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Technical, Economic, and Environmental Sustainability Assessment of Reclaimed Asphalt and Waste Polyethylene Terephthalate Pavements

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Abstract: In the era of the global drive for sustainability in line with the United Nations Sustainable Development Goals (UN SDGs), sustainability measures are encouraged to be taken at all levels. This study explores a novel mix design integrating Reclaimed Asphalt (RAP) with waste Polyethylene Terephthalate (PET) to enhance pavement performance and sustainability. It adopts a holistic approach by investigating the technical, economic, and environmental aspects of the proposed mix to assess its sustainability. Industry experts emphasize the necessity of mitigating the resource intensiveness of pavement construction to foster sustainable infrastructure. RAP enables resource-efficient pavement construction by promoting asphalt recycling. However, increasing RAP quantity in the mix compromises asphalt structural stability, making it more susceptible to moisture damage and rutting. In this study, PET-modified Bitumen (PMB) is incorporated in higher RAP quantities in the asphaltic mix without compromising asphalt's structural performance and durability. Various PMB amounts (2% to 10% by mass of mixture) were tested with 40% RAP (by mass of mixture), evaluating performance in terms of moisture damage, Marshall stability, rutting, etc. Optimal results were achieved with 6% PET and 40% RAP, showing a 7%, 57%, and 23% improvement in moisture resistance, rutting resistance, and Marshall stability, respectively, compared to unmodified asphalt (technical aspects). The novel asphalt mix demonstrated a 17% reduction in material cost (economic aspect) and a 53% decrease in CO_2 emissions (environmental aspect) using Building Information Modeling (BIM). This study devises a prospective solution for the construction of resilient, resource-efficient, cost-effective, environmentally friendly, and sustainable pavements in line with UN SDGs and circular economy goals.

Keywords: asphalt additives; circular economy; green pavements; polyethylene terephthalate (PET); reclaimed asphalt; sustainability assessment

Citation: Sajid, Z.W.; Hussian, A.; Khan, M.U.A.; Alqahtani, F.K.; Ullah, F. Technical, Economic, and Environmental Sustainability Assessment of Reclaimed Asphalt and Waste Polyethylene Terephthalate Pavements. *Sustainability* **2024**, *16*, 4911. https://doi.org/10.3390/su16124911

Academic Editors: Zengping Zhang, Hongliang Zhang and Xiaoping Ji

Received: 26 April 2024
Revised: 24 May 2024
Accepted: 4 June 2024
Published: 7 June 2024

1. Introduction

Bitumen, a key ingredient of asphalt, is derived from burning fossil fuels excessively, which leaves a significant carbon footprint, accounting for its high global warming potential and the consumption of lots of energy in the process [1–4]. The depletion of fossil fuels will increase the cost of asphalt, making asphalt road paving expensive. Additionally, roads constructed with pure bitumen require frequent maintenance due to poor structural stability, leading to exponentially higher lifecycle costs. Consequently, the pavement industry has focused on sustainable solutions for road network development [5,6]. Many studies have been conducted to devise means for constructing flexible pavements that are structurally sound and pose low economic and environmental concerns. In this regard, the effects of using various bitumen modifiers have been studied and documented. The use of Sasobit, Crumb Rubber, Asphaltan B, Evotherm, etc., has been evaluated against the backdrop of sustainable development to varying degrees of success [7].

Polyethylene Terephthalate (PET) has emerged as a promising bitumen additive for improving asphalt performance. Recycling PET offers a potential solution for waste management due to its difficulty in decomposing. By partially replacing pure bitumen, PMB offers economical and environmentally friendly paving compared to traditional methods as well [8]. Mashaan et al. [9] examined the effects of PET on the physical and rheological properties of bitumen. They concluded that adding PET to bitumen improves its characteristics such as Penetration, Softening Point, and complex shear modulus. Moreover, the addition of PET increases the aging resistance by up to 8% as compared to pure bitumen.

Ali et al. [10] added that incorporating ground plastic as a modifier in bitumen, at replacement ratios ranging from 0.5% to 2% in incremental steps, led to variations in index properties such as flash point, softening point, fire point, and penetration when compared to virgin bitumen. Mahdi et al. [11] studied the effects of PET sizes on the rheological properties of bitumen and documented that the addition of 0–10% PET content with a size increase from 75 micrometer to 15 micrometer marks a decrease in penetration and ductility while increasing its softening point. This was cross-referenced by a study conducted by Sojobi et al. [12], in which it was observed that as the content of PET increased in Polymer Modified Bitumen (PMB), the penetration values decreased. This decrease in penetration values indicated an increase in the stiffness and softening point. Additionally, the tests revealed that the higher PET content resulted in a more stable asphalt, increasing ductility values. Amir Modarres, in his research, used the dry mixing technique to use PET (0–10%) additive and reported an increase in fatigue resistance and stiffness of modified asphalt.

Ferreira et al. proposed PET to replace sand, which provides added resistance to moisture damage [12]. Bekheda et al. [13] also examined asphalt mixtures containing PET in varying percentages (3%, 5%, and 7%) and concluded that it improves the resistance of asphalt to permanent deformation. Also, according to Khorshidi et al.'s study, the mechanical characteristics of asphalt mixtures containing different proportions (0%, 2%, 4%, 6%, 8%, and 10%) of PET demonstrated enhanced properties, including increased stiffness, stability, and viscosity [14]. Moreover, adding polyethylene to asphalt modification improved resistance against fatigue and deformation. Haider et al. [15], in their study, reported similar trends of improvement in fatigue, the Tensile Strength Ratio (TSR%), and rutting resistance upon an increase in PET content in asphalt.

Reclaimed asphalt is another asphalt technology that has garnered much attention against the backdrop of sustainable pavements. The production of bitumen has always been expensive, and its cost will continue to rise due to the depletion of fossil fuels. Therefore, many researchers have highlighted the importance of recycling asphalt to endorse sustainable construction [16]. Not only does RAP provide a sustainable alternative to unmodified asphalt, but it also improves the performance of asphalt [17]. Noferini et al. [18] studied the interaction between virgin bitumen and RAP bitumen. He concluded that with increased RAP content, the dynamic viscosity of the composite increases, resulting in a harder material. Zhao et al. [19] evaluated the effect of RAP in WMA on the Rutting Resistance, Moisture Susceptibility, and Fatigue Resistance of pavements. His study concluded that WMA mixtures with high percentages of RAP exhibited improved structural stability of pavements. Obaid et al. [20] and Mensching et al. [21] evaluated the performance of asphalt influenced by temperature in their respective studies. Their studies point out that RAP is more susceptible to temperature cracking due to aged asphalt [20,21]. However, they also suggested the use of a softer grade virgin binder with RAP to mitigate the temperature susceptibility of RAP. Ma et al. [22] assessed the useability of rejuvenators to improve the low-temperature RAP performance. Mogawer et al. [23] examined the performance of RAP in terms of cracking resistance, moisture susceptibility, and rutting resistance. By varying RAP content from 0 to 40%, he illustrated an improvement in rutting resistance and moisture damage resistance while reporting a decline in cracking resistance. Ortiz et al. [24] replaced aggregates with RAP material and recorded improved ITS and rutting resistance values for RAP [24].

The use of RAP in paving offers environmental benefits compared to unmodified asphalt, which contributes significantly to carbon emissions during production. A Life Cycle Assessment by Rebekah Yang found that RAP usage reduces energy consumption, global warming potential, and construction costs. However, the study highlights the need for softer-grade bitumen or additives to rejuvenate the stiff, aged Asphalt present in RAP [25]. Other prominent studies regarding PET additive RAP use are listed in Table A1 in Appendix B.

Most studies report a higher softening point for reclaimed asphalt due to the presence of aged bitumen [26]. Similarly, in PET-modified asphalt, a reinforcing network of polymers is formed, which reinforces the bitumen against high temperatures, thus elevating its softening point [27]. However, M. Guru's [28] study documents a lower softening point for the PET modification technique that he employed [28]. PET waste was processed to derive a Thin Liquid Polyol PET (TLPP) additive to prepare the modified bitumen. The incorporation of PET as TLPP resulted in a lowered softening point due to the less viscous nature of the resulting PMB [28]. Similarly, bitumen penetration is usually lower in the case of PET-modified bitumen due to the hardening effect of added polymers [26]. This remains true in the case of reclaimed asphalt in response to its exposure to environmental conditions and elevated temperatures during the reclamation process, which causes the aging of bitumen [29,30].

Even though many valuable contributions have been made to use PET successfully on a commercial scale in the development of pavements, efforts have been made to incorporate RAP into paving on a larger scale. However, there are still various barriers to successfully implementing these technologies. Although RAP provides economic benefits by replacing unmodified asphalt with old asphalt, when added in controlled amounts, it also enhances the performance of asphalt. However, the pavement's structural stability is compromised when added in higher quantities into the asphalt mix. In fact, RAP is notorious for its susceptibility to fatigue failure upon use in significant amounts [31].

On the other hand, PET-modified asphalt has shown enhanced performance and structural stability. However, it does not offer the huge economic benefits RAP asphalt provides. Moreover, PET-modified asphalt also exhibits a decline in performance upon an increase in PET quantity, just like the trend followed by RAP technology [32–34].

The construction of pavements, being a resource-intensive process, is resulting in rapid consumption of the Earth's natural resources, causing their depletion [35–37]. Practitioners in the construction industry are prioritizing such methods and materials that can facilitate the implementation of a circular economy (CE) in the built environment to enhance the recycling and reuse of materials for curbing the excessive consumption of resources [38]. In the backdrop of the CE revolution, the pavement industry calls for a method of road construction that can be employed for sustainable development without compromising pavements' structural stability and performance. This study strives to solve this concern by using PMB in combination with RAP technology, which improves the structural stability and performance of asphalt by rejuvenating aged asphalt. Rather, it also provides a more economical and eco-friendly way of paving roads due to its cost-effectiveness, sustainable nature, and potential for implementing CE in pavement construction. However, the use of reclaimed asphalt and PET-modified asphalt has been documented separately in previous studies.

The current study is a novel approach that distinguishes itself from previous literature by devising and investigating a mix design that incorporates both RAP and PET in unmodified asphalt to enhance the structural stability of the composite. Previous efforts had modified asphalt with these additives separately to report a high moisture susceptibility and rigidity in the case of RAP [39]. PET-modified asphalt has been reported to possess lower rutting resistance and ductility, which compromises its structural stability [40]. Further, existing literature did not investigate the physio-mechanical properties of a mix design modified with both additives and how it could address the issues presented by RAP and PET-modified asphalts individually. In comparison, the current study extensively evaluates the performance of RAP-PET-modified asphalt in addressing common pavement distresses, including moisture susceptibility, rutting, and fatigue failure. The findings are then compared to those of asphalt modified with RAP and PET individually to report the merits and demerits of the conceived mix design in terms of its structural stability. The study also conducts a detailed BIM-based economic and environmental assessment of the RAP-PET mix design. The results are compared with existing studies to highlight its sustainability compared to the existing alternatives, which is an original contribution to the relevant literature. Such a holistic approach has not been previously reported.

The problems that arise with using RAP in higher quantities, such as moisture susceptibility and fatigue, limit its use on a commercial scale by jeopardizing its performance. This also holds true for PET-modified Asphalt since modifying bitumen with a higher percentage of polymers causes a decline in the asphalt's resilience. This study contributes to the existing body of knowledge by devising a novel asphalt mix design that can sustain higher quantities of RAP in the mix by using PMB, which reinforces the aged asphalt, thus improving its structural performance. The current study integrates RAP with PMB for enhanced pavement performance, which has not been studied previously in the existing literature. Doing so creates avenues for the mass recycling of asphalt, providing breakthroughs for implementing CE in pavement construction without jeopardizing the structural performance and quality of pavements. Moreover, it also creates a sustainable outlet for the reuse of PET plastics, which are responsible for a high percentage of landfilling. For this purpose, the performance of different PMB and RAP mix designs was assessed by characterization and performance tests. The performance of RAP-PMB-modified asphalt was compared to that of virgin asphalt, RAP, and PET-modified asphalt. Ultimately, the mix design, which imparts optimum performance to asphaltic concrete, was proposed for application.

2. Methodology

In this study, a multi-stepped approach was adopted to assess the performance and sustainability of PMB-RAP-modified asphalt comprehensively. This involved procuring materials and performing standardization tests on them. This was followed by determining the Optimal Bitumen Content through Marshall testing and performance evaluation of PMB. Later, performance tests were performed for Controlled and Modified Hot Mixed Asphalt (HMA) samples, and the results were compared. Ultimately, the economic and environmental impacts of using different HMA mix types under study were evaluated through BIM. This approach is illustrated in Figure 1.

2.1. Materials and Methods

This study conducted experiments on Virgin asphalt, RAP samples, PET-modified samples (Type Y), and RAP-PMB-modified samples (Type Z) to evaluate their performance. The Type Z specimens had multiple percentages of PMB blended with RAP in HMA. The four types of combinations are examined in Table 1.

Table 1. Types of asphalt mixtures under study.

HMA Mix Types	Composition
Virgin Asphalt	0% PET and 0% RAP
RAP Asphalt	40% RAP and 60% unmodified asphalt
PET-modified Asphalt-Type Y	0%, 2%, 4%, 6%, 8%, and 10% PET by weight of Bitumen.
PMB with RAP-Type Z	0%, 2%, 4%, 6%, 8%, and 10% PET by weight of Bitumen and 40% RAP

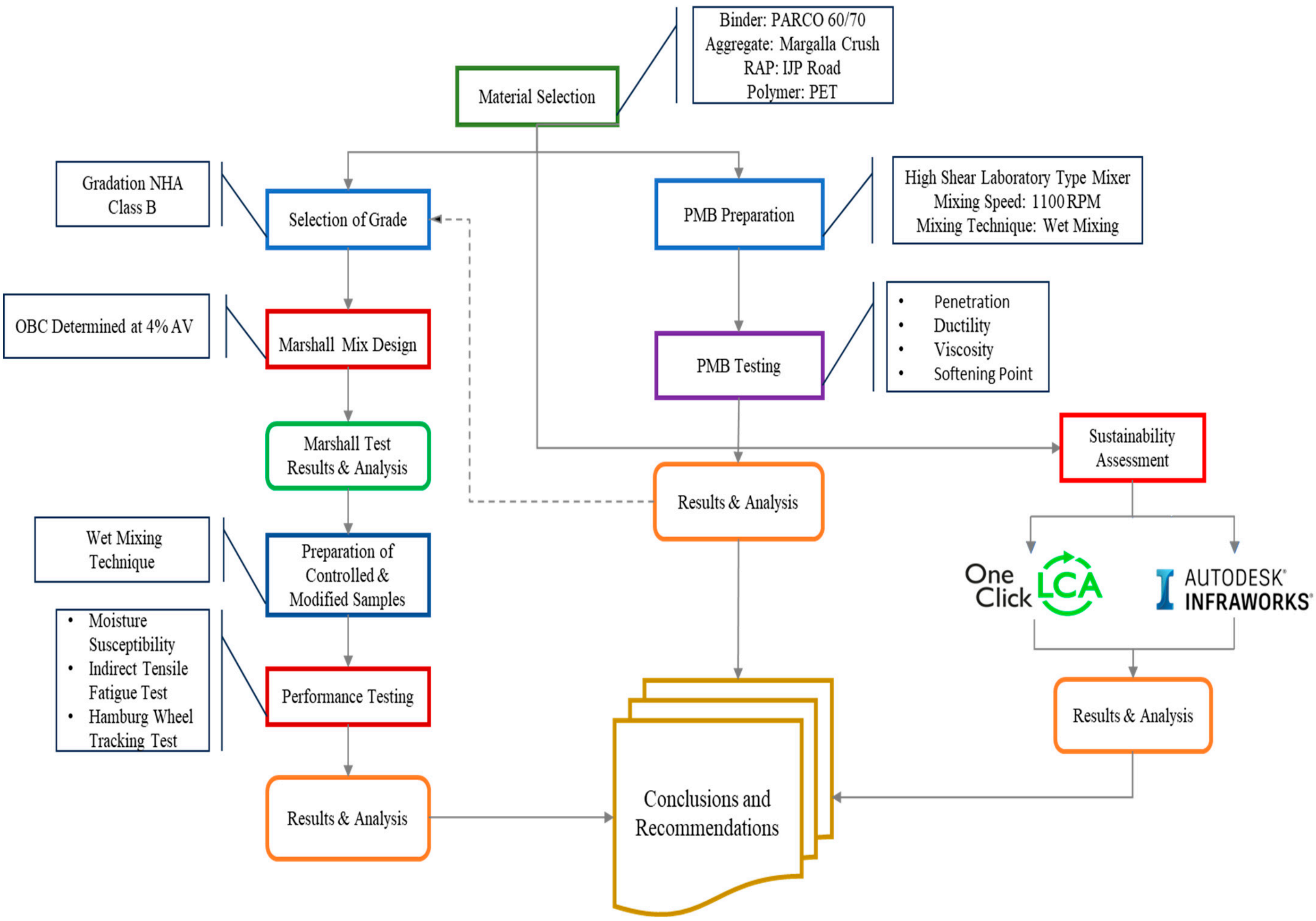


Figure 1. Research methodology flowchart.

A testing matrix was devised for different types of mixes, including controlled as well as modified samples, as illustrated by Table A2 in Appendix B. The primary tests conducted were aimed at evaluating the Optimum Bitumen Content (OBC), the Hamburg Wheel Tracker (HWT) test for rutting resistance assessment, the Indirect Tensile Fatigue test, and the Moisture Susceptibility test for moisture damage. Three samples were prepared for every test mentioned above for all variations in PET included in this study. For the ITFT and Hamburg wheel tracking test, 36 samples were prepared. For these tests, three samples were each cast for both unmodified and RAP HMA mixes having 0% PET content. For the rest of the iterations, PET content ranging from 2% to 10% was prepared, and Type Y and Type Z mixes were prepared.

Similarly, for the moisture susceptibility test, 72 samples were conceived. Six samples were prepared for unmodified and RAP-modified HMA samples. For other iterations with PET content ranging from 2% to 10%, six samples were prepared for each variation of Type Y and Type Z mixes, respectively.

2.1.1. Binder

For this study, base bitumen of 60/70 penetration grade was selected because of its widespread use in the local industry of Pakistan and its adequate performance in the climate conditions of Pakistan. The bitumen was procured from the TOTAL PARCO Pakistan LTD outlet in Rawalpindi. Standard tests conforming to the prescribed ASTM guidelines were performed to characterize the base bitumen and its properties. The results acquired have been provided in Table 2.

Table 2. Standardization tests performed on bitumen.

Test Description	Specification	Result	Limits
Penetration Test @ 25 (°C)	AASHTO T49-15 [41]	66	60–70
Flash Point (°C)	ASTM D 92 [42]	235	280
Fire Point (°C)	ASTM D 92 [42]	251	320
Specific Gravity	ASTM D 70 [43]	1.03	35–45 °C
Softening Point (°C)	AASHTO T-53 [44]	48.2	>100 cm
Ductility Test (cm)	AASHTO T51-09 [45]	>100	0.97–1.02

2.1.2. Aggregate

For this research, fine and coarse aggregates were obtained from Margalla Querry, Pakistan. Several aggregate quality control and standardization tests were conducted to assess the index properties of selected aggregates and their conformity to the standard criteria. These tests included the Impact Value Test, Aggregate Shape Test, Water Absorption Test, Specific Gravity, and Los Angeles Abrasion Test. The results of the tests are presented in Table 3.

Table 3. Standardization tests performed on aggregates.

Test Description	Specification Reference		Result	Limits
Elongation Index (EI)	ASTM D 4791 [46]		3.578%	≤15%
Flakiness Index (FI)	ASTM D4791 [46]		12.9%	≤15%
Aggregate Absorption	Fine Agg:	ASTM C 127 [47]	2.45%	≤3%
	Coarse Agg:		0.73%	≤3%
Impact Value	BS 812 [48]		17%	≤30%
Los Angles Abrasion	AASHTO T96 [49]		22%	≤45%
Specific Gravity	Fine Agg:	ASTM C 128 [50]	2.61	-
	Coarse Agg:	ASTM C127 [47]	2.63	-

Furthermore, the aggregates' gradation was chosen to conform with the Pakistan National Highway Authority (NHA) standard Gradation-B for use in the Asphaltic Wearing course. It is presented in Figure 2. The nominal maximum aggregate size chosen for NHA gradation class B was 19 mm, which complies with the Marshall mix design standard.

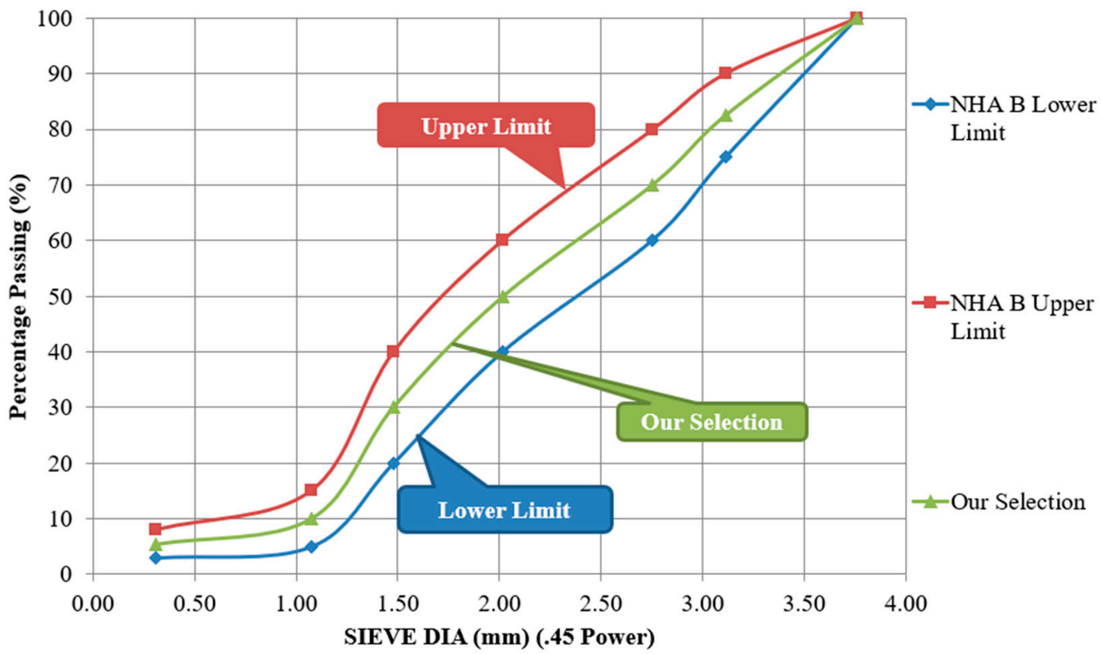


Figure 2. Aggregate gradation curve according to NHA Gradation B.

In addition to the gradation of aggregates, the blend ratios of 1200 g controlled HMA samples and modified HMA samples are presented in Table A3 in Appendix B.

2.1.3. Polyethylene Terephthalate (PET)

Waste plastic bottles were collected from the local streets, hostels, and public areas of the National University of Sciences and Technology, Islamabad. They were crushed and converted into pellets of size <2.36 mm. The characteristic properties of PET were tabulated as shown in Table 4.

Table 4. Characteristics of Polyethylene terephthalate (PET).

S. No.	Property	Specification
1	Chemical Formula	(C10H8O4) n
2	Melting Point	260 °C
3	Heat Deflection Temperature	70 °C at 0.46 MPa
4	Tensile Strength	152 MPa
5	Flexural Strength	221 MPa
6	Specific Gravity	1.56

2.1.4. Reclaimed Asphalt (RAP)

Reclaimed asphalt for the current study was procured from the NHA as a milling material. NHA extracted the reclaimed asphalt from the IJP road situated in Islamabad, Pakistan. RAP, having fundamental characteristics similar to those of base bitumen, was procured to eradicate issues originating from significant fluctuations in the properties of new and reclaimed asphalt. The gradation of aggregates in reclaimed asphalt complied with "NHA Gradation Class B", which conformed with the gradation standard adopted for the study. The reclaimed asphalt was originally prepared using 60/70 grade bitumen, which is common for the majority of pavements in Pakistan. The bitumen content of the procured RAP was 4%. The moisture content of RAP varied between 4% and 4.5%, and the bulk density of RAP was measured to be 2230 kg/m^3 [34]. These characteristics of RAP illustrate its viability for use in this study as they conform to the properties of RAP reported in the prevailing literature [34].

In the current study, 40% RAP concentration was used in combination with different percentages of PET. The waste PET was acquired from the recycling facilities of the National University of Sciences and Technology (NUST). The choice of 40% concentration was inspired by the existing literature, which indicates that RAP concentrations ranging between 20% and 50% of asphalt mixtures exhibit the most desirable properties in terms of structural stability and sustainability (economic and environmental performance) [51]. Studies have indicated that 40% RAP concentration strikes an optimal equilibrium, offering both ecological benefits and structural stability in asphalt. In comparison, 25% RAP lacks in providing significant sustainability improvements, while 50% RAP suffers from poor structural performance [22,52]. Owing to these considerations drawn from the established body of knowledge addressing RAP, a 40% RAP concentration in asphalt is used in the current study to achieve balanced benefits in structural integrity and environmental performance.

2.2. Sample Preparation

2.2.1. Preparation of Plastic-Modified Bitumen

The mixing conditions for the preparation of PMB were derived from the findings of the prevailing literature. PET-modified samples were prepared using a high-shear laboratory-type mixer operating at a speed of 1100 rpm. This mixing speed was inspired by the works of Nisma Agha, who reported that 1100 rpm was the optimum mixing speed for preparing PMB in her study [53]. Virgin Bitumen was heated to 150–160 °C until a fluid state was achieved, and PET was added gradually to the heated bitumen [53]. Although a mixing time of 1 h is generally suggested for modifying bitumen with plastics, this study employed a shorter mixing time of 30 min for preparing PMB. This is because multiple studies have concluded that the optimum mixing time for PET-modified bitumen is 30 min [54,55].

Moreover, PET-modified bitumen is reported to lose its binding potency when mixing is continued for a relatively longer time. Findings of Camilo Vargas have even suggested that mixing PET and bitumen for 1 h instead of 30 min results in faster aging of PMB [54,56]. Thus, in light of the previous literature, a 30 min mixing time for PET and virgin bitumen was preferred in this study. The conceived PMB samples containing a PET content of 2%, 4%, 6%, 8%, and 10% were stored in small containers for later testing and use.

2.2.2. Marshall Mix Design-OBC Determination

The controlled HMA samples for Marshall Mix Design were prepared as per ASTM D-6927 criteria. The National Asphalt Pavement Association procedure was adopted to determine the OBC of bitumen. This procedure prepared HMA samples with varying bitumen content of 3.0%, 3.5%, 4.0%, 4.5%, 5.0%, and 5.5%. Cylindrical HMA samples containing a mass of 1200 g were produced, having a 4″ diameter and 2.5″ height. The mixing temperature of the samples was 160 °C, while they were compacted at 135 °C. The samples were compacted by giving 75 blows to each side. The OBC for Type Y and Type Z mixes was also determined, conforming to the ASTM D-6927 standard. Like the controlled HMA samples, Type Y and Type Z samples having PET (2% to 10%) and 40% RAP content, respectively, were prepared with varying bitumen content of 3%, 3.5%, 4%, 4.5%, 5%, and 5.5% followed by the assessment of their volumetric properties. The conditions for the preparation of Type Y and Type Z Marshall samples, such as the mixing temperature, sample mass, and number of blows for compaction, were kept identical to those used for the controlled HMA samples. This process is illustrated in Figure A1 in Appendix A.

The OBC was determined against 4% air voids as per the National Asphalt Pavement Association guidelines. Generally, it is recommended to use asphalt mixtures with 7% air voids, especially for measuring the moisture susceptibility of HMA mixes as they provide an accurate representation of the level of compaction of asphalt achieved under field conditions. However, a higher percentage of air voids is undesirable as it creates passageways for water intrusion, thus increasing the moisture susceptibility of the asphalt mixture and facilitating the rapid deterioration of pavements. Multiple studies have concluded that the design air void level in a laboratory-compacted sample of HMA ought to be 4 percent for assessing the optimum moisture resistance of asphalt mixtures [55,57].

Field manuals and industry standards such as the renowned "MS-2 Asphalt Mix Design Methods" and AASHTO M 323 [58] also advocate the use of 4% air voids, which validates the appropriateness of this design choice [59]. Therefore, 4% of the air voids were chosen for the determination of OBC and other pertaining tests in this study based on the outlined considerations, as well as the fact that this study is a laboratory exploration rather than a field study. The resulting OBC recorded for unmodified bitumen turned out to be 4.4%.

The OBC for Type Y and Type Z mixes were also determined as the addition of 40% RAP and PMB alters the required bitumen content in the resulting mixtures. The OBC determined for Type Y mix was 4.33%, which is lower as compared to unmodified bitumen owing to the addition of PMB, which enhances the binding capacity of bitumen, causing a decreased requirement of pure bitumen. However, the OBC for the Type Z mix was 4.38%, which is slightly higher than the Type Y mix due to the presence of aged bitumen, which retards the binding capacity of bitumen. The OBC of Type Z mix is still lower than that of unmodified bitumen, as PMB used in Type Z samples lowers the demand for pure bitumen. This was followed by determining the volumetric properties of asphalt samples, which include stability (KN), flow (mm), voids in mineral aggregate (VMA) (%), voids filled with aggregate (VFA) (%), and air voids (AV) (%) against their relative OBCs. The volumetric properties of controlled and modified HMA samples at their respective OBCs are summarized in Table 5.

Table 5. Volumetric properties of controlled and modified HMA samples.

Unmodified Asphalt						
Bitumen Content (%)	**Unit Weight (mg/cm^3)**	**VA (%)**	**VMA (%)**	**VFA (%)**	**Stability (kN)**	**Flow (mm)**
3	2.325	6.74	14.53	53.61	10.13	2.14
3.5	2.359	4.88	13.76	64.54	12.39	2.47
4	2.38	3.66	13.41	73.43	12.1	2.91
4.5	2.389	2.77	13.54	79.56	11.15	3.47
5	2.393	2.36	13.85	82.91	9.52	4.32
5.5	2.396	2.29	13.88	83.47	9.03	4.64
Asphalt Modified with PET (Type Y mix)						
Bitumen Content (%)	**Unit Weight (mg/cm^3)**	**VA (%)**	**VMA (%)**	**VFA (%)**	**Stability (kN)**	**Flow (mm)**
3	2.321	6.937	14.674	52.729	10.275	2.321
3.5	2.354	4.966	13.909	64.3	12.068	2.354
4	2.378	3.608	13.485	73.246	12.329	2.378
4.5	2.384	2.892	13.72	78.921	11.424	2.384
5	2.389	2.49	13.644	82.209	9.792	2.389
5.5	2.392	2.34	13.532	84.176	9.253	2.394
Asphalt modified with RAP and PET (Type Z mix)						
Bitumen Content (%)	**Unit Weight (mg/cm^3)**	**VA (%)**	**VMA (%)**	**VFA (%)**	**Stability (kN)**	**Flow (mm)**
3	2.329	6.466	14.377	55.027	10.753	2.193
3.5	2.35	4.935	14.053	64.88	12.46	2.69
4	2.365	3.784	13.955	72.887	12.97	2.99
4.5	2.378	3.136	13.935	77.492	11.43	3.27
5	2.385	2.772	14.136	80.389	10.63	3.83
5.5	2.388	2.678	14.157	82.462	10.021	3.96

HMA samples with virgin asphalt with higher bitumen with virgin asphalt with higher bitumen content yielded better VFA, VMA, and flow but lower stability and VA generally. In the case of Type Y samples, the presence of PET lowered the flow of bitumen and improved the stability along with other volumetric properties with the increasing bitumen content. However, a decrease in stability and an increase in flow was observed beyond the addition of 4% bitumen. The Type Z mix recorded the optimum results for volumetric properties as compared to other asphaltic mixes. The flow and stability improved for the Type Z mix, up till the addition of 4% bitumen content, after which a downward trend was observed. Even though 4.5% bitumen content also yielded desirable results, the optimum performance was measured for 4%.

2.2.3. Virgin and RAP HMA Sample Preparation

The controlled HMA samples were prepared as per ASTM D-6927 [60] standard procedure. According to this procedure, 1200 g samples were prepared by preheating heating aggregates and virgin bitumen up to 110 °C in an oven. Then, samples were mixed at 160 °C followed by compaction at 135 °C by giving 75 blows to each side. Similarly, for the Hamburg Wheel Tracking test, samples of 6 kg mass were prepared as per ASTM 324. A Gyratory Compactor was used to prepare the sample. A diamond cutter was used to cut the sample into two equal parts that complied with the dimensions mentioned in the standard. The required number of these samples was prepared to assess different properties in later stages, keeping in view Table A2.

2.2.4. Modified HMA Sample Preparation

Similar to the controlled HMA samples, the modified HMA samples (Type Y and Type Z) prepared had a mass of 1200 g. The Type Y samples were prepared by mass-replacing pure bitumen with percentage amounts of PET additive and mixing the modified bitumen with preheated aggregates at 160 °C. Meanwhile, Type Z samples were prepared by replacing the weight of the mix with reclaimed asphalt and using PMB to replace the percentage of pure bitumen according to its OBC. Then, aggregates were preheated up to 110 °C, followed by mixing with RAP, PMB, and pure bitumen at 160 °C using the wet mixing procedure. Later, the mix was compacted at 135 °C by giving 75 blows on both sides to prepare cylindrical samples. To conduct the Hamburg Wheel Tracking test, specimens weighing 6 kg were fabricated following the guidelines outlined in ASTM 324. The preparation of the samples involved the utilization of a Gyratory Compactor. To ensure compliance with the standard, a diamond cutter was employed to divide the specimens precisely into two halves, adhering to the specified dimensions stipulated in the standard. The required number of these samples was prepared for testing later, keeping in view Table A2.

2.3. Assessment of Environmental and Economic Sustainability of Asphaltic Mixtures

A multi-faceted approach was adopted in this study to evaluate and compare the economic and environmental sustainability of the asphaltic mixtures under scrutiny. Two Building Information Modelling (BIM) based platforms called Autodesk Infraworks and One Click LCA were utilized for the environmental impact assessment of the materials under study. First, a model was prepared using Autodesk Infraworks version 2023.1, a BIM-based software integrated with Geographic Information System (GIS). The model as shown in Figure A2 in Appendix A comprises a two-lane local road situated in sector H-12 of Islamabad, Pakistan. The model was developed up to LOD 300 (Level of Development). BIM models with a LOD of 300 possess a precise geometry of their constituents, such as pavements, which assists in making accurate estimates of the quantities of materials involved [61]. Only a 1 km-long segment of the selected pavement was considered.

The chosen pavement was 7.2 m wide. The dimensions of the pavement chosen for the study were inspired by the existing literature [62]. The quantities were extracted for the Base Course and Wearing Course only as asphalt is predominantly used in these layers, which have a collective thickness of 200 mm [63]. Since the materials under study are not used in other layers, such as subgrade, they were excluded from the assessment. Then, the quantity of asphalt for the selected pavement segment was extracted using the "Materials" function provided in the analyze tab of Autodesk Infraworks (2023.1). Subsequently, the estimated quantity of asphalt was uploaded to One Click LCA. It has been used in the existing literature to assess the environmental impacts of materials over their lifecycle [64]. It has a vast material library of construction materials along with their properties, such as embodied emissions of materials, which are used to conduct Life Cycle Assessment (LCA) of construction materials. The materials under study were first traced in the inventory of One Click LCA, and the estimated quantity of asphalt to be used was applied to them. Carbon emission was chosen as the prime indicator of environmental sustainability in this study because the carbon emissions of asphaltic mixtures are a major contributor to climate change, which is a pressing issue faced by mankind globally [65–67]. The calculations were performed for pavements with a lifespan of 20 years, and the assessment was carried out according to the LEED standard.

In order to evaluate the economic performance of materials under assessment, numerous expenditures that can be incurred during the preparation of these materials were determined. These included the costs of pure bitumen, reclaimed asphalt, waste PET, aggregates, shredding PET, preheating bitumen, and mixing pure bitumen with additives, to name a few. The included costs have been summarized in Table 6. Some expenditures, such as transportation costs, were excluded from the study as they highly vary from case to case.

Table 6. Summary of costs considered in economic analysis.

Materials	Costs Incurred
Virgin Asphalt	Cost of Bitumen, Costs of Aggregates, Cost of Mixing Aggregate and Bitumen, Cost of Preheating Pure Bitumen
Reclaimed Asphalt	Cost of Bitumen, Costs of Aggregates, Cost of Mixing Aggregate and Bitumen, Cost of Preheating Pure Bitumen, Cost of Preheating RAP, Labor Costs
Type Y Mix	Cost of Bitumen, Costs of Aggregates, Cost of Mixing Aggregate and Bitumen, Cost of Shredding PET, Cost of Waste PET, Cost of Preheating Pure Bitumen Aggregates and PET
Type Z Mix	Cost of Bitumen, Costs of Aggregates, Cost of RAP, Cost of Shredding PET, Cost of Waste PET, Cost of Mixing Aggregate, PET and Bitumen, Cost of Preheating Pure Bitumen Aggregates and PET

Moreover, expenditures only pertaining to the material costs of the mixtures were included in this study as opposed to their lifecycle costs since conducting a Life Cycle Cost Assessment (LCCA) of materials requires a dedicated study of its own to provide a comprehensive outlook on the concerned research theme. The quantity of bitumen required for each asphaltic mix was calculated by multiplying the relevant density of each asphalt mix with its OBC. The cost of bitumen was calculated based on the rate of bitumen (60–70) mentioned in the NHA's section on the Composite Schedule of Rates (CSR)—2022, District of Rawalpindi [68]. The cost of shredding PET was assessed based on the productivity of the shredder and the electricity consumed in the process. Similarly, the cost of preheating and mixing bitumen with other additives was estimated based on equipment productivity and electricity consumed in running them. The quantity of aggregates was determined based on the quantity of asphalt extracted from Autodesk Infraworks (2023.1) and the amount of aggregates used in each asphalt type's mix design. The cumulative costs incurred for all mixtures were compared with each other in the end to bring forth the most economical asphaltic mixture.

3. Laboratory Testing—Results and Discussion

3.1. PMB Testing

The PET-modified bitumen was assessed using various tests to determine the properties of the modified samples. These tests included the following:

- Softening Point [ASTM D 36-95] [69];
- Penetration [ASTM D 5-06] [70];
- Ductility [ASTM 113-99] [71];
- Viscosity [ASTM D 88-07] [72].

Each test was performed according to the prescribed standards for the respective test. The results for the index properties of bitumen were plotted for each sample containing different amounts of the PET modifier. Figure 3 illustrates the effect of variation in PET content on the index properties of PMB samples.

The results indicate that with the increase in PET in bitumen, a gradual decrease in the ductility and penetration of bitumen is observed. This decrease in ductility is a by-product of the stiffening of bitumen resulting from adding a plastic modifier [73]. However, the softening point and viscosity of PMB bitumen increase with the increase in PET content. The softening point and viscosity of the modified binder increase because PET imparts a reinforcing effect on the bitumen matrix by enhancing its viscoelastic properties, thus reducing the flow and deformation of the binder at elevated temperatures. Therefore, a higher PET content assures reduced susceptibility of PMB to temperature changes and softening phenomenon in hot weather as compared to virgin bitumen.

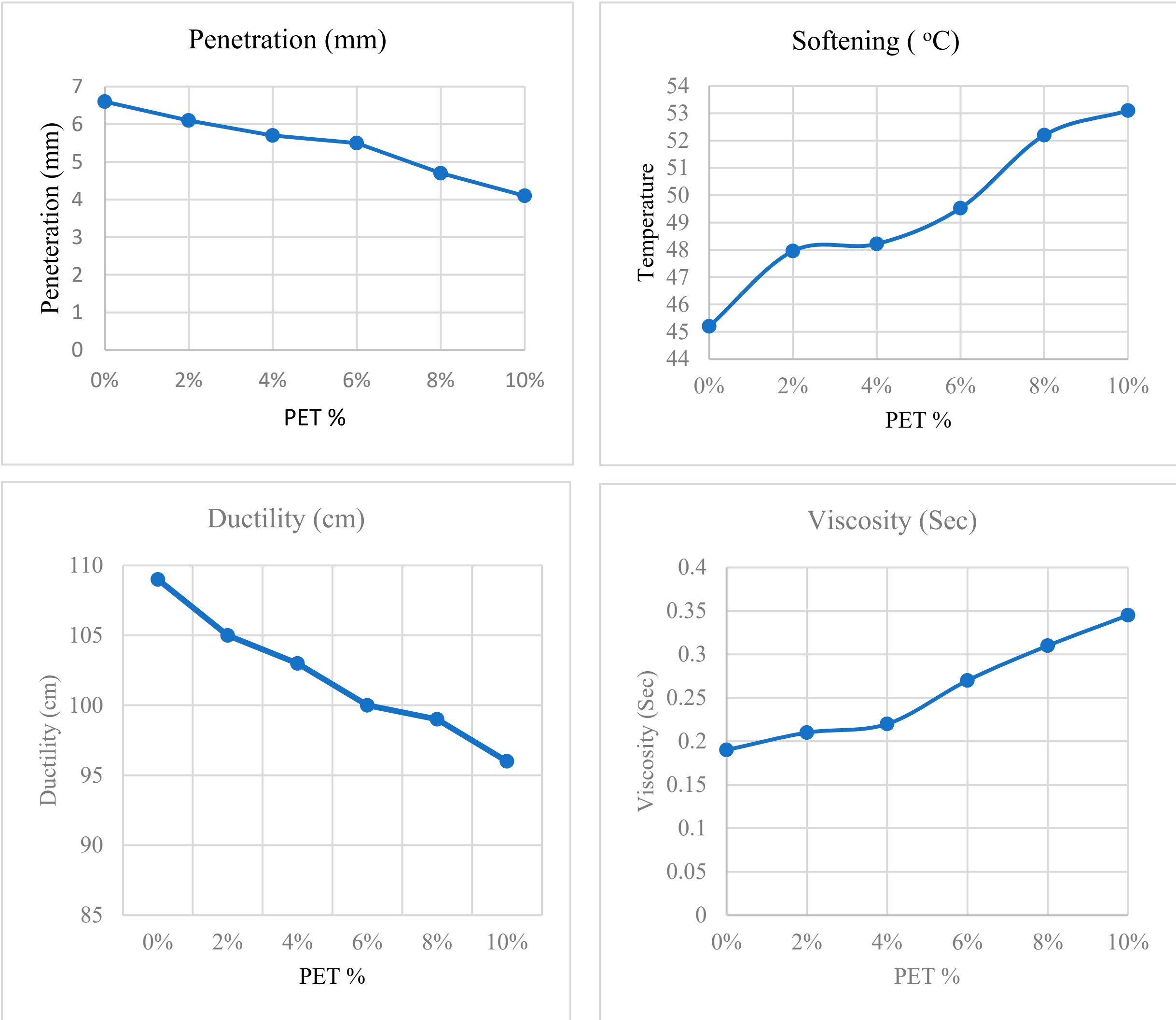


Figure 3. Preliminary testing on PMB.

3.2. Moisture Susceptibility Test

To assess the performance of pavements, it is important to evaluate their susceptibility to moisture damage. The intrusion of moisture in pavements is a prominent issue for the transportation industry as it drastically reduces the lifespan of roads by forming cracks. Therefore, a moisture susceptibility test was performed in this study to evaluate the moisture resistance of PET-RAP-modified asphaltic concrete. The test was performed according to the prescribed instructions in the ASTM D 6931-07 [74] standard. The samples prepared for this test had a diameter of 4″ (100 mm) and a thickness of 2.5″ (63 mm). This procedure involves preparing two types of samples:

- Unconditioned samples;
- Conditioned samples.

The samples were conditioned according to the ALDOT-361-88 [75] criteria. The conditioned samples were prepared by placing the samples in a hot water bath (60 °C) for 24 h. Later, the samples were placed at a temperature of 25 °C for 4 h in a controlled chamber. Finally, the samples were tested in UTM by applying load at a 50 mm/min constant rate. The maximum load leading to the failure of the sample was observed and noted. The unconditioned samples were placed in dry conditions at room temperature, and procedures similar to those performed on the conditioned samples were performed. The test assembly is shown in Figure A3 in Appendix A.

According to the ASTM D 6931-07 [74] standard, the indirect tensile strength is measured for conditioned and unconditioned samples using Equation (1):

$$St = 2000 \times P/\Pi \times D \times T \quad (1)$$

Here,
St = tensile strength (kPa);
D = sample diameter (mm);
T = sample thickness (mm);
P = maximum load (N).

The Tensile Strength Ratio (TSR) was used to compare and present the indirect tensile strength of conditioned and conditioned samples as per Equation (2).

$$TSR = S2/S1 \quad (2)$$

Here,
S2 = average tensile strength of conditioned sample;
S1 = average tensile strength of unconditioned sample.

It was observed that all of the samples maintained a minimum of 80% TSR. This TSR (%) value is also the minimum criteria adopted by Superpave and other prominent roadway agencies [76]. The TSR (%) values of the controlled and the modified samples are illustrated in Figure 4. The results indicate that the moisture susceptibility of RAP-PMB-modified samples is lesser than that of RAP-controlled samples, PET-modified, and virgin samples, considering the improved TSR (%). This increase in TSR (%) is governed by the RAP-PMB modifier, which imparts higher stiffness and viscosity, increasing the tensile strength of asphalt. Moreover, the increase in PET content tends to increase the TSR (%) values for asphalt, as indicated by the results. This is because PET further improves bitumen's binding capacity, resulting in improved TSR (%).

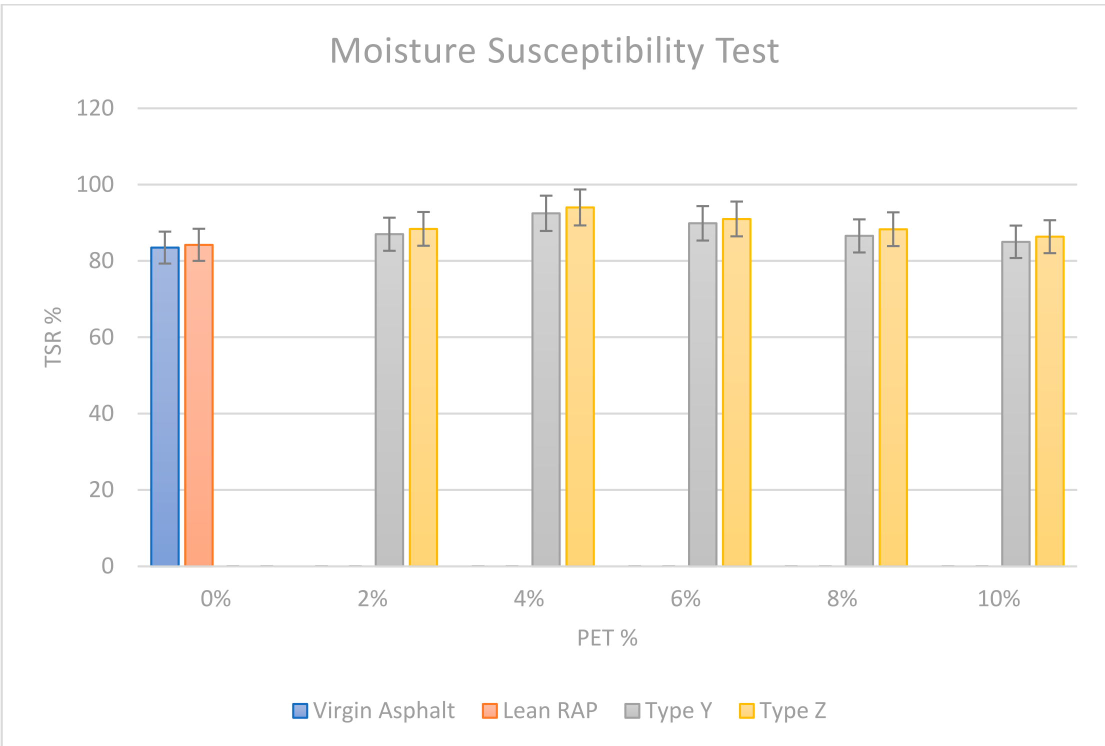


Figure 4. Moisture susceptibility test results.

The increase in TSR value is gradual when the PET content is increased from 0% to 2% for RAP-PMB modified samples. This increase is governed by the improved aggregate-bitumen adhesion imparted by the PET fibers to the modified mix. By filling the voids between aggregates, PET enhances the compactness of the mix and improves its performance against tensile stresses [77]. However, since the inclusion of 2% PET is not uniform throughout the mix due to its lower concentration, the TSR is lower than that of samples containing 4% and 6% PET content, where a uniform dispersion of PET polymers is observed [78].

Type Z mix with 6% PET content rendered slightly lower TSR than 4% PET samples due to excessive stiffness and brittleness imparted by PET and RAP. This trend stays consistent for 8% and 10% PET samples, which demonstrated lower TSR than other Type Z samples. This gradual increase in the TSR value was observed up to the addition of 4% PET content in RAP samples. However, a decline in TSR values was noted when the PET content was increased beyond 4%. The decline in TSR (%) values after the addition of PET beyond 4% is a function of the disruption to the binder's ability to coat and bond with aggregate particles effectively. Moreover, PET is a rigid polymer, and its addition in excessive amounts can impart brittleness to asphalt, causing cracking under stress. However, the TSR (%) of Type Z samples remained higher than that of virgin, RAP, and Type Y samples, even exceeding 6%.

The addition of PET in the mix improves the moisture susceptibility of the composite by imparting an improved bonding strength and adhesion between aggregates and the binder. Such addition thereby enhances the ability of asphalt to withstand tensile stresses [79]. PET additives, when added through the wet mixing technique, form a coat around the aggregates, which enhances the bonding between aggregate–binder systems, leading to improved resistance to damage induced by moisture [53]. PET also acts as a rejuvenating agent for RAP, softening the aged asphalt to improve its bonding capacity, leading to improved performance against moisture susceptibility.

Meanwhile, in laboratory exploration, 4% air voids are achievable owing to controlled conditions. Moreover, moisture susceptibility increases with increasing air voids, as proven in the existing literature (reference). Therefore, to evaluate the maximum moisture susceptibility of RAP-PET asphalt, 4% air voids were preferred.

3.3. Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking test is a standard test for determining the rutting resistance of asphalt. This test determines the deformation induced in the asphalt samples due to repeated loading. Rutting is also a common failure type in pavements, especially in regions like Pakistan, which are characterized by elevated temperatures and high service loads due to excessive population. So, this test was included in this study to cater to this issue by measuring the rutting resistance of the materials under study. For this test, 33 samples were prepared. Each sample was prepared according to the specifications of ASTM T 324 [80] standard. The mass of each sample was around 6 kg. The samples were cut using a diamond cutter to the required dimensions per the test standards. Test samples were cut into two equal parts and placed in the assembly. The test was carried out under dry conditions at 25 °C temperature by applying 10,000 passes to the samples. The average rut depth was recorded from both samples to minimize any potential errors. The failure criteria suggested that samples having a rut depth of more than 12 mm were not fit enough to be used. The rut depths for the samples under study are illustrated in Figure 5.

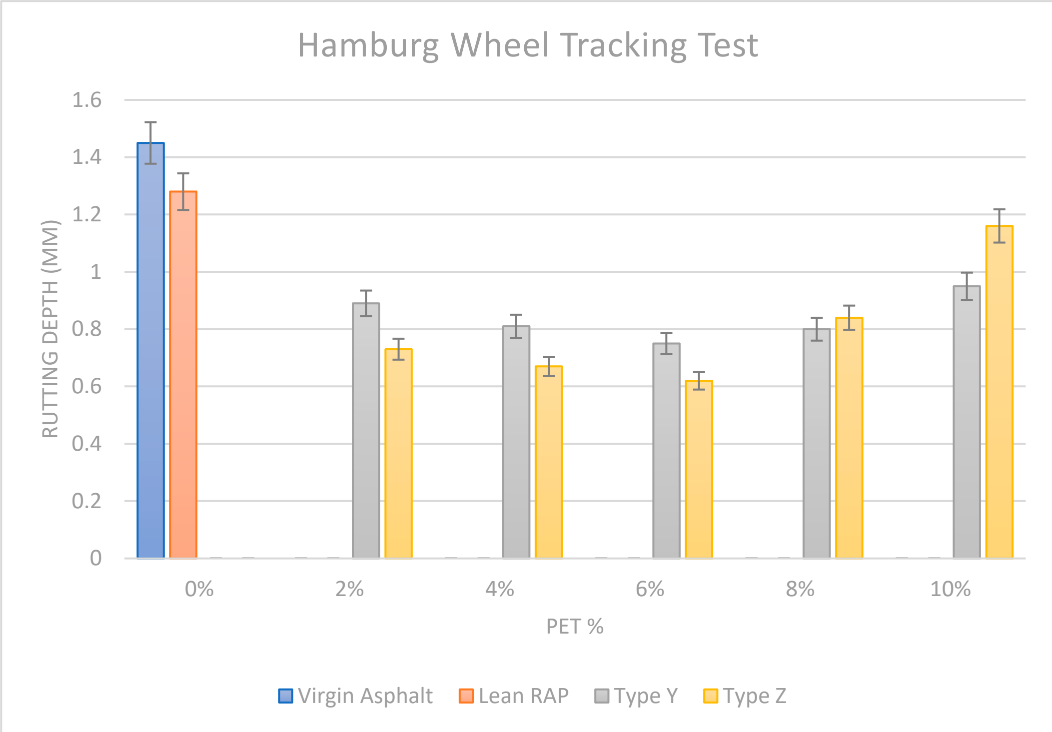


Figure 5. Hamburg Wheel Tracking test results.

Previous studies have suggested a decrease in rutting depths can be observed with increasing PET content in unmodified asphalt [81]. Also, with the increase in the amount of RAP in asphalt, a reduction in rut depth is noticed. A similar trend can be seen in Figure 5 for our study. The rutting depth reduces as the PET content increases in controlled and modified samples. The rutting resistance of RAP-PMB-modified samples was observed to be higher than that of virgin asphalt and RAP samples.

Moreover, the rutting depths for Type Z mixes were found to be lesser than Type Y mixes, up to a PET percentage of 6%. In the Type Z mix, the addition of PET improves the binding capacity of bitumen, whereas RAP imparts stiffness to the mix due to the presence of aged asphalt. This accounts for the improved resistance to permanent deformation in terms of rutting for these proportions. Type Z mixes have RAP content in their blend, which results in stiffer mixes. Therefore, Type Z mixes have a superior rutting resistance than Type Y mixes. However, an inflection point occurs when PET content is increased up to 6%. After this point, the rutting depths for Type Y mixes are less than those for Type Z. This is because, in the case of Type Z samples, an excessive increase in RAP and PET content causes the bitumen to lose its binding capacity due to reduced aggregate interlocking capacity and become more susceptible to permanent deformation. The best results were recorded for samples with 6% PET and 40% RAP content with 6% PET and 40% RAP content with rutting resistance up to 57% compared to virgin asphalt. The assembly for the test is shown in Figure A4 in Appendix A.

The Type Z mix demonstrates a higher resistance to rutting than the alternatives, with up to 6% addition of PET. The improved rutting resistance can be accredited to the stiffening effect imparted by RAP to asphalt, which reduces the deformation of asphalt under repeated loading [82]. Aged asphalt hardens over time after undergoing repeated cycles of traffic loads and exposure to environmental factors. Consequently, it becomes stiff, losing its ductility to a certain extent [81]. Rutting is witnessed in fresh asphalt as its binder is soft and susceptible to deformation caused by high traffic loads. In contrast, RAP contains an aged binder, which is harder in nature and less susceptible to rutting. Moreover, the incorporation of PET in asphalt hardens the bitumen, reducing its ductility and, in turn, susceptibility to rutting [11].

3.4. Indirect Tensile Fatigue Test

The Indirect Tensile Fatigue test was adopted in this study to evaluate the fatigue life of asphalt mixes subjected to cyclic loading. A Universal Testing Machine (UTM) was used, and the test was performed according to the EN-12697-34 [83] standard. The test was performed in a controlled condition whereby a vertical load was applied, leading to horizontal tensile stress in the specimens. The thickness of the samples was 51 mm, and their diameter was 100 mm, as per the prescribed standard. The maximum allowable aggregate size was kept at 25 mm. Prior to testing, samples were conditioned at 25 °C for 4 h. Later, they were tested under a load of 3500 N with a loading time of 0.1 s and a resting time of 0.4 s. The temperature during the test was maintained at room temperature. The machine stopped when the samples failed, marking the end of the test. The assembly of the machine and the cracked sample afterward are shown in Figure A5 in Appendix A.

The addition of PET in unmodified asphalt is known to improve the fatigue life of pavements [53]. The results obtained for ITFT values of conditioned and modified samples are illustrated in Figure 6. This illustration shows that the fatigue life of asphalt is improved with an increase in PET amount for both virgin and modified samples up to a certain point. A dramatic improvement in fatigue resistance is observed as PET content increases from 0% to 2%. Fatigue resistance is further improved by adding 6% PET for Type Y and Z mixes. Type Z samples showed much-improved fatigue resistance than lean RAP samples due to the rejuvenating effect of the PMB modifier in the mix. However, the Type Y mix had better performance overall than the Type Z mix against fatigue cracking due to the presence of aged asphalt in the Type Z mix, which is more susceptible to fatigue failure. Type Z mix having 6% PET content showed optimum fatigue resistance. However, fatigue life decreases as PET content increases in samples beyond 6%.

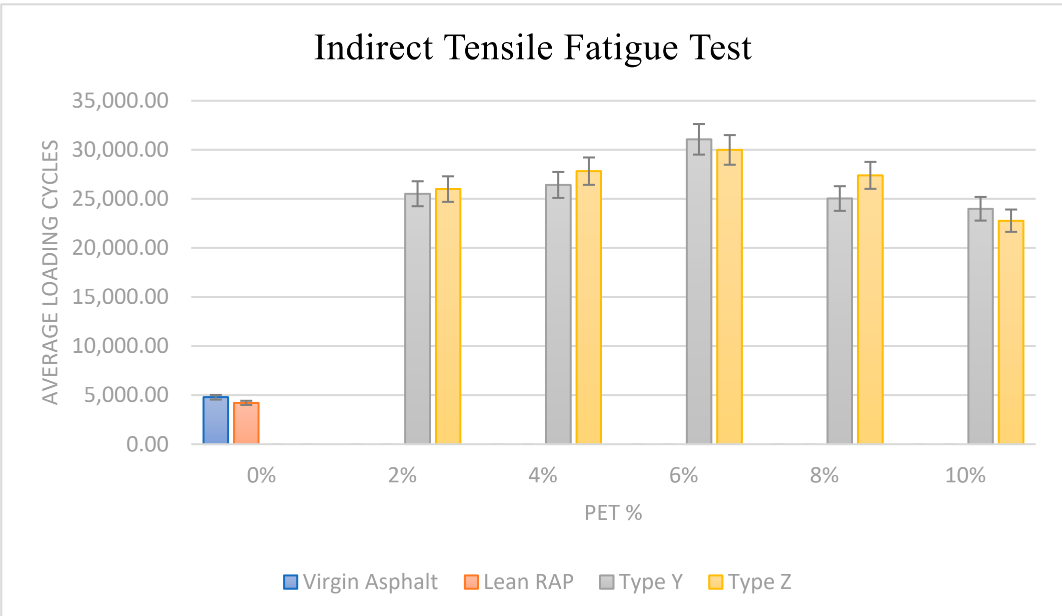


Figure 6. ITFT test results.

It was noted that Type Z mixes experienced a steeper decline in fatigue resistance beyond 6% PET content compared to the Type Y samples. This is because the amount of pure bitumen is progressively reduced in Type Z samples with excessive addition of PET and RAP content as compared to the Type Y mixes. Therefore, the bond between aggregate and binder is exhausted, causing fatigue upon cyclic loading. Despite underperforming as compared to the Type Y mix, the Type Z samples containing up to 6% PET content exhibited desirable fatigue resistance, which is much improved compared to lean RAP samples.

The PET polymers rejuvenate the aged asphalt of RAP to improve its bonding capacity, which in turn reinforces the bond between aggregate and binder, resulting in improved performance against fatigue [84]. This trend stays valid for 4% PET and 6% PET samples in the Type Z mix, which demonstrate improved performance against fatigue, respectively [84]. Increasing the amount of PET in the mix enhances the aggregate–binder bonds by rejuvenating RAP content, providing a sound asphaltic mixture. However, Type Z samples with PET content higher than 6% demonstrate a decline in performance against fatigue as the amount of PET in the mix becomes excessive, causing the bitumen to lose its ductility and become more susceptible to fatigue failure [85].

The incorporation of PET into the Type Z mix enhances the performance of the mix against fatigue failure by reinforcing the aggregate binder bonds through the bridging effect of the PET polymers [86]. The soft amorphous component of PET (liquid) improves the bonding between the asphalt binder and aggregates [55]. This enhanced adhesion secures the aggregates in place, resulting in a more cohesive mixture that is resistant to displacement under load, which causes fatigue failure. Moreover, the solid and rigid crystalline part of PET helps distribute traffic loads evenly, reducing stress on individual points and thereby minimizing deformations [55]. Simultaneously, incorporating RAP into the mix adds well-graded, angular aggregates that enhance the interlocking and mechanical stability of the pavement [22]. This improved aggregate interlock leads to better load distribution and lower stress concentrations, thereby boosting fatigue resistance. Consequently, an improved response was noted for Type Z mix to fatigue failure.

3.5. Stability and Flow

Stability and flow tests of asphalt are essential evaluation standards for evaluating asphalt performance. In this research, AASHTO T245-15 [87] was used to conduct Marshall stability and flow tests. The specimens were placed in a water bath at a temperature of 60 °C for 30 min. The samples were dried and placed in the Marshall apparatus. Using the apparatus, vertical load was applied at a given strain rate of 2 inches per minute to bring about the failure. Marshall stability is given by the maximum load applied leading up to the failure of the sample. Marshall flow is given by a gauge in the apparatus, which measures the vertical deformations (in millimeters) occurring in the samples. The assembly of the apparatus for the Marshall stability and flow test is shown in Figure A1.

The results for stability and flow of the mixes under study were plotted in Figure 7. The results show that the addition of PET in both controlled and RAP-modified samples increases the stability of the samples while simultaneously reducing their flow [88,89]. Type Z mixes' stability is higher than that of virgin samples, lean RAP samples, and Type Y mixes. This is because, in the Type Z mix, the addition of RAP in asphalt imparts stiffness to the mixture, and PET content increases the binding capacity of asphalt. Together, they improve the resistance of asphalt to permanent deformation under high loads, thus increasing its stability. The stability increases when the PET content is increased up to 4 percent for both Type Y and z samples. A gradual increase in stability is observed for 6% PET content as well.

Then, a decline in stability is observed drastically for all types of samples containing 8% and 10% PET content. Subsequently, the flow values indicating the pavement's susceptibility to deformations also follow a similar trend as that of stability. Flow values decreased up to 6% PET content addition across all samples. However, a significant increase in flow was observed when the PET content was increased beyond 6%. The increase in flow upon the addition of PET content beyond 6% is due to an excessive reduction in pure bitumen, which reduces the bonding between the aggregate and binder, making it vulnerable to deformations. The optimum flow is observed for Type Z samples having 6% PET content.

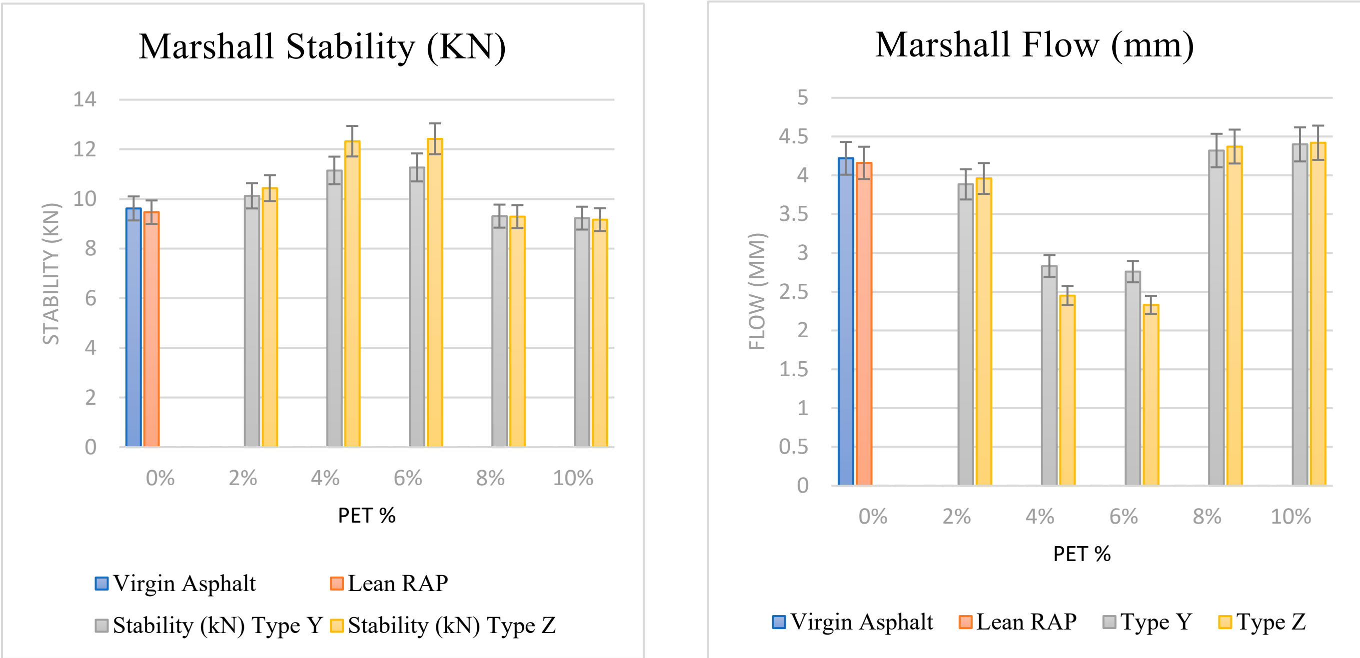


Figure 7. Stability and flow test results.

The improved stability of the Type Z mix can be accredited to the enhanced stiffness of RAP due to its exposure to traffic loads and environmental elements [88]. The incorporation of RAP in the mix makes it more resistant to deformation under loads owing to increased stiffness, thereby imparting higher stability to asphalt [88]. Another factor contributing to this phenomenon is the modification of asphalt with PET, which improves the cohesion between aggregate and binder [86]. The increased cohesion between aggregate and binder accounts for better load distribution and resistance to shear forces, resulting in higher stability and lower flow characteristics for the Type Z mix design.

3.6. Results of Environmental and Economic Assessments

Owing to the environmental assessment conducted using One Click LCA, the lifetime emissions of CO_2 from each asphalt mix under study were evaluated. Unmodified bitumen was accredited with the highest emissions, measuring around 145 Tons. The major reason behind the high carbon footprint of unmodified asphalt is its reliance on raw bitumen, which is produced by burning a large amount of fuel. The combustion of high quantities of fuel in the case of unmodified asphalt accounts for it possessing a massive carbon footprint [90]. It is evident from the findings that the Type Z mix had the lowest CO_2 emissions of all materials, amounting to 68 Tones, making it the optimal asphalt mix. As compared to unmodified mix, Type Z asphalt results in a 53% reduction of CO_2 emissions. This reduction in emissions occurs due to the 40% replacement of new bitumen with recycled bitumen in the case of the Type Z mix. Production of asphalt is a carbon-intensive process, which accounts for the majority of embodied emissions associated with it. Therefore, by reducing the amount of virgin asphalt required in its mix design, Type Z mix cuts down a majority of embodied emissions associated with asphalt, accounting for its substantial reduction in CO_2 emissions [91]. Type Y mix was the second-best alternative, with 139 Tons of CO_2 emissions. Emissions in the Type Y mix are 4.5% lower than the unmodified mix due to the replacement of new bitumen with PET. The reduction in the required quantity of new bitumen in the case of Type Y mix results in lowering the embodied emissions associated with the production of raw bitumen asphalt, which accounts for its lower overall CO_2 emissions. However, the Type Y mix does not replace a large amount of new bitumen, unlike the Type Z mix, which is why its emissions are much higher than those of the Type Z mix.

The findings regarding the carbon emissions of asphalt types under scrutiny are in line with the prevalent literature. Eliza et al. [92] documented a 55% to 64% reduction in carbon emissions of RAP-modified asphalt mixtures as opposed to virgin asphalt. Schuur et al. [93] backed up these findings by reporting a 57% reduction in carbon emissions associated with RAP-modified mixtures when compared to unmodified asphalt in their study. For PET-modified asphalt, Fernandes documented a 5% reduction in carbon emissions, which is similar to the findings reported in the current study. The findings of Xing Zhou validate the carbon emissions measured for PET-modified asphalt by reporting lower emissions as compared to unmodified asphalt [94]. Most of the mentioned studies accredit the lowering of carbon emissions to the replacement of new asphalt with a recycled one, as the embodied emissions of the new asphalt are exponentially higher than aged asphalt, accounting for its alarming carbon footprint [92].

The economic assessment conducted in this study presents the costs incurred for the different HMA mixes under consideration. The detailed expenditures conceived for each asphaltic mix are tabulated in Table A4. The analysis illustrates that the unmodified HMA mix had the highest cost (USD 497,076.64) among the other mixes under consideration. The high cost of new bitumen is the definitive factor that exponentially elevates the total cost of unmodified bitumen compared to other options. The Type Y mix with PET modifiers had a 2.3% lower cost than the unmodified mix due to replacing new bitumen with PET additives (USD 495,219.2). Even though the Type Y mix has some added expenditures, such as the cost of shredding PET, preparation of PMB, and replacement of bitumen, results indicate a small but notable cost-cutting due to the expensive nature of new bitumen. The RAP-modified mixture had an 11.2% lower cost than the unmodified mix due to the substitution of virgin asphalt with a recycled one, thus trimming the costs accumulated for raw materials (USD 441,313.3). The cost incurred for the Type Z mix measured USD 412,294.4, which is lower than all the other HMA mixtures. It marked a substantial 17.1% decrease in its cost as compared to the cost of the unmodified HMA mixture. This is credited to the substantial replacement of new bitumen with RAP and PMB in the case of Type Z mix, which significantly lowers the total cost of the mixture. The quantity of new bitumen substituted in the case of Type Z mix is even higher than RAP modified HMA mix as the Type Z mix reinstates new bitumen with 40% Rap and 6% PMB, unlike lean RAP, which does not offer plastic modification.

The prevailing literature documents findings similar to those of other studies, thus validating the contribution of the current research. Rafiq reported a 20% reduction in material costs or asphaltic mixtures of RAP and polymers when measured against unmodified asphalt [95]. Sarmad argued that it is possible to further reduce the materials cost of RAP by incorporating polymer-modified bitumen in it, as illustrated in the current study [96]. This phenomenon is observed due to the replacement of new bitumen in higher amounts by using PMB and RAP as opposed to using them separately in asphalt mixtures [96]. Literature addressing the cost-effectiveness of PET-modified asphalt is limited. However, studies have shown that PET-modified asphalt reduces material costs by up to 8.4% when used in substantially high percentages [97].

4. Conclusions and Recommendations

This paper adopted a multi-stepped approach to evaluate the effect of PET-RAP modification on the structural stability and performance of pavements. The characteristics of PMB were assessed and compared to that of pure bitumen. The PMB was used in different proportions with reclaimed asphalt to create multiple types of samples based on the quantities of PET and RAP in the mix. The samples were used to perform different tests that evaluated the performance of asphaltic concrete. The tests performed were used to determine the cracking resistance (ITS test), fatigue resistance (ITFS test), rutting resistance (Wheel Tracking Test), and Marshall stability and flow of PET-RAP modified asphalt. The results obtained from this study suggest that PET-modified bitumen enhances the resistance to deformation, albeit at the cost of reduced ductility. The PET-RAP modified asphalt (Type

Z) with 6% PET and 40% RAP content outperformed other samples in performance tests, demonstrating superior fatigue resistance, rutting resistance, and moisture susceptibility. The Type Y mix, with 6% PET, showed the highest resistance to fatigue failure. Economically and environmentally, the Type Z mix with 6% PET proved to be the most beneficial, reducing material costs by 17% and carbon emissions by 53% over a 20-year lifecycle, underscoring the potential for sustainable infrastructure).

This study illustrates the effect of using PET-RAP-modified asphalt on the structural stability and sustainable development of pavements through extensive experimentation and BIM-based studies. For future studies, researchers may focus on evaluating the effects of using different types of aggregates with PET-RAP asphalt. Furthermore, the effects of utilizing the Warm Mix Asphalt paving approach compared to Hot Mix Asphalt in the backdrop of reclaimed asphalt and PET modifiers should be assessed extensively. Future studies should also focus on developing reagents that preserve the ductility of PET-RAP-modified asphalt so that its inherent ductility as a flexible pavement is not compromised. RAP and PET have a hardening effect on asphalt, which can lead to increased deterioration in pavements, especially under low temperatures. This aspect of RAP-PMB asphalt should be assessed in the follow-up studies to build on the knowledge established by this research. Moreover, a detailed Life Cycle Cost Assessment (LCCA) should be conducted to holistically evaluate the economic feasibility of using RAP-PMB-modified asphalt. Such studies should adopt a case study approach to provide more accurate insights into the economics of RAP-PMB-modified asphalt, which would vary highly on a case-to-case basis.

The current study did not address the micro-structure of the Type Z mix due to limited institutional capacity and access to equipment necessary for relevant investigations. The experiments were conducted in Pakistan, a developing country where there is no access to the necessary equipment for such experimentation. In the future, the authors aim to utilize the labs of international universities to collaborate on such experimentation. Nevertheless, micro-investigations should be conducted to reveal the interaction between PET, RAP, fresh bitumen, and aggregates to advance the body of knowledge regarding the conceived mix design.

Author Contributions: Conceptualization: Z.W.S., M.U.A.K. and A.H.; methodology: M.U.A.K. and A.H.; software: Z.W.S.; validation: A.H. and F.K.A.; formal analysis: Z.W.S. and M.U.A.K.; investigation: Z.W.S. and M.U.A.K.; resources: A.H., F.K.A. and F.U.; data curation: Z.W.S., M.U.A.K. and A.H.; writing—original draft preparation: Z.W.S. and M.U.A.K.; writing—review and editing: A.H., F.K.A. and F.U.; visualization: Z.W.S. and M.U.A.K.; supervision: A.H. and F.U.; project administration: A.H., F.K.A. and F.U.; funding acquisition: F.K.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Researchers Supporting Project number (RSP2024R264), King Saud University, Riyadh, Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are available with the first two authors and can be shared upon reasonable request. It cannot be shared publicly due to institutional restrictions.

Acknowledgments: The authors extend their appreciation to the Researchers Supporting Project number (RSP2024R264), King Saud University, Riyadh, Saudi Arabia, for funding this research work. The authors also owe gratitude to the NUST Institute of Civil Engineering (NICE) and its students for supporting this research.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

Abbreviations	**Full-Form**
RAP	Reclaimed Asphalt Pavement
PET	Polyethylene Terephthalate
PMB	Polymer Modified Bitumen
BIM	Building Information Modelling
LCA	Life Cycle Assessment
HMA	Hot Mix Asphalt
UTM	Universal Testing Machine

Appendix A

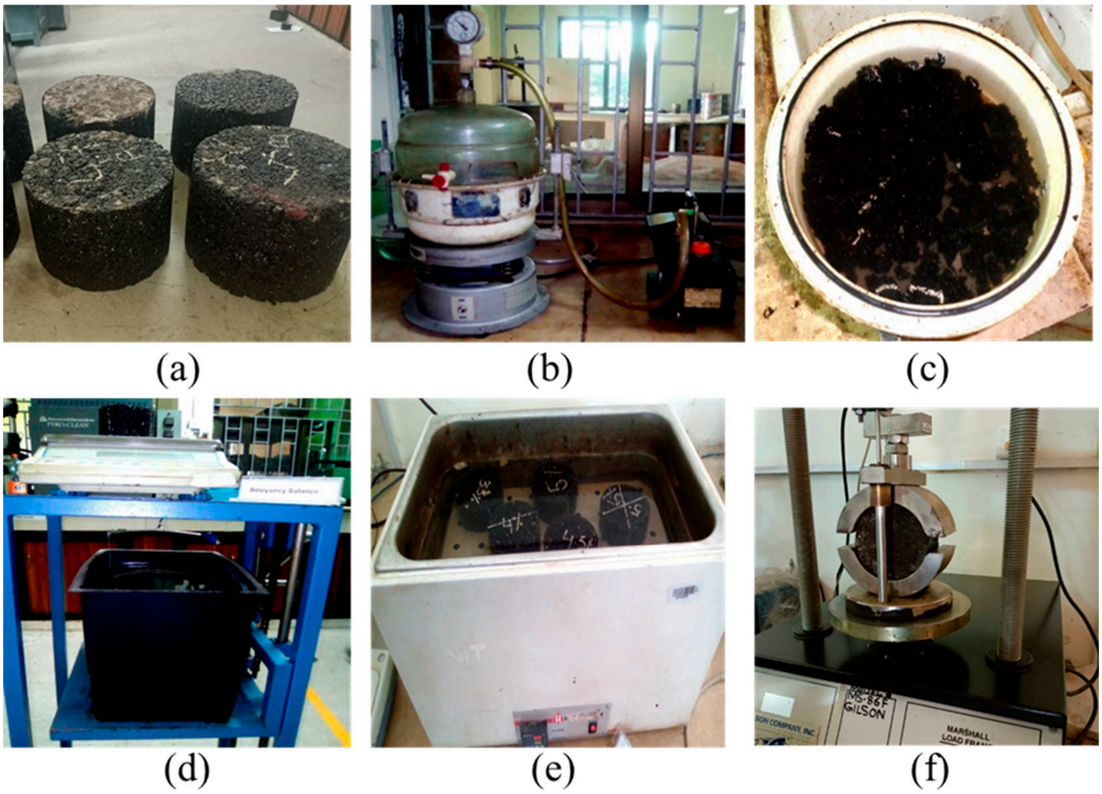
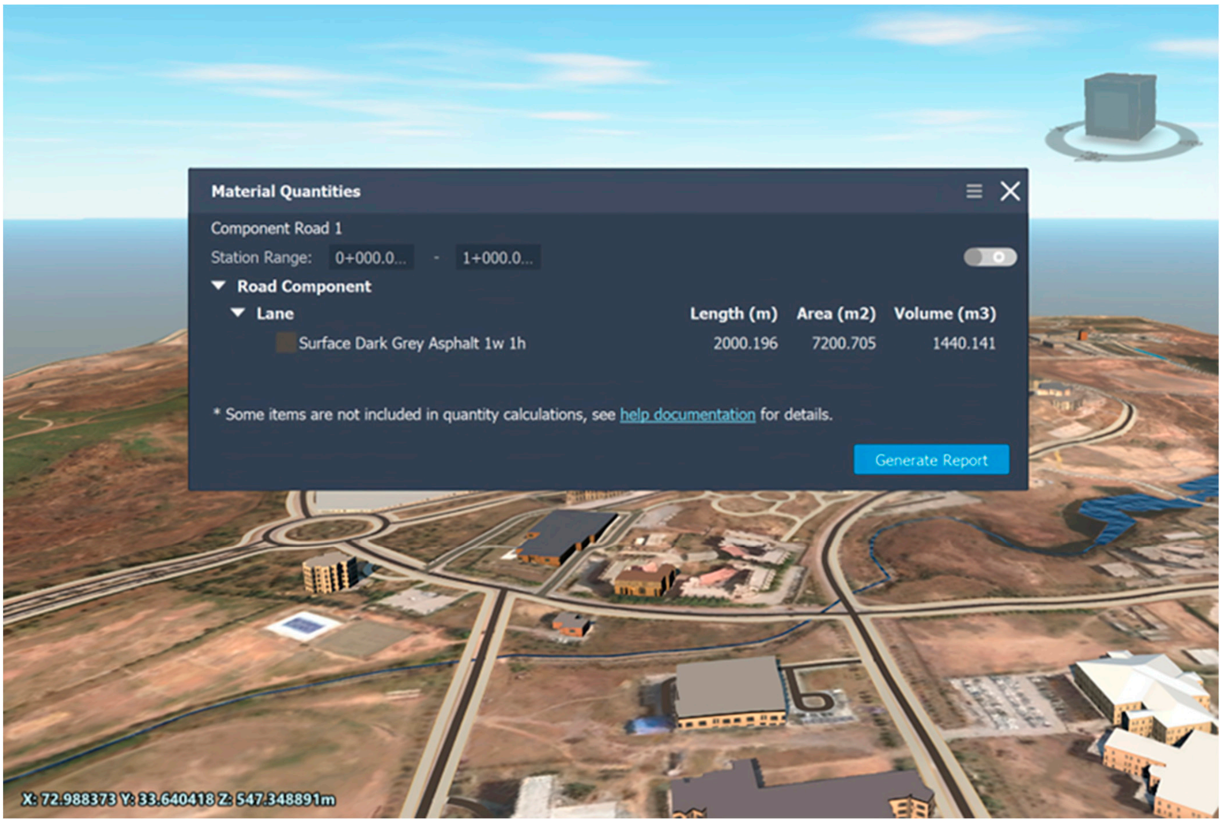


Figure A1. Marshall Mix Design tests: (**a**) samples prepared for Marshall test; (**b**) determination of Maximum Specific Gravity using pycnometer; (**c**) asphalt sample in pycnometer; (**d**) determination of Bulk Specific Gravity using buoyancy balance; (**e**) conditioning of sample in water bath at 60 °C for 1 h; (**f**) determination of Marshall stability of samples.

(**a**)

(**b**)

Figure A2. *Cont*.



(**c**)

Figure A2. (**a**) Autodesk Infraworks Model; (**b**) segment of pavement selected for assessment; (**c**) extracted quantities of asphalt for analysis.

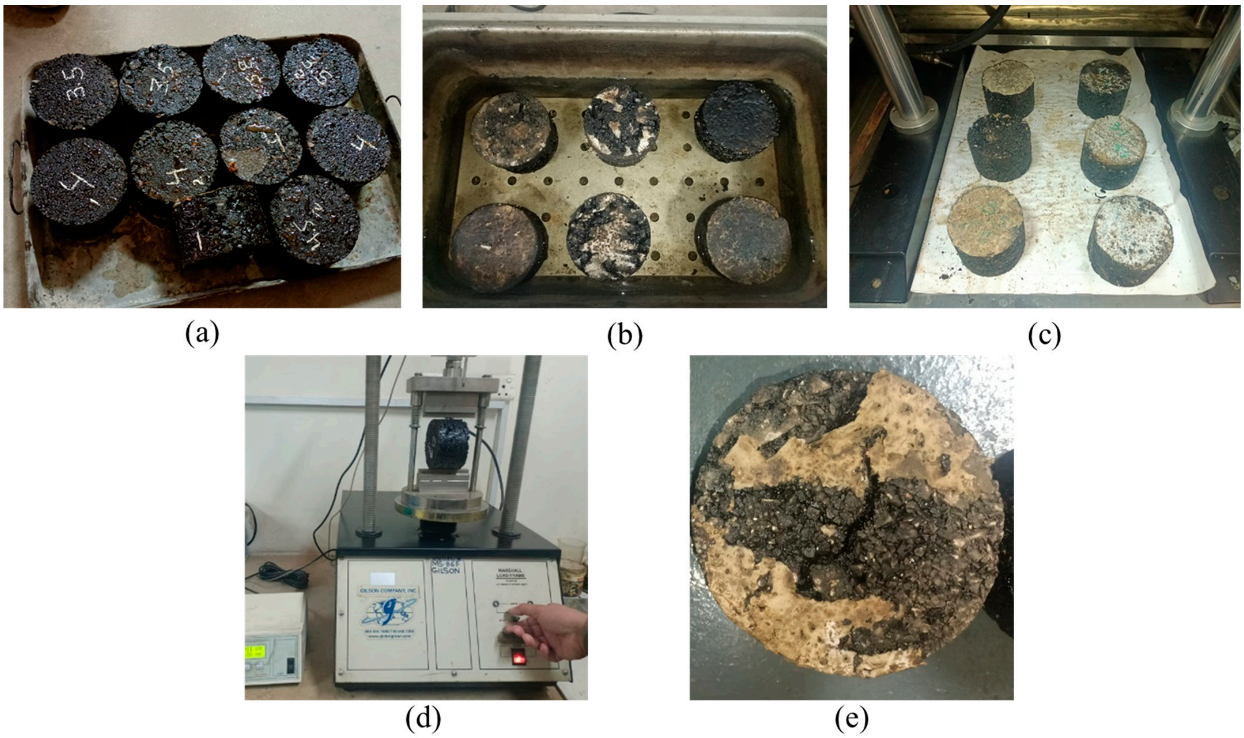


Figure A3. Moisture Susceptibility test: (**a**) samples prepared for the test; (**b**) conditioning of samples in a water bath for 24 h; (**c**) unconditioned and conditioned samples kept at 25 °C for 4 h; (**d**) load assembly for testing sample; (**e**) fractured sample post test.

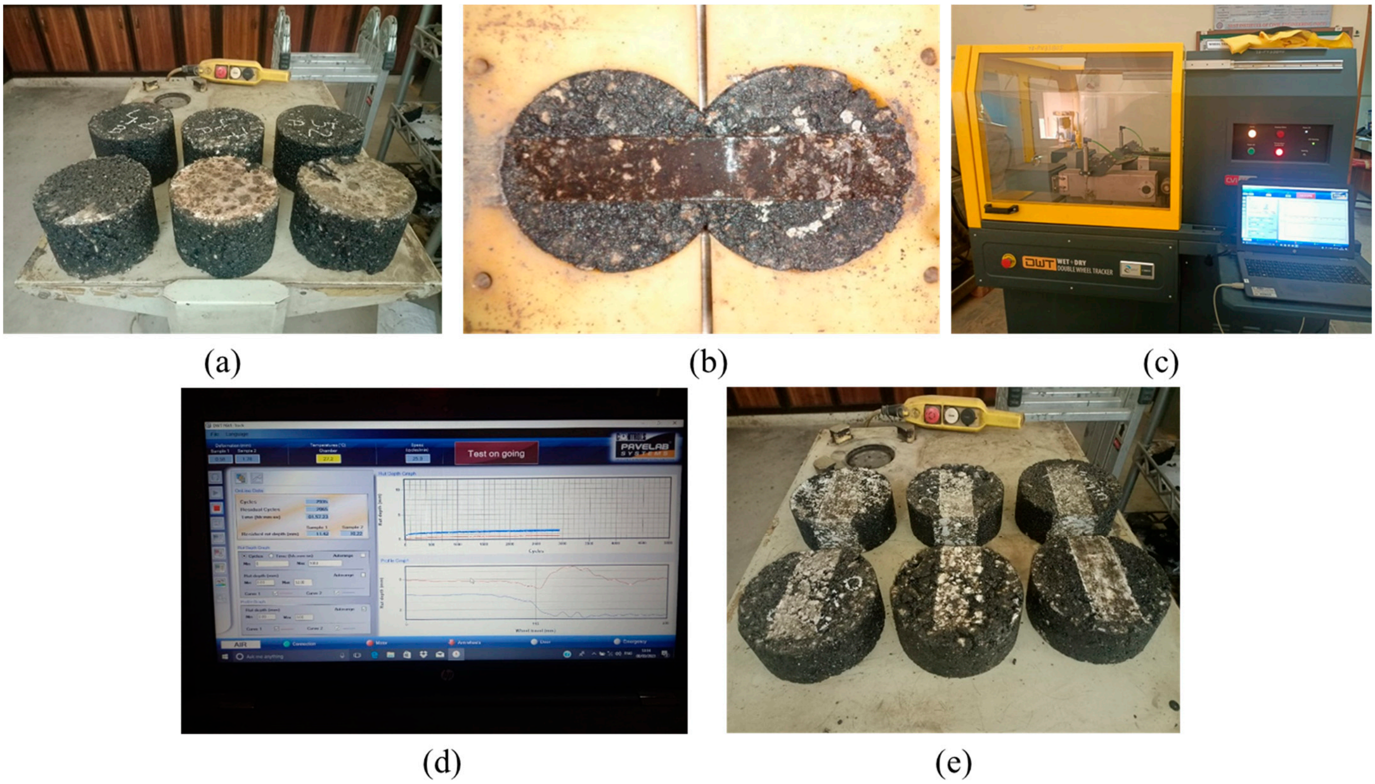


Figure A4. Hamburg Wheel Test: (**a**) samples prepared for Hamburg Wheel Test; (**b**) samples placed in Wheel Tracking Apparatus; (**c**) apparatus operating at 10,000 passes on samples; (**d**) test results being recorded; (**e**) deformed samples after 10,000 passes.

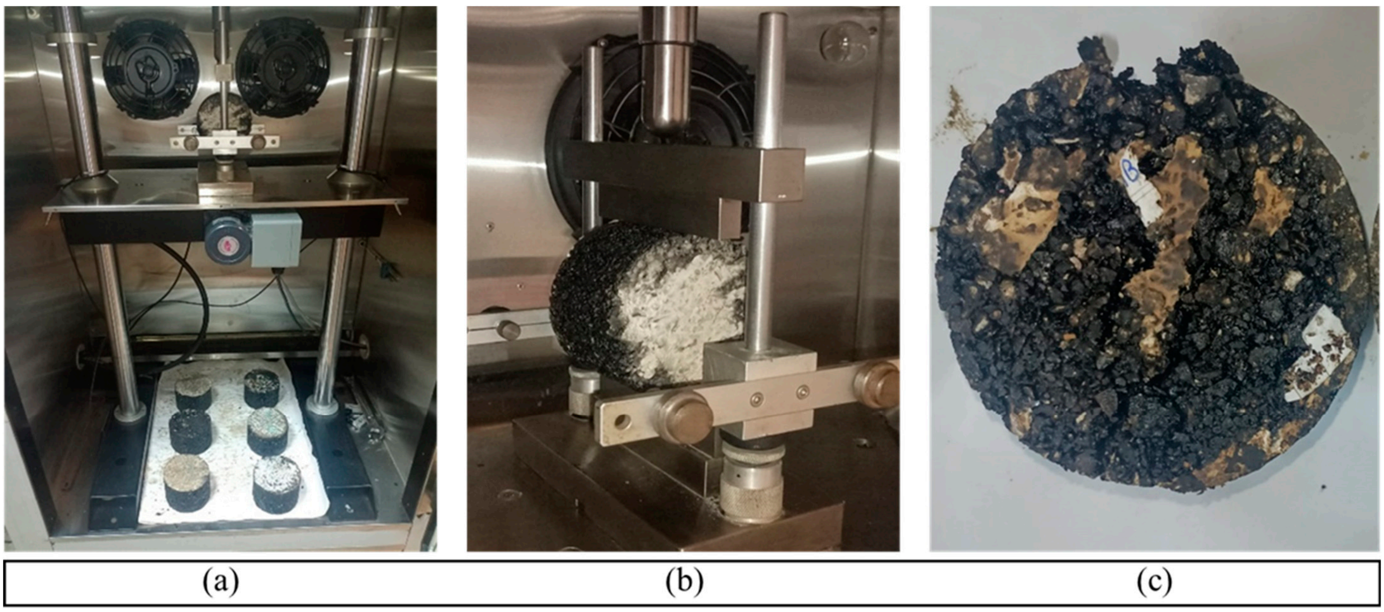


Figure A5. Indirect Tensile Fatigue test: (**a**) samples prepared for ITFT Test; (**b**) ITFT load assembly; (**c**) fractured sample post failure.

Appendix B

Table A1. Past studies on the use of PET and RAP in pavements.

S. No.	Author	Additive	Ductility	Viscosity	Softening Point	Penetration	Stability	Flow	Rutting Resistance	Fatigue Resistance	ITS	Reference
1.	Rabindra Kumar Padhan	PET	_	↑	↑	↓	↑	_	↑	↑	_	[26]
2.	A.A. Gupta	PET	↓	↑	↑	↓	_	_	↑	↑	↑	[27]
3.	Zohreh Dehghan	PET	↓	↑	↑	↓	↑	↓	_	↑	_	[33]
4.	Metin Gürü	PET	_	↓	↓	↓	↑	↓	↑	↑	↑	[28]
5.	Soheil Heydari	PET	↓	_	↑	_	↑	↓	_	_	_	[34]
6.	Yuhong Wang	RAP	↓	_	_	_	↑	↓	↑	↓	↓	[35]
7.	Amirhossein Norouzi	RAP	↓	↑	_	↓	_	_	↑	↓	_	[29]
8	Ali Zalghout	RAP	↓	↑	↑	↓	_	_	↑	↓	↑	[36]
9.	Donald E. Watson	RAP	↓	_	_	_	↑	↓	↑	↓	↑	[30]
10	A K Arshad	RAP	_	↑	↑	↓	↑	↓	↑	_	↑	[37]

Table A2. Testing matrix for performance tests.

Tests	**PET %**					
	0%	**2%**	**4%**	**6%**	**8%**	**10%**
ITFT Test	6	6	6	6	6	6
Hamburg Wheel Tracking Test	6	6	6	6	6	6
Moisture Susceptibility Test	12	12	12	12	12	12
Total Samples	24	24	24	24	24	24

Table A3. Blend Ratios for HMA mix samples: (**a**) controlled virgin asphalt mix; (**b**) lean RAP asphalt mix; (**c**) PMB modified asphalt mix; (**d**) PMB-RAP modified asphalt mix.

(a)	**Controlled Virgin Asphalt Mix**					
	Bitumen Content					
Aggregate Sizes (mm)	3%	3.50%	4%	4.50%	5%	5.50%
19	0	0	0	0	0	0
12.5	204	203	202	201	200	198
9.5	146	145	144	143	143	142
4.75	233	232	230	229	228	227
2.38	233	232	230	229	228	227
1.18	233	232	230	229	228	227
0.075	52	52	52	52	51	51
Pan	64	64	63	63	63	62
Bitumen	36	42	48	54	60	66
(b)	**Lean RAP (40%) Modified Mix**					
	Bitumen Content					
Aggregate Sizes (mm)	3%	3.50%	4%	4.50%	5%	5.50%
19	0	0	0	0	0	0
12.5	122.22	121.59	120.96	120.33	119.7	119.1
9.5	87.3	86.85	86.4	85.95	85.5	85.05
4.75	139.68	138.96	138.24	137.52	136.8	136.1
2.38	139.68	138.96	138.24	137.52	136.8	136.1
1.18	139.68	138.96	138.24	137.52	136.8	136.1
0.075	31.43	31.27	31.104	30.94	30.78	30.62
Pan	38.4	38.21	38.02	37.82	37.62	37.42
Bitumen	21.6	25.2	28.8	32.4	36	39.6

Table A3. *Cont.*

(c)	**PMB Modified Asphalt Mix**					
	PET *w*/*w* of OBC					
Aggregate Sizes (mm)	0%	2%	4%	6%	8%	10%
19	0	0	0	0	0	0
12.5	200.76	200.76	200.76	200.76	200.76	200.76
9.5	143.4	143.4	143.4	143.4	143.4	143.4
4.75	229.44	229.44	229.44	229.44	229.44	229.44
2.38	229.44	229.44	229.44	229.44	229.44	229.44
1.18	229.44	229.44	229.44	229.44	229.44	229.44
0.075	51.62	51.62	51.62	51.62	51.62	51.62
Pan	63.1	63.1	63.1	63.1	63.1	63.1
Bitumen	52.8	51.74	50.69	49.63	48.58	47.52
PET	0	1.06	2.11	3.17	4.22	5.28
(d)	**PMB-RAP Modified Asphalt Mix**					
	PET *w*/*w* of OBC					
Aggregate Sizes (mm)	0%	2%	4%	6%	8%	10%
19	0	0	0	0	0	0
12.5	120.2	120.2	120.2	120.2	120.2	120.2
9.5	86	86	86	86	86	86
4.75	137.7	137.7	137.7	137.7	137.7	137.7
2.38	137.7	137.7	137.7	137.7	137.7	137.7
1.18	137.7	137.7	137.7	137.7	137.7	137.7
0.075	31	31	31	31	31	31
Pan	38	38	38	38	38	38
Bitumen	31.68	31.05	30.41	29.78	29.15	28.51
PET	0	0.63	1.27	1.9	2.53	3.17

Table A4. Comparison of costs for preparing various asphalt mix designs.

Name	**Value**	**Unit**	**Reference**
Costs Incurred in Preparing Unmodified Asphalt (α)			
Unit cost of Pure Bitumen	356.64	USD/Ton	CSR
Density of Virgin Asphalt	2200	Kg/m^3	32
Unit Cost of Aggregates	35	USD/Ton	[98]
Quantity of Bitumen Required	139.39	Ton	
Quantity of Aggregates Required	2060.61	Ton	
Cost of Bitumen	49,712.5	USD	
Cost of Aggregates	44,7125	USD	
Unit Cost of Electricity	0.161	USD/kWh	[99]
Cost of Preheating Pure Bitumen	58.34	USD	[100]
Energy consumed in mixing 1 ton of Asphalt	85	kW/h	[101]
Productivity of Mixer	240	Ton/hr	[102]
Quantity of Asphalt to be prepared	3168	Ton	
Cost of Mixing Aggregate and Bitumen	180.6	USD	
Total cost of Producing Unmodified Asphalt	$497,076.64 USD		
Costs incurred in preparing PMB (β)			
Unit cost of waste PET	32	USD/ton	[103]
Total Material Cost of Waste PET	608.3	USD	
Quantity of PET to be Shredded	19.008	Ton	
Productivity of Shredder	3	Ton/Hour	[104]
Energy Consumption of Shredder	22	kW/h	[104]
Cost of Shredding PMB	25.43	USD/Ton	
Quantity of PMB to be prepared	19.008	Ton	
Productivity of asphalt mixer	240	Ton/Hour	[102]
Cost of Preparing PMB by mixing Shredded PET and bitumen	16.73	USD	

Table A4. *Cont.*

Name	Value	Unit	Reference
Cost of Mixing PMB, Bitumen, and Aggregates	180.6	USD	
Total cost of Producing PMB	$805 USD		
Costs incurred in preparing RAP (γ)			
Unit Cost of RAP	55	USD/Ton	[105]
Quantity of RAP required	1267.2	Ton	
Total cost for 40% RAP	69,696	USD	
Density of RAP	2000	Kg/m^3	[35]
Quantity of Required New Aggregates	1236.4	Ton	
Quantity of Required New Bitumen	83.7	Ton	
Cost of Bitumen	29,827.65	USD	
Cost of Aggregates	43,247	USD	
Cost of Preheating RAP	65	USD	
Cost of Pre-hating Unmodified Bitumen	58.4	USD/Ton	[100]
Cost of mixing RAP, Aggregates, and Virgin Bitumen (and PMB in Type-Z)	180.6	USD	
Total Cost of Producing Mix Containing RAP	$143,068 USD		
Cost of Unmodified Bitumen	$497,076.64 USD		
Cost of HMA mix Modified with RAP	$441,313.6 USD		
Cost incurred for Type Y Mix ($\alpha + \beta$)	$495,219.2 USD		
Cost incurred for Type Z Mix ($\alpha + \beta + \gamma$)	$412,294.4 USD		

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