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Effect of Glass Fiber and Polyester Fiber on Reclaimed Asphalt Pavement (RAP) Mixed Bituminous Mixture: A Comprehensive Review

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Abstract: Reclaimed asphalt pavement (RAP) has become a popular economic and environmentally sustainable material. It is used globally into bituminous mixture for pavement construction. The aging of bituminous mixes makes binder brittle , which affect the durability of RAP containing bituminous pavements by reducing their ability to resist induced cracking, extend their fatigue life and increase their sensitivity to moisture damage. Therefore, the use of fibers are one of numerous methods to improve the performance of bituminous mixes prepared with RAP..

This study delivers an extensive systematic literature review that studied the performance effects of using glass fibers (GF) or polyester fibers (PF) in with or without recycled asphalt pavement (RAP)-mixed bituminous mix sample. These include performance criteria such as Marshall Stability, Indirect Tensile Strength (ITS), Tensile Strength Ratio (TSR), Rutting Resistance, Fatigue Life, Cracking Performance Criteria SCB and IDEAL-CT and Moisture Susceptibility. Performance was assessed based upon the type of fiber used, size of the fiber, percentage of fiber, method of combining fiber (dry method or wet method) with aggregate mix, and the individual contributions made by each of these factors.

Previous research studies demonstrate that the addition of a glass fiber in the optimum amount by weight of total aggregate mix produces significant improvements to the fatigue resistance and ITR properties of RAP mix bituminous concrete. It however varies for various RAP types. Also, it has been found that the use of polyester fibres at dosages ranging from 0.2-0.4 % by weight of total aggregate mix can produce improvements to fatigue life, rutting resistance and water sensitivity. Furthermore, interaction effects between a 20 to 60 percent RAP percentage and fiber type were studied. The review shows that both types of fibres are helpful in reducing the brittle behaviour of high-RAP mixtures which is caused due to excessive stiffness. There are still some gaps in the present knowledge regarding the long-term behaviour of fibre-reinforced RAP mixes under different environmental conditions and also about the cost during its life time. The future research in this area can be started on the basis of results obtained from this study.

Keywords: Bituminous mixes, Reclaimed Asphalt Pavement (RAP), Glass Fiber, Polyester Fiber, Sustainable Pavement, and Fiber-Reinforced Bituminous mix

I. INTRODUCTION

Flexible pavements deteriorate due to traffic loads, environmental factors that include high temperatures and extreme variation among them, rainfall besides site condition related factors. The recycling of asphalt pavements, which involves the asphalt layers to be removed, milled and blended with virgin materials and re-laid by various techniques resulting in a useful recycled product prepared from aged asphalt layers. It is being generated in large volumes through maintenance and rehabilitation operations. The recycling of asphalt pavement has become a well-established practice throughout the world, and in India, during the construction of roads, largely as a result of both compelling economic and environmental advantages (Vijay et al., 2023). Studies show that use of RAP in new asphalt mixtures reduces net lifecycle cost by 5% to 68% and environmental burden by 3% to 95% compared to scenarios using virgin materials. Asphalt production in the US is over 430 million tonnes/year, 22% of which comes from RAP added to new asphalt in the form of reclaimed materials. The economy of RAP placement indicates that adding 40% of RAP can lead to approximately 20% in lifecycle cost savings, while 100% recycling can lead to 50% to 74% reductions in total production cost.(Moins et al., 2022).

Reclaimed Asphalt Pavement (RAP) adoption in India is emerging but lags behind the developed countries. Despite issuing guidelines driven by NHAI/MoRTH mandates, allowing up to 20-30% RAP in bituminous mixes for highways, the average use by quantity is still low (<10-12% in surface layers and <30% in general, though some projects have successfully achieved 50% RAP in the base layers and a few with advanced recycling plants are achieving >50%).

Despite these advantages, the use of RAP brings some technical challenges. The old binder coating the RAP particles is substantially stiffer, harder, and more brittle than the new binder; this produces a stronger pavement mix, but one weaker against cracks, having a reduced fatigue life and more sensitivity to moisture damage (Ziari et al., 2019; Zhu et al., 2024). These things become greater with greater RAP percentages, so we need additional modifiers to ensure that we have a strong enough structural mix (Ziari et al., 2020).

The use of fiber-reinforcement in addition to other modification methods (such as warm-mix additives, mineral fillers, and rejuvenator or polymer-modifiers) is receiving increasing scientific interest due to its ability to create a three-dimensional matrix within the asphalt binder. A 3-D matrix will produce an added level of toughness to the bitumen by providing an interlocking "bridging" effect that can help prevent cracking from initiating and propagating through the pavement system, and also increase the bitumen binders' tensile strain capacity.

Even though there are many peer reviewed articles which have been written about fiber reinforced bitumen concretes as well as about mixtures containing RAP separately, however, there are no peer-review articles which specifically assess the combined effect of GF and PF specifically in RAP bitumen concrete. The current review addresses this lack of coverage for RAP by synthesizing findings from 55 peer-reviewed articles that were published between 2007 and 2025. The objectives of this review are:

1) To characterize the physical and mechanical properties of GF and PF relevant to bitumen based mix,
2) To analyse and compare the effects of addition of these fibers on the performance of RAP-based bituminous concrete with respect to Marshall stability, ITS, fatigue, rutting, cracking, and moisture resistance,
3) To identify optimum fiber dosages and dimensions for use in Bituminous Concrete , and
4) To examine the interaction effects between RAP content and fiber dosage.

II. MATERIALS FOR FIBER REINFORCED RAP MIXED BITUMINOUS MIXES

A. Reclaimed Asphalt Pavement (RAP): Characteristics and Challenges

Reclaimed Asphalt Pavement (RAP) is a product derived from milling or breaking up old asphalt layers. Old RAP contains aged asphalt-coated aggregate with hardened binders due to extensive oxidation with age. Compared to new binder, RAP typically exhibits: high viscosity and stiffness; low ductility and high brittleness; lower penetration values; and high softening points.
(Ziari et al., 2019).

Recycling of asphalt pavement is now common practice all over the world in transportation sector, with RAP use ranging from about 10% in developing countries to over 60% in top European and North American markets . In India RAP usage is growing fast as MoRTH pushes recycling through its Green Highways policy.

High amounts of Recycled Asphalt Pavement (RAP), more than thirty percent, has a major problem related to how much blending occurs between the original binder in the RAP and the new binder. As a result, there are large areas of uneven binder coverage which creates weak and brittle areas of the material that can crack or shatter with little effort. Rejuvenators, warm mix additives and fibre reinforcement have been studied as the possible solutions for these issues. Among these, fibre reinforcement is getting more interest because of its ability to provide both crack bridging and also protection from water infiltration into the material.

B. Glass Fiber (GF): Properties and Mechanism in Asphalt mixture

Glass fibers used for bituminous mixture are usually made from E-glass (electrical grade) or high-performance types like S-glass and A-glass. They have high tensile strength (1,500–3,500 MPa), good heat stability (melts above 700°C, much higher than asphalt mixing temps), resist alkalis and smooth surface that helps bitumen stick even if interlocking is less.

In asphalt mixes, glass fibers mainly work as crack-arresting bridges. When small cracks induced due to load, fibers across the crack faces must pull out or break before the crack can grow further. This bridging effect of glass fiber absorbs crack energy. It also greatly boosts the mix's fracture toughness.(Ziari et al., 2019; Enieb et al., 2021). GF also gives reinforcement into bituminous concrete, similar to fiber reinforced concrete, especially at low temperatures when asphalt becomes very brittle. In this condition GF spread stresses across the fiber network.

Studies show glass fiber improves SCB fracture toughness, Indirect Tensile Strength (ITS), and resistance to moisture damage. Higher percentage of GF show balling effect (especially higher length fiber), making the mix uneven and lowering performance bituminous concrete mixes.
(Ziari et al., 2019; Wei et al., 2022). The optimum GF content from studies falls between 0.10% and 0.50% of total weight of aggregate. Optimum fiber content percentage varies with length of fiber.

C. Polyester Fiber (PF): Properties and Mechanism in Asphalt mixture

Polyester fibers used in bituminous pavement are mostly made from PET (polyethylene terephthalate). In India, common types are monofilament and multifilament fibers sold as brands like Recron 3S (Malik et al., 2024) . Some important proper as per requirement for asphalt concrete are tensile strength of 600–900 MPa, elongation at break 10–30% (much higher than GF), heat stable up to 230°C, water-repellent surface, and good oil (bitumen) absorption.
Polyester fiber's (PF) high elongation at break as well as its ability to absorb large amounts of energy when broken makes it an excellent choice for fatigue as well as crack resistance at low temperature. Within bituminous mixtures PF has three main effects: (1) By virtue of capillary action absorbing excess binder which is beneficial in controlling excess bitumen, (2) Creating a 3 dimensional reinforcement matrix to prevent shear deformation from repeated loading, and (3) Bridging small cracks at both medium and lower temperatures (Hong et al., 2020; Zhu et al., 2024). PF also helps against rutting by stabilizing binder at high temperatures.
The optimum PF content from studies is determined between 0.15–0.5% of total mix weight of aggregate mix. It has higher range than GF optimum because polyester has less tensile stiffness per volume. Research shows PF works better than glass fiber for fatigue resistance, while glass fiber has good cracking resistance properties than polyester.

III. TABULATED ANALYSIS DETAIL OF FIBER REINFORCED ASPHALT MIXTURE (WITH OR WITHOUT RAP)

In table 1, Details of experiments done by various researchers on asphalt mixtures mixed with fibers are given. This includes the nature of fiber used in the research, length, percentage variations tested, optimum percentage of fiber, and details of the tests they performed.

Table 1: Summary of Reviewed Studies on Fiber-Reinforced Bituminous Concrete (2007–2025)

S.No.	Authors & Year	Fiber Type use for modification	Fiber Length & Percentage variation of fiber	Optimum fiber percentage and properties enhancement	Tests Performed in study
1	Haoran et al. (2007)	Polyester Fibres	L: 6 mm, D: 0.014 mm; 2% (optimal)	2% fibre content improved wheel tracking, residual stability, freeze-thaw fracture & fatigue simulation	Wheel tracking, Residual stability, Freeze-thaw fracture, Low-temp. Indirect Tensile Strength, Indirect fatigue simulation
2	Wu et al. (2008)	Polyester Fiber	L: 6 mm, D: 20 µm; 0.1%, 0.3%, 0.5%	0.3% by asphalt weight was optimum; reduced dynamic modulus and phase angle	Viscosity, DSR, Dynamic modulus, Indirect tension fatigue
3	Tapkın (2008)	Polypropylene Fiber	L: 10 mm (±2 mm); 0.3%, 0.5%, 1%	1% fibre content gave 58% increase in Marshall stability and 27% increase in fatigue life	Marshall stability & flow, IDT fatigue, Repeated load IDT, Volumetric properties
4	Abtahi et al. (2010)	PP, Polyester, Glass, Carbon, Cellulose, Nylon	Various; 6–12 mm typical	Review: dry process preferred; fibers enhance SMA & OGFC performance	Marshall, Resilient Modulus, Fatigue, Rutting, Indirect Tensile Strength, Tensile strength ratio, Moisture damage
5	Abtahi et al. (2011)	Polypropylene Fiber	L: 6 mm & 12 mm; 0.1%, 0.2%, 0.3%, 0.5%	0.3% of 12 mm PP fibre is optimum for Marshall stability	Marshall, Superpave analysis, Unit weight, ANOVA
6	Abtahi et al. (2013)	PP + Glass Fiber (combined)	Both 12 mm; GF: 0.05–0.2% of agg.; PP: 2–6% of binder	Best: 6% PP (binder wt.) + 0.1% GF (agg. wt.) combination	Penetration, Softening, Ductility, Marshall, VTM, Unit weight
7	Taherkhani (2015)	Glass Fiber + Nanoclay	L: 12 mm, D: 20 µm; 0.2%, 0.4%, 0.6%	Highest ITS with 0.6% GF + 2% nanoclay	Marshall, Bulk density, Max. theoretical density, Indirect Tensile Strength

8	Mirbahaa et al. (2017)	Polyester Fiber + Nano-carbon black	L: 12 mm; 0.1%, 0.2%, 0.3%, 0.4%	0.4% PF + 5% nano-carbon: good mechanical & economic performance	Marshall stability, flow, unit weight
9	Anand & Naganjanaya (2017)	Polyester + Polypropylene	Not specified; 0.1–0.5%	0.3% by total mix weight is optimum for both fiber types in SDBC	Marshall stability, Aggregate & bitumen tests
10	Kim et al. (2018)	PP, Polyester, Nylon, Carbon	PP & PF: 6 mm; Ny & C: 12 mm; 0.5% & 1.0% volume	Nylon 12 mm at 1.0% gave best overall performance (IDT, TSR, flexibility)	Marshall, Porosity, IDT, TSR, Wheel tracking, Three-point flexure
11	Ziari et al. (2019)	Glass Fiber (high-perf. ballistic)	L: 12 mm, D: <0.13 mm; 0.06%, 0.12%, 0.18%	0.12% GF optimum; significant SCB crack resistance improvement; 0.18% caused agglomeration	Binder properties, Aggregate tests, RAP binder extraction, Marshall (OBC), SCB fracture at -15°C, 0°C, 15°C
12	Zarei et al. (2018/2019)	A-Glass Fiber + Lignin	L: 6 mm & 12 mm; GF: 0.3% fixed; Lignin: 0–12%	3LF12 (0.3% GF-12 mm + 3% lignin) best technical and economic performance	Marshall, VTM, VFA, VMA, Unit weight, Resilient Modulus
13	Ameri et al. (2019)	Basalt + Glass Fiber	Both 6 mm; 0.1–0.7% (total mix wt.)	0.1% GF: 13% increase in Marshall stability; 0.1% fiber (both types) best flow number performance	Marshall, ITS, TSR, Moisture sensitivity, Resilient Modulus
14	Ziari et al. (2020)	Glass Fiber + RAP	L: 12 mm, D: <0.13 mm; 0.06%, 0.12%, 0.18% (with 0–60% RAP)	0.12% GF optimum in RAP mixes; GF mitigates stiffness increase from RAP aging	Binder & aggregate tests, RAP extraction, Marshall, SCB fracture (as per ASTM D8044)
15	Zhu et al. (2020)	Lignin, Polyester, Basalt Fiber (with 0/20/40% RAP)	PF: 5–7 mm, 20–25 μm; BF: 6–7 mm, 10–13 μm; LF: <5 mm; 0.3% fixed	PF and BF improved high-temp. rutting & moisture resistance in RAP mixes; BF best for fatigue	DSR, BBR, Wheel tracking, Bending creep, Moisture susceptibility, Fatigue, Self-healing
16	Guo et al. (2020)	Basalt, Polyester, Lignin Fiber	BF: 6, 9, 15 mm; 0.2–0.5%	BF at 6 mm and 0.4% optimal; superior rutting and low-temp. crack resistance	Penetration, Softening, Ductility, Drain-down, Wheel tracking, Low-temp. bending, Moisture susceptibility
17	Hong et al. (2020)	Polyester Fiber	L: 12 mm, D: 20 μm; 0%, 0.3–0.5%	0.4% PF in AC-13: best SCB and Marshall stability; improved cracking resistance	SCB, Marshall, Binder tests (penetration, ductility, softening, viscosity), SEM
18	Khater et al. (2021)	Lignin + Glass Fiber (AC-16)	LF: 1.10 mm; GF: 12 mm; both at 0.3%	Composite LG (0.3% LF + 0.3% GF) gave best all-round performance	Marshall, Marshall Immersion, Freeze-thaw splitting, Three-point bending (low-temp.)
19	Eisa et al. (2021)	Glass Fiber (dry mix)	L: 10 mm, W: 1 mm; 0.25%, 0.50%, 0.75%, 1.0%	0.25% GF optimal for MS, flow, loss of stability, wheel tracking & ITS	LA abrasion, Water absorption, Marshall & flow, Loss of stability, Wheel tracking, ITS
20	Aboutalebi Esfahani & Mirian (2021)	Glass Fiber + EVA (SMA)	L: 12 mm, D: 1 mm; 0.1%, 0.2%, 0.3%	0.1% GF optimal; higher % impaired SMA structure due to fiber brittleness	DSR, Resilient modulus, Dynamic creep, Fatigue
21	Enieb et al. (2021)	Glass Fiber (6 & 12 mm)	L: 6 mm & 12 mm, D: 13 μm; 0.3% & 0.6%	0.6% GF increases ITS; 12 mm vs 6 mm showed no significant change in short/long-term properties	ITS & fracture energy, Moisture susceptibility, Creep compliance, Resilient modulus, IDT fatigue
22	Eltwati et al. (2022)	Glass Fiber	L: 6 mm, D: 0.12 mm; 0.0%, 0.1%, 0.2%, 0.3%	0.2% GF optimum for ITS, TSR, Resilient Modulus, and Hamburg wheel tracking	ITS, TSR, Resilient Modulus, HWTT
23	Wei et al. (2022)	E-type Fiberglass	L: 3, 6, 9, 12 mm; 1%, 2%, 3%, 5%	5% GF at 9 mm optimal: +43.5% Marshall stability, +33.7% flexural tensile strength	Tensile, SEM, Marshall, Three-point bending, Four-point fatigue
24	Jia et al. (2023)	Review: Glass, Aramid, Carbon, Polyester, Nylon	GF: 6–15 mm; PF: 6–14 mm; optimal PF: 0.15–0.30%; GF: 0.12%	PF optimal 0.3% for fatigue; GF 6–12 mm for anti-cracking; Nylon 1.0% optimal	Wheel tracking, SCB, ITS, TSR, Four-point bending, Cyclic fatigue, SEM, FTIR, Dynamic modulus, Marshall
25	Khaler et al. (2021)	Glass Fiber (RAP mix)	L: 10 mm, W: 1 mm; 0.25–1.0%	0.25% GF with 50% RAP best moisture damage resistance and anti-stripping	Marshall, Moisture susceptibility, Immersion wheel rutting

26	Li et al. (2023)	PP, Polyester, Lignin (SMA-13)	LF: 5 mm; PF: 8 mm; PPF: 6 mm; 0.3% mixture / 5 wt% binder	PF outperformed LF in overall binder rheology; PPF shows best toughness at low temps	Tensile, Density, Oil absorption, SEM, Penetration, Ductility, DSR, Volumetric, IDT resilience
27	Halim et al. (2023)	Glass Fiber (SMA-20)	0–5% of total sample weight, 1% intervals	3% GF optimal for mechanical characteristics in SMA 20	Marshall, volumetric (implied)
28	Deeksha et al. (2023)	Alkali-resistant Glass Fiber	L: 12 mm; 0–2.5% (0.5% intervals)	1.5% GF optimal: best ITS and moisture resistance	Marshall, ITS, TSR, Repeated ITS
29	Oral & Cetin (2023)	PP, Glass, Basalt, Crumb Rubber (PA)	PP, BF, GF: 12 mm; 0.2–0.8%	0.2% BF and 0.4% GF optimal; PP and crumb rubber failed Cantabro criterion	Void analysis, Permeability, Cantabro loss, ITS, Moisture susceptibility
30	Akram et al. (2024)	Glass Fiber + Polypropylene	L: 18 mm; 0.5%, 1.0%, 1.5% of agg. wt.	1% GF and 1% PPF optimal overall; GF superior in flexibility & crack resistance at 1%	SCB, IDEAL-CT, Three-point bending, Marshall
31	Abd & Latief (2024)	Steel, Glass, Basalt Fiber	GF: 12 mm; SF: 13 mm; BF: 16 mm; GF: 0.10–0.20%	Optimal: 0.10% GF, 0.25% SF, 0.15% BF	Marshall, TSR / Moisture damage
32	Wei et al. (2024)	Basalt, PP, Glass (SMA-10)	All 6 mm; 0%, 2%, 4% of binder mass	4% PP fiber: best crack resistance & toughness; GF improves intermediate-temp behavior	SEM, Oil absorption, DSR, Force-Ductility, IDT, SCB
33	Borhanuddin et al. (2024)	Glass Fiber Waste (SMA-14)	Chopped: 25 mm; Wet: 0.5–2.0%; Dry: 0.3%	Dry method: 0.3% GF by total mix; wet method: 2.0% for binder modification	Penetration, Softening, Viscosity, DSR, RTFO; Marshall, Drain-down, Cantabro, ITS, DWTT
34	Zhu et al. (2024)	Basalt + Polyester (RAP mixes)	BF: 6.03 mm, D: 17 µm; PF: 6 mm, D: 21.5 µm; 0.3% of total mix	PF improved fatigue; BF improved rutting; both improved SCB cracking in RAP mixes	Rutting, Dynamic water scouring, SCB, Indirect tensile fatigue, Gyratory compaction
35	Malik et al. (2024)	Polyester Fiber – Recron 3S (SMA)	L: 12 mm; 0.3–0.7% of total agg. wt.	0.4% PF optimal: best drain-down, ITS, fatigue, flow number	Drain-down, Marshall, ITS, ITSM, Dynamic modulus, Flow number, Fatigue, RMS
36	Xiao et al. (2024)	Lignin, Polyester, Polypropylene (SMA-13.2)	LF: avg. 2.6 mm; PPF: 12 mm; PF: 20 mm; 0.3% of mix	PF and PPF better water resistance under dynamic conditions; LF best static water stability	TSR, RMS (static & dynamic water), CT scanning
37	Akram et al. (2025)	Polypropylene + Glass Fiber	Both 35 mm; 0.25–1.5% of agg. wt.	PPF: 1.5% best mechanical (Marshall, compressive, creep); GF: 1% best crack resistance (IDEAL-CT, SCB)	Water absorption, Marshall, Compressive, Static creep, Immersion Marshall, TSR, IDEAL-CT
38	Jalota & Suthar (2025)	Polypropylene Fiber (BC Grading II)	L: 6 mm; 0.3% & 0.6% of bitumen wt.	0.04% Wetbond-S + 0.6% PPF: best overall durability and ITS	DSR (MSCR), Marshall, ITS, Durability (wet-dry cycles)

D. Comparative Performance Summary: GF vs. PF in RAP Mixes

Table 2 below provides a qualitative comparative assessment of GF versus PF across key performance criteria for RAP-inclusive bituminous concrete:

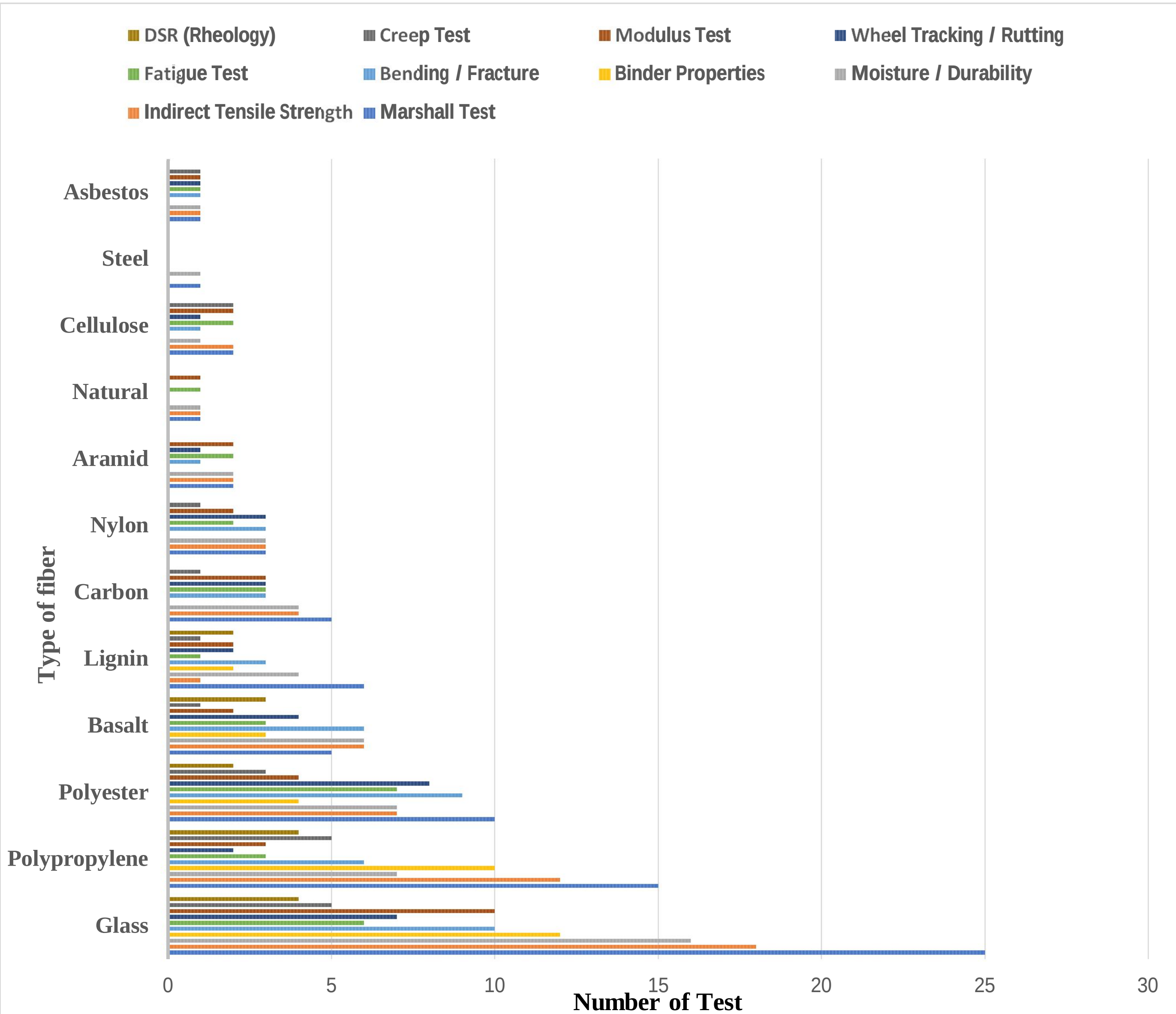
Table 2: Comparative Performance of Glass Fiber (GF) vs. Polyester Fiber (PF) in RAP Mixes

Performance Criterion	GF Effect	PF Effect	Superior Fiber	Key References
Marshall Stability	High (increase by 13 to 44%)	Moderate (increase by 10 to 25%)	GF	Ameri et al. 2019; Malik et al. 2024
ITS / Crack Resistance	High (SCB, IDEAL-CT)	Moderate-High (SCB)	GF	Ziari et al. 2019; Akram et al. 2024
Fatigue Life	Moderate improvement	High improvement	PF	Zhu et al. 2020; Malik et al. 2024
Rutting Resistance	High (rigid network)	Moderate-High (binder stab.)	GF/Equal	Guo et al. 2020; Wang et al. 2024
Moisture Susceptibility	High	High	Both show comparative	Eltwati et al. 2022; Xiao et al. 2024

(TSR)			improvement	
Low-Temp. Cracking	Moderate	High (ductility)	PF	Hong et al. 2020; Akram et al. 2025
Drain-down Control (SMA)	Moderate	Very High	PF	Malik et al. 2024; Jia et al. 2023
RAP Mix Compatibility	High (crack bridging)	High (fatigue restoration)	Both effective	Zhu et al. 2024; Ziari et al. 2020
Risk of Agglomeration	High (Depend on type of fiber ;E-type, S-type, etc)	High	PF	Ziari et al. 2019; Wei et al. 2022
Optimum Dosage (total mix %)	0.12–0.50%	0.1–0.40%	Context-dependent	Multiple studies

E. Type of fiber and test perform into specimen

A detailed review of 50 research articles has shown that most of these articles are based on the use of synthetic fibres (specially glass fibre and polypropylene fibre) rather than other types. These fibres are widely used as compared to other types. In order to further explore upto what extent glass fibre and polyester fibre have been researched, an analysis was done on the distribution of different fibre types within various experimental categories. The overall results are shown in Figure 1.



F. Effect of GF and PF on Marshall Stability

Marshall stability is the most common test for asphalt mix design. It shows the load-bearing capacity of compacted bituminous mix at appropriate 60°C and specified time of conditioning. Most studies result say both GF and PF improve Marshall stability. The increase of stability value depends on fiber type, dosage, and mixing process use for preparation of bituminous concrete.

For glass fiber, Ameri et al. (2019) reported a 13% improvement in Marshall stability with 0.1% GF in a Stone Mastic Asphalt mix. Eisa et al. (2021) found that 0.25% GF (10 mm length) in a wearing surface mix (Mix 4C) maximized Marshall stability, with further addition causing slight reductions. Deeksha et al. (2023) similarly identified 1.5% GF (12 mm, alkali-resistant) as the optimum for BC Grade 2 mixes. Halim et al. (2023) reported that 3% GF (by weight of total sample) in SMA-20 mixes produced the best mechanical characteristics. Wei et al. (2022) demonstrated the most dramatic improvement with E-type glass fiber: 5% GF at 9 mm length increased Marshall stability by 43.5% in epoxy asphalt concrete. IEEE GF (2022) study found that 5% bitumen content with varied GF from 0 to 4% significantly influenced Marshall stability.

For polyester fiber, Haoran et al. (2007) established an early benchmark, showing that 2% PF in AK-13A and Modified AC-20 mixes significantly improved wheel tracking and residual stability. Hong et al. (2020) reported 0.4% PF in AC-13 dense-graded mixes as optimum for Marshall stability and SCB performance. Malik et al. (2024) found 0.4% Recron 3S polyester in SMA optimized Marshall stability and drain-down simultaneously.

In RAP-inclusive mixes, Zhu et al. (2024) incorporated both PF and Basalt Fiber (BF) at 0.3% in mixes with 0–40% RAP content and observed that PF contributed more consistently to fatigue life improvement, while BF favored rutting resistance. Ziari et al. (2020), using 0.12% GF in mixes with varying RAP content (0, 20, 40, 60%), found that GF at optimum dosage largely restored the Marshall stability losses caused by high-RAP binder variability.

G. Effect on Indirect Tensile Strength (ITS) and Tensile Strength Ratio (TSR)

Indirect Tensile Strength (ITS) is use for evaluating crack resistance and moisture damage susceptibility. With the help of Tensile Strength Ratio (TSR) able to identify moisture damage by using ITR ratio which is calculated by value of ITS before and after water conditioning cycles.

For glass fiber, Eltwati et al. (2022) found 0.2% GF (6 mm, D: 0.12 mm) to be the optimum dosage in RAP mixes with 12.5 mm nominal aggregate size, reporting improvements in ITS, TSR, Resilient Modulus, and Hamburg Wheel-Track results. Enieb et al. (2021) showed that increasing GF content from 0.3% to 0.6% by total mix weight monotonically increased ITS, with 12 mm fibers showing no significant advantage over 6 mm fibers in terms of binder aging characteristics. Taherkhani (2015) reported the highest ITS for Iranian AC mixes with 0.6% GF combined with 2% nanoclay.

The fiberglass study by Khaler et al. (2021) demonstrated that 1.5% fiberglass with 50% RAP content provided the best resistance to moisture damage and stripping, highlighting a synergy between GF dosage and RAP content in moisture susceptibility control.

For polyester fiber, Kim et al. (2018) found nylon (12 mm) superior to polyester for ITS in Korean WC-2 surface mixes; however, PF at 1.0% volume fraction showed acceptable TSR values above the 80% threshold. Akram et al. (2025) reported GF superior to PPF in crack resistance (ITS-based IDEAL-CT), with GF at 1% providing the best CRI (Crack Resistance Index).

The Oral & Cetin (2023) study on porous asphalt (PA) found 0.4% GF and 0.2% Basalt Fiber to be optimal.

H. Effect on Rutting Resistance and Permanent Deformation

Rutting defect in the cause permanent deformation under repeated traffic loading at high environmental temperatures. This is a major distress mode for hot climates. Both GF and PF have good rutting resistance but due to different mechanisms. GF provides a rigid fiber skeleton that resists shear flow. On other hand PF stabilizes excess binder and forms a network that resists aggregate displacement.

Zhu et al. (2020), found that fiber-reinforced asphalt with 0 to 40% RAP. Both PF and BF at 0.3% improved rutting resistance over unfibered control. PF showing slightly better high-temperature performance than BF in the wheel tracking test.

Wang et al. (2024) investigated rubber particles combined with PF (6 mm) in single grade aggregate mixes, finding that 1.2% PF dosage optimized rutting resistance (rutting test) and compressive strength simultaneously.

Malik et al. (2024) found, PF superiority over cellulose fiber for flow number (rutting proxy) in SMA mixes at 0.4% Recron fiber dosage.

Ziari et al. (2020) observed that GF mitigated the slight rutting susceptibility increase that sometimes accompanies high-RAP mixtures when insufficient virgin binder is added. At 0.12% GF, high-temperature performance was maintained across 0 to 60% RAP levels.

I. Effect on Fatigue Life

Fatigue resistance is the ability of an asphalt mix to withstand repeated tensile strain before failure. As the percentage of RAP increases, this property reduces a lot because the percentage of RAP binder increases, which have stiffened and ages. Fiber reinforcement helps recover fatigue life by improving ductility and energy absorption capacity.

For polyester fiber, the review demonstrates a consistent pattern of fatigue life enhancement. Haoran et al. (2007) showed improvement in the Indirect Fatigue Simulation Test with 2% PF. Kim et al. (2018) found PF at 1.0% of volume fraction among the best performers in the three-point flexure fatigue test (WC-2 Korean surface mix).

Malik et al. (2024) reported that Recron 3S PF at 0.4% significantly extended fatigue life compared to conventional cellulose fiber in SMA mixes. Jia et al. (2023) in their review paper confirm that PF optimal content of 0.15–0.30% enhances fatigue cracking resistance.

Zhu et al. (2020) showed that in RAP-inclusive mixes (with 0, 20 and 40% RAP content), PF gave better fatigue test results (midpoint bending test) as compared to lignin fibre. Basalt fibre showed the best self-healing behaviour after fatigue-healing-fatigue cycles. From the above findings, it can be said that for long-term pavement durability in RAP mixes, PF gives immediate improvement in fatigue, while BF is more superior for resilience under damage-and-recovery cycles.

For glass fiber, fatigue performance data are less uniformly positive. Enieb et al. (2021) reported that GF at 0.3–0.6% improved IDT continuous and discontinuous fatigue life, with 0.6% providing the better result. Akram et al. (2025) confirmed GF at 1% (35 mm fiber, by aggregate weight) improved IDEAL-CT cracking performance, indicating improved fatigue crack initiation resistance. However, Ziari et al. (2019) cautioned that beyond 0.12% GF, crack resistance in SCB tests declined. So they suggesting that fatigue and fracture performance may not monotonically improve with GF dosage.

J. Effect on Moisture Susceptibility

Moisture damage cause stripping of binder from aggregate surfaces. It is a common failure in RAP mixes where the old binder-aggregate bond weakens. Both GF and PF help to gain resistance against moisture variation in different ways. GF forms a physical barrier network that slows water entry and binder stripping. PF acts as a stabilizer that holds binder in place and slows drainage-induced binder loss.

Eltwati et al. (2022) reported that 0.2% GF (6 mm) in RAP mixes improves TSR (ASTM D4867 / AASHTO T283). Abd & Latief (2024) found that at 0.10% GF (the minimum dosage tested), TSR improved over control, showing that even very small GF additions beneficially affect moisture resistance without exceeding the agglomeration threshold. Khater et al. (2021) found that composite mixes with 0.3% LF + 0.3% GF (AC-16) gave the best freeze-thaw splitting test results, outperforming individual fiber additions.

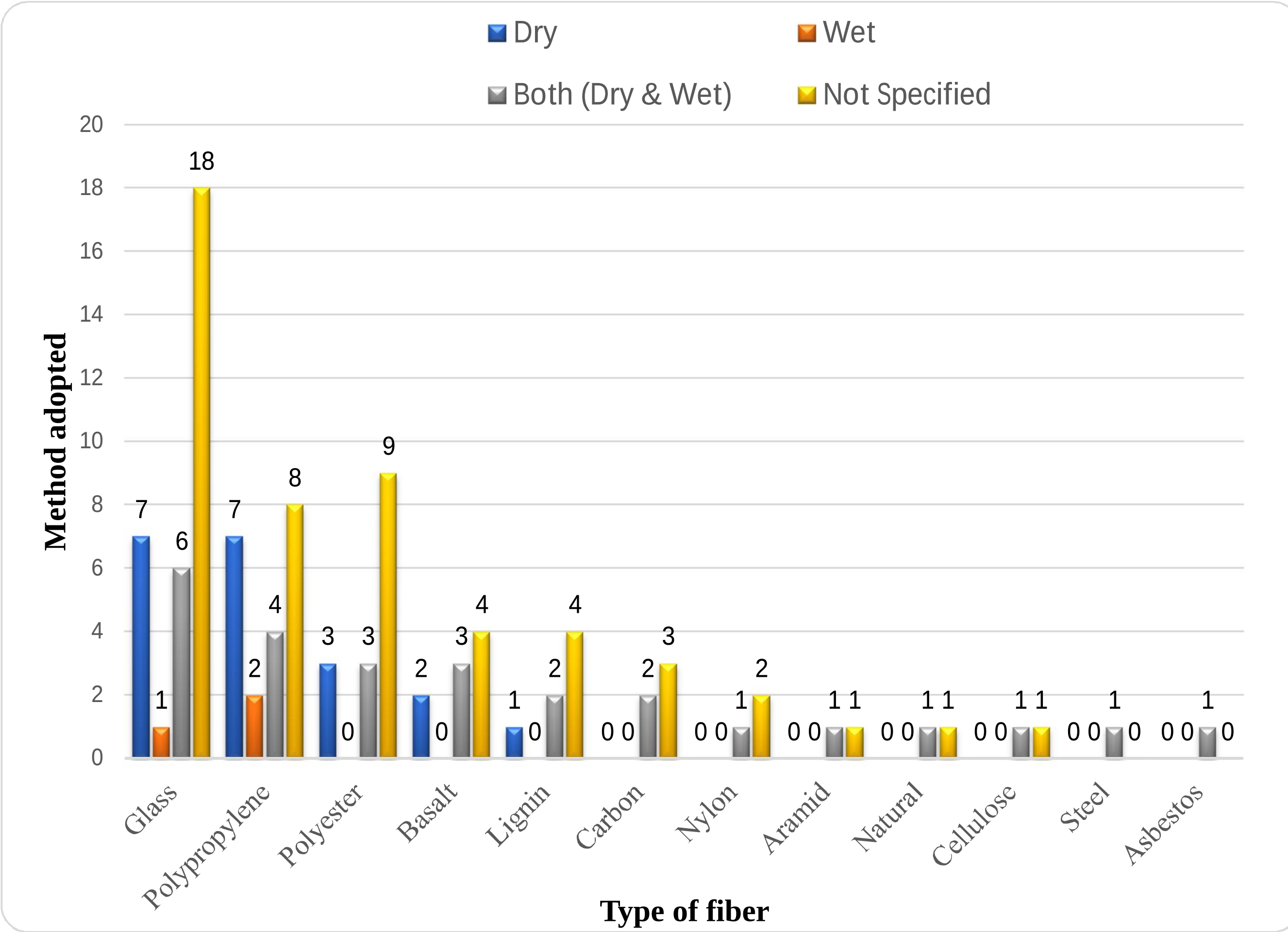
For polyester fiber, moisture susceptibility benefits are well-documented. Abtahi et al. (2011) found that 0.3% PP (12 mm) and 0.3% PP (12 mm) PF dosages reduced sensitivity to water. It improves binder film integrity around aggregates.

Zhu et al. (2024) demonstrated that BF and PF at 0.3% both improved the dynamic water scouring resistance compared to unfibered RAP mixes, with PF marginally superior.

The above findings clearly show that PF absorbs binder and strengthens the binder-aggregate interface physically. This strenthen the poor adhesion of aged RAP binder.

K. Dry and Wet Mixing Methods Across Fiber Types

The method used for mixing fiber into a bituminous mixture. Whether through the dry process (mixing fiber with aggregate before binder addition) or the wet process (blending fiber with asphalt binder before aggregate mixing), significantly influences fiber dispersion, binder–fiber interaction, and ultimately the mechanical performance of the resulting mixture. Figure 2 present the mixing method adopted in different type of fiber .



L. Predominance of the Dry Process in Reviewed Literature

The literature review suggests that Dry Mixing is the most documented and used methods in combining artificial fibers with bituminous materials. In fact, there were 13 studies that specifically identified the Dry Method when using different types of fibers. Only 3 studies reported a Wet Process. The reason why the Dry Method was found to be an operational preference is that the Dry Method does not alter the standard heat treatment procedure for bitumen, and eliminates the risk of fiber agglomeration from being heated too long or at too high of a temperature. The Dry Method also has practical advantages as a field application (Abtahi et al., 2010; Abiola et al., 2014). In this method, fibers are typically blended with heated aggregates for 30 to 90 seconds prior to binder addition, ensuring relatively uniform distribution before full mixing commences.

IV. RESEARCH GAPS

Despite the substantial body of literature reviewed, several significant research gaps remain:

1) Combined effect of glass fibre and polyester fibre in RAP based bituminous mixes: While individual GF and PF effects in RAP mixes are known, no study has properly till perform which adding both fiber types together to RAP bituminous concrete.
2) High RAP content (>50%) with fibre reinforcement: most fibre studies have used RAP contents in the range of 0%–40%. Research on fibre-reinforced mixes containing 50%–100% RAP is very limited, and there is a need to determine the appropriate dosages of GF and PF for higher RAP contents.
3) Long-term field performance: all the reviewed studies are laboratory-based. There is no field-trial data available regarding the performance of GF- and PF-reinforced RAP mixes under five or more years of in-service conditions. Owing to the absence of long-term field performance data, the service life of glass fibre- and polyester fibre-modified bituminous concrete cannot be reliably determined.

4) Temperature-specific performance in tropical and hot climates: most cracking studies have been conducted at intermediate or low temperatures. For hot countries such as India, the Middle East, and Southeast Asia, where RAP usage is increasing rapidly, there is a critical need for high-temperature cracking and rutting evaluation of fibre-reinforced RAP mixes.

V. CONCLUSIONS

The main conclusions are after reviewing the several paper and article between 2007 to 2025 based on Fiber modified asphalt concrete (with or without) :

1) Both GF and PF significantly enhance the performance of bituminous concrete in conventional as well as RAP modified bituminous mixes. They improve Marshall stability, TSR, fatigue, rutting, cracking, and moisture resistance of the specimens.
2) The optimum dosage range for glass fibre is 0.25%–0.6% by weight of total aggregate (fibre length 3–35 mm) in conventional and RAP-modified asphalt concrete. This dosage range consistently improves crack resistance (SCB and IDEAL-CT), TSR, and ITS in Marshall specimens. The crack-bridging mechanism of GF is particularly valuable in high-RAP mixes, where aged-binder brittleness is the primary performance limitation.
3) Polyester fiber at an optimum dosage of 0.15 % to 0.4% total aggregate mix (fiber length 6–14 mm) consistently improves fatigue life, ductility, and moisture damage resistance in Marshall specimen. PF is particularly effective in restoring the fatigue life lost due to RAP binder stiffening and in controlling drain-down in SMA mixes.
4) GF is superior to PF for crack resistance and short-term Marshall stability, Whereas PF is superior for fatigue life improvement and drain-down control.
5) The optimum GF dosage does not increase with RAP content , while the relative performance benefit of GF in crack resistance grows with increasing RAP content.
6) The dry mixing method is the most commonly used and preferred method for both glass fiber and polyester fiber. It is simple to use and easy to handle during mixing. In this method, fibers are added directly with hot aggregates, which makes it suitable for RAP-based mixtures, where two different types of aggregate, mixed together, virgin aggregate and RAP particles being combined.

VI. RECOMMENDED FUTURE RESEARCH

Based on the identified gaps, the following research agenda is proposed for the next decade:

1) Systematic experimental study for combined GF + PF additives in asphalt mixtures containing 20–60 percent Recycled Asphalt Pavement (RAP), with evaluation of Marshall, Indirect Tensile Strength, SCB, Fatigue and Rutting performance.
2) Field trials for evaluating fibre-reinforced RAP content mixes by using Accelerated Pavement Testing (APT) so that the laboratory predictions can be verified.
3) Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of fibre-reinforced high-RAP content mixes, including the environmental costs of production as well as recycling at end-of-life. Microstructural characterization (SEM, X-ray CT, FT-IR, DSR) of GF and PF interactions with aged RAP binder to understand the physical mechanisms of fiber binding to the RAP binder.
4) Establishment of performance-based specification limits for GF and PF in RAP mixes, on the basis of Superpave and other international mix design approaches.

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