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INCORPORATING WASTE PLASTIC BOTTLES AS AN ADDITIVE IN ASPHALT MIXTURES THROUGH A DRY METHOD

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Abstract

The rise in plastic waste is attributed to the varied types and sizes of containers used for liquids like mineral water, oils, detergents, etc. This increase in solid waste, which is driven by population growth, developmental activities, and changes in lifestyle, has led to a significant global issue. Plastic waste, known for its durability and lack of aesthetic appeal, poses a challenge in its disposal. This study aims to explore the Marshall engineering properties of asphalt mixtures infused with recycled plastic from water bottles (polyethylene terephthalate or PET) at concentrations of 0.25%, 0.5%, 0.75%, and 1% relative to the weight of the aggregates. The findings indicate that the inclusion of plastic improves the asphalt's stability to a certain point, beyond which its effectiveness diminishes due to the excessive plastic content. The study establishes that incorporating 0.5% plastic into the asphalt mixture meets all the criteria of the Marshall test, including stability, flow, air voids, VMA, and VFA. Therefore, it is concluded that 0.5% is the optimal percentage for the addition of plastic to enhance the Marshall properties of an asphalt mixture.

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Key words

- Hot mix asphalt (HMA),
- Waste plastic,
- Water bottles,
- Polyethylene terephthalate (PET),
- Marshall properties.

1 INTRODUCTION

Numerous studies have delved into the utilization of diverse alternative waste materials, including reclaimed asphalt pavement, various plastics, waste oils, steel slag, and scrap tires, in the composition of hot-mix asphalt (HMA) pavements. This approach aims at mitigating road deterioration (Karmakar et al. 2018), (Al-Saffar et al. 2023), (Bilema, et al. 2021a), (Cheng et al. 2019), (Bilema, et al. 2021b). Utilizing recycled materials in pavement construction offers three main advantages: improved performance, cost savings, and enhanced environmental sustainability. The oversupply of plastics, which are extensively used and contribute substantially to global waste, underscores the urgency for efficient waste management (Karahrodi et al. 2017). These plastics are commonly found in packaging such as bottles and cups, disposable items like medical devices, and long-lasting products such as furniture, construction materials, and tires (Somarathna et al. 2018). In 2023, the worldwide consumption of plastics was around 400.3 million tons ("Plastic Waste Worldwide, 2024). Various types of plastic, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), etc., are recycled into asphalt mixtures (Abd Karim et al. 2023).

In particular, PET, which accounts for a significant portion (55%-60%) of plastic bottles, is recycled into standard asphalt mixtures, which not only deal with the issue of postconsumer plastic waste but also enhance the properties of asphalt (Mashaan et al. 2021). The use of PET waste in flexible pavement asphalt is vital (Bilema 2024), considering that flexible pavements constitute the majority of global roads (Sreeram et al. 2018). The economic benefits of adding PET to asphalt include a reduction in material costs. PET is known for its ease of handling, strength, durability, and chemical stability and does not release harmful gases when softened (Leng et al. 2018a). PET comprises around 60% of plastic waste, which emphasizes its importance in waste management (Leng et al. 2018b). The addition of PET to asphalt binder and mixtures, coupled with treating aggregates against moisture, enhances the mixture's strength. Incorporating plastic waste into asphalt not only improves pavement flexibility but also helps reduce environmental pollution (Mahdi et al. 2022). Plastic waste is applied in road pavements through dry or wet methods, with the dry method involving the blending of heated aggregates with plastic waste particles. Hard plastics like HDPE and PET are preferred in this process due to their high melting points and contribute to the durability of asphalt mixes (Jamdar et al. 2017). PET is commonly favored for dry modification due to its high melting point (Ahmad et al. 2017). PET does not emit toxic gases during heating (Menaria et al. 2015).

Previous studies have investigated the use of PET waste in asphalt mixtures. (Hassani et al. 2005) focused on the Marshall stability, flow, and density of such mixtures; they found stability comparable to that of virgin asphalt, which suggests the viability of using PET as an aggregate. (Sarang et al. 2014) employed crushed plastic waste in stone matrix asphalt to enhance its stability, while (Dalhat et al. 2019) observed that asphalt mixtures with finer plastic sizes exhibit better performance than those with larger sizes. This study aims to assess the Marshall properties of asphalt mixtures modified with different proportions of waste plastic using a dry method.

2 LITERATURE REVIEW

(Baghaee et al. 2015a) investigated the use of 80/100 PEN bitumen mixed with various percentages of PET waste from water bottles by employing a dry method; the size of the plastic was 2.36mm. The study concluded that the amount of PET and environmental conditions significantly influence the rutting performance of asphalt mixtures, with a noted decrease in cumulative permanent strain when PET is used. Similarly, (Modarres et al. 2014) examined the effects of incorporating different percentages of plastic waste (from water bottles) into 60/70 PEN bitumen. Using a dry method with plastic particles smaller than 1.18mm, the study found that adding 2% PET to the mixture made its resistance modulus and indirect tensile strength (ITS) higher at various testing temperatures. However, as more PET was added, the ITS values went down. A comprehensive study conducted by (El-Naga et al. 2019) mixed polyethylene terephthalate (from plastic bottles) with asphalt using both dry and wet methods. The bitumen, graded 60/70 AC, was mixed with plastic in percentages ranging from 2% to 15%. This research indicated that adding plastic bottles reduced penetration and increased the softening point. The mixture with PET showed enhanced Marshall stiffness modulus, ITS, and rutting, thereby improving the resistance of pavement to cracking. Additionally, the study noted an increase in air voids and voids in mineral aggregate with higher PET concentrations. Another investigation by (Baghaee et al. 2014) used 80/100 PEN bitumen with waste PET from water bottles in amounts ranging from 0.1-1%, which was mixed using a dry method and a plastic size of 2.36mm. The findings indicated that ITS values decreased with the application of PET, and higher PET quantities resulted in diminished tensile strength. The study also observed varying rutting behaviors under static and dynamic loadings in PET mixtures. A comprehensive study conducted by (Ahmadinia et al. 2012) explored mixing PET with asphalt using both dry and wet methods, employing 80/100 PEN bitumen with plastic percentages of 2%, 4%, 6%, 8%, and 10%, and a PET size of less than 1.18mm. The results demonstrated that the resilient modulus value of SMA mixtures was improved by 16% using 6% PET, compared to conventional mixtures. The most effective rut depth reduction, i.e, 29%, was achieved with a 4% PET mix. Additionally, all the TSR values exceeded 70%, indicating enhanced resistance to moisture damage in the PET-modified asphalt mixtures. (Rahman et al. 2013) experimented with varying PET percentages (5-25%) in 80/100 PEN asphalt, using a dry method and plastic sizes ranging from 2.36-1.18mm. The study concluded that a 20% PET-modified asphalt mixture showed significant resistance to permanent deformation, although increased PET contents resulted in lower asphalt stiffness. Research conducted by (Movilla-Quesada et al. 2019) used 50/70 PEN bitumen mixed with PET waste from water bottles at percentages of 10 and 20%, which were relative to coarse and fine aggregate sizes (10-5 mm and 2-0.25 mm, respectively). The study found that the addition of PET led to lower moisture sensitivity and boosted ITS. It had a higher air void content and lower permanent deformation values. In a study done by (Ahmadinia et al. 2011), 80/100 PEN bitumen was mixed with various PET percentages (2-10%) from water bottles using a dry method with plastic sizes smaller than 1.18mm. The study noted that adding PET increased the air voids in the mixture while reducing its bulk-specific gravity. A 6% PET content according to the weight of the bitumen resulted in optimal stability. (Baghaee et al.2015b) conducted a comprehensive study using 80/100 PEN bitumen treated with PET and mixed by a dry method with a plastic size of less than 2.36mm. The findings showed that modified asphalt mixtures achieved a higher degree of stability with an asphalt binder content of less than 5.5% and 0.2–0.8% PET. Optimal values of 5.88% asphalt content and 0.18% PET content were identified to meet Marshall mix design requirements. A study conducted by (Arifin et al. 2024) explored the impact on the Marshall characteristics and optimal asphalt content of incorporating PET waste into asphalt. Using a wet mixing method, PET plastic was added to hot asphalt and stirred until homogeneous in 4%, 5%, and 6% proportions according to the weight of the asphalt. The results indicated that the inclusion of PET increases the stability value, while reducing VFB and VMA values. The optimal asphalt content for each PET percentage was determined: 4%, 5%, and 6% PET yielded optimal asphalt contents of 6.2%, 6.25%, and 6.28%, respectively. The proper incorporation of PET into asphalt achieves optimal results when the appropriate proportion is selected. In a separate investigation, (Majka et al.2023) examined two types of PETs (recycled PET (RPET) and mechanically recycled PET (MRPET)) using three analytical techniques: differential scanning calorimetry (DSC), thermogravimetric analysis (TG), and Fourier transform infrared spectroscopy (FTIR). The TG analysis showed that modified PET decomposed at approximately 400°C. In a polymer-modified asphalt (PMA) preparation, MPET was exposed to 240°C, thereby preventing thermal decomposition of the modified mixture. The DSC curve revealed that the MRPET melting process began at 235°C, thus ensuring that it fully melted under PMA preparation conditions. The FTIR analysis showed that the MRPET sample exhibited a higher infrared absorption intensity for specific functional groups compared to the RPET sample. Its IR spectrum also displayed absorption bands corresponding to bond vibrations associated with a cationic emulsifier.

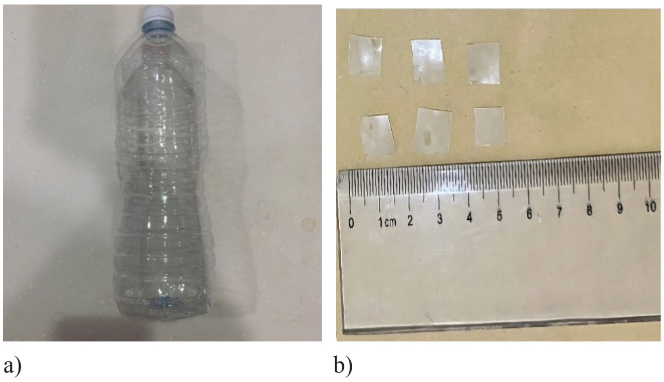
3 MATERIALS AND METHODS

3.1 Materials

Our research utilized 60/70 PEN grade raw bitumen, which is commonly employed by construction firms in Libya. The bitumen and aggregates were sourced from a local Libyan supplier. The properties of the bitumen utilized in this study are detailed in Table 1. For the experiment, plastic water bottles were air-dried at an ambient temperature and subsequently cut into 1x1 cm pieces prior to being mixed with the asphalt using a dry method. Illustrative images of the water bottles before and after being cut are presented in Figure 1.

Tab. 1 *Properties of the bitumen 60/70 PEN.*

Test	Unit	Standard	Value
Softening point	°C	D36	50.5
Specific gravity	g/cm^3	D70	1.027
Penetration at 25°C	0.1mm/PEN	D5	68
Viscosity at 135°C	CST	D2170	405
Flash point	°C	D92	298
Ductility at 25°C	cm	D113	136
Loss on heating	%	D6	0.029



a) b)

Fig. 1 *Plastic water bottle a) dried water bottle b) after cutting water bottle*

3.2 Mixing method

In this study, the aggregate was initially dried to a constant weight at 110ºC, sorted into specific sizes, and then recombined to achieve the desired gradation for each sample. Subsequently, the aggregates were heated to 155 ºC in preparation for mixing with bitumen, which was itself heated to the appropriate mixing temperature for two hours. To create the plastic asphalt, a plastic modifier was added in varying proportions of 0.25%, 0.5%, 0.75%, and 1% by weight of the aggregates. The process of blending PET was carried out at 165 °C, where aggregate and bitumen were mixed using a heavy-duty mixer. According to the dry process, the aggregates and the PET were mixed for two minutes; the bitumen was then added and mixed for two minutes (Baghaee et al. 2015a), (El-Naga et al. 2019). The samples were transferred to an oven set at a compaction temperature of 135 °C and left for two hours prior to the compaction process. The asphalt mixes then underwent compaction, receiving 75 blows on each side using the standard Marshall hammer. Post-compaction, the specimens were extracted from the molds and allowed to cool for 24 hours before the Marshall test process was conducted. Figure 2 shows the preparation, mixing, and testing process for the samples.

3.3 Marshall method

The Marshall method involves assessing the resistance to the plastic flow of cylindrical bituminous paving mixture samples using the Marshall apparatus, as outlined in ASTM D1559. The mixture is positioned in a preheated mold measuring 101.6mm in diameter and 76.2mm in height. Each sample is compacted by delivering 75 blows on each side with a 4.536 kg hammer, which has a free fall distance of 457.2 mm, to both the top and bottom of the specimen. After compaction, the specimens are left to cool at an ambient temperature for 24 hours. Marshall stability and flow tests are then conducted on each sample as per ASTM D-1559 guidelines. This involves placing the cylindrical specimen in a water bath maintained at 60 °C for 30 to 40 minutes, followed by compression on the lateral surface at a steady rate of 50.8 mm/min. The process continues until the maximum load resistance and the associated flow value are recorded. For each mix variation, three samples are prepared, and the average results are documented. Additionally, the bulk specific gravity of each specimen is determined in accordance with ASTM D-2726.

Fig. 2 *The mixing and testing process for all the samples in this study*

4 RESULTS

4.1 Aggregate

Tables 2 and 3 present the specific gravity and absorption values for coarse and fine aggregates, respectively. The Aggregate Impact Value (AIV) is a relative indicator of the aggregate's capacity to withstand sudden shocks or impacts, which may vary from its resistance to gradual compressive stress. Typically, the AIV should not exceed 30% for aggregates intended for use in the wearing course of pavements. As per the data in Table 4, the average AIV results, which registered at 15.53%, were well within the acceptable limit When compared with American standard specifications. The Los Angeles abrasion test results confirm that the aggregate materials are suitable for the surface layer of pavements. This is supported by the data in Table 5, which shows that the Los Angeles abrasion values for the asphalt mixtures are within the maximum permissible limit of 40% as per the American standards.

The aggregate grading was conducted following the Marshall grading system, utilizing a 19mm maximum size and the 0.45 power grading chart for dense-graded mix designs. The sieve sizes employed in this process included 25mm, 19mm, 12.5mm, 9.5mm, 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.075mm, and the Pan. Both the gradation and the specification limits were plotted on the 0.45 power grading chart. Figure 3 illustrates the aggregate gradation and depicts the passing line as well as the upper and lower specification limits.

Tab. 2 *Specific gravity and absorption for the coarse aggregates*

Description of sample	Unit	Coarse aggregate 22/12 mm	Coarse aggregate 6/12 mm
Bulk specific gravity	g/cm³	2.5475	2.521
SSD specific gravity	g/cm³	2.578	2.559
Apparent specific gravity	g/cm³	2.6275	2.621
Absorption	%	1.208	1.542

Tab. 3 *Specific gravity and absorption for the fine aggregates*

Description of sample	Unit	Fine aggregate Agg-0/6 mm
Oven dry bulk specific gravity	g/cm³	2.587
SSD bulk specific gravity	g/cm³	2.625
Apparent specific gravity	g/cm³	2.692
Absorption	%	1.505

Tab. 4 *Aggregate impact value results for the aggregates*

Description of Samples	Unit	Average
Total weight of tested sample S1	g	15.53
Weight of sample passing from 2.36 mm sieve S2	g	
Weight of sample retained on 2.6 mm sieve S3	g	
Loss in material after sieving (S1-(S2+S3))	g	
Aggregate impact value AIV (dry) =(S2/S1)*100	%	

Tab. 5 *Los Angeles abrasion results for the aggregates*

Description of sample	Result
12/22 mm	23.91
6/12 mm	28.6

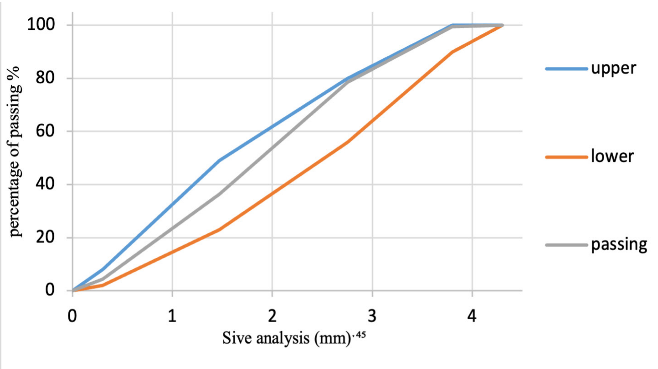


Fig. 3 *Aggregate gradation for 19mm on 0.45 power chart*

4.2 Optimum bitumen content

The determination of the optimal bitumen content was carried out using the Marshall mix design method, following the formulation of an aggregate-bitumen-plastic mixture. For this purpose, five different asphalt contents were trialed, namely 4.5%, 5%, 5.5%, 6.0%, and 6.5%, considering a heavy traffic scenario with equivalent single axle loads (ESALs) exceeding 10^6. Each sample in this study underwent compaction with 75 blows on each side. A graph depicting the relationship between the air voids and binder content was constructed. The binder content corresponding to 4.0% air voids was identified as the optimal bitumen content, in line with the guidelines set by the National Asphalt Pavement Association (NAPA). Consequently, the ideal bitumen content for this specific asphalt mixture design was established at 5.8%. Figure 4 shows the relationship between the air void versus the binder contents.

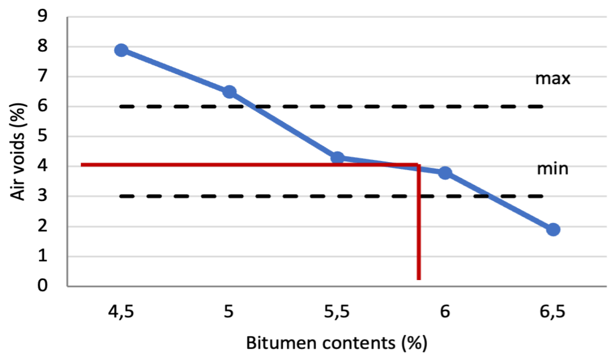


Fig. 4 *Air void versus binder contents.*

4.3 Optimum bitumen content

Figures 5 to 11 illustrate the findings of this study. It can be deduced that when the plastic content falls within the range of 0.75% to 1%, the stability value of the asphalt mixtures is lower than the original blend, despite achieving favorable flow percentages. Conversely, for plastic content falling within the range of 0.25% to 0.5%, higher stability and flow values are attained. The stability serves as an indicator of the performance of the asphalt mixture under the load conditions.

Figure 5 indicates that the introduction of plastic can enhance the stability of the asphalt mixture up to a certain threshold, beyond which the stability declines. These findings align with those of (Ogundipe, 2019), who observed a significant impact on the stability of the asphalt mixture upon the addition of the plastic waste (PET). While the flow results for the modified asphalt mixture exhibit fluctuations, they remain within acceptable limits as shown in Figure 6.

As seen in Figure 7, the air voids in the plastic-asphalt mixtures increase with higher quantities of the plastic waste (PET). The air voids for the 0.25% and 0.5% plastic content conform to the specified range of 2-6%. In contrast, the air voids for the 0.75% and 1% plastic content exceed the requirements and register percentages of 8% and 7.4%, respectively. All the modified and unmodified asphalt mixtures meet the minimum requirements for voids in a mineral aggregate (VMA) as shown in Figure 8. As shown in Figure 9, the asphalt mixtures containing 0.25% and 0.5% plastic content adhere to the specified range for voids filled with asphalt (VFA), i.e, falling between 65% and 75%. Conversely, the asphalt mixtures with 0.75% and 1% plastic content fail to meet the requirements, recording percentages of 52.42% and 58.12%, respectively. The quotient results for the plastic-asphalt mixtures display fluctuations linked to the flow results. It can be concluded from Figure 10 that all the results surpass the minimum required quotient value of 250 kg/mm. The increase in plastic led to increased variability in the bulk density and air void percentages, revealing greater challenges in controlling the manufacturing process of the mixtures. This effect occurs because plastic particles partially coat the aggregate but are not absorbed by it, leaving air voids due to the reduced binder content. Additionally, the lower viscosity of the plastic compared to the binder causes the aggregate particles to separate further, thereby contributing to an increase in air voids within the mixture. This trend becomes more pronounced with high plastic contents. In similar results, when the PET is mixed with hot aggregate at 160°C, softened PET tends to form a coating around the aggregate (Menaria et al. 2015). Asphalt mixtures containing 0.75% and 1% plastic exhibit higher air voids, resulting in reduced stability values. All asphalt mixtures in this investigation meet the specific gravity standards as shown in Figure 11. In conclusion, the examination of the Marshall properties results reveals that the sample containing 0.5% plastic content outperforms the other percentages, has a high stability of 1489 kg, and improves the flow rate by 2.2, which is a level that meets the acceptable standard.

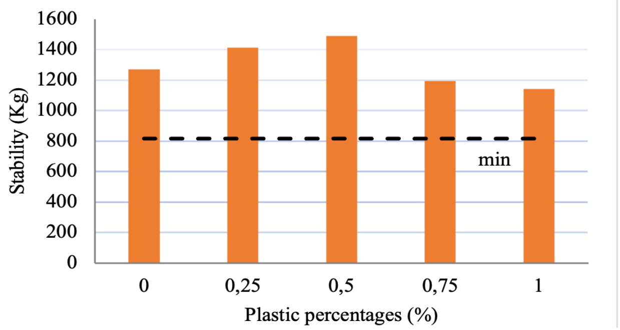


Fig. 5 *Stability results for the unmodified and modified asphalt mixtures.*

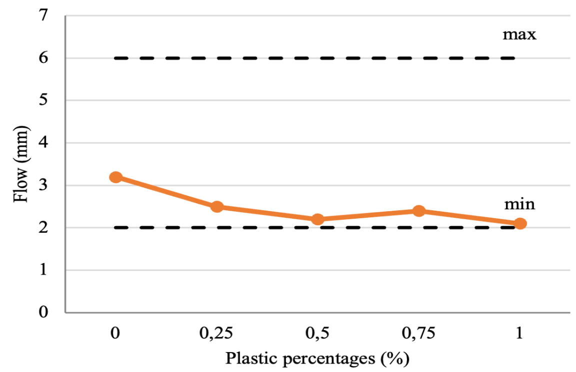


Fig. 6 *Flow results for the asphalt mixtures in this study.*

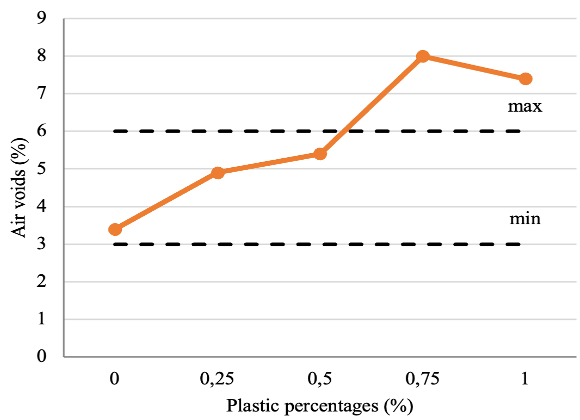


Fig. 7 *Air voids results for the unmodified and modified asphalt*

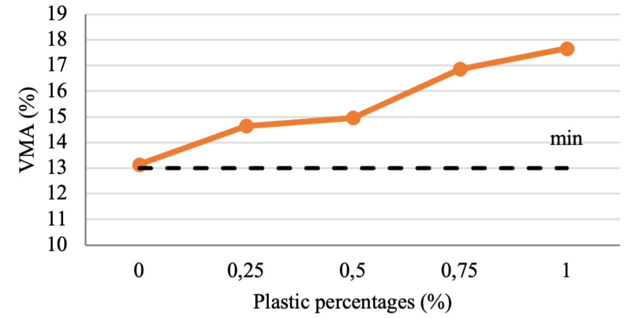


Fig. 8 *VMA results for the asphalt mixtures in this study.*

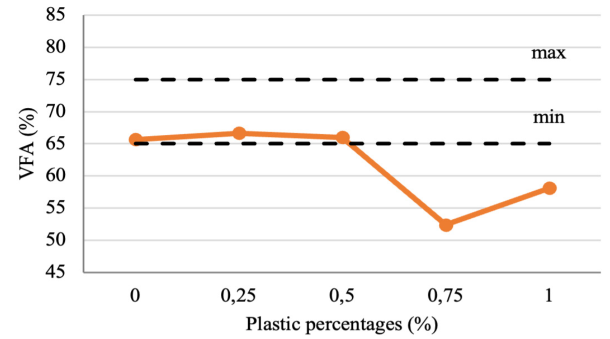


Fig. 9 *VFA results for the unmodified and modified asphalt mixtures.*

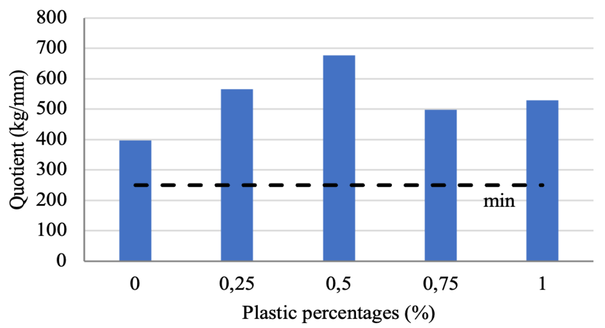


Fig. 10 *Quotient results for the asphalt mixtures in this study.*

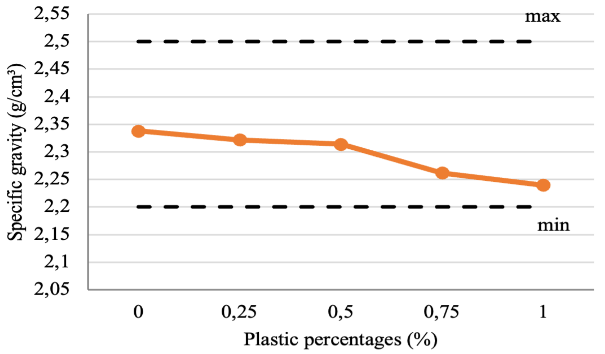


Fig. 11 *Specific gravity results for the unmodified and modified asphalt mixtures.*

5 Conclusions and Recommendations

Based on the laboratory tests conducted in this study, the following conclusions can be drawn:

1. Recycled plastic from water bottles can improve the Marshall properties of asphalt mixtures when integrated into aggregates of a specific size, thickness, and concentration through a dry process.
2. Incorporating finely shredded plastic waste particles of 1x1 cm into an asphalt mixture enhances the Marshall stability and exceeds that of conventional mixtures.
3. The inclusion of plastic waste particles exceeding 0.5% can reduce adhesion among the mixture's components due to the high proportion of plastic particles.
4. The ideal addition of plastic waste should be limited to 0.5% of the aggregate's weight, which is advantageous for road pavement construction as it improves the Marshall properties.

The study also offers the following recommendations:

- Vary the plastic content in the asphalt mixture across a range of 0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 0.6%, and 0.7% by weight of the aggregates.
- Experiment with different shapes of plastic, such as circles, triangles, wires, and chopped forms, instead of solely square pieces, to evaluate their impact on the adhesion within the mixture.
- Utilize smaller plastic particles can improve the uniformity and effectiveness of asphalt mixtures.
- Perform a comparative analysis of the most frequently used plastics, such as plastic bags and water bottles, to evaluate their relative performance in asphalt-plastic mixtures.

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