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IMPROVEMENT FOR ASPHALT MIXTURE PERFORMANCE USING PLASTIC BOTTLE WASTE

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ABSTRACT: Lately, plastic waste has become a problem in our society, due to the negative impact that it has on our environment. To mitigate this, the reuse of plastic bottle wastes and other local materials should be encouraged. In this paper, the authors present an innovative application for polyethylene terephthalate (PET) that is obtained from plastic bottle wastes, as an additive to Asphalt Concrete-Wearing Course (AC-WC), a hot mix asphalt (HMA) type. The AC-WC sample that contained the PET was measured using the wet method to determine the Marshall parameters of the samples. The type of bitumen used as the specimen is asphalt, which has a penetration value of 60/70. The optimum asphalt content (OAC) obtained from the preliminary study was found to be 5.7% of the total asphalt weight. The results show that AC-WC mixture strength improves when plastic bottle waste is used, which can be correlated with an increase in stability. This finding shows that plastic bottle waste and other local materials have an alternate use as a road pavement material.

Keywords: Polyethylene Terephthalate; Asphalt Concrete-Wearing Course; Hot mix asphalt; Asphalt mixture, Optimum Asphalt Content

1. INTRODUCTION

Lately, the use of recycled waste materials as additives to improve the properties of asphalt mixtures has brought environmental, economic, and technical benefits [1,2]. Premature damage to road pavement can occur due to poor asphalt performance resulting from insufficiencies in the concrete mix. Improvement of the asphalt concrete mixture is an effective way to prevent early damage [3]. The Ministry of Environment and Forestry said that Indonesia produces up to to 65 million tons of waste annually, with 14 percent, or 9 million tons of it consisting of plastic [4]. Due to the rise in urbanization and rapid increase in population, the amount of plastic waste has significantly increased in Indonesia. Plastic waste has become one of the most significant issues when it comes to environmental pollution [5,6].

The recycling and utilization of such waste material represents an alternative designed to alleviate the problems of municipal waste. With this in mind, to decrease the amount of plastic waste, the addition of Polyethylene Terephthalate (PET) to road pavement is a potential solution that can be applied [6,7]. The use of plastic waste commodity in asphalt concrete is a cheap and effective means to enhance the performance of asphalt concrete. It also provides a means of disposing of this plastic waste as solid waste [8,9]. The plastic bottle waste used during this study was PET, a material produced by a condensation process from the terephthalate acid and ethylene glycol polymers found in fossil fuels. Thermoplastic polyester industries throughout the world mainly produce PET, which contributes to around 18% of the world's total plastic manufactured and is categorized as the third most common material produced in the world’s plastic industry. Ethylene terephthalate ($C_{10}H_8O_4$) is the monomer that makes up PET. This substance is characterized as clear, transparent, and resistant to organic solvents, with a diverse melting point stretching from 110 to 137ºC [10].

The use of asphalt additives such as PET aims to improve pavement resistance, which includes: deformation rate, fatigue and adhesion [10,11]. Therefore, to determine the quality of asphalt pavement, the Marshall Stability method is used. The Marshall Stability technique was developed around 1939. The technique has now became the most widely used design and evaluation method for road pavement. Marshall Stability and flow tests were key indicators in measuring the performance of asphalt pavements [12]. Marshall Stability is related to the resistance of asphalt materials to distortion, displacement, rutting, and shear stresses. Marshall Stability measures the ability of asphalt mixture to sustain maximum traffic loads. The flow rate is indicated by the vertical deformation that occurs at maximum load conditions [7,13].

Previous studies indicate that plastic material additives have positive results but are costly and thus not suitable for developing countries [14,15].

To address the cost issue, the plastic material used in this study was taken from plastic bottle wastes, widely available in Indonesia, especially at landfills in Surabaya. The other materials used in this research are also local materials, consisting of aggregates obtained from the quarry in Mojokerto, East Java, and petroleum asphalt grade with a penetration value specification of 60/70, obtained from PT Pertamina Indonesia. Specimens using ordinary asphalt mixtures without the additional of PET were used as the control mixture.

2. LITERATURE REVIEW

2.1 Asphalt Pavement Material

Asphalt, PET, Portland cement, and combined aggregates were the materials used in this study. The PET was in the form of plastic bottle waste. The PET bottles were cut using a plastic waste crusher with a size of about 5 mm x 5 mm. Before that, it is washed to make sure it is not contaminated with any other materials. PET bottles were obtained from waste collectors around the Final Disposal Site (TPA) in Surabaya, Indonesia.

The combined aggregates consisted of coarse, medium, and fine grains. The fine aggregate as a filler was obtained from fly ash. The detailed gradation of the combined aggregate has fulfilled the specifications the Indonesian National Standard (SNI) aggregate gradation code was adopted for the AC-WC. We obtained the final composition of 12% CA (coarse aggregate), 48% MA (medium aggregate), 38% FA (fine aggregate), and 2% FF (filler) based on a combined aggregate analysis. Asphalt with a 60/70 penetration grade value was used for all of the experiments [6,11]. The results of chemical and physical tests in the laboratory are based on the specifications and standard code that was determined from the research that have been done before [16].

2.2 Quality Assessment of Asphalt Pavement

The Marshall method is used to assess the quality of asphalt pavements in Indonesia. This method refers to the provisions of the Indonesian National Standard (SNI). SNI 06-2489-1991 is used as a procedure to get the Marshall characteristic values from each tested specimen. Moreover, the Marshall Stability Method is also used in pavement design to determine the percentage of Optimum Asphalt Content (OAC) in the mixture [17,18]. In preliminary research, experiments were carried out to determine the percentage of OAC based on Marshall test parameters. The results showed that the OAC was 5.7% of the total asphalt weight. This OAC value is used as a reference for the variation ratio of PET addition as follows: 1%, 2%, 3%, 4%, 5%, 6%, and 7% [16].

Asphalt Concrete-Wearing Course (AC-WC) is a type of hot mix asphalt (HMA) mixture, which is widely used in Indonesia. In pavement structures, AC-WC is the layer of the road surface that interacts directly with vehicle tires. It is a flexible pavement layer consisting of a mixture of hardened asphalt with continuous aggregate compressed under a certain heating temperature. The AC-WC uses asphalt binder to produce a waterproof coating with high stability and long durability. However, it has weaknesses in flexibility, durability, and susceptibility to fatigue cracking. The use of plastic bottle waste is expected to overcome those weaknesses, and at the same time improve the quality of the asphalt mixture [19,20].

In prior studies, different waste plastics have been tested to determine their ability to improve the performance of asphalt mixtures, such as Buton Asphalt Additives in AC-WC [21], used plastic bottles in a modified asphalt mixture [1], PET-modified polymer in asphalt mixture [22], PET in asphalt concrete mixture [23], PET waste in paving materials [10], waste plastic bags in a modified asphalt mixture [24], polyethylene terephthalate (PTP) plastic waste as an asphalt binder [25], electronic waste plastic as a modified bitumen [26], LDPE and HDPE in asphalt mixture [27], Nano-HDPE in asphalt concrete (AC) mixture [17], and LDPE waste in asphalt concrete (AC) mixture [28].

3. METHODOLOGY

3.1 Mixing Method and Specimen Preparation

This study used a laboratory-based experimental approach, whereby PET content played an important role in variable differences. Two different methods can be used for the introduction of additives to an asphalt mix: dry- or wet-based mixing. The latter was used in this study [3,7,9]. The mixing process is carried out by adding PET particles to the hot asphalt mixture at a certain temperature. This is intended to ensure that the PET particles are well-blended with other components to create a homogeneous substance, which can be confirmed visually. The combined aggregate was mixed with an asphalt binder and PET particles [12,13]. The number of specimens and their preparation process followed the SNI 06-2489-1991 code, and it is explained step by step below:

a. Preparation of specimens for OAC determination of AC-WC mixture. Twenty-five specimens were prepared to determine OAC in the AC-WC mixture. The determination method used was variations of asphalt content, of 4.7%, 5.2%, 5.7%, 6.2%, and 6.7%. The mass of each aggregate was 1200 grams. The aggregates were mixed with asphalt at the optimum temperature of 200°C. Each specimen was compacted using an automatic Marshall compactor with a total of 75 blows from both above and below [16]. The specimens were then allowed to cool for about five hours at room temperature, then removed from the machine using the ejector. Finally, the specimens were soaked for about 24 hours before being testing for strength.

b. Preparation of specimens for the AC-WC mixture without the PET addition. These specimens did not need to be specially prepared, because they were the same as those produced when determining OAC. Based on the arithmetic mean values, the OAC was 5.7%. The specimen or data at 5.7% OAC was directly used as AC-WC mixed specimens without PET content. The AC-WC mixture without the addition of PET only had one variation, where five specimens were needed.
c. Preparation of specimens for AC-WC mixture with PET addition. These specimens were designed based on an OAC value of 5.7%. Each specimen had an aggregate mass of 1200 grams. The PET particles measuring 5 mm were mixed into the AC-WC with variations of 1%, 2%, 3%, 4%, 5%, 6% and 7%. Each variation required five specimens, thus resulting in a total of 35 specimens.

3.2 Mixing and Compaction Temperatures

The temperatures of mixing and compaction were determined according to the SNI 06-2489-1991 procedure. The combined aggregate with a composition of 12% CA, 48% MA, 38% FA, and 2% FF was heated to 150°C. At the same time, conventional asphalt or modified asphalt with PET content was heated to an optimal temperature of 200°C. Then, the aggregate that had been heated at a temperature of 150°C was poured into the asphalt that had been heated in a pan at 200°C. Then, both were mixed by stirring until a homogeneous AC-WC mixture emerged.

The compaction temperature for the AC-WC mixture specimens was maintained at 135°C. Asphalt with plastic waste was initially heated to a temperature of 200°C, then the combined aggregates at 150°C was added so that the stiff binder associated with it softened [29]. The AC-WC mix was compacted using a Marshall automatic compactor with a total of 75 blows from both above and below. After compaction, all specimens were allowed to cool for about five hours at room temperature, and then were removed from the machine using the ejector.

3.3 Specimens Testing Procedure

Marshall stability tests were used to evaluate density, voids in the mix (VIM), void filled asphalt (VFA), voids in the mineral aggregate (VMA), Marshall flow, stability, and Marshall Quotient (MQ). The Marshall stability test was carried out according to SNI 06-2489-1991.

4. RESULTS AND DISCUSSION

4.1 Optimum Asphalt Content Calculation

The important parameters for the calculation of the optimum asphalt content (OAC) are density, VIM, VFA, VMA, Flow, Stability, and MQ. In this study, OAC was calculated as the arithmetic mean of asphalt content at VIM, VAF, VAM, Flow, Stability, and MQ [11]. The Marshall parameters used to determine the optimum bitumen content were been calculated and described by Machsus et al. (2020) [16] in a preliminary study, who obtained an OAC of 5.7% by weight of the mixture.

4.2 Marshall Parameter Testing of AC-WC

The percentage of PET content added was 1%, 2%, 3%, 4%, 5%, 6% and 7% based on the OAC weight. These additional PET particles could reduce the total weight of the AC-WC. The results of testing the Marshall characteristics of the AC-WC with variations in the addition of PET waste are discussed below.

4.2.1 Density

Density can be defined as the unit weight of the asphalt concrete achieved through the compaction process compared to its volume. The density value drops as the PET content increases, with the highest density value of 2.2692 g/cm^3 occurring in conditions without PET content and the lowest of 2.2591 g/cm^3 at 7% PET content, as in Figure 1. This means that adding 7% PET decreases the density of the control mixture by 0.5%.

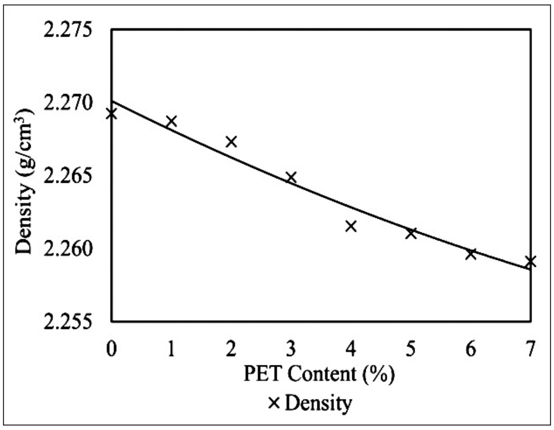

Fig.1 Relationship between PET and Density

The association between density and PET content is consistent with the findings in several previous studies. According to Hassani et al. (2005) [11] the replacement of various percentages of mineral aggregates with PET content results in a reduction of mixture density of between 2.8% for 20% PET content and 7.1% for 60% PET content. The plastic contents reduce the mixture density, which decreases the rutting resistance of the asphalt mixture and the adhesion between the asphalt and aggregates, which is unfavorable [12].

Sojobi et al. (2016) [14] stated that the bituminous asphaltic concrete (BAC) was found to experience a decrease in density with an increase in plastic content. Furthermore, the change in density is due to partial replacement of fillers with a material whose density is lower than the reference fillers, where the reduction in density is proportional to the amount of material added [30]. On the other hand, the density of the mixture increases with the addition of materials that have higher density [7]. Moreover, increased density makes the mixture less permeable and more uniform, which in turn results in better road pavement. Improved pavement density will increase fatigue life, rutting resistance, and overall durability [10].

4.2.2 Voids in mix

VIM is defined as the total volume of air between binder-coated aggregate particles of a compact asphalt mixture. VIM was found to be higher in mixtures that contain more recycled aggregates. The more PET plastic added to the mixture, the higher the VIM it had. The lowest VIM value was 3.85%, without PET, as in Figure 2. The VIM value increased after PET was added, and reached the highest value of 4.28% on 7% PET content. This means that the addition of PET can increase the VIM value by 11 percent to the control mixture. Yet, both the lowest and highest VIM values were still within the minimum and maximum threshold of VIM based on SNI 06-2489-1991.

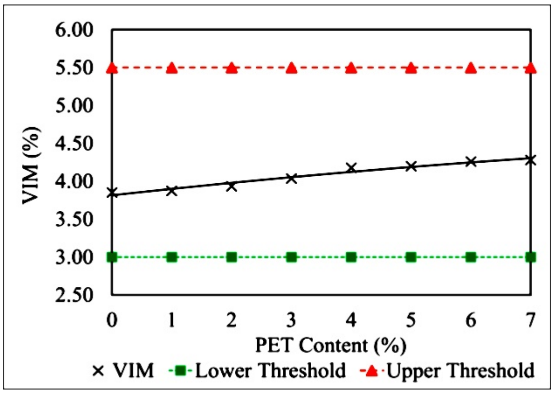

Fig.2 Relationship between PET and VIM

The correlation between VIM and PET content that we observed is consistent with a previous study, which found that if the PET content is increased, the VIM value is also increased. Ahmadinia et al. (2012) [31] stated that increasing PET content in a mixture results in more air voids. In addition, the plastic contents slightly increases air voids, which results in improved the rutting resistance of the asphalt mixture and provides better adhesion between the asphalt and aggregates [12].

4.2.3 Voids in mineral aggregates

VMA is defined as the percent void in the mineral aggregate, which is an important factor to ensure asphalt mixture durability and rutting performance [12,33]. As can be seen in Figure 3, the VMA value increases as the percentage of PET content increases, just like VIM. The lowest VMA value was 16.41%, without PET, while the highest VMA value was 16.78%, with 7% PET content. This means that PET addition slightly increases the VAM value, which was 2% for the control mixture.

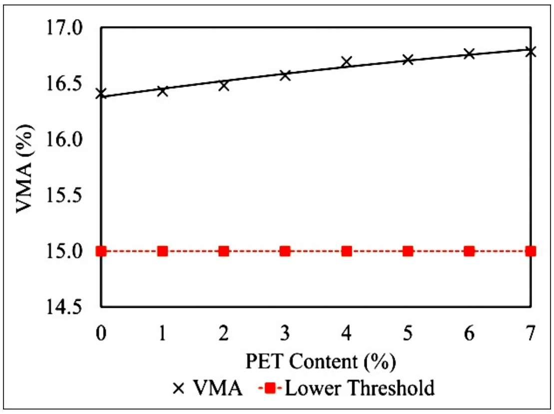

Fig.3 Relationship between PET and VMA

The plastic contents slightly increased the voids of mineral aggregates, which results in improved rutting resistance and the adhesion of the modified asphalt mixture [14]. This is confirmed from the graph of the AC-WC mixture made with plastic bottle waste content exceeds the VMA 15% requirement for all variations of PET addition, thus complying with SNI 06-2489-1991.

4.2.4 Voids filled with asphalt

VFA is the percent of voids in mineral aggregate that is filled with asphalt [33]. The VFA value of the asphalt mix decreases with the addition of PET content, which is evident in the graphic pattern. The highest VFA value was 76.52% before PET was added and after the addition of PET, the VFA value decreased until it reached the lowest value of 74.49%. This means that the addition of PET slightly decreases the VFA value, which is 3% to the control mixture.

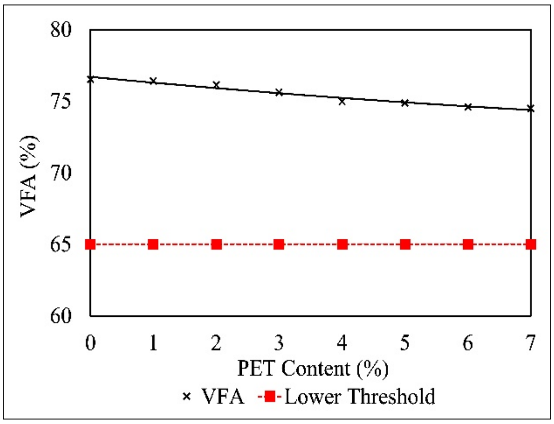

Fig.4 Relationship between PET and VFA

Even though it has decreased, the AC-WC mixture made with plastic bottle waste content meets a minimum VFA requirement of 65% under SNI 06-2489-1991. This high VFA value can penetrate sufficiently into the void of the aggregate particles to create a stable interface adhesion between the aggregate surface and the bitumen in the asphalt mixture [34].

4.2.5 Flow

Flow is measured simultaneously with a stability test. Flow value refers to vertical deformation when the maximum load is reached during the loading test. When 1% PET content was added to the AC-WC mixture, the Flow value decreased and continued to decrease until 5% PET content was added, when the mixture stiffness began to increase, as the pattern in Figure 5. Then, the Flow value began to increase again for PET plastic content between 6 to 7% PET, which shows the stiffness of the AC-WC mixture decreased as well [10]. The highest Flow value was 4.8 mm for 7% PET content, while the lowest Flow value was 4.0 mm for 5% PET content. This means that the addition of PET content decreased the Flow value by 18% compared to the control mixture, but after it reached the lowest point, the Flow value increased again.

The graphic trend confirms the relationship between Flow and the addition of PET content is in line with what was found in previous studies. Flow decreases slightly until it reaches 4% PET content, then moves upward, which can contribute to changes in the mixture stiffness [7,23,32]. Figure 5 also confirms that the AC-WC mixture made with plastic bottle waste content meets the minimum flow requirement of 3 mm for all variations of PET addition, as required by SNI 06-2489-1991.

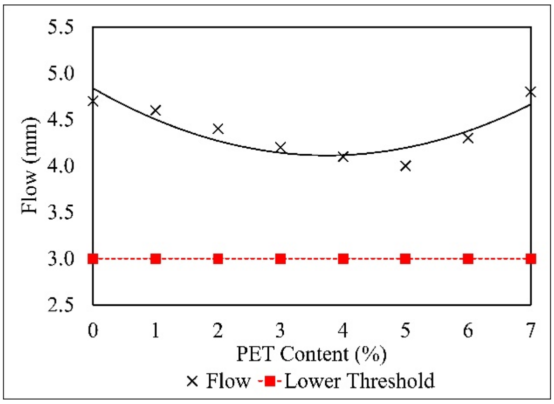

Fig.5 Relationship between PET and Flow

4.2.6 Stability

The stability test measures the maximum load that can be sustained by the specimen at a loading rate of 50.8 mm/minute. The test load was increased until it reached a maximum value. The addition of up to 5% PET caused stability to increase, while stability decreased when PET content was further increased, as in Figure 6. The highest Marshall stability achieved was 1855 kg for 5% PET plastic content, while the lowest value was 1602 kg when not using PET. This also means that the addition of PET can increase the Stability value until it reaches a peak of 16% of the control mixture, while the addition of more PET causes the Stability value to decrease. The higher the stability value, the better the pavement can resist distortion, displacement, rutting, and shearing stresses.

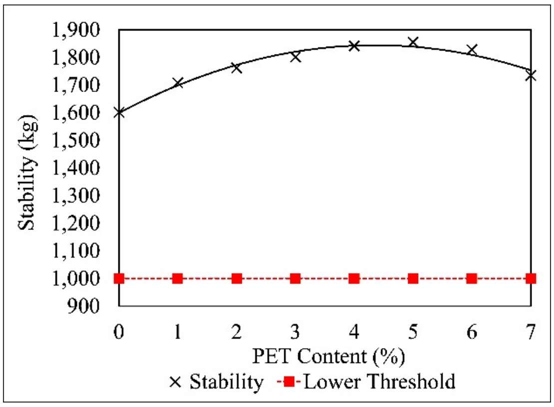

Fig.6 Relationship between PET and Stability

However, the lowest stability value acquired still met the minimum stability value requirement of 1000 kg under SNI regulations. The relationship between stability and PET plastic content was confirmed in the findings, which showed that the stability increased to a maximum level of 6% PET content, and after that it started to decline. [23,32]. This stability reduction may have been caused by decreased adhesion [12,30]. The PET stability behavior is inversely proportional to Flow: When the stability value increases the value of Flow decreases; conversely when the stability value decreases the Flow value increases [10,32,36].

4.2.7 Marshall quotient

The Marshall quotient (MQ) is an indication of a mixture's stability and resistance to permanent deformation. In some countries, MQ is used for performance verification. MQ is calculated as Stability divided by Flow. The MQ value as a function of PET content is illustrated in Figure 7. This value is used to determine the asphaltic mixture's resistance to shear stress and permanent deformation [23,36]. Based on Figure 7, the addition of PET content in amounts ranging from 1% to 5% increased the MQ value, which indicates that the AC-WC mixture was harder and more resistant to permanent deformation. Above 5%, the MQ value decreases to a PET content of 7%. The highest MQ was 464 kg / mm at 5% of PET content, while the lowest was 341 kg / mm where PET was not added to the mixture. This means that the addition of PET to a certain level increases the MQ value until it reaches its peak at 36% of the control mixture. Further addition of PET makes the MQ value decrease.

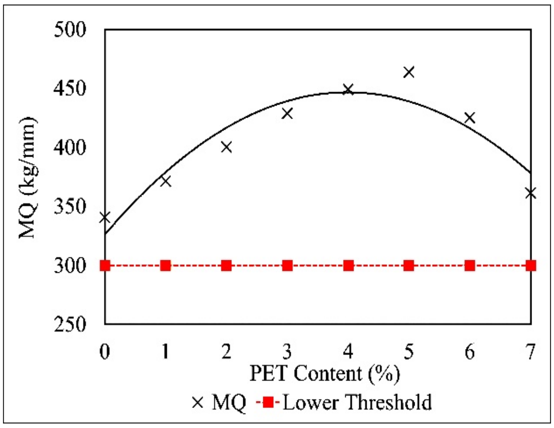

Fig.7 Relationship between PET and MQ

The AC-WC mixture made with plastic bottle waste content met the minimum MQ requirement of 300 kg/mm for all variations of PET addition. The relationship between MQ and PET plastic content was consistent with findings in previous studies, where the addition of PET increases MQ [10]. At high MQ conditions, the pavement is stiffer and more resistant to deformation due to heavy loads [23,32].

Flow versus PET content shows a parabolic convex pattern, because it represents the result of the deformation test under loading, and is influenced by the stiffness of the mixture using modified asphalt. MQ is the quotient between Stability and Flow obtained from the compressive test [36,37]. MQ versus PET content shows a concave path, because it is strongly influenced by the value of Stability which is directly proportional to MQ, which also shows a concave path. Although the flow value also affects MQ, the effect is relatively small because the value is also small.

5. CONCLUSION

Conclusions obtained: (1) Marshall parameter test results show that the AC-WC mixture with or without the addition of PET can meet the Indonesian National Standard (SNI) code. (2) The pattern of the changes in the variation of PET content with the Marshall parameter is consistent with that found in previous studies. The addition of PET content can reduce an AC-WC mixture's density value by 0.5%, its VFA value by 3%, and its flow value 18%, but the flow value increases again after reaching the lowest value. The addition of PET content increases the mixture's VIM value by 11%, its VMA value by 2%, its Stability value by 16%, and its MQ value by 16%, but Stability and MQ values decrease again after reaching the peak on a certain PET content. (3) The results of this study can be applied to the development of sustainable materials in infrastructure development, which then can reduce the impact of climate change by utilizing plastic waste, especially PET plastic waste, as road pavement material to reduce global environmental problems. The authors recommend further investigation regarding the analysis of other characteristics, namely rutting, resistance, durability, and fatigue.

6. ACKNOWLEDGMENTS

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