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Performance of recycled polyethylene terephthalate (pet) waste plastic modified bitumen in hot mix asphalt production

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ABSTRACT

Asphalt is widely used in road pavement construction to bind aggregates. Road surface distress occurs when there is a sign of poor pavement performance. Therefore, asphalt modification is sometimes used to improve its performance. This study was carried out to investigate the use of Polyethylene Terephthalate (PET) to modify bitumen in Hot Mix Asphalt (HMA). The optimum bitumen content (OBC) for mixed design was determined, and the modified HMA was prepared by replacing the OBC with 2, 4, 6, 8, and 10% PET. The effect of PET on HMA was examined. The OBC was 6%. The addition of PET changed the penetration grade from 60/70 to 50/60 at 6% PET replacement, and an improvement in marshal stability was noticed as PET content increased. An increase in void in mix, and a reduction in the bulk density of the modified HMA were observed as PET content increased up to 6%. The modified HMA developed more resistant to deformation with an increase in Marshall Quotient as PET content increased up to 6%, and had more potential to resist moisture damage. This study revealed that HMA with bitumen modified with 6% PET waste is suitable for pavement construction.

1. Introduction

Globally, the volume of solid wastes generated increases on yearly basis due to increase in population, socioeconomic activities and social development. These wastes come from agricultural, industries, as well as construction activities. Plastic wastes are examples of industrial wastes which constitute major fraction of total solid wastes. The world's annual consumption of plastic material was reported to be 204 million tons in 2002, and increased to 300 million tons in 2013 (Plastic, 2013). In 2015, it was recorded as 407 million tons (Geyer, et al., 2017) while in 2023, it was around 400.3 million tons (Plastic Waste Worldwide, 2024). According to Borrelle et al., 2020, in 2016, about 23 million tonnes of plastics was estimated to have entered into aquatic ecosystems, and with ambitious reduction targets, by 2030, this amount was predicted to be an increase of 300–400% by 2050 (Geyer et al., 2017). However, by 2050, the record stated that oceans would have become a reservoir, contain more plastics than fish in terms of weight due to unabated rate of plastic production, and in ability to monitor disposal of plastic products in the environment through different water channels such as rivers, lakes, and freshwater (World Economic Forum, 2016 and Sutter, 2016). Consequently, this has been a threat to the ecosystem for many years and has become an issue of global concern (Wagner and Reemtsma, 2019, Angelone et al., 2016) due to its detrimental environmental effects which include animal choking, pollution, blockage of channels, rivers, and landscape disfigurement (Ujeh, 2021). Besides, its contribution to greenhouse gases is enormous. According to CIEL, 2019, the equivalent of 850 million tons of carbon dioxide (CO2) was emitted to the atmosphere in 2019. However, the emissions could rise to 1.34 billion tons by 2030, and by 2050, plastic could emit 56 billion tons of greenhouse gas emissions. Plastics are industrial products of polymerization and geopolymerization reactions, which possess elastoplastic properties. They are solid, lightweight and cheap materials. Their low cost, excellent moisture-resistant, biological resistance, and low weight properties make them excellent packaging materials (Olanrewaju and Oyebade, 2019.). The everyday use of plastic bottles, bags, and other single-use plastic products including take-home food packs, straws, cups, water bottles, and spoons, among others has made it available everywhere. According to [Ayo et al., 2018], plastics are of five major categories which are Polyethylene (PE), Polyethylene Terephthalate (PET), Polypropylene (PP), Polystyrene (PS), and Polyvinylchloride (PVC).

PET is not a degradable material, and it takes several years to decompose. It belongs to a thermoplastics with excellent physical properties. It makes up around 18% of all polymers produced globally, and more than 60% of it is utilized to make synthetic fibers and bottles, which account for about 30% of the demand for PET worldwide (Bottenbruch 1996). In US alone, 2,675 tons of PET was wasted in 2010, from which only 29.1% was recycled and the rest was disposed (Container Recycling Institute. 2017). Likewise, in Nigeria, plastic wastes are hardly recycled, less than 12% are recycled and about 80% of these wastes ending up in landfills and dump sites (Richie and Max, 2022). Therefore, managing these huge amounts of waste plastic, and improve the environment condition has become the major focus of researchers ((Heydari et al., 2021; Xu et al., 2022b; Zhang et al., 2018). However, one of the best means of managing these wastes and reduce its impacts on the environment and human health is its recycling, and re-use them in construction industries as asphalt pavement materials (Menaria and Sankhla. 2015, Mashaan et al., 2019, Mashaan et al., 2019a, Baghaee Moghaddam et al., 2014a, Baghaee Moghaddam et al., 2014b, Modarres and Hamedi, 2014).

Generally, a review of the literature has shown that many researchers have explored different forms of plastic wastes to modify bituminous mixtures and found to have improved some of its properties (Ameri and Nasr, 2017). Recycling these waste materials in crushed or amorphous forms as geo-materials into useful construction materials has been proven technically reliable worldwide in the field of pavement materials (Sojobi et al., 2016). According to Kumar and Khan, 2020; Al-Haydari and Al-Haidari, 2020, utilizing plastic polymer into asphalt, improves the bitumen's temperature susceptibility and stiffness. This enhancement of bitumen leads to an improvement in the rutting and fatigue cracking resistance of asphalt pavement. Li et al., 2022, evaluated the use of waste plastic in asphalt as a modifier and established increase macromolecules number in the asphalt, hence, changed its performance in terms of penetration reduction and improves pavement flexibility (Mahdi et al. 2022. Abdul Rahman and Omardin (2016) examined the optimum bitumen content and the effects of recycled PET as a partial replacement for fine aggregates in asphalt concrete for road pavements on rutting, fatigue, and stiffness properties. The results showed the highest stiffness modulus value for 0% PET-modified asphalt recorded at 5.5% bitumen content, and concluded that all PET-modified asphalt were capable of resisting the rutting of road pavements, but 5% and 15% PET-modified asphalt were more resistance to fatigue compared with the unmodified asphalt. Sulyman et al 2016 and Abu, 2016, among others also examined the use of PET in road pavements, and concluded that PET improved the properties of asphalt concrete, and this concept however reduces both the exploitation of natural resources and the environmental pollution level, saving energy and money. Bitumen is a non-volatile, adhesive, and waterproofing material derived from crude petroleum or present in natural asphalt, which is completely or almost completely soluble in toluene and very viscous or almost solid at ambient temperatures. It is a viscoelastic material that is characterized by a certain level of rigidity of an elastic solid. Bitumen is an important constituent in the production of asphaltic concrete as it acts as a binding material for all ingredients. Asphalt has been in use worldwide in road pavement construction as the binder of aggregates. However, it was recognized that asphalt mixture or coating layer showed severe temperature susceptibility such as high temperature rutting, medium temperature fatigue, and low temperature cracking damage. As a result, asphalt mixture modification is occasionally employed to enhance its subsequent use. Consequently, this research focuses on the effect of waste Polyethylene Terephthalate (PET) plastics modified bitumen as one the constituent materials in asphalt concrete production.

2. Materials and Methodology

2.1. Materials

The materials used were coarse and fine aggregates, filler materials (stone dust), bitumen, and waste PET plastics. The waste PET plastics were collected at Federal University of Agriculture, Abeokuta, Ogun State while fine aggregate (Sharp sand), coarse aggregate (granite), and bitumen were sourced from local suppliers in Abeokuta, Ogun state.

2.2. Methods

Physical and engineering properties of bitumen, coarse aggregate, fine aggregate, crushed stone dust, and waste PET plastics were determined. The components of the asphalt were subjected to a series of tests in accordance with the standard specifications, namely: Penetration test of bitumen (ASTM. 2013), Flash and fire point test of bitumen (ASTM D92. 2015), Specific gravity of bitumen (ASTM, D70. 2009), Specific gravity of the aggregates (ASTM D854-00), and Marshall Test (ASTM D 1559-89. 1994). The optimum bitumen content (OBC) suitable for design mix was determined by adding various sets of specimens made at 5.0%, 5.5%, 6.0%, 6.5% and 7.0% bitumen contents according to the weight of the aggregates. Specimen were prepared, and tested in accordance with (ASTM D 1559-89. 1994), (Marshall Mix Design Method). Marshall Stability and flow tests were conducted on each specimen by placing cylindrical specimen in water bath at 600C for a period of 30 to 40 minutes.

Compression on the lateral surface at constant rate of 50 mm/min was done until the maximum load was reached. The maximum load resistance, and the corresponding flow value observed were recorded. Each combination was tested on three specimens, and the average findings were given. Thereafter, bitumen was modified with the treated waste PET plastics at 2%, 4%, 6%, 8%, and 10% replacement by weight of the bitumen to produce specimen of asphalt concrete according to the mix design following the standard procedure. The modified bitumen were applied at optimum bitumen content for all the specimens prepared and the samples were tested for Marshall Stability, Flow and Density to evaluate the effect of the modifier on the properties of the specimen asphalt concrete (Figure 1).

Figure 1. Asphalt Concrete with Waste PET Plastics Bitumen Modified

3. Results and Discussion

Preliminary test results revealed that the bitumen used conformed to the specified standard and was found to be grade 60/70 (Table 1). A flash and fire point tests conducted to determine the safest temperature for bitumen exposure showed that the results met the criteria. Hence, the bitumen is adequate and can be utilized in the design of an asphalt mix. Mix Design curve (Figure 3) showed that the total aggregate proportion used for this research conformed to the (FMW&H, 1997), and the engineering implication of the result is that the selected aggregates gradation was quite suitable for asphalt concrete trial mix.

Table 2. Summary of bitumen and PET properties Test

Properties	Specifications	Range Value	Results	
			Bitumen	Waste PET Plastic
Penetration (0.1 mm)	ASTM D5	60 – 70	64	90/100
Flash point (0C)	ASTM D92	250 (min)	256.7	200
Fire point (0C)	ASTM D92	302 (min)	325	240
Specific gravity	ASTM D70	1.01-1.06	1.01	1.38
Melting Point			347	148
Shrinkage				62

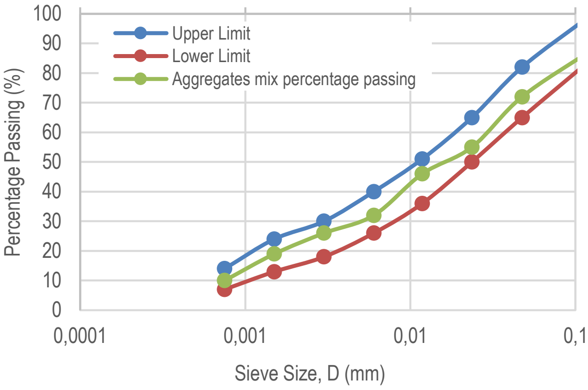

Figure 3. Asphalt Mix Design Curve Envelope for the aggregates

3.1. Control Asphalt Mix

Results of the control sample showed that 6% OBC was suitable for control asphalt mix design. The stability value increases incrementally from 5.0% bitumen content to 6.0% (8.94 kN) before a reduction in value from 6.5% to 7.0% (Figure 2) but the flow increased consistently with an increase in bitumen content from 5.0% to 7.0% (Figure 4). The values obtained for Marshall Mix method were within the specification limits ASTM D 1559-89. 1994).

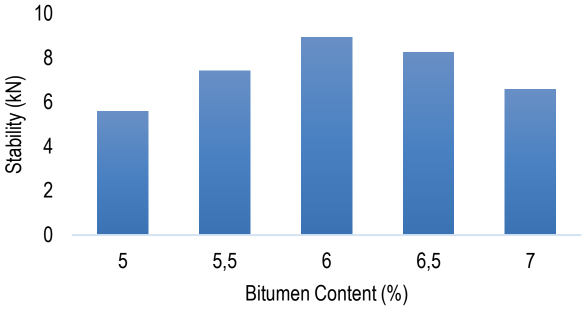

Figure 4. Marshall Stability against Bitumen Content

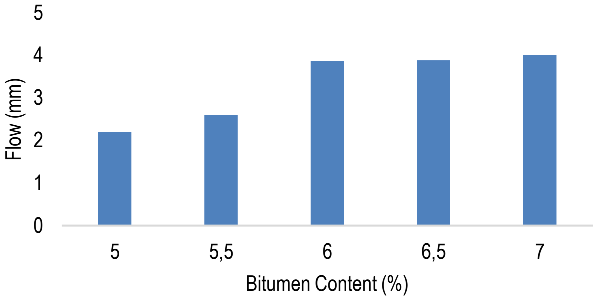

Figure 5. Flow against Bitumen Content

The value of Void in Mix (VIM) decreased with an increase in bitumen content up to 6% (Figure 5) while an increase in value was observed at 6.5% and 7%. A consistence increase in void Filled with Bitumen (VFB) value was observed with an increment in bitumen content, and the maximum value (74.01%) was at 6.0%

bitumen content (Figure 5) while a decrease in Voids in Mineral Aggregates (VMA) value was observed up to 5.5% and thereafter increased consistently with the maximum value (21.88%) at 7.0% bitumen content (Figure 7), and all the values obtained satisfied the specification limits (ASTM D 1559-89. 1994).

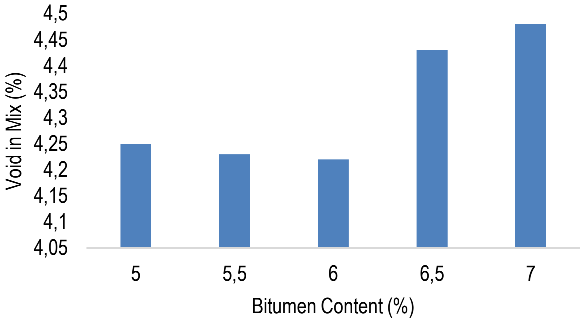

Figure 6. Void in Mix against Bitumen Content

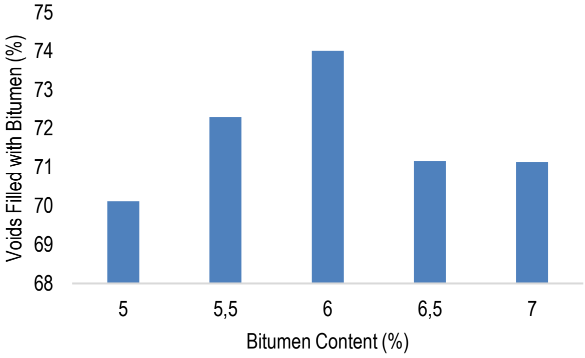

Figure 7. Void Filled with Bitumen against Bitumen Content

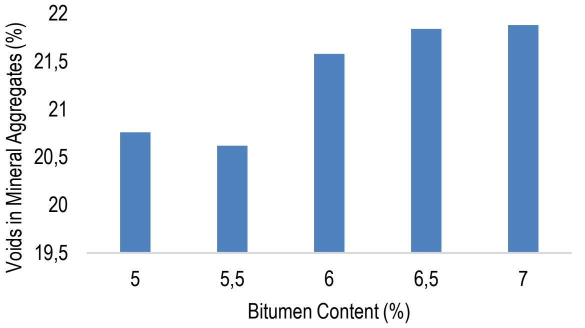

Figure 8. Voids in Mineral Aggregates against Bitumen Content

3.2. Effect of PET Content on Penetration Depth and Specific Gravity of bitumen

The penetration value of bitumen reflects its grade which plays a crucial role in determining its thermal susceptibility, essentially how well the material can withstand changes in its physical state due to temperature variations. The penetration values of the control bitumen decreased with every increment in PET content, and change in penetration grade from 60/70 (64 mm) to 50/60 (58 mm) was observed at 6% PET (58 mm) (Figure 8), and this was in line with (Basha and Anteneh, 2022; Henok et al., 2018). Lower penetration value indicates that the bitumen is hard, and this harder bitumen, indicated by lower Penetration grades, excel in resisting softening when exposed to high temperatures, thus minimizing the risk of deformation under heat. The reduction in penetration compared with the control sample may be attributed to the increase in viscosity, adhesion and cohesion properties of the binder with increasing PET content as agreed with (Praticò, et al., 2011). This invariably implied that PET improved the penetration values of control bitumen and created new modified bitumen which can withstands higher loads. On the other hand, increase in specific gravity was observed with every increment in PET content (Figure 9), and this could be as a result of high specific gravity of Polyethylene Terephthalate (PET) compared with bitumen as already stated in Table 1.

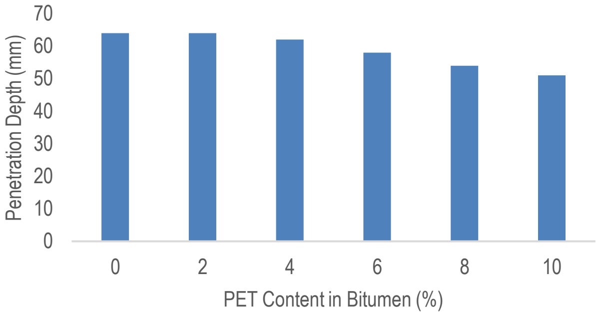

Figure 9. Effect of Plastic content on the Penetration Depth of Bitumen

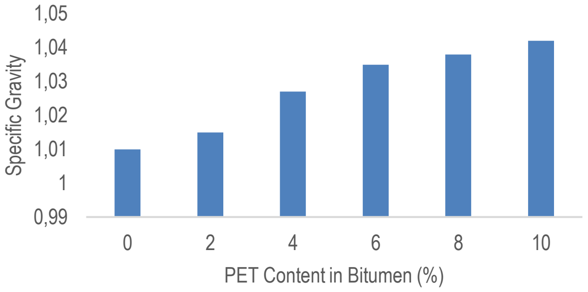

Figure 10. Effect of Plastic content on the Specific Gravity of Bitumen

3.3. Stability and Flow of the modified Asphalt with PET

Stability establishes the performance of the asphalt mixture under loading. The results (Figure 10) showed a consistent increase in stability of the modified Asphalt concrete with an increment in PET content at 2 to 6%, and started declining afterwards. This trend was in line with (Ravi Shankar et al., 2013). The maximum value (10.01 kN) was observed at 6% PET content with 11.97% increase in percentage compared with control sample. The improvement in stability of Polyethylene Terephthalate (PET) modified asphalt could be as a result of increase in adhesion and cohesion properties of the binder. This however would enhance fatigue resistance, improve thermal stress cracking, and reduce rutting as observed by (Abdul Rahman and Omardin, 2016. A consistent reduction in flow value was observed with increase in PET content (Figure 11). The flows of the modified asphalt concrete mixtures were lower than that of the control sample. The reduction in flow suggested an increase in viscosity and stiffness of the binder as PET content increases, which would in turn increase the internal friction, and improve permanent deformation resistance of the asphalt concrete. This trend is in line with the result of (Shiva et al., 2012).

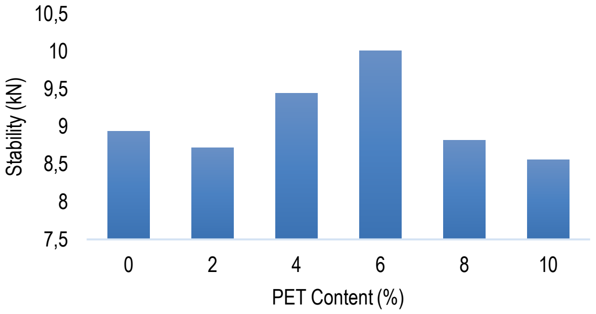

Figure 10. Effect of Plastic Content on Marshall Stability of Modified Asphalt Concrete

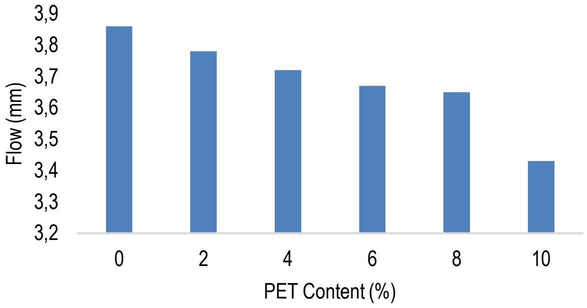

Figure 11. Effect of Plastic Content on Flow of Modified Asphalt Concrete

3.4. Void in mix for the modified Asphalt with PET

A consistent increase in VIM value was observed in modified asphalt with an increment in Polyethylene Terephthalate (PET) up to 6%, and further increase in PET content resulted in a reduction value compared with the control sample (Figure 12) and were within the standard specification limit by Federal Ministry of Works and Housing (FMW&H, 1997). The increase in air voids could be attributed to the fact that the chopped PET remained in crystal form which led to an increase in surface area of the mixture as PET Increases. Besides, the stability of the mixture of bitumen and PET, and because PET could not be fully melted as its content increased with reduction in bitumen content. Therefore, the aggregates could not be coated properly, and affected the bonding between aggregate and caused increasing of the void. Consequently, the increased surface area must be wetted with the binder, and eventually would decrease its compactability. The trend was in agreement with (Ahmad, et al., 2017; Mahrez and Karim. 2010)

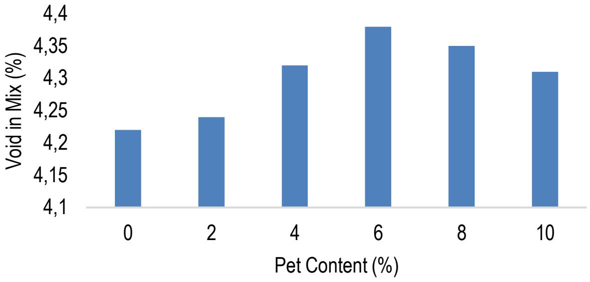

Figure 12. Effect of Plastic Content on VIM of Modified Asphalt Concrete

3.5. Voids Filled with Bitumen (VFB) of the modified Asphalt with PET

The value of VFB in modified asphalt concrete decreased with an increment in PET content (Figure 13). The decrease in VFB value compared with the control sample implied that more bitumen filled the voids, and blended with PET. The values were within the ASTM Specification which showed that addition of PET would result in satisfactory pavements except at 8 and 10% PET replacement, and the trend agreed with (Mohammad, et al., 2007).

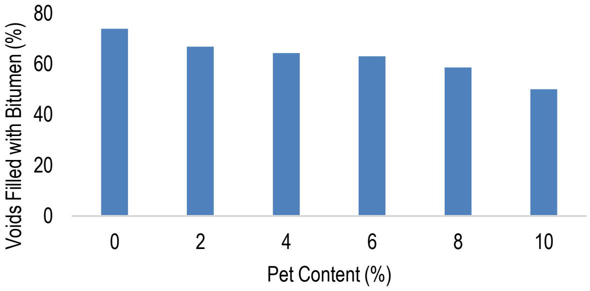

Figure 13. Effect of Plastic Content on VFB of Modified Asphalt Concrete

3.6. Voids in the mineral aggregates (VMA) of the modified Asphalt with PET

The results show a consistence increase in VMA value with an increment in PET content compared with the control sample. The maximum VMA value was in the addition of 10% PET content with 21.83% (Figure 14).

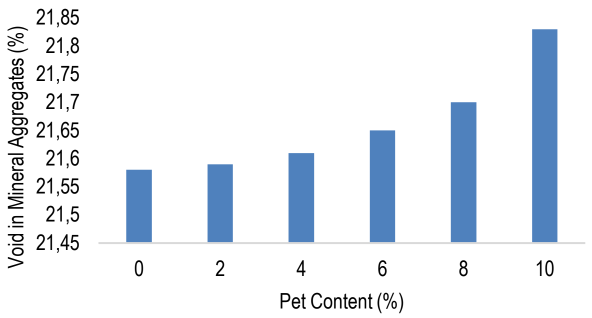

Figure 14. Effect of Plastic Content on VMA of Modified Asphalt Concrete

3.7. Effect of PET Content on Compacted Density of the modified Asphalt

The bulk density of the asphalt concrete with PET were lower than that of the control sample (2.38 g/cm3) for all polythene percentages. The maximum value 2.37 g/cm3 was observed at 6%. Further increase in PET content resulted into a consistent decrease in value (Figure 15). Reduction in values of bulk density could be as a result of lower specific gravity of PET. This observation agreed with (Ogundipe 2019). All the values were within the standard specification by (FMW&H, 1997).

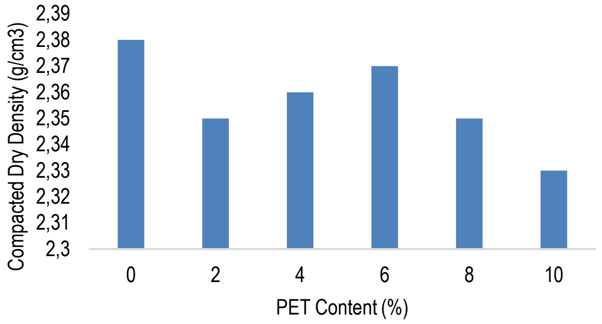

Figure 15. Effect of Plastic Content on Compacted Dry Density of Modified Asphalt Concrete

3.8. Marshall Quotient of the modified Asphalt with PET

Marshall Quotient (MQ) as shown in Figure 16 gave the material resistance to deformation during material's life span while in use. There was an improvement in MQ value of the modified asphalt concrete with an increment in PET. Modified asphalt concrete with PET had the highest value at 6% PET replacement. The improvement noticed at 6% PET replacement compared with control sample was 12.50% in percentage. The value at this replacement suggests that the modified asphalt concrete had stiffer combination, and more resistant mixtures.

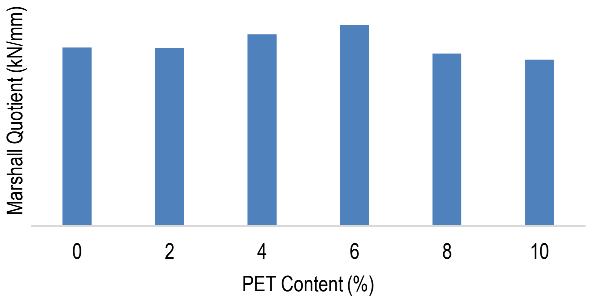

Figure 16. Marshall Quotient of Modified Asphalt with PET

3.9. Water sensitivity of the modified Asphalt with PET

Figure 17 revealed that increase in PET contents gave a decrease in ITSR value initially at 2% PET replacement compared with the control value. This implied that an average loss in strength due to water damage was lower in the samples at this percentage than in the control asphalt mix sample. The reason could be attributed to more pores created by the addition of PET in the mixture which allowed the asphalt cement to penetrate more, creating better bonding and resistance to stripping. But at every further increment in PET content, an increase in ITSR up to 8% PET replacement was observed with an increase of 0.74% compared with the control mix, and this implied that the samples is less susceptible to moisture damage and hence, improved resistance to moisture. However, asphalt concrete modified with PET has the potential to resist moisture damage because the ITSR values obtained are greater than the 80% minimum value of ITSR recommended by (AASHTO. 2003).

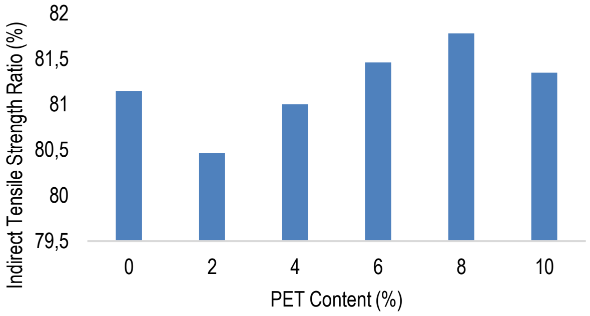

Figure 17. Indirect tensile strength of the different asphalt concrete mixes with PET

4. Conclusion

Recycling PET plastic is one of the crucial solutions for safe disposal in order to reduce crisis associate with these waste in the environment, and sustainability of the natural construction materials.

PET is an inexpensive, lightweight, and durable material, which can readily be processed into different forms that are used in a broad range of applications such as bitumen modifier in asphalt concrete production among others. Hence, this study examined the suitability of recycled waste plastic, Polyethylene Terephthalate (PET) as modifier in bitumen for Hot Mix Asphalt production. Changes in the physical and mechanical properties of the various blends were observed and evaluated.

The overall study revealed that PET as bitumen modifier in asphalt concrete showed excellent performance with a proper HMA mix design. However, based on the outcomes and discoveries, the following conclusions can be drawn: There was a significant decrease in the penetration depth of bitumen with every increment in PET content, and change in penetration grade from 60/70 (64 mm) to 50/60 (58 mm) at 6% PET replacement. This caused a visible increase in hardness of the base bitumen when cooled indicating that new penetration grade excel in resisting softening when exposed to high temperatures, thus minimizing the risk of deformation under heat, reduce the possibility of distortion when heated, and improves pavement flexibility.

There was an increase in specific gravity with every increment in PET content. A consistent increase in stability of the modified Asphalt concrete with an increment in PET content was observed with the highest value at 6% PET content with 11.97% increase in percentage compared with control sample. The improvement in stability caused by PET enhance fatigue resistance, improve thermal stress cracking, and reduce rutting. There was a consistent reduction in flow value with an increment in PET content which suggested an increase in internal friction of the asphalt concrete. There was an improvement in Marshall Quotient value of the modified asphalt concrete with an increment in PET. The value at this replacement suggested that the modified asphalt mixtures had stiffer combination, and more resistant mixtures.

Addition of PET as a modifier improved ITSR which implied that the modified asphalt concrete sample is less susceptible to moisture damage and hence, improved resistance to moisture. Managing these huge amounts of waste plastic PET as asphalt pavement materials will reduce its contribution to greenhouse gases emission, and improve the environmental conditions. This concept however will reduce the exploitation of natural construction materials.

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