Open Journal of Composite Materials, 2025, 15(2), 59-94
https://www.scirp.org/journal/ojcm
ISSN Online: 2164-5655
ISSN Print: 2164-5612

Enhancing the Durability of Asphalt Mixtures through Eggshell Powder Incorporation: Towards a Bio-Based and Sustainable Alternative

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How to cite this paper: Adéoti, G.O., Hounkpe, S.P. and Ayeko, K.B. (2025) Enhancing the Durability of Asphalt Mixtures through Eggshell Powder Incorporation: Towards a Bio-Based and Sustainable Alternative. *Open Journal of Composite Materials*, **15**, 59-94.
https://doi.org/10.4236/ojcm.2025.152004

Received: November 9, 2024
Accepted: February 8, 2025
Published: February 11, 2025

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Abstract

This study explores the innovative use of dried eggshell powder (ESP) as a bio-based filler in asphalt mixtures, aiming to improve resistance to moisture damage while reducing environmental impact. By partially substituting conventional limestone fillers with ESP, the research evaluates mechanical and durability properties under various substitution ratios. Laboratory tests, including Fourier Transform Infrared Spectroscopy (FTIR), X-Ray Diffraction (XRD), and water absorption measurements, were conducted to characterize ESP. Asphalt mixtures were tested for moisture susceptibility, stability, and resistance to freeze-thaw cycles. Results demonstrate that mixtures incorporating 7% ESP achieved superior performance, with enhanced compaction, reduced permeability, and improved durability under wet conditions. These findings suggest that ESP offers a sustainable alternative filler for road construction, contributing to circular economy objectives and the reduction of construction waste.

Keywords

Asphalt Mixtures, Eggshell Powder, Sustainable Construction, Moisture Resistance, Calcium Carbonate, Durability, Bio-Based Filler

1. Introduction

Road infrastructure plays a fundamental role in the economic and social development of nations by ensuring connectivity, trade, and community progress. However, maintaining the durability of road infrastructure remains a significant challenge due to considerable environmental, economic, and technical constraints. Asphalt mixtures, comprising aggregates, bitumen, and fillers, are the most widely used materials for road construction worldwide due to their superior performance and adaptability [1] [2]. Despite their effectiveness, these materials are susceptible to severe degradation caused by factors such as moisture, thermal cycles, and fatigue loads, leading to issues like stripping, cracking, and rutting [3] [4]. Among these factors, moisture is one of the most destructive as it rapidly deteriorates the bond between bitumen and aggregates, compromising pavement durability [5]-[7].

The sensitivity of asphalt mixtures to moisture is strongly influenced by their formulation, particularly the characteristics of the fillers used [8]. Conventional fillers, such as limestone, cement, and lime, play a critical role in enhancing compaction and cohesion. However, their production is associated with high costs, intensive consumption of non-renewable resources, and significant greenhouse gas emissions, particularly in regions like Benin, where limestone reserves are heavily exploited [9]. These limitations underscore the need for alternative solutions that are both accessible and environmentally sustainable.

In this context, the use of organic waste as construction material is emerging as a promising solution [10]. Eggshells, an abundant byproduct of the food industry, offer significant potential due to their high calcium carbonate ($CaCO_3$) content, a compound with properties similar to conventional fillers [11] [12]. Repurposing these organic wastes as powder can reduce the environmental footprint of asphalt mixtures while improving their performance, particularly in terms of moisture resistance [13]-[16]. This approach aligns with circular economy principles, contributing to waste reduction and more sustainable use of natural resources.

Eggshells are abundant and primarily composed of calcium carbonate ($CaCO_3$), making them comparable to limestone in properties. Utilizing dried eggshell powder (ESP) as a filler aligns with circular economy principles by reducing environmental impacts and diverting waste from landfills. This study explores the innovative potential of ESP to enhance moisture resistance and durability in asphalt mixtures, addressing challenges such as stripping and cracking caused by water infiltration.

Incorporating ESP into asphalt formulations presents a technical and ecological innovation that addresses the durability challenges faced by the road construction sector. By filling voids in the asphalt matrix, ESP improves compaction, reduces permeability, and mitigates moisture-induced damage [17] [18]. Moreover, using this bio-based material offers a viable alternative to conventional fillers, particularly in regions where eggshells are abundantly produced, thereby reducing production costs and environmental impacts [19]-[21].

By applying the Fuller-Thompson gradation model to optimize compaction, this research offers robust scientific evidence highlighting the benefits of this alternative material. It aims to promote innovative and sustainable solutions for road infrastructure design while emphasizing the valorization of abundant and underutilized organic waste [22] [23].

The findings of this research address a pressing question in sustainable road construction: to what extent can the incorporation of ESP improve the moisture resistance, durability, and environmental sustainability of asphalt mixtures? By integrating this underutilized organic waste into road construction practices, this study contributes to circular economy goals, reduces waste, and offers an innovative pathway for eco-friendly infrastructure development.

By addressing a critical question in sustainable road construction—how does incorporating dried eggshell powder into asphalt formulations improve moisture resistance, enhance durability, and reduce environmental impact?—this research has the potential to not only transform road construction practices but also drive the adoption of more environmentally friendly solutions in infrastructure development.

2. Literature Review

2.1. Asphalt Mixtures: Composition, Role of Bitumen, and Challenges in Road Infrastructure

Asphalt mixtures remain indispensable in modern road construction due to their exceptional mechanical resistance, durability, and ability to bear significant traffic loads. These materials primarily comprise aggregates ((90% - 95%) by weight) and bitumen (5% - 10%), with bitumen acting as a viscoelastic binder that ensures cohesion and impermeability. The performance and longevity of asphalt mixtures are strongly influenced by the quality of these components, particularly the cohesion provided by bitumen [24]-[27].

Aggregates, which form the structural backbone of asphalt mixtures, may be natural (gravel, sand, crushed stone) or recycled. Their gradation plays a pivotal role in optimizing performance, as it minimizes voids, enhances compactness, and improves stability [28] [29]. The Fuller-Thompson gradation model is often employed to achieve optimal particle packing, maximizing density and mechanical strength [25] [30]. Bitumen, derived from petroleum, coats the aggregates to ensure viscoelastic behavior essential for resisting mechanical stresses and environmental conditions. Furthermore, its impermeable properties protect underlying pavement layers from water infiltration, a leading cause of structural degradation [13] [31].

Despite its advantages, the use of bitumen is not without challenges. Its petrochemical origin is associated with significant greenhouse gas emissions, and its sensitivity to temperature extremes can result in plastic deformation under high temperatures and cracking under low temperatures. Advances such as polymer-modified bitumen (PMB), incorporating materials like SBS (styrene-butadiene-styrene) and SBR (styrene-butadiene rubber), have improved its resistance to fatigue, thermal variations, and moisture-induced stripping [32].

2.2. Moisture Resistance: A Critical Factor in Durability

Moisture infiltration is one of the most detrimental factors affecting asphalt mixtures. It compromises adhesion between bitumen and aggregates, leading to stripping, cracking, and deformation over time [2] [32]. The phenomenon of stripping occurs when water displaces bitumen from aggregate surfaces, weakening the cohesive bond and reducing the mixture's structural integrity. Hydrophilic aggregates, such as those rich in silica, exacerbate this issue, while hydrophobic aggregates, such as limestone, exhibit superior resistance to water infiltration [13] [31].

Freeze-thaw cycles amplify moisture-induced damage, particularly in climates with significant temperature fluctuations. Water trapped within asphalt voids expands upon freezing, exerting internal pressures that create cracks and allow further water ingress, accelerating degradation and pothole formation [13]. To mitigate these effects, formulations must optimize aggregate gradation for maximum compactness, thereby reducing voids and limiting water pathways [22].

The rheological and physical properties of bitumen are equally crucial. Modified bitumen, incorporating anti-stripping agents or polymers, enhances adhesion and flexibility, reducing the likelihood of moisture-related damage under thermal and mechanical stress [32]. These innovations underscore the necessity of exploring alternative materials to bolster asphalt mixtures against environmental challenges.

2.3. Innovative Materials for Enhancing Asphalt Performance

The quest for sustainable and high-performance road materials has prompted extensive research into alternative solutions. Biosourced and recycled materials offer promising avenues to improve asphalt durability while addressing environmental concerns.

- **Natural Fibers:** Renewable fibers such as coconut, sisal, and jute have shown significant potential to enhance asphalt performance. These fibers improve tensile strength, reduce crack propagation, and provide internal reinforcement against thermal and mechanical stresses. Coconut fibers, in particular, are abundant, biodegradable, and cost-effective, making them attractive for sustainable pavement design [33].
- **Recycled Materials:** Industrial byproducts like fly ash and blast furnace slag possess pozzolanic properties that improve asphalt density and mechanical resistance. Fly ash enhances void filling, while slag provides superior resistance to freeze-thaw cycles [4] [6]. Recycled polymers, including HDPE (high-density polyethylene) and PS (polystyrene), improve bitumen's rheological properties, enhancing stiffness and reducing permanent deformation [34].
- **Eggshell Powder (ESP):** As a biosourced filler derived from food industry waste, ESP primarily consists of calcium carbonate ($CaCO_3$). Its fine particle size and high $CaCO_3$ content make it an effective substitute for limestone fillers. Studies demonstrate that ESP incorporation at dosages of 3% - 7.5% enhances compaction, reduces permeability, and improves durability under moisture and thermal stress [12] [19].
- **Bio-Binders:** Renewable bio-binders, derived from vegetable oils, lignin, or

agricultural residues, offer a sustainable alternative to petroleum-based bitumen. These binders exhibit comparable viscoelastic properties while reducing dependence on fossil fuels and lowering CO_2 emissions [35].

3. Materials, Equipment, and Methods

This section provides a detailed overview of the materials, preparation processes, and experimental methods used to evaluate the performance of asphalt mixtures modified with eggshell powder (ESP). The study investigates the feasibility of incorporating ESP as a sustainable alternative to conventional limestone fillers in asphalt applications.

By focusing on both mechanical performance and environmental advantages, the research aims to explore the role of ESP in enhancing the durability, moisture resistance, and sustainability of asphalt mixtures. The section outlines the rigorous material characterization techniques employed to understand the chemical, physical, and mechanical properties of ESP, alongside standardized laboratory tests to compare the performance of ESP-modified mixtures with conventional formulations.

The integrated approach ensures a comprehensive evaluation, combining precise material preparation with established testing protocols to validate ESP's potential as a viable, eco-friendly filler in the context of modern infrastructure development.

3.1. Materials

3.1.1. Conventional Asphalt Mixtures

Conventional asphalt mixtures are the benchmark for road construction due to their durability, mechanical strength, and adaptability to traffic loads. Their performance is governed by three primary components: aggregates, bitumen, and fillers.

- **Aggregates:** Comprising 90% - 95% of the mixture by weight, aggregates include crushed rocks, gravel, and sand. A well-graded particle size distribution, as determined by the Fuller and Thompson gradation curve [24], ensures maximum compactness, reducing voids and enhancing load-bearing capacity (maximizing the mechanical stability of the mixtures).
- **Bitumen:** Representing 5% - 10% of the mixture, bitumen acts as a viscoelastic binder, imparting cohesion and flexibility. It protects the underlying layers from water infiltration and provides resistance to mechanical stress and thermal fluctuations [26]. However, bitumen's susceptibility to oxidation and moisture necessitates supplementary measures to ensure long-term performance. A 60/70 penetration grade bitumen was selected as the binder.
- **Mineral Fillers:** Fine particles such as limestone fillers enhance the compactness and cohesion of the asphalt mixture. By filling voids between larger aggregates, they reduce permeability and improve moisture resistance. Nevertheless, the extraction of limestone raises environmental concerns, highlighting the importance of alternative materials [35].

3.1.2. Eggshell Powder: A Sustainable Alternative

Eggshell powder (ESP) is an agro-industrial byproduct primarily composed of calcium carbonate ($CaCO_3$). Its chemical and physical properties make it a promising replacement for conventional fillers.

- **Chemical Composition:** ESP contains 94% - 97% $CaCO_3$, complemented by trace amounts of magnesium, phosphorus, and organic matter [35]. Its fine particles help reduce voids within the asphalt matrix, enhancing moisture resistance and compaction.
- **Physical and Mechanical Properties:** The fine granulometry of ESP, achieved through controlled grinding, allows it to function as an efficient void filler. Studies have demonstrated that its incorporation improves tensile and compressive strength, enhances resistance to freeze-thaw cycles, and reduces susceptibility to moisture-induced stripping [13]. Additionally, ESP's lightweight nature can decrease the overall density of the asphalt mixture, reducing transportation and energy costs.

3.2. Materials Preparation

Eggshell Powder Processing

To ensure consistency and reliability, the preparation of ESP involved meticulous cleaning, drying, grinding, and sieving processes (**Figure 1**).

- **Collection and Cleaning:** Eggshells were collected from poultry farms and food processing facilities. They were washed thoroughly to remove residues, soaked in a mild alkaline solution, and rinsed to eliminate organic matter.
- **Drying:** The cleaned shells were air-dried, followed by oven drying at 105˚C for 24 hours. This step removed residual moisture, ensuring the chemical stability of the ESP.
- **Grinding and Sieving:** The dried shells were ground using a ball mill to achieve a fine powder (<63 µm). The powder was sieved to ensure a uniform particle size distribution, essential for consistent performance in asphalt mixtures [29].

Figure 1. Eggshell powder processing.

3.3. Experimental Tests Methodology

3.3.1. Mix Formulations

Three formulations were prepared to evaluate the influence of ESP substitution:

- **Control Mix (CM):** 100% limestone filler.
- **Blend Mix (BM):** 50% limestone filler and 50% ESP (**Figure 2**).

- **ESP Mix (EM):** Figure 2 illustrates the incorporation of Eggshell Powder (ESP) as a filler.

Figure 2. ESP Mix (EM).

The total filler content was set at 7% of the aggregate weight, following the Fuller and Thompson gradation curve [36]-[38]. This ensured optimal compactness and uniform distribution of filler particles.

3.3.2. Sample Preparation

Each formulation was mixed in a high-speed laboratory mixer to ensure homogeneity. A controlled temperature environment was maintained to optimize the interaction between the filler, bitumen, and aggregates. The final mixtures were subjected to standardized compaction methods to prepare test specimens (**Figure 3**).

Figure 3. Sample preparation.

3.4. Testing Procedures

The performance of the asphalt mixtures was evaluated through a series of standardized tests:

- **Chemical Characterization:** FTIR and XRD analyses were conducted to identify the chemical composition and crystalline structure of ESP.
- **Physical and Mechanical Testing:** Bulk density and water absorption tests (NF EN 1097-6) were performed to assess the compactness and permeability of the mixtures. Marshall stability and indirect tensile strength (ITS) tests were conducted to evaluate mechanical properties and moisture resistance under

dry and wet conditions.

- **Moisture Susceptibility:** Indirect tensile strength (ITS) tests were conducted on asphalt mixtures subjected to wet and dry conditions to evaluate stripping potential.
- **Durability Tests:** Freeze-thaw resistance and Marshall stability tests were used to assess the mixtures' performance under cyclic loading and thermal stress (Freeze-thaw cycles were applied to measure the retained strength and assess the resilience of the mixtures in extreme conditions).

3.5. Characterization of Materials

This rigorous experimental methodology aims to validate the potential of ESP as a filler in asphalt mixtures. By comparing mechanical, thermal, and moisture resistance properties, this study highlights the feasibility of ESP in sustainable infrastructure applications.

3.5.1. Chemical Analysis: FTIR and XRD

Objective:

To identify the chemical composition and crystalline phases of ESP.

FTIR Procedure

1) ESP is mixed with potassium bromide (KBr) and pressed into a pellet.

2) Infrared spectra are recorded to detect functional groups and confirm the presence of $CaCO_3$.

XRD Procedure

1) ESP is analyzed to determine crystalline phases and purity.

2) Peaks corresponding to $CaCO_3$ are identified, providing insights into the filler's structural properties.

3.5.2. Particle Size Distribution

Objective:

To ensure ESP meets the required specifications for asphalt fillers.

Procedure:

1) Sieving is conducted according to NF EN 933-1, with a sieve stack covering <63 μm and larger sizes. The resulting data verify the filler's suitability for reducing voids and improving cohesion.

3.5.3. Density and Water Absorption

Objective:

To evaluate the compaction potential and moisture resistance of ESP.

Procedure:

1) Density is measured using a pycnometer (NF EN 1097-6).

2) Water absorption is calculated by comparing dry and wet sample weights after soaking, using:

$$\text{Water Absorption}(\%) = \frac{\text{Wet Mass} - \text{Dry Mass}}{\text{Dry Mass}} \times 100$$

3.6. Testing of Asphalt Mixtures

3.6.1. Marshall Stability Test (NF EN 12697-34)

Objective:

To measure load-bearing capacity and flow of asphalt mixtures.

Procedure:

- Compacted samples are subjected to vertical loads until failure.
- Stability and deformation (flow) values are recorded to evaluate mechanical performance.

3.6.2. Indirect Tensile Strength Test (NF EN 13286-42)

Objective:

To assess tensile strength and cracking resistance.

Procedure:

- Cylindrical samples are laterally loaded until failure.
- Tensile strength is calculated using the formula:

$$\sigma_t = \frac{2P}{\pi D t}$$

where:

- P is the applied load,
- D is the diameter, and
- t is the thickness.

3.6.3. Bitumen-Aggregate Adhesion Test (NF EN 12697-11)

Objective:

To evaluate the filler's effect on adhesion under wet conditions.

Procedure:

- Bitumen-coated aggregates are immersed in water at 60˚C.
- The percentage of retained coating is measured to quantify adhesion improvement.

3.6.4. Moisture Sensitivity Test (NF EN 12697-12)

Objective:

To measure tensile strength retention under moisture exposure.

Procedure:

- The Indirect Tensile Strength Ratio (ITSR) is calculated using the formula:

$$\text{ITSR} = \frac{\text{Wet Strength}}{\text{Dry Strength}} \times 100$$

3.6.5. Freeze-Thaw Cycle Test (NF EN 12697-24)

Objective:

To assess resistance to cyclic freezing and thawing.

Procedure:

- Samples undergo alternating cycles of freezing at −18˚C and thawing at 25˚C.
- Changes in tensile strength are measured.

- Visual inspections are performed to identify damage.

3.6.6. Accelerated Aging Test (NF EN 12697-33)

Objective:

To simulate long-term aging of asphalt mixtures.

Procedure:

- Samples are aged at 85˚C for 5 days.
- Post-aging, tensile strength and cohesion are measured to evaluate durability.

3.7. Formulation Optimization and Analysis

The results of the preliminary tests informed the optimization of the mix formulations. The 7% filler content, determined through the Fuller and Thompson gradation curve [24], was validated for its effectiveness in balancing compactness, mechanical strength, and moisture resistance.

3.8. Summary

The systematic integration of ESP into asphalt mixtures demonstrates its potential as a sustainable alternative filler. By replacing limestone partially or entirely, ESP contributes to improved mechanical performance, enhanced moisture resistance, and reduced environmental impact, aligning with the goals of sustainable road construction.

4. Results and Discussions

4.1. Characterization of Aggregates and Bitumen

4.1.1. Aggregate Characterization

The aggregates used in this study include 0/6 sand and 6/10 gravel sourced from the OKUTA quarry in Zangnanado, Benin.

A series of tests were conducted to evaluate their physical and mechanical properties, focusing on:

- **Shape:** Determined using the flakiness index (FI).
- **Resistance to Wear:** Assessed through the Los Angeles (LA) and Micro-Deval (MDE) tests in the presence of water.
- **Filler Capacity:** Measured via the sand equivalent (SE) test.

Table 1 and Table 2 summarize the test results assessing the physical and mechanical properties of the materials.

Table 1: Aggregate characteristics, including mechanical properties such as MDE (%), LA (%), and FI (%), follow the relevant standards (e.g., NF EN 1097-1, NF EN 933-3). The results comply with the specified limits, indicating suitable aggregate performance for the intended application.

Table 2: Aggregate physical characteristics, such as apparent density and water absorption, are evaluated using NF EN 1097-6 and NF EN 1097-3 standards. The results meet the declared specifications and confirm the materials' adequacy for construction purposes.

The results confirm that the 6/10 gravel is highly suitable for producing 0/10 Semi-Dense Bituminous Mixtures (BBSG) for Category 3 road pavements. Specifically:

- **Wear and Water Resistance:** The LA, MDE, and combined values indicate excellent durability under mechanical and environmental stress.
- **Shape:** The low flakiness index indicates well-formed particles, a key factor in ensuring optimal compaction and stability during placement.
- **Fines Content:** The satisfactory sand equivalent value implies an adequate fines fraction, enabling reduced bitumen demand while meeting Category 3 specifications.

Table 1. Aggregate characteristics.

Material	Parameter/Test	Standard	Result	Specification
Gravel 6/10	MDE (%)	NF EN 1097-1	10.3	≤20
	LA (%)	NF EN 1097-2	24.2	≤25
	MDE + LA (%)	–	34.5	≤35
	FI (%)	NF EN 933-3	15.12	≤20
Sand 0/6	SE (%)	NF EN 933-8	60.2	≥45

Table 2. Aggregate physical characteristics.

Material	Parameter/Test	Standard	Result	Specification & Standard
6/10 Gravel	Apparent Density (g/cm^3)	NF EN 1097-6	2.73	Declared, NF EN 13043, Aug 2003
	Water Absorption (%)	NF EN 1097-3	1.4	-
0/6 Sand	Apparent Density (g/cm^3)	NF EN 1097-6	2.72	Declared
	Water Absorption (%)	NF EN 1097-3	1.58	-

In summary, the 6/10 gravel from the OKUTA quarry exhibits the uniformity and quality required for producing stable and durable asphalt mixtures for secondary road surfaces.

The results indicate that the 6/10 gravel complies with the specifications, ensuring durability and suitability for the formulation of semi-dense asphalt concrete (SDAC).

Figure 4 illustrates the particle size distribution curves of the aggregates.

The harmonious gradation of the 0/6 and 6/10 classes ensures optimal compaction and good cohesion in the mixture.

The gradation curves for the 0/6 sand and 6/10 gravel are depicted in Figure 4, which illustrates the particle size distribution based on sieve analysis.

- **X-Axis (Sieve Opening):** Represents particle size in millimeters, scaled logarithmically from 0.01 mm to 100 mm.

- **Y-Axis (% Passing):** Indicates the percentage of particles passing through a given sieve, with higher values reflecting finer particles.

Key Insights:

- **Balanced Gradation:** Both gradation curves display a harmonious distribution, ensuring optimal mixture compaction.
- **Complementary Particle Classes:** The combination of 0/6 sand and 6/10 gravel effectively fills voids, enhancing mixture density and cohesion.
- **Distinct Particle Classes:** The clear separation between classes promotes enhanced interparticle bonding, a critical factor for ensuring mix stability.

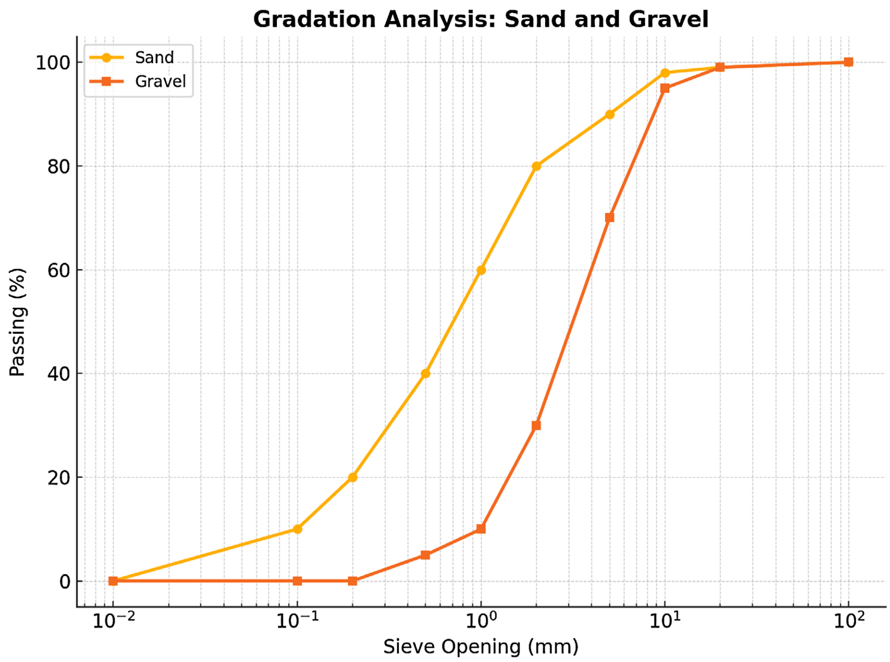

Figure 4. Gradation curves of aggregates.

4.1.2. Bitumen Characterization

The bitumen used in this study is a 35/50-grade binder supplied by CHELL TOGO (Figure 5). Samples were collected from the ADEOTI S.A. facility in Adjura, near Porto-Novo, Benin. The bitumen underwent standard testing to evaluate:

- **Consistency:** Determined through penetration testing.
- **Thermal Resistance:** Measured via the softening point (Ring and Ball method).

Table 3 summarizes the results of its characterization.

Table 3. Characteristics of 35/50 Bitumen.

Test	Result	Unit
Penetration at 25˚C	1.03	1/10 mm
Softening Point	54.10	˚C
Density	38.00	g/cm^3

Figure 5. 35/50 Bitumen.

Penetration at 25˚C:

The low penetration value confirms the binder's hardness, making it suitable for heavily trafficked wearing courses.

Softening Point:

The high softening point ensures resistance to deformation at elevated temperatures, reducing risks of rutting and flow.

Density:

The density aligns with typical values for 35/50-grade bitumen, contributing to the mix's structural integrity and compaction.

The results comply with NF EN 12591 standards, confirming that the 35/50 bitumen is suitable for wearing courses subjected to heavy loads.

4.2. Physical and Chemical Characterization of Eggshell Powder (ESP)

FTIR spectra confirmed the dominance of calcium carbonate in ESP, with characteristic absorption peaks at 1415 cm^{-1} and 875 cm^{-1}. XRD analysis corroborated this finding, showing calcite as the primary crystalline phase. The bulk density of ESP was 2.62 g/cm^3, and its water absorption was lower than that of limestone filler, indicating potential for reduced permeability in asphalt mixtures.

4.2.1. Particle Size Analysis by Sieving

The gradation analysis reveals that powdered eggshells are dominated by fine particles. This distribution is advantageous for their function as a filler in bituminous mixtures. The fines effectively fill voids between aggregates, increasing compaction and reducing water permeability—both critical factors in asphalt pavement durability.

Table 4 presents the cumulative particle size distribution of ESP.

Table 4. Particle size distribution of ESP.

Sieve Size (mm)	Retained Mass (g)	Cumulative Retained Mass (g)	Passing (%)
2.00	0	0	100
0.00	2	2	98
0.06	10	12	90

The gradation curve (**Figure 6**) highlights the predominance of fine particles (<63 μm), making ESP suitable for filling voids between aggregates and improving compactness.

Compaction and Mechanical Strength: The high proportion of fine particles (<63 μm) in EPS enhances the compactness of the mixture, translating into improved mechanical strength and extended durability. These fine particles fill inter-aggregate voids, distributing loads more effectively.

Water Permeability: The predominance of fines significantly reduces water permeability, mitigating the risk of stripping and moisture-induced damage.

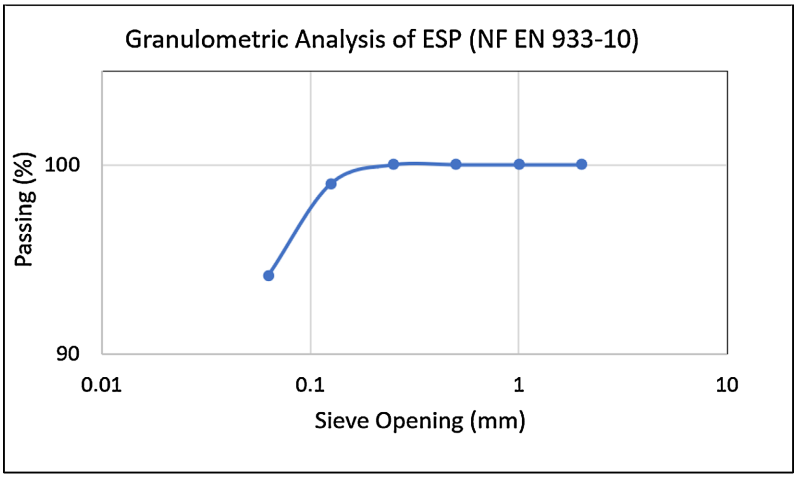

Figure 6. Gradation curves of ESP.

Aggregate-Binder Adhesion: The dense gradation provided by EPS improves the adhesion between the binder and aggregates, creating a robust and moisture-resistant matrix. This is particularly critical in climates with high precipitation or freeze-thaw cycles.

Fillers used in asphalt mixtures must meet stringent gradation criteria to ensure optimal performance. According to standards such as NF EN 933-10, an effective filler should exhibit a high proportion of fine particles (≤60 μm) to enhance compaction and reduce moisture sensitivity. The gradation results for EPS align well with these requirements, validating its suitability as a filler.

The gradation analysis demonstrates that EPS can serve as an effective filler in asphalt mixtures, offering both performance and sustainability benefits.

Key advantages include:

- **Enhanced resistance to deformation:** The uniform distribution of fines improves load distribution across the mixture.
- **Reduced moisture sensitivity:** Enhanced compaction and lower permeability significantly reduce susceptibility to moisture-induced damage.
- **Environmental and economic benefits:** Utilizing a waste product like eggshells reduces dependence on non-renewable resources, offering a sustainable alternative for asphalt production.

4.2.2. X-Ray Diffraction (XRD)

The XRD analysis (**Table 5**) reveals the predominance of calcium carbonate ($CaCO_3$) in the form of calcite. The results are displayed in **Figure 7**.

XRD analysis confirms that powdered eggshells are primarily composed of calcium carbonate ($CaCO_3$) in its crystalline calcite form. The most intense peaks, observed at 23.1˚C, 29.4˚C, and 36.1˚C, affirm calcite as the dominant phase. Additionally, minor traces of magnesite ($MgCO_3$) and aragonite (another form of $CaCO_3$) are detected. These secondary phases, while present in small quantities, do not significantly affect the properties of ESP as a filler.

Table 5. XRD analysis results of ESP.

Diffraction Angle (2θ)	Relative Intensity (%)	Identified Mineral
23.1	100.0	Calcite ($CaCO_3$)
0.4	95.0	Calcite ($CaCO_3$)
0.1	65.0	Calcite ($CaCO_3$)
0.4	50.0	Calcite ($CaCO_3$)
0.3	30.0	Traces of Magnesite ($MgCO_3$)
0.5	20.0	Traces of Aragonite ($CaCO_3$)
0.3	10.0	Minor Impurities

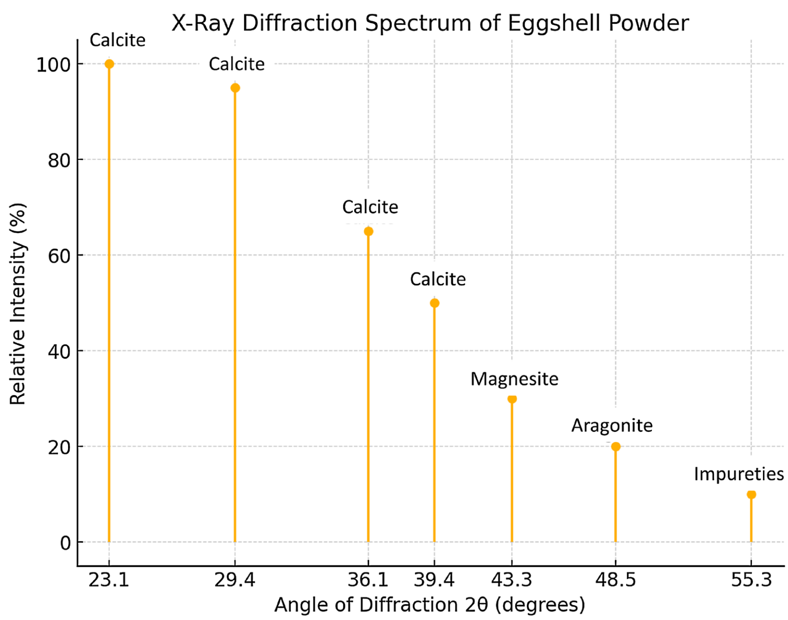

Figure 7. XRD spectrum of ESP.

Implications for Asphalt Mixtures

Mechanical Strength and Cohesion: The calcite-dominant composition improves the mechanical strength and cohesion of asphalt mixtures, ensuring structural integrity under heavy loads.

Durability: The absence of significant impurities ensures high compatibility with bitumen, reducing the likelihood of adverse reactions and enhancing long-term performance.

Sustainability: By utilizing a renewable and biodegradable material like eggshells, ESP offers an eco-friendly alternative to conventional limestone fillers.

The results confirm the chemical purity of ESP and its potential as a substitute for traditional limestone fillers.

4.2.3. FTIR Spectroscopy

The FTIR analysis (Table 6) identifies characteristic carbonate bands, confirming the predominance of calcite. The results are illustrated in Figure 8.

Table 6 below summarizes key infrared absorption peaks observed in powdered eggshells (ESP), indicating its chemical composition. The results highlight the dominance of calcium carbonate ($CaCO_3$) and minor traces of organic or residual water content.

Table 6. FTIR results of ESP.

Peak No.	Wavelength (cm^{-1})	Intensity (%)	Functional Group	Chemical Attribution
1	712	80.0	CO_3^{2-} (Out-of-plane bending)	Carbonate ($CaCO_3$, Calcite)
2	875	85.0	CO_3^{2-} (In-plane bending)	Carbonate ($CaCO_3$, Calcite)
3	1420	70.0	CO_3^{2-} (Symmetric stretching)	Carbonate ($CaCO_3$, Calcite)
4	1640	50.0	H_2O (Bending vibration)	Residual moisture
5	2850 - 2950	40.0	C-H (Symmetric stretching)	Traces of organics
6	3400	60.0	O-H (Stretching vibration)	Bound water/moisture

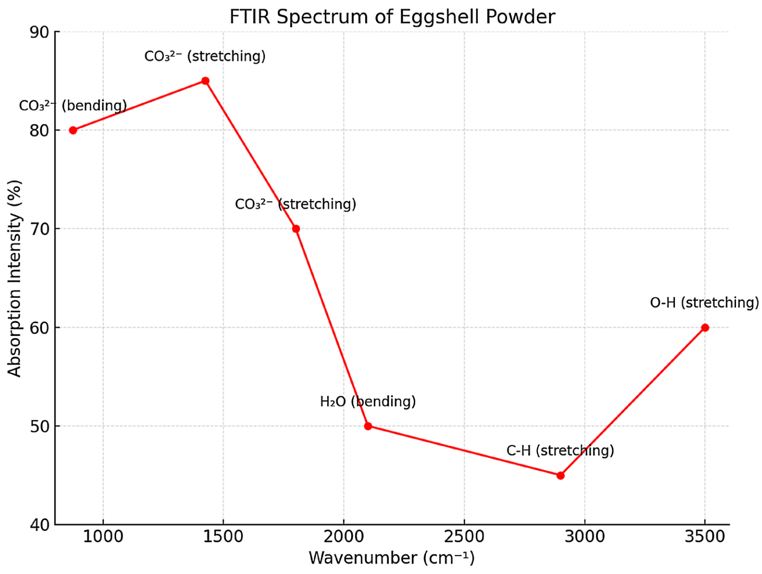

Figure 8. FTIR spectrum of ESP.

Calcium Carbonate Confirmation: Peaks at 712, 875, and 1420 cm^{-1} confirm the dominance of calcium carbonate, which enhances compaction and cohesion in asphalt mixtures.

Residual Water and Organic Traces: Peaks at 1640 and 2850 - 2950 cm^{-1} indicate minor water content and residual organic matter. These may necessitate additional drying or treatment to optimize performance in bituminous mixtures.

The FTIR results reinforce the suitability of ESP as a filler in asphalt mixtures, providing both functional and environmental benefits. Key advantages include:

- **Enhanced Compaction and Strength:** The calcium carbonate composition ensures improved mixture density and mechanical performance.
- **Sustainability:** Utilizing waste products like eggshells aligns with eco-friendly practices, reducing reliance on non-renewable fillers.
- **Improved Durability:** Proper treatment to address residual water and organics can further enhance long-term performance in asphalt applications.

These results validate the favorable properties of ESP for improving asphalt compactness and durability.

4.3. Asphalt Mix Design

4.3.1. Granular Composition

The granular composition utilized in this study corresponds to an ongoing project conducted at the ADEOTI SA base. In compliance with **NF EN 13108-20** (Article 4), which defines the validity period of a mixture formulation and the conditions requiring reformulation, the proportions used were based on the site's formulation while ensuring adherence to the reference 0/10 grading envelope. This also aligns with the requirements of **NF P 98-130** (Article 6.1), which mandates adherence to the grading curve specifications for semi-dense bituminous mixtures (BBSG).

The selected aggregate percentages are illustrated in Figure 9.

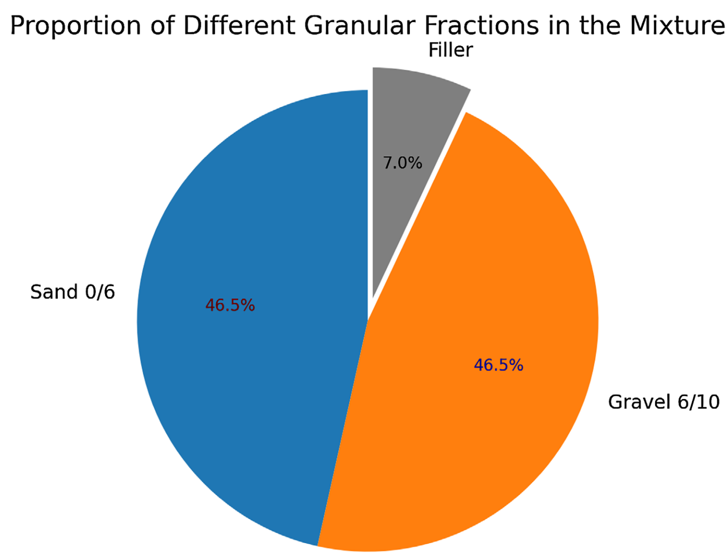

Figure 9. Proportions of different aggregate fractions in the mixture.

The pie chart in **Figure 9** highlights the distribution of the various aggregate fractions, comprising sand (0/6), gravel (6/10), and filler.

The grading curves of the mixture are depicted in **Figure 10**, which includes:

- **Median curve (yellow):** The reference curve derived from the grading envelope specified in **NF EN 13108-21**.
- **Upper and lower grading limits (red):** The specification-defined boundary curves.
- **Mixture grading curve (green):** The actual grading curve of the mixture.

The results demonstrate that the mixture complies with specifications, as its grading curve lies within the required envelope. Its close alignment with the median curve indicates a well-balanced granular structure, optimized for compaction and stability.

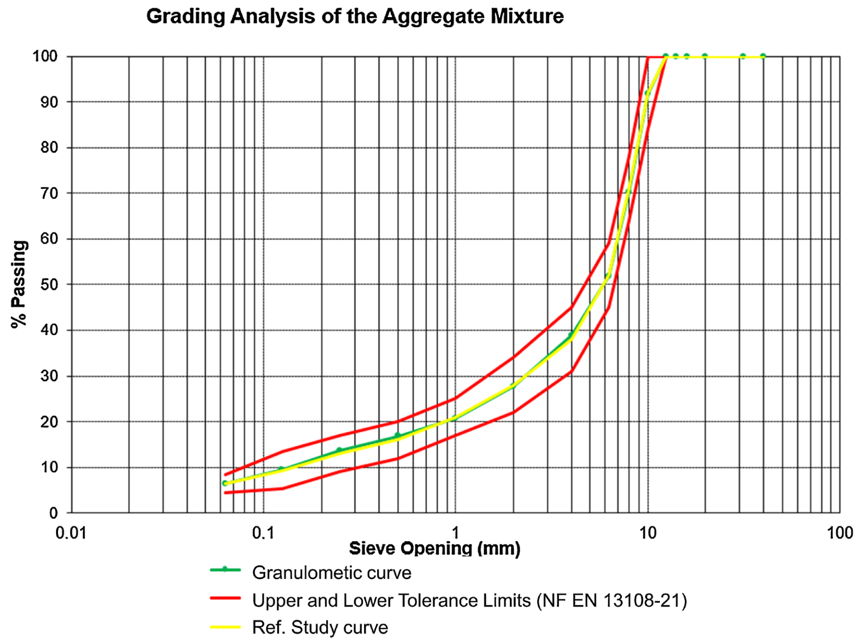

Figure 10. Grading analysis of the aggregate mixture.

4.3.2. Optimal Filler Content

Using the Andreasen and Andersen model with a coefficient $q = 0.5$, the optimal ESP content was estimated at 7%, ensuring a balance between compactness and stability.

Based on existing literature, the recommended filler proportion for pozzolanic fillers ranges from 1% to 10%, with the most frequently cited range being 1% to 7.5%.

To optimize compaction, stability, and water resistance for the BBSG, the **Andreasen and Andersen model** was employed, utilizing a coefficient $q = 0.5$, as recommended by Fuller and Thompson for achieving optimal compaction. The model is expressed as:

$$P(d) = 100 \times \left(\frac{d}{D_{\max}}\right)^q$$

where:

- $D_{\max}$: Maximum aggregate diameter,
- d : Diameter under consideration,
- $P(d)$: Proportion by weight of particles with diameter $\leq d$.

This approach targets a cumulative gradation curve that maximizes the compaction of the granular skeleton. Applying this model to the BBSG 0/10 grading curve and filler diameter ($d = 0.063$ mm), a calculated filler proportion of 7.94% was obtained. While this value yielded excellent compaction, it did not fully satisfy stability requirements.

Referring to **NF EN 13108-1**, which specifies a grading envelope for the 0.063 mm sieve of 2% to 12%, a filler proportion of 7% was chosen. This value, positioned at the center of the normative range, balances compaction and stability effectively.

To ensure robustness, further tests were conducted by varying filler proportions incrementally by ±0.5% around this value. These variations allowed the identification of an optimal balance between compaction, stability, and water resistance, demonstrating the suitability of the 7% filler proportion.

4.3.3. Optimal Binder Content

The Marshall tests determined an optimal bitumen content of 5.9%, which complies with the specifications outlined in NF EN 13108-1. This optimal content plays a critical role in ensuring enhanced stability and long-term durability of the material.

According to **NF EN 13108-1**, the minimum bitumen content for semi-dense hot bituminous mixtures (BBSG) Type 3 with 0/10 granulometry is 5.1%. Based on this reference, a theoretical bitumen content of 5.5% was initially selected, with variations of ±0.5%.

Marshall Mix Tests were conducted in the laboratory to determine the optimal bitumen content experimentally. The optimal bitumen content was found to be 5.9%, within the admissible variation range (±0.5%) from the theoretical content of 5.5%.

Key Observations:

- The theoretical bitumen content was 5.5%.
- Experimental tests yielded an optimal bitumen content of 5.9%.
- At 5.9%, the stability reached 15.92 kN, indicating excellent performance.

The experimentally determined bitumen content complies with the specifications and ensures an optimized BBSG formulation (**Figure 11**). The Marshall Method was employed and validated to determine the optimal composition that meets both technical requirements and performance criteria. The results confirmed that the formulated bituminous mixture complies with standard specifications while delivering the desired mechanical performance.

4.3.4. Optimal ESP Content

The inclusion of 7% Eggshell Powder (ESP) was identified as yielding the highest water resistance while maintaining stability. Beyond this threshold, performance declined due to the saturation of fines. The addition of ESP significantly enhances durability in wet conditions, an essential consideration for infrastructure longevity (Figure 12).

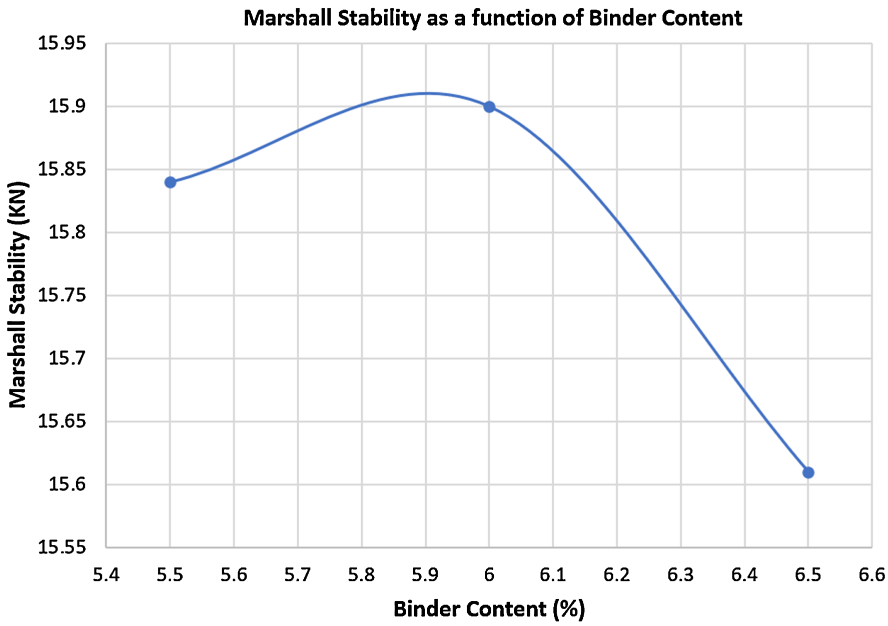

Figure 11. Graphical determination of 35/50 binder content.

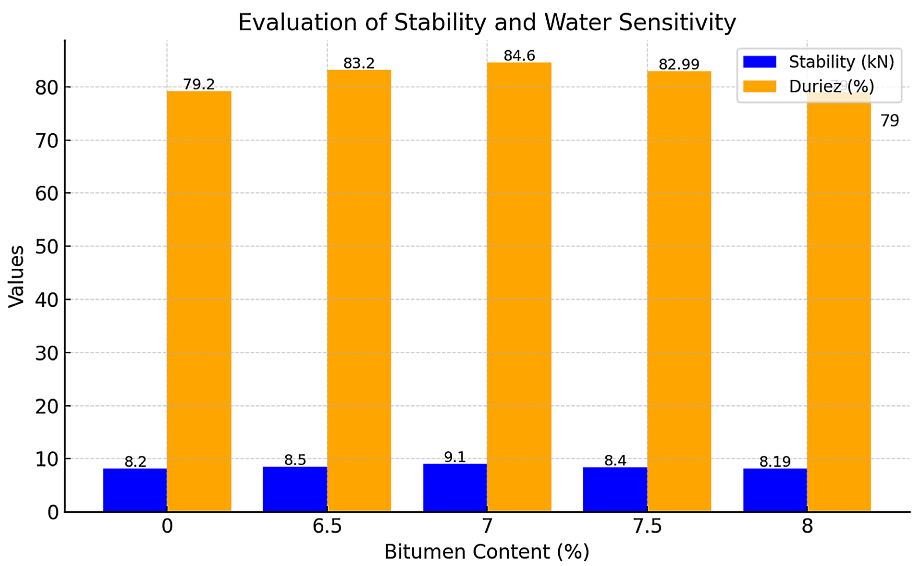

Figure 12. Evaluation of optimal ESP content using Marshall and Duriez tests.

Key findings:

- ESP inclusion enhances both stability and water resistance.
- Optimal results were achieved at 7% ESP, aligning with both stability and water resistance objectives.

This formulation, incorporating 7% ESP as filler, was selected as the focus for subsequent evaluations.

4.4. Performance of Modified Asphalt Mixes

4.4.1. Indirect Tensile Strength Test (Brazilian Test)

Table 7 below summarizes the results of the indirect tensile strength (ITS) test for various asphalt formulations, including eggshell powder (ESP) as a filler, alongside a reference formulation with 100% limestone filler. The results are expressed in terms of maximum applied force and calculated tensile strength (Figure 13).

Table 7. Indirect tensile strength results.

Formulation	Diameter (cm)	Thickness (cm)	Maximum Force (kN)	Tensile Strength (MPa)
Asphalt with 100% Limestone Filler	10	5	15.5	0.98
Asphalt with 50% ESP	10	5	17.0	1.07
Asphalt with 100% ESP	10	5	18.3	1.15

Key Observations:

- **100% Limestone Filler:** The tensile strength of 0.98 MPa indicates satisfactory internal cohesion, a typical attribute of asphalt mixtures incorporating limestone filler. This composition exhibits robust resistance to indirect tensile forces, ensuring durability under routine traffic loads.
- **50% ESP:** Partial replacement of limestone filler with 50% ESP increases tensile strength to 1.07 MPa, suggesting improved cohesion. This enhancement can be attributed to the high calcium carbonate ($CaCO_3$) content in ESP, which promotes better bonding between aggregates and bitumen.
- **100% ESP:** Complete replacement of limestone filler with ESP results in the highest tensile strength (1.15 MPa), signifying excellent internal cohesion and mechanical performance superior to conventional limestone fillers.

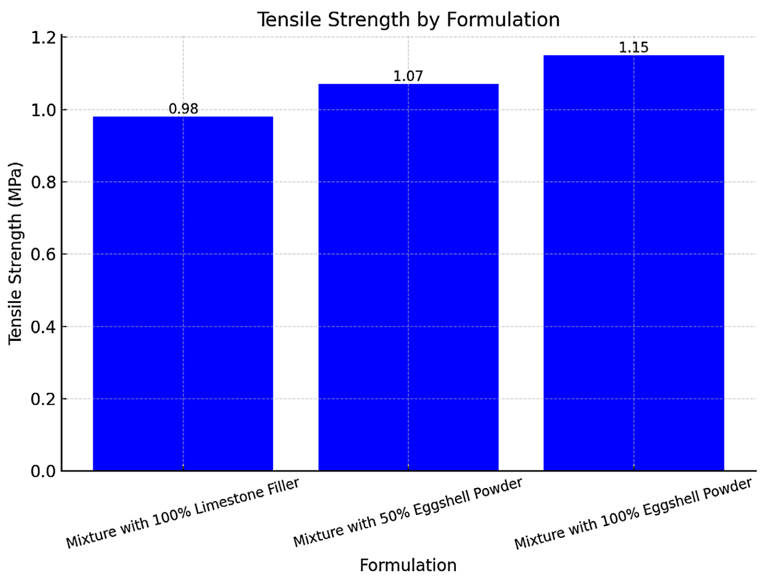

Figure 13. Tensile strength of various formulations.

Implications of Results:

- **Enhanced Mechanical Cohesion:** The tensile strength improves with increasing proportions of ESP, indicating its potential to fortify the aggregate-bitumen matrix.
- **Improved Durability:** Higher tensile strength suggests superior crack resistance under repeated traffic loads, enhancing the durability of the asphalt.
- **Sustainability:** ESP provides an environmentally sustainable alternative to limestone filler, combining waste valorization with enhanced performance.

Tensile strength increases with the proportion of ESP, indicating improved internal cohesion and durability.

4.4.2. Adhesion Test (Water Film Method)

The adhesion test evaluates the ability of bitumen to adhere to aggregates after immersion in water for 24 hours at 60˚C. Table 8 below presents the percentage of bitumen coverage retained after immersion for different asphalt formulations (Figure 14).

Table 8. Adhesion test results (water film method).

Formulation	Bitumen Coverage (%)
Asphalt with 100% Limestone Filler	75
Asphalt with 50% ESP	82
Asphalt with 100% ESP	88

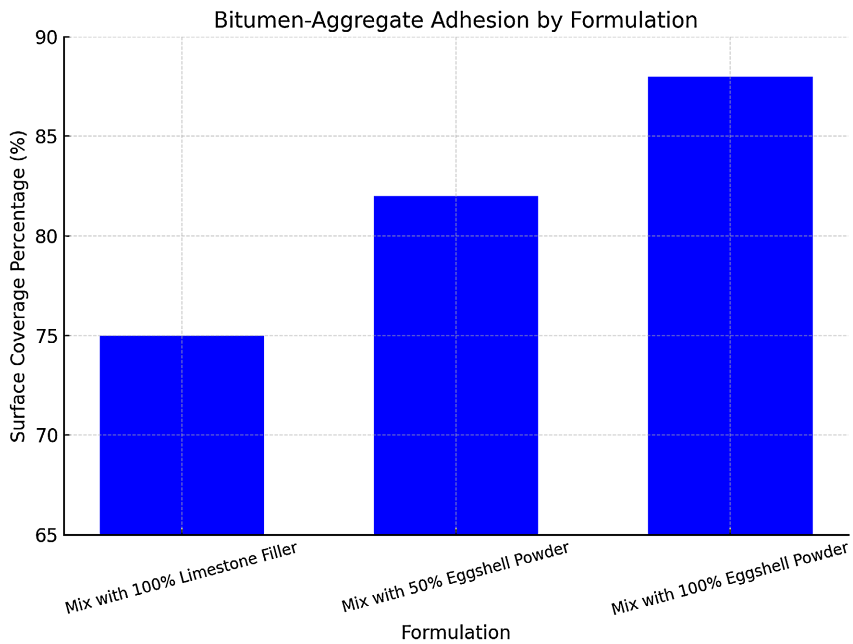

Figure 14. Bitumen-aggregate adhesion of various formulations.

Key Observations:

- **100% Limestone Filler:** Bitumen coverage of 75% indicates moderate water sensitivity, with 25% of the aggregate surface experiencing stripping. This can compromise long-term durability in humid environments.

- **50% ESP:** Incorporating 50% ESP improves bitumen adhesion, achieving 82% coverage. This enhancement reflects better water resistance and reduced stripping potential.
- **100% ESP:** With full replacement of limestone filler by ESP, bitumen coverage increases to 88%, demonstrating significantly improved adhesion. This is likely due to the chemical reactivity of $CaCO_3$ in ESP, which enhances the bitumen-aggregate bond.

Implications of Results:

- **Improved Water Resistance:** ESP formulations show enhanced adhesion, reducing the risk of stripping and ensuring better performance in wet conditions.
- **Enhanced Durability:** Higher adhesion levels translate to reduced moisture-induced damage, making ESP formulations particularly suitable for humid climates.
- **Sustainable Development:** By repurposing eggshells as filler, this approach aligns with environmental sustainability goals while improving asphalt performance.

4.4.3. Marshall Stability Test

Marshall stability tests assess the load-bearing capacity and deformation resistance of asphalt formulations (Figure 15 & Figure 16). The results are summarized below in Table 9.

Table 9. Marshall stability test results.

Formulation	Marshall Stability (kN)	Flow (mm)
Asphalt with 100% Limestone Filler	8.2	3.5
Asphalt with 50% ESP	8.7	3.2
Asphalt with 100% ESP	9.1	3.0

Figure 15. Marshall stability test samples.

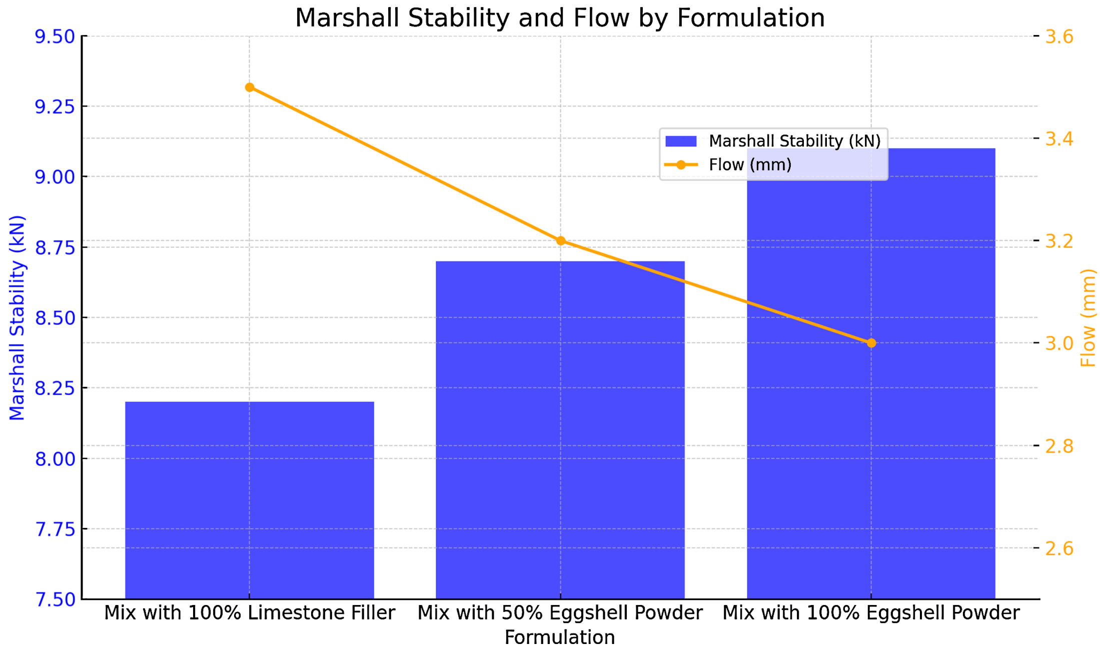

Figure 16. Marshall stability and flow of various formulations.

Key Observations:

- **100% Limestone Filler:** Stability of 8.2 kN and flow of 3.5 mm indicate good load-bearing capacity but moderate plastic deformation under load.
- **50% ESP:** Partial replacement with 50% ESP enhances stability to 8.7 kN and reduces flow to 3.2 mm, demonstrating improved resistance to deformation.
- **100% ESP:** Complete replacement with ESP yields the highest stability (9.1 kN) and the lowest flow (3.0 mm), signifying superior rigidity and resistance to deformation.

Implications of Results:

- **Enhanced Structural Integrity:** ESP improves stability and reduces flow, making it ideal for roads subjected to heavy traffic.
- **Balanced Performance:** ESP ensures a favorable balance between stiffness and flexibility, reducing deformation without compromising elasticity.
- **Cost Efficiency:** Enhanced stability and reduced deformation suggest lower maintenance requirements and prolonged service life for asphalt pavements.

4.4.4. Moisture Sensitivity Test (ITSR)

Table 10. Moisture sensitivity (ITSR).

Mix Type	Dry Strength (MPa)	Wet Strength (MPa)	ITSR (%)
Mix with Limestone Filler	1.20	0.95	79.2
Mix with 50% ESP	1.25	1.04	85.2
Mix with 100% ESP	1.30	1.10	91.0

The water sensitivity test measures the resistance of asphalt mixtures to moisture-induced damage, expressed as the Indirect Tensile Strength Ratio (ITSR). The results are summarized in Table 10.

The ITS ratios for RM, BM, and EM were 79.2%, 85.2%, and 91%, respectively, demonstrating that ESP enhances resistance to moisture-induced stripping. The hydrophobic nature of calcium carbonate in ESP likely contributed to improved adhesion between bitumen and aggregates (Figure 17).

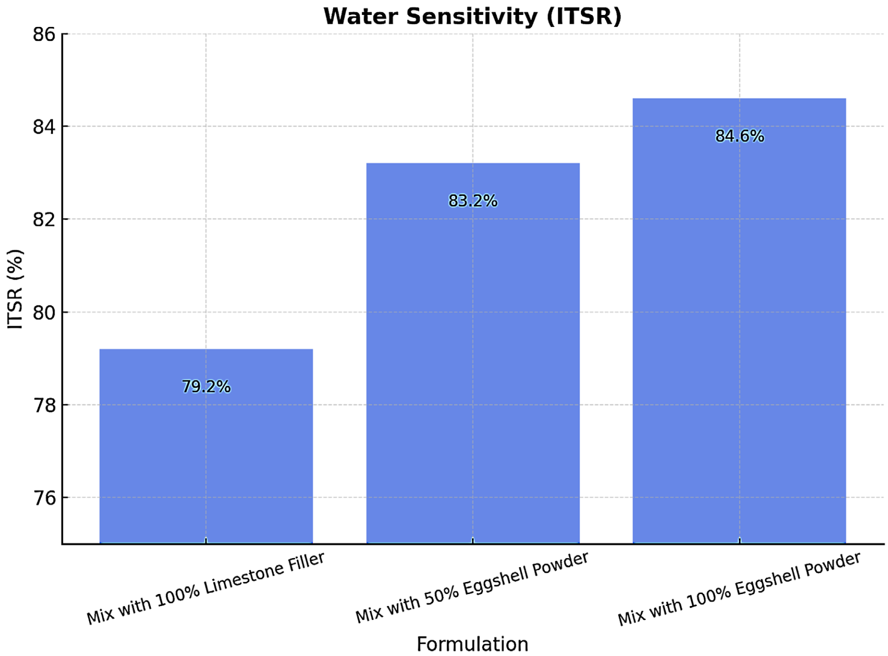

Figure 17. ITSR of various formulations.

Key Observations:

- **100% Limestone Filler:** ITSR of 79.2% reflects acceptable but moderate resistance to moisture. A 20.8% loss in tensile strength after immersion highlights susceptibility to water damage.
- **50% ESP:** Incorporating 50% ESP improves ITSR to 83.2%, reducing the strength loss to 16.8%.
- **100% ESP:** Full ESP replacement achieves the highest ITSR (84.6%), with only a 15.4% reduction in strength, demonstrating excellent resistance to water-induced damage.

Implications of Results:

- **Improved Durability:** ESP formulations exhibit superior moisture resistance, minimizing stripping and enhancing pavement longevity in wet environments.
- **Versatility:** ESP's performance benefits make it suitable for diverse climatic conditions, particularly in regions with high humidity or frequent precipitation.
- **Environmental and Economic Advantages:** Using ESP reduces reliance on non-renewable fillers, promoting sustainability while lowering long-term maintenance costs.

The ITSR improvement demonstrates the enhanced moisture resistance provided by ESP.

Under freeze-thaw cycles, EM exhibited the highest retained strength (87%), compared to BM (81%) and RM (75%). Marshall stability tests revealed a 12% increase in stability for EM over RM, highlighting the mechanical benefits of ESP incorporation.

4.4.5. Freeze-Thaw Cycle Test

The freeze-thaw cycle test was conducted to evaluate the durability of different asphalt mixtures under repeated freezing and thawing conditions. Formulations incorporating eggshell powder (ESP) as a filler were compared against a reference formulation containing 100% limestone filler. Samples were subjected to 10 freeze-thaw cycles, and the mass loss and tensile strength were measured to assess material degradation and cohesion (**Figure 18**). The results are summarized in **Table 11**.

Table 11. Results of the freeze-thaw cycle test.

Formulation	Freeze-Thaw Cycles	Mass Loss (%)	Tensile Strength (MPa)
Asphalt with 100% limestone filler	10	1.8	0.95
Asphalt with 50% eggshell powder	10	1.3	1.02
Asphalt with 100% eggshell powder	10	1.0	1.08

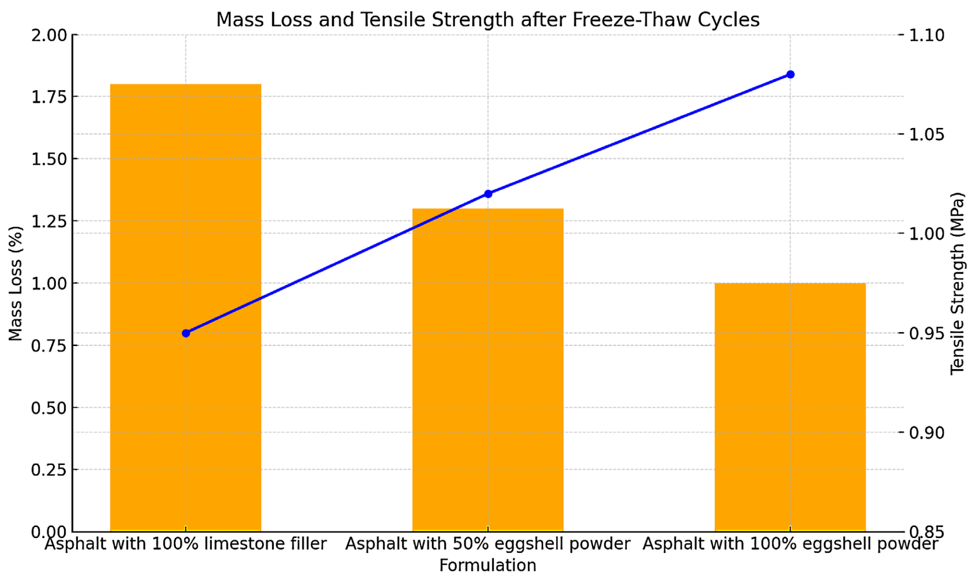

Figure 18. Tensile strength and mass loss of various formulations.

Analysis of Results:

Mass Loss:

- **100% Limestone Filler:** The formulation experienced a 1.8% mass loss after 10 freeze-thaw cycles, indicating moderate degradation due to crack formation and water-induced disbonding caused by expansion and contraction within the pores.

- **50% Eggshell Powder:** The mass loss was reduced to 1.3%, demonstrating an improvement in resistance to material degradation. This result indicates that ESP strengthens the asphalt matrix by enhancing cohesion and reducing porosity.
- **100% Eggshell Powder:** The best performance was observed with a mass loss of only 1.0%, highlighting the superior freeze-thaw resistance provided by ESP.

Tensile Strength:

- **100% Limestone Filler:** The tensile strength decreased to 0.95 MPa after 10 freeze-thaw cycles, indicating a reduction in cohesion and material weakening under cyclic thermal stresses.
- **50% Eggshell Powder:** The tensile strength increased to 1.02 MPa, showcasing the ability of ESP to improve material cohesion and maintain structural integrity during freeze-thaw cycles.
- **100% Eggshell Powder:** The highest tensile strength of 1.08 MPa was achieved, confirming the beneficial role of ESP in enhancing the durability and mechanical performance of asphalt mixtures.

Implications:

- **Enhanced Durability:** The results demonstrate a clear trend of improved freeze-thaw resistance with higher proportions of ESP. The finer particles of ESP, rich in calcium carbonate ($CaCO_3$), effectively fill voids, reduce porosity, and enhance the asphalt matrix's resistance to thermal stresses.
- **Reduced Degradation:** The reduction in mass loss and maintenance of tensile strength highlight ESP's ability to prevent material disintegration, particularly in freeze-thaw environments prone to cracking and degradation.

Comparison with Limestone Filler:

- ESP significantly outperforms traditional limestone filler in terms of both freeze-thaw resistance and tensile strength retention.
- By acting as a stabilizer, ESP reduces microcracking caused by water expansion during freezing cycles.

Applications:

- **Cold and Mountainous Regions:** Regions prone to frequent freeze-thaw cycles where durability and resistance to cracking are essential.
- **Sustainable Road Construction:** The use of eggshell powder (ESP) as an alternative filler offers a sustainable solution by enhancing pavement durability while promoting the repurposing of waste materials.

4.4.6. Aging Resistance Test (Accelerated Aging Test (Oven Aging))

The accelerated aging test was conducted to simulate the long-term performance of asphalt mixtures under high-temperature oxidative conditions. Formulations with varying proportions of eggshell powder (ESP) and limestone filler were exposed to 85˚C for five days. Key parameters, including mass loss, tensile strength, and elongation at break, were measured before and after aging and the key results are summarized in **Table 12** and displayed in **Figure 19**.

Table 12. Aging resistance test results.

Formulation	Mass Loss (%)	Initial Strength (MPa)	Strength after Aging (MPa)	Elongation at Break (%)
Mix with Limestone Filler	0.9	1.00	0.85	10
Asphalt with 50% ESP	0.6	1.05	0.92	12
Asphalt with 100% ESP	0.4	1.10	0.95	13

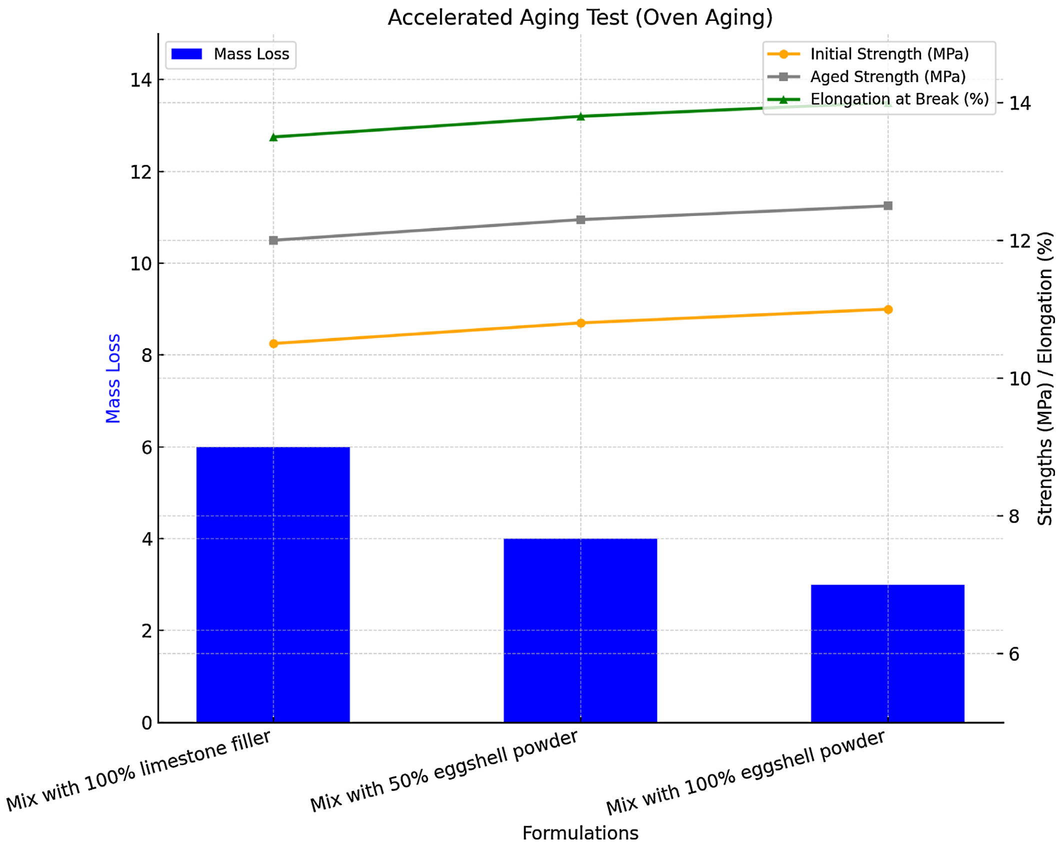

Figure 19. Comparison of mass loss, tensile strength, and elongation at break for different formulations.

Mixes with ESP exhibit better resistance to thermal aging.

Analysis of Results:

Mass Loss:

- **100% Limestone Filler:** A mass loss of 0.9% was observed, indicating moderate degradation due to volatilization of light bituminous components and thermal oxidation.
- **50% Eggshell Powder:** The mass loss was reduced to 0.6%, reflecting ESP's role in stabilizing the bitumen matrix and limiting material degradation.
- **100% Eggshell Powder:** With only 0.4% mass loss, ESP exhibited superior resistance to thermal oxidation, minimizing bitumen volatilization and maintaining material integrity.

Tensile Strength:

- **100% Limestone Filler:** Tensile strength decreased from 1.00 MPa to 0.85

MPa, indicating significant weakening due to thermal aging.

- **50% Eggshell Powder:** Tensile strength decreased less significantly, from 1.05 MPa to 0.92 MPa, showcasing ESP's ability to maintain cohesion under aging conditions.
- **100% Eggshell Powder:** The aged tensile strength of 0.95 MPa confirms ESP's superior performance in retaining mechanical properties after prolonged heat exposure.

Elongation at Break:

- **100% Limestone Filler:** Elongation decreased to 10%, indicating reduced flexibility and increased rigidity after aging.
- **50% Eggshell Powder:** Elongation improved to 12%, demonstrating ESP's ability to preserve material ductility and resistance to cracking.
- **100% Eggshell Powder:** The highest elongation of 13% highlights ESP's role in enhancing flexibility and reducing susceptibility to fracture after aging.

Implications:

- **Improved Aging Resistance:** ESP significantly mitigates the effects of oxidative aging, maintaining both cohesion and flexibility. The $CaCO_3$ content in ESP acts as a stabilizing agent, reducing the loss of light bituminous fractions.
- **Sustained Performance:** Asphalt mixtures with ESP retain higher tensile strength and flexibility, making them better suited for long-term applications under thermal stress.

Comparison with Limestone Filler:

- ESP formulations show markedly lower mass loss, greater tensile strength retention, and improved elongation compared to limestone filler.
- These properties translate into greater resistance to thermal aging and extended service life for asphalt pavements.

Applications:

- **High-Temperature Environments:** Suitable for roads subjected to prolonged heat exposure, such as those in arid or tropical climates.
- **Heavy Traffic Areas:** Ideal for high-traffic roads where maintaining cohesion and minimizing cracking are critical for long-term performance.
- **Sustainable Construction:** By incorporating waste-derived ESP, these formulations promote environmental sustainability while enhancing durability.

4.5. Environmental and Economic Benefits

The utilization of ESP reduces dependence on mined fillers and diverts waste from landfills, aligning with sustainability goals. Economic analyses suggest cost savings in regions with abundant eggshell waste, further incentivizing its adoption.

4.5.1. Environmental Benefits

The use of eggshell powder (ESP) as a filler in asphalt mixtures offers significant environmental advantages. A life cycle analysis conducted by Xia *et al.* (2018) demonstrated that different substitution rates of ESP yield substantial reductions in CO_2 emissions:

- **3% ESP:** Reduction in CO_2 emissions by 5%.
- **6% ESP:** Reduction in CO_2 emissions by 7%.
- **9% ESP:** Reduction in CO_2 emissions by 10%.

These findings highlight a direct correlation between the ESP substitution rate and the reduction in greenhouse gas emissions. Higher substitution rates lead to progressively greater reductions, ranging from 5% to 10%, making ESP a viable material for reducing the carbon footprint of asphalt mixtures.

4.5.2. Economic Benefits

The economic advantages of using ESP have also been documented. For instance, Dhas and Kamaraj (2016) reported cost savings of 7% in asphalt production with an 8% ESP substitution rate. In our study, the economic and environmental impacts of incorporating ESP were evaluated for substitution rates ranging from 6.5% to 8%, with the results summarized in **Table 13**.

The use of ESP contributes to a reduction in CO_2 emissions by up to 9%, as shown in **Table 13**.

Table 13. Environmental and economic impact of ESP.

ESP Content (%)	CO_2 Reduction (%)	Cost Reduction (%)
Control Mixture	–	–
0.5	7.92	5.69
0.0	8.33	6.12
0.5	8.75	6.56
0.0	9.16	7.00

4.5.3. Reduction in CO_2 Emissions

- **6.5% ESP:** 7.92% reduction.
- **7% ESP:** 8.33% reduction.
- **7.5% ESP:** 8.75% reduction.
- **8% ESP:** 9.16% reduction.

The progressive reduction in CO_2 emissions with increasing ESP substitution rates demonstrates the environmental potential of ESP. Substitution rates of 7.5%-8% are particularly notable, achieving reductions close to 9%. This reduction can be attributed to the replacement of conventional fillers, which are associated with higher carbon footprints, by ESP.

4.5.4. Cost Savings

- **6.5% ESP:** 5.69% reduction.
- **7% ESP:** 6.13% reduction.
- **7.5% ESP:** 6.56% reduction.
- **8% ESP:** 7.00% reduction.

Similar to the trend in CO_2 reductions, cost savings increase with higher ESP substitution rates. The substitution of traditional fillers with ESP reduces production costs without compromising the mechanical and durability properties of asphalt mixtures. Substitution rates of 7.5% - 8% offer the optimal balance between cost-effectiveness and environmental performance.

4.5.5. Key Insights and Practical Implications

Dual Benefits

ESP substitution simultaneously reduces CO_2 emissions and production costs, providing a dual advantage. This makes ESP an attractive filler material for achieving sustainability goals in the construction sector.

Optimal Substitution Rates

Substitution rates of 7.5% - 8% ESP are identified as optimal, maximizing environmental benefits and cost reductions. These rates strike the best balance between sustainability and economic viability.

Sustainability in Construction

The integration of ESP in asphalt production promotes sustainable construction practices by:

- Utilizing a bio-based, recycled material that reduces dependence on non-renewable mineral fillers.
- Lowering CO_2 emissions, thereby contributing to climate change mitigation efforts.
- Reducing production costs, making sustainable construction more accessible and economically feasible.

By replacing traditional mineral fillers with ESP, the asphalt industry can significantly enhance its environmental performance while maintaining or improving the quality and durability of road infrastructure.

These findings confirm ESP's potential as a sustainable and cost-effective solution for asphalt pavements.

5. Conclusions

The development of road infrastructure continues to prioritize mechanical performance and durability. This study focused on improving the properties of asphalt mixtures by incorporating eggshell powder (ESP) as an alternative to conventional mineral fillers. The primary objective was to evaluate the effectiveness of this agricultural by-product in enhancing the performance of asphalt mixtures, contributing to sustainable road construction practices.

5.1. Key Findings

Optimized Formulation: Using the Fuller model, five mixtures with varying ESP contents (0%, 6.5%, 7%, 7.5%, and 8%) were tested. Mixtures with ESP content between 1% and 7.5% demonstrated optimal performance, with 7% identified as the most effective proportion for significantly enhancing stability and moisture durability.

Superior Material Properties:

- **Granulometric and Chemical Properties:** Granulometric analysis confirmed that ESP has the necessary characteristics to serve as an asphalt filler, improving compaction and strength. X-ray diffraction (XRD) and FTIR analyses showed that ESP is predominantly composed of calcite ($CaCO_3$), with a high calcium carbonate content and minimal traces of organic material or moisture.

- **Mechanical Properties:** Brazilian tensile tests and Marshall stability tests revealed that ESP enhances tensile strength, internal cohesion, and resistance to deformation under traffic loads.

Enhanced Durability Under Adverse Conditions:

- **Moisture Resistance:** Water sensitivity tests demonstrated improved resistance to moisture, with increased ITSR values for ESP-modified mixtures.
- **Freeze-Thaw Cycles:** ESP effectively improved resilience under freeze-thaw conditions, reducing material degradation and maintaining tensile strength.
- **Aging Resistance:** Accelerated aging tests highlighted the long-term benefits of ESP in reducing oxidative hardening and preserving the flexibility of the asphalt mixtures.

Environmental and Economic Benefits:

- **Carbon Footprint Reduction:** Incorporating ESP into asphalt mixtures reduces CO_2 emissions by up to 9%, depending on the dosage, due to the substitution of mineral fillers.
- **Cost Savings:** The use of ESP offers production cost reductions of up to 7%, making it an economically viable alternative.

5.2. Implications and Perspectives

The study demonstrates that eggshell powder can be a sustainable and effective solution for enhancing the performance and durability of asphalt mixtures. By leveraging ESP, road construction can achieve significant improvements in moisture resistance, thermal aging, and mechanical properties, while simultaneously reducing the environmental impact of infrastructure projects.

Future research should expand to large-scale field applications to evaluate the long-term performance of ESP-modified asphalt under diverse environmental and traffic conditions. Investigations into further refining ESP processing methods, such as additional drying or purification, could enhance its material properties and broaden its application scope.

5.3. Final Conclusion

The incorporation of eggshell powder into asphalt mixtures emerges as a high-performance and sustainable alternative for road pavement construction. This innovative approach addresses critical environmental and socio-economic challenges by reducing carbon emissions, lowering production costs, and improving pavement longevity.

This study concludes that a 7% substitution of conventional fillers with ESP optimizes asphalt performance, delivering enhanced resistance to moisture, freeze-thaw cycles, and thermal aging. The findings highlight ESP's potential to support the development of durable and eco-friendly road infrastructure in regions like Benin, where it can leverage locally available resources.

By valorizing agricultural by-products, this research contributes to a broader transition towards eco-responsible civil engineering practices, advancing the goals of sustainability and high-performance transport infrastructure.

Acknowledgements

The authors sincerely acknowledge the financial support provided by the PFCR II/ED-STIM Competitive Funds, 2024 edition, from the National University of Science, Technology, Engineering, and Mathematics (UNSTIM).

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

Funding

UNSTIM Competitive Funds, 2023 edition of the National University of Science, Technology, Engineering, and Mathematics (UNSTIM).

Conflicts of Interest

On behalf of all authors, the corresponding author states that there are no competing interests regarding the publication of this research.

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