Development of Sustainable Flexible Pavements Using Recycled Plastic Waste for Improved Performance

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Abstract

Recycled plastic waste and fly ash can improve flexible pavements while diverting waste from landfills and open burning. This study examines three applications across the pavement section: recycled PET fibre with fly ash to stabilise a clayey subgrade, shredded low-density polyethylene (LDPE) in bituminous concrete (BC) by the dry and wet processes, and fly ash coated with molten LDPE as a composite mineral filler. Adding 1.2% PET fibre and 15% fly ash raised the unsoaked and soaked CBR of the subgrade to 2.33 and 2.04 times those of the natural soil, increased shear strength by 45% and reduced the plasticity index by 31%. A plastic coat of 9% of the bitumen weight reduced the crushing value of aggregate from 18.2% to 10.7%, the impact value from 16.4% to 10.6% and Los Angeles abrasion from 15.6% to 9.1%, and eliminated water absorption and stripping. With VG-30 bitumen and 8.3% plastic, the dry process raised Marshall stability from 2012 kg to 2780 kg (+38.2%) against 2350 kg (+16.8%) for the wet process. With VG-10 bitumen, 9% plastic raised stability from 1534 kg to 2006 kg and the tensile strength ratio (TSR) from 81% to 99%. The composite filler raised TSR from 84.5% to 93.8% and the resilient modulus at 35 °C from 2900 MPa to 4400 MPa. The dry process saves about Rs 37,600 per kilometre of single-lane premix carpet and consumes about 760 kg of plastic waste.

Keywords: Flexible pavement; Waste plastic; Dry process; PET fibre; Fly ash; Marshall stability; Tensile strength ratio; Resilient modulus

1. Introduction

Flexible pavements dominate India's road network, but they frequently suffer rutting, stripping, moisture damage and fatigue cracking under heavy traffic and monsoon conditions, and weak clayey subgrades demand thick granular crusts. At the same time, India generates large quantities of plastic waste, much of it thin film that is difficult to recycle and is dumped or burnt, while thermal power plants produce fly ash that occupies vast ash ponds.

Waste plastic can be added to bituminous mixes by the wet process, in which it is blended into hot bitumen, or by the dry process, in which it is melted onto hot aggregate before the bitumen is added. IRC:SP:98-2013 permits 6–8% plastic by weight of bitumen in the dry process. Recycled PET fibres can reinforce soil, and fly ash serves both as a soil stabiliser and as a mineral filler. This study evaluates these wastes across the pavement section, with three objectives: (i) to stabilise a clayey subgrade with PET fibre and fly ash, (ii) to compare the dry and wet processes and identify the optimum LDPE content for VG-30 and VG-10 bituminous concrete, and (iii) to assess a fly ash–plastic composite filler for moisture resistance and stiffness, together with the cost and environmental benefit.

2. Literature Review

Reviews of plastic-modified asphalt report that HDPE and LDPE generally raise Marshall stability and reduce air voids [11]. They also note that the plastic's melting point governs the choice of process, with low-melting polyethylenes suiting the dry process [3], [9]. Mashaan et al. found that 8% PET gave the highest Marshall stability and quotient and the lowest rut depth [10]. Miranda et al. showed that five commercial recycled-plastic additives used by the dry process maintained or slightly improved Marshall properties and moisture sensitivity [6]. Jitsangiam et al. developed a modified Marshall design for dry-process mixes that treats the plastic as partly replacing the binder, improving resilient modulus by 49% and TSR by 23% [7].

Wet-process studies report gains in cracking and rutting resistance but persistent storage-stability problems [2]. Recycled-HDPE binder performed comparably to a polymer-modified binder at lower environmental impact [5], and the environmental performance of directly added waste plastic [4] and its use with high RAP content [1] have also been examined. For subgrades, Khalid and Alshawmar found that 2% PET strips with 12% palm-leaf ash roughly doubled CBR [8]. Chandra and Choudhary showed that fly ash performs well as filler in bituminous concrete [12]. Few studies combine plastic waste and fly ash in the subgrade, the aggregate, the mix and the filler within one programme, which this study does.

3. Materials and Methodology

The work was carried out in three phases (Fig. 1), each compared with a conventional control made from the same constituents.

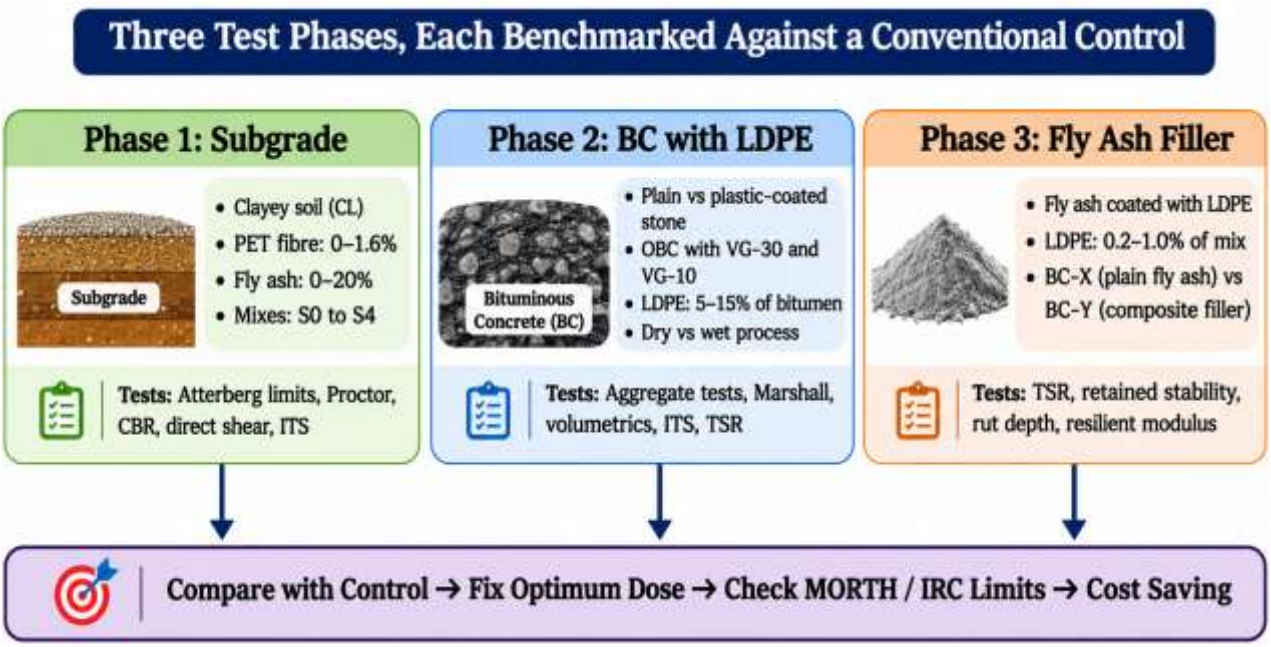


Fig. 1. Experimental programme in three phases

3.1 Materials

The subgrade soil was a low-plasticity clay (CL) passing the 4.75 mm sieve (Table 1). Recycled PET fibres 20–25 mm long, with an aspect ratio of 80–125, were made from waste beverage bottles (Table 2). Non-plastic fly ash from a thermal power plant (specific gravity 2.20, methylene blue value 0.56) was used as soil stabiliser and filler. LDPE film waste under 60 µm thick (carry bags and packaging) was segregated, cleaned and shredded. Pieces of 0.6–2.36 mm were used in the BC mixes and torn pieces of 2–8 mm in the composite filler. The LDPE melts at 125–160 °C and decomposes only above about 275 °C, so it can be melted safely onto aggregate at 160–170 °C. VG-30 and VG-10 bitumen (Table 3) and 19 mm crushed granite aggregate graded to MORTH (Fig. 3) were used.



Fig. 2. Materials: (a) clayey soil passing 4.75 mm sieve, (b) fly ash, (c) shredded LDPE waste

Table 1. Properties of the soil

Property	Value
Specific gravity	2.75
Sand (%)	32
Fine-grained particles (%)	66
USCS classification	CL
Liquid limit (%)	28.4
Plastic limit (%)	21.3
Shrinkage limit (%)	19.0
Optimum moisture content (%)	16.18
Maximum dry density (g/cm³)	1.74

Table 2. Properties of the recycled PET fibre

Property	Value
Specific gravity	1.22
Moisture content (%)	0.4
Young's modulus (MPa)	2800–3100
Tensile strength (MPa)	200–400
Length (mm)	20–25
Diameter (mm)	0.20–0.25
Fusion temperature (°C)	252

Table 3. Specified properties of the bitumen

Property	IS code	VG-10	VG-30
Penetration at 25 °C (0.1 mm)	IS 1203	80–100	50–70
Softening point, min (°C)	IS 1205	40	47
Ductility at 27 °C, min (cm)	IS 1208	75	40
Specific gravity at 27 °C	IS 1202	1.02	1.02
Absolute viscosity at 60 °C, min (poise)	IS 1206 (Part 2)	800	2400
Kinematic viscosity at 135 °C, min (cSt)	IS 1206 (Part 3)	250	350
Flash point, min (°C)	IS 1209	220	220



Fig. 3. Aggregate fractions used in the BC mix: 20 mm, 10 mm, stone dust and filler

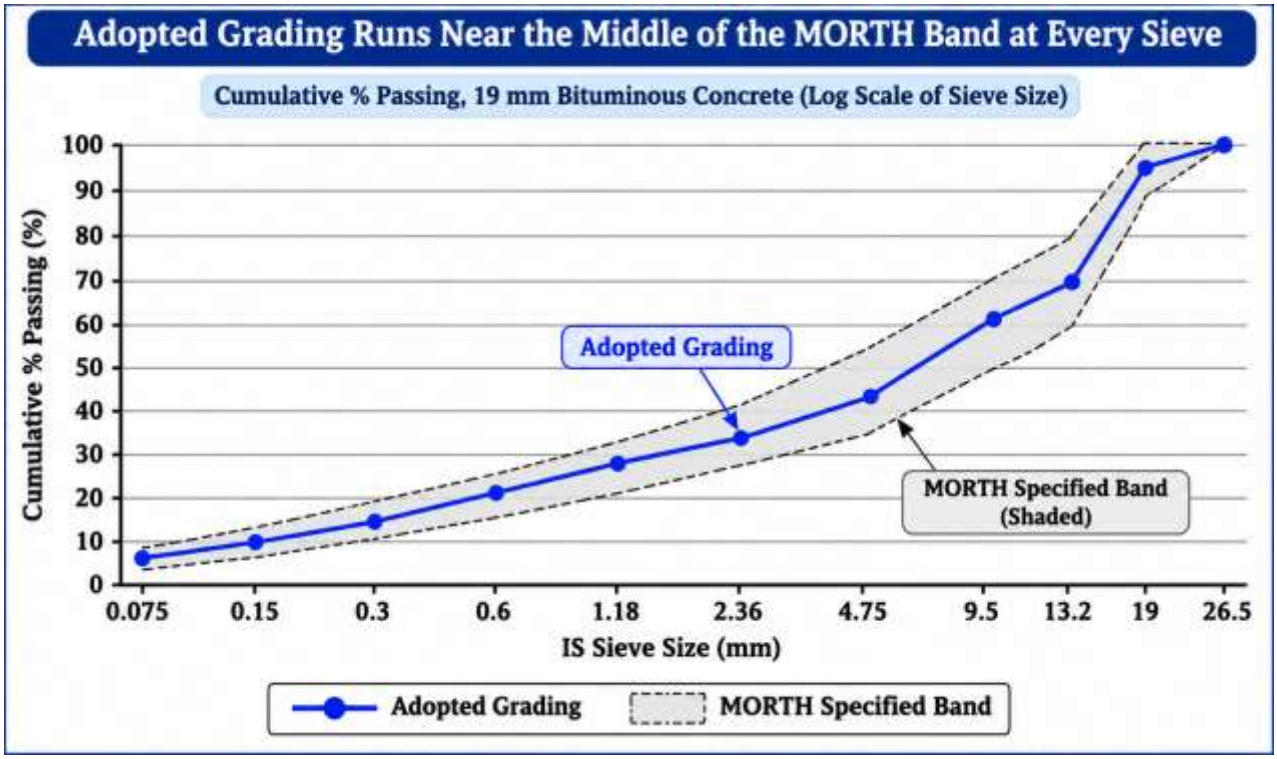


Fig. 4. Aggregate gradation for the 19 mm bituminous concrete mix (MORTH)

3.2 Mixes and Test Methods

Subgrade. PET fibre and fly ash were increased together in steps of 0.4% and 5% by weight of soil (Table 4). Atterberg limits, modified Proctor compaction (IS 2720 Part 8), soaked and unsoaked CBR (IS 2720 Part 16), direct shear (ASTM D3080) and indirect tensile strength were determined.

Table 4. Soil–PET fibre–fly ash mixes

Mix	Soil (%)	PET fibre (%)	Fly ash (%)
S0	100	0	0
S1	94.6	0.4	5
S2	89.2	0.8	10
S3	83.8	1.2	15
S4	78.4	1.6	20

Aggregate and bituminous mixes. Aggregate tests were performed as per IRC:111-2009 and IS 2386 on plain aggregate and on aggregate coated with 5, 7, 9 and 11% plastic by weight of bitumen. Marshall specimens (101.6 × 63.5 mm, 75 blows per face) were prepared with 4.0–6.0% bitumen to find the optimum bitumen content (OBC). In the dry process, shredded plastic was added to aggregate at 165–170 °C and mixed for 30–60 s before bitumen at about 160 °C was added; in the wet process, the plastic was first blended into hot bitumen. With the OBC fixed, plastic was added at 5–15% of the bitumen weight. Moisture susceptibility was assessed by indirect tensile strength (ITS) and TSR (ASTM D4867) and by retained Marshall stability (IRC:SP:53), and stiffness by resilient modulus (ASTM D4123) at 25, 35 and 45 °C.

Composite filler. Torn LDPE (2–8 mm) was mixed with fly ash heated above 125 °C for 8–10 minutes so that the molten plastic coated the ash grains, and the composite replaced plain fly ash filler at 0.2–1.0% plastic by weight of mix. The mixes were checked against the MORTH, IRC:111-2009 and IRC:SP:98-2013 limits (Table 5).

Table 5. Specification limits for bituminous concrete

Parameter	MORTH	IRC:111-2009	IRC:SP:98-2013
Marshall stability at 60 °C, min	900 kg (9 kN)	900 kg	1200 kg
Flow (mm)	2–4	2.5–4.0	2.0–4.0
Marshall quotient (kg/mm)	—	250–500	250–500
Air voids (%)	3–6	3–5	3–5
VFB (%)	65–75	65–75	65–75
VMA, min (%)	—	15	16
TSR, min (%)	—	80	90
Plastic content (% of bitumen)	—	—	6–8

4. Results and Discussion

4.1 Subgrade Stabilised with PET Fibre and Fly Ash

The liquid limit rose with fibre and fly ash content, to 1.03–1.18 times that of the natural soil, but the plastic limit rose faster, so the plasticity index of S3 fell from about 7.1% to 4.9%. MDD and OMC both fell, as PET (specific gravity 1.22) is much lighter than the soil and absorbs almost no water. Strength increased up to S3 and declined at S4 (Table 6). The crinkled fibres grip the soil and act as tension members across potential shear planes. Beyond 1.2%, fibre-to-fibre contact replaces fibre-to-soil friction. The soaked CBR of S3 was 2.04 times that of the natural soil, which permits a thinner granular crust under IRC:37. The fibre-reinforced specimens also showed fewer and narrower drying cracks. Because fibre and fly ash were increased together, their separate effects cannot be distinguished.

Table 6. Improvement of the S3 mix (1.2% PET fibre + 15% fly ash) over natural soil

Property	S3 relative to natural soil
Plasticity index	0.69 times (31% lower)
Shear strength at 0.1667 N/mm²	1.45 times
Shear modulus	1.23 times
CBR, unsoaked	2.33 times
CBR, soaked	2.04 times
Indirect tensile strength	0.149 N/mm² (maximum of all mixes)

4.2 Plastic-Coated Aggregate

Coating the aggregate with molten plastic improved every strength property (Table 7). Toughness peaked at 9% plastic, where the crushing value fell by 41%, the impact value by 35% and the abrasion loss by 42%; at 11% the values worsened slightly as a thicker, softer coat began to cushion and smear. Even 5% plastic reduced water absorption, soundness loss and stripping to nil, because the film seals surface pores and repels water (Fig. 5). Marginal aggregate can therefore be brought well inside the specification limits.

Table 7. Properties of conventional and plastic-coated aggregate

Test	0%	5%	7%	9%	11%	IRC:111-2009 limit
Crushing value (%)	18.2	14.1	12.6	10.7	11.2	max 30
Impact value (%)	16.4	14.6	12.3	10.6	11.4	max 24
Los Angeles abrasion (%)	15.6	14.8	11.2	9.1	10.6	max 30
Flakiness + elongation index (%)	25.5	24.8	23.8	23.8	23.8	max 35
Specific gravity	2.64	2.67	2.70	2.72	2.78	2.5–3.0
Water absorption (%)	0.62	nil	nil	nil	nil	max 2
Soundness (%)	6	nil	nil	nil	nil	max 12
Stripping (%)	5	nil	nil	nil	nil	max 5



Fig. 5. Plastic-coated aggregate with 9% LDPE and plain aggregate

4.3 Bituminous Concrete with VG-30: Dry versus Wet Process

The OBC of the conventional VG-30 mix was 5.0%, at which stability (2012 kg) and bulk density peaked and air voids reached about 4% (Table 8). With the OBC fixed, the dry-process mix had a higher ITS than the wet-process mix at every plastic content up to 9% (Fig. 6). Both peaked at about 9% and dropped sharply at 11%, where the dry mix fell below the conventional mix. The optimum plastic content was taken as 8.3% of the bitumen weight. At this dose (Table 9), the dry process raised stability by 38.2% and ITS by 17.0%, against 16.8% and 4.7% for the wet process. In the dry process the plastic melts directly onto clean, hot stone, forming a thin film that roughens the surface and bonds to both stone and bitumen. In the wet process, the poorly compatible LDPE forms droplets in the binder and tends to separate. The dry process also needs only a feeder at an ordinary hot-mix plant.

Table 8. Marshall results for the conventional VG-30 mix

Bitumen (%)	Max. theoretical SG	Bulk SG	Air voids (%)	VFB (%)	Stability (kg)	Flow (mm)
4.0	2.350	2.226	5.28	72.74	1680	6.88
4.5	2.380	2.272	4.54	74.96	1858	4.52
5.0	2.420	2.325	3.93	76.42	2012	3.28
5.5	2.410	2.320	3.73	78.37	1814	3.60
6.0	2.390	2.302	3.68	79.93	1788	4.12

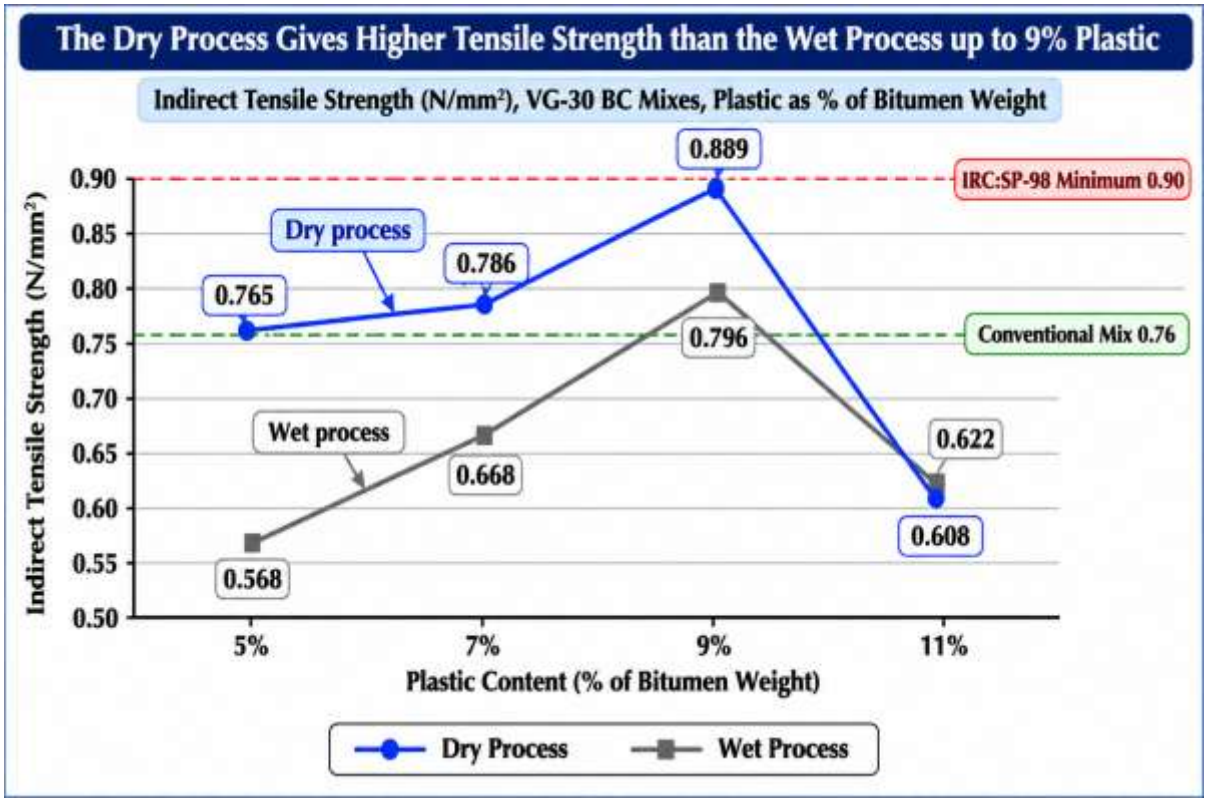


Fig. 6. Indirect tensile strength of VG-30 mixes, dry versus wet process

Table 9. VG-30 mixes at the optimum plastic content of 8.3%

Property	Conventional	Wet process	Dry process	IRC:111-2009	IRC:SP:98-2013
Marshall stability (kg)	2012	2350	2780	min 900	min 1200
Change in stability	—	+16.8%	+38.2%	—	—
Indirect tensile strength (N/mm²)	0.760	0.796	0.889	—	min 0.90
Change in ITS	—	+4.7%	+17.0%	—	—
Flow (mm)	3.28	3.15	3.65	2–4	2–4
Air voids (%)	3.93	3.95	3.60	3–5	3–5
VFB (%)	76.42	74.20	76.20	65–75	65–75

4.4 Bituminous Concrete with VG-10

With VG-10 bitumen and the dry process, the OBC was 5.17%. The optimum plastic content was the average of the contents at maximum stability (11%), maximum bulk density (9%) and 4% air voids (7%), giving 9% of the bitumen weight. At 9% plastic, stability rose by 30.8% to 2006 kg and the Marshall quotient to 502 kg/mm, while flow reached the 4.0 mm limit (Table 10). Beyond 11%, stability fell and flow exceeded the limit. Moisture resistance improved markedly (Table 11). TSR rose from 81.0%, which barely met IRC:111 and failed the 90% minimum of IRC:SP:98, to 98.9% at 9% plastic, as the plastic film kept water away from the stone–bitumen bond. VG-30 gave stronger mixes than VG-10, with and without plastic, and a larger gain from it, so VG-30 with about 8% plastic is preferred for heavy traffic and hot climates.

Table 10. VG-10 mixes at different plastic contents (OBC = 5.17%)

Property	0%	5%	7%	9%	11%	13%	15%
Marshall stability (kg)	1534	1622	1891	2006	2212	1963	1872
Flow (mm)	3.51	3.20	3.50	4.00	4.25	4.00	3.50
Marshall quotient (kg/mm)	437	507	540	502	520	491	535
Max. theoretical density (g/cm³)	2.45	2.44	2.43	2.44	2.43	2.41	2.41
Bulk density (g/cm³)	2.360	2.335	2.338	2.354	2.344	2.335	2.324
Air voids (%)	3.70	4.48	4.00	3.59	3.54	3.11	3.43

Table 11. Indirect tensile strength and TSR of VG-10 mixes

Plastic (% of bitumen)	ITS unconditioned (MPa)	ITS conditioned (MPa)	TSR (%)
0	0.814	0.660	81.0
7	0.822	0.689	83.9
9	0.861	0.852	98.9
11	0.845	0.810	95.8

4.5 Fly Ash–Plastic Composite Filler

Stability peaked at 0.8% plastic by weight of mix (1502 kg), which was taken as the optimum. Compared with the conventional mix with plain fly ash (BC-X), the composite-filler mix (BC-Y) was denser and had fewer air voids, and its stability was 17.2% higher (Table 12). Its flow of 4.25 mm was slightly above the 4.0 mm limit. Moisture resistance improved substantially. Dry ITS rose by 26%, TSR from 84.5% to 93.8% (clearing the IRC:SP:98 minimum of 90%, which BC-X did not), and retained stability from 78.2% to 84.0% (Table 13). The plastic coat makes the bitumen–filler mastic water-repellent, so the mix suits high-rainfall regions.

Table 12. Designed mixes with plain and composite filler

Property	Test method	BC-X (fly ash)	BC-Y (composite)	Change
Bitumen content (%)	Marshall	5.2	5.3	+0.1
Bulk density (g/cm³)	ASTM D2726	2.345	2.358	+0.6%
Air voids (%)	ASTM D3203	5.32	4.80	−0.52
VMA (%)	ASTM D1559	17.0	16.5	−0.5
VFB (%)	ASTM D1559	70	72	+2
Marshall stability at 60 °C (kg)	ASTM D1559	1282	1502	+17.2%
Flow at 60 °C (mm)	ASTM D1559	3.75	4.25	+0.50
Marshall quotient (kg/mm)	stability / flow	342	353	+3.2%

Table 13. Moisture resistance of the two mixes

Property	BC-X (fly ash)	BC-Y (composite)
ITS, unconditioned (kg/cm²)	9.76	12.32
ITS, conditioned (kg/cm²)	8.25	11.56
Tensile strength ratio (%)	84.53	93.83
Marshall stability, unconditioned (kg)	1282	1502
Marshall stability, conditioned (kg)	1002	1262
Retained stability (%)	78.16	84.02

The composite filler also raised the resilient modulus at every temperature, by 36% at 25 °C, 52% at 35 °C (2900 to 4400 MPa) and 20% at 45 °C (1445 to 1735 MPa), as shown in Fig. 7. The higher modulus results from lower air voids and the combined effect of the fly ash and the plastic film. A stiffer surface layer spreads load better and reduces strain in the layers below. The higher modulus at 45 °C and the higher Marshall quotient also indicate better resistance to rutting, although this was not confirmed by a wheel-tracking test.

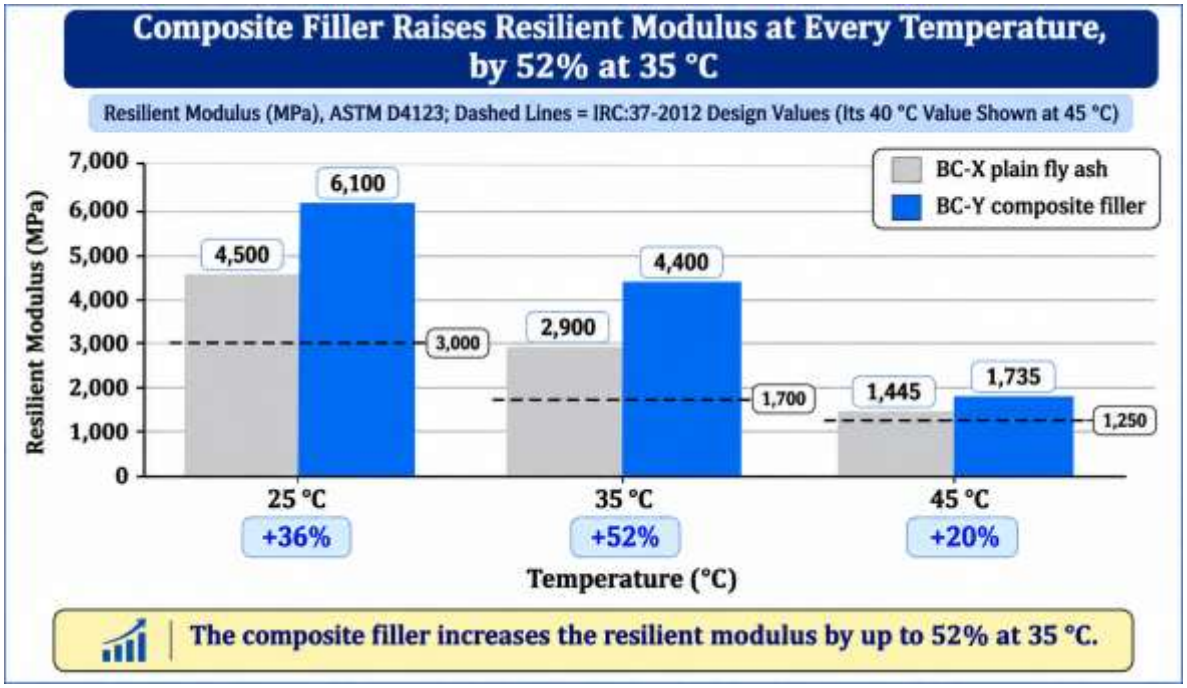


Fig. 7. Resilient modulus of BC-X (plain fly ash) and BC-Y (composite filler)

4.6 Economy and Environmental Benefit

For a 1 km, 3.75 m wide, 20 mm premix carpet requiring 9150 kg of bitumen, replacing 8.3% of the bitumen with plastic by the dry process reduces material cost from Rs 5,49,000 to Rs 5,11,407, a saving of Rs 37,593 (6.8%). The estimate assumes bitumen at Rs 60/kg, processed plastic at Rs 10/kg and a mixing cost of Rs 0.50/kg (Table 14). Each kilometre also consumes about 760 kg of thin-film plastic that would otherwise be dumped or burnt. Fly ash replaces stone dust as filler, and the stronger subgrade permits a thinner granular crust. These savings exclude the further benefit of longer pavement life from mixes that are 30–38% more stable and far more resistant to stripping.

Table 14. Material cost per kilometre of single-lane premix carpet

Item	Conventional	With 8.3% plastic
Bitumen (kg)	9150	8390.55
Plastic waste (kg)	nil	759.45
Cost of bitumen (Rs)	5,49,000	5,03,433
Cost of plastic (Rs)	nil	7,595
Cost of adding plastic (Rs)	nil	380
Total (Rs)	5,49,000	5,11,407
Saving per km (Rs)	—	37,593 (6.8%)

5. Conclusions

1. Adding 1.2% recycled PET fibre and 15% fly ash to a clayey subgrade raised the unsoaked and soaked CBR to 2.33 and 2.04 times those of the natural soil, increased shear strength by 45% and reduced the plasticity index by 31%; strength declined beyond 1.2% fibre.
2. A plastic coat of 9% of the bitumen weight reduced the crushing, impact and Los Angeles abrasion values of aggregate by 35–42% and eliminated water absorption, soundness loss and stripping.
3. The dry process outperformed the wet process: with VG-30 bitumen and 8.3% plastic it raised Marshall stability by 38.2% and ITS by 17.0%, against 16.8% and 4.7% for the wet process.
4. The optimum plastic content was 8.3% of the bitumen weight for VG-30 and 9% for VG-10, close to the 6–8% of IRC:SP:98-2013; above about 9–11%, stability, tensile strength and TSR fell. At 9% plastic, VG-10 stability rose by 30.8% and TSR from 81% to 99%.
5. Fly ash coated with 0.8% plastic as filler raised stability by 17.2%, TSR from 84.5% to 93.8% and the resilient modulus at 35 °C by 52%.
6. The modified mixes met the stability, flow, air-void and VMA limits of MORTH, IRC:111-2009 and IRC:SP:98-2013. VFB and Marshall quotient were at or slightly beyond their upper limits, so the base mix design should be refined before field use.
7. The dry process saves about Rs 37,600 per kilometre of single-lane premix carpet and uses about 760 kg of plastic waste.

Field trial sections, fatigue and ageing tests, wheel-tracking tests, separate study of PET fibre and fly ash in the subgrade, and measurement of fumes and microplastic release are recommended for future work.

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