: impact on mechanical and durability properties, *Innovative Infrastructure Solutions*, 11, (2026), 101. <https://doi.org/10.1007/s41062-026-02495-3>
- [24] M. Ali, O. Mirza, C. Camille, F. Mashiri, Incorporation of recycled PET fibre as reinforcement in structural and Non-Structural concrete: A systematic literature review, *Innovative Infrastructure Solutions*, 10, (2025), 578. <https://doi.org/10.1007/s41062-025-02384-1>
- [25] Madhu T, Vijaya Kumari O, Rajeev Kumar G, Chaitanya Reddy E. Analysis of geological factors for successful dolomite mining exploration at Venkatampalli Village, Narpala Mandal, Anantapur District, Andhra Pradesh. *Bulletin of Pure and Applied Sciences-Geology*. 2019, 38F(2). <https://bpasjournals.com/geology/index.php/journal/article/view/141>
- [26] M.Y. Daksi, M. Dib, Z. Matougui, A. Gherbi, Experimental analyses of the effect of polypropylene fibers on consistency limits and permeability of clays, *Studies in Science of Science*, 42(9), (2024), 77-88.
- [27] T. Dave, D. Patel, G. Saiyad, N. Patolia, Use of Polypropylene Fibres for Cohesive Soil, *Geotechnical Applications of Nanotools and Fiber Reinforcement*, Springer, (2020), 411—420. https://doi.org/https://10.1007/978-981-15-0890-5_34
- [28] O.P. Navagire, V. Srinivasan, A. Patel, D. Gowrisankar, Stabilization of expansive soils using polypropylene fiber for enhanced engineering properties: A study on black cotton soils from India, *Indian Geotechnical Journal*, (2025). <https://doi.org/https://10.1007/s40098-025-01225-3>
- [29] R. Odek, J. Oluoch, Cost benefit analysis origin and applicability of its recent advances: A critical review, *Management Ecos Research Journal*, 9(1), (2023). <https://doi.org/https://10.18639/MERJ.2023.9900075>
- [30] F. Aneke, D. Kalumba, S. Hanandeh, H.M. Shiferaw, Quantifying the Influence of Matric Suction on California Bearing Ratio of Compacted Unsaturated Subgrades for Flexible Pavement Design, *Transportation Infrastructure Geotechnology*, 13, (2026), 135. <https://doi.org/10.1007/s40515-026-00883-x>
- [31] C.S. Fletcher, W.K.Humphries, California Bearing Ratio Improvement of Remolded Soils by the Addition of Polypropylene Fiber Reinforcement, *Transportation Infrastructure Geotechnology*, 1295, (1991), 80–86.

- [32] H.J.A. Hassan, J. Rasul, M. Samin, Effects of Plastic Waste Materials on Geotechnical Properties of Clayey Soil, *Transportation Infrastructure Geotechnology*, 8, (2021), 390–413. <https://doi.org/10.1007/s40515-020-00145-4>
- [33] I.S. Al-Haydari, H.S. Al-Haidari, H. Mohammed-Noor Khudhur, N. Waleed Jummah, M. Abd Al-Hamza, Durability and Aging Characteristics of Sustainable Paving Mixture, *International Journal of Engineering, Transactions B: Applications*, 34(08), (2021), 1865-1873. <https://doi.org/10.5829/ije.2021.34.08b.07>
- [34] A. M. Mosa, I.T. Jawad, L.A. Salem, Modification of the Properties of Warm Mix Asphalt Using Recycled Plastic Bottles, *International Journal of Engineering (IJE), IJE TRANSACTIONS C: Aspects*, 31(9), (2018), 1514-1520. <https://doi.org/10.5829/ije.2018.31.09c.06>
- [35] B.H. Basheet, R.H. Latief, The Impact of Using Polyethylene Polymer on the Properties of Hot Asphalt Mixture by Conducting Semi-Wet and Dry Mixing Process, *International Journal of Engineering, Transactions B: Applications*, 38(05), (2025), 1108-1119. <https://doi.org/10.5829/ije.2025.38.05b.13>
- [36] Vikas K. Integrated landslide process analysis for sustainable hazard management in the Bhagirathi Valley. *Bulletin of Pure and Applied Sciences-Geology*. 2026, 45F(1), 1-9. <https://bpasjournals.com/geology/index.php/journal/article/view/170>
- [37] S. Venkateshwaran, A. Alex Rajesh, A Review on the Study of Strength Properties of High Performance Concrete Using Various Fibers, *International Research Journal of Multidisciplinary Technovation*, 1 (6), (2019), 411-15. <https://doi.org/10.34256/irjmtcon56>
- [38] D. Bharath Naik, R. Srinivasa Kumar, Assessment of Strength Properties of Clayey Sand Soils Admixed With Marble Powder, GGBS and Geotextile Reinforcement, *International Research Journal of Multidisciplinary Technovation* 6 (6), (2024), 159-68. <https://doi.org/10.54392/irjmt2461>
- [39] B. Tadele T. Q. Emer, Multiple Stress Creep Recovery (MSCR) Test for Determination of Waste Engine Oil Modified Asphalt Binder As Pavement Material, *International Research Journal of Multidisciplinary Technovation*, 4 (1), (2022), 8-14. <https://doi.org/10.54392/irjmt2212>