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# Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 7, No. 09, September, 2021

# The Impact of HDPE Plastic Seeds on the Performance of Asphalt Mixtures

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Received 12 June 2021; Revised 05 August 2021; Accepted 17 August 2021; Published 01 September 2021

**Abstract**

Plastic waste processing is a problem that almost several countries in the Asian region are unable to overcome. One of the latest innovations carried out in the field of road pavement construction is mixing HDPE type plastic waste that has been processed into plastic seeds into the asphalt concrete mixture. Previous research has shown that HDPE plastic waste may be reused to improve the physical properties of temperature-sensitive asphalt and improve the stability of asphalt concrete. This study was conducted to determine the effect of using HDPE plastic ore as a mixed additive on the Asphalt Concrete-Wearing Course (AC-WC) using Marshall parameters. Marshall Parameters used are stability, flow, VIM, VMA, VFA, and MQ. The study was conducted in a laboratory by testing 42 samples with different levels of HDPE plastic seeds, mixed using wet methods to determine Marshall Characteristics. Manufacture of test objects using asphalt type, which has a penetration rate of 60/70. The initial research results showed that the optimal asphalt content (OAC) is 5.5%, with the percentage content of HDPE plastic seeds around 0, 1, 2, 3, 4, 5, 6, and 7% compared to asphalt weight. The results showed that the effect of HDPE plastic seed content on the AC-WC mixture increased the value of Marshall Characteristics and met all the requirements of SNI 06-2489-1991. This finding shows that HDPE plastic seeds deserve to be an alternative material for road pavements.

*Keywords:* HDPE Plastic Seeds; Asphalt Concrete-Wearing Course (AC-WC); Indonesian National Standard (SNI); Marshall Test.

## 1. Introduction

Asphalt, Concrete Layer is one type of asphalt layer. A layer of asphalt concrete that serves as a street development cover is possible. This layer is made up of totals, fillers, and folios that have been blended and dispersed at a specific temperature. Inadequate asphalt execution caused by insufficiencies in the concrete mix can cause premature damage to roadway asphalt [1]. Recycled waste materials have recently been utilized as added ingredients in asphalt mixtures, resulting in natural, financial, and specialized benefits [2]. Inadequate asphalt execution caused by insufficiencies in the concrete mix can cause premature damage to street asphalt. Improving the asphalt concrete blend has proven to be an effective method of avoiding early injury [3]. The ability of asphalt pavement to withstand the effects of water without significant weakening within the asphalt was a key solidness concern. The moisture damage is typically referred to as a failure of the gripping bond at the asphalt-aggregate interface or a problem with asphalt cover cohesiveness [4]. According to the Ministry of Environment, Indonesia produces up to 65 million tons of plastic waste every year, with plastic responsible for 14%, or 9 million tons [5]. The plastic waste in Indonesia has substantially increased as a result of increased urbanization and rapid population growth. Plastic waste has evolved as one of the most critical environmental issues.

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http://dx.doi.org/10.28991/cej-2021-03091744

The repurposing and use of such squander cloth are an option designed to alleviate the problems associated with urban squander. With this in mind, expanding the use of Tall Thickness Polyethylene (HDPE) in street asphalt could be a viable option for reducing plastic waste [6, 7]. HDPE or PEDH is a plastic polymer with elastomeric qualities, making it ideal for various applications. High-density polyethylene has a higher specific density than standard thickness polyethylene, as the name implies, albeit the difference is minor. The lack of branching distinguishes HDPE's physical qualities, meaning that it is lightweight and highly flexible. HDPE is a coordinating polymer because of its denser structure [8, 9].

The use of asphalt-added materials such as HDPE appears to be making progress in terms of asphalt resistance, including distortion rate, weakness, and grip [10-12]. As a result, the Marshall Stability approach is used to determine the quality of asphalt pavement. Around 1939, the Marshall Stability technique was developed. The procedure has now established itself as the most widely utilized design and assessment method for street asphalt. Marshall Stability and flow testing were essential indicators of asphalt pavement execution [12, 13]. The resistance of asphalt materials to distortion, displacement, rutting, and shear loads is known as Marshall Stability. Marshall Stability is a measurement of an asphalt blend's ability to handle the most intense activity loads. The vertical distortion that occurs at the most extreme stack conditions [14, 15] indicates the stream rate.

Previous studies have shown that plastic fabric-added chemicals have good benefits, but they are costly and thus unsuitable for developing countries [16]. The plastic fabric used in this study was made from HDPE plastic seeds, which are widely available in Indonesia, to address the far-fetched issue. Other resources employed in this study include totals taken from a quarry in Tarakan, North Kalimantan, and seeds, petroleum asphalt review purchased from PT Pertamina Indonesia with an infiltration esteem determination of 60/70. As a control mix, examples of standard asphalt mixtures without the addition of HDPE were employed.

## 2. Materials and Procedures

### 2.1. Asphalt Pavement Material

Coarse aggregate, fine aggregate, asphalt, and plastic were used in this research (HDPE plastic seeds). Coarse aggregate and fine aggregate can be found in retail shops, while HDPE plastic seeds can be found in Tarakan, North Kalimantan, as indicated in Figure 1. The physical features of HDPE Plastic Seeds shown in Table 1 are used to create HDPE plastics commonly used in plastic bags, plastic rolls, and sheet plastic [3]. HDPE Plastic Seeds are recommended for single usage only due to increasing antimony trioxide compounds over time. Clean, sound and calibrated equipment are required for testing coarse aggregate, fine aggregate, asphalt, and plastic ore, as well as Marshall Test specimens [17].

**Figure 1. Seeds made of HDPE plastic**

**Table 1. Physical Properties of HDPE plastic seeds**

| Parameter | Value |
|---|---|
| Density | 0.94 gr/cm$^3$ |
| Melting point (°C) | 128 |
| Fiber type | Polyethylene |
| Acid and alkali resistance | strong |
| Length (mm) | 5 |
| Break elongation | 750% |
| Fibre diameter (mm) | 3-5 |

There were coarse, medium, and refined grains in the combined aggregate. Fly ash was used as a filler and provided a fine texture. The combined add-point-by-point up's degree has met the nuanced features of the Indonesian National Standard (SNI) add up to degree code for the AC-WC. Based on a combined aggregate assessment, the final composition is 14 percent CA (coarse aggregate), 46 percent MA (medium aggregate), 40 percent FA (fine aggregate), and 4 percent FF (filler). All of the tests were conducted on asphalt with a 60/70 entrance audit respect [18]. Figure 2 illustrates the gradation of selected aggregates for the wearing course. The results of practically all chemical and physical tests conducted in the inquiry office are based on the judgments and standard code derived from a few recent investigations [19, 20].

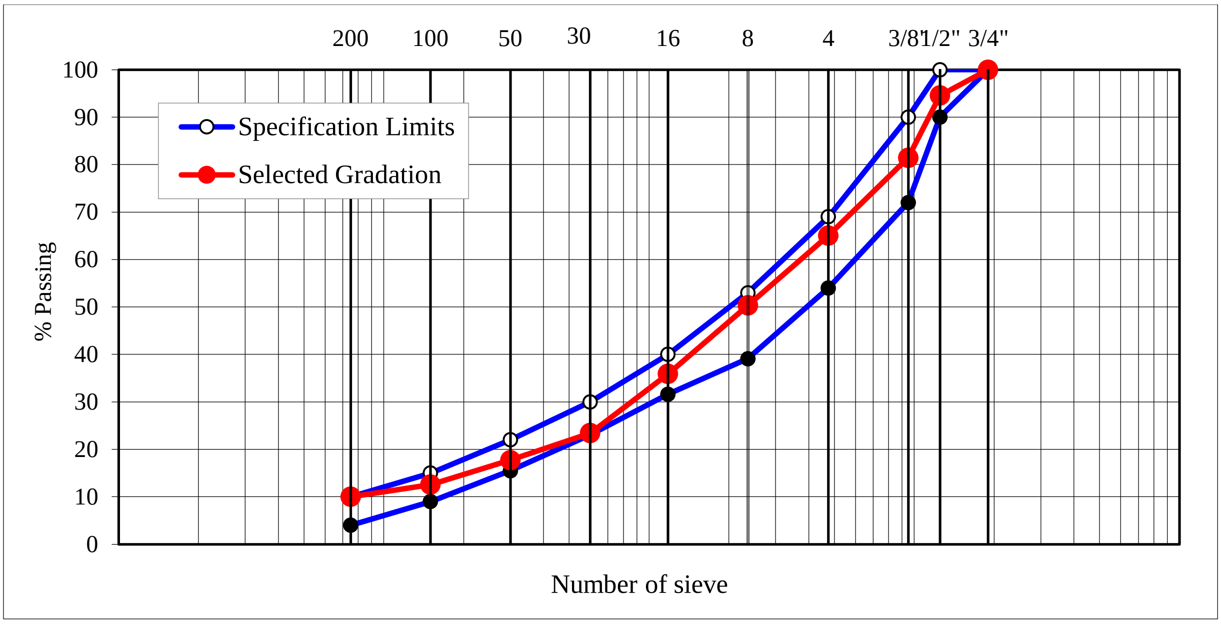


**Figure 2. Wearing course aggregates gradation**

## 2.2. Asphalt Pavement Quality Assessment

In Indonesia, the Marshall approach is used to assess the quality of asphalt pavements. This technique references the Indonesian National Standard's structures (SNI). The Marshall characteristic values are urged from each tried example, using SNI 06-2489-1991 as a strategy. In addition, the Marshall Stability Method is used in pavement design to determine the rate of Optimum Asphalt Content (OAC) in the mix [20, 21]. Preliminary studies included experiments in determining the rate of OAC using Marshall Test settings. The OAC appeared to be 5.5% of the total asphalt weight based on the results. This OAC value is used as a reference for the various proportions of HDPE expansion, which are as follows: 1, 2, 3, 4, 5, 6, and 7% [21].

AC-WC (Asphalt Concrete-Wearing Course) is a hot mix asphalt (HMA) composition regularly used in Indonesia. AC-WC is the layer of the road surface that interacts directly with car tires on asphalt structures. It could be a flexible asphalt layer made up of a mix of hardened asphalt and constant complete compression at a specific temperature [22]. The AC-WC uses an asphalt layer to provide a waterproof coating that is both solid and long-lasting. In any case, it has flaws in flexibility, solidity, and tiredness, splitting vulnerability. The use of plastic seeds HDPE is expected to address these flaws while improving the asphalt blend's quality [23, 24].

Various waste plastics have been tested in the past to determine their capacity to advance the execution of asphalt mixtures, including HDPE-modified polymer in asphalt mixture [24, 25], HDPE in asphalt concrete mixture, Buton granular Asphalt in AC-WC, Buton rock asphalt, used plastic bottles in a modified asphalt mixture, HDPE waste in paving materials [26].

# 3. Applications of Methods

After the literature study then conducted an experimental plan preparation. The first stage is to determine the optimum asphalt content of the control mixture without any addition of plastic HDPE seeds. The second stage is to add variations of HDPE plastic seeds as an additive to the concrete asphalt mixture. Determination of optimal asphalt content requires 15 specimens based on five variations of asphalt content, with each variation made of three specimens. The number of specimens needed for the marshall test is 24 samples, adjusted to 8 kinds of HDPE plastic seeds variations. The flow chart of the research procedure in outline can be seen in Figure 3.

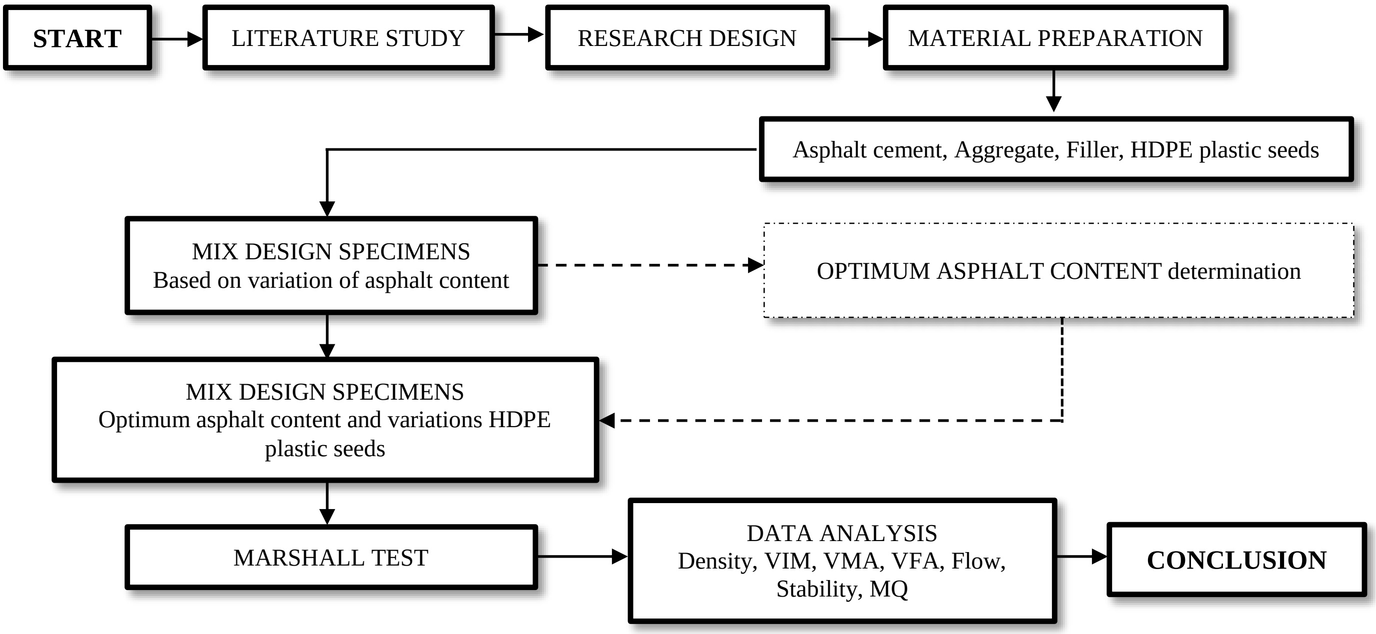


**Figure 3. Research procedure flowchart**

### 3.1. Specimen Preparation and Mixing Procedures

This additive can be added to an asphalt mix using one of two methods: dry-based mixing or wet-based mixing. This study [27] relied on the latter. The HDPE plastic seed particles are added to the hot asphalt mixture at a precise temperature during the mixing process. This ensures that the HDPE plastic seeds particles are well-blended with other components, resulting in a homogeneous solution that HDPE can visually check. The content of HDPE plastic seeds played a crucial influence in variable differences in this study, which used a laboratory-based efficient investigation. An asphalt binder and HDPE plastic seed particles were added to the resulting aggregate [28, 29]. The number of specimens and the technique of preparing them followed the SNI 06-2489-1991 code, which also is mentioned below:

The content of HDPE plastic seeds has an important influence on the changes in variables in this study, which uses a laboratory-based experimental approach. Two techniques are used to improve asphalt mixing performance: a. Using a wet method (wet process). To mix evenly or homogeneously, plastic is poured into hot asphalt and swirled at a high pace. b. In the dry process, plastic is mixed with heated aggregate before being mixed with hot asphalt. Wet mixing is accomplished by introducing HDPE plastic seeds in a hot asphalt mixture at a predetermined temperature. This guarantees that the HDPE plastic seeds are mixed with the other aggregates to produce a homogeneous mixture. Asphalt binder and HDPE plastic seeds are added to the combined aggregate [30, 31]. The number of specimens and the implementation procedure are based on SNI 06-2489-1991 and are detailed below:

a. Specimen preparation for OAC analysis of AC-WC blend. To determine OAC within the AC-WC blend, twenty-five specimens were arranged. The asphalt substance kinds of 4.5 percent, 5.0 percent, 5.5 percent, 6.0 percent, and 6.5 percent were used in the analysis. Each total weighed in at 1200 grams. At an optimal temperature of 200°C, the totals were blended with asphalt. Each example was compacted using an automatic Marshall compactor [32], which added up to 75 blows from both above and below. The specimens were allowed to cool to ambient temperature for over five hours before being ejected from the machine using the ejector. After nearly 24 hours of soaking, the specimens were finally evaluated for quality [32].

b. Specimen preparation for the AC-WC mixture without the addition of HDPE plastic seeds. Because these specimens were the same as those used to determine OAC, they were not unusually organized. The OAC was 5.5 percent based on the arithmetic mean values. The specimens or data containing 5.5 percent OAC were used as AC-WC mixed specimens without HDPE plastic shields. The AC-WC blend had only one variety before the introduction of HDPE plastic seeds, requiring five trials.

c. Preparation of specimens for the AC-WC combination with the addition of HDPE plastic seeds. The OAC value of 5.5 percent was used to create these specimens. The HDPE plastic seed particles were mixed with the AC-WC at different percentages: 1, 2, 3, 4, 5, 6, and 7%. Each variation necessitated the collection of five specimens for a total of 35 samples. Each sample weighed in at 1200 grams total

### 3.2. Temperatures for Mixing and Compaction

The temperature for combining aggregates and compaction is set according to SNI 06-2489-1991 method. At the same time, the mixed aggregate, which contained 14 percent CA, 46 percent MA, 40 percent FA, and 4 percent FF, was heated to 150°C, and the aggregate heated conventional asphalt or modified asphalt HDPE plastic seeds to an ideal temperature of 200°C. The aggregate, which had been warmed to 150°C, was then poured into asphalt that had been preheated to 200°C in a container. The two were then stirred together until a homogenous AC-WC blend emerged. For the AC-WC mixture specimens, the compaction temperature was kept at 135°C.

The combined aggregate is added at a temperature of 150°C after the asphalt mixed with plastic waste has been heated to 200°C, allowing the stiff binder to melt [32]. With a total of 75 blows from both above and below, the AC-WC Mix was compacted using a Marshall programmed compactor. All instances were allowed to cool for about five hours at room temperature after compaction and then were ejected from the machine using the ejector [32].

### 3.3. Procedure for Testing Specimens

Density, voids in the mix (VIM), Void filled asphalt (VFA), voids in the mineral aggregate (VMA), Marshall flow, stability, and Marshall Quotient were all evaluated using Marshall stability tests (MQ). SNI 06-2489-1991 was used to conduct the Marshall Stability test.

## 4. Analysis Discussion Result

### 4.1. Calculation of the Optimal Asphalt Content

Density, VIM, VFA, VMA, Flow, Stability, and MQ are the factors used to determine the optimum asphalt content needed. In a preliminary investigation, Nawir et al. (2021) [32] estimated and explained the Marshall parameters used to determine the optimum bitumen content, obtaining an OAC of 5.5 percent by weight of the mixture. The arithmetic means of asphalt content at VIM, VAF, VAM, Flow, Stability, and MQ was used to determine OAC in this investigation [33].

### 4.2. AC-WC Marshall Parameter Testing

Based on the weight of OAC to be added, the percentage of HDPE plastic seeds content is 1 percent, 2 percent, 3 percent, 4 percent, 5 percent, 6 percent, and 7 percent. The addition of HDPE plastic seeds to AC-WC can reduce its total weight [33]. The following discussion is based on evaluating the Marshall AC-WC characteristics with different amounts of HDPE waste added. Figures 4 and 5 show a Marshall Sample group and Marshall test, respectively.

**Figure 4. Group of Marshall Specimens**

**Figure 5. Marshall Test**

### 4.3. Density

The density value is a volume weight value that shows how dense the asphalt concrete mixture is. Compaction temperature, constituent materials, filler substance, compaction energy, and asphalt substance are all factors that influence density. As the HDPE content of the seeds increases, the density value decreases. As shown in Figure 6, the highest density value of 2.203 g/cm$^3$ happens when no seeds plastic HDPE content is present, while the lowest density value of 2.115 g/cm$^3$ occurs when 7% of seeds plastic HDPE content is current. This suggests that adding 7% seeds polyethene HDPE to the control mixture reduces the density by 0.5 %.

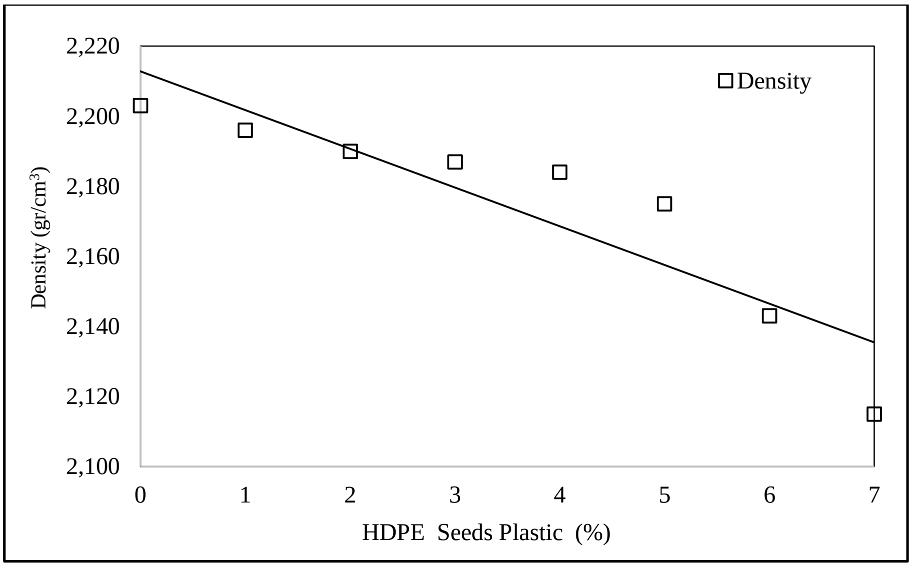


**Figure 6. Correlation between HDPE seeds with density**

The relationship between density and seed polymeric HDPE material is consistent with findings from previous studies. Previous research [34] found that replacing various percentages of mineral aggregates with HDPE plastic ore content reduced the density of the mixture by 2.5 percent for 20 percent HDPE content and 6.8% for 60 percent HDPE content. The plastic content can lower the density of the mix, reducing the adhesive connection between the asphalt and the aggregate and the asphalt mixture's rutting resistance, reducing the asphalt pavement's service life [34].

According to Giri et al. (2020) [34], the density of bituminous asphaltic concrete (BAC) with an increasing plastic content would decrease. Furthermore, the density shift is caused by partial filler replacement with a lower density material than the reference filler, with the density drop proportional to the amount of material injected [34]. The density of the mixture, on the other hand, increases when a substance with a higher density is added [35]. Furthermore, greater density makes the mixture less permeable and more homogenous, resulting in a superior pavement. Fatigue life, rutting resistance, and overall durability all improve with increased pavement density [35].

### 4.3.1. Voids in Mix (VIM)

The Void in the mix (VIM), also known as the cavity in the mixture, is used to determine the size of the mixed hole so that the niche is not too small, causing bleeding, or too large, causing oxidation/aging of the asphalt due to air and ultraviolet light entrance (SNI-06-2489- 1991). VIM values will be more significant in mixtures containing more recycled aggregate [36]. With the addition of HDPE plastic seed content, the VIM value increased. As indicated in Figure 7, the lowest VIM value was 3.75 percent when no HDPE plastic core was present, and the maximum value was 4.21 percent when 7 percent HDPE plastic seeds were present. This suggests that adding HDPE plastic seeds to the control mixture can increase the VIM value by 9%.

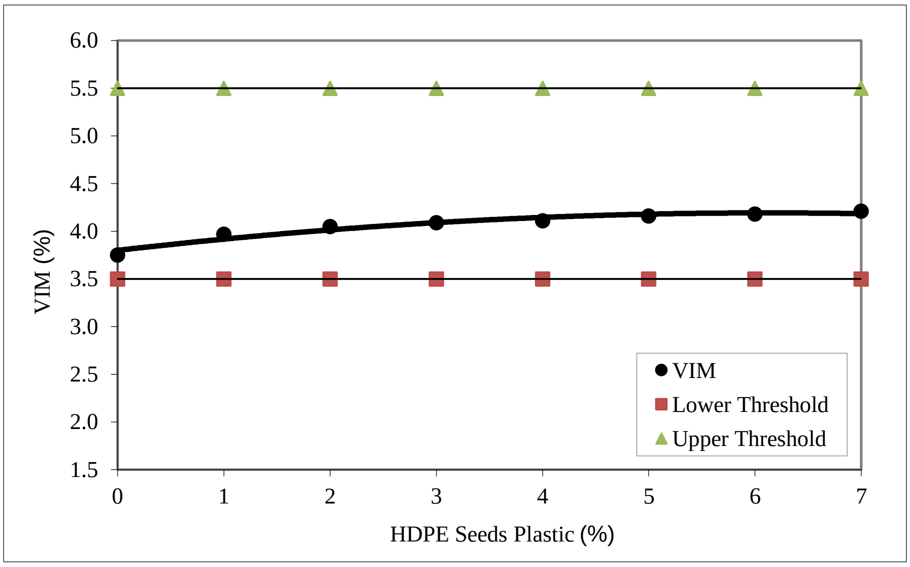


**Figure 7. Correlation between HDPE seeds with VIM**

After earlier investigations, which have enhanced the value of VIM and added HDPE plastic seed content, the association between VIM and HDPE content follows. According to previous research [36], increasing HDPE in the mixture resulted in more fabulous air spaces. Furthermore, the plastic element can create air spaces, boost the asphalt mixture's corrosion resistance, and improve adhesion between the asphalt and aggregate. [37].

### 4.3.2. Voids in Mineral Aggregates (VMA)

The VMA value [38] is one of the most critical metrics determining the asphalt mixture's durability and rutting effectiveness. The volume of voids between aggregate particles in a compacted mixture, expressed as a percentage of the total volume of the specimen [38], is known as the VMA. The VMA value increased, as did the VIM value, along with the first increase in the proportion of HDPE plastic seeds contained, as seen in Figure 8. Without HDPE plastic seeds, the lowest VMA value is 15.65 percent, whereas, with 7 percent HDPE plastic seeds, the highest VMA value is 16.75 percent. This suggests that adding HDPE plastic seeds raises the VMA value slightly above the control mixture's value of 2%.

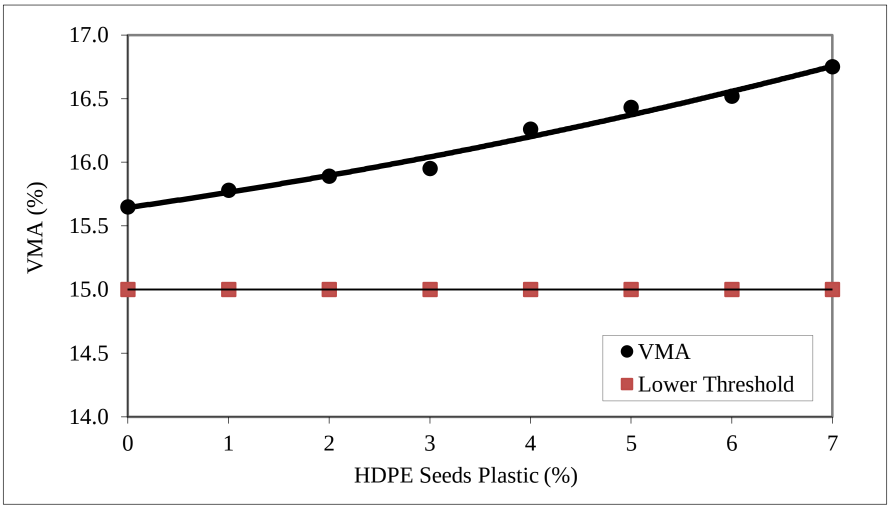


**Figure 8. Correlation between HDPE seeds with VMA**

The VMA process was performed under SNI 06-2489-1991, and the VMA graph demonstrated, in addition to the requirements, that the VMA value showed the accumulation of HDPE plastic ore on the graph over the 15 percent limit. The plastic content increases the vacuum content of minerals, increases routing resistance, and ensures adhesion to the asphalt mixture [38].

### 4.3.3. Voids filled with asphalt (VFA)

The percentage of voids between VMA aggregate particles that are filled with asphalt (VFA), excluding asphalt absorbed by the aggregate [4], is called Void Filled with Asphalt (VFA). Figure 9 shows that the most significant VFA value is 0% plastic ore, 77.65% and that the lowest value is 7%, 75.47%. The added value of VFA can be slowly reduced by adding HDPE plastic seeds, in line with earlier studies [39]. This results in a modest decline in the VFA, 3% of the control combination, by adding the HDPE plastic seeds.

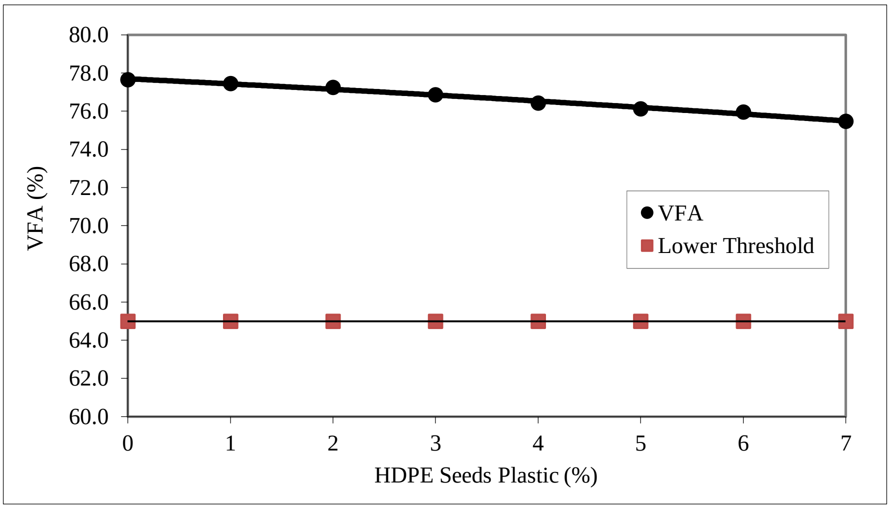


**Figure 9. Correlation between HDPE seeds with the VFA**

The application of an AC-WC asphalt concrete layer containing HDPE plastic seeds is made by SNI 06-2489-1991. The addition of plastic material satisfies the specified criteria of 65 percent. This high VFA value can penetrate sufficiently into the voids of aggregate particles to establish a stable interfacial adhesion between the aggregate and bitumen surfaces in the asphalt mixture, as shown in the graph [39]. VFB has the primary effect of limiting the maximum VMA and asphalt content [39, 40]. For combinations with a VMA value near to the minimal value, the presence of VFB also reduces the permissible volume of air voids.

#### 4.3.4. Flow

Flow is an empirical metric that serves as an indicator of the asphalt mixture's flexibility or changes in plastic shape due to the load. The asphalt content of the mix influences the melting of the mix in the combination, as well as the temperature, asphalt viscosity, and aggregate particle form [40]. Figure 10 shows the flow value of the AC-WC mixture with plastic content, which continues to drop by 1 percent to 4 percent HDPE plastic seed content before increasing at 5 percent to 7 percent level. The most excellent Flow value for 7% HDPE plastic seeds content is 4.86 mm, while the lowest Flow value of 4% HDPE plastic seed content is 4.43 mm. This means that the addition of HDPE plastic seeds reduces the Flow value by 14% compared to the control mixture; however, the Flow value increases after reaching the lowest point. Deformation resistance is usually better in AC-WC combinations with a low melting value at the Optimum Asphalt Content [41].

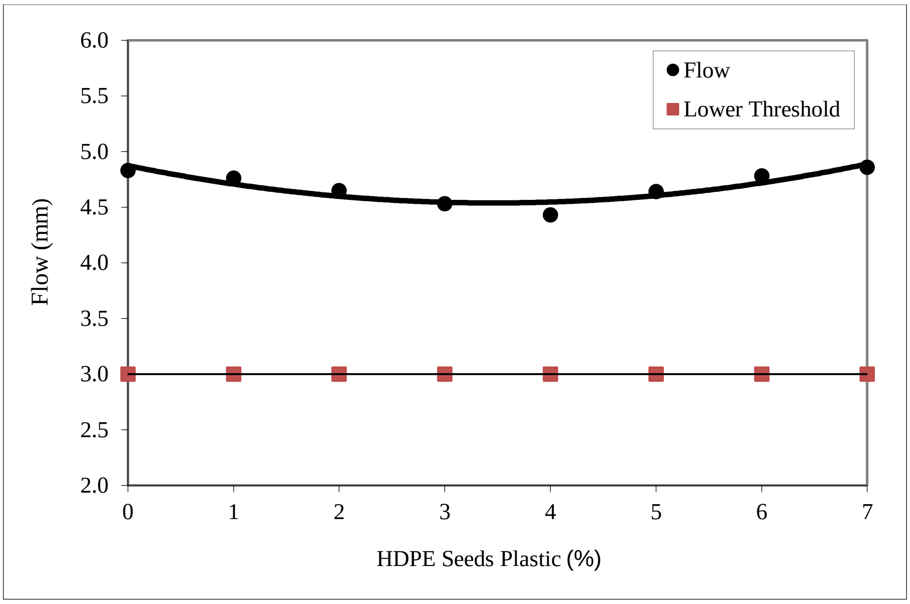


**Figure 10. Correlation between HDPE seeds with Flow**

The graphical trend in Figure 10 is based on earlier research [42, 43]. It also demonstrates that the AC-WC mixture with plastic content meets the SNI 06-2489-1991 minimum criterion of 3 mm for all variants of the inclusion of HDPE plastic seeds. Low flow values paired with high stability indicate a mixture that is susceptible to cracking. The addition of plastic content to the AC-WC mixture results in a lower flow value at the 5% threshold, as shown in the research data. This is due to an excess of plastic content in the AC-WC mixture, which causes the mix to become brittle and susceptible to breaking [44].

#### 4.3.5. Stability

Stability is a measure of the mixture's capacity to carry activity loads until plastic yielding happens. When the test is stacked with the Marshall Test instrument, the stability value is measured explicitly from the trial [44]. Figure 11 shows that increasing the stability value by up to 4% by adding HDPE plastic seeds increases the stability value. When the content of HDPE plastic seeds is increased from 5% to 7%, the stability declines. The highest value of Marshall Stability is achieved when 4 percent is added, with a weight of 1820 kg, while the lowest value is achieved when no plastic content is used, with a value of 1658 kg. This indicates a 16 percent rise in instability from the state without plastic content but a loss in stability by 5 percent to 7 percent plastic. The better the pavement can tolerate distortion, displacement, rutting, and shear stress, the greater the stability value [44].

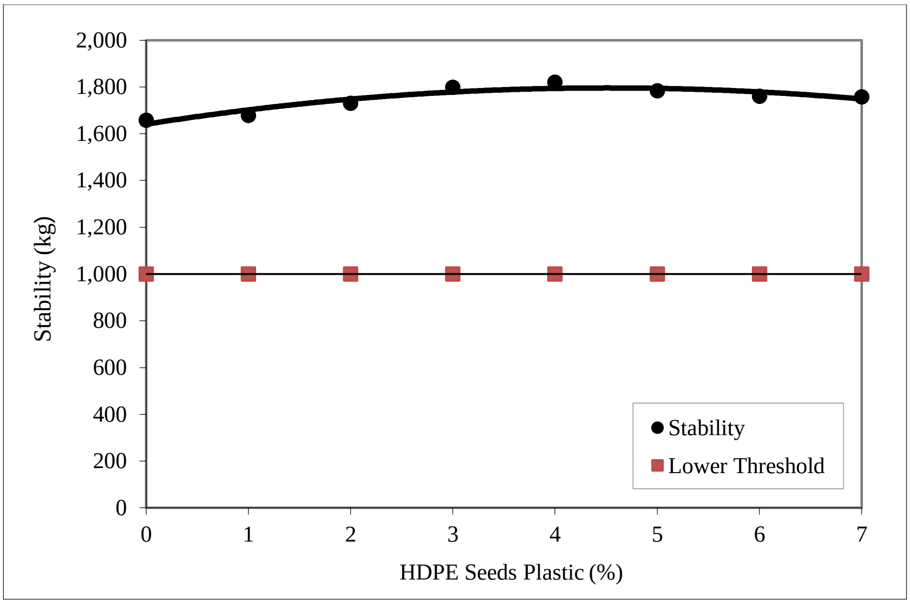


**Figure 11. Correlation between HDPE seeds with stability**

If the proportion of plastic in the asphalt content is up to 4% by weight, likely, the asphalt will no longer qualify as 60/70 penetration asphalt. As a result, the author believes that adding HDPE plastic seeds to the AC-WC asphalt concrete mixer at a ratio of 4% plastic content of asphalt weight is ideal. Although stability improves when blended to a concentration of 5% or greater, the construction of AC-WC is threatened by rigid characteristics that are susceptible to fracture, breaking, and fatigue. The fall in the stability value is caused by a decrease in the mixture's adhesion [45]. The flow value is inversely proportional to the stability value. Therefore, an increase in the stability value will result in a drop in the flow value, and conversely versa, if the stability value decreases, the flow value will rise [45].

### 4.3.6. Marshall Quotient

The Marshall Quotient (MQ) is a comparison of the stability and melt (flow) values, which is also an empirical indicator of the stiffness of the mixture [46]. The greater the MQ value, the stiffer a combination is and the more vulnerable it is to break [47]. Figure 8 shows that adding HDPE plastic seeds in amounts ranging from 1% to 4% to the AC-WC mixture can enhance the MQ value, indicating that the AC-WC mix is more complex and resistant to permanent deformation. When the MQ value exceeds 4%, the plastic content reduces to 7%. The most excellent MQ value is 4%, which equals 411 kg/mm, while the lowest value is 0%, which equals 343 kg/mm. This means that adding a particular amount of HDPE plastic seeds can raise the MQ value until it reaches a maximum of 32 percent of the control combination. The inclusion of HDPE plastic seeds lowers the MQ value even more [48].

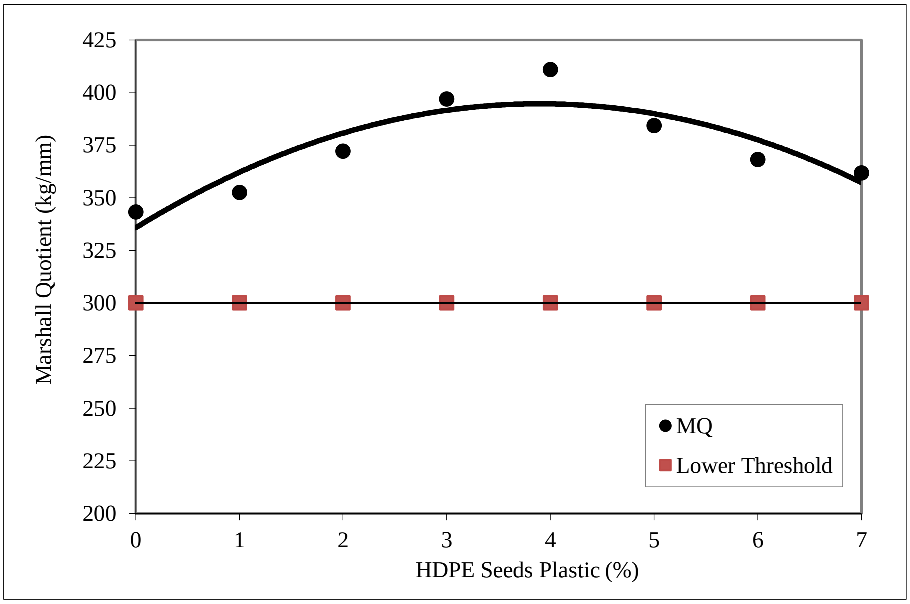


**Figure 12. Correlation between HDPE seeds with MQ**

The MQ value of the AC-WC combination, including HDPE plastic seeds, was more significant than 300 kg/mm. The graph in Figure 12 demonstrates that the addition of plastic can increase the MQ value; this is consistent with earlier research. When a material has a high stability value and a low yield point, its stiffness makes it susceptible to breaking [48, 49]. MQ-rich states provide more flexible pavements that resist deformation under substantial loads [50].

## 5. Conclusions

By examining the performance of asphalt mixtures with various HDPE plastic seeds, several conclusions can be drawn:

- The results showed that HDPE plastic seeds in AC-WC concrete asphalt mixture meet SNI 06-2489-1991 requirements.
- The influence of HDPE plastic seed variation as additive with optimum asphalt content of 5.5% improves asphalt mix stability performance from 1658 kg to 1820 kg. The addition of HDPE plastic seeds on the oil asphalt causes the penetration of asphalt 60/70 to be more minor, then the level of asphalt hardness is higher. Asphalt viscosity increases (thickens) when the chemical components of metals in the asphalt increase, resulting in a stronger bond to the aggregate.
- By inserting HDPE plastic seeds into the AC-WC mixture, the density and VFA values can be reduced by 7% and 3%, respectively. In addition, it can increase the VIM value by 9% and the VMA value by 2%.
- Variations of HDPE plastic seeds affect the characteristics of AC-WC concrete asphalt mixture at a maximum concentration of 4% to the asphalt weight, namely:
  - Improved mix stability by 16% and MQ value by 32% from 0% plastic HDPE ore addition. The effect has increased ac-WC concrete asphalt mixture (road construction) to shoulder the traffic load until plastic melting occurs.
  - Lower the Flow value by 5% until it reaches the minimum value, but the flow value increases again after reaching the minimum value.
- The study results strengthen previous research with the novelty of using plastic seeds materials that are easily obtained, low prices, and environmentally friendly. This research supports the appeal of environmentally acceptable and cost-effective plastic waste products as road shipping materials, reducing global environmental problems.
- The author advises that additional research be conducted to determine the resistance, fatigue, and rutting of asphalt pavements exposed to water using waste materials.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, D.N., and A.Z.M.; writing—original draft preparation, D.N., and A.Z.M.; writing—review and editing, D.N. and A.Z.M. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available in article.

### 6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 6.4. Conflicts of Interest

The authors declare no conflict of interest.

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