# Modification of Bituminous Binder and Asphalt Mixture with Chemically–Processed Polyethylene Terephthalate (PET) Waste: A Systematic Literature Review

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**Abstract.** Polyethylene terephthalate (PET) waste is a major contributor to global environmental pollution, and if it is not well managed, it can seriously risk both environmental and human health. Chemical processing of PET offers a promising method to reduce these negative effects. Recent studies have investigated the chemically–processed of PET waste products in bituminous binder and asphalt mixture modifying. So, this paper aims to review the recent development of the incorporation of PET waste degradation products into bituminous binders and asphalt mixtures. The systematic literature review (SLR) was conducted utilizing the Web of Science (WoS) database. Reference papers were selected based on specific keywords and the Preferred Reporting Items for Systematic Reviews and Meta–Analyses (PRISMA) guidelines. The result shows the current research on PET waste preparation methods, synthesis, mixing method, and effects on bituminous binder characteristics and asphalt mixture. To create the "success story" of the implementation of PET waste degradation products in bituminous binder and asphalt mixture, some recommendations for future research are also provided in this paper.

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# 1 Introduction

Plastic is one of the most widely used materials by humans for daily needs. Since their initial manufacturing in the 1900s, plastic production has increased dramatically, with projections indicating a global output of 34 billion tons by 2050 [1]. This is because plastic has several advantageous properties, including its strength, water resistance, and the ability to shaped into different shapes and applications [2]. However, the high volume of plastic waste generated presents a substantial environmental and public health concern if it is not well managed. Globally, the plastic recycling rate remains critically low, at only 9% [3]. Consequently, a significant proportion of untreated plastic waste is openly disposed of in landfills, incinerated, or contaminates marine ecosystems [3,4].

Polyethylene terephthalate (PET), which is the one of polymer types, contributes to environmental plastic pollution [5]. PET has excellent physical and chemical properties, such as resistance to oxidation and organic solvents, high stability, thermostability, and tensile strength, have made it one of the most widely produced polymers, ranking fourth globally [2,6,7]. However, the recycling rate of this type of plastic is very low, at less than 30% globally [2]. Despite its prevalence, the global recycling rate for PET remains critically low, at under 30%.

Generally, the handling of PET waste can be done by several processing methods. These methods consist of: primary recycling (closed–loop recycling) by combining PET waste with virgin PET; secondary (mechanical recycling) which is carried out by processing PET using the same equipment as the manufacture of virgin PET; tertiary (chemical recycling) which uses the PET degradation process into components that can be reused; and quarternary recycling which uses the PET combustion process to produce energy[8,9]. Among the four methods, the tertiary method has a promising potential in the PET waste processing industry, as it can produce high–priced by–products that can support the circular economy, such as: paraxylene (PX), ethylene glycol (EG), and carbon nanotubes (CNT) [8].

In practical application, various solvents–including water, amines, alcohols, and acids–can degrade or depolymerize PET, resulting monomeric products such as terephthalic acid (TPA), dimethyl terephthalate (DMT), bis(2–hydroxyethyl) terephthalate (BHET/BHETA), and ethylene glycol (EG), or even oligomers and other chemicals [9–11]. For example, research by Cosimbescu et al. successfully achieved high–purity TPA (97–98%) from PET using a combination of NaOH and EG solvents [12]. Similarly, another study achieved the production of BHET with a purity of 93% via a glycolysis process catalyzed by $Fe_3O_4$ nano catalysts [13].

Furthermore, chemically–processed PET waste products have been utilized as modifiers in bitumen and asphalt mixtures. For instance, Padhan et al. demonstrated that incorporating BHET as a bitumen modifier markedly improved the anti–stripping properties and physico–chemical characteristics of the modified bitumen, as well as enhanced the Marshall stability of asphalt mixtures [14]. Zou et al. employed BHET obtained through the aminolysis of PET waste as a bitumen modifier, reporting a 14% increase in resilient modulus along with 13% and 23% improvements in dry and wet indirect tensile strength (ITS), respectively, compared to control mixtures [15]. Additionally, another investigation observed that modified bitumen exhibited a reduced softening point difference (0.3–0.7°C), which was attributed to enhanced compatibility between PET and bitumen, alongside significantly improved storage stability[16].

From the after–mentioned context above, the extensive research has been conducted on the chemical treatment of PET waste and the implementation of its synthesized products in bitumen and asphalt mixtures. However, current research on PET degradation methods remains limited, primarily concentrating on a narrow range of synthesis techniques, specifically aminolysis and glycolysis. Moreover, the increasing body of research in this area has not been comprehensively summarized, causing a challenge for new researchers seeking to identify relevant topics. Therefore, this article aims to contribute to the state–of–the–art by systematically collecting, critically analyzing, and synthesizing the existing literature on the use of chemically–processed of PET waste products in bitumen and modified asphalt mixtures, employing a systematic literature review (SLR) methodology.

## 2 Method

**Figure 1** shows the SLR flowchart diagram for this article. The data are collected on April 14, 2025, from original articles from Web of Science (WoS) database. The prompt search conducted with the keywords: "waste*" AND "polyethylene terephthalate" AND "chemical recycle" AND "bitumen". Inclusion and exclusion criteria were applied during this stage, specifically:

- Publication year of the literature within the last 10 years (2015–2025), with the distribution of publication years;
- Only journal articles and proceedings were used; and
- Only articles published in English were included.

The next stage is data selection and reduction using the Preferred Reporting Items for Systemic Reviews and Meta–Analyses (PRISMA) method [17].

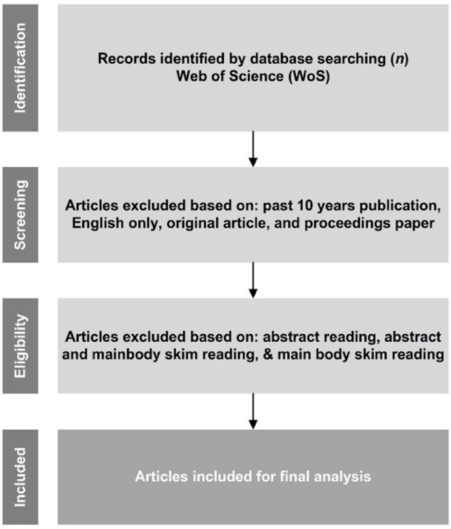

**Figure 1.** SLR Writing Diagram in This Research

Lastly, the collected data were combined and synthesized using narrative descriptions. At this stage, it can be determined that the focus of this literature study was organized into several research questions (RQ) as follows.

- RQ1: What is the chemical synthesis techniques are employed to produce PET waste monomers as bituminous binder and asphalt mixture modifier?
- RQ2: How are chemically–processed PET waste product incorporated as modifiers in bituminous binder and asphalt mixture?
- RQ3: What are the laboratory performance characteristics of bituminous binder and asphalt mixture modified with chemically–processed PET waste product?

# 3 Result and Discussion

## 3.1 PET Waste Preparation

PET waste was obtained from waste drinking water bottles. The collected bottles are then separated according to their parts, such as caps, labels, and body parts. However, some studies do not perform this stage, because of to investigate the tolerance of the preparation process to the purity level of the synthesized PET [18]. After that, the bottles were shredded to a small size using a machine. Then, the bottles were washed using water with soap solution to remove dirt and oil. The next step is to dry the shredded bottles in an oven at a certain temperature and time. Briefly, these preparation stages can be seen in **Table 1.**

**Table 1.** PET Waste Preparation

| Waste PET Source | Shredding Process | Washing Process | Drying Process | Ref. |
|---|---|---|---|---|
| N/A | N/A | N/A | N/A | [19] |
| Beverage bottles | Shredded into 10 × 10 mm pieces | √ | Dried twice; ambient temperature for 48 hours and vacuum oven at 50 ºC | [20] |
| Different sources | Shredded into small pieces | √ | Dried in oven for 2 hours at 40ºC | [21] |
| Bottles | Shredded into small pieces | N/A | N/A | [22] |
| Bottles | Shredded into small pieces | √ | √ | [18] |
| Bottles | Shredded into small pieces | N/A | N/A | [23] |
| Bottles | Shredded into small pieces up to 5 cm | √ | Dried in oven for 4 hours at 80 ºC | [14] |
| Bottles | Shredded into small pieces | N/A | N/A | [24] |
| Bottles | Shredded into 5 × 5 mm pieces | √ | Dried in oven for 4 hours at 80ºC | [25] |

N/A = not described in the paper
√ = described, but not explained in detail

## 3.2 Synthesis of Monomer Products from PET Waste

### *3.2.1 Aminolysis*

Aminolysis is the degradation process of PET waste using various types of amines, such as ethanolamine, triethanolamine, and polyamines as degradation agents and catalysts such as zinc acetate [11]. The temperature used for this synthesis process is between 130–160ºC and the time required ranges from 2–8 hours. Furthermore, the yield and purity levels of the PET waste monomer products obtained are very high, so it is very potential to be applied on a larger production scale [11]. From the literature study that has been conducted, aminolysis is the most widely used method as shown in **Table 2**.

**Table 2.** Synthesis of Monomer Products from PET Waste via Aminolysis Method

| Degradation Agents | Catalyst | Temperature (ºC) | Time (hours) | Ref. |
|---|---|---|---|---|
| EA | – | Tidak dijelaskan | 4 | [22] |
| TETA | – | 140 | 2 | [21] |
| EA | – | N/A | 8 | [14] |
| EA | – | 130 – 140 | 8 | [24] |
| EA dan Triethanolamine | – | 160 | 3 – 4 | [19,26] |
| TETA | – | 130 – 140 | 2 | [25] |
| EA, 3–amino–1–propanol, 2–amino–1–butanol, 5 amino–1–pentanol, diethanolamine, n–hexylamine, and n–dodecyl–amine | Zinc acetate | 130 – 150 | 2 | [18] |

EA = Ethanolamine
TETA = Triethylenetetramine

### *3.2.2 Glycolysis*

Glycolysis is the process of degrading PET waste into its monomers through reactions with glycol compounds, such as diethylene glycol (DEG) and polyethylene glycol (PEG) with the help of a catalyst in the form of zinc acetate. The summary of the literature shows that, the use of this method requires a high temperature, which is about 190 – 240ºC and a degradation time of 5 hours. This method produces BHET, which can be purified and used to make new PET [11]. **Table 3** shows a summary of the use of the glycolysis method in the reviewed literature.

**Table 3.** Synthesis of Monomer Products from Waste PET via Glycolysis Method

| Degradation Agents | Catalyst | Temperature (ºC) | Time (hours) | Ref. |
|---|---|---|---|---|
| DEG, PEG400, and PEG600 | Zinc acetate | 190 – 240 | 5 | [20] |
| EG | Zinc acetate | 190 | 5 | [23] |

EG = ethylene glycol

## 3.3 Mixing Method

Wet method is the most widely used method in blending PET degradation products into bitumen. Previously, the wet method was a technique to blend waste materials through direct mixing with bitumen to produce a homogeneous mixture [27]. In practice, some studies incorporated other materials, such as styerene–butadine–styerene (SBS), crumb rubber (CR), reclaimed asphalt pavement (RAP), and methylene diphenyl diisocyanate (MDI) as bitumen modifiers. In this process, the mixing temperature, speed, and time need to be considered. In summary, this mixing method is shown in **Table 4**.

**Table 4.** Mixing Method of PET Waste Monomer Products to Bitumen

| Result of PET Degradation | Variation of PET Degradation Result | Other Materials Blended | Mixing Temperature (ºC) | Mixing speed (rpm) | Mixing Time | Ref. |
|---|---|---|---|---|---|---|
| N,N'–bis(2 hydroxyethyl) terephthaldiamide | 1% and 3% by weight of bitumen | – | 160 – 180 | 270 – 300 | Up to 4 hours | [19] |

| Result of PET Degradation | Variation of PET Degradation Result | Other Materials Blended | Mixing Temperature (°C) | Mixing speed (rpm) | Mixing Time | Ref. |
|---|---|---|---|---|---|---|
| Glycolysis product | 5.0%, 6.5%, and 7.1 % by weight of bitumen | Methylene diphenyl diisocyanate (MDI–50) | 140 | 2,000 – 3,000 | 1 hour 05 minutes | [20] |
| N/A | 1%, 2%, and 3% by weight of bitumen | – | 140 | 1,600 | 30 minutes | [21] |
| N/A | 3% and 5% by weight of bitumen | Styrene butadiene–styrene (SBS) | 170 – 180 | 5,000 | 2 hours | [22] |
| N1, N4–bis(2–hydroxyethyl)terephtalamide; N1, N4–didodecylterephtalamide; N1, N4–dihexylthalamide; ground PET; N1, N4–bis(3–hydroxypropyl)terephtalamide; N1, N4–diethyl– N1, N4–bis(2–hydroxyethyl)terephthalamide; N1, N4–bis(5–hydroxypentyl)terephtalamide; N1, N4–dioctylterephtalamide | 5% by weight of bitumen | | 130 | 400 | 5 minutes | [18] |
| Degradated polyethylene terephtalate (DPET) | 2%, 4%, 6%, 8%, 10%, and 12% by weight of bitumen | – | 200 | 250 | 2 hours | [23] |
| Bis(2–hydroxy ethylene) terephthalamide | 2% by weight of bitumen | 4,4–Diphenylmethane Diisocyanate (MDI) | 90 – 130 | N/A | 2 hours | [14] |
| Bis(2–hydroxy ethylene) terephthalamide | 3%, 5%, and 7% by weight of bitumen | Crumb rubber (CR) | 180 | 5,000 | 1 hour | [24] |
| N/A | 1%, 1.5%, and 2% | Recycled asphalt | 150 | 4,000 | 2 hours | [25] |

| Result of PET Degradation | Variation of PET Degradation Result | Other Materials Blended | Mixing Temperature (°C) | Mixing speed (rpm) | Mixing Time | Ref. |
|---|---|---|---|---|---|---|
| | by weight of bitumen | pavement (RAP) | | | | |

## 3.4 Effects on Bituminous Binder Characteristics

### *3.4.1 Effect of Chemically–Processed of PET Waste Products on Physical Characteristics*

The physical properties of bitumen are assessed through various tests, including conventional bitumen tests (penetration, softening point, and ductility) and storage stability. Regarding conventional tests, Shirokova *et al.* [19] reported an increase in the softening point of their modified bitumen. Similarly, another study demonstrated that incorporating PET waste monomer into high–volume reclaimed asphalt pavement (RAP) led to an elevated softening point but a reduced penetration value compared to conventional bitumen [25]. Furthermore, under short–term aging conditions, all modified bitumens consistently exhibited an increased softening point and decreased penetration [14].

Furthermore, bitumen storage stability tests are conducted to evaluate the homogeneity of modified bitumen during storage [28]. Test specimens are typically poured into a container, aged at 163°C for 48 hours, cooled, and then sectioned into three pieces according to ASTM D5892 [22,24]. The literature suggests that the addition of PET waste monomer can actually reduce the softening point difference in modified bitumen, likely due to the formation of a stable microstructure with the bitumen [22,24].

### *3.4.2 Effect of Chemically–Processed of PET Waste Products on Rheological Characteristics*

The rheological properties of bitumen describe its flow and deformation behavior under varying temperatures and loading frequencies to evaluate its performance as bituminous binder in asphalt mixture [29]. These properties are determined through several tests, including viscosity test, dynamic shear rheometer (DSR) analysis, which assesses rheological parameters through frequency sweep and multiple stress creep and recovery (MSCR); and bending beam rheometer (BBR) testing, which evaluates creep stiffness at low temperatures.

Viscosity testing of bitumen quantifies its resistance to flow at a given temperature, which is crucial for determining appropriate mixing, transportation, and compaction temperatures during road construction [30]. This test can be performed using various methods, such as Brookfield viscosity (ASTM D4402), kinematic viscosity (ASTM D127), and Saybolt–Furol viscosity (ASTM D88). The result of this literature review indicates that Brookfield viscosity testing is the most employed method and showed an improvement in stiffness and viscosity in SBS–bitumen, CR–bitumen, and RAP that incorporating of the degradation of PET [22,24,25].

Furthermore, DSR testing is utilized to evaluate the viscoelastic properties of bitumen, particularly its resistance to deformation under traffic loads and high temperatures [29]. This test was conducted for the assessment of three types of properties based on variations in temperature and loading frequency. First, the complex shear modulus (G*) and phase angle (δ) is determined at fixed temperature and various loading frequency. These values are then used to calculate bitumen rutting resistance (G*/sin δ) and fatigue resistance (G*sin δ). As depicted in **Table 5,** previous studies often report only the rutting and fatigue resistance values from DSR tests, rather than the complex shear modulus and phase angle directly. The general trend observed is an increase in rutting and fatigue resistance values. However, some instances show a decrease in fatigue value when PET waste monomer is incorporated compared to control bitumen.

For the second parameter, the frequency sweep test, results typically show only the complex shear modulus (G*) and phase angle (δ) values as a function of loading frequency (rad/s) at a fixed temperature. **Table 5** indicates an increasing trend in the complex shear modulus and a decreasing trend in the phase angle in these tests.

The next is the MSCR test evaluates bitumen's ability to resist permanent deformation at high temperatures through cyclic loading [31]. In this test, a shear load is applied for 1 second (creep), followed by a 9–second recovery period without load, repeated over several cycles at different stress levels [31]. The outcomes of this test include the percent recovery (R%), which signifies the bitumen's elastic recovery capacity, and non–recoverable compliance ($J_{nr}$), which indicates its susceptibility to permanent deformation. As shown in **Table 5**, the addition of PET waste monomer can lead to a decrease in the $J_{nr}$ value and an increase in the R% value, depending on the applied loading level and temperature.

**Table 5.** Test Results of Modified Bitumen Using DSR Machine

| DSR Test | | | | Frequency Sweep Test | | MSCR Property | | Ref. |
|---|---|---|---|---|---|---|---|---|
| **G*** | **δ** | **G*/sinδ** | **G*sinδ** | **G*** | **δ** | **R%** | **Jnr** | |
| – | – | ↑ | – | – | – | – | – | [19] |
| ↑ | ↓ | ↑ | – | – | – | – | – | [20] |
| – | – | ↑ | ↑↓ | ↑ | ↓ | ↑ | ↓ | [22] |
| ↑↓ | – | ↑↓ | ↑↓ | – | – | – | – | [18] |
| – | – | ↑ | ↑ | ↑ | ↓ | – | – | [14] |
| – | – | ↑ | ↑ | ↑ | ↓ | ↑↓ | ↓ | [24] |
| – | – | ↑ | ↑ | ↑ | ↓ | – | – | [25] |

↑ = increase; ↓ = decrease; ↑↓ = increase and decrease.

Lastly, creep stiffness at low temperature is a rheological characteristic of bitumen that is conducted to evaluate the viscoelasticity properties of bitumen at low temperatures using the BBR test [32]. The specimen in this test is a beam that is given a compressive load, resulting in load (N) and deflection/strain (μ) data. The data can be processed into a thermal stiffness value (stiffness [S]) in MPa and the value of the bitumen in releasing its internal stress or stress relaxation rate (m–value). The permissible stiffness value should not exceed 300 MPa and the minimum m–value should not be less than 0.3 in order to avoid crack reduction due to low temperature [32]. The literature study summarizes some BBR test results of modified bitumen showing better values compared to its conventional/control bitumen at a temperature of –12ºC and within the prescribed specification limits [14,22,25]. On the other hand, as the bitumen ages, the control and modified bitumen experience an increase in stiffness (S) and a decrease in m–value due to short–term thermo–oxidative bitumen which becomes stiffer and more brittle, thus reducing the resistance to cracking resistance at low temperatures [20].

### 3.5 Effect on Morphological Characteristics

Morphological examination aims to determine the dispersion characteristics of a material, in this case the modified bitumen. Morphological analysis has significance in describing the formation or separation of functional groups between bitumen and chemically–processed of PET waste product. Several types of tests are conducted to determine these characteristics, such as fourier transform infrared (FTIR) analysis, thermal analysis, scanning electron microscopy (SEM), fluorescence microscopy (FM), and atomic force microscopy (AFM).

FTIR analysis/spectroscopy, is a testing and analysis technique to identify the chemical properties of organic materials, polymers, and inorganic materials using infrared radiation with a certain wavenumber range [33]. In this context, FTIR analysis was used to characterize the functional groups in the synthesized PET waste or modified bitumen specimens as shown in **Table 6**. From the table, it is found that there is a trend of changes in functional groups from both the degradation process of PET waste and its blending into bitumen.

**Table 6.** Summary of FTIR Analysis Results

| Sample tested | Findings | Ref. |
|---|---|---|
| PET waste synthesis results | • Successful degradation of PET waste indicated by the disappearance of peaks in the range of 1,740–1,720 cm$^{-1}$ (C=O group) on the PET molecule.<br>• The formation of branched/crosslinked structure during polycondensation is indicated by the peaks in the range of 3,300–3,500 cm$^{-1}$ in the amino group (N–H). | [19] |
| Modified bitumen | • Ageing/oxidation process occurs which is characterized by an increase in carbonyl (C=O) and sulfoxide (S=O) groups.<br>• There was a smaller increase in ΔIS=O in the modified bitumen which indicates a better resistance to oxidation.<br>• The PU network formed can protect the bitumen matrix from the effects of heat and oxygen. | [20] |
| Modified bitumen | • There was a successful conversion of PET through the aminolysis process characterized by the presence of absorption peaks in the aromatic group and two amid groups.<br>• There were differences in the absorption peaks of unaged bitumen and aged bitumen. | [22] |
| Modified bitumen | • The in–situ polymerization technique of BHETA–PU in base bitumen, successfully confirmed the formation of a new polymer, polyurethane based on the formation of absorbance bands at 3,000 cm$^{-1}$, 3,446 cm$^{-1}$, and 3,446 cm$^{-1}$ for N–H groups and carbonyl bands at 1.711 cm$^{-1}$ and 1,724 cm$^{-1}$ which were not found in virgin bitumen and BHETA–PU. | [14] |
| Synthesized waste PET | • There was a loss of ester group peak at wavenumber 1,735 cm$^{-1}$ and the appearance of new amide peaks at 1,637 cm$^{-1}$ and 1,547 cm$^{-1}$ in the FTIR spectrum. Not only that, but the presence of primary alcohol was also shown at the peaks of 1,054 cm$^{-1}$, 1,637 cm$^{-1}$, and ,.547 cm$^{-1}$, so the PET and BHETA conversion was successfully carried out. | [24] |
| Waste PET synthesis results | • Aged bituminous RAP shows an increase in oxidative groups such as sulfoxide, anhydride, and carbonyl.<br>• The addition of PET reduces the intensity of these oxidative groups, which indicates that the oxidation process in modified bitumen can be suppressed by the presence of PET. | [25] |

Furthermore, thermal analysis is conducted to determine the properties of modified bitumen when heated, cooled, or even stored at a constant temperature using several methods, such as differential scanning calorimetry (DSC) and differential thermal/thermogravimetric analysis (DT/TGA). Liu, et al.'s research showed that ageing of modified bitumen can cause an increase in the glass transition temperature (Tg) using DSC test, which means that the bitumen is getting stiffer and more brittle [20]. The DSC test results also showed different peak transitions for each type of monomer added to the bitumen [18]. The use of another method, TGA, can also identify a significant percentage of mass loss in the constituents of modified bitumen, such as saturates, aromatics, CR, and BHETA at high temperatures [24].

SEM analysis is a method used to evaluate the morphological characteristics of modified bitumen by scanning the surface of a specimen using an electron beam in a specific magnification, scale, and focus [34]. The results of this test are microscopic images of the sample surface that have high resolution and can show the physical and morphological properties of the sample tested [34]. The use of this method shows the presence of new structures formed and good dispersion between particles of chemically–processed of PET waste product in the modified bitumen, which is not found in the control bitumen [22]. Another type of the test is FM that aims to observe the distribution of polymers and additives in the modified bitumen [25]. The test results using this method showed that the PET waste degradation particles were evenly distributed into the modified bitumen matrix as shown by the white dots.

AFM was employed to characterize the micro–morphology and micro–mechanical properties of the tested bitumen specimens [35]. A study by Liu et al. on bitumen tested in *ungagged (virgin)* and *aged* conditions which resulted in the presence of three "phases" formed on the bitumen surface, consisting of catana phase (asphaltenes), peri phase (resins and aromatics), and para phase (saturates). In the aged condition, it was found that the para phase decreased, while the catana phase increased. This indicates the conversion of light to heavy fractions. Not only that, the micro–mechanical results of this study were an increase in the Derjaguin–Muller–Toporov (DMT) modulus which resulted in harder bitumen and a decrease in the adhesion value [20].

## 3.6 Effect on Asphalt Mixture Characteristics

### 3.6.1 Effect on Physical Characteristics of Asphalt Mixture

The physical properties of asphalt mixture, as identified in this literature review, include percent air voids, bulk density, and hot water stripping resistance. The incorporation of modified bitumen into asphalt mixtures has been observed to decrease both air voids and bulk density values, a phenomenon attributed to the lower density of the added PET degradation products [23]. Regarding other parameters, hot water stripping resistance was evaluated by screening and weighing aggregates, followed by mixing them with modified bitumen. The results consistently indicated that the modified bitumen demonstrated a good stripping resistance [14,25]. However, despite its significance, this property has not been thoroughly investigated, highlighting a promising direction for future research.

### 3.6.2 Effect on Mechanical Characteristics of Asphalt Mixtures

Mechanical characteristics refer to the properties exhibited by an asphalt mixture when subjected to specific forces or loads, serving as critical indicators for evaluating its quality and performance. In this context, these characteristics are assessed through a range of tests conducted on asphalt mixtures composed of aggregates and modified bitumen, including Marshall stability and flow, rutting resistance, moisture susceptibility, resilient modulus, and low–temperature cracking resistance.

Marshall stability and flow are the main tests in evaluating the performance of asphalt mixtures in terms of strength and plastic deformation [36]. Marshall stability testing aims to determine the maximum load an asphalt mixture can withstand before failure and is expressed in kilograms (kg) or kiloNewtons (kN). In contrast, the flow value is used to determine the amount of plastic deformation that occurring at the point of maximum load application, thereby reflecting the mixture's flexibility, and is expressed in millimeters (mm). Several studies have shown an increasing trend in this value. Research conducted by Alzuhairi, *et al.*

produced the most optimum Marshall stability value of 19 kN and flow 4 mm in asphalt mixtures with 8% modified bitumen variation and indicated the increasing value by 20% and 15% respectively when compared to the control asphalt mixture [23]. In another study, namely that conducted by Padhan, *et al.,* also showed an increasing trend in the Marshall stability and flow values of asphalt mixtures with modified bitumen compared to the control mixture and the results met the requirements used (IRC: 53–2010) [14].

The rutting resistance of asphalt mixtures can be assessed using various testing methods, including dynamic creep and wheel tracking tests [29]. These evaluations aim to measure the mixture's capability to endure repeated or dynamic traffic loading [37]. Badaradan et al. conducted an assessment of this property using the dynamic creep test in accordance with the Australian standard AS 2891–12–1, and found a reduction in the permanent deformation of mixtures modified with PET waste monomer when compared to conventional mixtures [21].

Moisture susceptibility refers to the asphalt mixture's ability to withstand deterioration caused by water infiltration [32]. This property is typically assessed using the tensile strength ratio (TSR), which involves comparing the indirect tensile strength (ITS) values between conditioned (wet) and unconditioned (dry) samples. A TSR value greater than 80% is generally regarded as indicative of adequate resistance to moisture–induced damage [38,39]. The incorporation of 2% chemically–processed of PET waste product showed an optimal TSR of 95%, attributed to the reactivation of amine groups in the monomer and the enhancement of adhesive and cohesive interactions between the aggregate and the modified binder [21].

The resilient modulus ($M_R$), derived from stiffness modulus testing, represents the asphalt mixture's capacity to withstand repeated loading and recover its original shape following deformation [40]. Literature findings indicate that this parameter was evaluated under both conditioned and unconditioned states (as per ITS procedures) at testing temperatures of 25°C and 40°C. The highest $M_R$ values were observed in specimens incorporating 2% chemically–processed of PET waste product [21].

Furthermore, low–temperature cracking resistance was determined through semi–circular bending (SCB) tests, conducted following AASHTO TP124–6 standards. Specimens with a diameter of 150 mm and a thickness of 30 mm were tested at –15°C [41]. The review revealed that the inclusion of 2% additive improved both fracture energy and fracture toughness, indicating enhanced resistance to cracking under low–temperature conditions [21].

# 4 Conclusion

This study explored the recent developments and future challenges of using chemically–processed of PET waste products in bitumen and asphalt mixtures. In this study, SLR method is utilized as a detailed and comprehensive summary of summary with the following results.

- The synthesis of PET waste monomers that are used as modifiers in bitumen and asphalt mixtures was carried out by aminolysis and glycolysis.
- The wet method is the commonly mixing technique in blending chemically–processed of PET waste products in bituminous binder and asphalt mixture by adjusting temperature, time, and mixing speed.
- Laboratory performance of both modified bituminous binder and asphalt mixture showed the improvement in performances, such as physical, morphological, and rheological characteristics.

To enhance the use of chemically–processed of PET waste products in bitumen and asphalt mixtures, future studies should explore alternative synthesis techniques, including hydrolysis, methanolysis, ammonolysis, and acidolysis. Additionally, it is also important to conduct toxicity characteristic leaching procedure (TCLP) tests to evaluate the potential release of hazardous substances during the incorporation and processing of these waste materials in bituminous systems. Further studies should focus on analyzing the mechanical behavior of bituminous mixtures—especially at the macrostructural level—when using modified binders. Furthermore, assessing the economic feasibility and environmental impact of these applications through life cycle cost analysis (LCCA) and life cycle assessment (LCA) is essential for determining the long–term performance and sustainability of the modified asphalt.

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## References

1. R. Geyer, J. R. Jambeck, and K. L. Law, Sci. Adv. **3**, (2017)
2. K. Chan and A. Zinchenko, J. Clean. Prod. **433**, 139828 (2023)
3. Organisation for Economic Co-operation and Development, Oecd.Org (2022)
4. M. Fava, Oceanliteracy.Unesco.Org (2022)
5. A. G. Paladhi, S. Vallinayagam, S. Rajendran, V. Rathinam, and V. K. Sharma, in *Microbes Microb. Biotechnol. Green Remediat.* (Elsevier, 2022), pp. 575–587
6. N. A. Rorrer, S. Nicholson, A. Carpenter, M. J. Biddy, N. J. Grundl, and G. T. Beckham, Joule **3**, 1006 (2019)
7. S. Lu, Y. Jing, B. Feng, Y. Guo, X. Liu, and Y. Wang, ChemSusChem **14**, 4242 (2021)
8. Z. Jia, L. Gao, L. Qin, and J. Yin, RSC Sustain. **1**, 2135 (2023)
9. B. Shojaei, M. Abtahi, and M. Najafi, Polym. Adv. Technol. **31**, 2912 (2020)
10. M. T. Chin and T. Diao, ACS Catal. **14**, 12437 (2024)
11. R. K. Padhan and A. Sreeram, *Chemical Depolymerization of PET Bottles via Combined Chemolysis Methods* (Elsevier Inc., 2019)
12. L. Cosimbescu, D. R. Merkel, J. Darsell, and G. Petrossian, Ind. Eng. Chem. Res. **60**, 12792 (2021)
13. Q. Sun, Y. Y. Zheng, L. X. Yun, H. Wu, R. K. Liu, J. T. Du, Y. H. Gu, Z. G. Shen, and J. X. Wang, ACS Sustain. Chem. Eng. **11**, 7586 (2023)
14. R. K. Padhan and A. A. Gupta, Constr. Build. Mater. **158**, 337 (2018)
15. F. Zou, X. Xu, R. Chen, J. Lan, G. Li, Z. Tan, J. Xu, X. Jiang, and Z. Leng, Resour. Conserv. Recycl. **202**, 107377 (2024)
16. G. Chen, J. Ma, X. Xu, T. Pu, Y. He, and Q. Zhang, Waste and Biomass Valorization **16**, 601 (2024)
17. D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, Int. J. Surg. **8**, 336 (2010)
18. D. R. Merkel, W. Kuang, D. Malhotra, G. Petrossian, L. Zhong, K. L. Simmons, J. Zhang, and L. Cosimbescu, ACS Sustain. Chem. Eng. **8**, 5615 (2020)
19. E. S. Shirokova and M. A. Vokhmyanin, ChemChemTech **68**, 93 (2025)
20. H. Liu, S. Zhang, Z. Zhang, Y. Luo, Z. Mao, S. Kan, X. Yu, and J. Wang, J. Environ. Chem. Eng. **12**, 114891 (2024)

21. S. Baradaran, J. Rahimi, M. Ameri, and A. Maleki, Case Stud. Constr. Mater. **20**, e02740 (2024)
22. R. K. Padhan, Z. Leng, A. Sreeram, and X. Xu, J. Clean. Prod. **277**, 124286 (2020)
23. M. Alzuhairi, A. Al-Ghaban, and S. Almutalabi, MATEC Web Conf. **162**, 1 (2018)
24. Z. Leng, R. K. Padhan, and A. Sreeram, J. Clean. Prod. **180**, 682 (2018)
25. Z. Leng, A. Sreeram, R. K. Padhan, and Z. Tan, J. Clean. Prod. **196**, 615 (2018)
26. R. L. Vesnin, M. A. Vokhmyanin, and A. A. Alalykin, Izv. Vyss. UCHEBNYKH Zaved. KHIMIYA KHIMICHESKAYA TEKHNOLOGIYA **63**, 99 (2020)
27. C. Hadhinata, A. Setyawan, and F. P. Pramesti, J. Rehabil. Civ. Eng. (2024)
28. N. Haji Seyed Javadi, A. Hajimohammadi, S. Heydari, J. J. Kien Chung Ng, J. E. Kypreos, and N. Khalili, Constr. Build. Mater. **441**, 137451 (2024)
29. D. Mehta, N. Saboo, S. M. Abraham, and U. Diwaker, Mech. Time-Dependent Mater. **66**, 1 (2023)
30. M. Mirsepahi, J. Tanzadeh, and S. A. Ghanoon, Constr. Build. Mater. **233**, 117183 (2020)
31. H. Liu, W. Zeiada, G. G. Al-Khateeb, A. Shanableh, and M. Samarai, Constr. Build. Mater. **269**, 121320 (2021)
32. T. Wang, F. Xiao, S. Amirkhanian, W. Huang, and M. Zheng, Constr. Build. Mater. **145**, 483 (2017)
33. Y. Gong, X. Chen, and W. Wu, Adv. Sample Prep. **11**, 100122 (2024)
34. A. Ali, N. Zhang, and R. M. Santos, Appl. Sci. **13**, 12600 (2023)
35. M. Farré and D. Barceló, in (2012), pp. 1–32
36. Departemen Permukiman dan Prasarana Wilayah, *RSNI M-01-2003 Tentang Metode Pengujian Campuran Beraspal Panas Dengan Alat Marshall* (Departemen KimpraSWIL, Jakarta, 2003)
37. N. Şahan, A. Kumandaş, E. Kabadayı, E. Çavdar, and Ş. Oruç, Constr. Build. Mater. **407**, 133423 (2023)
38. P. Kasikitwiwat, S. Thongchart, S. Prayongphan, and K. Jantarachot, Eng. J. **25**, 51 (2021)
39. ASTM International, *ATM D 4867/D 4867M - Standard Test Method for Effect of Moisture on Asphalt Concrete Paving Mixtures* (2009)
40. M. S. Pourtahmasb, M. R. Karim, and S. Shamshirband, Constr. Build. Mater. **82**, 257 (2015)
41. H. Du, F. Ni, and Y. Zhao, J. Transp. Eng. Part B Pavements **147**, 04021016 (2021)