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Characterization of Air Voids and Permeability in Porous Asphalt Mixtures with Eggshell Ash as an Eco-Friendly Additive

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Abstract

Recently, there has been a lot of interest in the use of eco-friendly additives in asphalt mixtures in the field of pavement engineering. Such additives have been found to have the potential to enhance pavement performance while also mitigating the environmental impact of road construction. Eggshells are a restaurant waste product that is one of the additives that have been investigated in this study. The research aims to investigate the effect of eggshell ash (EA) on the air voids and permeability of porous asphalt mixtures. Two temperatures, 100°C (EA100) and 200°C (EA200), were used to prepare EA with varying percentages of 2%, 5%, 7%, 10% and 12% by weight of bitumen. The samples were then prepared and compacted by applying 50 blows on each side to measure air voids, and permeability testing was performed in the laboratories. The results indicated that the use of EA had impacted the permeability and air voids of the porous asphalt mixture. The amount of air voids in the mixes had a direct impact on the permeability coefficient, as the value of the permeability coefficient decreased with decreasing air voids. EA can serve as an additive to improve the permeability of asphalt mixtures, which may increase the pavement's durability and longevity. Furthermore, the use of EA has the potential to reduce the environmental impact of the egg industry while improving the sustainability of road construction

1. Introduction

Roadway construction is an essential aspect of global infrastructure development. Among the available pavement materials, asphalt mixture has become the most popular due to its durability, cost-effectiveness, and ease of maintenance [1]. The potential of porous asphalt, a specialized asphalt mixture, to reduce stormwater runoff and improve water quality has garnered significant attention in recent years [2], [3]. With its high void content, porous asphalt permits water to infiltrate through the surface of the pavement, thus replenishing groundwater resources. However, concerns about its durability persist, leading to ongoing research to enhance its performance.

Air voids within porous asphalt mixtures are crucial to their durability [4], [5]. Excessive air voids can allow moisture to penetrate the pavement, resulting in structural deterioration. Inadequate air voids can lead to water accumulation on the surface of the pavement, resulting in hazardous conditions such as hydroplaning and increased skid resistance. Therefore, a thorough understanding of the air void characteristics of porous asphalt mixtures is essential for improving their performance. Permeability, which measures the pavement's capacity to allow water to permeate its surface and subsurface layers, is an additional essential characteristic of porous asphalt mixtures [6]. Permeability is a fundamental factor in porous asphalt design and has a significant impact on its performance. Considering that a pavement with high permeability effectively manages stormwater runoff and helps prevent flooding, it is crucial to investigate and optimize this property [7].

In response to the need for sustainable additives in asphalt mixtures. The incorporation of biological shell wastes, such as faunus ater shells, oyster shells, and crayfish shell into asphalt mixtures improved the mechanical properties and durability of pavements [8]-[10]. As an abundantly produced waste material, the use of eggshell ash in asphalt mixtures provides a sustainable solution to waste management challenges [11]. This study aims to examine the air void and permeability characteristics of porous asphalt mixtures with an eco-friendly additive, eggshell ash. This research aims to contribute to the development of a sustainable and long-lasting porous asphalt pavement by evaluating the effect of eggshell ash on the air void content and permeability of porous asphalt mixtures. In addition, the results of this research will encourage the use of waste materials as additives in asphalt mixtures, thereby fostering environmentally conscious engineering practices. Moreover, this research seeks to advance our knowledge of sustainable pavement design by investigating the characterization of air voids and permeability in porous asphalt mixtures with eggshell ash as an additive.

2. Materials and Methods

2.1 Binder Properties

The binder employed in this study was specifically formulated to fulfill the requirements of porous pavement applications. It possesses key characteristics, including penetration, softening point, ductility, and viscosity. The penetration test (ASTM D5-20) was conducted to determine the depth to which a standard needle penetrated a sample of the binder at 25°C. The obtained penetration value of 64.5 (0.1 mm) provided insights into the consistency and stiffness of the binder. The softening point (ASTM D36-14), measured using the Ring and Ball apparatus, was found to be 48.5°C. Furthermore, the degree of ductility (ASTM D113-17) at 25°C, which denotes the binder's ability to stretch without breaking, was determined to be 130 cm. Lastly, the viscosity (ASTM D4402) of the binder at 135°C was evaluated at 440 cts, indicating its flow characteristics under high-temperature conditions.

2.2 Aggregate Properties

The aggregates employed in the porous asphalt mixtures were meticulously chosen to satisfy the specified gradation requirements for porous pavement applications. The selected aggregate gradation aligns with the recommendations outlined in the Australian Asphalt Pavement Association's (AAPA) OGA-14 guidelines for porous asphalt. Table 1 provides a comprehensive overview of the properties of the aggregates employed in this study. Table 2 offered valuable insights into the proportion and grading of different particle sizes present in the aggregates, thus ensuring adherence to the necessary gradation criteria.

2.3 Eggshells Preparation

The eggshells used in this study were obtained from the food industry's waste stream. Several steps were taken to ensure that the aggregates were suitable for incorporation into the asphalt mixtures. Initially, the eggshells were cleaned thoroughly to eliminate any contaminants or residues. Subsequently, they were thoroughly dried to eliminate moisture content and enhance their grinding stability. To achieve the desired particle size, the eggshells were ground into a powder with a grinding device [12]. Using a No. 400 sieve, the resulting powder was then subjected to sieve analysis. This analysis involved passing the eggshell powder through a sieve to determine its particle size distribution, which yielded insightful information regarding the range and proportion of particle sizes present.

Table 1 *Properties of aggregate*

Test Properties	Standard	Test Result
Relative density (gr/cm3)	ASTM C127	2.74
Absorption (%)	ASTM C127	1.74
Abrasion (%)	ASTM C131	16.44
Impact (%)	ASTM C131	6.49
Flakiness index (%)	ASTM D4791	9.83
Elongated index (%)	ASTM D4791	9.63

Table 2 *Aggregate gradation OGA-14*

Sieve Size (mm)	Percentage Passing (%)
19.0	100
13.2	90-100
9.5	30-55
6.7	20-35
4.75	18-30
2.36	15-28
1.18	13-24
0.60	12-21
0.30	10-18
0.15	9-14
0.075	8-12

In addition to the grinding and sieving procedures, a portion of the eggshell powder was heated at 100°C (referred to as EA100) and 200°C (referred to as EA200). The purpose of this thermal treatment was to examine the potential effect of temperature on the resulting eggshell ash's properties.

2.4 Air Voids Test

ASTM D2041-19, the standard test method for the theoretical maximum specific gravity and density of bituminous paving mixtures, was employed to ascertain the air void content of the porous asphalt mixtures. This widely accepted standard offers a comprehensive procedure for assessing the air void characteristics of asphalt mixtures, ensuring reliable and reproducible results. The following Eq. (1) can be utilized to determine the number of voids in compacted specimens:

$$n = 100 \text{ x } (1 - \frac{G_{mb}}{G_{mm}}) \tag{1}$$

where: n = the air void, G_{mb} = the bulk specific gravity of the compacted specimen, G_{mm} = the theoretical maximum density.

2.5 Coefficient of Permeability

The permeability of porous asphalt mixtures plays a critical role in ensuring proper drainage. Therefore, it is essential that the addition of additives does not significantly reduce the mixture's permeability. Previous studies [4], [13], [14] have utilized a flow-falling head permeameter to measure the permeability of the samples. The permeability coefficient, k, can be calculated using the following Eq. (2):

$$k = 2.3 \frac{al}{AT} \log (\frac{h_1}{h_2}) \tag{2}$$

where k represents the permeability coefficient (cm/s), A denotes the area of the sample (cm^2), a represents the area of the standpipe (cm^2), l indicates the height of the sample (cm), h_1 represents the initial water height above the sample (cm), h_2 denotes the final water height above the sample (cm), and t represents the time taken for the water to fall from h_1 to h_2 (seconds).

2.6 Image Analysis

The sample was divided into two halves, and the surface of the cut section was scanned using a printer. The resulting image of the cut sample was subjected to analysis using ImageJ, an image processing software [15]. ImageJ possesses the capability to analyze particles present in an image and measure their size and area. Moreover, ImageJ can be calibrated using optical density step tablets and radioactive isotope standards to ensure accurate measurements. Additionally, ImageJ was employed to investigate the bond between eggshell ash and bitumen.

3. Results and Discussions

3.1 Air Voids

Void in mixture (VIM) is a critical parameter used to assess the compactness and density of the asphalt mixture. Fig. 1 illustrates the air void test results for the different specimens, including the control mixture and mixtures with varying percentages of eggshell ash at two heating temperatures (100°C and 200°C). The control sample, devoid of eggshell ash, exhibited a VIM value of 21.47. Incorporating 2% eggshell ash (EA100–2%) led to a slight decrease in VIM to 20.36, indicating a denser mixture compared to the control. With increasing percentages of eggshell ash in the EA100 mixtures (5%, 7%, 10%, and 12%), further reductions in VIM were observed (18.23, 18.11, 17.57, and 17.17, respectively). The inclusion of eggshell ash resulted in a decrease in the air void content of the porous asphalt mixture, suggesting improved compactness and potentially enhanced performance.

Similar trends were noted for the EA200 mixtures prepared at a higher heating temperature. The VIM value after incorporating 2% eggshell ash (EA200-2%) reached 21.19. It's possible that 2% eggshell ash was within the optimal range for improving the mixture's properties. At this percentage, the ash might have contributed to densifying the mixture without causing a significant change in the VIM value. As the percentage of eggshell ash increased to 5%, 7%, 10%, and 12%, the VIM values decreased to 18.52, 18.24, 18.12, and 17.34, respectively. These results align with the observations for the EA100 mixtures, indicating consistent effects of eggshell ash on the air void characteristics across different heating temperatures.

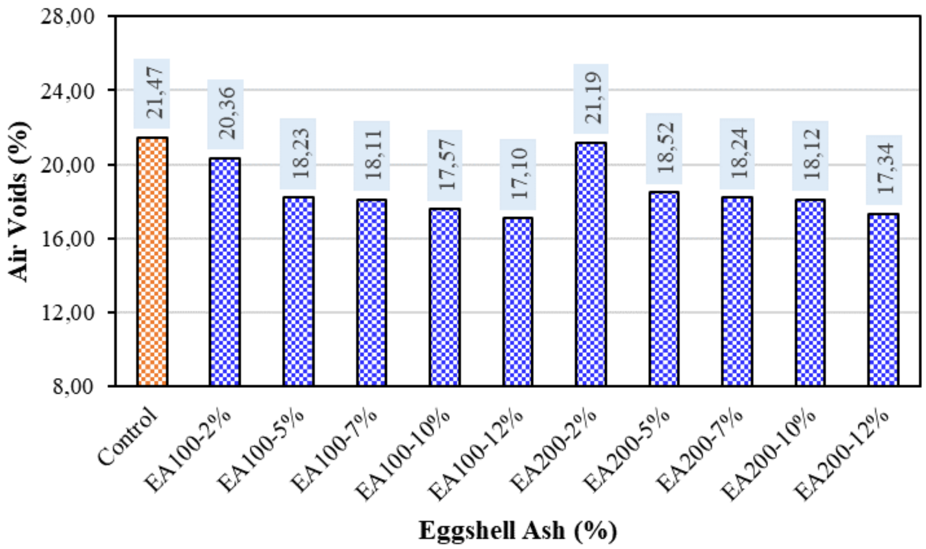

Fig. 1 *Air voids at various percentages of eggshell ash and temperatures (EA100 and EA200)*

The decrease in VIM resulting from the addition of eggshell ash can be attributed to several factors. As a fine and reactive material, eggshell ash likely filled the voids between aggregates, leading to increased particle packing. Additionally, the presence of calcium compounds in eggshell ash may have contributed to enhanced adhesion between the binder and aggregates, thereby improving aggregate-binder interlocking and reducing air voids.

3.2 Permeability

Fig. 2 illustrates the results of permeability tests conducted on different types of eggshell ash. In the absence of eggshell ash, the control sample exhibited a permeability value of 0.22. Adding 2% eggshell ash (EA100-2%) resulted in a slightly lower permeability value of 0.21, indicating a slight improvement in the permeability properties of the mixture. As the percentage of eggshell ash in the EA100 mixtures increased to 5%, 7%, 10%, and 12%, the permeability further decreased (0.20, 0.19, 0.18, and 0.17, respectively). These findings demonstrate that incorporating eggshell ash reduced the permeability of the porous asphalt mixture, indicating increased resistance to water flow and potentially enhancing pavement performance.

Identical permeability trends were observed for EA200 mixtures prepared at higher temperatures. The permeability was 0.20 after the addition of 2% eggshell ash (EA200-2%). As the percentage of eggshell ash increased to 5%, 7%, 10%, and 12%, respectively, the permeability values decreased to 0.19, 0.19, 0.18, and 0.17, respectively. These results align with the observations for EA100 mixtures, indicating that the effect of eggshell ash on permeability remains constant regardless of the heating temperature.

The reduction in permeability is due to the physical properties of eggshell ash and its interaction with the bitumen binder. Fine eggshell ash particles likely filled the voids in the mixture, reducing the number of interconnected pores and impeding water flow. In addition, the presence of calcium compounds in eggshell ash may have improved binder-aggregate adhesion, leading to increased compactness and decreased permeability.

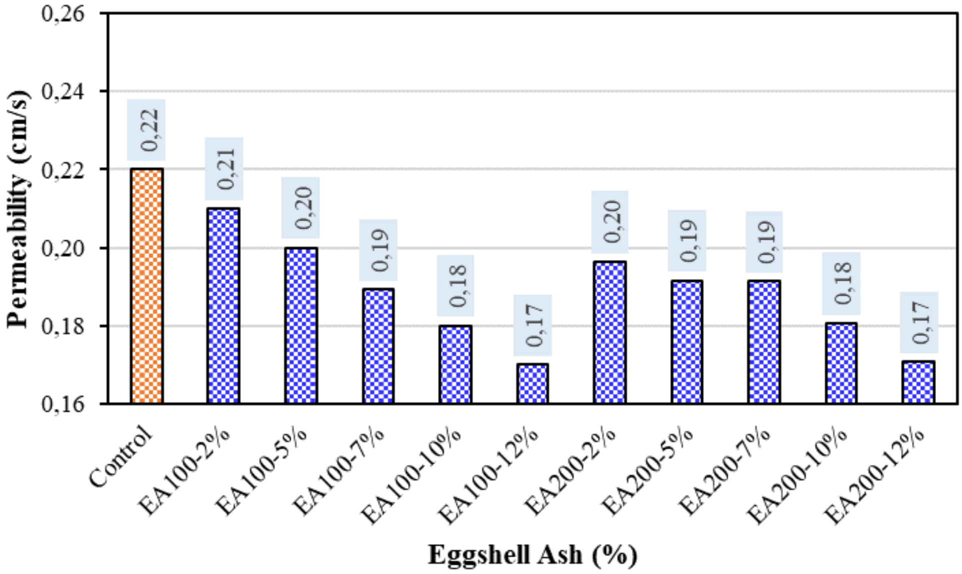

Fig. 2 *Permeability coefficient at various percentages of eggshell ash and temperatures (EA100 and EA200)*

3.3 Relationship between Air Void and Permeability

The relationship between air void content (VIM) and permeability for EA100 mixtures is illustrated in Fig. 3. The control sample, without eggshell ash, had an air void content of 21.47% and a permeability value of 0.22. Upon adding 2% eggshell ash to the bitumen binder, the air void content decreased to 20.36% and the permeability decreased to 0.21%. Further increases in the percentage of eggshell ash (5%, 7%, 10%, and 12%) resulted in progressively lower air void contents (18.23%, 18.11%, 17.57%, and 17.10%) and permeability values (0.20, 0.19, 0.18, and 0.17, respectively). The addition of eggshell ash reduced permeability, indicating enhanced resistance to moisture infiltration by the bitumen binder.

Fig. 4 illustrates the relationship between air void content and permeability for EA200 mixtures heated at a higher temperature. The control sample exhibited an air void content of 21.47% and a permeability value of 0.22. With the addition of 2% eggshell ash, the air void content decreased to 21.19%, and the permeability dropped to 0.20. Further increases in the percentage of eggshell ash to 5%, 7%, 10%, and 12% led to additional decreases in air void contents (18.52%, 18.24%, 18.12%, and 17.34%) and permeability values (0.19, 0.19, 0.18, and 0.17, respectively). These results indicate that the effect of eggshell ash on the air void content and permeability remains consistent regardless of the heating temperature.

The relationship between air void content and permeability observed at both heating temperatures demonstrates the positive impact of incorporating eggshell ash as an additive into the bitumen binder. The presence of eggshell ash particles fills the voids within the binder, effectively reducing the interconnected pore spaces and limiting the flow of air and moisture. Consequently, the decrease in permeability values indicates a reduction in the quantity of air voids and an enhancement in the resistance to moisture infiltration.

3.4 Image Analysis

In the present research, samples were scanned to visualize the difference in bitumen content and particle size between aggregates coated with bitumen-containing eggshell as well as the porous asphalt mixture. Fig. 5 compares a representative image of the samples to their actual profile. Clearly, the darkest color in the scanned profiles corresponds to air voids, while the lighter patterns represent aggregates, and the remaining portion indicates the presence of bitumen.

The ellipses in the image (Fig. 6) depict the best-fit ellipse for each measured particle in the porous asphalt sample. The outline image clearly illustrates the distinction between bitumen content and aggregate size, with bitumen represented by the red color and aggregates displayed in white with various shapes corresponding to different sizes and configurations. Fig. 6 demonstrates the effective blending of eggshell ash and bitumen, as no discernible differences are observed between them. Furthermore, it is evident that the smaller aggregates and fillers occupy the empty spaces within the porous asphalt mixture.

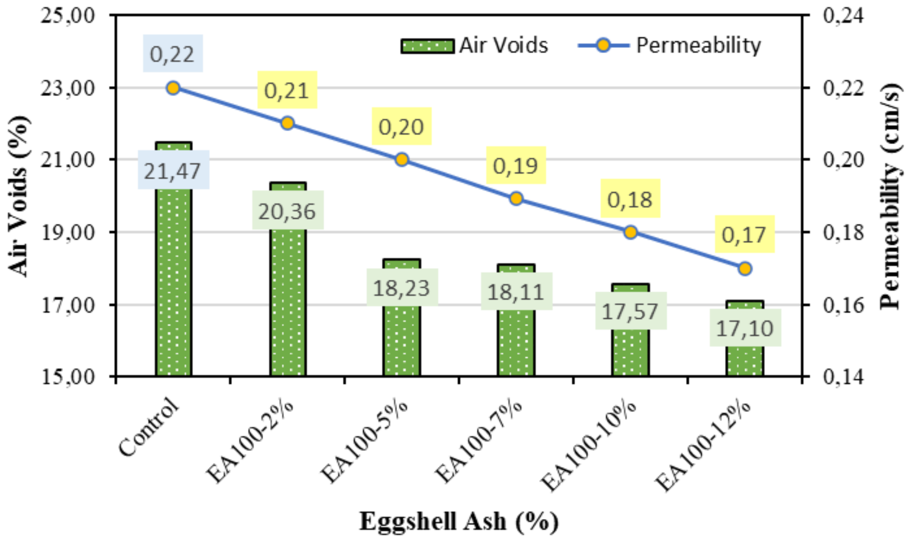

Fig. 3 *Relationship between air voids and permeability at 100 °C with various eggshell ash percentages*

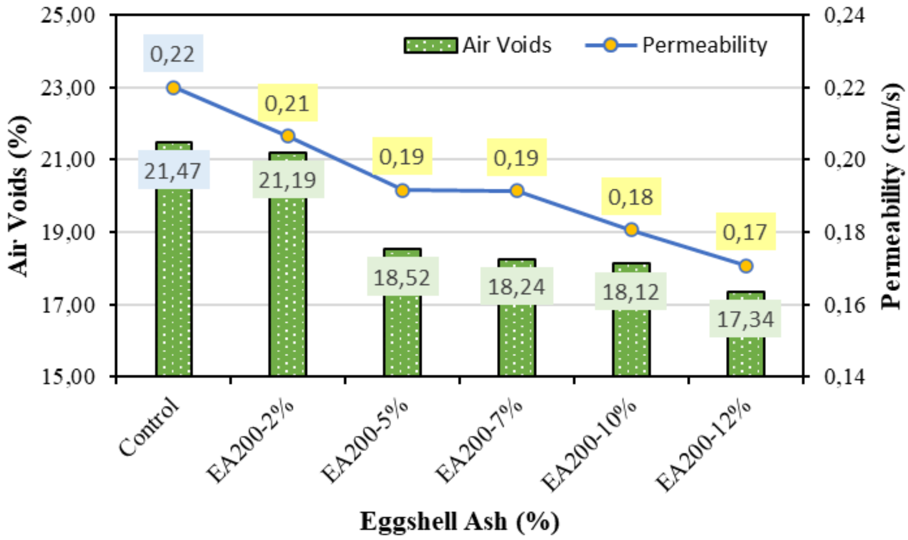

Fig. 4 *Relationship between air voids and permeability at 200 °C with various eggshell ash percentages*

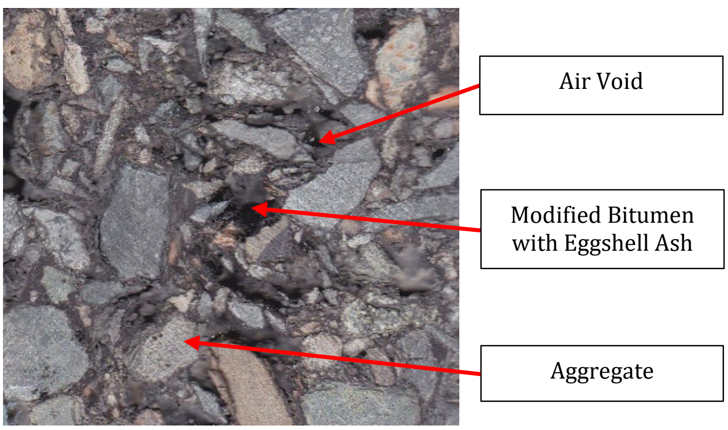

Fig. 5 *Porous asphalt mixture modified*

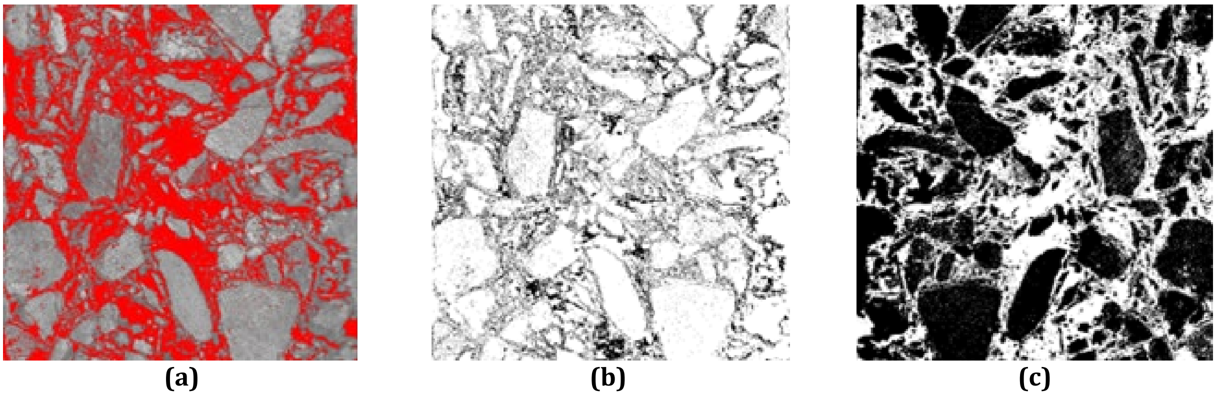

Fig. 6 *Porous asphalt mixture modified using (a) Outline image; (b) Ellipses image; (c) Threshold image*

4. Conclusion

The relationship between air void content and permeability in EA100 and EA200 mixtures, observed at various heating temperatures, consistently followed similar trends. As the percentage of eggshell ash increased, both the air void content and permeability decreased. These results provide empirical evidence supporting the hypothesis that the presence of eggshell ash particles fills the voids within the bitumen binder, thereby reducing interconnected pore spaces and impeding the flow of air and moisture.

Comprehensive scanning analysis provided visual confirmation of the disparities in bitumen content and aggregate size between samples coated with bitumen-containing eggshell and the porous asphalt mixture. The images vividly depicted the presence of air voids, aggregates, and bitumen, affirming the effective filling of void spaces within the mixture by eggshell ash.

The incorporation of eggshell ash as an additive confers several advantages to porous asphalt mixtures. Firstly, it enhances densification, leading to a decrease in air void content. This densification fortifies the structural integrity of the pavement and enhances its overall durability. Second, the inclusion of eggshell ash reduces permeability, improving resistance to water infiltration, a crucial element in preventing early pavement deterioration due to water damage. By impeding the flow of water through the mixture, eggshell ash significantly enhances the long-term performance of porous asphalt pavements.

The findings of this study have significant implications for the construction and maintenance of porous asphalt pavements. The utilization of eggshell ash as an additive offers a sustainable and cost-effective approach to enhancing the quality and performance of porous asphalt mixtures. It has the potential to prolong the service life of porous asphalt pavement by reducing permeability and enhancing moisture resistance.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

*The authors confirm contribution to the paper as follows: **study conception and design:** Tamalkhani Syammaun, Husaini; **data collection:** Tamalkhani Syammaun; **analysis and interpretation of results:** Muhammad Isya, Abdullah; **draft manuscript preparation:** Tamalkhani Syammaun, Muhammad Isya. All authors reviewed the results and approved the final version of the manuscript.*

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