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Performance Evaluation of Porous Asphalt Mixtures Incorporating Cotton Cloth Ash as Filler Based on Marshall Characteristics and Permeability

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Abstract: Porous asphalt is designed to improve surface drainage and reduce water accumulation; however, its performance depends on the balance between mechanical strength and permeability. The use of alternative filler materials, particularly textile-derived waste such as cotton cloth ash, remains limited. **Objective:** This study aims to evaluate the performance of porous asphalt mixtures incorporating cotton cloth ash as a substitute filler, focusing on optimum asphalt content, Marshall characteristics, and permeability behavior. **Methodology:** An experimental quantitative approach was conducted in a laboratory. The mixture design followed the Australian Asphalt Pavement Association (AAPA, 2004) method. Data were obtained through material testing, Marshall testing, and permeability testing. Key parameters analyzed included Void in Mix (VIM), Stability, Flow, Marshall Quotient (MQ), Cantabro Loss (CL), Asphalt Flow Down (AFD), and permeability. **Findings:** The Optimum Asphalt Content (OAC) was identified at 4.80%. The best mechanical performance occurred at 4.5%–5% asphalt content, with maximum stability of 832 kg and MQ of 530 kg/mm. Permeability increased with asphalt content, reaching 0.20 liter/second at 6%, indicating improved drainage but reduced structural performance at higher binder levels. **Implications:** The results highlight the importance of optimizing asphalt content to achieve a balance between mechanical strength and hydraulic performance in porous asphalt design. **Originality:** This study introduces cotton cloth ash as an alternative filler, demonstrating its feasibility in maintaining functional and structural performance while supporting sustainable pavement materials.

Keywords: Porous Asphalt; Cotton Cloth Ash; Marshall Characteristics; Permeability; Optimum Asphalt Content

INTRODUCTION

Indonesia, as a tropical country, is characterized by high rainfall intensity that directly affects the performance of flexible pavement systems. In many regions, annual rainfall exceeds 2,000 mm, creating conditions that accelerate the accumulation of surface water on road pavements (BMKG, 2023). Under these conditions, inadequate drainage frequently leads to moisture-induced damage, stripping, ravelling, and premature deterioration of asphalt layers. The Ministry of Public Works and Housing has also identified water infiltration and poor drainage as major contributors to road damage in Indonesia (Direktorat Jenderal Bina, 2021, 2023). Beyond reducing pavement service life and increasing maintenance demand, persistent surface water also poses safety hazards, particularly by increasing the risk of hydroplaning and lowering skid resistance.

In response to these practical problems, porous asphalt has gained attention as a pavement technology capable of improving surface drainage through its interconnected air-void structure. By allowing water to infiltrate rapidly through the wearing course, porous asphalt can reduce water ponding, splash, and spray, thereby improving functional road performance under wet conditions (Chen & Yang, 2020). Nevertheless, its implementation is still constrained by several engineering limitations. Open-graded mixtures are generally more vulnerable to binder draindown during production, particle loss or ravelling during service, and reduced resistance to repeated traffic loading compared with dense-graded asphalt mixtures (Huang et al., 2022; Wu et al., 2019). At the same time, Indonesia is also facing increasing pressure from textile waste generation, which has become a significant environmental issue according to national waste management data (Bappenas, 2021; Kementerian Lingkungan Hidup dan, 2022). This condition creates an engineering opportunity to address two problems simultaneously, namely pavement performance and waste utilization.

Recent literature on porous asphalt has consistently shown that its performance is governed by a delicate balance between hydraulic functionality and mechanical durability. Reviews and experimental studies have demonstrated that porous asphalt offers clear advantages in permeability and surface drainage, yet remains highly sensitive to ravelling, moisture damage, and aging (Chen & Yang, 2020; Huang et al., 2022; Wu et al., 2019). The internal void structure that enables water infiltration must therefore be carefully controlled, since excessive air voids may weaken stability, whereas insufficient voids may reduce permeability and undermine the functional purpose of the mixture (Yan et al., 2025). In addition, the long-term performance of porous asphalt is strongly influenced by environmental exposure, particularly the combined effects of heat, water, and traffic loading, which accelerate degradation of the binder–aggregate system (Li et al., 2022). These findings indicate that improving the durability of porous asphalt without sacrificing its drainage capacity remains a central engineering challenge.

To address this issue, another major line of research has focused on the incorporation of fibers and textile-based modifiers into asphalt mixtures. Fiber reinforcement has been widely reported to improve binder retention, reduce draindown, and enhance the cohesion of asphalt mixtures, particularly in open-graded systems (Guo et al., 2023). Several experimental studies have shown that recycled fibers and other waste-derived materials can improve rutting resistance, cracking resistance, and overall durability of asphalt mixtures (Jin et al., 2024; Slebi-Acevedo et al., 2020). Similar benefits have also been reported from the use of bamboo fibers, human hair, and other unconventional fibrous materials, which contribute to improved rheological and mechanical properties of asphalt composites (Shahnewaz et al., 2023; Youssef & Fahmy, 2023). Furthermore, broader studies on textile waste utilization in construction suggest that textile residues should be viewed not merely as waste streams, but as potential secondary engineering resources (Miera-Domínguez et al., 2025; Rahman et al., 2022). However, most of these studies have concentrated on textile materials in fibrous form, leaving their ash-derived form relatively underexplored.

A parallel development in asphalt engineering is the growing use of waste-based fillers as substitutes for conventional mineral fillers. Recent reviews have shown that waste fillers such as fly ash, sludge ash, and other industrial by-products may improve asphalt stiffness, durability, rutting resistance, and environmental performance, depending on their physical and chemical characteristics (Jwaida et al., 2024). Experimental studies further indicate that ash materials rich in silica and alumina can improve adhesion and strengthen the asphalt mastic, thereby affecting the mechanical behavior of the mixture (Elmagarhe et al., 2024). Agricultural ashes such as rice husk ash and bagasse ash have also shown promising performance as sustainable filler alternatives because of their pozzolanic activity and fine particle characteristics. Despite these advances, the use of cotton cloth ash waste as filler in porous asphalt mixtures has not been extensively examined, especially in terms of its simultaneous effect on Cantabro Loss, Asphalt Flow Down, Marshall properties, and permeability. This unresolved issue defines the specific research gap addressed in the present study.

Based on the above gap, this study aims to evaluate the engineering performance of porous asphalt mixtures incorporating cotton cloth ash waste as filler using the Marshall method and AAPA criteria (Australian Asphalt Pavement, 2004). Specifically, the study seeks to determine the optimum asphalt content, analyze the influence of cotton cloth ash variation on Cantabro Loss, Asphalt Flow Down, Void in Mix, Marshall stability, flow, Marshall Quotient, and permeability, and identify the filler proportion that provides the most appropriate balance between drainage performance and mechanical stability.

Accordingly, the technical argument of this study is that cotton cloth ash waste has the potential to function as an alternative filler capable of modifying asphalt mastic behavior and improving the overall response of porous asphalt mixtures. The working hypothesis is that, when used at an appropriate dosage, cotton cloth ash can reduce binder draindown, maintain adequate interconnected voids for permeability, and preserve Marshall performance within acceptable limits. If validated experimentally, this approach will not only broaden the engineering application of porous asphalt materials, but also support sustainable pavement development through the productive reuse of textile waste.

RESEARCH METHOD

The unit of analysis in this study was the porous asphalt mixture incorporating cotton cloth ash waste as filler. The research focused on evaluating the engineering response of the mixture in terms of permeability, Cantabro Loss, Asphalt Flow Down, and Marshall characteristics, including Void in Mix (VIM), stability, flow, and Marshall Quotient (MQ). The main experimental variables consisted of variations in cotton cloth ash filler content of 0%, 0.3%, 0.5%, and 0.7%, while the asphalt content variation used for determining the optimum asphalt content ranged from 4% to 6%. Therefore, the study specifically examined the behavior of porous asphalt as a material system under controlled laboratory conditions.

This study employed a quantitative experimental design because the objective was to measure the effect of filler variation on the engineering performance of porous asphalt mixtures. An experimental approach was selected because it allows direct observation of changes in technical parameters caused by controlled variations in material composition. The Marshall method was used as the primary evaluation approach because it is widely applied in asphalt mixture design to assess stability, flow, and volumetric properties. In addition, the determination of Optimum Asphalt Content (OAC/KAO) referred to the Australian Asphalt Pavement Association (Australian Asphalt Pavement, 2004), since porous asphalt mixtures require performance criteria not only in terms of strength but also in terms of draindown resistance and void structure.

The data used in this study were entirely derived from primary laboratory data and supporting technical standards. Primary data were obtained from material testing, asphalt mixture specimen preparation, and performance testing of porous asphalt specimens. The tested materials included coarse aggregate, fine aggregate, asphalt penetration grade 60/70, limestone filler, and cotton cloth ash waste as a substitute filler. Supporting information was obtained from technical references and standards, including AAPA, Japan Road Association criteria for permeability, SNI 06-2489-1991 for Marshall testing, and the General Specifications of Bina Marga Revision 2 (Direktorat Jenderal Bina, 2021).

Permeability is used to assess the drainage capability of the mixture, which is a critical aspect of porous asphalt performance. The classification of permeability based on the coefficient of permeability (K) is presented in Table 1.

Table 1. Permeability Requirements

Permeability Level	Coefficient (K)
Very Good	$K > 10^{-2}$ cm/s
Good	$10^{-3} – 10^{-2}$ cm/s
Poor	$K < 10^{-4}$ cm/s

Furthermore, the mechanical performance of the mixture is evaluated using the Marshall method, which includes parameters such as stability, flow, Marshall Quotient (MQ), and Void in Mix (VIM). These parameters are used to determine the resistance of the mixture to load and deformation, as summarized in Table 2.

Table 2. Marshall Parameter

Parameter	Description
Stability	Maximum load resistance
Flow	Plastic deformation
Marshall Quotient (MQ)	Stiffness (kg/mm)
Void in Mix (VIM)	Air void content (%)

In addition, the determination of the Optimum Asphalt Content (OAC) is based on three main criteria, namely Cantabro Loss (CL), Void in Mix (VIM), and Asphalt Flow Down (AFD), in accordance with the specifications of the Australian Asphalt Pavement Association (Australian Asphalt Pavement, 2004). The required criteria for OAC determination are presented in Table 3.

Table 3. Requirements for Determining the KAO

Parameter	Requirement
Cantabro Loss (CL)	≤ 35%
Void in Mix (VIM)	18% – 25%
Asphalt Flow Down (AFD)	≤ 0.3%

Data collection was carried out through a sequence of laboratory procedures. First, the constituent materials were tested to verify their compliance with the required specifications. After the material properties were confirmed, aggregate gradation and trial asphalt contents were prepared to determine the Optimum Asphalt Content. The OAC determination was based on three parameters, namely Cantabro Loss, Void in Mix, and Asphalt Flow Down. After the OAC was obtained, porous asphalt specimens were produced using filler variations of cotton cloth ash waste at 0%, 0.3%, 0.5%, and 0.7%. Each specimen was then subjected to permeability testing and Marshall testing to obtain the relevant performance parameters. The overall research workflow, from material preparation to performance evaluation, is illustrated in Figure 1**.**

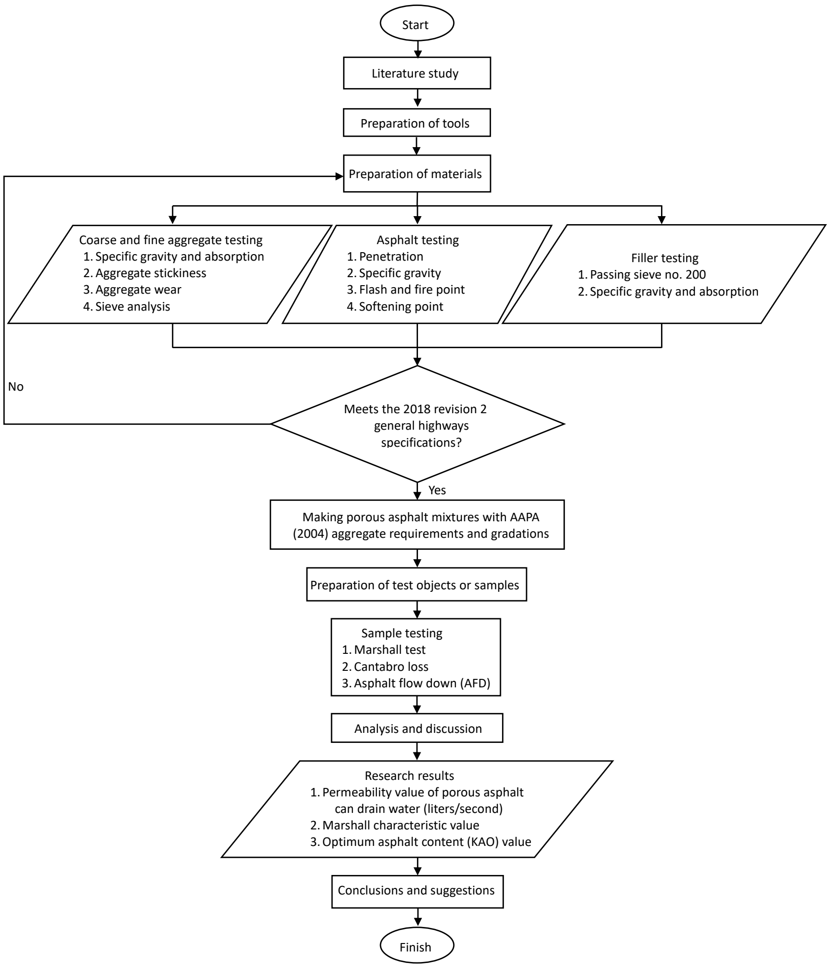

Figure 1. Research Scheme

The collected data were analyzed quantitatively by comparing the measured values of each mixture variation against the specified criteria for porous asphalt. The analysis began with determining the Optimum Asphalt Content from the relationship among Cantabro Loss, VIM, and Asphalt Flow Down. Subsequently, the Marshall test results and permeability values of each filler variation were tabulated, averaged, and interpreted to identify the mixture that best satisfied the AAPA requirements. The analysis emphasized the effect of cotton cloth ash filler on the balance between hydraulic performance and mechanical performance of porous asphalt. Based on this procedure, the optimum filler variation was identified from the mixture that showed the most acceptable combination of permeability, durability, and Marshall characteristics.

RESULT

Material Testing and Optimum Asphalt Content Determination

Material testing was carried out in the laboratory to verify the suitability of all constituent materials prior to the preparation of porous asphalt mixtures. The tested materials included coarse aggregate, fine aggregate, 60/70 penetration asphalt, limestone filler, and cotton cloth ash used as a substitute filler. The purpose of this stage was to ensure that all materials met the technical requirements specified in the applicable standards, thereby providing a reliable basis for subsequent mixture design and performance evaluation.

Table 4. Recapitulation of Material Testing Results

MATERIAL TESTING RECAPITULATION						
Limestone Filler Test Results						
No	**Test**	**Test Method**	**Unit**	**Specification**	**Result**	**Description**
1	Sieve Analysis	SNI ASTM C136-2012	%	>75	95.38	Meets
2	Specific Gravity	SNI 1970-2016	gram	>2,5	3.43	Meets
Filler Test Results (Cotton Fabric Ash)						
No	**Test**	**Test Method**	**Unit**	**Specification**	**Result**	**Description**
1	Sieve Analysis	SNI ASTM C136-2012	%	>75	94.64	Meets
2	Specific Gravity	SNI 1970-2016	gram	>2,5	2.62	Meets
Fine Aggregate Test Results Fraction (0–5)						
No	**Pengujian**	**Metode Pengujian**	**Satuan**	**Spesifikasi**	**Hasil**	**Keterangan**
1	Sieve Analysis	SNI ASTM C136-2012	%	<10	4.89	Meets
2	Bulk Specific Gravity	SNI 1970-2016	gram	>2,5	2.60	Meets
3	Saturated Surface Dry (SSD) Specific Gravity	SNI 1970-2016	gram	>2,5	2.63	Meets
4	Apparent Specific Gravity	SNI 1970-2016	gram	>2,5	2.68	Meets
5	Water Absorption	SNI 1970-2016	%	<3	1.07	Meets
Coarse Aggregate Test Results Fraction (5–10) and (10–15)						
No	**Test**	**Test Method**	**Unit**	**Specification**	**Result**	**Description**
1	Sieve Analysis 10–15	SNI ASTM C136-2012	%	<1	0.99	Meets
2	Sieve Analysis 5–10	SNI ASTM C136-2013	%	<1	0.99	Meets
3	Bulk Specific Gravity	SNI 1969-2016	gram	>2,5	5.90	Meets
4	Saturated Surface Dry (SSD) Specific Gravity	SNI 1969-2016	gram	>2,5	5.96	Meets
5	Apparent Specific Gravity	SNI 1969-2016	gram	>2,5	6.31	Meets
6	Water Absorption	SNI 1969-2016	%	<3	1.11	Meets
7	Aggregate Abrasion	SNI 2417-2008	%	<40	36.07	Meets
Asphalt Test Results Penetration 60/70						
No	**Test**	**Test Method**	**Unit**	**Specification**	**Result**	**Description**
1	Asphalt Penetration	SNI 2456-2011	0,1 mm	≥54	65	Meets
2	Asphalt Specific Gravity	SNI 2441-2011	gram	≥1	1.21	Meets
3	Asphalt Flash Point	SNI 2433-2011	°C	≥ 230	339	Meets
4	Asphalt Softening Point	SNI 2432-2011	°C	≥54	62	Meets

As shown in Table 4, all tested materials satisfy the requirements of the General Specifications of Bina Marga (Direktorat Jenderal Bina, 2021). This indicates that the selected aggregates, asphalt binder, and filler materials possess adequate physical and mechanical properties for porous asphalt applications. No material exhibited values outside the allowable limits, confirming that the mixture components were suitable for further experimental stages.

After the suitability of the materials had been confirmed, the mixture design process was continued by determining the Optimum Asphalt Content (OAC). In this study, the OAC was established using three key parameters, namely Cantabro Loss (CL), Void in Mix (VIM), and Asphalt Flow Down (AFD), in accordance with the criteria of the Australian Asphalt Pavement Association (AAPA, 2004). Since porous asphalt requires not only sufficient strength but also adequate void structure and resistance to draindown, the use of these three parameters provides a more representative basis for identifying the optimum binder content.

Table 5. Aggregate Gradation of Porous Asphalt Mixture

LIMESTONE FILLER COMPOSITION 1%	
Aggregate Material	**Percentage**
Fraction 0-5 mm	5%
Fraction 5-10	14%
Fraction 10-15	80%
Limestone Filler	1%
Total	**100%**
LIMESTONE FILLER COMPOSITION 0.3% : 0.7% COTTON FABRIC ASH FILLER	
Aggregate Material	**Percentage**
Fraction 0-5 mm	5%
Fraction 5-10	14%
Fraction 10-15	80%
Limestone Filler	0.3%
Cotton Fabric Ash Filler	0.7%
Total	**100%**
LIMESTONE FILLER COMPOSITION 0.5% : 0.5% COTTON FABRIC ASH FILLER	
Aggregate Material	**Percentage**
Fraction 0-5 mm	5%
Fraction 5-10	14%
Fraction 10-15	80%
Limestone Filler	0.5%
Cotton Fabric Ash Filler	0.5%
Total	**100%**
LIMESTONE FILLER COMPOSITION 0.7% : 0.3% COTTON FABRIC ASH FILLER	
Aggregate Material	**Percentage**
Fraction 0-5 mm	5%
Fraction 5-10	14%
Fraction 10-15	80%
Limestone Filler	0.7%
Cotton Fabric Ash Filler	0.3%
Total	**100%**
COTTON FABRIC ASH FILLER COMPOSITION 1%	
Aggregate Material	**Percentage**
Fraction 0-5 mm	5%
Fraction 5-10	14%
Fraction 10-15	80%
Cotton Fabric Ash Filler	1%
Total	**100%**

Table 5 presents the aggregate gradation used in the porous asphalt mixture. The gradation is dominated by coarse aggregate fractions with limited fine aggregate content, which is consistent with the characteristics of porous asphalt. This composition is essential for forming interconnected voids that allow water to pass through the mixture. The selected gradation therefore supports the intended hydraulic function of porous asphalt while maintaining the aggregate skeleton required for structural stability.

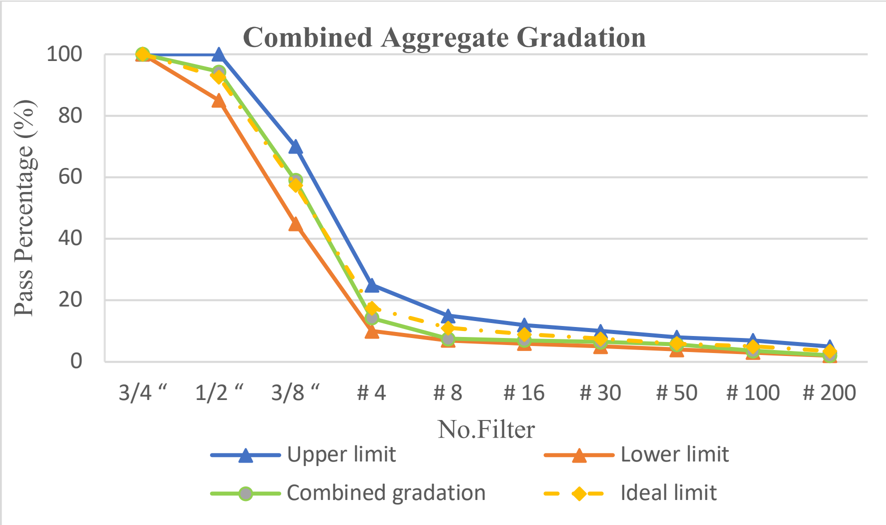

Figure 1. Aggregate Gradation with Limestone Filler for OAC Determination

As illustrated in Figure 1**,** the gradation curve of the mixture using limestone filler follows the specified gradation envelope. The curve indicates that the aggregate composition was arranged to maintain an open-graded structure, thereby supporting the formation of a permeable mixture. This figure also confirms that the limestone filler-based mixture was appropriate for the preliminary determination of OAC.

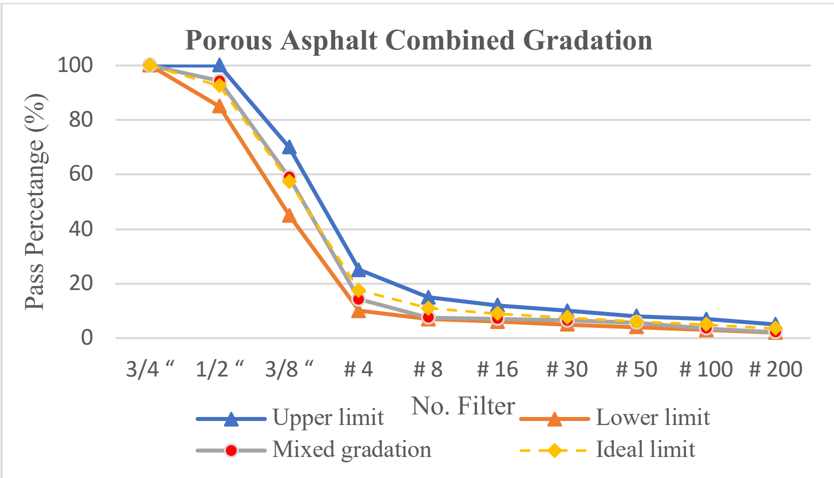

Figure 2. Aggregate Gradation with Cotton Cloth Ash Filler for OAC Determination

Similarly, Figure 2 shows the gradation curve of the mixture incorporating cotton cloth ash filler. The curve remains within the acceptable gradation range, indicating that the substitution of filler material did not significantly disturb the overall aggregate grading. This suggests that cotton cloth ash can be incorporated into the mixture without compromising the aggregate framework required for porous asphalt.

Following the gradation analysis, the midpoint values (Pb) for asphalt content variation were calculated in order to determine the trial asphalt contents used in the OAC evaluation.

Table 6. Midpoint Value (Pb) of Asphalt Content Variations

Parameter	Value
Coarse Aggregate (CA)	80%
Medium Aggregate (MA)	14%
Fine Aggregate (FA)	5%
Filler (FF)	1%
Constant (K)	1%
Midpoint Value (Pb)	4.86%
Percentage (%)	4.86%
Rounded Value	5%

As presented in Table 6, the midpoint values provide the basis for selecting the asphalt content variations used in the experimental program. These values were obtained from the aggregate composition and filler proportion, allowing the determination of representative asphalt content levels for testing. The use of Pb values ensures that the selected trial binder contents are systematically derived rather than arbitrarily assigned.

Based on the combined evaluation of CL, VIM, and AFD, the Optimum Asphalt Content was found to be approximately 4.80%**.** This result indicates that the selected binder content was sufficient to maintain particle cohesion while preserving the air-void structure required for porous asphalt functionality. Several important trends can be identified from this first stage. First, all constituent materials met the technical specifications, indicating that the mixture design was based on acceptable raw materials. Second, the aggregate gradation was dominated by coarse fractions, which is appropriate for the formation of interconnected voids. Third, the calculated OAC falls within a practical range for porous asphalt mixtures. Fourth, the use of CL, VIM, and AFD as combined criteria provided a stable and technically sound basis for selecting the optimum asphalt content. Overall, these findings confirm that the selected materials and mixture design were suitable for further evaluation of mechanical and hydraulic performance.

Marshall Characteristics of Porous Asphalt Mixtures

After determining the Optimum Asphalt Content, Marshall testing was performed to evaluate the mechanical performance of porous asphalt mixtures at different asphalt content levels, namely 4%, 4.5%, 5%, 5.5%, and 6%. The evaluated parameters included stability, flow, Marshall Quotient (MQ), and Void in Mix (VIM). These parameters were used to assess the load-bearing capacity, deformation behavior, stiffness, and volumetric characteristics of the mixtures.

Table 7. Marshall Characteristics Requirements Based on AAPA (2004)

Parameter	Specification	Variations in asphalt content				
		4.0%	**4.5%**	**5.0%**	**5.5%**	**6.0%**
Void in Mix (VIM), %	18–25	25.25	20.03	18.02	12.31	8.14
Marshall Stability, kg	≥ 500	784	820	832	808	796
Flow, mm	2–6	1.7	1.8	2.0	1.9	1.8
Marshall Quotient (MQ), kg/mm	≥ 400	404	468	530	514	448
Number of Strikes	50 times on each side (top and bottom)					

Table 7 presents the reference requirements for Marshall characteristics according to AAPA (2004). These criteria were used to determine whether the tested mixtures satisfied the minimum mechanical performance expected from porous asphalt. The table serves as the benchmark for evaluating the stability, flow, MQ, and VIM values obtained in this study.

The Marshall test results indicate that at 4% asphalt content, the mixture produced an average stability of 784 kg**,** a flow of 1.7 mm, an MQ of 404 kg/mm, and a VIM of 25.25%**.** When the asphalt content increased to 4.5%**,** the stability rose to 820 kg, the flow to 1.8 mm, the MQ to 468 kg/mm**,** and the VIM decreased to 20.03%**.** The highest mechanical performance was observed at 5% asphalt content, where the average stability reached 832 kg and the MQ reached 530 kg/mm, while the VIM was 18.02%**.** However, as the asphalt content increased further to 5.5% and 6%**,** the stability decreased slightly to 808 kg and 796 kg, respectively, while the VIM declined more sharply to 12.31% and 8.14%**.**

These data reveal several clear patterns. First, the addition of asphalt improved stability and stiffness up to an optimum point, after which both parameters began to decline. This indicates that a moderate increase in binder content enhances particle bonding, but excessive binder reduces the structural efficiency of the aggregate skeleton. Second, VIM decreased consistently as the asphalt content increased, showing that the additional binder progressively filled the available voids within the mixture. Third, MQ followed the same general trend as stability, confirming that the stiffness of the mixture was highest near the optimum asphalt content. Fourth, the flow values remained relatively stable across all variations, suggesting that the deformation response was less sensitive to asphalt content than the stability and void characteristics.

From an engineering perspective, these findings demonstrate that asphalt content has a decisive influence on the mechanical behavior of porous asphalt mixtures. The optimum mechanical performance was observed in the range of 4.5% to 5% asphalt content, where the mixtures achieved high stability and MQ values without excessive reduction in air voids. This result implies that the porous asphalt mixture requires a carefully controlled binder content to maintain both structural resistance and the internal void structure necessary for drainage.

Permeability Performance of Porous Asphalt Mixtures

In addition to mechanical evaluation, permeability testing was conducted to assess the hydraulic performance of the porous asphalt mixtures. This test was intended to determine the ability of each mixture to allow water to pass through the interconnected void structure. Since porous asphalt is primarily designed to improve surface drainage, permeability is one of the most important functional parameters in the present study.

Table 8. Permeability Test Results of Porous Asphalt Mixtures

Testing with 1% Filler		Unit	Asphalt Content Variation (%)				
			4%	4.5%	5%	5.5%	6%
Water Volume		liter	1	1	1	1	1
Briquette Height		cm	7.2	7.6	7.4	7.1	7.6
Time		detik	37.29	33.01	26.07	21.26	19.03
Permeabilty	$K = 2.3\ [d/t]\ \log\ [(5+d)/d]$	liter/detik	0.10	0.12	0.15	0.18	0.20

As presented in Table 8, the permeability values increased as the asphalt content increased. At 4% asphalt content, the permeability value was 0.10 liter/second. This increased to 0.12 liter/second at 4.5%, 0.15 liter/second at 5%, 0.18 liter/second **at** 5.5%, and reached the highest value of 0.20 liter/second at 6% asphalt content. These results indicate that each increase in asphalt content was accompanied by a corresponding increase in water flow capacity through the mixture.

Several trends can be identified from the permeability data. First, the increase in permeability was consistent across all asphalt content variations, indicating a systematic relationship between binder content and hydraulic performance. Second, the rate of increase was gradual rather than abrupt, suggesting that the internal structure of the mixture changed progressively with asphalt content. Third, the highest permeability was observed at the highest asphalt content level. Fourth, the lowest permeability occurred at the lowest asphalt content, indicating that lower binder content was associated with a reduced ability to pass water.

These findings suggest that asphalt content affects not only the mechanical performance of porous asphalt but also its internal flow characteristics. A higher asphalt content may improve aggregate coating and internal bonding, thereby contributing to a more uniform arrangement of void channels that facilitate water movement. However, when these results are considered together with the Marshall characteristics, it becomes clear that increased permeability alone cannot be used to determine the optimum mixture. Although the highest permeability was obtained at 6% asphalt content**,** this variation also exhibited reduced stability and a substantial decrease in VIM. Therefore, the optimum design of porous asphalt must be based on a balance between hydraulic functionality and structural performance, rather than on permeability alone.

Overall, the permeability results confirm that the porous asphalt mixtures developed in this study have good drainage capability. Nevertheless, the final selection of the most appropriate mixture must consider both permeability and Marshall performance in order to achieve a technically balanced and functional porous asphalt design.

DISCUSSION

This study evaluated the performance of porous asphalt mixtures incorporating cotton cloth ash as a substitute filler through material verification, optimum asphalt content determination, Marshall characteristics, and permeability performance. The results showed that all constituent materials met the applicable specifications, the Optimum Asphalt Content (OAC) was identified at approximately 4.80%, the best Marshall performance was observed in the asphalt content range of 4.5%–5%, and permeability increased progressively as the asphalt content increased. These findings indicate that the best porous asphalt performance cannot be determined from a single parameter alone, but from the balance between stability, void structure, and hydraulic functionality, which is consistent with the general design principle of porous asphalt mixtures (Chen & Yang, 2020).

From an engineering perspective, the relationship between asphalt content and Marshall performance can be explained by the role of binder in controlling aggregate adhesion and internal structural integrity. At lower asphalt content, the binder is not sufficient to fully coat the aggregate surfaces, resulting in weaker cohesion and lower stability. As the asphalt content increases, adhesion between aggregate particles improves, which explains the increase in stability and Marshall Quotient observed up to the optimum range. However, once the binder content exceeds this range, excess asphalt begins to occupy the voids and weaken the effectiveness of the aggregate skeleton, thereby reducing structural efficiency. This behavior aligns with the established understanding that porous asphalt performance depends on balancing binder retention, aggregate interlock, and void preservation (Chen & Yang, 2020; Huang et al., 2022).

The permeability trend obtained in this study also requires careful interpretation. The results showed that permeability increased from 0.10 liter/second at 4% asphalt content to 0.20 liter/second at 6%. In porous asphalt, water flow is influenced not only by the total volume of air voids but also by the continuity and connectivity of the internal flow channels. This suggests that the increase in asphalt content may have contributed to a more uniform internal arrangement of the aggregate structure and improved flow-path continuity, even though the measured VIM decreased. In other words, the mixture structure may have become more hydraulically connected despite the reduction in total air voids. This interpretation is consistent with recent studies emphasizing that the drainage performance of porous materials depends strongly on internal void structure and connectivity rather than on volumetric indicators alone.

When compared with previous studies, the present findings generally agree with the established behavior of open-graded asphalt mixtures. Porous asphalt is widely recognized for its ability to remove water from the pavement surface, but it is also known to be vulnerable to ravelling, moisture damage, and durability loss if the binder content and mixture structure are not properly controlled (Chen & Yang, 2020). Similarly, Huang reported that the durability of porous asphalt is closely related to adhesion performance and resistance to particle loss under cyclic impact (Huang et al., 2022). In the present study, the optimum mechanical performance at 4.5%–5% asphalt content confirms that a moderate binder content is necessary to strengthen cohesion without excessively reducing the porous structure. Therefore, the findings of this study are in line with previous porous asphalt research, while also extending the discussion to the use of textile-derived ash as filler (Chen & Yang, 2020; Huang et al., 2022). The novelty of this study lies in the use of cotton cloth ash as a substitute filler in porous asphalt mixtures. Previous literature has shown that fibres in asphalt mixtures commonly act as stabilizers to reduce draindown and as reinforcing additives to improve mechanical performance (Guo et al., 2023). However, most of these studies focus on textile-derived materials in fibrous form rather than in ash form. This distinction is important because filler materials interact with the asphalt mastic differently from fibers and may affect stiffness, durability, and volumetric behavior through their particle characteristics and chemical composition. Reviews on waste fillers in asphalt mixtures have shown that alternative fillers can provide acceptable engineering performance while contributing to sustainability when their properties are properly controlled (Guo et al., 2023; Jwaida et al., 2024). In this context, the present study shows that cotton cloth ash can be introduced into porous asphalt without disrupting the gradation framework and while still allowing the mixture to achieve acceptable mechanical and hydraulic behavior.

The broader meaning of these results is that the design of porous asphalt mixtures should be treated as a multi-criteria optimization problem. A mixture with the highest permeability is not necessarily the best mixture if its mechanical resistance declines, and a mixture with the highest stability is not automatically optimal if it sacrifices the void structure required for drainage. The present results demonstrate that the most appropriate design is located in the intermediate range, where both structural resistance and hydraulic function remain acceptable. This reinforces the view that porous asphalt performance must always be evaluated through the combined analysis of Marshall characteristics, void content, and permeability rather than through a single design indicator (Chen & Yang, 2020). From a sustainability perspective, the incorporation of cotton cloth ash as filler also offers practical value. The reuse of waste-derived materials in asphalt mixtures is increasingly recognized as an important strategy for reducing environmental burden and supporting circular material use in construction. Recent reviews indicate that waste fillers such as ash-based and recycled materials can contribute to both acceptable pavement performance and improved sustainability outcomes when they are properly characterized and proportioned (Jwaida et al., 2024). Therefore, the present study contributes not only to porous asphalt mixture design, but also to sustainable pavement engineering by demonstrating a potential utilization pathway for textile-derived waste.

Nevertheless, several limitations should be acknowledged. Although higher asphalt content improved permeability in this study, it was also associated with lower stability and a substantial decline in VIM at the higher binder levels. This means that a design focused solely on drainage could lead to a mechanically less efficient mixture. In addition, this research was conducted under laboratory conditions and did not yet evaluate long-term performance aspects such as clogging, environmental aging, repeated traffic loading, or moisture-related degradation in field conditions. Previous literature has shown that these factors can significantly influence the long-term performance of porous asphalt and should therefore be examined in future work (Chen & Yang, 2020; Huang et al., 2022)

Based on these findings, several practical implications can be proposed. First, the design of porous asphalt mixtures should adopt a performance-based approach that simultaneously considers Marshall properties, air-void structure, and permeability. Second, cotton cloth ash may be considered a feasible alternative filler, particularly in areas with abundant textile waste. Third, further studies are needed to evaluate the long-term durability, clogging resistance, and field performance of mixtures containing cotton cloth ash under real service conditions. Finally, pavement engineers and infrastructure planners should consider waste-based filler utilization as part of sustainable pavement development strategies, provided that both laboratory and field evaluations confirm consistent performance (Jwaida et al., 2024).

CONCLUSION

This study demonstrates that the performance of porous asphalt mixtures containing cotton cloth ash filler is governed by the balance between mechanical characteristics and hydraulic functionality. The main finding is that the Optimum Asphalt Content (OAC) was identified at approximately 4.80%, while the most favorable mechanical performance was observed in the asphalt content range of 4.5% to 5%. At 5% asphalt content, the mixture achieved the highest Marshall stability (832 kg) and Marshall Quotient (530 kg/mm), with a VIM value of 18.02%, indicating a balanced structural condition. In contrast, permeability increased progressively from 0.10 liter/second at 4% asphalt content to 0.20 liter/second at 6%, showing that higher asphalt content improved water flow capacity but did not necessarily provide the best overall mixture performance. Therefore, the study confirms that the optimum design of porous asphalt cannot be determined from permeability or strength alone, but from the simultaneous consideration of VIM, stability, flow, MQ, CL, AFD, and permeability.

The scientific contribution of this research lies in the application of cotton cloth ash as an alternative filler material in porous asphalt mixtures. While previous studies have largely focused on fibers or conventional mineral fillers, this study provides empirical evidence that textile-derived ash can be incorporated into porous asphalt without compromising the feasibility of the mixture design. The study also contributes practical data on the interaction between asphalt content variation and key porous asphalt parameters under the AAPA (2004) framework. In this way, the research expands the understanding of sustainable porous asphalt design by introducing cotton cloth ash as a potential waste-based filler for pavement engineering applications.

This study, however, has several limitations. The experimental program was conducted under laboratory conditions and was limited to the evaluation of permeability, Marshall characteristics, and OAC-related parameters. Long-term aspects such as clogging resistance, field durability, rutting performance, aging behavior, and moisture susceptibility under real traffic and environmental conditions were not examined. In addition, the study focused on a limited range of asphalt content and filler substitution conditions. Therefore, future research is recommended to investigate the long-term field performance of porous asphalt mixtures containing cotton cloth ash, including durability under cyclic loading, environmental aging, and drainage efficiency over time, in order to provide a more comprehensive basis for practical implementation.

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