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Review

Structural Performance of Waste Plastic Bottles Modified Asphalt: A Review

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Abstract: The usage of plastic materials in our daily life is increasing day by day. These plastic materials are somehow beneficial for us, but the disposal of waste plastic materials has become a serious problem. The use of plastic not only enhances road construction but also helps extend the life of roads and improves the environment. Waste plastics use in roads increases durability and also reduces water retention. This research reviews the use of waste plastics in asphalt pavement. In this study, the properties such as Marshall stability, flow, resilient modulus, fatigue, etc., are studied to boost the usage of waste plastic in asphalt pavements. It is concluded that with the use of waste plastic in asphalt pavement, the quality of roads will be enhanced, and it will also be very beneficial for our environment. The other major advantage is that it will be very cost-effective for underdeveloped countries.

Keywords: pavement; asphalt; plastics

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1. Introduction

The chain of roads for the connectivity of different parts of the country is the basic need of any country. The increase in traffic volume due to the increasing population demands higher performance from road pavements. Normal materials used for pavement fail to resist the load of the higher volume of traffic. Hence, natural and synthetic polymers are incorporated into the asphalt to fulfill the high demand for loads on pavements. In the last decade, several research groups from Canada, the USA, China, and a few European countries have devoted their research facilities to enhance the performance of asphalt by incorporating different polymers. Various modifiers can be used to improve the properties of pavements, but few are found in nature [1]. These modifiers are tough to discover and are uneconomical when incorporated as a modifier [2]. Using waste material as a modifier will be a smart choice as it will reduce the cost of production of high-performance pavement as well as reduce the problem of dumping waste [3].

The use of PET bottles is increasing worldwide. Global plastic production has increased steadily for over 50 years. Approximately 299 million tons of plastic were manufactured in 2013, which contributed to a 3.90% increase in manufacturing in 2012. The average growth rate of plastics was 8.70% from 1951 to 2012 annually, increasing from 1.7 million tons to almost 300 million tons today. At the same time, its negative environmental impact is well known, affecting all types of organisms in the universe [4–8]. However, plastic recovery and recycling remain inadequate, with millions of tons of plastic being dumped into landfills and oceans each year. Since plastic does not naturally decompose, alternative methods must be implemented to recycle plastic materials. Recent research shows that waste PET bottles can not only be used as modifiers but also partially replace aggregates in pavement construction [9]. PET bottles are made of poly-ethylene terephthalate (PET), which makes them impact-resistant and provides an excellent barrier against moisture [10]. Therefore, using PET bottles on road surfaces may help decrease material waste and advance road performance [11–15].

The key objective of this review article is to explore an updated and critical review of the use of plastic bottles in pavements as an aggregate and modifier replacement. In Section 2, a brief introduction to various types of plastics used in asphaltic pavements is discussed. A comparison of different kinds of mixing procedures used for the mixing of plastics in asphalt is presented in the Section 2. A broad review of experimental tests made to study the mechanical behavior of PET asphalt is presented in Section 3. These sections also highlight needs, research gaps, and new directions for researchers. Finally, Section 4 deals with conclusions.

2. Plastics

The word "plastic" refers to the property of plasticity, the capability to distort without breaking [16]. All synthetic or semi-synthetic organic polymers are called plastics. The Society of the Plastics Industry (SPI) developed an identification structure in 1988 to help clients and recyclers classify various categories of plastics. The manufacturer usually puts its number (SPI code) on each product. It will give a basic overview of the types of plastics linked with each code number. Plastics can be classified into two types.

- *Thermosetting polymers*

Thermosetting polymers are also recognized as thermosets and harden into an everlasting shape. Because they are amorphous and have unlimited molecular weights, they cannot be used as modifiers.

- *Thermoplastics*

Thermoplastics can be molded into any shape and can also be remolded. These plastics are generally amorphous, but some have a moderately crystalline structure. Their molecular weights range from 20,000–500,000 amu. All thermoplastics can be used in asphalt as a modifier.

2.1. Methods of Mixing

For mixing plastics generally, two methods are used to incorporate polymers:

- Wet Process (addition of latex polymers).
- Dry Process (addition of solid polymers).

The solid polymer is added to asphalt at elevated temperatures, and the modified asphalt is incorporated into the paving mix while using the wet process. The temperature during mixing and time depends upon the nature of the bitumen and polymer. Naskar et al. [17] studied the result of plastic waste as a modifier on the degradation rate and thermal stability of bitumen. The researchers diversified a variety of plastic waste with 60/70 permeable bitumen at 180 °C for 45 min. Garcia Morales et al. [18] used four categories of polymer waste and mixed them with 60/70 permeable bitumen. After that, these samples were treated at 180 °C for 6 h. A report by Shell [19] proposes that the mix temperature should not surpass 185 °C. Else, bitumen will burn, and the mixing time must be sufficient to evenly distribute the plastic waste into the bitumen matrix.

The dry process is carried out by mixing polymer with aggregate in the form of solids, such as chips or granules, before bitumen is incorporated. Awwad and Shbeeb [20] tested the dry method for mixing in their study. Researchers used two different forms of poly-ethylene, i.e., high-density poly-ethylene (HDPE) and low-density poly-ethylene

(LDPE). Ref. [21] also used the dry process to study the microstructural properties of hot rolled asphalt modified with various percentages and different crumb rubber sizes. If we compare both processes, the wet process requires a huge investment, more plants, and powerful machinery, so it is not commonly used. On the other hand, by using a dry process, the binding property of aggregates becomes double and the bitumen bonding becomes stronger than normal; besides this dry process, malleable film of various plastics can be incorporated. There is no need for heavy machines for the dry process.

2.2. Publications and Subject Areas

To discover the significant research areas, an analysis is performed with the help of a Scopus analyzer. Figure 1 elaborated that engineering 31%, material science 27%, and environmental science with 15% contributed as three units generating leading articles and contributing approximately 73% of the total document count. On the other hand, Figure 2 describes the types of articles for the investigated terms in the database of Scopus. According to the results, 65% contribute towards research articles, 16% are related to book chapters, and 13% go toward review articles. Moreover, the data for annual research publications in the respective field are shown in Figure 3. From 2010 to 2022, the highest number of articles published was 436 in the year 2022, while in 2010, there were only 27 papers published. This shows a significant increase in the research on waste plastics in asphalt pavements.

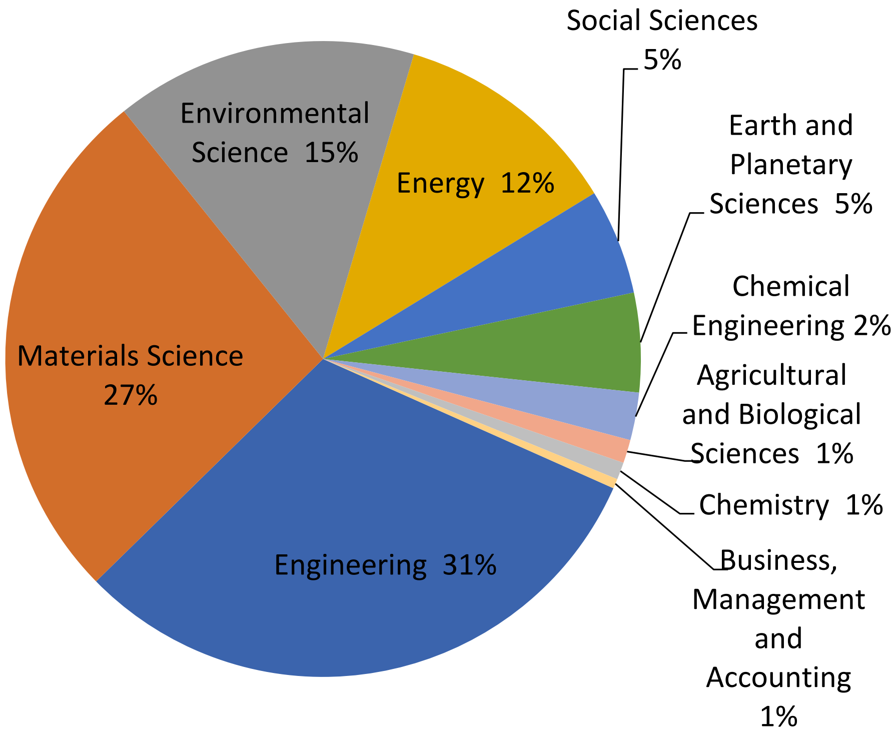

Figure 1. Subject Area of Articles.

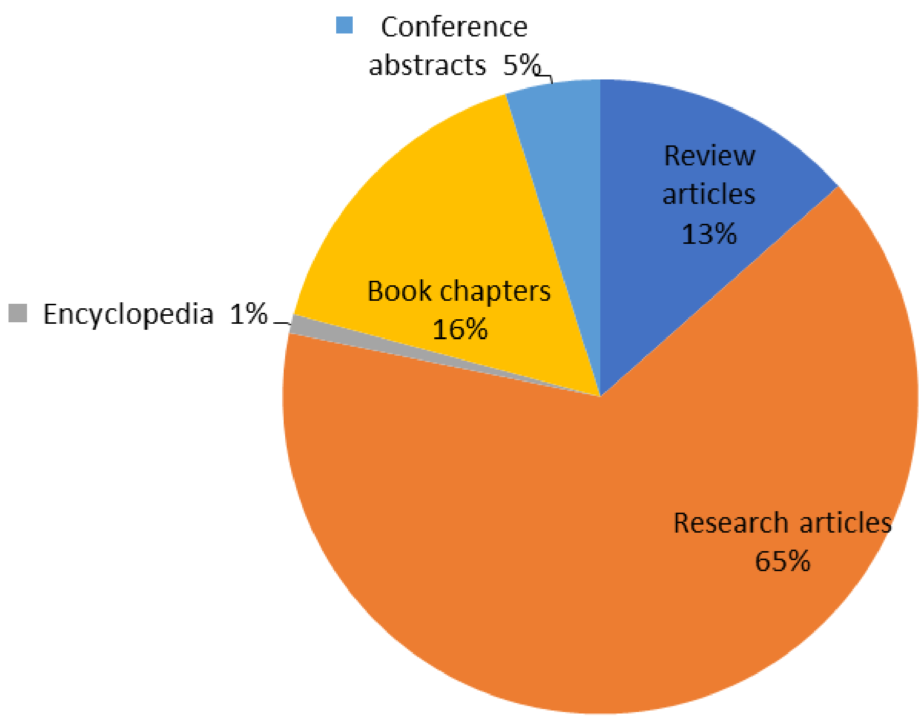

Figure 2. Article Types Published.

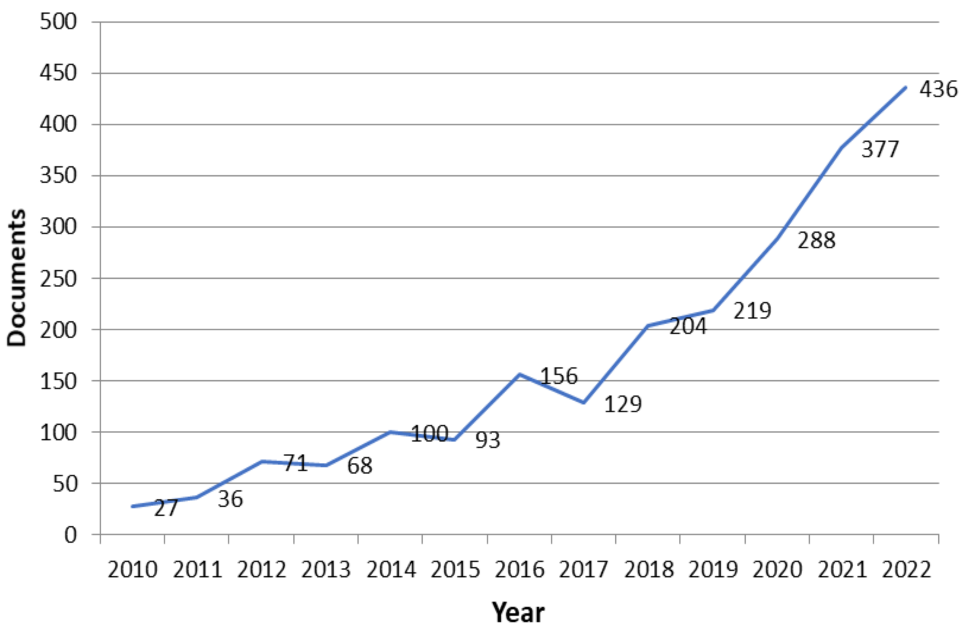

Figure 3. Annual Publication Trend of Articles.

3. Tests for PET Asphalt

Tests for Bituminous Mix

The following are tests commonly performed to evaluate various properties of bituminous materials.

- Marshall Stability;
- Marshall Flow;
- Marshall Quotient;
- Bulk Specific Gravity;
- Stiffness;

- Air Voids;
- Indirect Tensile Strength (ITS);
- Wheel Track Test;
- Resilient Modulus (MR);
- Drain Down Test;
- Density;
- Dynamic Creep;
- Fatigue.

Tests for Aggregate

- Aggregate Impact Value Test;
- Aggregate Crushing Value;
- Water Absorption;
- Stripping Value;
- LOS Angeles Abrasion Test;
- Specific Gravity;
- Voids in Mineral Aggregate (VMA);
- Voids Filled with Bitumen (VFA);
- Voids in Total Mix (VTM).

3.1. Marshall Stability

The Marshall stability (MS) is described as the extreme strength load achieved during a constant strain rate loading sequence and is one of the most significant properties used in asphalt mix design [22]. MS can be used to observe the manufacturing procedure of asphalt mixtures in factories. MS can also be used to evaluate relatively different mixtures.

Ref. [23] reported the effect of poly-ethylene as a modifier on the MS value of the asphalt mixture. The author studied six various percentages (15, 10, 7.5, 5, and 2.5% by weight of bitumen) of poly-ethylene. The maximum increase in MS value was observed when 12.5% poly-ethylene was added to the mixture. Ref. [24] performed a similar study while using HDPE instead of poly-ethylene. The maximum increase was observed for 4% HDPE. Ref. [25] performed similar studies by using devulcanized PET as a modifier in seven different percentages (2.5–15% by the wt.% of asphalt binder). The highest increase of 25.44% in MS value was witnessed for 10% devulcanized PET. The results of these studies are summarized in Figure 4 for comparison purposes. The MS value of the mixture increases due to the addition of plastic till optimum content due to the reduction in viscosity of the mixture. However, after the optimum content, the MS value decreases due to the enhanced friction between different particles of the mixture. The difference observed in the optimum percentages is due to the usage of various types of plastic, different amounts of asphalt content, and a different mixing method.

PET reinforced in Stone Mastic Asphalt (SMA) with a size of 2.35 mm was used by the researcher in [26]. The PET used was 0.2–1% by following the dry method for mixing. The author concluded that the PET-enriched blend shows a higher MS value than the control blend (the blend does not contain PET particles). Adding PET particles up to 0.4% was shown to increase the MS value, while further addition of PET (e.g., 1% PET) decreased the MS value. Therefore, a PET content of 0.4% is considered to be the stability case. On the other hand, the MS of the PET blend increased by 9.98%, Ref. [2] determined the effect of PET incorporation (2–10%) on the SMA mix and its properties. The author concluded that the stability values increased after the addition of PET until reaching a maximum level, which was about 6% of the PET used, and then started to decrease as shown in Figure 5. MS values were generally higher compared to control blends (blended with 0% PET). The single blend that showed a lower stability value was the 10% PET blend. Adding polymer to HMA improved stability because it improved adhesion between materials in the mixture. Adding the optimum amount of PET, i.e., 6%, to the blend increased the DM of the PET blend by 4.5%.

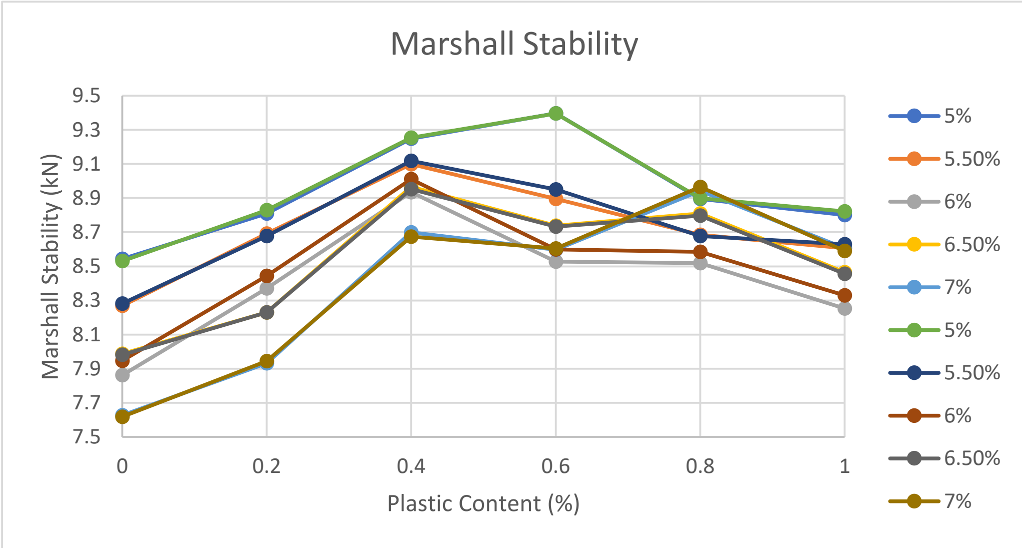

Figure 4. Marshall Stability vs. Plastic Content.

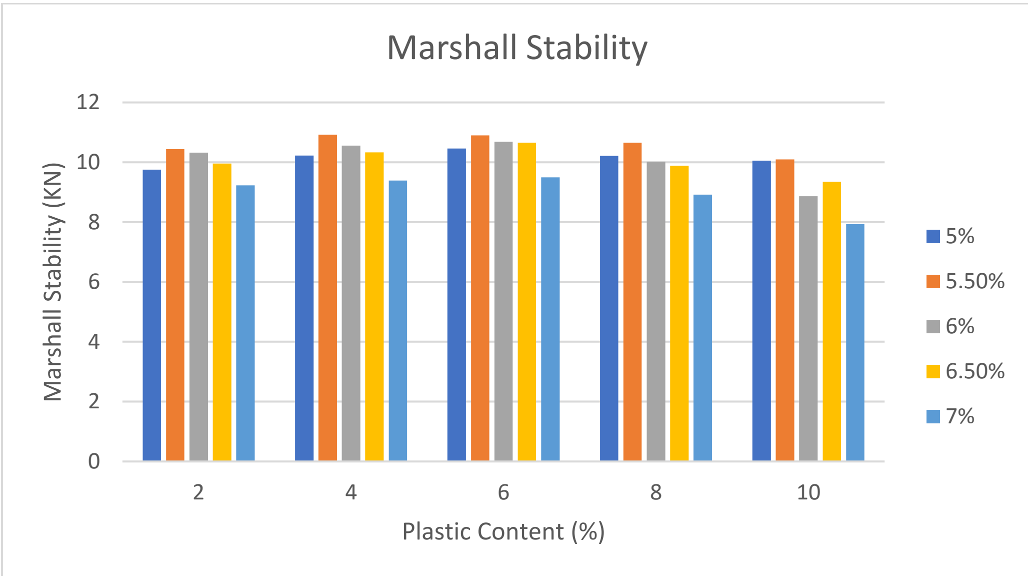

Figure 5. Marshall Stability vs. Plastic Content.

Ref. [27] used plastic waste as part of aggregate replacement in the asphalt mixture. Different percentages (5–25%) of aggregates were replaced with plastic waste, as shown in Figure 6. All replacements were made with % weight of aggregate, and the particle sizes ranged from 19 mm to 0.3 mm. The author reported an increase in the MS when a portion of aggregate is replaced with proper-sized plastic waste, with 15% replacement showing the optimum value. However, if the aggregate size is too large (retained on sieve #3/4), MS tends to decrease with an increase in aggregate replacement. In [28,29], PET was used as reinforcement in tests. The author added different percentages of PET (% of aggregate) in the range of 4–10%. From the results, the authors concluded that increasing the PET content of the improved blends tended to increase the MS until reaching the maximum value for the blends containing 4% PET, as shown in Figure 7. Further increase of this polymer reduces the stability of the blend under compressive stress. The rise or fall in stability can be credited to the increase in the viscosity of the binder in the existence of the polymer. MS of PET mixtures was increased by 67.65% when an optimum amount of PET, i.e., 4%, was added to the mixture.

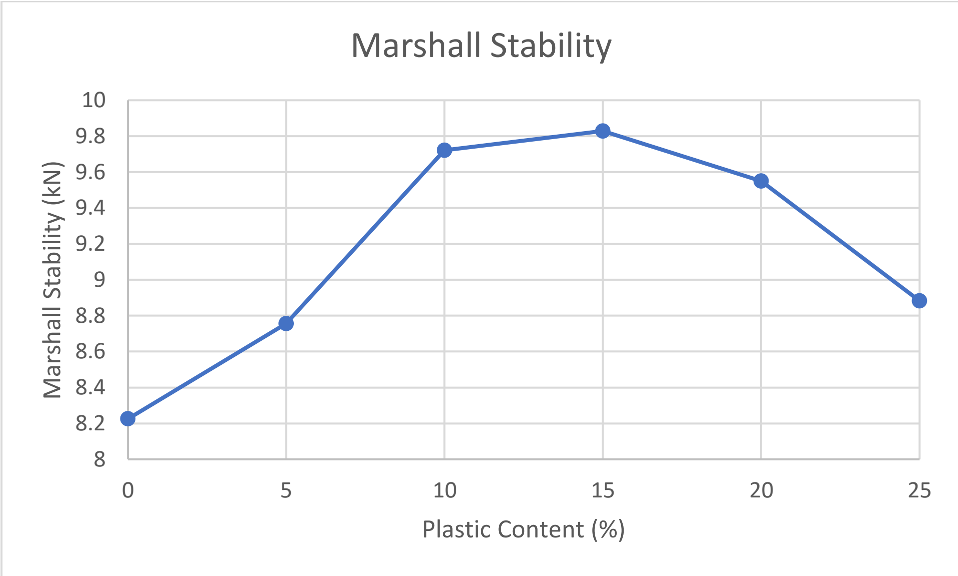

Figure 6. Marshall Stability vs. Plastic Content.

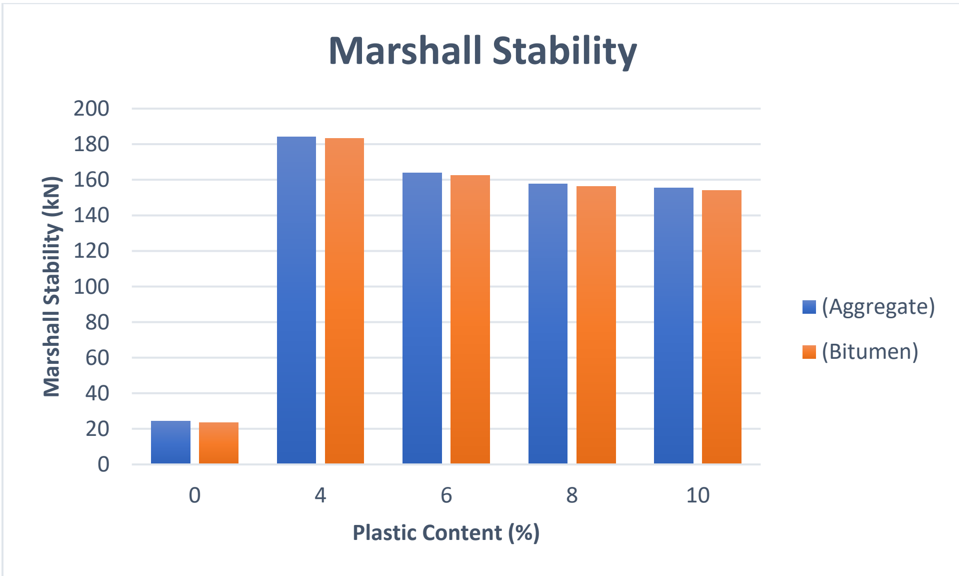

Figure 7. Marshall Stability vs. Plastic Content.

In Figure 8 MS of PET mixtures was increased by 19.5% when an optimum amount of PET, i.e., 15%, was added to the mixture. While on the other hand, ref. [30] used waste PET bottles in different percentages of 0.2–1% by weight of aggregate particles. The authors concluded that incorporating waste PET bottles up to 0.6% plastic into the asphalt mixture increases MS; however, higher plastic content reduces MS. In addition, it was noted that the MS value decreases with increasing asphalt content. MS of PET mixtures was increased by 9.99% when an optimum amount of PET, i.e., 0.6%. was added to the mixture. This result specifies that the incorporation of waste PET bottles improved the adhesion between aggregate particles and asphalt binder.

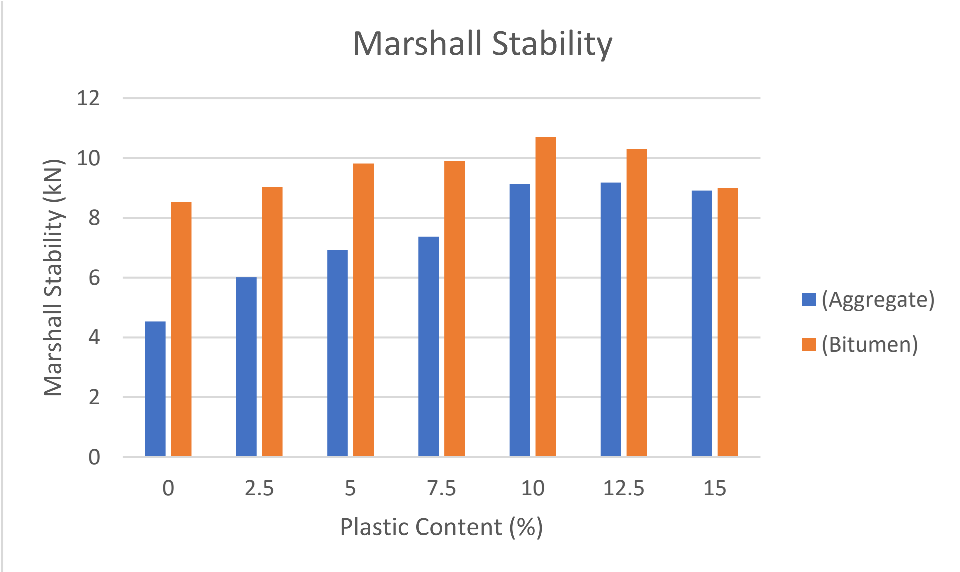

Figure 8. Marshall Stability vs. Plastic Content.

3.2. Marshall Flow

The Marshall flow (MF) is the measure of elastoplastic distortion of asphalt determined during stability testing. The MF value refers to vertical distortion when the extreme load is reached. In addition, MS and MF can be used to monitor the asphalt mixture manufacturing process and evaluation of different mixtures. The MF value indicates the flexibility and plasticity performance of HMA under cyclic loading.

In ref. [17], the authors used different proportions of poly-ethylene (2.5–15 wt.% bitumen). According to the authors [23], the MF of the modified asphalt-concrete mix was lesser than that of the control (no modifier (3.5 mm)) for all percentages of poly-ethylene. This may be credited to the decrease in binder viscosity with increasing poly-ethylene content. This agrees with the result of ref. [25]. A decrease in MF suggests an increasing effect of poly-ethylene content on the internal friction of concrete. Generally, MF decreases with the increase in poly-ethylene content [25].

In ref. [24], the author added HDPE-based waste material to the bitumen as a modifier in the amount of 1–4%. A slight increase of MF was observed by 2% and 3% of coded specimens. The maximum value was obtained by 4%. MF of PET mixtures was increased by 6% when an optimum amount of PET was added.

Ref. [26] used different content of PET ranging from 0.2–1% by the % weight of aggregate. The asphalt content used in the mixture was 5–7%. The author concluded from the results that, with the increase of plastic content and asphalt content, the MF increases due to the lower internal friction as compared to the normal samples (having 0% PET). MF of PET mixtures was increased by 12.84% when an optimum amount of PET, i.e., 1%, was added to the mixture. On the other hand, the same proportion (0.2–1% by the wt. of aggregate) of PET content was used by [28], while the asphalt content was 5–7%. As a result, MF increased directly with the increase in PET content. The results may show that PET-reinforced mixtures have less internal friction as compared to the control samples (with no plastic). MF of PET mixtures was increased by 28.16% when an optimum amount of PET, i.e., 1%, was added to the mixture. In ref. [2], the same asphalt content (5–7%) and different ratios of PET (2–10% by the wt. of the bitumen) were studied. The author concluded that adding PET up to 4% results in a decrease in MF, as shown in Figure 9. Ref. [27] also used plastic waste with five different percentages (5–25%) by wt. of total aggregate. It is reported that with the addition of plastic, the value of MF goes up, as shown in Figure 10. MF of PET mixtures was increased by 48.11% when an optimum amount of PET, i.e., 25%, was added to the mixture. [29] reported the effect of MF at different plastic percentages (4–10%)

per weight % aggregate in asphalt mixtures. The lowest MF of a normal asphalt mixture was 2.85 mm. The MF of the modified asphalt mixture was higher than that of the normal asphalt mixture. The variance between modified asphalt and normal asphalt varied from 18% to 38%. The maximum MF was 3.9 mm, and this was with 10% plastic added.

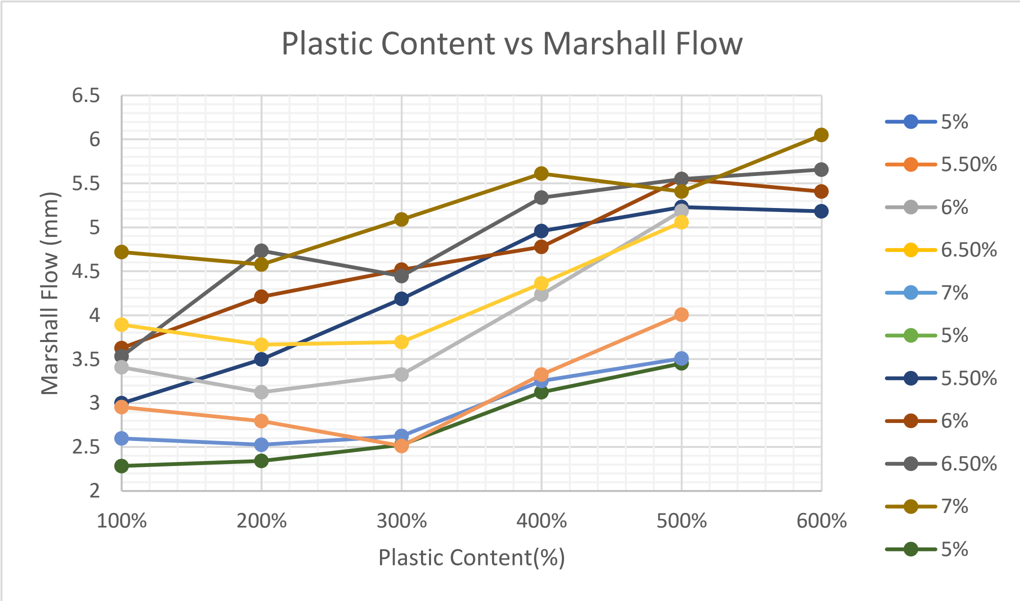

Figure 9. Marshall Flow vs. Plastic Content vs. Asphalt Content.

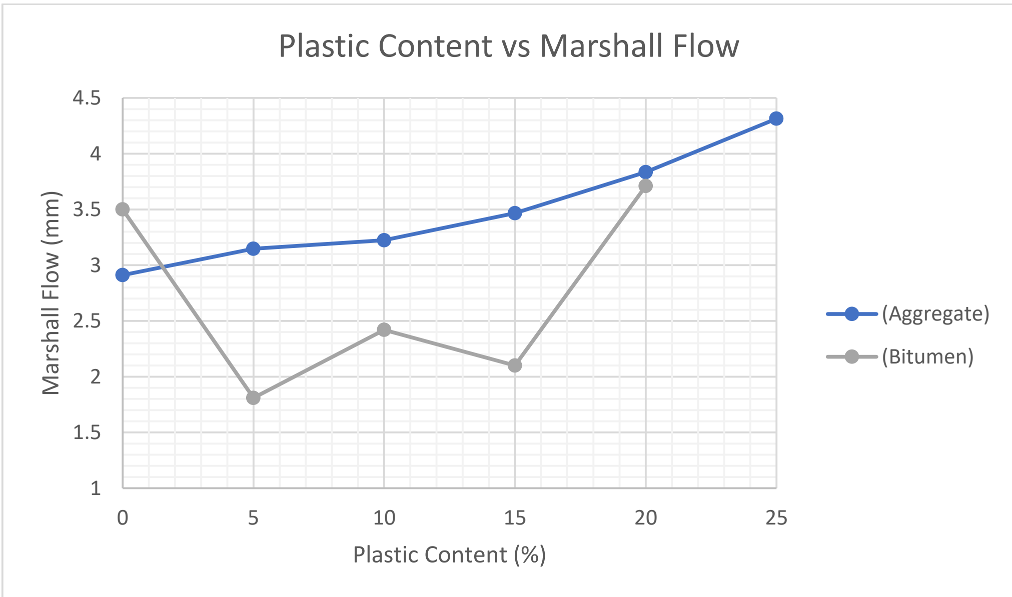

Figure 10. Marshall Flow vs. Plastic Content.

However, if PET is added more than 4%, then MF increases, showing an increase in flow. MF of PET mixtures was increased by 46.35% when an optimum amount of PET, i.e., 10%, was added to the mixture, as shown in Figure 11.

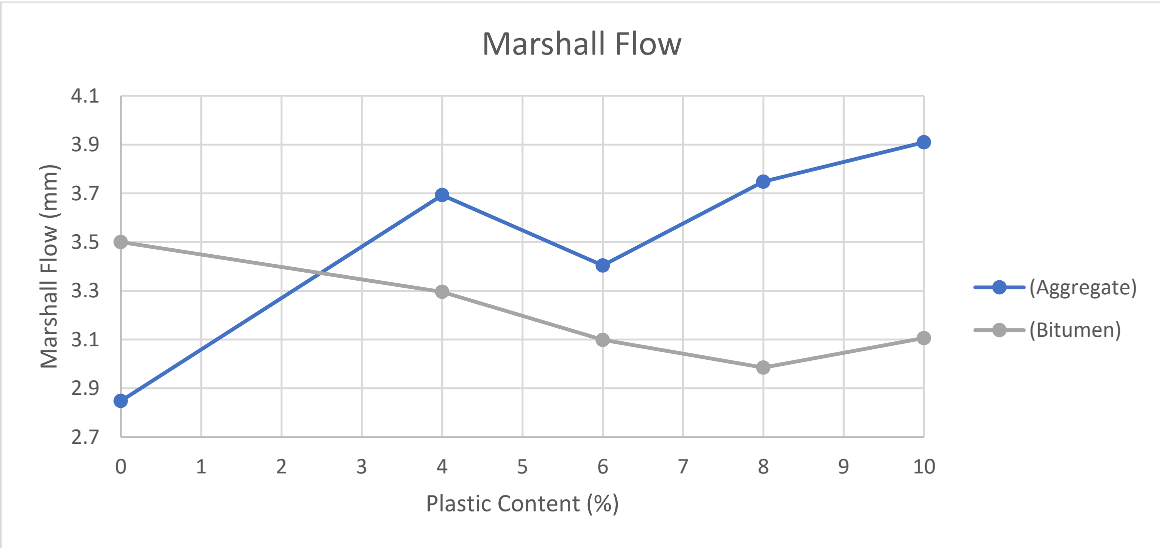

Figure 11. Marshall Flow vs. Plastic Content.

3.3. *Marshall Quotient*

The Marshall quotient (MQ) is the relation of stability to flow and can be used to measure a material's struggle with permanent deformation during service (Hinislioglu and Agar, 2004). MQ is an index of shear stress resistance, mix stiffness, and rutting of bituminous mixtures. A high MQ value indicates high stiffness and resistance to cracking.

In [2], MQ was calculated to assess the specimen's resistance to deformation. For this purpose, the author used PET from 2 to 10% by weight of bitumen. From the results, it can be observed that adding PET increases MQ. This is because it is stiffer and more resistant to severe deformations due to heavy loads. MQ of PET mixtures was increased by 11.52% when an optimum amount of PET, i.e., 4%, was added to the mixture, as shown in Figure 12.

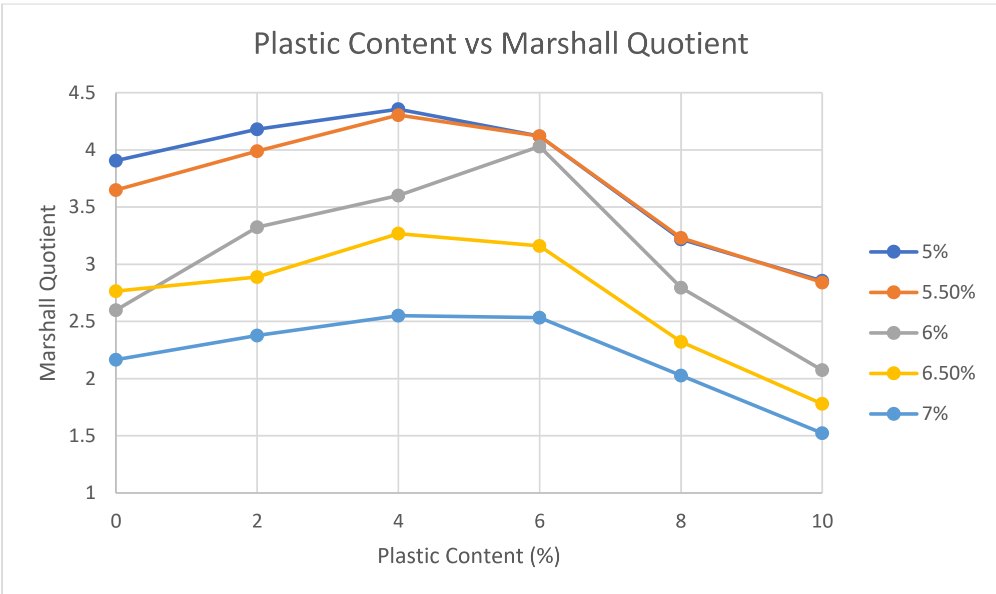

Figure 12. Marshall Quotient vs. Plastic Content.

3.4. *Bulk Specific Gravity*

The bulk specific gravity (BSG) is used to check the specific gravity of a compressed HMA sample by computing the ratio of its weight to the weight of an equal amount of water. The HMA BSG is required to identify weight-volume relations and to determine various volume-related quantities, such as air voids and mineral aggregate (VMA) voids.

In [2], the authors determined the properties of mixtures having various proportions (2–10%) of PET to the weight of bitumen. For each binder content, increasing the PET content decreases the BSG of the mixture. The decrease in BSG (for PET blends) is due to the lower PET compared to single aggregates. BSG of PET mixtures was increased by 12.93% when an optimum amount of PET, i.e., 4%, was added to the mixture, as shown in Figure 13.

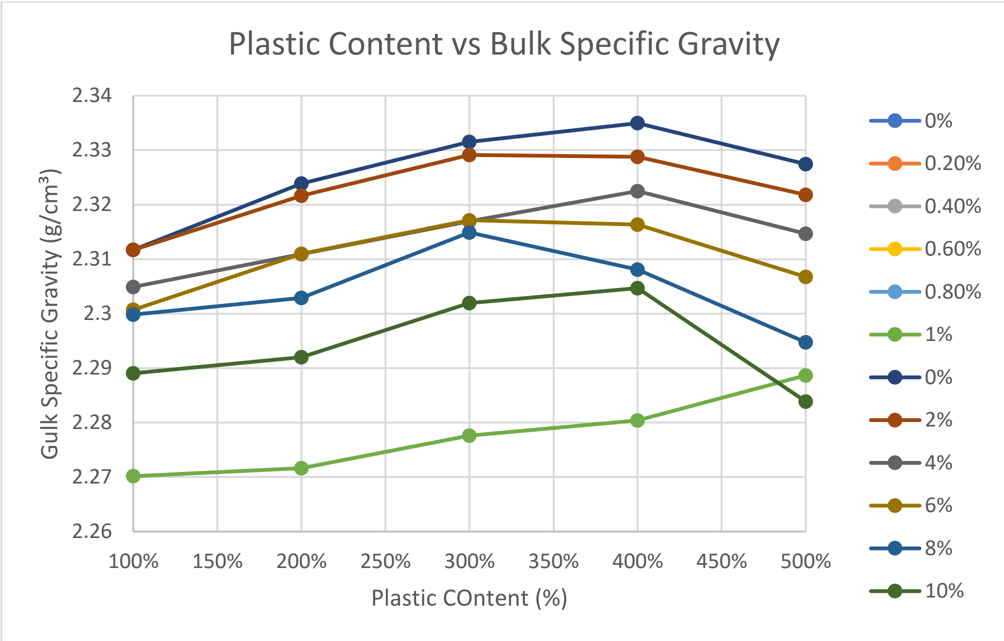

Figure 13. Bulk Specific Gravity vs. Plastic Content.

In [30], the author performed the BSG test on the specimens containing waste PET bottles in different percentages (0.2–1%) by the weight of aggregate. The author concluded that after the addition of waste plastic, the BSG tends to decrease. BSG of PET mixtures was increased by 0.79% when an optimum amount of PET, i.e., 1%, was added to the mixture, as shown in Figure 14.

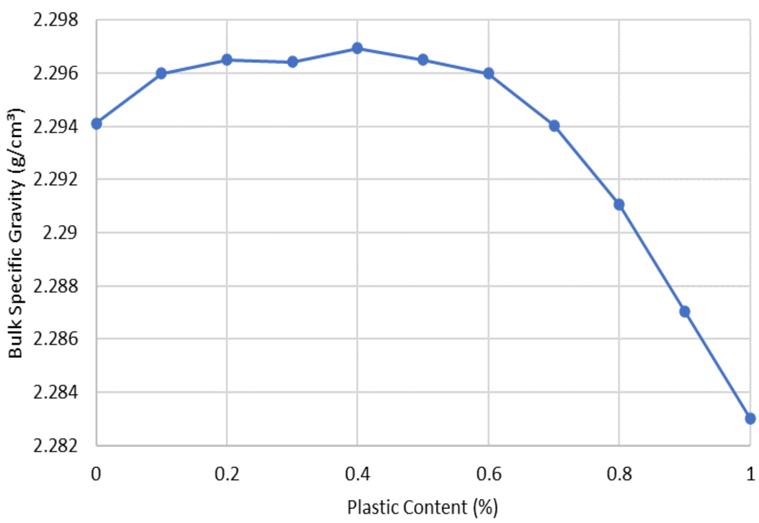

Figure 14. Bulk Specific Gravity vs. Plastic Content.

3.5. Stiffness

The stiffness of the mixtures is attained as a relationship between applied stress and the specimen's distortion. Stiffness is the essential parameter for measuring rutting. A pavement with higher stiffness is worth it. However, if the stiffness is too high, fatigue cracks can occur.

Ref. [26] determined the variation of stiffness values as a function of PET content (0.2–1%) at different stress levels. The results show that the mixture's stiffness decreases at high-stress levels. Adding PET reduces the stiffness of the blend. It is also worth noting that the blends reinforced with 1% PET exhibited nearly identical stiffness values at different stress levels. This result may specify that the PET-enhanced blend is more flexible than the control blend, specifically the higher amount in PET-enhanced samples. The stiffness of PET mixtures was increased by 3.88% when an optimum amount of PET, i.e., 0.2%, was added to the mixture; the same proportion of PET is used by weight of aggregate particles at the stress level of 250 kPa, 350 kPa, and 450 kPa [30]. The author determined that with the increase in PET content, the stiffness of the specimen decreases. The stiffness of PET mixtures was increased by 3.88% when an optimum amount of PET, i.e., 0.2%, was added to the mixture, as shown in Figure 15.

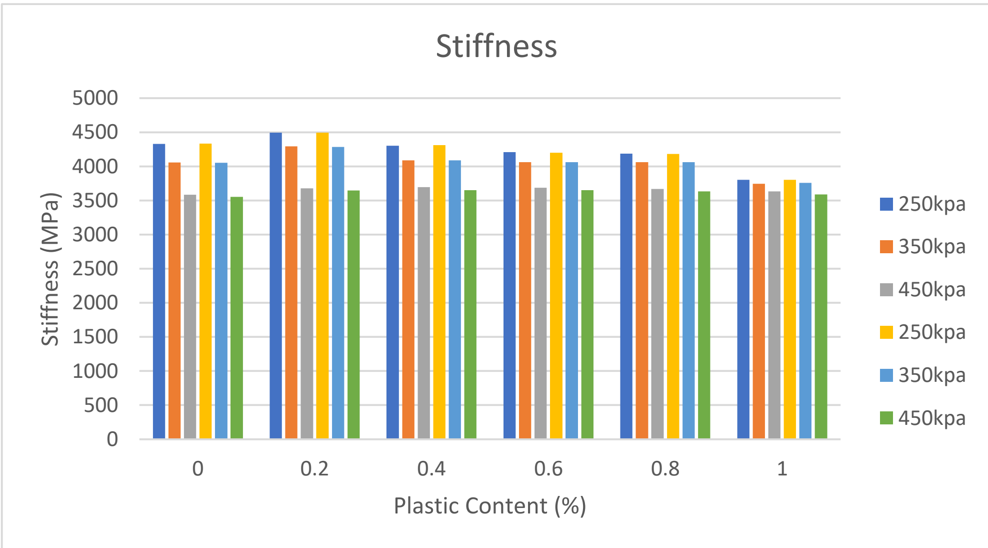

Figure 15. Stiffness vs. Plastic Content.

Ref. [29] reported the effect of diverse percentages of plastic (0.4–1%) on stiffness. The modified asphalt's stiffness increases by 4% and 6% and decreases by 8% and 10%. Therefore, plastics can increase stiffness up to a certain percentage and decrease it after reaching the optimum value. Regular asphalt mixtures have the lowest stiffness, i.e., 8.53 kN/mm. The stiffness of PET mixtures was increased by 539.5% when an optimum amount of PET i.e., 6%, was added to the mixture, as shown in Figure 16.

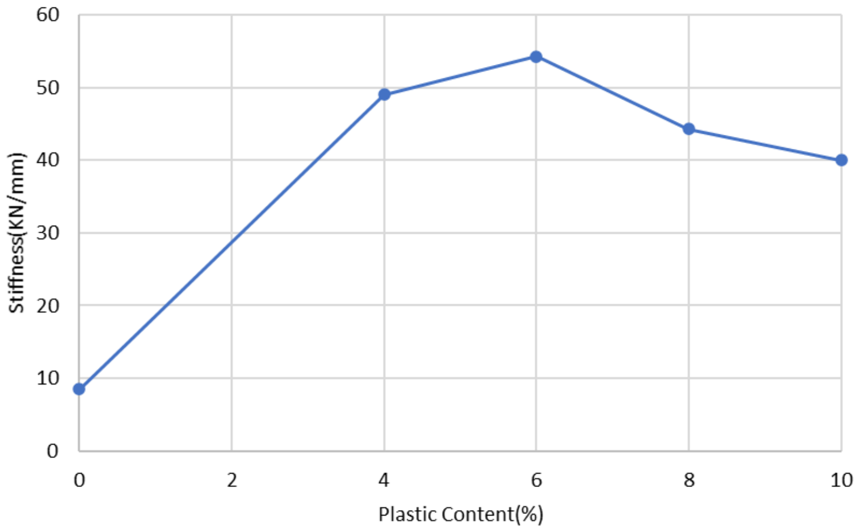

Figure 16. Stiffness vs. Plastic Content.

3.6. Aggregate Impact Value

The ability of a material to oppose an impact is said to be toughness. Thus, the aggregate should have sufficient toughness so that it can resist fragmentation due to impact. To measure this, an Impact Value Test is used.

Eight % and 10 % propylene were used by [31], and from the results, it is concluded that by increasing the propylene ratio the quality of aggregate becomes good, which results in improving AIV as shown in Figure 17. Hence, poor aggregate quality can therefore be enabled by coating with a polymer. It also contributes to improving the quality of the flexible pavement.

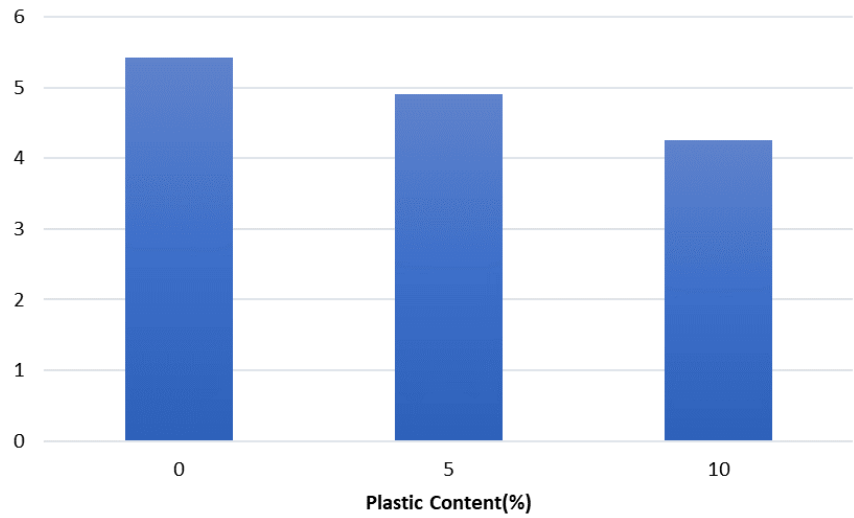

Figure 17. Aggregate Impact Value vs. Plastic Content.

3.7. Aggregate Crushing Value

Aggregate crush value (ACV) offers a comparative measure of aggregate resistance to crushing under progressively applied loads.

In [31], the author used 8% and 10% propylene, and the results are shown in Figure 18. From this result, it was concluded that aggregates with lower ACV had a lower fracture rate under load and a longer road service life. Weaker aggregates are crushed due to traffic load. It can be observed that plastic-coated aggregates have lower ACV and withstand traffic loads more effectively than plain aggregates.

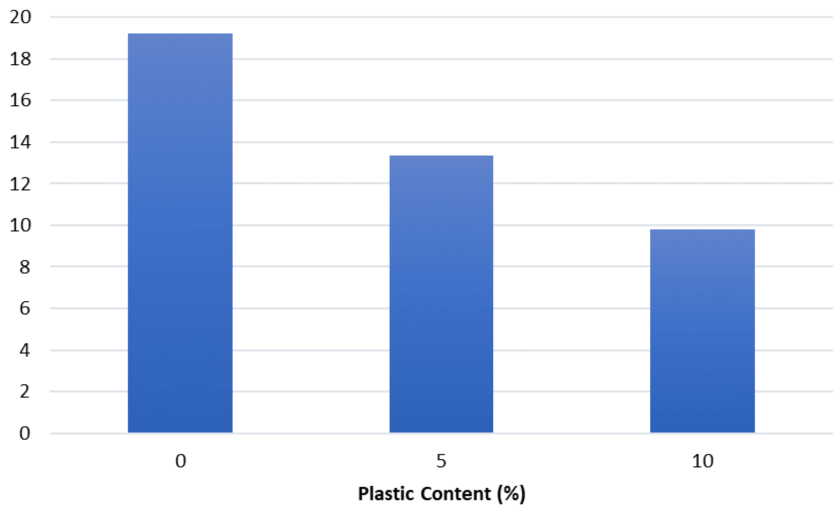

Figure 18. Aggregate Crushing Value vs. Plastic Content.

3.8. Specific Gravity

The specific gravity (SG) of an aggregate is an unintended measure of its strength. The higher the SG, the higher will be the strength. The SG value of a plain aggregate is lower than that of plastic-coated aggregate. Since aggregates with lower SG are commonly weaker than aggregates with higher SG values, this result indicates that the incorporation of plastic increases the SG of the aggregate. The range should be 2.5 to 3.0% [31]. In Figure 19, the SG of PET mixtures is increased by 42.86% when an optimum amount of PET, i.e., 10%, is added to the mixture.

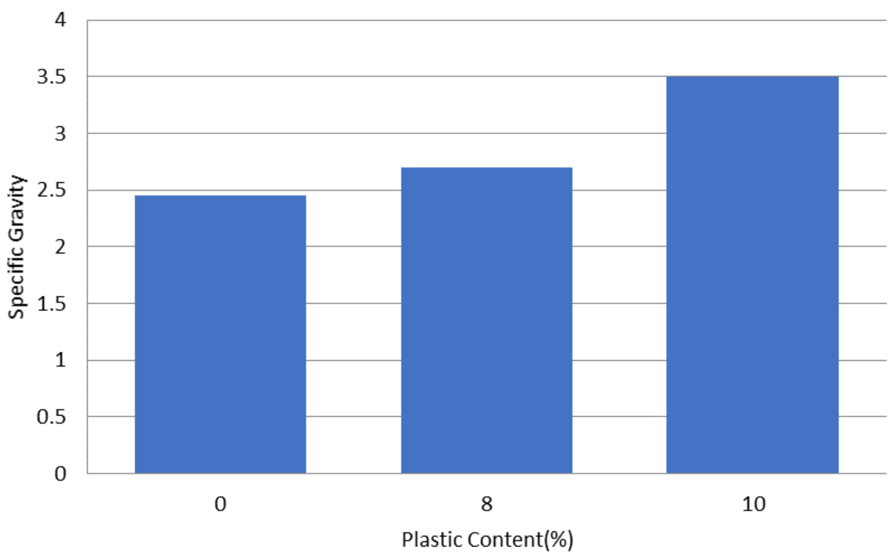

Figure 19. Specific Gravity vs. Plastic Content.

3.9. Stripping Value

The stripping value of an aggregate is calculated as the ratio of the visually observed uncoated surface to the total surface of the aggregate, articulated as a percentage.

This value indicates the effect of moisture on the bond of the bituminous layer to the surface particles of the aggregate. Aggregates containing plastic coatings have zero delamination value. So, the aggregate is more appropriate for the bituminous road than the ordinary aggregate. In [31], the results obtained with the control sample are within the IRC criteria, but the aggregate coating reduces the aggregate's affinity for water, as shown in Figure 20. The range must be less than 25%.

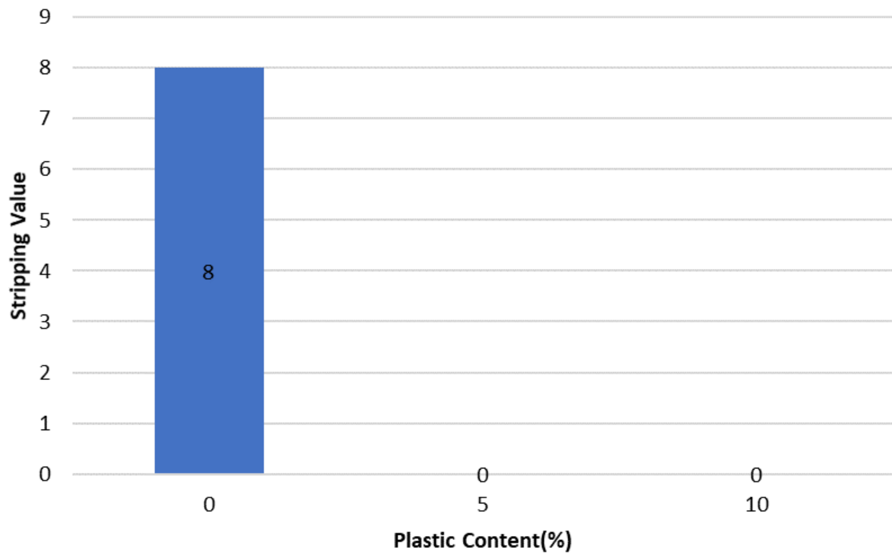

Figure 20. Stripping Value vs. Plastic Content.

In [14] the plastic laminated aggregates and bitumen were placed in water for 72 h. The mixture exposed no signs of delamination. This verifies that it has excellent water resistance.

3.10. Water Absorption

Aggregates are also selected based on their ability to absorb moisture. Covering the aggregate with plastic improves its absorbency. Plastic coatings reduce moisture absorption and improve aggregate quality and performance in flexible paving. In [31], the authors demonstrated that the moisture absorption of the aggregate is within IRC specifications and reduced to zero by the coating. The range must be less than 10%, as shown in Figure 21.

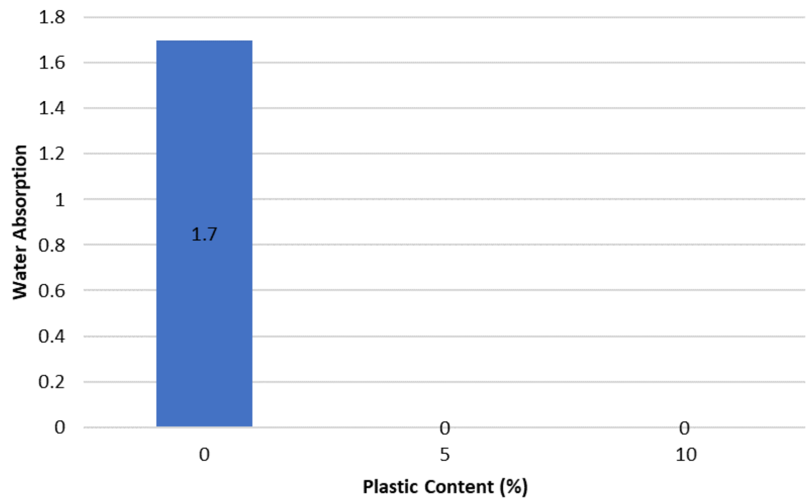

Figure 21. Water Absorption vs. Plastic Content.

The authors [14] reported that the amount of water absorbed decreased with increasing plastic coating. This shows that the plastic coating decreases air voids. Therefore, plastic coating of aggregates helps to increase aggregate quality.

3.11. Los Angeles Abrasion Value

Frequent vehicle movements will cause wear to the pavement. The test shows this wear and tear as a percentage. In this research, the wear values for plastic laminated aggregates were in descending order to the percentage of plastic. Comparing the abrasion value of plain aggregate with that of plastic laminated aggregate, the value of a coated aggregate is lower. From the pp8 and pp10 specimens of [31], the results attained are in range and can therefore be used for construction, as shown in Figure 22. So the range must be less than 35% [31].

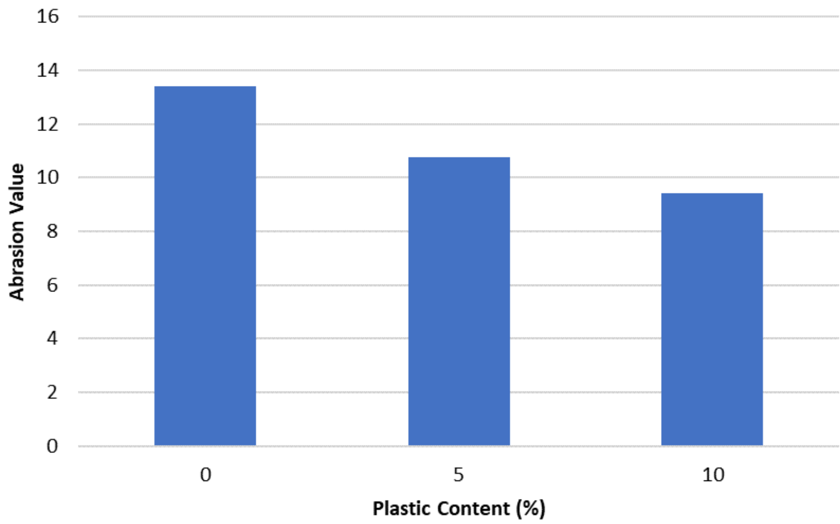

Figure 22. Los Angeles Abrasion Value vs. Plastic Content.

3.12. Air Void

The air void (AV) is known as the key parameter of bituminous mixtures used in pavement design and obtaining optimal asphalt content. Excessive AV causes cracking due to inadequate asphalt binder covering the aggregate, while low AV can cause more plastic flow (rutting) and asphalt bleeding. Ref. [2] determined the effect of varying percentage plastic content from 2 to 10% on the AV of SMA. In this case, increasing the PET content results in more AVs remaining as crystal. However, the increased surface area must be wetted by the binder, ultimately leading to increased AV in the mixture. Further, when PET was used in the blend, it appeared to be less compact, allowing higher AV values to be obtained. The AVs of the PET blend increased by 9.02% when the optimal amount of PET, i.e., 10%, was added to the blend as shown in Figure 23.

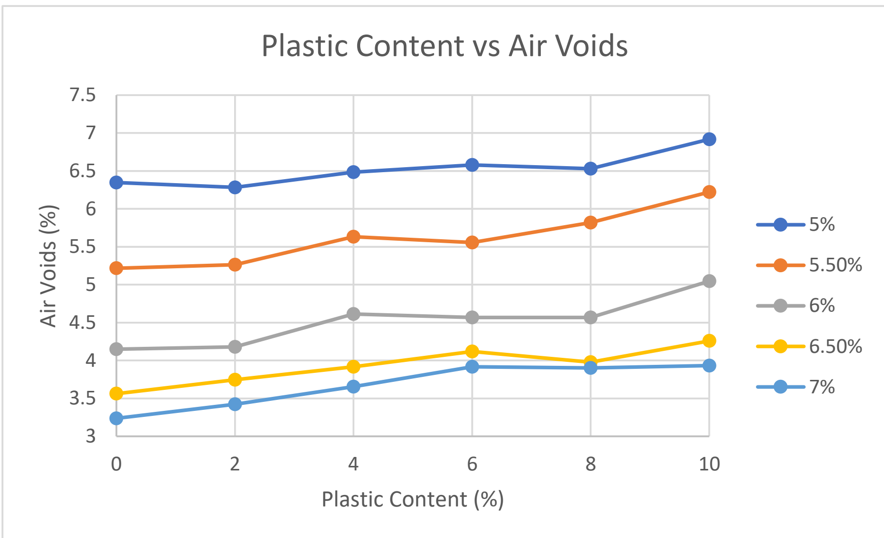

Figure 23. Air Voids vs. Plastic Content.

Ref. [26] used some different percentages of PET, which was 5–25% by the weight of aggregates. However, in the result, the same reasons are concluded that with the increase in the percentage of plastic waste, the AVs decrease, as shown in Figure 24.

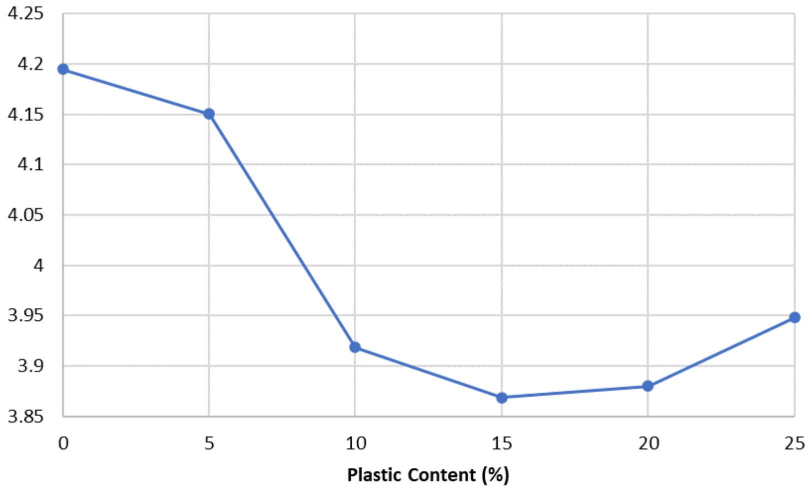

Figure 24. Air Voids vs. Plastic Content.

Ref. [15] reported that the values were below the acceptable range of 3 to 5% for AV content, except for samples containing PET at a temperature of 140 °C. However, the slope of the experimental mixture was steeper than the normal mixture. Similarly, the maximum AV content obtained was 5.20% at a constant temperature of 140 °C for 6% PET, and the lowest AV content was 3.17% at a compression temperature of 170 °C, as shown in Figure 25. In [2], the author confirms that the incorporation of PET created more AVs, with the chopped PET left as crystals yielding more surface area.

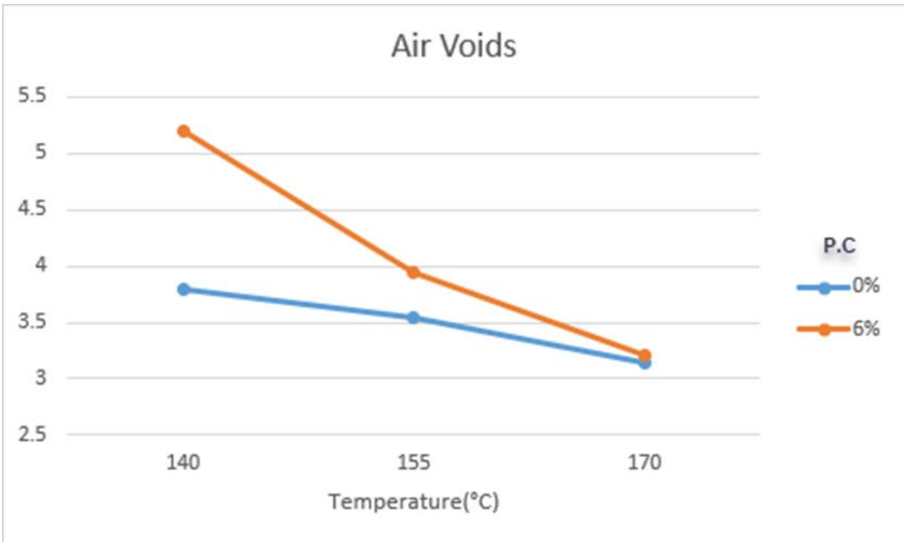

Figure 25. Air Voids vs. Plastic Content.

Increasing the compression temperature reduces the amount of AVs. In addition, ref. [32] verified that the AV percentage reduced with increasing compaction temperature due to the greasing effect of asphalt in maintaining a binder viscosity appropriate for compaction. Therefore, the plastic particles are mostly melted and can range throughout the AV. So, if the AV content is too high, air and water can get into the AV space, but if the AV content is too low, the binder will come out, and the two will be in the asphalt mixture, reducing durability.

3.13. ITS Test

Indirect tensile strength (ITS) testing is used to determine the indirect tensile strength of a mixture and helps determine the heat crack resistance of a mix.

In [33], the authors reported that temperature affects the ITS of samples. The authors tested the specimens at 5 °C and 20 °C, as shown in Figure 26. The addition of 2% PET increased ITS at both test temperatures. Moreover, the ITS decreased constantly with the addition of PET content. Due to higher PET contents, bitumen gathers on the external surface of the plastic particles. The ITS of the PET blend increased by 13.1% when the optimal amount of PET, i.e., 2%, was added to the blend.

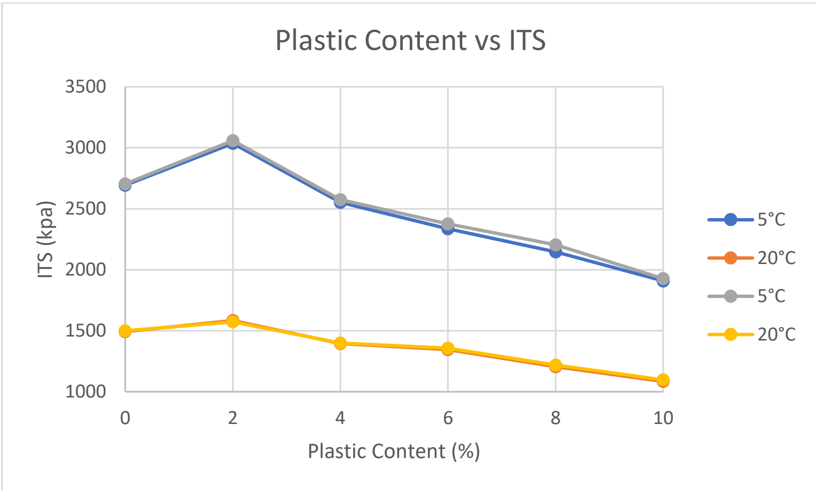

Figure 26. ITS vs. Plastic Content.

In [34], ITS tests performed on samples containing different plastic content variations (2.5–15%) show that the addition of PET raises the tensile strength of the modified asphalt mix as compared to the control mix. Based on the results, it can be perceived that the PET modification increases the moisture sensitivity of the asphalt mixture, but with higher PET percentages (above 12.5), the improvement decreases, as shown in Figure 27. The ITS of the PET blend increased by 35.68% when the optimum amount of PET, i.e., 7.5%, was added to the blend. From the result of [29], it can be observed that the ITS of the modified asphalt mixture is lesser than that of the normal asphalt mixture. The ITS of a normal asphalt mixture is 1094 kPa. The highest ITS among the modified asphalt concretes is 1049 kPa, 8% plastic, which is 4% lesser than the tensile strength of normal asphalt mixtures. It has a minimum ITS of 844 kPa and contains 4% plastic, which is 24% less.

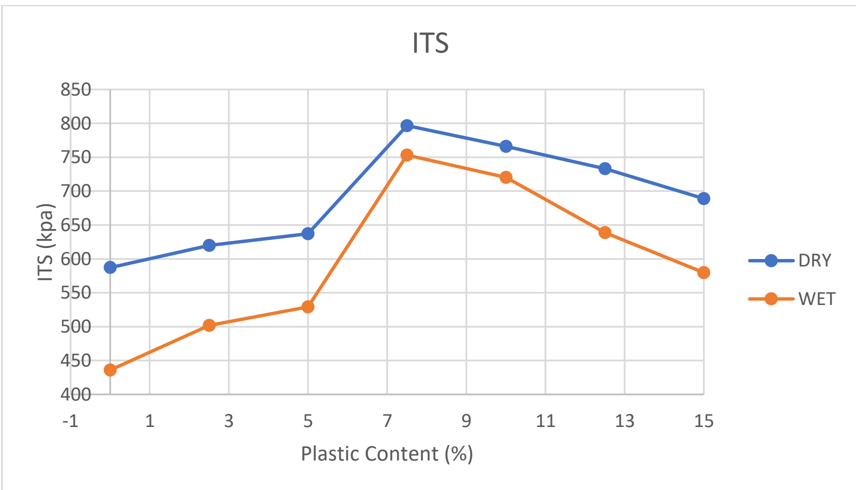

Figure 27. ITS vs. Plastic Content.

Ref. [35] found that temperature has a significant effect on the ITS of samples. The addition of 2% PET increased the ITS at both test temperatures. Moreover, the ITS decreased constantly by adding PET content. The ITS of the PET blend increased by 12.74% when the optimal amount of PET, i.e., 2%, was added to the blend as shown in Figure 28.

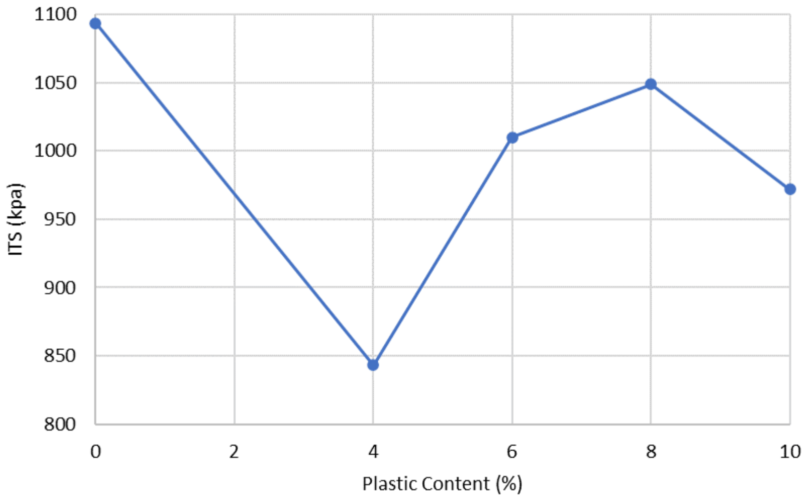

Figure 28. ITS vs. Plastic Content.

3.14. Wheel Track Test

In [35], the authors used various percentages of plastic ranging from 2.5 to 15%. According to the wheel track test results of [35], the values of all modified blends were lower than those of the control blends, indicating that the addition of polymer improved sensitivity and permanent stress in modified mixtures.

Based on the results attained, we conclude that the use of polymers to modify asphalt mixtures is an effective method for creating mixtures with greater resistance to shear forces in asphalt pavements. The results of [36] show that blends comprising waste PET have better resistance to everlasting distortion compared to normal blends. Further, the rut depth value increases sharply during the first 15 min; after that, the increase slows and tapers off. After 45 min, the rut depths for the mixtures containing 2–10% PET were 1.78 mm, 1.50, 1.25, 1.35, 1.62, and 1.56 mm, respectively, compared to the mixtures containing 4% plastics, as shown in Figures 29 and 30. The minimum rut depth was obtained with a 28% reduction in rut depth compared to normal formulations.

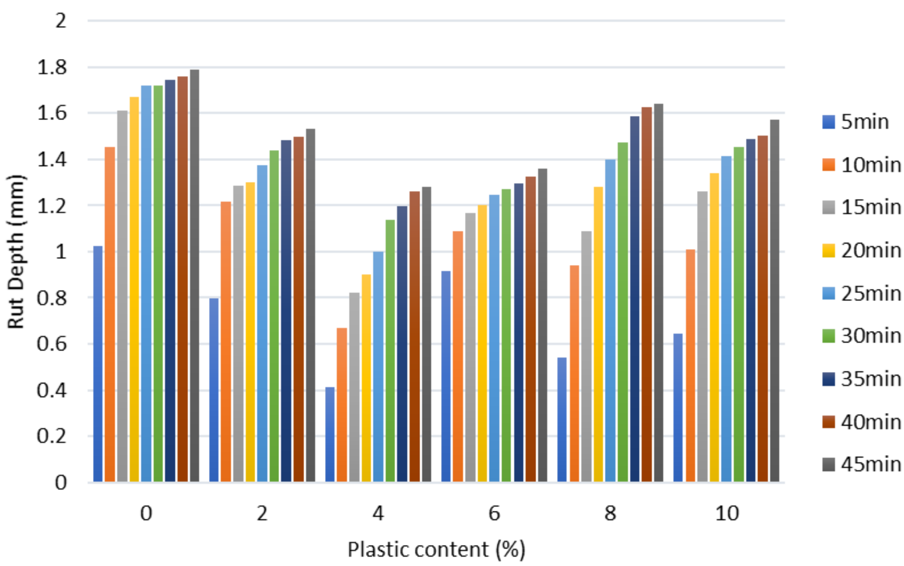

Figure 29. Rut Depth vs. Plastic Content.

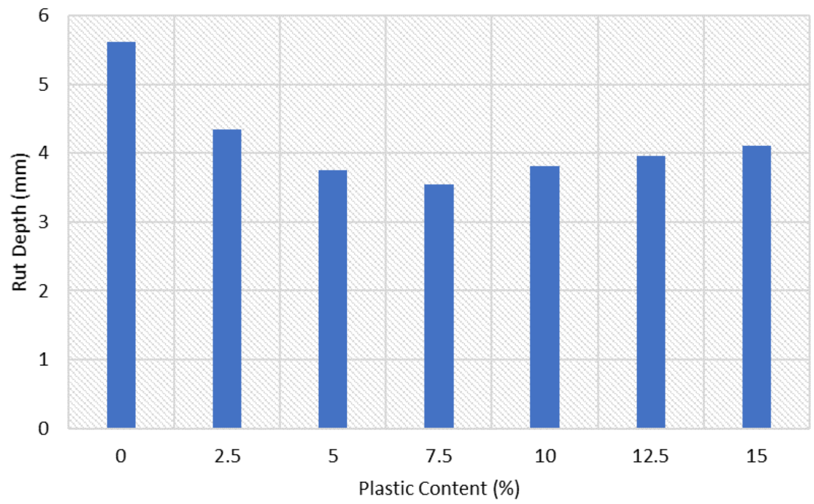

Figure 30. Rut Depth vs. Plastic Content.

3.15. Resilient Modulus

The resilient modulus (MR) is an important property of the material used to describe unbonded pavement materials. MR is the measure of the stiffness of a material and offers a way to examine material stiffness under various circumstances, such as density, humidity, and stress levels. MR is normally calculated by laboratory testing by determining the stiffness of a specimen cylinder under cyclic axial loading. MR is the ratio of the stress on the axle diverter to the recoverable strain of the axle.

In [36], PET was used as reinforcement in varying proportions (2–10%) based on the weight of the bitumen content. The authors reported that after the incorporation of PET, MR values increased until reaching a maximum level and then started to decrease. MR values of the blends comprising plastic were commonly higher than the normal blends (0% PET), and the results obtained showed that the MR was maximized by the addition of 6% PET, which showed a 16% increase in MR. The MR of the PET blend increased by 15.62% when the optimal amount of PET, i.e., 6%, was added to the blend.

In [34], the fatigue and stiffness behavior of modified PET blends were calculated at two different temperatures of 5 °C and 20 °C. Varying contents of PET (2–10 wt.% bitumen) were integrated into the asphalt mixture using the method of dry mixing. The authors concluded that MR decreased with increasing stress levels. However, at a perpetual stress level, the highest MR values are attained with 2% PET. The MR of the PET blends increased when the optimal amount of PET, i.e., 2%, was added to the blend, as shown in Figure 31.

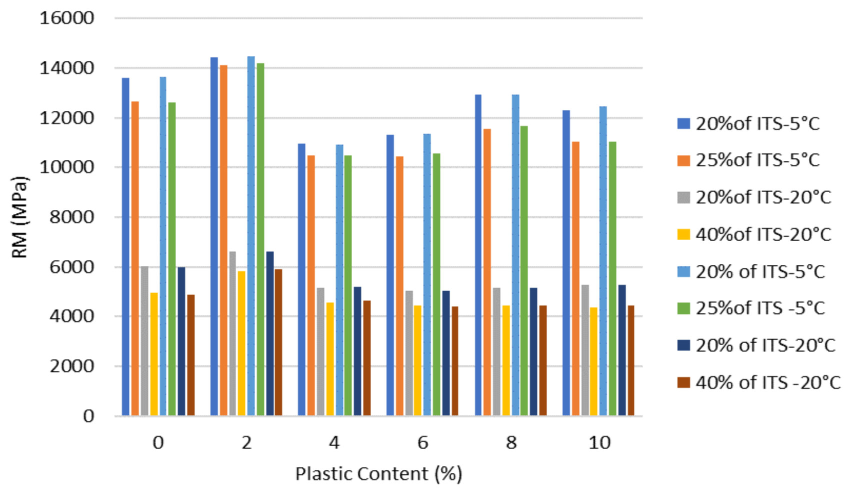

Figure 31. Resilient Modulus vs. Plastic Content.

In [29], the author used different percentages of plastic waste from 4 to 10% at temperatures of 25 °C and 40 °C. MR increases with increasing plastic until the optimum plastic content is reached. MR is reduced with an additional increase in plastic. The modified asphalt mixture containing 8% plastic has the highest MR at temperatures of 25 °C and 40 °C, which is nearly double that of the normal asphalt mixture. Furthermore, the MR of the 4% plastic is a minimum of 69%, which is 51% lesser than the simple asphalt mixture, at temperatures of 40 and 25 °C as shown in Figure 32.

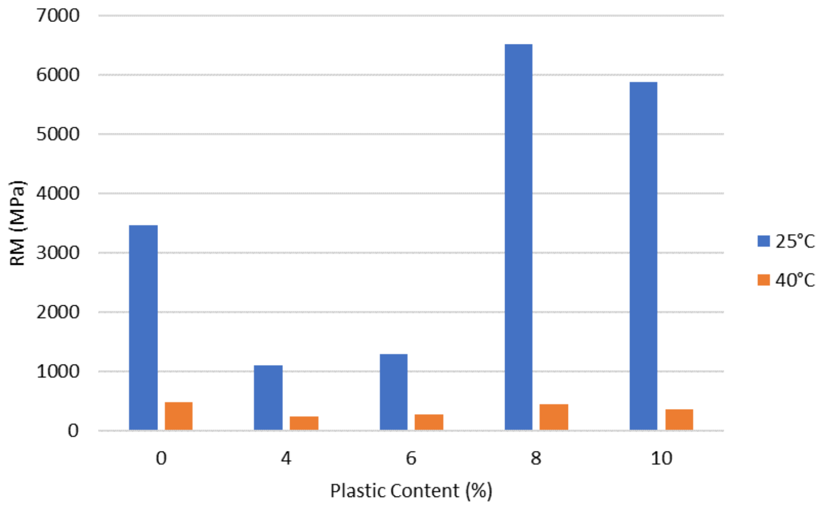

Figure 32. Resilient Modulus vs. Plastic Content.

In the same study, a test was run for MR on the modified PET blend. The authors used different PET contents between 0.2% and 1% of the total aggregate weight. Likewise, they found that using 0.2% PET improved the stiffness of the mixture, whereas adding more than 0.2% as shown in Figure 33 adversely affected the stiffness of the mixture [25]. With the increase in PET amount, the particles obtain more volume within the mixture. These particles are less rigid than aggregates, so the total rigidity of the mixture decreases with the increase in PET content. Moreover, the decrease in bitumen film on the aggregate particles could be an additional reason for the decrease in stiffness with higher PET content.

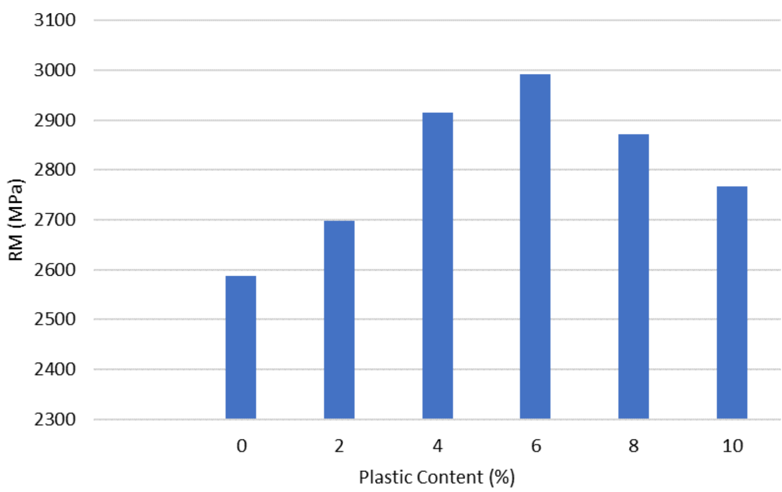

Figure 33. Resilient Modulus vs. Plastic Content.

3.16. Drain Down

A drain-down test can be used to determine whether the measured drainage for a particular asphaltic mixture is within quantified satisfactory levels. This test is primarily intended for mixes with a high content of coarse aggregates, such as Stone Mastic asphalt and porous asphalt.

Ref. [36] conducted drain-down tests on mixtures containing various proportions of waste PET and 2–10% by the weight of bitumen. Experiments have determined that a suitable range for the quantity of waste plastic is 4–6% by the weight of bitumen content, as shown in Figure 34. Irrespective of the PET content used, the void values of the PET blends were lower than those of the control blends, and increasing the PET content in the blends decreased the void values. The reduced drainage values may be a result of the sliced PET used in the mixture, which rests in crystalline form, thereby increasing the surface area. However, the increased surface area must be wetted by the binder, which ultimately stabilizes and holds the binder to the surface, reducing binder flow.

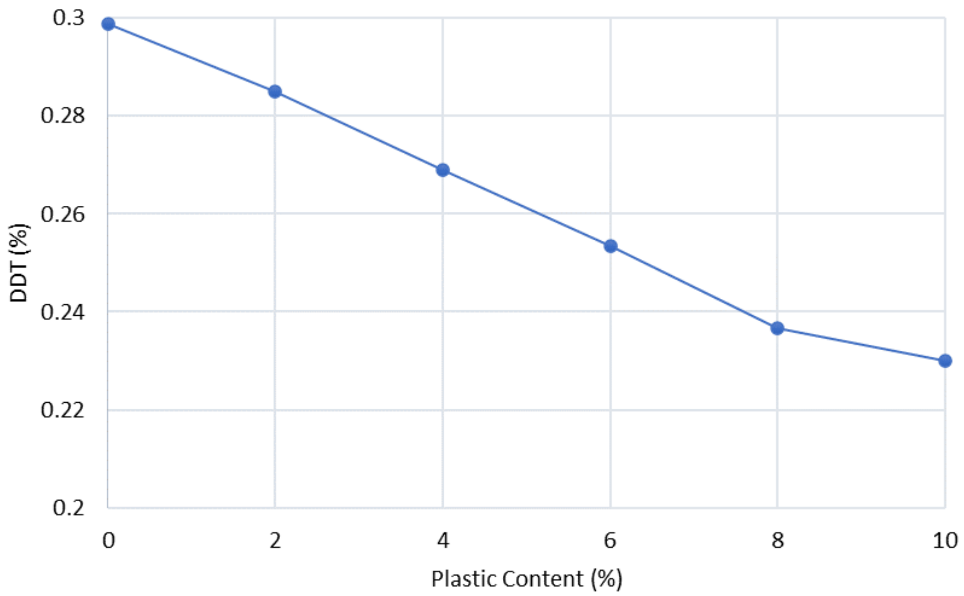

Figure 34. DDT vs. Plastic Content.

Ref. [15] examined the influence of temperature on properties when mixing PET waste and Stone Mastic asphalt (SMA) before compaction. The quantity of bitumen added was 6% of the total aggregate weight, as shown in Figure 35. However, the results of [15] show that both samples passed the reference range based on the tolerance of 0.3% residual particles. The controlled mixture retained only 0.0346% in a beaker with a filling temperature of 170 °C. Besides this, a value of 0.0188% was obtained for the experimental mixture. Specimens with PET have lower retention rates. Ref. [2] conducted research that concluded that adding PET lowered the excretion values of the normal mixture. The incorporation of PET made the mixture easier to dispense and less sticky.

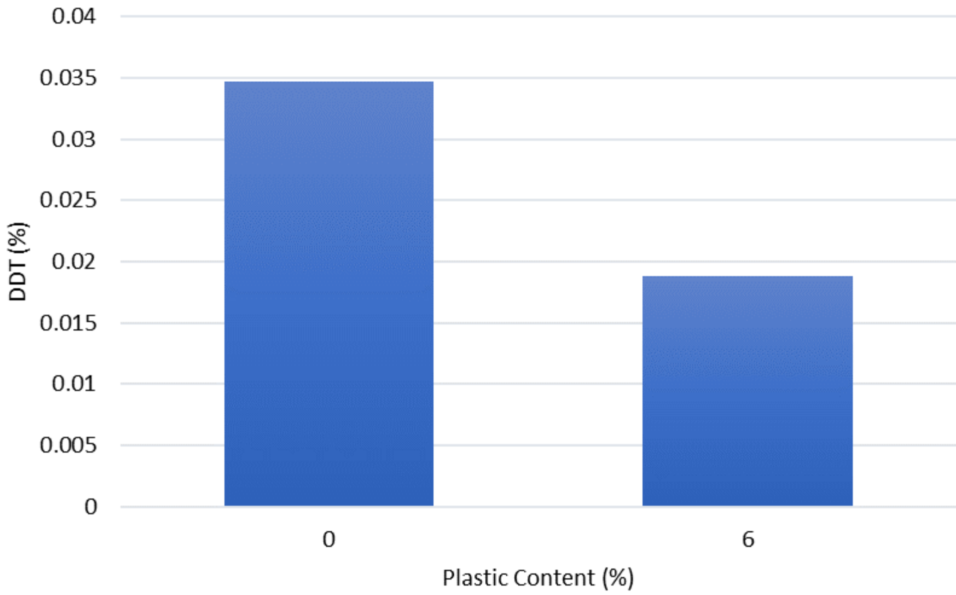

Figure 35. DDT vs. Plastic Content.

3.17. *Volumetric Properties*

The volumetric properties are mirrored in the amount of aggregate and bitumen essential to create the desired combination of properties. The volumetric properties of the mixture are critical to the long-term durability and performance of the pavement.

3.17.1. Density

Mass per unit volume is said to be density. The asphalt mixture decreases with the increasing proportion of plastic in the case of density. A simple asphalt mixture has a density of 2.35 g/cm3. A plastic-added asphalt mixture containing 4% of plastic has the maximum density, namely 2.5 g/cm3, which is 6% greater than a normal asphalt mixture. With the increase in plastic percentage, the density of the mixture decreases. The density of PET mixtures was increased by 6.39% when an optimum amount of PET i.e., 4%, was added to the mixture, as shown in Figure 36.

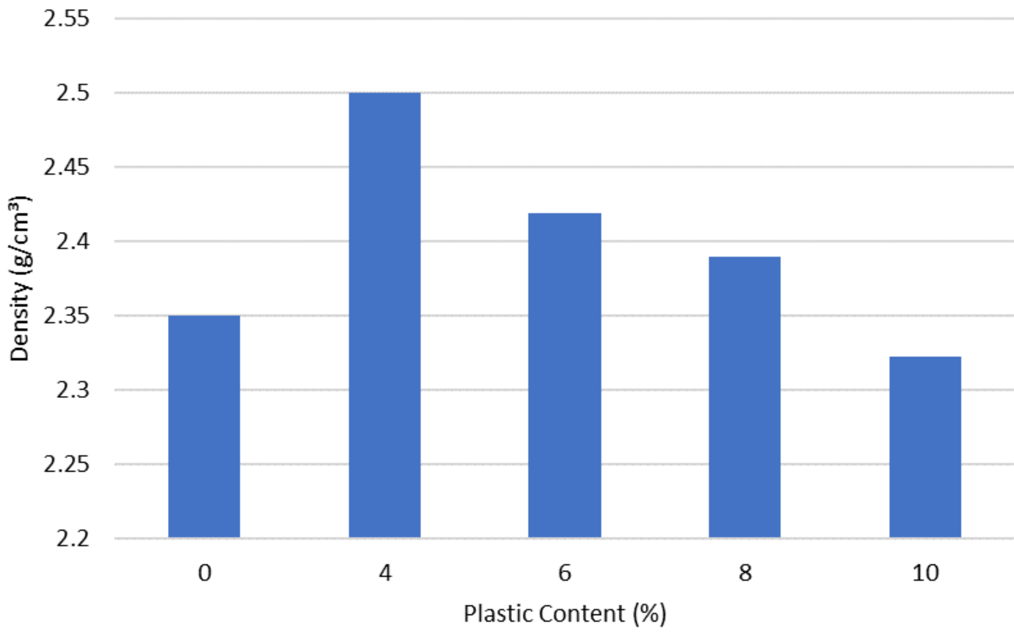

Figure 36. Density vs. Plastic Content.

3.17.2. Voids in Total Mix

A void in the total mix was observed in the specimens of different percentages (4–10%). The results show the effect of additional plastic on voids throughout the mixture. The VTM for simple asphalt mixtures is 3.7%, while the VTM for plastic-incorporated asphalt mixtures ranges from 4.0 to 7.0%. In the report of JKR [37], the range of VTM is 3 to 5%. Results show that 4% and 8% of plastics have VTM values out of range, while 6% and 10% of plastics have VTM values within a range. VTM are also known as air voids, which is the relation of the volume of voids in the compressed mixture to the total volume of the compressed mixture. Correct compaction can reduce voids. Compressors require regular maintenance to function properly during the compression process. VTM of PET mixtures was increased by 95.25% when an optimum amount of PET, i.e., 4%, was added to the mixture, as shown in Figure 37.

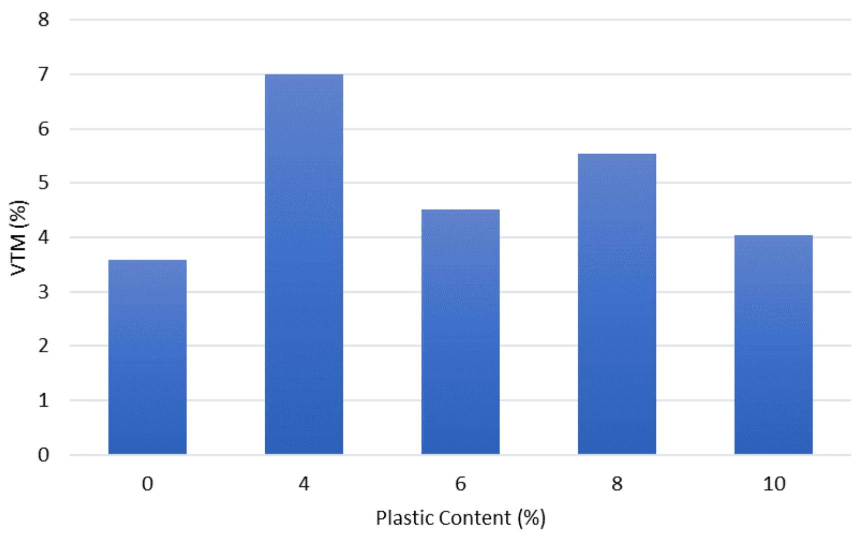

Figure 37. VTM vs. Plastic Content.

3.17.3. Voids Filled with Asphalt

The voids filled with asphalt (VFA) are observed depending on the amount of plastic addition at different weight percentages (4–10%) of bitumen. Voids filled with asphalt binder is the percentage of voids in mineral aggregate (VMA) filled with asphalt cement. For a normal asphalt mixture, the VFA is 76%, and for 10% plastic, the VFA is 73% which is very similar. Four % plastic has the highest VFA (i.e., 141%). The 6% and 8% VFAs are constant (that is, 97% and 95%, respectively) but fall outside the JKR specification, which is between 70% and 80%, as shown in Figure 38.

In [15], the author experimented with VFA for experimental and temperature-controlled mixing. All specimens passed 65–78% tolerance except for the temperature of 140 °C on PET. The researcher reduced the VFA value with the addition of PET due to the increased surface area of the asphalt-covered mineral aggregates. Higher VFA values can deliver adequate asphalt content to increase durability. As the temperature increases, more binder fills the voids. Blends with PET give lower VFA values compared to normal blends [15].

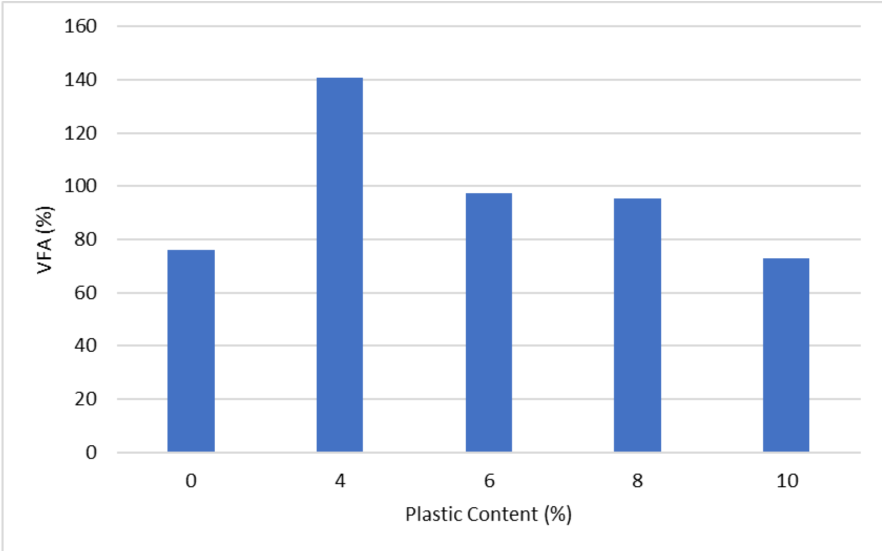

Figure 38. VFA vs. Plastic Content.

3.17.4. Voids in Mineral Aggregate

Ref. [15] used 6% of plastic content in the specimen. The results of the control mixture show that the maximum value of VMA is 12.36%, and the consistent temperature is 155 °C. On the other hand, for the experimental mixture, the maximum value is 13.80% at 140 °C, as shown in Figure 39. This confirms a study by [2] that the incorporation of plastic resulted in the rise of VMA values compared to the controlled mixtures, as bulk-specific gravity values were reduced due to the irreconcilable properties of aggregates and PET. Ref. [32] reported decreased VMA with increasing compression temperature due to the greasing effect of the binder. The greater the VMA value, the more space is available for asphalt penetration.

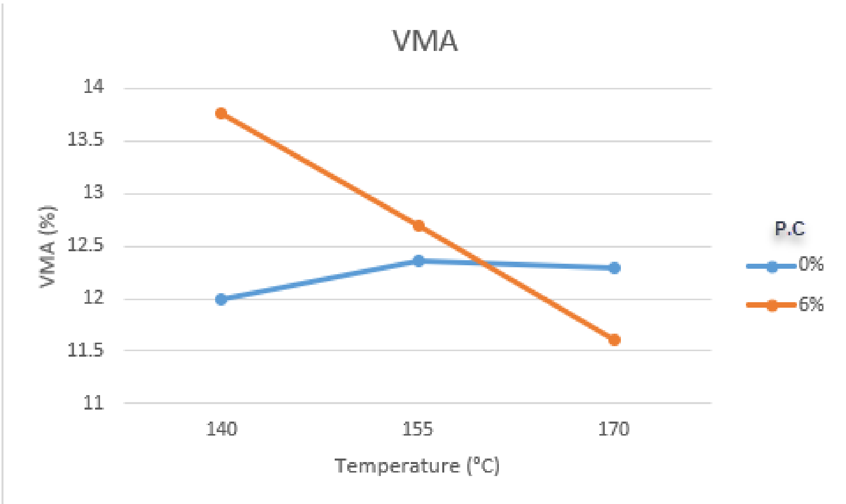

Figure 39. VMA vs. Plastic Content.

3.17.5. Dynamic Creep

The findings for dynamic creep are presented in [29]. The test is repetitive on asphalt concrete, and rutting occurs at plastic contents between 4 and 10%. The results show that the modulus of creep rises with an increasing proportion of plastic up to 8% and then falls. The maximum creep is 72.95 Megapascal after 8% usage of plastic. The lowermost creep factor is 24.87 MPa for 4% plastic, which is 5% lower than normal asphalt mixtures, as shown in Figure 40. Reutilizing waste plastics helps to reduce the everlasting distortion of ruts and cold cracking of pavement surfaces.

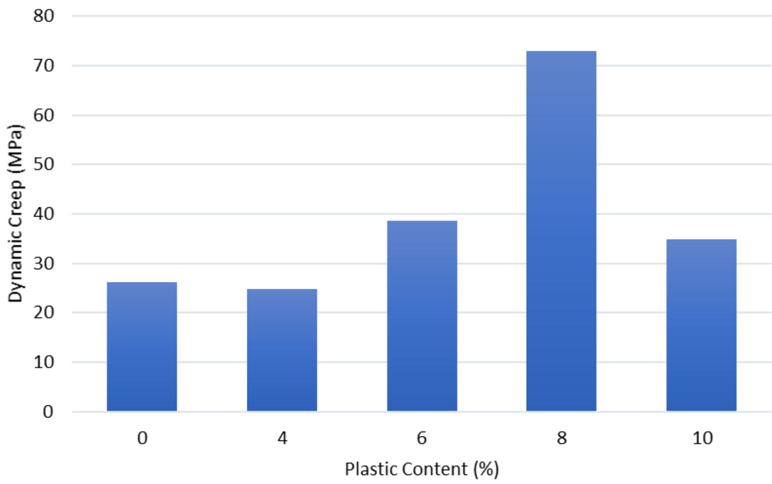

Figure 40. Creep vs. Plastic Content.

3.17.6. Fatigue

Fatigue damage, which typically arises at moderate temperatures, is a common problem in asphalt mixtures. The phenomenon mainly appears as cracks in cobblestones called alligator cracks. Fatigue life is explained as the number of cycles of loading before the specimen fails or the maximum deformation of 9 mm is reached. In [28], the author reported the effects of different percentages of plastic content (0.2–1%) for 250 KPa, 350 KPa, and 450 KPa, respectively.

These PET-reinforced blends had significantly longer fatigue life compared to the control blend. For example, at a stress level of 250 KPa, fatigue life nearly doubles as the value increases from less than 30,000 cycles for mixtures to more than 60,000 cycles for mixtures reinforced with 1% of PET. This is perhaps due to the plastic particles improving the elastic properties of the mixture, absorbing the amount of energy generated by cyclic loading, and slowing crack opening and circulation in the mixture.

4. Conclusions

The usage of waste plastics in asphalt pavements has proven beneficial for improving pavement properties, as evidenced by research results in the last 20 years. There seems to be a consensus among researchers that the proper mixing of certain plastic wastes with bitumen under optimal conditions can significantly improve the performance and longevity of pavements. The usage of waste plastics in asphaltic pavements has also been presented to improve certain pavement properties to levels similar to the use of the virgin polymer. From the basic economic perspective, the use of waste in the paving and construction of roads is favorable in many ways, including benefits from better pavement performance and less burial. Many polymer wastes are hazardous and can be an environmental problem if they are not recycled or reprocessed effectively. Using waste plastics in pavements not only improves pavement capabilities and reduces environmental contamination but also reduces the need to use aggregates in pavements, resulting in long-term cost savings. The following Tables 1 and 2 shows the summary of the test performed after using different percentages of plastics and the effect of that addition.

Table 1. Summary of Usage of Different Percentages of Plastics by Various Authors.

Author	% Replacement of Plastics	Optimum Value Attained At	Replacement
[2]	0, 2, 4, 6, 8, 10	6%	By wt. of bitumen
[11]	0, 4, 6, 8, 10	4%	By wt. of bitumen
[13]	0, 4, 6, 8, 10	8%	By wt. of bitumen
[38]	0, 0.2, 0.4, 0.6, 0.8, 1	1%	By wt. of aggregate
[39]	0, 15, 20, 25, 30	15%	By wt. of bitumen
[36]	0, 1, 3, 5	1%	By wt. of bitumen
[37]	0, 6, 8, 10, 13, 16, 18	8%	By wt. of aggregate
[37]	0, 2, 4, 6, 8, 10	4%	By wt. of bitumen
[38]	0.1, 0.3, 0.5, 0.7, 0.9, 1.1	0.5%	By wt. of aggregate
[39]	5, 5.5, 6, 6.5, 7, 7.5, 8	6.6%	By wt. of bitumen
[20]	6, 8, 10, 12, 14, 16, 18	12%	By wt. of bitumen
[23]	2.5, 5.0, 7.5, 10, 12.5, 15%	12.5%	By wt. of bitumen
[24]	0, 1, 2, 3, 4	4%	By wt. of bitumen
[25]	0, 1, 2, 3, 4	2%	By wt. of bitumen
[28]	0, 0.2, 0.4, 0.6, 0.8, 1	0.4%	By wt. of bitumen
[33]	0, 2.5, 5, 7.5, 10, 12.5, 15	7.5–10%	By wt. of bitumen
[34]	2, 4, 6, 8, 10	4%	By wt. of bitumen
[35]	0, 2, 4, 6, 8, 10	4%	By wt. of bitumen
[36]	0, 2, 4, 6, 8, 10	4%	By wt. of bitumen

Table 2. Summary of Tests Performed after Using Waste Plastics.

Author	Effect On													
	MS %	MF %	MQ %	BSG %	VMA %	VIM %	VFA %	VTM %	Stiffness %	Density %	ITS %	RM %	Specific Gravity %	AV %
[2]	6	10	4	0	10	10	-	-	-	-	-	-	-	-
[11]	4	10	-	-	-	-	4	4	6	4	-	-	-	-
[13]	4										0	8	-	-
[38]	-	-	-	-	-	-	-	-	-	-	-	-	-	-
[39]	15	15	-	-	-	-	-	-	-	-	-	-	-	-
[36]	7	8	-	-	-	-	7.5	5	-	6.5	-	-	-	-
[37]	18	10	-	13	-	-	-	-	-	-	-	-	13	-
[37]	10	10	-	-	-	-	-	-	-	0	-	-	8	-
[38]	0.5	1.1	-	-	1.1	-	-	-	0.3	-	1.1	-	-	1.1
[39]	6	8	6	-	5	-	-	-	-	7	-	-	-	-
[20]	-	8	-	-	12	-	-	-	-	12	-	-	-	12
[23]	10	2.5	-	-	-	-	-	-	-	7	-	-	-	-
[24]	4	4	-	-	-	-	-	-	-	-	-	-	-	-
[25]	4	0	-	-	-	-	-	-	-	-	-	-	-	-
[28]	5	7	-	-	-	-	-	-	0.2	-	-	-	-	-
[33]	10	-	-	-	-	-	-	-	-	-	7.5	-	-	15
[34]	4	4	-	-	-	-	-	-	-	-	-	4	-	-
[35]	4	4	-	-	-	-	-	-	-	-	-	-	-	-
[36]	-	-	-	-	-	-	-	-	-	-	0	6	-	-

Author Contributions: Conceptualization, A.M.S. and R.H.L.; validation M.F.J.; Writing—original draft, A.M.S., R.H.L. and M.F.J.; Writing—review and editing, M.J., E.J. and M.G.; Supervision, M.F.J. and M.G., Visualization: E.J., project administration: M.J.; founding: E.J. All authors have read and agreed to the published version of the manuscript.

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

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