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Potential Usage of Waste Eggshell Powder in Hot Mix Asphalt Modification

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Hot Mix Asphalt (HMA) is a strong and versatile material widely used in road pavement construction. Despite its cost-effectiveness and extensive application, further research is necessary to improve its sustainability. One promising solution involves incorporating waste eggshell powder as a partial replacement for conventional filler materials. In Malaysia, approximately 20 million eggshells are discarded daily, contributing significantly to landfill waste. This issue can be mitigated by reusing eggshell waste in pavement construction as a replacement material. This study investigates the effect of substituting cement with eggshell powder on the performance of HMA mixtures. Control samples were prepared using Ordinary Portland Cement (OPC) at 2% and quarry dust at 4%, while modified samples incorporated eggshell powder sieved through a 75 µm sieve at replacement levels of 25%, 50%, 75%, and 100% by weight of the active filler content. All samples were designed using the Marshall Method and evaluated for strength and volumetric properties. Furthermore, the Tensile Strength Ratio (TSR) test was conducted to assess moisture susceptibility. The results revealed that the modified sample containing 50% eggshell powder exhibited superior stability, improved volumetric characteristics and greater resistance to moisture damage where the increment of TSR value is about 7 % compared to control sample. These findings indicate that waste eggshell powder has significant potential as a sustainable and eco-friendly filler material in HMA production.

Keywords: sustainability; eggshell powder; filler; waste; TSR

I. INTRODUCTION

Hot Mix Asphalt (HMA) is one of the most widely used materials in the construction of flexible road pavements around the world. It is a mixture of well-graded aggregates, filler and bitumen that are heated and combined at high temperatures in a central mixing plant. The heating process with temperature around 150°C ensures proper coating of the aggregates with bitumen, resulting in a durable and cohesive material suitable for various traffic and environmental conditions. Once mixed, the HMA is transported, spread and compacted while still hot to form a dense, smooth and stable pavement surface.

The primary purpose of HMA is to provide a strong and flexible layer that can withstand repeated traffic loads, resist deformation and offer a comfortable and safe driving surface.

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Its performance depends on several factors, including material selection, mixing temperature, compaction quality and layer thickness. Compared to other pavement materials, HMA offers advantages such as high strength, good workability, ease of maintenance and recyclability.

In recent years, sustainability has become an important consideration in HMA production. Researchers and engineers have focused on improving the performance of HMA while reducing environmental impacts through the use of waste materials, recycled asphalt pavement and alternative fillers. These innovations not only lower production costs but also contribute to waste reduction and energy conservation.

In HMA, filler is considered a material that passes through the 75 μm sieve and retains on the pan. It is used to increase bitumen viscosity, strengthen the binding between aggregates, fill the voids between aggregates, minimise moisture susceptibility of the mix (particularly when using hydrated lime filler) and increase stiffness of the overall mixture. According to Jabatan Kerja Raya (JKR) Malaysia (JKR/SPJ/2008-S4) on the design manual for flexible pavements, the filler should constitute approximately 6% of the total HMA mix, with 4% being natural filler and another 2% is mineral or active filler, such as hydrated lime or Portland cement. Mineral filler or known as the active filler help to reduce moisture damage and oxidative aging to the pavement, enhances resistance to rutting and fatigue and also contributes to the overall improvement of the HMA pavement performance (Little & Epps, 2001).

Malaysians consumes and dispose of approximately 20 million eggshells per day (Saparuddin *et al.*, 2020). Most of it is dumped in landfills where it has no further use and may pose environmental and health risks. For example, eggshells tend to attract vermin such as rats which causes serious health issues such as vector borne diseases to nearby communities. Hence, incorporating eggshell powder into HMA offers a potential solution to reduce the amount of eggshell waste disposed of in landfills. Eggshells that are primarily composed of magnesium carbonate, calcium phosphate, some organic matters and large amounts of calcium carbonate is a suitable material to be used as a filler in HMA productions (Puspitasari *et al.*, 2019).

II. REVIEW ON MODIFICATION OF HMA USING EGGSHELLS WASTE

Several studies have been conducted on the modification of HMA using eggshell waste, either as aggregate replacement or as a filler replacement. For instance, a study conducted by Ming *et al.* (2021) investigated the properties of an Asphaltic Concrete Wearing-14 (ACW14) HMA mix incorporating eggshells as a coarse aggregate replacement. Their findings revealed that the performance of the ACW14 HMA mix did not improve when coarse aggregates were replaced with eggshells. According to Marshall test results, an increase in eggshell content led to a decrease in the stability value. This poor performance of the mix may be attributed by the weak mechanical properties of eggshell as indicated by the result of aggregate impact value (AIV) and aggregate crushing value (ACV) conducted on eggshell where the value is 93% and 75% respectively.

Another study conducted by Masued (2019) investigated the properties of wearing course mix incorporating eggshell powder (EP) as mineral filler replacement. Eggshell content was added to the mix in increments of 0%, 3%, 6%, 9%, 12%, 15%, 20%, 25% and 100% of the total Portland cement content. The results showed that 6% eggshell powder was the optimum replacement ratio, as it improved the density, stability, flow and tensile strength of the asphalt mixtures. For instance, based on the stability test results, the mixture containing 6% eggshell powder achieved the highest stability value compared to other percentages and satisfied the Iraqi specifications.

A study conducted by Erfen and Mohd Yunus (2015) investigated the properties of an ACW14 mix incorporating eggshell powder as a filler. The modified samples contained 1.0%, 3.0%, and 5.0% eggshell powder by weight of the optimum bitumen content. The optimum eggshell powder content was determined by comparing the results of stability and flow tests for the different mix configurations. The findings showed that all tested parameters—stability, flow, stiffness, voids in total mix (VTM), and voids filled with bitumen (VFB)—for all variations of the modified samples satisfied the JKR specifications. However, to determine which percentage yielded the best overall performance, it was concluded that the optimum eggshell powder content lies between 3% and 5%.

In 2018, a study conducted by Razzaq *et al.* investigated the properties of HMA mixes incorporating eggshell powder as an additive to bitumen, evaluating both the physical and rheological characteristics of the asphalt mixture and binder. Six Marshall blends, with three samples each, were prepared with eggshell powder contents of 0%, 3.0%, 5.0%, 7.0%, 10.0%, and 15.0% by total weight of asphalt content, using a fixed bitumen content. The findings showed that the density of the mixes increased with the addition of eggshell powder, while Marshall stability also improved as the eggshell powder content increased.

III. MATERIAL PREPARATIONS

The materials used in this study included bitumen, aggregates, filler, cement and eggshell waste. Several laboratory tests were conducted to determine the physical and mechanical properties of these materials.

A. Aggregates

The aggregates used in this study were obtained from local quarries and subjected to sieve analysis to separate them into their respective size fractions. After segregation, the aggregates were stored in different containers to ensure they were readily available during the preparation of Marshall samples. The aggregate gradation limits used in this study followed the specifications for ACW14, as adapted from the JKR and presented in Table 1.

Table 1. Gradation limits of asphaltic concrete retrieved from JKR Standard Specification for Road Works.

Mix Type	**Wearing Course**			
Mix Designation	**ACW14**			
BS Sieve Size (mm)	**Percentage passing by weight (%)**	**Design Gradation (Percentage passing by weight) (%)**	**Design Gradation (Percentage retained by weight) (%)**	**Equivalent weight of aggregates (g)**
20.0	100	100	0	0
14.0	90 - 100	95	5	60
10.0	76 - 86	81	14	168
5.0	50 - 62	56	25	300
3.35	40 - 54	47	9	108
1.18	18 - 34	26	21	252
0.425	12 - 24	18	8	96
0.150	6 - 14	10	8	96
0.075	4 - 8	6	4	48
Pan	0	0	6	72

B. Bitumen

The bitumen used in this study was a 60/70 penetration grade bitumen that complied with all JKR requirements. Several tests were conducted to determine the characteristics of the bitumen, as it serves as the binding agent in the HMA mixture. Table 2 presents the range of bitumen content used for the ACW14 HMA mix.

C. Filler

The filler material constituted 6.0% of the total aggregate weight (1200 g), which is equivalent to 72 g. For the control sample, quarry dust was used as the natural filler at a content of 4.0%, while Ordinary Portland Cement (OPC) served as the active filler at a content of 2.0%.

Table 2. Range of bitumen content for ACW14 HMA mix.

Mix Type	**Bitumen Content (%)**
ACW14 – Wearing course	4.0 – 6.0

D. Eggshell Powder

Before the eggshell powder could be prepared for incorporation in this study, the raw eggshells required pre-treatment to obtain their pure calcite form. Eggshells primarily consist of calcium carbonate ($CaCO_3$), also known as calcite. To obtain pure calcite, the inner membrane of the eggshell must be removed. Various treatment techniques have been reported in previous studies, such as heat treatment and bleach treatment (Cree & Rutter, 2015). Another study utilised an aqueous sodium chloride solution to boil and dry the eggshells to achieve purified calcite (Huang *et al.*, 2022). However, due to the limitations of this study, a traditional treatment method was adopted. The collected eggshells were thoroughly washed, and their membranes were manually removed. The cleaned shells were then oven-dried at approximately 150°C for 24 hours, as proposed by Shcherban *et al.* (2022), to completely remove any moisture content. After drying, the eggshells were allowed to cool to room temperature before being ground into powder using a mechanical grinder or blender. Finally, the eggshell powder was sieved through a 75 µm sieve and the portion passing through was categorized as filler material. This ensured compliance with the ASTM filler material specification, which requires 70% to 100% passing through the 75 µm sieve. Figure 1 and Figure 2 illustrate the flowcharts for obtaining pure calcite and for the eggshell treatment process to produce eggshell powder.

IV. EXPERIMENTS AND TESTING

Several tests were conducted on the aggregates and bitumen to determine their physical and mechanical properties. The Marshall mix design method was employed to determine the Optimum Bitumen Content (OBC) for this study, while the Tensile Strength Ratio (TSR) test was carried out to evaluate the performance of the modified samples.

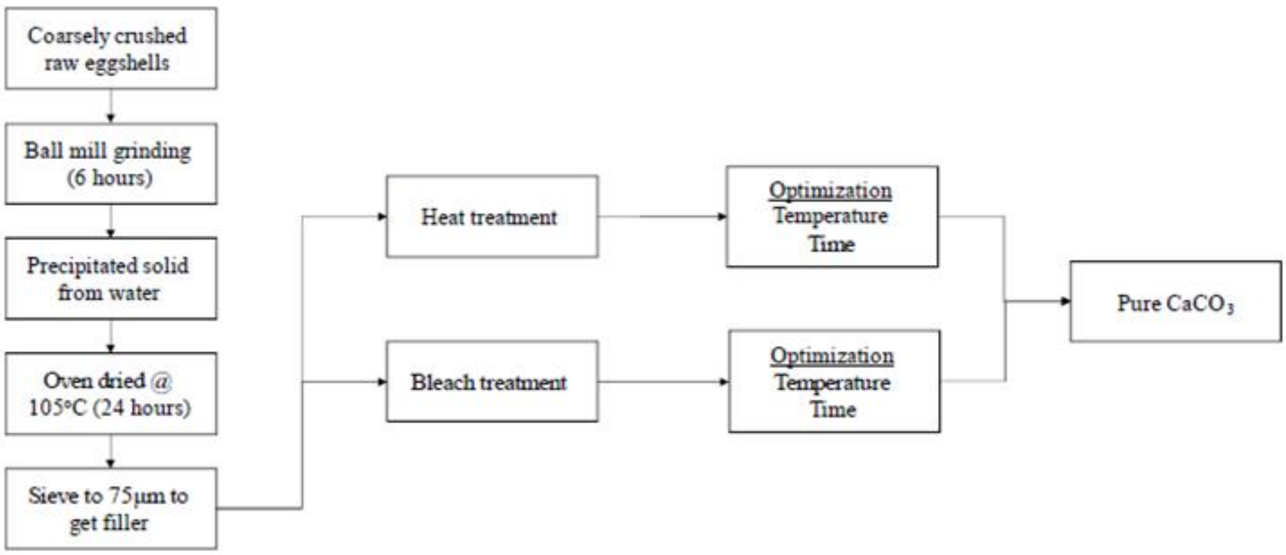

Figure 1. Process to obtain Pure Calcite

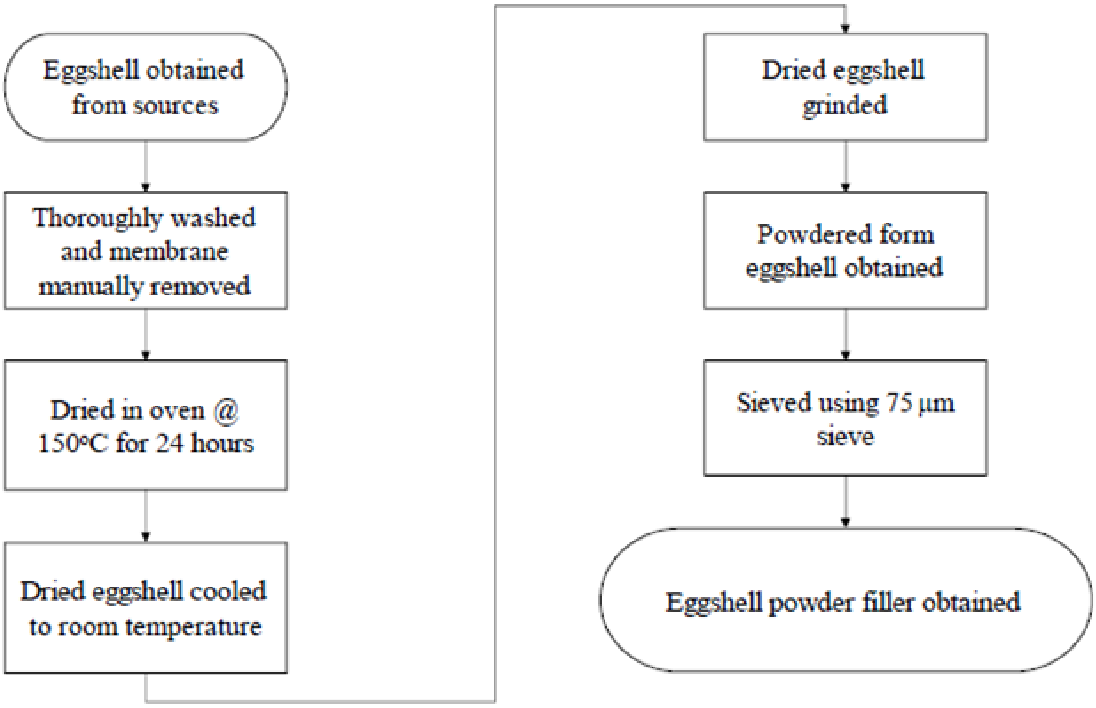

Figure 2. Process for eggshell treatment to obtain eggshell powder.

A. Aggregate Impact Value (AIV) Test

The Aggregate Impact Value (AIV) test provides a comparative measure of an aggregate's resistance to sudden shock or impact. During service, aggregates are subjected to repeated loading from moving vehicles, which may cause them to fracture into smaller particles. Therefore, the aggregates must possess sufficient strength to withstand disintegration due to impact. This test was conducted in accordance with the BS 812-112:1990 standard.

B. Flakiness and Elongation Test

The aggregate shape test for flakiness and elongation characteristics was conducted in accordance with BS 812-105.1:1989 and BS 812-105.2:1990. The proportions of flaky and elongated particles in an aggregate sample determine its particle shape characteristics. The presence of such particles is considered undesirable in base courses and in the construction of bituminous and cement concrete layers, as they can introduce structural weaknesses and increase the likelihood of failure under heavy loads. Therefore, it is essential to evaluate the morphology of the aggregates, particularly with respect to flakiness and elongation.

C. Penetration Test

The penetration test for bitumen serves as an indicator of the material's hardness or consistency. It measures the distance a standard needle penetrates vertically into a bitumen sample under specified conditions of load, time, and temperature. The consistency of bitumen reflects its susceptibility to temperature variations and its resistance to flow, which directly influences the mixture's ability to resist deformation (Suleiman & Rosli, 2011). This test was performed in accordance with ASTM D5-06.

D. Softening Point Test

The softening point test is conducted to determine the temperature at which bitumen softens within a specified range, using the ring-and-ball apparatus immersed in water. As temperature increases, the viscosity of bitumen decreases, causing it to become softer. Therefore, determining the softening point is essential to establish the appropriate temperature for pavement design. This test was carried out in accordance with ASTM D36-09.

E. Ductility Test

The term ductility refers to the ability of bitumen to stretch or elongate under load without cracking, which is essential for accommodating the stresses induced by moving vehicles during road service. The ductility test evaluates the adhesive and elastic properties of bitumen, both of which are crucial for flexible pavement design. The binder must form a continuous, ductile film around the aggregates to ensure proper physical interlocking and durability. Bitumen with inadequate ductility tends to crack under repeated traffic loading, leading to a permeable and deteriorated pavement surface. In this test, ductility is determined by measuring the distance a standard briquette specimen can be stretched before breaking at a specified rate and temperature. The procedure was conducted in accordance with ASTM D113-07.

F. Marshall Mix Design

The Marshall mix design method was adopted in this study to determine the Optimum Bitumen Content (OBC) for the control sample. The mix type used was Asphalt Concrete Wearing Course 14 (ACW14), and the range of bitumen content is presented in Table 2. Three Marshall specimens were prepared for each bitumen content with the increments of 0.5%. The preparation of the Marshall samples followed the ASTM D6926–16 standard. The OBC was determined by averaging the bitumen contents corresponding to the peak points obtained from five plotted graphs:

1. Peak of curve obtained from stability vs. bitumen content graph.
2. Flow equals to 3.0mm from the flow vs. bitumen content graph.
3. Peak of curve taken from bulk specific gravity vs. bitumen content graph.
4. VFB @ 75% for wearing course and 70% for binder course from the VFB vs. bitumen content graph.
5. VTM @ 4% for wearing course and 5% for binder course from the VTM vs. bitumen content graph.

For the modified samples, the Optimum Bitumen Content (OBC) obtained from the control sample was adopted. Four types of modified HMA samples with varying percentages of eggshell powder (EP) were prepared to examine the effect of EP as a filler replacement in the mixture. The percentages of eggshell powder used in this study were 25%, 50%, 75%, and 100%, calculated based on the total weight of the active filler.

G. Marshall Stability and Flow Test

The Optimum Bitumen Content (OBC) of the control sample was determined based on the results of the Marshall stability and flow tests, as well as the analysis of its volumetric properties. Table 3 presents the test parameters related to strength and volumetric characteristics for the ACW14 mix.

Table 3. Test and Analysis Parameters.

Parameters	**Wearing Course**
Stability, S	> 8000 N
Flow, F	2 – 4 mm
Stiffness, S/F	> 2000 N/mm
Voids in total mix (VTM)	3 – 5 %
Voids in aggregate filled with bitumen (VFB)	70.0 – 80.0 %

H. Tensile Strength Ratio (TSR) Test

The AASHTO T 283-03 test method, also known as the Modified Lottman Test, is used to evaluate the effectiveness of additives and to determine the susceptibility of asphalt mixtures to moisture-induced damage, commonly referred to as stripping. Stripping can cause pavement distress such as rutting and fatigue cracking. In this test, two sets of specimens are prepared: wet (conditioned) and dry (unconditioned), which are then subjected to the tensile splitting test. In this study, the wet and dry samples were prepared following the ATJ 5/85 procedure. The conditioned samples were immersed in water at 60°C for 48 hours prior to testing while the unconditioned samples were immersed in water at 25°C for 2 hours.

V. RESULT AND DISCUSSION

The results of the aggregate and bitumen tests are presented in Table 4 and Table 5, respectively. All test results complied with the JKR requirements. Table 6 presents the volumetric properties, Marshall stability and flow values for all mixes, including the control sample and modified samples with different eggshell powder content (EP 25%, EP 50%, EP 75%, and EP 100% mixtures).

Upon careful analysis, it was observed that the sample modified with 50% eggshell powder exhibited the highest stability value among all modified mixtures. Hence, this mix was selected for further evaluation using the tensile strength test. Table 7 presents a comparison of the Tensile Strength Ratio (TSR) between the control, and the 50% eggshell powder modified samples.

As shown in Table 7, the modified mix containing 50% eggshell powder achieved a higher TSR value compared to the control sample. This indicates that the modified mixture possesses lower moisture susceptibility and improved resistance to stripping. These findings are consistent with those reported by Masued (2019), who observed that asphalt mixtures modified with eggshell powder achieved a TSR value of approximately 95.16%, compared to 87.88% for the control sample. This correlation reinforces the relationship between TSR and the moisture susceptibility performance of asphalt mixtures.

In this study, the lower moisture resistance observed in the control samples can be attributed to the surface chemical properties of both the aggregates and the bitumen. Generally, aggregates are classified into two main types: siliceous and calcareous (limestone). Compared to limestone aggregates, which are hydrophobic, siliceous aggregates are hydrophilic and therefore more prone to stripping. Mertens and Wright proposed an alternative classification system, suggesting that both siliceous and limestone aggregates are inherently hydrophilic but differ in their electrochemical characteristics. They introduced the terms electropositive and electronegative to describe limestone and siliceous aggregates, respectively. Electropositive aggregates possess a positive surface charge, whereas electronegative aggregates have a negative surface charge (Hicks, 1991).

Bitumen, whose primary constituent is carboxylic acid, carries a negative charge. As a result, the interaction between bitumen and electronegative aggregates is characterised by weak bonding due to charge repulsion. When exposed to moisture, hydrophilic aggregates tend to attract water molecules, displacing the bitumen film and weakening the adhesive bond between the binder and the aggregates (D'Hooghe, 2010).

Eggshell powder, which mainly consists of calcium carbonate with a positively charged surface, can enhance adhesion between the asphalt binder and aggregates by neutralising opposing surface charges. This electrochemical stabilisation leads to stronger bonding and reduced stripping potential, thereby improving the mixture's resistance to moisture damage. Consequently, the modified samples containing eggshell powder exhibited higher Tensile Strength Ratio (TSR) values compared to the control samples, confirming their superior moisture susceptibility performance.

Table 4. Result for Aggregate Test.

Test	Result	Requirement	Specification
AIV	23.5%	< 30%	BS882:1992
Flakiness	12.7%	< 25%	JKR/SPJ/2008
Elongation	18.7%	< 30%	MS 30

Table 5. Result for Bitumen Test.

Test	Result	Requirement	Specification
Penetration	64 d-mm	60 – 70 d-mm	ASTM D5-06
Softening Point	53°C	N/A	ASTM D36-95
Ductility	1289 mm	> 1000 mm	MS124:1996

Table 6. Volumetric Properties and Marshall Test Results for Control and Modified Mixes.

Eggshell Powder Content (%)	OBC (%)	VTM (%)	VFB (%)	Stability (N)	Flow (mm)	Stiffness (N/mm)
Specifications	4.0 - 6.0	3.00 – 5.00	70.00 – 80.00	> 8000	2.00 – 4.00	> 2000
0	5.1	4.99	75.00	14945.10	4.50	3321.13
25	5.1	2.65	88.89	15292.80	4.80	3186.00
50	5.1	3.55	83.22	16159.70	5.15	3137.81
75	5.1	4.50	77.88	14077.20	5.92	2377.91
100	5.1	4.71	76.61	14727.90	4.66	3160.49

Table 7. Tensile Strength Ratio (TSR) Results.

Sample	TSR (%)	ATJ 5/85 Specification	AASHTO Specification
Control	87	> 75%	70 -80 %
Modified (50% EP)	93		

VI. CONCLUSION

The modified sample containing 50% eggshell powder exhibited the highest stability value compared to both the other modified samples and the control sample. In terms of the Tensile Strength Ratio (TSR), both the modified and control samples satisfied the minimum requirements specified by the Jabatan Kerja Raya (JKR) and AASHTO standards. Owing to the chemical composition of eggshell powder, which is primarily calcium carbonate, the modified sample demonstrated superior moisture resistance compared to the control mix where the increment of TSR value is about 7 % compared to control sample.

Therefore, it can be concluded that waste eggshell powder possesses significant potential for application as a filler material in the road pavement industry. Its incorporation in Hot Mix Asphalt (HMA) not only enhances the mechanical performance of the mixture but also contributes to environmental sustainability by reducing the volume of eggshell waste disposed of in landfills.

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