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Research Article

Statistical models for porous asphalt mixtures containing pulverized surface dressed pavement material/low-density polyethylene waste

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Abstract

Porous asphalt (PA) mixtures typically contain a high proportion of coarse aggregates with minimal fine aggregates, along with a binder that creates ample space for water drainage. Since road construction consumes large quantities of aggregates, recycling and reusing materials have become common practices. This study focuses on developing PA by partially replacing traditional aggregates with pulverized surface-dressed pavement material (PSM) and modifying bitumen with low-density polyethylene (LDPE). The mixtures were produced using 60/70 penetration grade bitumen modified with 2%, 4%, and 6% LDPE waste and 20%, 40%, 60%, and 80% PSM. Adding LDPE waste to the bitumen altered key properties, such as the softening point, penetration, flashpoint, and ductility, resulting in a stiffer binder. Replacing aggregates with PSM reduced both stability and flow, leading to a lower Marshall quotient. Flow values for all trial mixes did not meet AAPA (2004) standards, while stability values slightly decreased as LDPE content increased from 2% to 6%. Despite this, all samples met the AAPA (2004) stability standard. The sample containing 2% LDPE and no PSM exhibited the highest Marshall quotient. Linear regression models were developed from experimental data to highlight the relationships between the measured responses and the variables. These polynomial equations demonstrated a strong correlation, indicated by high coefficients of determination. The study introduces an innovative approach by incorporating PSM and LDPE, largely unexplored in PA production, especially in Nigeria. The major societal benefits include reducing environmental pollution through plastic waste reuse, conserving natural aggregates, and promoting cost-effective construction practices. By advancing the use of recycled materials, this research supports sustainable infrastructure development while maintaining compliance with industry standards.

1. Introduction

Porous asphalt (PA) is an innovative pavement technology widely applied across the globe. Designed as a specialized wearing course, it improves road safety, especially under wet conditions. The permeable friction layer in PA rapidly drains water from the surface, offering numerous safety, economic, and environmental benefits [1,2]. European countries extensively use PA to enhance driving quality, visibility during wet weather, and reduce road traffic noise [3].

Structurally, PA is an open-graded asphalt mixture composed of coarse aggregates, minimal fine aggregates, binder, and high air voids [4]. Its high content of coarse aggregates creates a porous

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structure with 25%-30% voids. This porosity allows water from rain and snow to drain effectively from the road surface, improving slip resistance and reducing braking distances [5].

PA pavement offers significant advantages over traditional asphalt pavement, particularly in terms of drainage, noise reduction, skid resistance, and other functional properties. To enhance and expand the capabilities of road pavements, PA pavement has become a key area of research in highway engineering [6]. The most notable feature of PA is its high air void content exceeding 20% compared to the 3-6% air voids found in traditional asphalt pavements [5]. This high porosity enables rainwater to infiltrate the road surface and drain through interconnected pores to the road edges. However, PA mixtures also have some drawbacks. These include aging, stripping, raveling, drain down, reduced porosity over time, higher maintenance requirements, and a shorter service life. Addressing these issues is important for the effective use of porous asphalt.

Studies suggest that improvements in PA can be made by enhancing the properties and gradation of aggregates, modifying bituminous binders, and reinforcing the mixture with fibers [7]. Ashour investigated the stability and permeability of PA and provided reliable results on both aspects [8]. The study focused on optimizing aggregate mix ratios to achieve the desired permeability while maintaining the necessary stability. The findings showed that the tested samples exhibited excellent permeability, highlighting the effectiveness of these adjustments. Mayuni et al. evaluated PA mixtures by varying bitumen content, using a specific type of aggregate native to the West Kalimantan region of Indonesia [9]. The structural performance of the PA mixes was assessed using Marshall stability and Cantabro tests, while the functional performance was evaluated through an analysis of volumetric properties. This comprehensive approach allowed for an in-depth understanding of how bitumen content and aggregate properties affect the overall performance of porous asphalt.

The improvement of PA quality through the use of polymer-modified asphalt, other additives, and coarse aggregates has been widely studied [10,11,12]. The durability of PA mixtures is typically evaluated based on their resistance to traffic impact, abrasion, and aggregate stripping, with the Cantabro test being a common method for measuring these properties [13]. Additionally, the Marshall stability test is frequently used to determine the stability of compacted PA mixes, ensuring they can withstand loads and maintain structural integrity. In a study exploring the mechanical characteristics of PA pavement, the influence of polymer modifications and aggregate compositions was examined. The research revealed that mixtures containing conventional bitumen failed to meet the Cantabro loss test criteria of a maximum 20% loss. However, polymer-modified asphalt mixtures demonstrated significantly superior performance in terms of permeability, Cantabro loss, and the ratio of indirect tensile strength, highlighting the impact of polymer modifications on improving the essential mechanical properties of PA [14]. Gupta et al. evaluated bitumen modified with high vinyl content SBS polymer. PA mixtures prepared with 4.5% polymer-modified bitumen exhibited higher elasticity, better fatigue resistance, and improved rutting behavior [7]. Ma et al. explored additives like SBS-modified bitumen, hydrated lime, and fibers. They found that hydrated lime improved moisture stability, while fibers enhanced durability and low-temperature cracking resistance of PA mixtures [15]. Zhang et al. assessed four fiber types (lignin, polyester, basalt, polyacrylonitrile) and their effects on PA. Fiber modifications improved drainage, rutting resistance, and fatigue life, with polyester fiber providing the best overall performance [16]. Sarsam compared PA and stone mastic asphalt under repeated tensile stresses. While stone mastic asphalt showed higher tensile strength ratios, PA with carbon fiber modifications had better resistance to moisture damage [17]. Ranieri et al. investigated Warm Mix Asphalt (WMA) technologies for PA in cold climates. Results showed that PA could be laid at temperatures 20°C lower without significant performance loss, though further study is recommended [18].

Road construction and rehabilitation consume large quantities of virgin materials, resulting in high costs, particularly for highways. Surface-dressed roads, typically used for light traffic, consist of aged chippings embedded in bitumen. These reclaimed materials, primarily made up of coarse aggregates and bitumen, may be suitable for open-graded mixes [19]. Developing porous asphalt by partially replacing traditional aggregates with pulverized surface-dressed pavement material (PSM) and modifying bitumen with low-density polyethylene (LDPE) presents a promising approach to enhancing pavement performance and sustainability [20]. Incorporating recycled materials like PSM into porous asphalt mixtures can improve environmental sustainability and resource efficiency. Reclaimed asphalt pavement (RAP), a similar recycled material, has been successfully used in various pavement applications, demonstrating that recycled aggregates can maintain or even enhance pavement performance when properly processed and integrated. Modifying bitumen with LDPE enhances corrosion resistance and the mechanical properties, offers low moisture permeability of asphalt mixtures [21]. LDPE is generally used in the form of films as well as in the production of bags for food and other products [22]. Studies have shown that adding LDPE to asphalt binders improves resistance to deformation and aging, leading to longer-lasting pavements [23]. Combining PSM as a partial aggregate replacement with LDPE-modified bitumen in porous asphalt mixtures could synergistically enhance pavement performance. The recycled aggregates contribute to sustainability and cost-effectiveness, while the polymer-modified binder improves mechanical properties and durability. This integrated approach aligns with sustainable construction practices by reducing waste and conserving natural resources [24].

In Nigeria, many surface-dressed roads are being upgraded to dense asphalt mixes. Reclaiming these materials presents a valuable alternative, especially for porous asphalt, which requires a significant amount of coarse aggregates. Nigeria generates approximately 2.5 million tons of plastic waste annually, placing it ninth globally among contributors to plastic pollution [25,26]. Unfortunately, most of this plastic waste remains unrecycled. The use of Recycled Surface-dressed Pavement (RSP) and LDPE in hot mix asphalt has similarities to studies incorporating recycled asphalt pavement (RAP) and LDPE in porous asphalt. However, the use of RSP and LDPE in developing PA remains largely unexplored, particularly in Nigeria. Globally, Nigeria ranks 28th in publications on porous asphalt, with only three studies published between 1974 and 2022 [9]. Although many experimental works have been carried out to determine the properties of PA containing recyclable materials like LDPE and PSM, yet to the best of our knowledge, no models have been introduced to predict the properties of such material. Therefore, the aim of this study is to explore the potential of utilizing PSM and LDPE in the development of porous asphalt, focusing on their effects on the performance characteristics of the mix using statistical models.

2. Materials

2.1. Material Characterization

For the purpose of this research, the following materials were used:

- *Aggregates:* Two types of aggregates were used in this experimental study, which include:

Pulverized Surface-Dressed Pavement Material (PSM): This material was obtained from an old surface-dressed road in Bida, Niger State. It was then pulverized into smaller sizes, as shown in Fig. 1. RAP has been used in several studies in different percentages ranging from 5 to 100% in PA mixtures with varying levels of success [27,28]. The material used in this study is quite similar to RAP. They are pulverized surface dressed pavements materials that are aged with aggregate chippings embedded in bitumen physically [19]. Since bulk of this type of treatment is coarse aggregates and bitumen, they might be good for open graded mixes. For this study 20%, 40%, 60%, 80% of PSM was replaced with conventional aggregate by weight.

Virgin Aggregates: This crushed granite was obtained from local vendors in Minna, Niger State.

- *Bitumen 60/70:* The bitumen was obtained from Dantata Construction Company in Abuja, Nigeria.

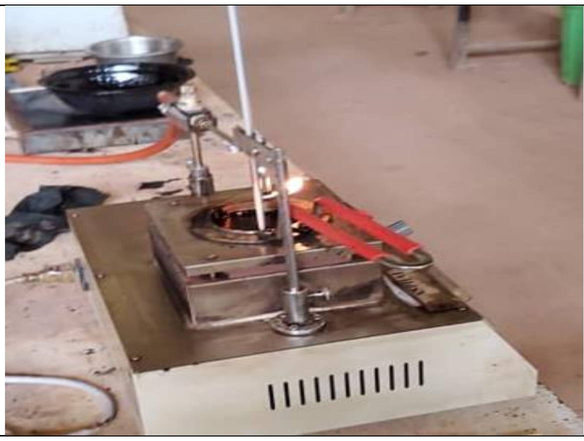
- *Low-Density Polyethylene Bags:* The LDPE was obtained from Sani Basket Plastic Company in Minna, Niger State (Fig. 2). The LDPE used is colorless and has a density of 0.92 g/cm^3 and a melting temperature between 110–160°C. Many studies have used LDPE in asphalt mixtures in various percentages ranging from 1 to 15% [29-32]. The optimum binder content used by them was 5%. Optimum Binder Content (OBC) refers to the percentage of binder in the mix that optimizes performance parameters such as stability, flow, and durability while meeting the required standards. This study uses 2%, 4%, and 6% LDPE as a modifier for bitumen at an OBC of 5%. This is because PSM is already coated with aged bitumen; thus, higher percentages of LDPE and OBC were not used, as higher percentages might affect the stability of the mixtures. At more than 6% LDPE, the stability of the mix decreases [32].

Fig. 1. Pulverized surface dressed pavement material

Fig. 2. Shredded LDPE

Table 1. Bitumen tests

No	Test Standards	Image of the tests
1	Penetration test ASTM D5 [36]	
2	Softening point test ASTM D36 EN 1427 [37]	

3	Specific gravity ASTM D113 [40]	-
4	Flash point ASTM D92 [39]	
5	Ductility (ASTM D70) [38]	

Sieve Analysis [33], specific gravity test [34], water absorption [35], Flakiness and Elongation tests were carried out on both virgin aggregates and PSM aggregates. The following tests on bitumen and binder (bitumen + LDPE) were conducted to characterize the binder. For porous asphalt, an asphalt binder with a penetration value higher than that of conventional asphalt types is used. Additional properties and details of the procedures can be found in the relevant standards, as shown in Table 1.

3. Methods

This study primarily focuses on the development of PA using readily available materials, such as PS) and bitumen modified with LDPE. The experimental procedure encompasses the following steps: material characterization, mix design, sample preparation, and testing of PA properties. Material characterization includes evaluating aggregates (sieve analysis, specific gravity, water absorption, flakiness, and elongation) and bitumen (penetration, softening point, flashpoint, and ductility). The mix design involves creating PA mixtures with varying proportions of PSM (20%, 40%, 60%, 80%) and LDPE (2%, 4%, 6%) based on ASTM D704. The prepared samples undergo mechanical, hydraulic, and durability testing, such as stability, flow, permeability, and Cantabro loss evaluations. Statistical modeling techniques are applied to analyze the relationships between the variables and assess compliance with industry standards. An experimental procedure flowchart has been added and is shown in Fig. 3 to illustrate these steps clearly. The findings from these tests provide insights into the performance of PA mixtures and their suitability for sustainable road construction.

3.1. Mix Design

In order to achieve the set-out objectives virgin aggregates are blended together with PSM aggregates and are both mixed together with the binder with varying percentage of LDPE. Mixing multiple types of aggregates with different gradations is a crucial first step in producing any asphalt mix. The design criteria used are based on ASTM D704. The aggregate gradation, as outlined by NAPA, is presented in Table 2.

Table 2. Porous asphalt aggregate gradation

SN	Sieve Sizes(mm)	Gradation limits (% passing)
1	19	100
2	12.5	85-100

3	9.5	55-75
4	4.75	10-25
5	2.36	5-10
6	0.075	2-4

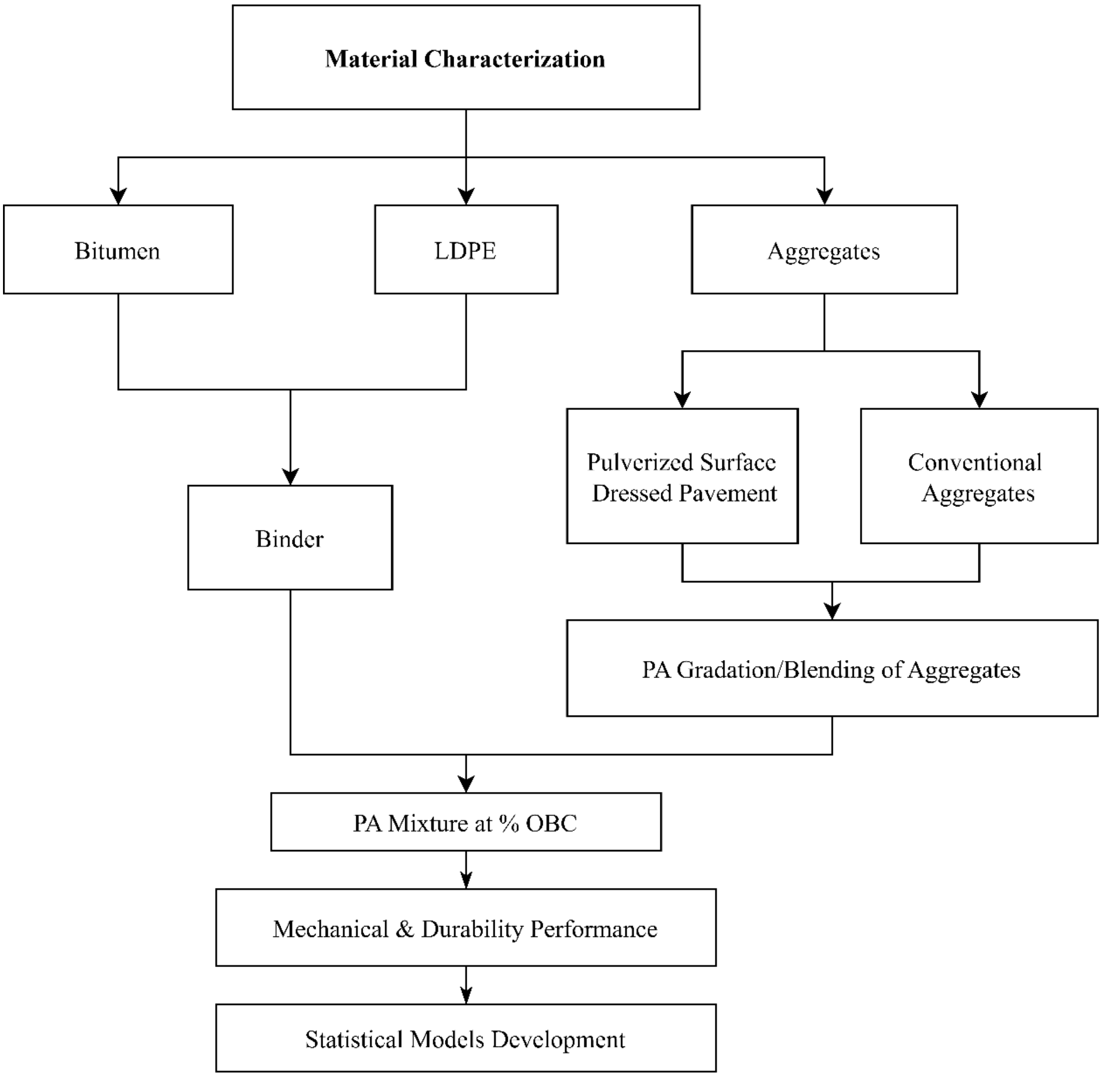


Fig. 3. Experimental procedure flowchart

3.2. Mechanical and Durability Performance

The PA mixtures was produced using a LDPE modified bitumen previously produced from optimum bitumen content of 5% and varying 0%, 2%, 4%, 6%, of LDPE. The binder was now mixed with 1200 g of blended aggregates 20,40,60.80% PSM by weight of conventional aggregates to produce a test sample 63.5±1.27 mm thick. Cylindrical samples of 50 mm diameter and 100 mm height were used for the Marshall hammer test which used 75 blows on each face following the ASTM standards. The porous asphalt mix are then subjected to the following tests presented in Table 3 based on ASTM standards.

The Drain down test was carried out to determine the portion of material which separates itself from the sample as a whole and is placed outside the wire basket during the test. The drained material could be either asphalt binder or a combination of asphalt binder, additives, or fine aggregate. The test was performed on one un compacted sample

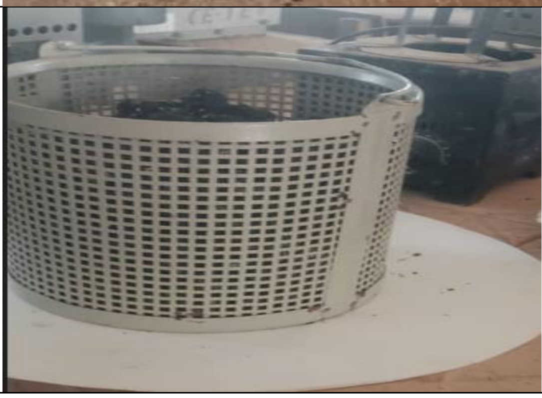
Marshall Properties of the asphalt mix such as stability and flow was carried out on compacted samples and the Cantabro abrasion test was performed based to determine the abrasion loss of porous asphalt samples where the test was performed on un-aged compacted samples for each binder content. Also the permeability of porous asphalt was carried out on the samples. All standards used can be found in Table 3.

3.3 Statistical Modelling

Statistical analysis including correlation analysis, covariance analysis, trend lines, and regression analysis were employed to assess the strength of relationship between the variables. The models were created based on experimental data only to illustrate the relationships between the measured responses and variables and the interactions among the measured responses.

Microsoft Excel package was used for the model development since all the models considered here is one parameter model. This is to allow validation of the models through statistical analysis. The regression was done at 95% confidence interval.

Table 3. Mechanical and durability performance

No	Properties/specification	Image
1	Permeability ASTM D5084 [41]	
2	Particle Loss (Cantabro) (%) Maximum ASTM D7064 [42]	
3	Bitumen Drain down (%), Max ASTM D6390 [43]	

4	Marshal Stability ASTM D6927/AASHTO T 245-13 [44]	

4. Results and Discussion

4.1. Physical Properties of Materials and Mechanical/Durability of the Mix

The results of the physical properties of the virgin and recycled surface-dressed aggregates used in this study are presented in Table 4.

Table 4. Physical properties of Virgin and PSM aggregates

Test	Statistics	Virgin Aggregates	Recycled Surface-dressed Aggregates	Units
Specific gravity	Mean	2.64	2.45	-
	Standard deviation	0.04	0.17	
Water Absorption	Mean	5.04	4.30	%
	Standard deviation	0.96	0.23	
Flakiness	Mean	10	5	%
	Standard deviation	0.14	1.41	
Elongation	Mean	44	15	%
	Standard deviation	0.7	1.12	

From Table 4, the specific gravity of virgin aggregate is higher than that of PSM, as the specific gravity of PSM is typically reduced due to the inclusion of asphalt binder. The water absorption of virgin aggregate is slightly higher, indicating a dense rock with fewer pores. While asphalt binder may expose more pores, the characteristics of the original parent aggregate before coating with bitumen are unknown. The elongation and flakiness indices of both aggregates provide insights into their quality and suitability for road construction, and both meet the NAPA 2003 general specifications.

Table 5 presents the percentage passing of the aggregate blends comprising virgin aggregates (VA) and PSM aggregates. It illustrates the different blends of virgin aggregates and PSM in varying proportions and their gradation for porous asphalt. These gradations meet the standards specified by NAPA 2003.

Table 5. Percentage passing of Virgin and PSM aggregates

Test	Percentage Passing					
	100% PSM	100% VA	80% VA & 20% PSM	60% VA & 40% PSM	40% VA & 60%PSM	20% VA & 80%PSM
20mm	86.96	81.67	81.93	79.25	82.33	84.80
14mm	54.16	70.77	71.43	57.18	57.36	60.03
10mm	26.58	53.67	40.99	34.96	39.45	34.62
6.30mm	13.14	40.23	24.80	21.78	27.66	21.22
5.00mm	9.33	34.83	19.70	18.67	23.78	17.58
Pan						

The physical properties of the bitumen and binder (bitumen + LDPE) are shown in Table 6. All tests were repeated 3 times and the average values and standard deviations are shown in Table 6. The physical properties of the bitumen + LDPE mixture show that as the proportion of LDPE increases, significant changes occur in the material's behavior. The penetration test results reveal a decrease in penetration values from 62 (0% LDPE) to 51 (6% LDPE), indicating that the bitumen becomes stiffer with the addition of LDPE. This increased stiffness enhances the mixture's resistance to deformation under load, making it more suitable for applications requiring high stability. The softening point test shows a clear trend of increased temperature stability, with the softening point rising from 55°C at 0% LDPE to 74.5°C at 6% LDPE. This suggests that the bitumen + LDPE mixture can withstand higher temperatures before softening, which is crucial for pavement performance in hot climates. However, the ductility test results indicate a reduction in flexibility as the LDPE content increases, with ductility dropping from 57 cm at 0% LDPE to 25.67 cm at 6% LDPE. This reduction in ductility means the material becomes more brittle and less capable of elongating without breaking, which could affect its crack resistance under heavy traffic. Furthermore, the flash point improves with the addition of LDPE, increasing from 104°C to 167°C as the LDPE content rises. This higher flash point suggests that the bitumen + LDPE mixture is less prone to ignition at high temperatures, contributing to overall safety during handling and application. The results of the physical properties of the LDPE modified bitumen are quite similar and to the results reported by recent studies [29,30,31,32].

Similarly, the mechanical and durability tests were repeated 3 times and the average values and are shown in Table 7.

Table 6. Physical properties of bitumen and binder (bitumen + LDPE)

Test	Statistics	0% LDPE	2% LDPE	4% LDPE	6% LDPE
Penetration	Mean	62	60	55	51
	Standard deviation	1	1	1	1.41
Softening point test	Mean	55	62.5	69	74.5
	Standard deviation	1.41	0.7	0	0.7
Specific gravity	Mean	1.0845	0.769	0.602	0.59
	Standard deviation	0.04	0.12	0.16	0.16
Flash point	Mean	104	127	149	163
	Standard deviation	2.87	0.82	2.05	10
Ductility	Mean	104	127	149	163
	Standard deviation	2.87	0.82	2.05	10

The Stability values marginally decreases as LDPE content increases from 2 to 6% at 0% PSM, but all the samples meet AAPA standard (> 500 kg) [45]. But as the PSM content increases all stability values (< 400 kg) do not meet this standard. The PSM materials has been coated with bitumen which will increase the bitumen content which will affect the stability of the porous asphalt mix. Flow values for all trial mixes do not meet the standards of 2-6% [45]. Even though a general trend shows that the addition of LDPE and PSM decreases the flow values closer to the standards.

The Cantabro loss shows marginally changes with addition of LDPE. However, as the percentage of RSM increases in the mix, the value exceeds the standards of less than 20%. The drain down value of < 0.3% is desired for porous asphalts. Most of the samples do not meet this standard. Only samples with no PSM materials meets the standards. This is connected with the fact that no fibres were used to prevent the drain down of the bitumen hence high values were recorded. Also because PSM materials are already coated with bitumen, so as the temperature increases, the more bitumen will melt and drain down. The occurrence of binder drain down through the specimen will reduce the permeability of mix. The addition of LDPE and PSM decreases permeability values. Since most agencies do not have standard values for the coefficient of permeability or permeability value It is therefore recommended that the standard values be selected based rainfall intensity of the pavement location in question [46].

Table 7. Mechanical and durability properties of porous asphalt mixtures

SN	PSM (%)	LDPE (%)	Stability (kg)	Flow (mm)	Permeability (m/s)	Drain down (%)	Cantabro (%)
			Mean	Mean	Mean	Mean	Mean
1	0	2	650	9.3	449	0	6.94
2	20	2	370	7.3	413	0.8	8.14
3	40	2	360	7.6	278	5.5	11.42
4	60	2	290	9.9	275	9.4	14.52
5	80	2	285	9.6	222	28.9	14.7
6	0	4	590	9.6	397.5	0	6.72
7	20	4	395	7.8	303.97	0	8.52
8	40	4	380	8.3	283.13	4.7	14.25
9	60	4	395	9.5	300.61	8.5	15.56
10	80	4	295	7.7	293.83	19.2	19.72
11	0	6	640	8.6	235.13	0	6.36
12	20	6	395	8.2	279.4	0	8.92
13	40	6	572	9.7	223.17	0.9	16.37
14	60	6	520	9.5	329.4	5.7	21.52
15	80	6	480	7.9	294.77	14.9	21.9

4.2. Statistical Model Development

Correlation analysis, covariance analysis, trend lines, and regression analysis were employed to develop these models. The models were created based on experimental data to illustrate the relationships between the measured responses and variables and the interactions among the measured responses.

4.2.1 Correlation Analysis

This analysis demonstrates the strength and direction of the relationship between the variables. The values range from -1 to 1, with a value close to 1 indicating a strong relationship, and the sign denoting the direction of the relationship. Tables 8-10 present the relationships for 2%, 4%, and 6% LDPE while varying the content of PSM. The correlation coefficients are generally high, but the strength and direction vary depending on the specific relationship between variables. For instance, as the stability of the mix improves, the flow decreases, leading to a negative correlation. Similarly, the correlation between stability and the Cantabro value is also negative, indicating that as the stability of the mix decreases, the Cantabro value increases, suggesting poorer resistance to wear, tear, and disintegration. Similar trends can be observed in Tables 8 to 10.

Table 8. Correlation analysis for LDPE 2%

Factors	Flow (mm)	Permeability *(10^{-3}m/s)	Drain down test	Cantabro test (%)	Stability (kg)
Flow (mm)	1				
Permeability * (10^{-3}m/s)	-0.99327	1			
Drain down test (%)	0.772308	-0.809254379	1		
Cantabro test (%)	0.97284	-0.954629844	0.794474	1	
Stability (kg)	-0.7998	0.811538002	-0.59368	-0.81971	1

Table 9. Correlation analysis for LDPE 4%

Factors	Permeability* (10^{-3}m/s)	Drain down test (%)	Cantabro test (%)	Stability (kg)	Flow (mm)
Permeability * (10^{-3}m/s)	1				
Drain down test	-0.60055	1			
Cantabro test (%)	-0.76669	0.936227	1		
Stability (kg)	0.861298	-0.89128	-0.98573	1	
Flow (mm)	-0.67103	0.945931	0.950756	-0.91213	1

Table 10. Correlation analysis for LDPE 6%

Factors	Permeability *(10-3m/s)	Drain down test (%)	Cantabro test (%)	Stability (kg)	Flow (mm)
Permeability* (10^{-3}m/s)	1				
Drain down test	-0.8435	1			
Cantabro test (%)	-0.96523	0.773785	1		
Stability (kg)	0.968204	-0.89698	-0.93679	1	
Flow (mm)	-0.98812	0.873321	0.970246	-0.95289	1

4.2.2 Covariance Analysis

The covariance matrix further aids in understanding the direction of linear relationships between variables. Positive values indicate that the variables increase together, suggesting a direct relationship, while negative values signify an inverse relationship, where one variable increases as the other decreases. The results of the covariance analysis are presented in Tables 11 to 13.

Table 11. Covariance analysis for LDPE 2%

Factors	Flow (mm)	Permeability* (10^{-3}m/s)	Drain down test (%)	Cantabro test (%)	Stability (kg)
Flow (mm)	1.1544				
Permeability * (10^{-3}m/s)	-93.536	7681.84			
Drain down test (%)	8.7552	-748.368	111.3256		
Cantabro test (%)	3.33224	-266.7376	26.72352	10.16326	
Stability (kg)	-115.24	9538.6	-840.02	-350.444	17984

Table 12. Covariance analysis for LDPE 4%

Factors	Permeability* (10^{-3}m/s)	Drain down test (%)	Cantabro test (%)	Stability (kg)	Flow (mm)
Permeability* (10^{-3}m/s)	1719.117				
Drain down test	-177.132	50.6056			
Cantabro test (%)	-150.97	31.62988	22.55454		
Stability (kg)	3656.884	-649.26	-479.378	10486	
Flow (mm)	-21.0716	5.0964	3.41972	-70.74	0.5736

Table 13. Covariance analysis for LDPE 6%

Factors	Permeability* (10^{-3}m/s)	Drain down test (%)	Cantabro test (%)	Stability (kg)	Flow (mm)
Permeability *(10^{-3}m/s)	1522.212				
Drain down test(%)	-187.821	32.572			
Cantabro test (%)	-240.317	28.1812	40.72246		
Stability (Kg)	3129.594	-424.12	-495.272	6863.84	
Flow (mm)	-27.3041	3.53	4.38508	-55.912	0.5016

4.2.3 Relationships Between Responses and Proportion of LDPE and PSM

The results illustrated in Figs. 4-8 can be understood by looking at the contrasting characteristics of PSM and LDPE. The PSM tends to be rigid and somewhat brittle, while LDPE is a more flexible, ductile material. When these two materials are combined in pavement mixtures, they produce various effects on the mechanical and functional qualities of the final product. For instance, the decreasing stability seen in Fig.4 can be linked to PSM's rigidity. It seems to weaken the mix's cohesion and binding strength. The more PSM you include, the less stable the pavement becomes. LDPE, though flexible, doesn't quite make up for the cohesion loss caused by PSM particles. On the other hand, Fig. 5 shows that the flow increases as the PSM content rises, suggesting that PSM and LDPE together contribute to a more flexible and deformable mixture. LDPE's elasticity adds to the material's ability to endure deformation, while PSM adds bulk. However, too much PSM can result in too much deformation, making the pavement vulnerable to rutting under heavy loads.

Fig. 6 highlights how the Cantabro loss rises with higher PSM levels, which likely comes from the reduced cohesion and adhesion when more PSM is introduced. The rigid structure of PSM, particularly in large amounts, lowers the pavement's durability, increasing surface wear. This effect is more pronounced when LDPE is not present in sufficient quantities to maintain a flexible and cohesive binder. The rise in drain down (Fig. 7) with higher PSM content suggests that the binder has trouble staying in place. RSP, because of its rigidity and granular nature, separates from the binder, which leads to more binder loss. Although LDPE enhances the mixture's elasticity, it can't stop the binder from draining, especially as PSM content grows.

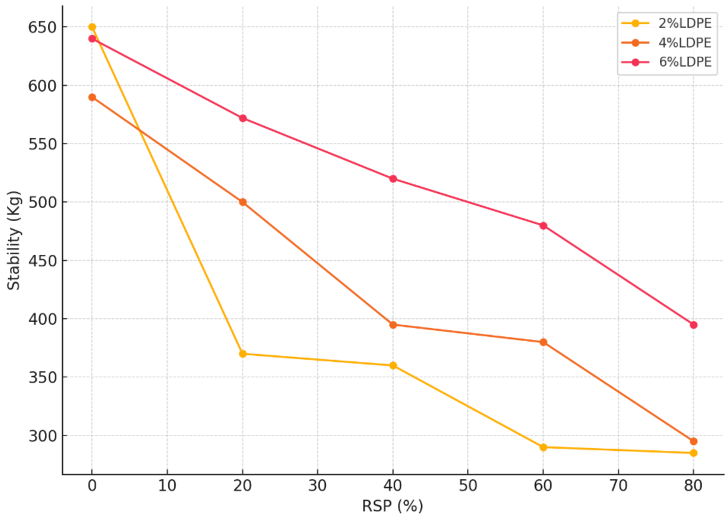


Fig. 4. Stability versus percentage PSM

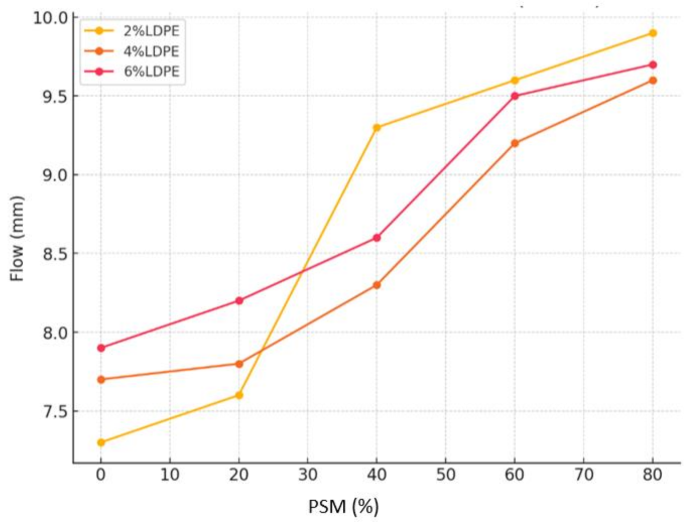


Fig. 5.: Flow versus percentage PSM

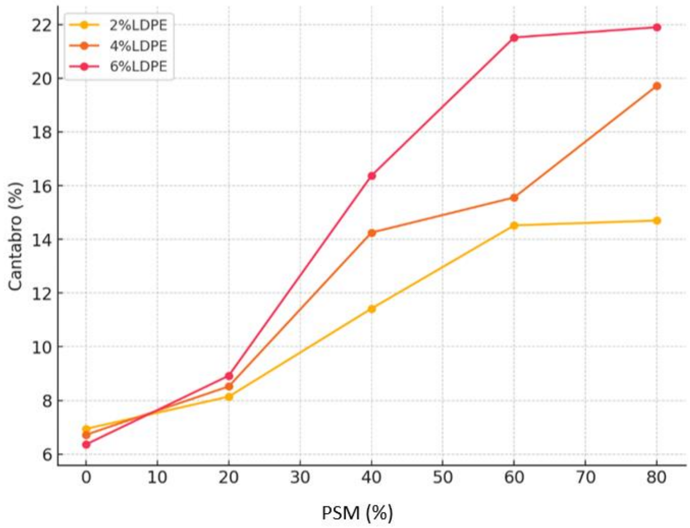


Fig. 6. Cantabro versus percentage PSM

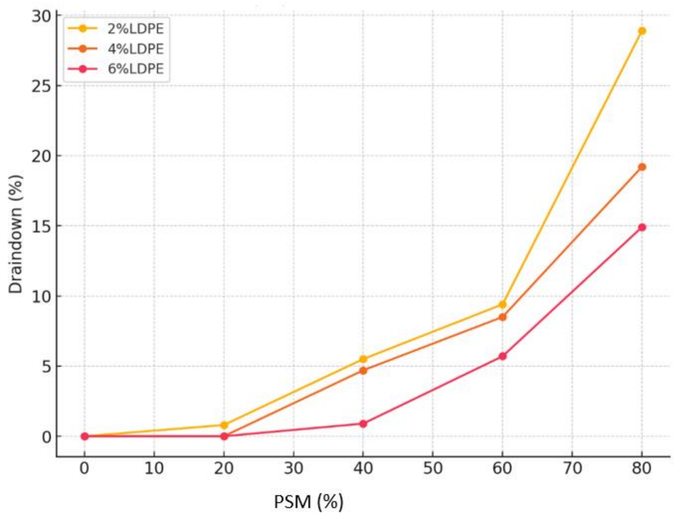


Fig. 7. Drain down versus percentage PSM

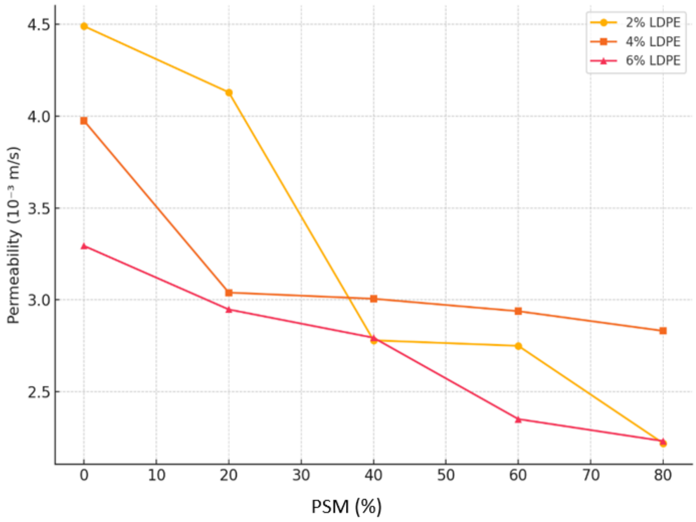


Fig. 8. Permeability versus percentage PSM

Lastly, the decrease in permeability shown in Fig. 8 can be attributed to the increased density and decreased porosity as more PSM is added. The relatively non-porous nature of PSM makes it harder for water to penetrate the mixture. LDPE fills in voids and forms a continuous matrix, further reducing permeability. However, too much PSM might make the pavement overly impermeable, which can cause problems with surface water drainage. In summary, the combination of PSM and LDPE shows a balance between stiffness and flexibility, and the results clearly demonstrate how these materials interact to influence pavement properties like stability, flow, durability, and permeability.

4.2.4 Regression Analysis of the Impact of PSM and LDPE Content on Pavement Properties

The regression analysis conducted on the relationship between pavement properties and the percentage of PSM at varying levels of LDPE content offers valuable insight into how these materials behave. For pavements containing 2% LDPE (Table 14), the results reveal a robust link between RSP content and permeability, with an R-squared value of 0.912, indicating a well-fitting model. This suggests that permeability decreases significantly as RSP increases, a trend further supported by a negative coefficient of -2.96 and a low P-value, which confirms the statistical relevance of the result. However, while stability also diminishes with more RSP, the model for this behavior is weaker, as shown by a lower R-squared of 0.729 and a P-value of 0.065, which suggests less confidence in this connection. Flow, by contrast, shows a strong positive relationship, as indicated by an R-squared of 0.898, meaning that as RSP rises, flow increases. For Cantabro loss, which is a measure of durability, the model demonstrates a strong fit with an R-squared of 0.943, and the positive coefficient points to reduced durability. Drain down also increases moderately as RSP content goes up, reflected by an R-squared of 0.792.

When LDPE content is raised to 4% (Table 15), the analysis suggests stronger correlations. The reduction in permeability with increasing PSM is even more pronounced, with an R-squared of 0.947, and is statistically significant. Similarly, the decrease in stability follows the same downward trend observed at the 2% LDPE level but with a better fit (R-squared of 0.935). Flow rates spike sharply, as seen by a very high R-squared value of 0.979, while Cantabro loss continues to increase, indicating a decline in durability. The drain down also rises significantly as PSM levels increase, with a reliable fit shown by an R-squared of 0.940. For pavements containing 6% LDPE (Table 16), the trends are consistent with the previous two LDPE levels. Permeability further decreases as PSM content rises, supported by a strong model fit (R-squared of 0.946). Stability continues to drop, again, with a very strong model fit (R-squared of 0.974). Flow increases further, with an R-squared of 0.947, while Cantabro loss continues to rise but with slightly less statistical strength than at lower LDPE levels. Drain down also increases, though its statistical significance is weaker.

In conclusion, these findings show clear linear relationships between PSM content and various pavement properties. As PSM content rises, permeability and stability decrease, while flow, Cantabro loss, and drain down increase. The models are reliable based on the high R-squared values, but the strength of statistical significance varies, particularly for Cantabro loss and drain down. These trends underscore the trade-off between incorporating recycled materials for environmental benefits and the associated drawbacks in terms of durability and cohesion, with LDPE offering some resilience but not entirely offsetting the effects of PSM.

Table 14. Regression Statistics for 2% LDPE

Statistics /Relationships	R^2	Adjusted R^2	F	Significance F	P-value		Coefficient	
					Intercept	Variable	Constant	variable
Permeability versus %PSM	0.91	0.88	31.26	0.01	0.0004	0.0112	445.8	-2.96
Stability versus %PSM	0.72	0.63	8.09	0.06	0.004	0.0653	553	-4.05
Flow versus %PSM	0.89	0.86	26.44	0.01	0.0001	0.0142	10.18	-0.036
Cantabro (%) versus %PSM	0.94	0.92	50.39	0.00	0.002	0.005	6.764	0.1095
Drain down (%) versus %PSM	0.79	0.72	11.42	0.04	0.43	0.043	-4.36	0.332

Table 15. Regression Statistics for 4% LDPE

Statistics /Relationships	R^2	Adjusted R^2	F	Significance F	P-value		Coefficient	
					Intercept	Variable	Constant	variable
Permeability versus %PSM	0.94	0.92	35.62	0.026	0.000	0.026	312.71	-0.34
Stability versus %PSM	0.93	0.90	28.76	0.033	0.003	0.033	550	-3.15
Flow versus %PSM	0.97	0.96	92.30	0.010	0.000	0.010	7.15	0.03
Cantabro (%) versus %PSM	0.94	0.92	37.39	0.025	0.065	0.025	5.785	0.17
Drain down (%) versus %PSM	0.93	0.90	31.30	0.030	0.137	0.030	-7.25	0.30

Table 16. Regression Statistics for 6% LDPE

Statistics /Relationships	R^2	Adjusted R^2	F	Significance F	P-value		Coefficient	
					Intercept	Variable	Constant	variable
Permeability versus %PSM	0.94	0.91	35.28	0.02	0.00	0.02	322.88	-1.29
Stability versus %PSM	0.97	0.96	75.0	0.01	0.00	0.01	634.5	-2.85
Flow versus %PSM	0.94	0.92	35.5	0.02	0.00	0.02	7.65	0.02
Cantabro (%) versus %PSM	0.88	0.82	15.1	0.05	0.18	0.05	6.15	0.22
Drain down (%) versus %RSP	0.87	0.81	14.2	0.06	0.19	0.06	-7	0.24

4.3. Failure Modes of Samples

The failure modes of the porous asphalt (PA) samples were carefully assessed during the mechanical and durability testing phases. These observations provide critical insights into the performance of the mixtures under various conditions and offer guidance for optimizing mix design. Samples with higher Pulverized Surface-Dressed Pavement Material (PSM) content exhibited a brittle failure mode, characterized by visible cracks forming under load during the Marshall Stability Test. Conversely, samples with higher Low-Density Polyethylene (LDPE) content demonstrated a ductile failure mode, with significant deformation but delayed cracking. The brittleness in PSM-heavy samples is attributed to the reduced flexibility of aged aggregates. LDPE content enhanced elasticity, counteracting brittleness but requiring optimal proportions for effectiveness. This highlights the trade-off between rigidity and flexibility in PA mix design. Excessive PSM reduces load-bearing capacity, while LDPE improves deformation tolerance. Surface raveling and aggregate dislodgment were observed during the Cantabro Abrasion Test in samples with insufficient binder content. High PSM content exacerbated this effect due to reduced cohesion. The aged and granular nature of PSM decreased binder adhesion, increasing Cantabro loss. Optimized LDPE content mitigated these effects, enhancing resistance to disintegration. Maintaining sufficient binder content and incorporating LDPE is critical for durability under abrasion. During the Permeability Test, clogging and reduced water flow occurred in samples with excessive PSM content, impairing permeability. Balanced LDPE and PSM contents preserved structural integrity and functional porosity. The compacted structure of PSM-heavy samples reduced voids, while LDPE enhanced void space continuity. Proper proportioning of PSM and LDPE is vital to retain permeability, a key functional property of PA.

Binder drainage was prevalent during the Drain Down Test in samples with low LDPE content, resulting in binder separation. This issue was mitigated in samples with higher LDPE content. LDPE increased binder viscosity and adhesion, reducing the likelihood of binder separation during mixing and compaction. Optimal LDPE content ensures uniform binder distribution and minimizes material loss.

Excessive flow and reduced stability were noted in samples with high PSM content, leading to structural instability under load. The rigidity of PSM decreased cohesive strength, while LDPE improved flexibility but required precise optimization. Achieving a balance between stability and flow is essential to prevent deformation or premature cracking. These failure modes underline the importance of balancing PSM and LDPE proportions in PA mix design. Excessive PSM compromises cohesion and stability, while insufficient LDPE limits elasticity and binder performance. By optimizing these components, durable and functional PA mixtures can be developed, meeting both performance and sustainability objectives.

5. Conclusions

From the results of this study, the following conclusions can be drawn:

- Aggregate Standards: The aggregates, including granite and recycled surface-dressed pavement (RSP), were shown to meet porous asphalt (PA) standards. The specific gravity of virgin aggregates was 2.64, slightly higher than RSP (2.45), reflecting their suitability for PA applications.
- Binder Property Enhancement: Adding low-density polyethylene (LDPE) significantly improved binder properties, increasing the softening point from 55°C to 74.5°C and flashpoint from 104°C to 167°C. However, ductility decreased from 57 cm to 25.67 cm, indicating reduced flexibility.
- Porous Asphalt Performance: Porous asphalt mixtures were successfully produced with local materials, incorporating RSP as an aggregate replacement and LDPE as a binder modifier. These mixtures demonstrated sufficient stability and met most industry standards.
- Stability and Permeability Trends: Stability decreased with increasing RSP content, and flow values were inconsistent, indicating room for optimization. Permeability also decreased due to reduced void spaces, impacting water drainage efficiency.
- Sustainability and Hydraulic Benefits: The use of RSP and LDPE reduces reliance on virgin aggregates, providing a cost-effective and environmentally sustainable solution for road construction. Additionally, PA's higher permeability enhances stormwater management and mitigates urban flooding, making it ideal for road shoulders and other applications.
- Societal and Academic Contributions: This research offers practical solutions for managing plastic waste and reclaiming road materials, promoting sustainable infrastructure development. Academically, it fills a gap by introducing statistical models to predict PA performance and provides valuable insights for further studies on sustainable materials in road construction.

6. Limitations and Recommendations

- • *Limitations:* The study primarily focused on laboratory-scale testing, and the performance of porous asphalt mixtures with RSP and LDPE under real-world traffic and environmental conditions was not assessed. Additionally, the flow values of the mixtures require further refinement to meet AAPA (2004) standards.
- • *Recommendations for Future Work:* Future studies should include long-term field performance evaluations under varying traffic loads and environmental conditions. Exploring the use of additional modifiers, such as fibers or alternative polymers, could help optimize the flow properties and overall durability of the mixtures. Research on the environmental impact and lifecycle assessment of these mixtures would also enhance their adoption in sustainable construction practices.

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