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Evaluate the Strength and Stability of the Waste Polyethylene Terephthalate (PET) Modified Flexible Pavement

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Abstract: This study aims to explore whether post-consumer PET can replace a portion of the bitumen used in the production of modified flexible pavement mixtures via the dry-mixing method. PET from clean, dried, shredded and sieved post-consumer PET bottles was combined with crushed aggregate materials (VG-30 bitumen and crushed stone) to create both standard and PET-modified mixtures. Five different percentages of PET by total binder content were tested as follows; 0%, 5%, 10%, 15% and 20%. As the preliminary optimal amount of bitumen was assumed to be 5%, it was therefore based on this amount that all subsequent mix proportions were calculated. The parameters evaluated were; Marshall stability & flow, volumetrics, indirect tensile strength & tensile strength ratio. It is evident from the data provided that at a PET replacement percentage of 10%, the best Marshall stability was attained. This value of 13.40kN represents an increase of 11.67 % when compared with the control mixture. The tensile strength ratio also exhibited a high value at this replacement percentage (85.9%). When higher percentages of PET were utilized, the mechanical characteristics of the material decreased while the percent air voids increased. Therefore, at a tentative optimum replacement percentage of 10% PET has been identified.

Keywords: *Waste PET; Flexible Pavement; Bituminous Mixture; Plastic Modification; Marshall Stability; Pavement Performance; Sustainable Highway Infrastructure; Recycled Plastica.*

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I. INTRODUCTION

➢ *Flexible Pavements and their Distresses*

Flexible pavement in India and other countries support most of the traffic on roads, mainly for their ability to be build sequentially, easily repairable, and made with locally available materials. The flexible pavement structure includes a layer of bituminous mixture, a composite of aggregate, filler, and bitumen. In the bituminous mixture, the aggregate forms a skeletal structure that bears the applied loads, while the bitumen acts as an adhesive holding together the particles of the aggregate through cohesive and flexural forces. Several types of distresses occur as result of this limitation. Repeated heavy loads cause rutting at higher temperatures. Tensile stresses produced due to repeated loading causes fatigue cracking; fatigue cracking is considered as one of the main modes of failure in asphalt pavement structures (Modarres & Hamedi, 2014a). At lower temperatures, thermal cracking develops when the binder stiffness exceeds its limits. Water or moisture damage causes loss of adhesive properties of binder-aggregate interface and promotes stripping (Agha et al., 2023). Binders used traditionally exhibit viscoelastic behavior and temperature sensitivity. As such, polymer modified binders that reduce or eliminate some of the previously mentioned distresses are generally expensive. This cost has been motivating researchers to find less expensive alternatives including using waste products as modifiers (Ahmadinia et al., 2011).

➢ *Plastic Waste and Waste PET*

Approximately 8,300 Mt of new virgin plastic was produced worldwide through 2015; about 9% of this amount of generated plastic waste has been recycled. Plastic waste generation in India increased from 3.90 million tons in 2021-22 to 4.14 million tons in 2022-23 based on reports made available by the Central Pollution Control Board (CPCB) to the Ministry of Environment, Forest and Climate Change (MoEFCC, 2024). Press Information Bureau PET is primarily utilized for manufacturing beverage containers and packaging and is a semi-crystalline polyester. The PET material resists deterioration and persists in the environment as well as in fragments of micro- and nano-plastic materials (Fahmy et al., 2024). Due to contamination of PET with other plastics and loss of molecular weight due to repeated heating processes, mechanical recycling processes are

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difficult. Properties typical for PET pertinent to pavement construction include a melting point near 265°C, a glass transition point of roughly 69–115°C and stiffness far greater than that of asphalt (Awaja & Pavel, 2005).

➢ *Previous Work and Need for the Present Study*

PET has been included in bituminous mixes in various ways, including as a binder additive, separate particulate material added to aggregate, fibers, and partially replacing aggregate (Hassani et al., 2005; Mashaan et al., 2021; Fahmy et al., 2024; Saleh et al., 2024). Examples of positive effects of adding PET include greater stiffness, improved rutting resistance, improved resistance to moisture damage, and longer fatigue lives in specific mix designs (Moghaddam et al., 2014a; Moghaddam et al., 2014b; Fahmy et al., 2024). However, the results published remain conflicting: Marshall stability was reduced when PET was utilized as a partial substitute for bitumen (Ogundipe, 2019); or when PET was added to mix designs with recycled asphalt pavement (Arshadi et al., 2024); In addition, increased air voids were documented in some PET modified mix designs (Fahmy et al., 2024). Rutting behavior was shown to be dependent upon the application of loadings (Moghaddam et al., 2014b). Few studies have compared the different methods of incorporating PET into a mixture design; Dry mixing resulted in better stability and fatigue performance compared to wet mixing (Agha et al., 2023), whereas wet mixing produced superior moisture resistance. Documented optimal PET replacement levels vary widely depending on whether they were determined on the basis of the percentage of aggregate by mass or binder by mass. This complicates direct comparison due to varying factors of measurement, type and size of PET particles, properties of binder, and mixing processes. Although there is growing interest in mixtures modified with PET to improve the performance of binders in bituminous mixtures, very little experimental data exists relative to the performance of flexible pavement mixtures utilizing Indian bituminous mixtures containing VG-30 grade binder and conventional aggregates. Specifically this relates to the use of post-consumer PET bottles as a partial replacement for binder via dry process. Additionally, research is needed regarding the effect of increasingly higher levels of PET replacement on Marshall properties, volume-related parameters, indirect tensile strength, and moisture sensitivity. Therefore, this current study evaluates the performance of flexible pavement mixtures containing 0%, 5%, 10%, 15%, and 20% of post-consumer PET as partial replacements for binder by weight of binder, by means of the dry blending method at an assumed maximum acceptable binder content of 5% .The purpose of the study is to determine which percentage of PET replacement offers best performance according to a comparative analysis of both mechanical and volumetric characteristics.

II. MATERIALS AND CHARACTERIZATION

➢ *Bitumen*

VG-30 grade paving bitumen conforming to IS 73:2013 was chosen for both conventional and PET-modified bituminous mixture manufacture. Bitumen has been sourced from a commercial petroleum refinery / supplier (name of supplier & batch number will be provided). IS 73:2013 categorizes paving bitumens by their viscosity at 60°C and includes the range of grades from VG-10 to VG-40. VG-30 was chosen due to its appropriateness to India's climate for road construction; specifically, it is suitable for locations that experience significant summer temperature extremes and/or are subject to moderately to heavily trafficked areas. The VG-30 selected binder balances workability throughout the hot-mix manufacturing process and provides resistance to deformation in-service.

Table 1 Physical and Engineering Properties of VG-30 Bitumen

Property	Test method	Representative result	Specification limit (IS 73:2013)
Penetration at 25°C (0.1 mm)	IS 1203	61	Minimum 45
Softening point (°C)	IS 1205	53	Minimum 47
Ductility (cm)	IS 1208	49	Minimum 40*
Specific gravity	IS 1202	1.01	Minimum 0.99
Absolute viscosity at 60°C (Poise)	IS 1206 (Part 2)	3,362	2,400–3,600
Kinematic viscosity at 135°C (cSt)	IS 1206 (Part 3)	605	Minimum 350

➢ *Aggregates*

Crushed Stone Aggregates (CSA) have been studied to be used as Coarse & Fine Aggregate for preparing both Conventional Bitumen Mixes (CBM) and Petrochemical Modified Bitumen Mixes (PET-MBM). Physical & Mechanical Properties of CSA's were determined in compliance with the corresponding methods given in IS 2386. The Specific Gravity of CSAs is 2.72 for coarse aggregate and 2.65 for fine aggregate, hence they can be utilized for preparation of BM. Water Absorption Value of CSAs are 0.65 % and 0.85 %, respectively showing less than average absorption by water. Impact Values of CSAs were 18.50% and Abrasion Values of CSAs were 22.50%, respectively, demonstrating acceptable levels of resistance to impacts & abrasions. Further, Combined Flakiness and Elongation Index was calculated to be 28.00%, which lies within the prescribed Maximum Limit of 35 %. Therefore, it can be concluded that the characteristic features of chosen aggregate satisfies the requirements of Physical and Mechanical Requirements for Pavement Application. Gradation of CSA has been designed according to the specifications of IRC :111; details of the grading are shown in Table 2.

ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/26nov822

Table 2 Physical and Mechanical Properties of Aggregates

Property	Test method	Representative result	Specification limit
Specific gravity (coarse aggregate)	IS 2386 (Part 3)	2.72	—
Specific gravity (fine aggregate)	IS 2386 (Part 3)	2.65	—
Water absorption – coarse aggregate (%)	IS 2386 (Part 3)	0.65	Maximum 2.0%
Water absorption – fine aggregate (%)	IS 2386 (Part 3)	0.85	Maximum 2.0%*
Aggregate impact value (%)	IS 2386 (Part 4)	18.50	Maximum 27% (DBM) / 24% (BC)
Los Angeles abrasion value (%)	IS 2386 (Part 4)	22.50	Maximum 35% (DBM) / 30% (BC)
Combined flakiness and elongation index (%)	IS 2386 (Part 1)	28.00	Maximum 35%

➢ *Waste PET*



Fig 1 Preparation of Waste PET for the Experimental Study

Table 3 Characteristics of Waste PET

Property	Method	Representative result
Form and colour	Visual examination	Shredded flakes; transparent, light blue and mixed-colour particles
Particle size distribution	Sieve analysis	0.5–4.0 mm (literature reference range)
Specific gravity	Pycnometer / ASTM D792	1.35
Bulk density (kg/m³)	Loose bulk density test	350
Melting temperature (°C)	Differential Scanning Calorimetry (DSC)	Approximately 250°C
Thermal stability	Thermogravimetric Analysis (TGA)	Major thermal decomposition generally occurs above 350°C
Surface texture and shape	Visual examination / SEM	Irregular, angular flakes with relatively smooth surfaces and rough edges

➢ *Mineral Filler*

The mineral filler used was obtained from a local crushing plant to use in bitumen mixtures as the mineral filler. This filler is finely divided particles of minerals which are incorporated into the void areas between fine and coarse aggregate particles that will increase density, cohesion & stability of the bituminous mixture. The specific gravity for the representative sample of the stone dust was considered to be 2.68. The particle size distribution of the mineral filler was evaluated with reference to grading requirements specified in morth specification for road and bridge works. The gradation indicated by the test data suggests that 100%, 97% and 90% of the material passed through the sieve openings of 600µm, 300µm and 75µm respectively. These values were within the limits specified for mineral fillers.

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➢ *Experimental Methodology*

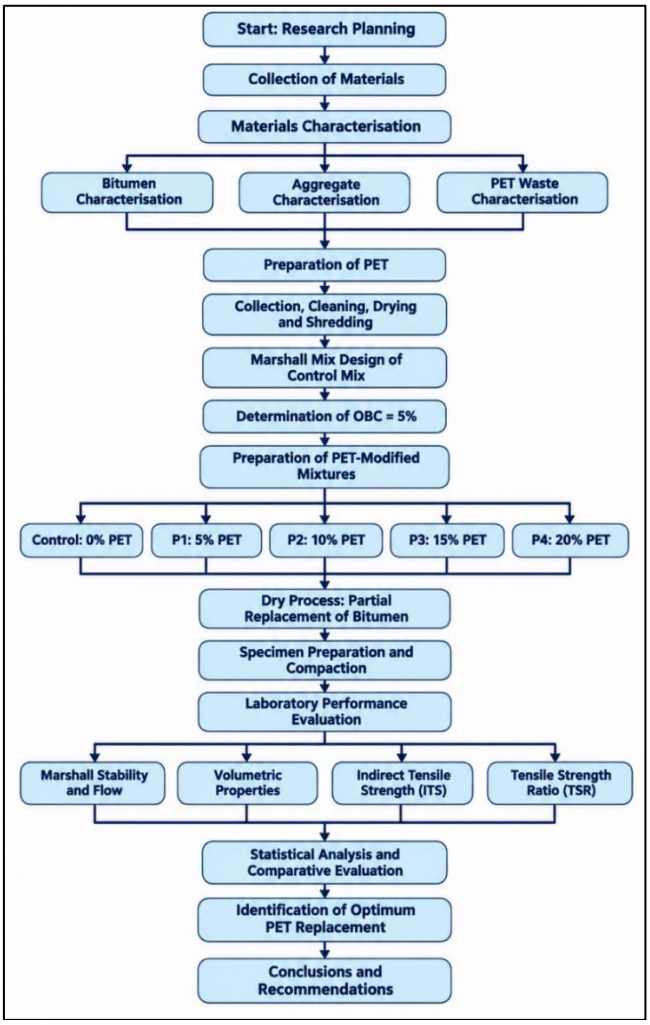


Fig 2 Experimental Methodology for Investigating the Performance of Flexible Pavement Modified with Waste PET Through Partial Replacement of Bitumen.

➢ *Preparation of Pet*

Post-consumer PET beverage packaging was obtained for this research study. This PET material is composed primarily of polyethylene terephthalate (PET). Firstly, the bottles were decontaminated. The plastic bottle's label was removed. The cap was also removed. The remaining contents were removed using a mild detergent solution to remove any dirt, grime or other contaminants on the exterior surfaces. Afterwards, the bottles were completely rinsed with potable water to remove any remaining soap residue. The bottles were then dried in an oven at approximately 60 degrees Celsius plus minus 5 degrees Celsius for 24 hours. This drying process removes any remaining moisture from the interior of the bottle. Following the cleaning and drying processes, the PET bottles were subjected to mechanical shredding to produce PET flakes. A sieve was utilized to separate the shredded PET into various fractions based upon particle size. Only those particles sized between 2.36 – 4.75 millimeters were selected for incorporation into PET-modified asphalt mixes. Those fractions greater than 4.75 millimeters and less than 2.36 millimeters were discarded and detail illustration is shown in Figure 1. Once the desired fraction of PET flakes had been identified and isolated, these flakes were stored in clean, sealed containers, in a dry environment to prevent moisture absorption or contamination. Prior to being mixed with hot asphalt, each container of PET flakes was again heated in an oven to approximately 60 degrees Celsius for two hours to ensure complete removal of all moisture and debris.

The above described process produced PET flakes which could be incorporated into asphalt mixes as a partial substitute for asphalt at levels ranging from 0% to 20% by weight of the total binder. These blends were created via the dry blending method.

➢ *Pet Incorporation Technique*

Wet Process & Dry Process Both the wet process and the dry process have been used in order to incorporate waste PET into bituminous mixes. In the Wet Process, PET is blended with heated bitumen. This blend of PET and heated bitumen is referred to as a "modified" or "PET-modified" binder. Once the PET-modified binder has cooled, it can be added back into the heated aggregate material. On the other hand, the Dry Process adds PET to the heated aggregate material prior to adding the binders (bitumen). The dry process was utilized in this study. Shredded PET flakes were added to the heated aggregate material in order to create a mixture that contained both the aggregate materials and the shredded PET flakes. Heating of Coarse Aggregates & Fine Aggregates. Prior to mixing, the coarse and fine aggregate materials were heated to an elevated temperature. A portion of the mineral filler was also heated along with the aggregates. At that time, the appropriate amount of shredded PET flakes were added to the heated aggregate mixture.

Following addition of the shredded PET flakes, the aggregate fillers and PET flakes were mixed together so that there would be an even dispersion of the shredded PET flakes within the aggregate fillers. Following mixing of the aggregate fillers and PET flakes, hot asphalt cement was added to the mixture based upon the pre-determined ratio of binder to PET content. All subsequent mixing steps were performed until the shredded PET flakes and aggregate particles had been fully coated with the hot asphalt cement. Upon completion of all mixing operations, a uniformly colored hot asphalt mixture containing shredded PET flakes was produced.

The inclusion rate of PET varied from 0%, 5%, 10%, 15%, and 20% by weight of total binder content. For each of these inclusion rates, the amount of traditional asphalt cement was decreased on a proportional basis while maintaining a consistent mass of binder plus PET. Each of the various mix designs including the control mixture received identical treatment regarding heat application for aggregate heating, filler application, shredding PET flake application, and asphalt mixing procedures. The two methods of adding PET to bitumen are illustrated in Fig. 3. As indicated previously, only the dry method was applied during this experiment; hence the results from this research apply only to the dry method of applying PET to bitumen, and should not be generalized to wet method applications.

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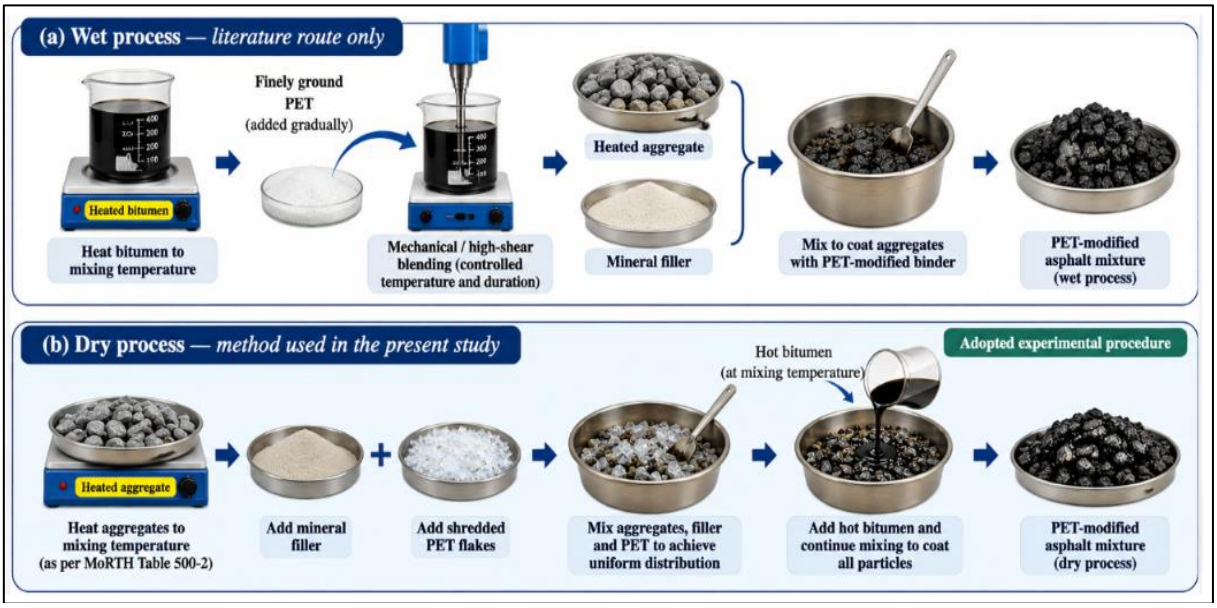


Fig 3 Mixing of the Materials

➢ *Experimental Mix Design*

An experiment program is designed to determine the effect of waste Polyethylene Terephthalate (PET) on the engineering characteristics of Flexible Pavement Mixture. PET has been used through the dry method as a partial substitute for normal Bitumen at five substitution ratios; 0%, 5%, 10%, 15% & 20% of the whole binder. The mixture with no PET was selected as a reference mixture (control), whereas the remaining mixtures were named as P1, P2, P3, P4 etc.

In order to obtain a first estimate of the best proportions of mix for this study, a value of optimal content of bitumen (OCB) of 5 % of the total mass of the mixture was adopted. Therefore, the binder content for each sample of 1200 g was estimated to be 60 g. For each ratio of PET, the mass of PET to replace the original binder was calculated as a function of the substituted rate and that of bitumen was reduced by an equivalent mass. Therefore, for all samples, the sum of masses of PET and bitumen remains constant and equal to 60 g. The mass of aggregates and mineral filler for each sample also remains constant and is equal to 1140 g.

Table 4 presents these proportions which result from the previous step. In addition to maintaining a constant total mass for each sample and constant mass of aggregates and filler, this composition allows to evaluate the effects of replacing PET up to a certain limit within a framework of identical proportions of other components. These preliminary estimates of OCB and calculated compositions will have to be confirmed using the Marshall Mix Design Procedure before they can be announced as definitive experimental compositions.

Table 4 Experimental Mix Proportions

Mix ID	PET replacement (% of binder)	PET (g)	Bitumen (g)	Aggregate + filler (g)	Total (g)
Control	0	0	60	1,140	1,200
P1	5	3	57	1,140	1,200
P2	10	6	54	1,140	1,200
P3	15	9	51	1,140	1,200
P4	20	12	48	1,140	1,200

➢ *Marshall Mix Design*

A Control Bituminous Mixture was designed according to IRC:111-2009 & IRC: SP :135-2022 through Marshall Method. Cylindrical Specimens (Diameter 101.6 mm Height 63.5 mm) were prepared at five Trial Bitumen Content levels with an increment of 0.5 % each time using Three Specimens per Content. A total of 75 Blows per Face were applied to each Specimen for Compaction. Specific Gravity Bulk (Gmb) was obtained from Saturated Surface Dry Method whereas Specific Gravity Maximum Theoretical (Gmm) was found from Vacuum Method ASTM D 2041. Air Void Volume (Va), Void Mineral Aggregate (VMA) & Void Filler Bitumen (VFB) are all Calculated. After conditioning the specimens in a Water Bath at temperature of 60±1 °C for 30 – 40 Minutes, Marshall Stability and Flow were evaluated. The Optimum Binder Content (OBC) is identified at approximately 4 % Air Void level considering Applicable Stability, Flow and Volumetric Requirements. Modified PET Mixtures were prepared as follows: Modified PET Mixtures were prepared using the OBC of the Control Mixture with PET replacing bitumen at 5 %, 10%, 15% & 20% By Weight of Original Binder Content. Maintaining Design Binder Content Constantly enables to compare the effect of PET Replacement on Properties such as Marshall and Volumetric.

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III. RESULTS AND DISCUSSION

This part presents the testing and analysis of conventional and PET modified asphaltic mixes which have been produced by the use of the dry incorporation method. The effects of PET inclusion of 0%, 5%, 10%, 15% and 20% by weight of the original binder content has been examined by means of Marshall stability, flow, volumetric test characteristics and mechanical test characteristics. The results from the analyses were used to examine the effects that PET addition had on the compressive strengths, deformations, volumetric characteristics and moisture resistances of the mixtures. Experimental results have been expressed as mean ± standard deviation based on duplicate specimen replicates.

➢ *Marshall Stability & Flow Tests*

These two tests were carried out to evaluate the influences of PET inclusion on the load bearing capacities and deformation behaviours of the bituminous mixes. A measure of the stiffness of the mixtures was given by the Marshall Quotient (MQ) calculated as the ratio of stability to flow. The results obtained from these two tests are summarized in Table 6.

From this table it is possible to observe how changes in Marshall stability affect the ability of a particular mix to withstand an applied load. It can also be observed that flow values indicate deformation when subjected to an applied load. By combining all three factors; i.e., stability, flow and MQ values, comparisons of the performances of the various mixes could be made and a relationship established for each of them to their respective PET replacement percentages, to establish the best PET percentage for each of the mixes tested.

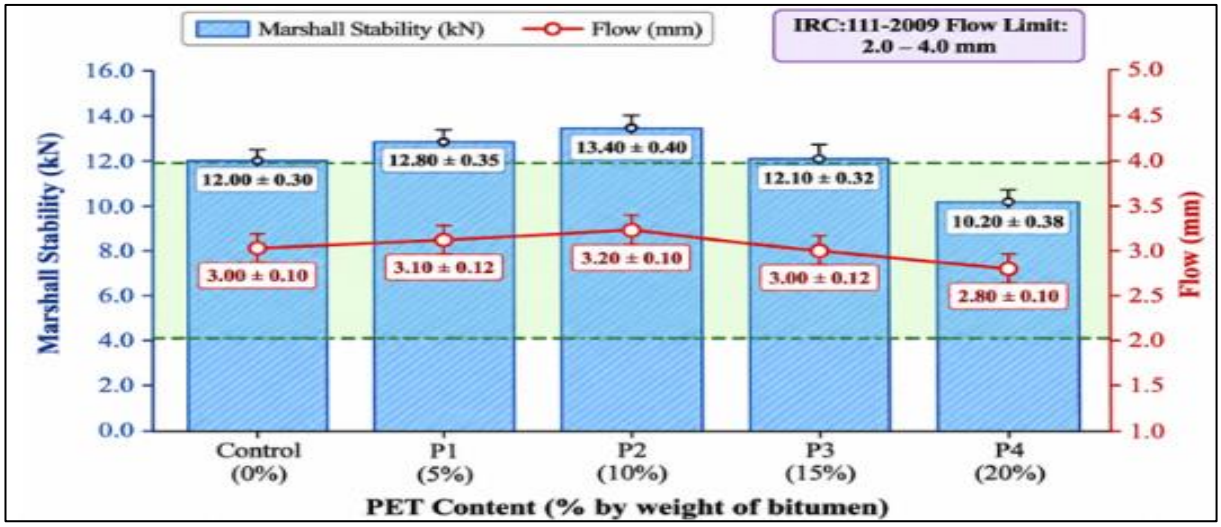


Fig 4 Variation of Marshall Stability and Flow with PET Content

➢ *Volumetrics*

The volumetric properties of the mixes prepared in accordance with previous sections are tabulated in Table 7. This data was analyzed to study the effects that PET inclusion had upon the compaction potentialities of the mixtures, internal void structures and bitumen distributions. These parameters were studied simultaneously with Marshall stability and flow data to see if there were any adverse effects that PET replacement may have caused to either or both of the above mentioned properties.

➢ *Mechanical Performance & Moisture Susceptibility*

Mechanical performance was assessed using indirect tensile strength (ITS) and tensile strength ratio (TSR) values when available. In order to determine if there was any difference due to PET inclusion between ITS values under normal conditions and under conditioned wet conditions (i.e., moisture susceptible), all such values were compared in Table 8. Values of rutting resistance, fatigue life and resilient modulus are only provided in instances where they were determined experimentally.

It is recommended that the optimum amount of PET inclusion be found by taking into consideration both Marshall stability and flow test results, volumetric property test results and mechanical performance test results.

Table 5 Marshall Properties of all Mixtures

Mix	PET (%)	Stability (kN)	Flow (mm)	MQ (kN/mm)	Stability change (%)
Control	0	12.00 ± 0.30	3.00 ± 0.10	4.00	—
P1	5	12.80 ± 0.35	3.10 ± 0.12	4.13	+6.67
P2	10	13.40 ± 0.40	3.20 ± 0.10	4.19	+11.67
P3	15	12.10 ± 0.32	3.00 ± 0.12	4.03	+0.83
P4	20	10.20 ± 0.38	2.80 ± 0.10	3.64	−15.00

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Table 6 Volumetric Properties of PET-Modified Mixtures

Mix	Bulk density (g/cm³)	Air voids (%)	VMA (%)	VFB (%)
Control	2.365	4.0	14.5	72.4
P1	2.372	4.2	14.7	71.4
P2	2.365	4.6	15.0	69.3
P3	2.348	5.3	15.4	65.6
P4	2.325	6.1	16.0	61.9

Table 7 Mechanical Performance Comparison

Mix	Dry ITS (kPa)	Conditioned ITS (kPa)	TSR (%)
Control	850	700	82.4
P1	890	750	84.3
P2	920	790	85.9
P3	820	670	81.7
P4	710	560	78.9

➢ *Overall Performance and Optimum PET Content*

Considering a combination of the illustrative Marshall stability, flow, volumetric characteristics and tensile strength ratios (TSRs) of the dry process mixtures studied, it was found that a PET binder replacement level of 10% by weight of the original binder content appeared to be the optimal replacement level. As a result of the 10% replacement level, the highest Marshall stability of 13.40 kN was obtained in comparison to other tested replacement levels; i.e., an 11.67% increase above the control. Additionally, at this replacement level, the TSR was also maximized at 85.9%. At replacement levels of 15% and 20%, both of which are higher than the identified optimal replacement level, the overall quality of each tested mixture decreased, likely as a result of lower effective bitumen content available to bind the aggregates together, increased air voids, and lower aggregate-binder bond strengths. In addition, the results of these studies indicated that the substitution of petrochemical-derived binder materials with PET materials may not improve all mixture properties. Therefore, based on the results from these tests alone, a replacement level of 10% appears to be the most desirable option among those tested.

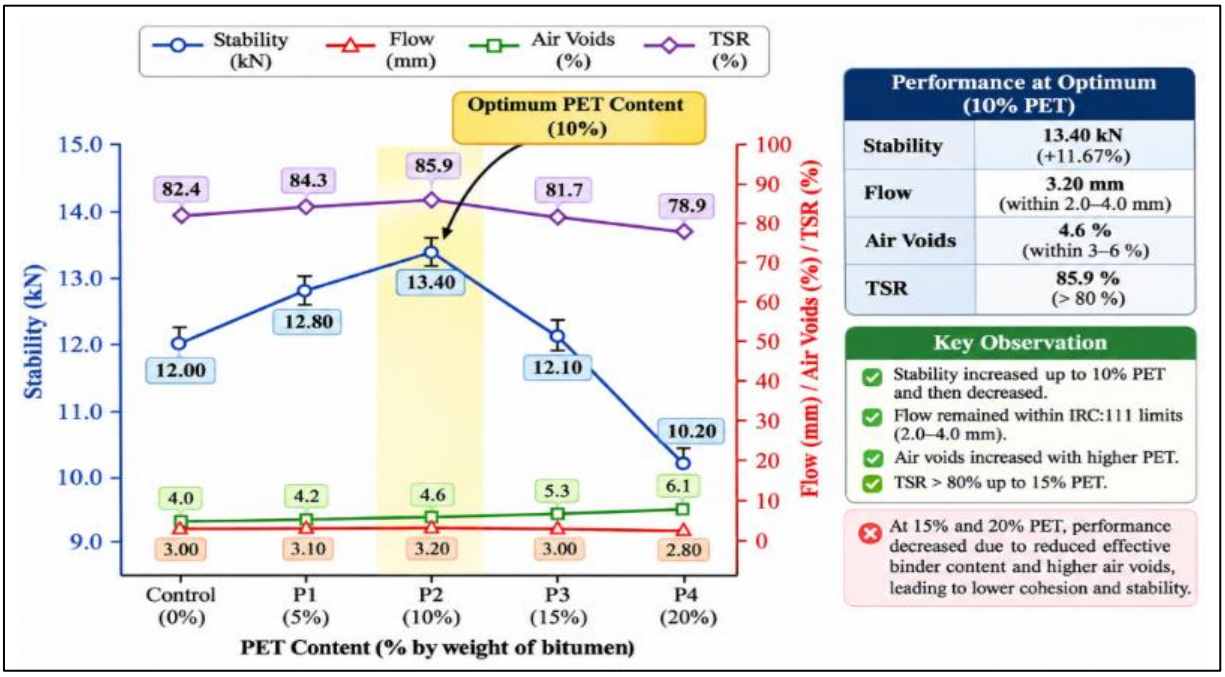


Fig 5 Overall Performance and Optimum PET Content

IV. CONCLUSIONS

The present investigation evaluates the potential use of waste polyethylene terephthalate (PET) flakes as a partial replacement for bitumen in flexible pavement mixtures through the dry incorporation process. Based on the preliminary experimental framework and illustrative results, the following conclusions are drawn:Waste PET flakes can be incorporated into bituminous mixtures through the dry process by introducing them into heated aggregates along with mineral filler before adding hot bitumen.Marshall stability showed an increasing trend up to 10% PET replacement, followed by a reduction at higher replacement levels. The illustrative maximum stability was 13.40 kN at 10% PET, representing an 11.67% increase over the control mixture.Marshall flow varied with PET content, indicating

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changes in the deformation characteristics of the mixtures. The illustrative flow values ranged from 2.80 to 3.20 mm.Increasing PET replacement was associated with a reduction in bulk density and an increase in air voids in the illustrative dataset. This behaviour may be related to changes in particle packing, compatibility and the effective binder available for aggregate coating. The illustrative mechanical performance results indicated that the 10% PET mixture achieved the highest indirect tensile strength and tensile strength ratio, with a TSR of 85.9%. These results suggest the potential of an appropriate PET replacement level to improve mixture performance. Considering Marshall stability, flow, volumetric characteristics and moisture resistance, 10% PET replacement by weight of the original binder content was identified as the preliminary optimum among the investigated proportions. At higher replacement levels, particularly 15% and 20%, the illustrative results indicated reduced performance, potentially due to lower effective bitumen content, increased air voids and inadequate aggregate-binder adhesion.

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