The Characteristics of Porous Asphalt Mixtures with HDPE and CSA

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Abstract: This study investigates the effects of incorporating High-Density Polyethylene (HDPE) and Coconut Shell Ash (CSA) on the performance and environmental sustainability of asphalt mixtures. Laboratory testing was conducted to evaluate the physical properties of the materials and the mechanical characteristics of porous asphalt mixtures. The results demonstrate that the inclusion of HDPE significantly enhances stability values, while the addition of CSA improves the permeability of the porous asphalt, making it a viable solution for sustainable road construction. This research contributes valuable empirical data to the field of civil engineering, showcasing the potential of asphalt modified with HDPE and CSA to improve road infrastructure while mitigating environmental impacts. Future studies are recommended to explore the use of alternative plastic waste types and variations in aggregate gradation to further optimize asphalt mixture performance.

Keywords: Porous Asphalt, High-Density Polyethylene (HDPE), Coconut Shell Ash (CSA), Environmental Sustainability.

1. INTRODUCTION

In recent years, the demand for sustainable infrastructure has significantly increased, prompting researchers and practitioners in the field of civil engineering to explore innovative materials that can enhance the performance of mixtures while minimizing environmental impact. One promising approach is the incorporation of recycled materials, such as High-Density Polyethylene (HDPE), into asphalt mixtures. HDPE, a widely used plastic, presents an opportunity to reduce plastic waste while simultaneously improving the mechanical properties of asphalt mixtures. A 2019 study by Eka Elsa demonstrates that using HDPE plastic as an additive effectively enhances the stability of porous asphalt mixtures. Elsa varied the porous asphalt mixtures by adding HDPE at different dosages, following the determination of the optimal asphalt content. Additionally, the use of natural by-products, such as Coconut Shell Ash (CSA), has garnered attention for its potential to improve the sustainability of asphalt mixtures. In Syammaun's 2020 study, it was identified that coconut shell ash contains activated carbon, a material characterized by numerous pores that adsorb substances passing through it. Consequently, it is expected to enhance the absorption capacity of asphalt.

This study aims to investigate the effects of using HDPE plastic as a substitute for asphalt and CSA as a filler substitute on the characteristics of porous asphalt mixtures. Through a series of laboratory tests, this research will evaluate the physical and mechanical properties of the modified asphalt mixtures, providing empirical data that can inform future applications in road construction. The findings of this research are expected to make a significant contribution to the field of civil engineering by offering insights into the feasibility of using recycled and natural materials to create more sustainable and resilient infrastructure solutions.

2. LITERATURE REVIEW

2.1 Porous Asphalt Mixtures

A porous asphalt mixture is a type of hot mix asphalt (HMA) characterized by an open-graded structure with interconnected voids that enhance the pavement's surface water drainage capacity during rainfall events (NAPA, 2002). These mixtures consist of a combination of coarse aggregates, fine aggregates, and modified asphalt binder. The open gradation with interconnected voids significantly improves water drainage from the pavement surface. In porous asphalt mixtures, coarse aggregates typically constitute between 70% and 85% of the total aggregate content. However, a higher proportion of coarse aggregates tends to reduce stability when compared to conventional pavement structures (Djumari, 2009).

The design of porous asphalt primarily aims to improve surface drainage, thereby reducing the risk of hydroplaning and enhancing road safety under wet conditions. The interconnected voids allow efficient water flow, which not only helps maintain surface integrity but also contributes to overall pavement durability. However, the enhanced drainage capacity comes at the expense of decreased structural stability, necessitating careful consideration during design and application to accommodate various environmental conditions (Verani, 2022).

The utilization of waste materials as additives in asphalt mixtures also contributes to waste management efforts. For example, Ola Eka Elsa (2019) found that incorporating HDPE plastic as an additive can improve the stability of porous asphalt mixtures. This improvement is particularly valuable because the strength of porous asphalt heavily depends on the binder's adhesive properties with the aggregates.

2.2 Composition of Porous Asphalt

The production of porous asphalt mixtures requires precise formulation to achieve optimal performance. Penetration asphalt with a grade of 60/70 is commonly used as a binder in road pavement construction. This asphalt type serves to bond the coarse and fine aggregates, resulting in a durable and robust surface layer.

Aggregate gradation refers to the distribution of different aggregate sizes within the mixture. In this study, the aggregate gradation follows the open-graded specifications of the Australian Asphalt Pavement Association (2004), as presented in Table 1. The gradation indicates the percentage of material passing through sieves by mass for each sieve size.

Table 1. Aggregate Gradation AAPA 2004

Sieve Size AS (mm)	Mix Designation		
	UTA10	OGA10	OGA14
	Percentage Passing Sieve Size (By Mass)		
19.0			100
13.2	100	100	85-100
9.5	80-100	85-100	45-70
6.7	30-55	35-70	25-45

Continuation of Table 1. Aggregate Gradation AAPA 2004

4.75	20-40	20-45	10-25
2.36	18-36	10-20	7-15
1.18	14-30	6-14	6-12
0.600	10-25	5-10	5-10
0.300	7-20	4-8	4-8
0.150	6-12	3-7	3-7
0.075	4-8	2-5	2-5
Total	100	100	100

2.3 Characteristics of Porous Asphalt

The properties of porous asphalt pavements are evaluated using tests such as Marshall testing and permeability tests. Key characteristics include stability, flow, Void in Mix (VIM), Marshall Quotient (MQ), and permeability.

Table 2. Planning Criteria for Porous Asphalt

Criteria	Value
Stability (*kg*)	Min. 500
Flow (*mm*)	2 – 6
Void In Mix (*VIM %)*	18 – 25
Marshall Quotient (*kg/mm*)	Max. 400
Permeability (*cm/second*)	0.1 – 0.5

Adhering to these criteria ensures that the porous asphalt mixture meets performance standards for effective drainage and structural integrity, contributing to safety and sustainability in road construction.

2.4 High Density Polyethylene (HDPE)

High-Density Polyethylene (HDPE) is a thermoplastic polymer composed of long polyethylene chains with high density, resulting in a material that is hard, strong, and durable. HDPE is widely used in applications requiring resistance to pressure, abrasion, extreme temperatures, and chemicals.

With a melting point between 200°C and 280°C, HDPE is easily molded when heated into a liquid state. It exhibits tensile strength ranging from 3100 to 5500 psi, making it one of the hardest and strongest materials available. Additionally, HDPE offers excellent opacity and improved resistance to elevated temperatures (Hardiman, 2018).

Incorporating HDPE as an additive in porous asphalt mixtures significantly enhances their properties, particularly by improving resistance to water and weathering, which increases the durability and lifespan of the pavement. Furthermore, the use of HDPE supports economic and environmental benefits by recycling plastic waste into valuable construction materials.

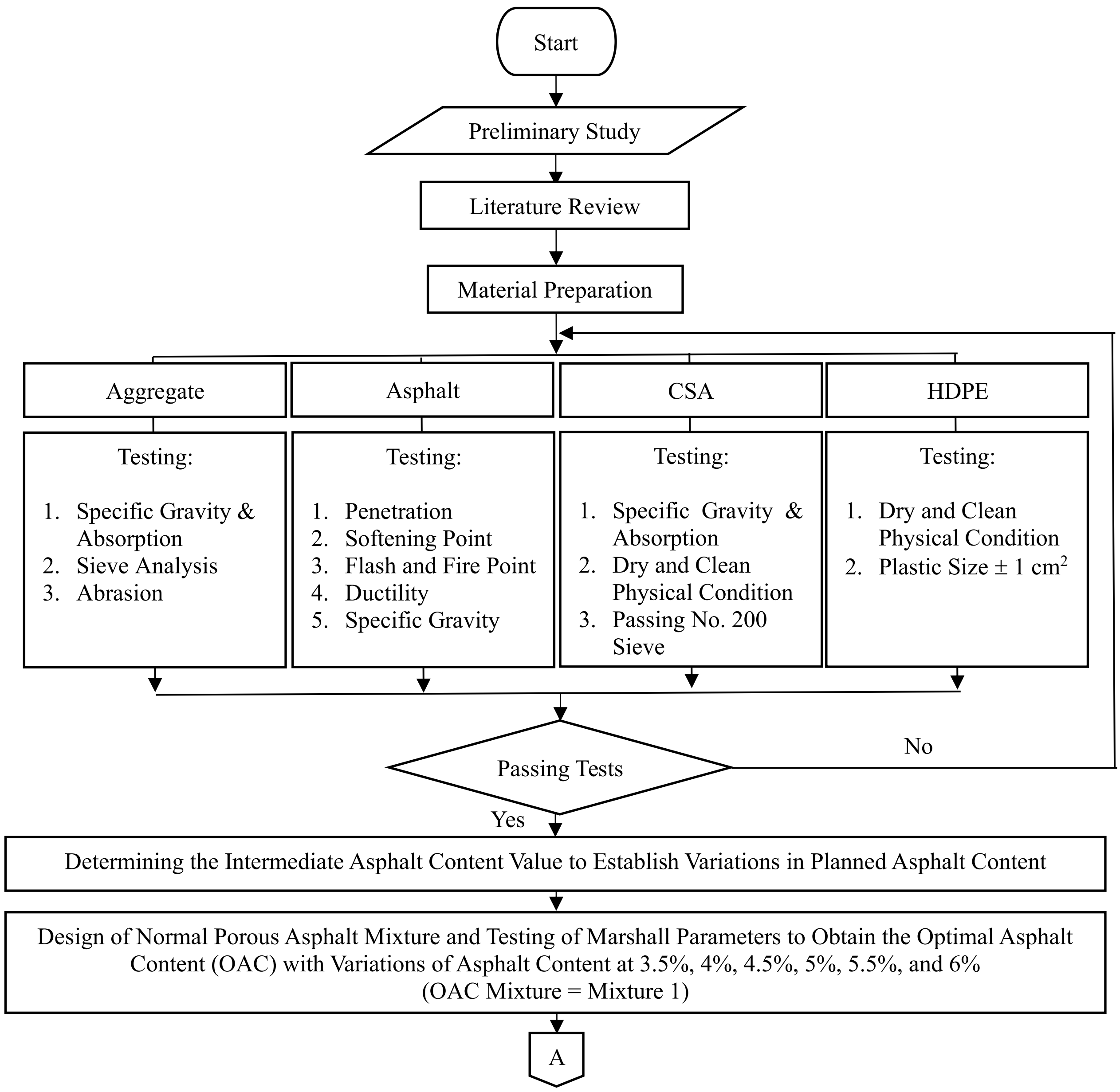
2.5 Coconut Shell Ash (CSA)

Coconut Shell Ash is a by-product generated from burning coconut shells, followed by sieving to obtain fine particles. Its chemical composition makes it suitable for various applications, including organic fertilizers, soil amendments, absorbent materials, and as a filler in porous asphalt mixtures. Using CSA promotes sustainability by recycling agricultural waste while simultaneously improving asphalt mixture performance.

Typically, coconut shell ash varies in texture from coarse to fine and in color from black to grey. Particle size and shape can influence its behavior within the mixture. CSA has a specific gravity of approximately 1.3 g/cm³, which is lower than that of stone ash (about 2.23 g/cm³). This lower specific gravity results in a lighter mixture, potentially enhancing workability and performance. Additionally, the pozzolanic properties of CSA can improve the binding capacity of the asphalt mixture, leading to increased strength and durability.

3. METHODOLOGY

This study was conducted in the Civil Engineering Laboratory at Mulawarman University, Samarinda. The overall research process is depicted in Figure 1.



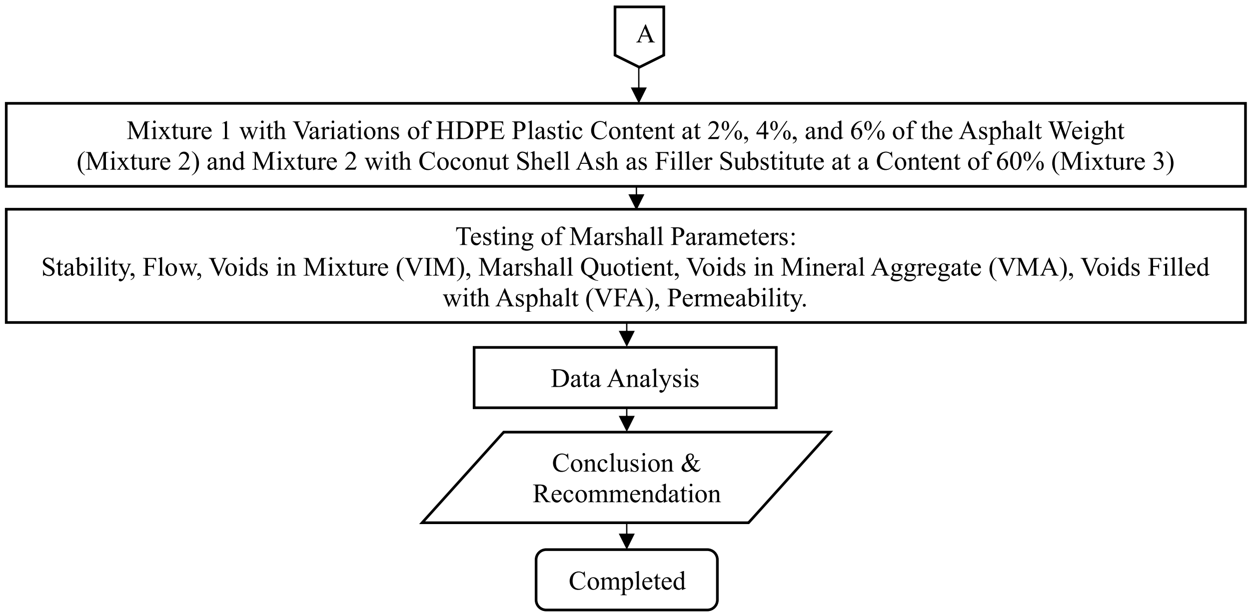


Figure 1. Research Flowchart

3.1 Laboratory Material Testing

The purpose of material inspection and testing is to determine the properties and characteristics of the constituents used in the porous asphalt mixture. The laboratory tests performed include the following:

1. Specific gravity and absorption testing of coarse aggregates, fine aggregates, and filler.
2. Sieve analysis (gradation) of coarse aggregates, fine aggregates, and filler.
3. Aggregate abrasion testing.
4. Specific gravity testing of asphalt binder.
5. Penetration testing of asphalt binder.
6. Softening point testing of asphalt binder.
7. Flash and fire point testing of asphalt binder.
8. Ductility testing of asphalt binder.

The results obtained from these tests will inform the design of the porous asphalt mixture and will be used to evaluate the Marshall characteristics of the resulting mixtures.

3.2 Porous Asphalt Mixture Production

3.2.1 Porous Asphalt Mixture Gradation Design

- Objective
  This study aims to establish a gradation design for the porous asphalt mixture based on the Open Graded Asphalt specifications from the Australian Asphalt Pavement Association (AAPA) 2004 (Table 1)
- Reference Standard
  Australian Asphalt Pavement Association (AAPA) 2004 Open Graded Asphalt.
- Implementation Procedure
  a. Conduct sieve analysis to determine the percentage of aggregates passing through each sieve size.

b. Determine the percentage fraction of each aggregate type using the trial-and-error method in accordance with the porous asphalt mixture gradation requirements until the total aggregate fraction reaches 100%.
c. Once the aggregate gradation conforms to the specification, the aggregates are ready for use in the porous asphalt mixture.
d. Calculate the specific gravity correction and determine the combined specific gravity for each aggregate type, which will be used in the calculation of Marshall parameters.

3.2.2 Determination of the Optimum Asphalt Content

- Objective
  To determine the percentage of asphalt content required in preparing porous asphalt mixture test specimens.
- Reference
  Bina Marga No:001-03/BM/2006 “Penentuan Kadar Aspal Optimum dari campuran beraspal panas dengan asbuton olahan”.
- Implementation Procedure
  The determination of the optimum asphalt content can be calculated using equation (3.12). The resulting optimum asphalt content is prepared for asphalt contents of (Pb-1) %, (Pb-0.5) %, Pb %, (Pb+0.5) %, (Pb+1) %, and (Pb+1.5) %. For each asphalt content, three test specimens are prepared.

$$Pb = 0{,}035\ (\%CA) + 0{,}045\ (\%FA) + 0{,}18\ (\%FF) + K$$

Description:
Pb = Estimated optimum asphalt content (%)
CA = Percentage value of coarse aggregate
FA = Percentage value of fine aggregate
FF = Percentage value of filler
K = Constant with a value ranging from 0.5 to 1.0

3.2.3 Preparation of Modified Asphalt

- Objective
  To prepare modified asphalt test specimens by partially substituting asphalt with HDPE plastic at 2%, 4%, and 6%.
- Procedure
  a. Shred the HDPE plastic into pieces approximately 0.5 cm in size.
  b. Place the asphalt and shredded plastic together in a furnace according to the substitution ratio and heat.
  c. Stir continuously until a homogeneous mixture is achieved.
  d. Maintain the stirring temperature below the asphalt flash point to avoid ignition.
  e. Pour the homogeneous mixture into the testing mold.

3.2.4 Preparation of Coconut Shell Ash Filler

- Objective
  To produce coconut shell ash by combusting coconut shells for use as filler in the mixture.
- Reference

The preparation of coconut shell ash in this study refers to the journal entitled “Proses pengolahan arang tempurung kelapa menggunakan tungku pembakaran termodifikasi” (Nicolas Tumbel, 2019).

- Procedure
  a. Clean the combustion furnace from residues of previous burns.
  b. Load 1–2 kg of coconut shells into the furnace.
  c. Add sufficient kerosene to ignite the shells.
  d. Let them burn evenly for 10–15 minutes.
  e. Add more shells gradually to maintain combustion until all are burned.
  f. Use a fan to sustain combustion.
  g. Seal the furnace tightly after combustion to prevent further burning.
  h. Stop the combustion according to the needed time and sample weight.
  i. Prepare a No. 200 sieve and sieve pan.
  j. Once cooled, sieve the ashes through the No. 200 sieve to collect fine ash particles.

3.2.5 Fabrication of Porous Asphalt Mix Test Specimens

1. Porous Asphalt Mix Composition - Mixture 1
   a. Heat the asphalt until reaching the desired viscosity.
   b. Weigh aggregates according to gradation and combine in a plastic bag.
   c. Dry aggregates in an oven at 150°C for 30 minutes to 1 hour.
   d. Weigh the tray, tare the scale, and weigh asphalt by variation percentage.
   e. Add heated aggregates to the mixing tray, stir thoroughly; monitor temperature (~150°C).
   f. Place mold on compaction plate and secure it with a mold holder.
   g. Place paper cut to mold diameter at mold base.
   h. Pour mixture into mold; level with spatula; tamp edges (15 times), center (10 times).
   i. Place paper cut to mold diameter on top of mixture.
   j. Tamp 50 times with a hammer drop height of 45.7 cm (AAPA 2004 specs).
   k. Turn mold over; tamp bottom 50 times similarly.
   l. Ensure hammer axis is perpendicular throughout tamping.
   m. Remove mold from plate and attach to specimen extractor/jack.
   n. Mark specimens with asphalt content; cure at room temperature for 24 hours.

2. Porous Asphalt Mix Composition - Mixture 2 and 3
   a. Heat the asphalt until the desired viscosity is reached.
   b. Weigh aggregates according to gradation and combine them in a plastic bag.
   c. Dry the aggregates in an oven at 150°C for 30 minutes to 1 hour.
   d. Weigh HDPE plastic according to predetermined substitution levels.
   e. Weigh the tray, tare the scale, and weigh asphalt by the optimum asphalt content (OAC).
   f. Heat asphalt, add HDPE plastic, and stir until homogeneous.
   g. Add heated aggregates and coconut shell ash filler to the mixing tray; stir thoroughly; monitor temperature (~150°C).
   h. Place mold on compaction plate and secure with mold holder.
   i. Place paper cut to mold diameter at mold base.
   j. Pour mixture into mold, level with spatula, tamp edges (15 times), center (10 times).
   k. Place paper cut to mold diameter on top.
   l. Tamp mixture 50 times as per AAPA 2004 specs (hammer drop height 45.7 cm).
   m. Turn mold over, tamp bottom 50 times similarly.

n. Ensure hammer axis remains perpendicular throughout tamping.
o. Remove mold and attach to specimen extractor.
p. Mark specimens with corresponding asphalt content and cure at room temperature for 24 hours before testing.

3.3 Characteristic Testing of Porous Asphalt Mixture

The characterization of porous asphalt mixtures was carried out using the Marshall test method, which is widely employed to evaluate the performance of asphalt mixtures, particularly for pavement layers. This test measures critical physical properties of the asphalt mixture, including stability, flow, and porosity.

3.3.1 Marshall Test

- Testing Objective
  The purpose of the Marshall test is to develop an asphalt mixture that meets the specified design parameters for porous asphalt characteristics.
- Reference
  RSNI M-01-2003 "Metode Pengujian Campuran Beraspal Panas Dengan Alat *Marshall*".
- Procedure
  a) Clean each test specimen by removing any adhering dirt and label the specimens for identification.
  b) Measure the dimensions of each specimen with a precision of 0.1 mm, and determine the dry weight.
  c) Place the specimen in a suspended basket and record its weight while submerged in water.
  d) Dry the specimen using a towel, then weigh it under saturated surface-dry (SSD) conditions.
  e) Activate the water bath and set its temperature to 60°C, verifying the temperature with a thermometer.
  f) Immerse the specimen in the water bath at a constant temperature of 60°C for 30 minutes.
  g) Remove the specimen and position it on the lower segment of the loading head.
  h) Place the upper segment on top of the specimen, then assemble it within the Marshall testing machine.
  i) Raise the loading head until it just contacts the base of the testing ring without applying load.
  j) Set the dial gauge to zero, ensuring the dial stem is perpendicular to the upper segment of the loading head.
  k) Apply load to the specimen at a rate of 50 mm per minute until the maximum load is attained.
  l) Record the stability and flow values at the maximum load point.
  m) Apply the correction and calibration factors of the proving ring to the recorded values to determine the final stability and flow.


Figure 2.a Porous Asphalt Mixing Process


Figure 2.b Test Specimen Molding Process


Figure 2.c Test Specimen for Marshall Testing

Figure 2. Sample Preparation Process

3.3.2 Permeability Testing

- Testing Objective
  This permeability test aims to measure the vertical flow velocity of water through the porous asphalt mixture, assessing its capacity to absorb and convey water. The falling head test formula is utilized for this purpose.
- Reference
  The test procedure refers to “Mekanika Tanah Prinsip-prinsip Rekayasa Geoteknik” (Braja M. Das, 1995).

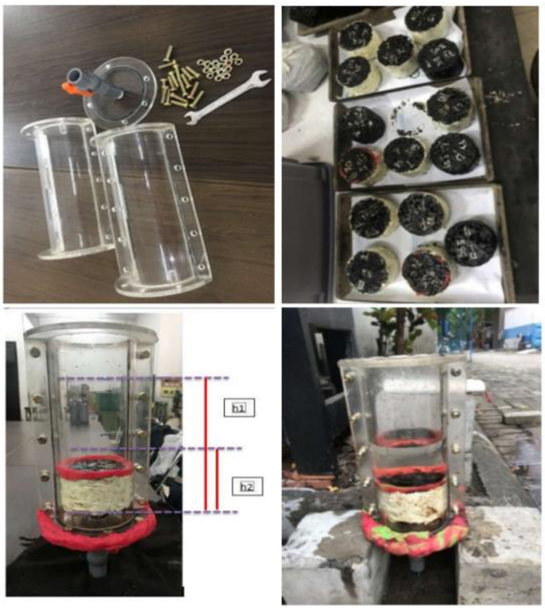


Figure 3. Permeability Test Apparatus

- Procedure
  a. Carefully place the porous asphalt mixture sample into the permeability testing apparatus, ensuring no leakage occurs.
  b. Verify that the top and bottom surfaces of the specimen are flush with the apparatus surfaces.
  c. Apply plasteline around the specimen sides to prevent leakage.
  d. Fill the tube with water to an initial height of 70 cm (h1).

e. Record the time required for the water level to drop to 20 cm above the specimen surface (h2).

- Calculation

The permeability coefficient (K) is calculated using the formula:

$$K = 2{,}3\,\frac{aL}{At}\;x\;\left(log\frac{h1}{h2}\right)$$

where:

K	= permeability coefficient (cm/s)
A	= cross-sectional area of the tube (cm²)
a	= cross-sectional area of the test specimen (cm²)
L	= length of the specimen (cm)
t	= time for water level to fall from h1 to h2 (seconds)
h1	= initial water height (cm)
h2	= final water height (cm)

Figure 4. Permeability Testing Process

3.4 Mix Design Formula

This study aims to determine the weight composition of the porous asphalt mixture, categorized into four mixture types: the asphalt mixture used to determine the Optimum Asphalt Content (OAC), asphalt mixture without substitution materials (Mixture 1), asphalt mixture with varying HDPE plastic content as an asphalt substitute (Mixture 2), and asphalt mixture with varying HDPE plastic content as an asphalt substitute combined with 60% coconut shell ash as a filler substitute (Mixture 3).

3.4.1 Material Requirements for Test Specimen of Mixture 1

The preparation of test specimens was conducted to determine the weight composition of Mixture 1 for producing porous asphalt research samples, utilizing the asphalt content derived from Optimum Asphalt Content (OAC) sample testing. The weight composition for Mixture 1 is detailed in Table 3 as follows:

Table 3. Weight Composition of Test Specimen for Mixture 1

Description	Mixture	Unit
Asphalt content	4,6	%
Asphalt content weight	52,9	gram
Aggregate weight	1064,18	gram
Total Mixture weight	1150	gram

3.4.2 Material Requirements for Test Specimen of Mixture 2

The preparation of test specimens aimed to determine the weight composition of the porous asphalt mixture with varying HDPE plastic content as an asphalt substitute (Mixture 2). The weight composition is presented in Table 4.
Total mixture weight = 1150 gram
Variation of HDPE plastic as asphalt substitute = 0%, 2%, 4%, and 6% of asphalt weight

Table 4. Weight Composition of Test Specimen for Mixture 2

Description	Mixture			Unit
Asphalt content		4,6		%
Asphalt content weight		52,9		gram
Description		Mixture 2		Unit
Plastic Content	2	4	6	%
Plastic Weight	1,06	2,12	3,17	gram
Asphalt Content Weight After Substitution	51,84	50,78	49,73	gram
Aggregate Weight	1097,1	1097,1	1097,1	gram
Total Mixture Weight	1150	1150	1150	gram

Description of material requirements in test specimen preparation:

A. Plastic Weight = $\frac{\text{Plastic Content \%}}{100\%}$ x Asphalt Content Weight
(1)

B. Asphalt Weight After Substitution = $\text{Asphalt Content Weight} - \text{Plastic Weight}$
(2)

C. Aggregate Weight = $\text{Mixture Weight} - (\text{Plastic Weight} + \text{Asphalt Content Weight})$
(3)

3.4.3 Material Requirements for Test Specimen of Mixture 3

The preparation of test specimens aimed to determine the weight composition of the porous asphalt mixture with variations in HDPE plastic content as an asphalt substitute and 60% coconut shell ash as a filler substitute (Mixture 3). The weight composition is presented in Table 5.
Total mixture weight = 1150 gram

Filler content = 3% Aggregate Weight
HDPE plastic content as asphalt substitute = 0%, 2%, 4%, and 6% of asphalt weight
Coconut shell ash content as filler substitute = 60% of filler weight

Table 5. Weight Composition of Test Specimen for Mixture 3

Description	Mixture			Unit
Asphalt content		4,6		%
Asphalt content weight		52,9		gram
Filler Weight		32,91		gram
Coconut Shell Ash Content		60		%
Coconut Shell Ash Weight		19,75		gram
Description	**Mixture 3**			**Unit**
Plastic Content	2	4	6	%
Plastic Weight	1,06	2,12	3,17	gram
Asphalt Content Weight After Substitution	51,84	50,78	49,73	gram
Aggregate Weight	1097,1	1097,1	1097,1	gram
Filler Weight (Coconut Shell Ash + Stone Ash)	32,91	32,91	32,91	gram
Total Mixture Weight	1150	1150	1150	gram

Description of material requirements in test specimen preparation:

A. Filler Weight $= \frac{\text{Filler content \%}}{100\%}$ x Aggregate Weight (4)

B. Coconut Shell Ash Weight $= \frac{\text{Ash Content \%}}{100\%}$ x Filler Weight (5)

3.4.3 Test Specimen Requirements

For each mixture, three test specimens are prepared for every variation in content. The total number of asphalt mixture samples prepared is 72, as detailed in Tables 6 and 7. This study employs the ideal gradation based on the OGA14 specifications (AAPA, 2004), as illustrated in Figure 5.

Table 6. Testing Specimen Requirements for Marshall Testing Porous Asphalt Mixtures

Testing Specimens	Number of Samples
Mixtures with Variations of Asphalt Content at 3.5%, 4%, 4.5%, 5%, 5.5%, and 6% to Determine the OAC	18 Samples
Mixture 1 (OAC 4.6% Without Material Substitution)	3 Samples
Mixture 2 (Mixture 1 + Variations of Asphalt Substitution with HDPE Plastic at 2%, 4%, and 6%)	9 Samples
Mixture 3 (Mixture 2 + 60% Filler Substitution with CSA)	9 Samples
Total Number of Testing Specimens	39 Samples

After conducting the Marshall test, permeability testing is performed on each optimal content variation by preparing three test specimens for each content variation.

Tabel 7. Testing Specimen Requirements for Permeability Testing Porous Asphalt Mixtures

Testing Specimens	Number of Samples
Mixture 1	3 Samples
Mixture 2 (Optimal Plastic Content at 4%)	3 Samples
Mixture 3 (Optimal Plastic Content at 4% + 60% Filler Substitution with CSA)	3 Samples
Total Number of Testing Specimens	9 Samples

In Figure 5, the straight line positioned at the center of the graph represents the gradation employed in this study.

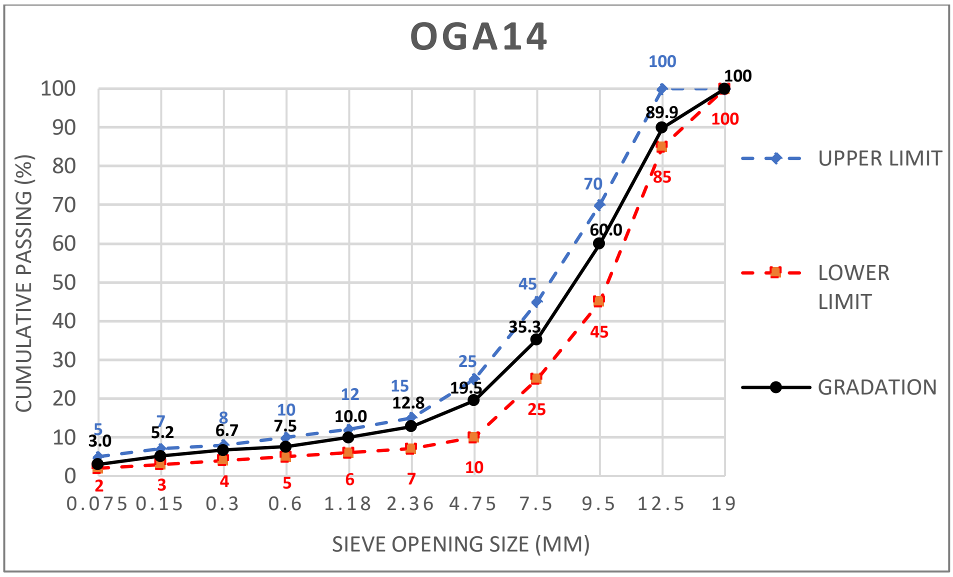


Figure 5. Graph of Central Gradation Sieve Analysis

4. RESULTS

4.1 Aggregate and Asphalt Materials

The results of the material examinations include tests on coarse aggregates, fine aggregates, filler, normal asphalt, and HDPE plastic-modified asphalt with variations of 2%, 4%, and 6% by weight of the asphalt material. All test results comply with the specifications of the Indonesian National Standard (SNI). The details are presented in the tables below.

Table 8. Results of Aggregate and Filler Material Testing

Test	Coarse Aggregate	Fine Aggregate	*Filler* (CSA)	Stone Ash
SSD Specific Gravity (*gr/cm³*)	2,74	2,55	1,45	2,30
Bulk Specific Gravity (*gr/cm³*)	2,70	2,49	1,30	2,23
Apparent Specific gravity (*gr/cm³*)	2,81	2,66	1,54	2,40

Absorption (%)	1,43	2,57	11,73	3,09
Aggregate Wear		19.68%		

Table 9. Results of Normal and Modified Asphalt Testing

Test	Normal	Modification			Specifications
		2%	4%	6%	
Specific Gravity (gr/cm^3)	1,006	1,012	1,009	1,000	≥1,0
Penetration (*mm*)	66	67,3	66,7	64,7	60
Softening Point (°*C*)	49,5	52	50	51	≥48
Flash and Fire Point (°*C*)	360	361	358	367	≥232
Ductility (*cm*)	127	140	137	112,5	≥100

4.2 Optimal Asphalt Content (OAC)

Testing with variations in asphalt content to determine the OAC indicates a value of 4.6%, based on Marshall characteristic testing utilizing an open gradation in accordance with AAPA (2004).

Table 10. Marshall Testing of Optimal Asphalt Content

Marshall Characteristics	Asphalt Content Variations						Specifications (AAPA, 2004)
	3,5%	4%	4,5%	5%	5,5%	6%	
Stability (*kg*)	376	457	677	740	722	697	≥ 500
Flow (*mm*)	3,24	3,9	4,85	5,8	6,5	6,49	2 - 6
VIM (%)	24,99	24,35	23,49	22,75	21,94	21,11	18 - 25
MQ (*kg/mm*)	116,08	117,18	139,67	127,50	111,08	107,43	≤ 400

4.3 Marshall Characteristics

The Marshall testing produced key parameters, including stability, flow, Voids in Mix (VIM), and Marshall Quotient (MQ). An Optimal Asphalt Content (OAC) of 4.6% was used to prepare specimens for three mixes: Mix 1 (control without HDPE and CSA), Mix 2 (HDPE plastic substitution at 2%, 4%, and 6%), and Mix 3 (HDPE plastic substitution combined with 60% filler replacement by CSA). The results represent the average of three samples per variation, as detailed in Table 11.

Table 11. Results of Marhsall Characteristics Testing

Marshall Characteristics	Mix 1	Mix 2			Mix 3			Specifications (AAPA, 2004)
		2%	4%	6%	2%	4%	6%	
Stability (*kg*)	608	788	815	779	620	636	589	≥ 500
Flow (*mm*)	5,25	5,67	5,44	5,15	5,06	5,75	5,74	2 – 6
VIM (%)	22,29	22,62	22,99	22,27	20,86	21,99	21,84	18 – 25
MQ (*kg/mm*)	115,81	138,98	149,82	151,26	122,53	110,61	102,61	≤ 400

Based on these results, test specimens for permeability testing were prepared using the mixes above at OAC and corresponding variations. The average values from permeability tests are recorded in Table 12.

Table 12. Results of Permeability Testing

Parameter	Asphalt Content (%)	Average Value			Specifications (AAPA, 2004)
		Mix 1	Mix 2	Mix 3	
Permeability	4,6	0,330	0,294	0,426	0,1 – 0,5 cm/s

4.4 The Relationship Between Stability and Flow Values

The research conducted on the Marshall parameter tests revealed significant findings regarding the stability and flow values of three variations of porous asphalt mixtures. Mix 1 served as the control, while Mix 2 demonstrated varying levels of stability with HDPE substitutions. Mix 3, which included both HDPE and a 60% substitution of filler with CSA, also exhibited notable results. The data presented in Table 13 indicate that the incorporation of HDPE and CSA can enhance the performance characteristics of porous asphalt mixtures, particularly in terms of stability.

Table 13. Recapitulation of Stability and Flow Values

Marshall Characteristics	Mix 1	Mix 2			Mix 3			Specifications (AAPA, 2004)
		2%	4%	6%	2%	4%	6%	
Stability (kg)	608	788	815	779	620	636	589	≥ 500
Flow (mm)	5,25	5,67	5,44	5,15	5,06	5,75	5,74	2 – 6

Stability significantly increases when moving from Mix 1 to Mix 2, with Mix 2 attaining the highest stability of 815 kg and a flow of 5.44 mm. This flow increase is not statistically significant. The transition from Mix 1 to Mix 3 also shows an increase in stability and similar flow trends, though the changes are less marked. These results indicate that HDPE substitution (Mix 2) enhances stability without detrimentally impacting flow. Stability reflects mixture density and rigidity, while flow represents flexibility; thus, Mix 2 improves rigidity while maintaining flexibility.

4.5 The Relationship Between VIM and Permeability Values

This study also analyzed the relationship between VIM and permeability in Mix 1, 2, and 3, using optimum asphalt content (OAC) for Mix 1 and optimum plastic content (OPC) for Mixes 2 and 3. Permeability measures the water flow through interconnected voids, closely related to VIM since higher voids typically imply higher permeability.

Coconut shell ash (CSA) contains natural fibers that presumably improve asphalt bonding, increasing permeability and mechanical performance. Syammaun (2020) supports this, showing increased permeability and stability with PET plastic plus 50% CSA additives.

Table 14. Recapitulation of VIM and Permeability Values

Marshall Characteristics	Mix 1	Mix 2	Mix 3	Specifications (AAPA, 2004)
Permeability (cm/s)	0,33	0,29	0,42	0,1 – 0,5

VIM (%)	22,29	22,99	21,99	18 - 25

Notably, VIM increased from Mix 1 to Mix 2 (22.99%), but permeability decreased to 0.29 cm/s. This suggests HDPE plastic creates isolated air bubbles rather than interconnected voids, elevating VIM but reducing permeability. Variations in mixing and compaction could also impact composition and density. Mix 3's higher permeability is attributed to CSA as filler.

Future research can explore other plastic wastes (e.g., LDPE, PET) and fillers (e.g., fly ash, organic ashes) to improve Marshall parameters further. Importantly, all mixtures meet AAPA (2004) specifications, supporting their practical application potential.

5. CONCLUSION

Based on the findings of this study concerning the substitution of HDPE plastic and coconut shell ash (CSA) as filler in porous asphalt mixtures, the following conclusions are drawn:

1. The incorporation of HDPE plastic significantly increases the stability of the mixture; however, the flow values tend to decrease with higher plastic content, indicating enhanced rigidity. Additionally, the inclusion of CSA positively contributes to an increase in permeability.
2. Both normal and modified asphalt mixtures with varying HDPE plastic substitutions comply with the specifications outlined by the Indonesian National Standard (SNI).
3. The optimum asphalt content (OAC) was determined to be 4.6% through AAPA characteristic tests, evaluated over variations of 3.5%, 4%, 4.5%, 5%, 5.5%, and 6%.
4. In mixtures incorporating different amounts of CSA, there is no significant improvement in stability; however, permeability values improve with increasing CSA content.

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