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ARTICLE

The effect of replacing aggregates with oyster shell powder on the performance of asphalt concrete

Efecto de la sustitución de áridos por polvo de concha de ostra en el rendimiento del hormigón asfáltico

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Abstract: In response to the global trend towards achieving net zero emissions, various industries are actively promoting the circular economy. Central to this goal is the strategic utilization of alternative materials to replace virgin materials, thereby reducing carbon emissions during the production and manufacturing processes. This study uses the maximum density line in the FHWA 0.45 power curve to determine the oyster shell powder (OSP) as a substitute for 6% of the fine aggregate and filler in dense-graded asphalt concrete (DGAC). With properties similar to calcium carbonate ($CaCO_3$) and hydrated lime, the inclusion of OSP was expected to enhance the performance of DGAC. For the Experimental Group, 6% of the fine aggregate and filler were replaced with OSP in the DGAC. The control groups used natural aggregate without hydrated lime anti-strip additive (Control Group A) and with hydrated lime anti-strip additive (Control Group B) in the DGAC. The aim was to assess the impact of replacing partial fine aggregate and filler with OSP on the performance of AC. The results indicated that while the Marshall stability, Marshall flow, and indirect tensile strength test values of the Experimental Group were lower than those of Control Group B, they were consistent with the results of Control Group A and complied with AI MS-2 7th. Subsequent evaluations, including the boil test, immersion-compression test, and tensile strength ratio, were conducted to assess moisture damage resistance. This revealed that the Experimental Group and Control Group B exhibited comparable and superior moisture damage resistance compared to Control Group A. Additionally, the Experimental Group outperforms the Control Groups in the Cantabro abrasion test. In summary, the OSP as a substitute for 6% of the fine aggregate and filler enhances the performance of AC, providing effects similar to hydrated lime anti-strip additives and increases moisture damage resistance. This study confirms that using recycled materials such as OSP to replace aggregates in AC, contributing to the goals of energy-saving and carbon reduction in road engineering.

Keywords: Oyster shell powder; Dense-graded asphalt concrete; Fine aggregate; Mineral filler; Moisture damage resistance; Pavements.

Resumen: En respuesta a la tendencia global hacia el logro de cero emisiones netas, varias industrias están promoviendo activamente la economía circular. Un elemento central de este objetivo es la utilización estratégica de materiales alternativos para reemplazar materiales naturales, reduciendo así las emisiones de carbono durante los procesos de producción y fabricación. Este estudio utiliza la línea de densidad máxima en la curva de potencia FHWA 0.45 para determinar el polvo de concha de ostra (OSP) como sustituto del 6% del árido fino y el filler en el hormigón asfáltico de granulometría densa (DGAC). Con propiedades similares al carbonato de calcio ($CaCO_3$) y la cal hidratada, se esperaba que la inclusión de OSP mejorara el rendimiento del DGAC. Para el Grupo Experimental, el 6% del árido fino y el filler se reemplazó con OSP en el DGAC. Los grupos de control utilizaron árido natural sin aditivo antidesprendimiento de cal hidratada (Grupo de Control A) y con aditivo antidesprendimiento de cal hidratada (Grupo de Control B) en el DGAC. El objetivo fue evaluar el impacto del reemplazo parcial del árido fino y el filler con OSP en el rendimiento del AC. Los resultados indicaron que, si bien los valores de estabilidad Marshall, flujo Marshall y resistencia a la tracción indirecta del Grupo Experimental fueron inferiores a los del Grupo de Control B, fueron consistentes con los resultados del Grupo de Control A y cumplieron con AI MS-2 7.ª edición. Se realizaron evaluaciones posteriores, incluyendo la prueba de ebullición, la prueba de inmersión-compresión y la relación de resistencia a la tracción, para evaluar la resistencia al daño por humedad. Esto reveló que el Grupo Experimental y el Grupo de Control B exhibieron una resistencia al daño por humedad comparable y superior respecto al Grupo de Control A. Además, el Grupo Experimental supera a los Grupos de Control en la prueba de abrasión de Cantabro. En resumen, el OSP como sustituto del 6% del árido fino y el filler mejora el rendimiento del AC, proporcionando efectos similares a los aditivos antidesprendimiento de cal hidratada y aumentando la resistencia al daño por humedad. Este estudio confirma que el uso de materiales reciclados como el OSP para reemplazar áridos en AC contribuye a los objetivos de ahorro de energía y reducción de carbono en la ingeniería vial.

Palabras clave: Polvo de concha de ostra; Hormigón asfáltico de granulometría densa; Árido fino; Filler mineral; Resistencia a los daños por humedad; Pavimentos.

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Supplementary information ↓

1. INTRODUCTION

With a trend towards achieving net zero carbon emissions and implementation of carbon border adjustment mechanisms (CBAM), there is a concerted effort to reduce reliance on virgin materials in engineering. People are actively utilizing by-products and waste from various industries as alternative materials to decrease the use of virgin materials. Studies that have explored different approaches for adding recycled materials to asphalt concrete have shown the potential in reducing the need for virgin aggregate and have been linked to changes in the aggregate-binder interfacial properties (1, 2).

Shell waste, such as oyster shells, mussel shells, and scallop shells, originating from the fishing industry, are abundant in certain regions but are often disposed of or landfilled without being reused. According to the Food and Agriculture Organization of the United Nations (FAO), the annual global oyster production is about 5.5 to 6 million metric tons. Oysters mainly come from Asian countries such as China, Japan, South Korea and Taiwan. These oyster shells are often discarded or buried everywhere, causing environmental problems. Oyster shells are typically hard and corrosion-resistant. Previous studies have confirmed their beneficial effects when incorporated into both cement concrete and asphalt concrete (3).

The drastic temperature fluctuations from extreme weather conditions, erosion caused by abundant rainfall, and excessive traffic loads contribute to an increased susceptibility of asphalt concrete pavement to damages such as rutting and stripping, consequently reducing service life. Adding anti-strip additives such as hydrated lime and cement to asphalt concrete is a good approach to stop rutting and stripping. This strategy seeks to improve asphalt concrete's stiffness, ductility at low temperatures, resistance to moisture damage, and aging of the asphalt binder (4). However, the extraction of virgin materials for hydrated lime and cement production contributes to environmental degradation, while the manufacturing process also increases the emission of carbon dioxide and greenhouse gases.

In many countries, oyster shell powder (OSP) is commonly utilized in applications such as animal feed, composting, and seedling cultivation. Taiwan generates over 190,000 metric tons of oyster shells as a waste product annually. In recent years, some companies, such as Taiwan Sugar Corporation in Taiwan (one of the largest enterprises in Taiwan's agricultural industry), have actively recycled waste oyster shells and reused them in medical, biotechnology, building materials, fertilizer, feed and other fields. However, too many waste oyster shells still pose an environmental burden to Taiwan, which is a small and densely populated country. There is no literature regarding the use of OSP to replace fine aggregates in asphalt concrete. Also, there is no comparison of the performance between asphalt concrete with OSP replacing fine aggregates and asphalt concrete using natural aggregates with added anti-strip additives. This study proposes the utilization of OSP to replace a portion of the fine aggregate in asphalt concrete and to serve as a substitute for hydrated lime or cement typically used as anti-strip additives in asphalt concrete. This approach aims to reduce reliance on river sand and gravel, which are used extensively due to rapid economic development. Additionally, this provides a sustainable outlet for waste oyster shells and enhances moisture damage resistance, thereby improving the quality of asphalt concrete pavement.

2. LITERATURE REVIEW

2.1. Oyster shell powder (OSP)

Due to variations in the marine environments that oysters inhabit, the size and composition of their shells can differ; however, their primary component is calcium carbonate ($CaCO_3$), typically comprising over 95% of the overall composition, classifying them as a natural calcium-based material (5). The processing of waste oyster shells can be categorized into calcined and uncalcined forms. After cleaning and coarse crushing, the shells may be subjected to high-temperature calcination, during which the main chemical component transforms into calcium oxide (CaO) (6, 7), as shown in Table 1. If not calcined, the shells retain their original calcium carbonate ($CaCO_3$) composition (5).

Table 1. Chemical composition of OSP.

Chemical composition (%)	Fishery Bulletin (5)	Lee (6)	Hsu and Chen (7)
SiO_2	0.16	2.17	29.78
Al_2O_3	---	1.10	5.58
Fe_2O_3	---	0.33	1.34
CaO	54.6	54.30	57.87
MgO	0.33	0.75	0.02
SO_3	0.16	0.45	0.05
K_2O	---	---	0.09
CO_2	43.5	---	---
Na_2O	0.32	---	---
SrO	0.12	---	0.12
H_2O	0.58	---	---
Basicity	---	---	2.13
Ignition loss	---	37.62	---

Shu *et al.* (8) stated that seashell powder is thought to enhance the performance of flexible pavement against all types of damage, including the three major distresses of rutting, fatigue cracking, and low-temperature cracking.

According to García *et al.* (9), seashells are utilized as the aggregate in concrete, but there has been no research yet on their use in hot mix asphalt (HMA). The use of seashells as aggregates in concrete and mortar has been assessed. According to test results, seashell cannot be regarded as aggregate because its qualities do not match those of coarse aggregates. As a result, it was tested as a mortar. However, because the mixture containing the seashells was intended to be utilized as structural concrete, the results were compared with the specifications. In order to ensure that seashells are used properly, the purpose of the study was to discover more about their mechanical, chemical, and physical characteristics.

Seashells of molluscs were used as filler aggregates in an experimental study conducted by Bezerra *et al.* (10). Mortar specimens with mass additions of 0%, 5%, 10%, 15%, 20%, and 30% to Portland cement were prepared. After being ground, the seashells passed through the 325-mesh sieve (0.044 mm). X-ray fluorescence and X-ray diffraction (XRD) were used to characterize the material. Seashell powder in two different states were examined: raw and burned. The results confirmed the effect of the filler material, indicating that it might be used as a partial replacement for cement.

Kuo *et al.* (11) substituted 5, 10, 15, and 20% waste oyster shells for fine aggregates and 20% fly ash for cement in order to assess the practical usage of waste oyster shells as controlled low-strength materials (CLSM). The findings showed that replacing sand with 20% waste oyster shells did not significantly lower the compressive strength. Waste oyster shells can be a good substitute for sand and a source of pure calcareous materials in CLSM with the proper application.

Arabani *et al.* (12) evaluated the usage of seashell as a replacement of virgin filler in HMA. Indirect tensile fatigue, indirect tensile strength, and permanent deformation tests were used to evaluate the properties of HMA mixtures. The findings showed that the fatigue life and permanent deformation of HMA at various temperatures were improved by the use of seashells as a mineral filler. Additionally, it was shown that the mixtures with seashells showed lower moisture susceptibility than conventional HMA. The study showed that seashell dust might be utilized as a filler material in HMA when available.

Mo *et al.* (13) examined the properties of different types of seashell waste and how integration affects the both fresh and hardened properties of concrete. Given the significant calcium oxide content, seashell waste may be an inert substance, much like limestone. Seashell waste might still be used as a partial aggregate at a replacement level of up to 20% for concrete used for non-structural purposes.

Nciri *et al.* (14) examined the impacts of various OSP fractions (such as 0, 5, 10, and 15 weight percent) on bitumen performance. Fourier transform-infrared spectroscopy, X-ray diffraction, thin layer chromatography–ionization detection, and scanning electron microscopy (SEM) were used to investigate the chemical characteristics of unfilled and OSP-filled asphalts. In comparison to plain asphalt, the results presented that a higher dose of OSP changed the binder's morphology, while lower and intermediate doses increased thermal stability and improved low-temperature, fatigue, and rutting performance. These findings confirm those of Arabani *et al.* (12).

Ruiz *et al.* (15) performed permanent deformation, indirect tensile strength, and moisture susceptibility tests – all common in Perú – to examine the characteristics of HMA mixtures with seashells. According to the findings, seashells can be added as a fine aggregate to HMA to increase its permanent deformation and indirect tensile strength. When compared to traditional HMA, seashells in decreased moisture susceptibility and raised the tensile strength ratio (TSR) by 22–262%.

In open-graded asphalt mixtures, Alharthai *et al.* (16) examined the replacement of conventional aggregate with a Florida washed shell and assessed the optimal percentage of substitution in aggregate gradations of different nominal maximum aggregate sizes (NMASs), such as 4.75, 9.5, and 12.5 mm. The Florida washed shell was used in laboratory experiments on specimens at different percentages (0, 15, 30, 45, and 100%) to substitute coarse aggregate with sizes ranging from 2.36 to 12.5 mm. The findings demonstrated that substituting Florida washed shell for the coarse aggregates had no significant effect on the indirect tensile strength and Marshall stability.

Wang *et al.* (17) used a modified asphalt material with waste oyster shells to prepare an asphalt binder of waste OSP. SEM analysis was used to examine the microstructure of OSP. FT-IR spectroscopy was used to determine the asphalt binder's chemical composition. The findings showed that the waste OSP was a biomass with an irregular, porous petal shape, and when it was mixed with asphalt, no new, distinctive absorption peaks appeared. Additionally, the thermal stability, viscosity, and temperature-sensitive properties of asphalt were enhanced by the addition of waste OSP.

Bamigboye *et al.* (18) used a water/cement ratio of 0.5, a concrete mix ratio of 1:2:4, and different proportions of granite 20 mm as coarse aggregates, 4.75 mm river sand as fine aggregates, and 2.5 mm seashells as fine aggregates to assess the eco-friendly concrete. Compressive strength had a substantial correlation with splitting tensile strength and a large negative correlation with seashell percentage, according to correlation and regression analysis.

Utilizing high-speed shear equipment, Fan *et al.* (19) prepared 10, 20, and 30% seashell powder-modified asphalt (SPMA) and stratum corneum-exfoliated seashell powder-modified asphalt (SCESPMA) accordingly utilizing seashell powder and SCESP. The findings demonstrated that the primary component of seashell powder and SCESP, CaCO3, is physically miscible with asphalt and that they are both rough and porous. The complex shear modulus (G*) and phase angle (δ) of SPMA and SCESPMA rise and fall, respectively, when the loading frequency falls between 0.1 and 10 Hz.

Ajah and Mbadike (20) found that adding oyster shell ash improved the asphalt concrete's flow and stability. While the content of oyster shell ash rose, so did void in mineral aggregate (VMA) and void filled with asphalt (VFA); conversely, while asphalt content rose, void in the mixture decreased and VFA increased. In comparison to the sample without oyster shell ash, the investigation also demonstrated that the asphalt concrete with oyster shell ash-filled increased in stiffness and stability. The results demonstrated the potential of oyster shell ash as an economical and environmentally friendly filler for asphalt concrete.

Hu *et al.* (21) created OSP modified asphalt by adding 40 mesh OSP to matrix asphalt up to 3, 6, 9, 12, 15, and 18% in order to investigate the impact of OSP on the mechanical properties of asphalt and the mechanism of OSP modification on asphalt. The findings demonstrated that OSP significantly affects asphalt's mechanical characteristics and that adding OSP improves asphalt's technical performance. According to the research, an OSP content of 12% had the best modification effect and the most impact on asphalt's mechanical properties. These findings confirm those of Arabani *et al.* (12).

The additive materials, like High Density Polyethylene (HDPE) waste and oyster shell ash, are able to increase the stability of porous asphalt. The chemical properties of oyster shell ash, which are comparable to those of calcium and silica, increase durability and lock the aggregate and pavement. HDPE is a binder that can enhance the bond between the aggregate and oyster shell ash, reinforcing the porous asphalt mix. Rani *et al.* (22) analyzed the ideal percentage of oyster shell ash filler and HDPE waste as replacement in asphalt pen 60/70.

2.2. Moisture damage in asphalt concrete pavement

Coarse aggregate, fine aggregate, mineral filler, and asphalt binder are compacted in the proper amounts to create DGAC. Despite its superior waterproofing capabilities and low permeability, repeated traffic loads and exposure to wet, humid weather can weaken the adhesive bond between the aggregate and the asphalt binder film, greatly raising the risk of stripping (23, 24). Evaluation of moisture susceptibility in asphalt concrete primarily involves qualitative methods such as the boil test (25) and quantitative methods such as the immersion–compression test. The boil test provides a rapid assessment of the susceptibility of asphalt concrete to stripping when exposed to water but may be influenced by operational factors. The immersion–compression index is the ratio between the Marshall stability values of dry and wet specimens. Xiao *et al.* (26) proposed ways to improve the boil test (25) for evaluating water-induced damage to asphalt concrete using digital imagery. In addition to the qualitative and quantitative methods, AI MS-2 7th (27) incorporates two evaluation methods: the TSR test (28) and the Hamburg wheel-tracking test (29).

2.3. Mineral filler and anti-strip additive in asphalt concrete

In asphalt concrete, a typical mineral filler completely passes a 1.18 mm (No. 16) sieve, with at least 70% of the particles passing the 0.075 mm (No. 200) sieve (30, 31). Air voids within asphalt mixtures are filled with filler. The filler strengthens the stiffness of asphalt mixtures by forming asphalt mastics with enhanced hardness and reduced temperature susceptibility when mixed with asphalt binder (32). Mineral filler shall consist of finely divided mineral matter such as rock dust, slag dust, hydrated lime, hydraulic cement, fly ash, loess, or other suitable mineral matter (31). Hydrated lime, which is mostly made of CaO, has potent adsorption properties that make it easier for it to bind with the asphalt binder when it is adhered to aggregate surfaces. As an anti-strip additive, 1% hydrated lime is usually added to asphalt concrete to enhance its stiffness, increase resistance to moisture damage, and improve durability and resistance to rutting (33). Furthermore, recycled fines obtained from dust collection equipment in asphalt plants are most commonly used as filler.

In conclusion, it is evident from the literature that in humid and rainy environments, rainwater is a primary factor causing damage to asphalt concrete pavement. Adding anti-strip additives such as hydrated lime or cement to asphalt concrete can reduce the surface tension between the asphalt binder and the aggregates, allowing the asphalt binder to fully coat the aggregates and enhance the adhesive bond between them. This effectively increases the moisture damage resistance of asphalt mixtures and improves pavement performance. Additionally, the literature suggests that the use of the boil test, immersion–compression test, and TSR test could effectively assess the moisture susceptibility of asphalt concrete.

In Taiwan, the processing of waste oyster shells into OSP is highly developed. OSP is widely used in commercial products such as soil stabilizers and animal feed additives. Relevant literature has explored the use of finely ground OSP as modifiers in asphalt binder by pre-mixing with the asphalt binder to alter the rheological properties, thereby enhancing the performance of asphalt mixtures. Additionally, oyster shells have been used as coarse aggregates in open-graded hot-mix asphalt concrete to improve asphalt concrete strength, moisture damage resistance, cracking resistance, and moisture susceptibility. However, there is no literature regarding the use of OSP to replace fine aggregates in asphalt concrete. Also, there is no comparison of the performance between asphalt concrete with OSP replacing fine aggregates and asphalt concrete using natural aggregates with added anti-strip additives. This study focuses on DGAC and aims to investigate the impact of replacing a portion of the fine aggregate and filler with OSP on the performance of asphalt concrete.

3. EXPERIMENTAL DESIGN

3.1. Materials

This study conducted performance comparisons using DGAC specimens with a 19.0 mm (3/4-inch) NMAS. The materials used are described as follows:

1. Natural coarse and fine aggregates: Natural river sand and gravel provided by an asphalt plant were used as natural coarse and fine aggregates.
2. Filler and anti-strip additive in asphalt concrete: The term of "filler" in this study refers to materials passing the 0.075 mm sieve, including both conventional mineral filler such as hydrated lime and recycled fines obtained from dust collection equipment in asphalt plants. Hence, recycled fines from an asphalt plant were used as filler. Additionally, hydrated lime purchased from a building materials supplier was added to the asphalt concrete of the Control Group as an anti-strip additive.
3. OSP: According to the product information provided by the OSP manufacturer used in this study, the waste oyster shells are collected in a dry state, eliminating the need for wastewater treatment. The collected waste oyster shells undergo coarse crushing and screening, followed by high-temperature calcination in a rotary kiln. The increased surface area resulting from coarse crushing enhances the efficiency of calcination. To reduce energy consumption,

the calcination temperature is maintained below 300°C, allowing simultaneous drying and sterilization. The calcined shells are then finely ground, and the particle size of the resulting OSP is controlled through the adjustment of grinder speed and sieve aperture. Further pulverization and sieving are performed based on specific application requirements, yielding approximately 20 kg per bag and resulting in the OSP used in this study. This production process reflects standard industrial practices for OSP manufacturing. In 2024, OSP sells for about USD 0.32~0.47/kg in Taiwan, which is more economical than the price of hydrated lime which is USD 0.63~0.95/kg. It is noted that temperature, dissolved oxygen saturation, suspended matter and other conditions in different sea areas will cause differences in the composition of OSP. The properties of OSP from different sources should be evaluated before the reuse of OSP.

According to the product information provided by the OSP manufacturer used in this study, its chemical composition is mainly $CaCO_3$, with small amounts of MgO, SiO_2, and Al_2O_3. This is consistent with the findings reported in the relevant literature (10, 12).

4. Asphalt binder: Following the recommendations from the Thickness Design - Asphalt Pavements for Highways and Streets (AI MS-1) (34) and considering Taiwan's average temperature of approximately 24.3°C in 2023, the asphalt binder grad of AC-20 was used for the experiment.

3.2. Experimental configuration

Recycled fines is commonly mixed in asphalt concrete as filler and to enhance moisture damage resistance. Anti-strip additives such as hydrated lime are often added. The experimental setup is listed in Table 2. The Experimental Group involves replacing a portion of the fine aggregates and the entire mineral filler required in the mix design with OSP. Control Group A consisted of asphalt concrete using natural aggregates without added hydrated lime as an anti-strip additive. Control Group B consisted of asphalt concrete using natural aggregates with added hydrated lime as an anti-strip additive. DGAC specimens were prepared for each group and their performances were evaluated.

Table 2. Experimental configuration.

Group	Detail
Experimental Group	Using OSP to replace 6% of the fine aggregates and the entire filler required in the mix design; recycled fines and hydrated lime are not included.
Control Group A	Natural aggregates without hydrated lime anti-strip additive; 2.8% recycled fines are included as filler.
Control Group B	Natural aggregates with 2.8% of hydrated lime anti-strip additive; recycled fines are not included.

3.3. Determining the gradation curve and aggregate blending ratio

Aggregate gradation is a crucial factor to the performance of asphalt concrete. In the early 1960s, the Bureau of Public Roads (today's FHWA) introduced a gradation chart which is an especially useful tool in evaluating aggregate gradations. The chart uses a horizontal scale, which represents sieve size openings in inches (millimeters) raised to the 0.45 power, and a vertical scale that represents percent passing. An important feature of the 0.45 power chart is the maximum density line. The maximum density line plots as a straight line from the maximum aggregate size to the origin of the chart. As part of the mix design process, the aggregate gradation can be plotted on the 0.45 power gradation chart. Based on the results of sieve analysis, this study utilized the maximum density line to determine the optimal replacement level of OSP, thereby obtaining the best mixture ratio of OSP to aggregates.

In addition, according to AI MS-2 7th, the gradation and blending operations normally result in an aggregate size distribution based on percentage of mass. Volumetric properties such as air voids and VMA are directly impacted by the amount and size of aggregate particles and the resulting packing characteristics in the final mixture. A gradation can give insight to the final volumetric properties in a particular mixture. However, when the specific gravities of the individual aggregates differ or vary significantly (by 0.20 or more), the blended gradation, based on the mass of the aggregates, may have different volumetric characteristics when compared to an equivalent gradation of materials with similar specific gravities. Therefore, when blending asphalt concrete, if the difference in the specific gravities between different aggregates is equal to or greater than 0.2, it is necessary to adjust the percent passing.

3.3.1. OSP replacement ratio

The study initially attempted a 10% substitution of fine aggregate and entire filler with OSP. However, at this substitution rate, the gradation curve deviated from the maximum density line. Using a trial-and-error method, the substitution rate was gradually reduced by 2% increments down to 6%. The aggregate size distribution curve closely aligns with the maximum density line as shown in Figure 1. Moreover, due to the significant difference in specific gravity between OSP and natural coarse and fine aggregates exceeding 0.2, adjustments were made to the percent passing, as indicated in Table 3. Subsequent research procedures were based on the adjusted percent passing.

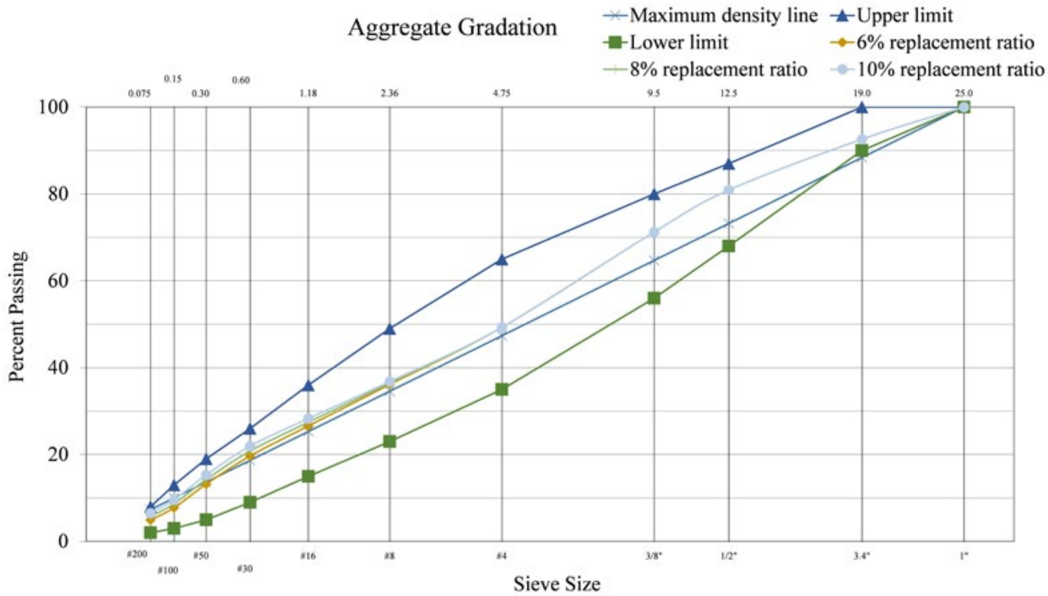

Figure 1. The aggregate size distribution curves for different OSP replacement ratios.

Table 3. Adjustment of the percent passing.

Material	Percent passing before adjustment (%)	Specific gravity	Weight (g)	Percent passing after adjustment (%)
3/4”	20	2.618	52.36	20.1
3/8”	26	2.599	67.57	26.0
1/4”	15	2.607	39.11	15.0
Sand	33	2.620	86.46	33.3
OSP	6	2.407	14.44	5.6
Total	100		259.94	100

3.3.2. Blended percentages of aggregates for each experimental configuration

Typically, multiple stockpiles of aggregate are blended to meet the final specified requirements. To avoid the influence of different gradations on the performance of asphalt concrete, the study used the gradation with 6% replacement of OSP to configure the blended percentages of aggregates for the

Experimental Group, Control Group A, and Control Group B, as shown in Table 4. It is noted that the 6% of OSP was used to replace the partial fine aggregates and the entire filler required in the mix design. Recycled fines and hydrated lime were not used in the Experimental Group.

Table 4. The blended percentages of aggregates in each experimental configuration.

Material / Group name	3/4″	3/8″	1/4″	Sand	OSP	Recycled fines	Hydrated lime
Experimental Group	20%	26%	15%	33%	6%	-	-
Control Group A	20%	26%	15%	36.2%	-	2.8%	-
Control Group B	20%	26%	15%	36.2%	-	-	2.8%

3.4. Marshall method of mix design

Marshall Method of Mix Design has been developed for many years and is widely used due to its simplicity, low cost, and few instrument requirements. The study employed AC-20 asphalt binder for the Marshall Method of Mix Design conducted on the Experimental Group, Control Group A, and Control Group B to determine the optimum asphalt content. The aggregate gradation and recommended asphalt content for each group were determined as shown in Figure 2. The curve of 6% replacement ratio in Figure 1 is the curve of the Experimental Group in Figure 2. The curves of Control Group A and Control Group B are the same and overlap in Figure 2.

In the equiviscous method, the viscosity of the asphalt binder is determined at two test temperatures, establishing a relationship between temperature and viscosity as the mixing and compaction temperature chart. Compaction temperatures are determined where the viscosity-temperature line crosses the compaction viscosity range of 0.28 ± 0.03 Pa-s. Mixing temperatures are determined where the viscosity-temperature line crosses the mixing viscosity range of 0.17 ± 0.02 Pa-s (27). According to AI MS-2 (27), the compaction temperature range of 141 to 145°C and the mixing temperature range of 151 to 157°C are determined in this study, as shown in Figure 3.

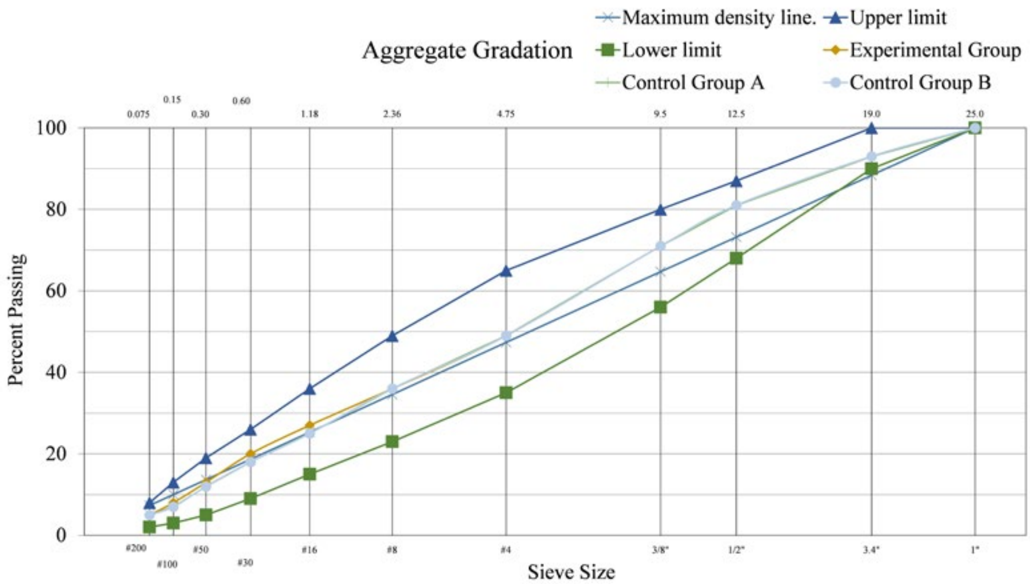

Figure 2. The aggregate size distribution curve of each experimental configuration.

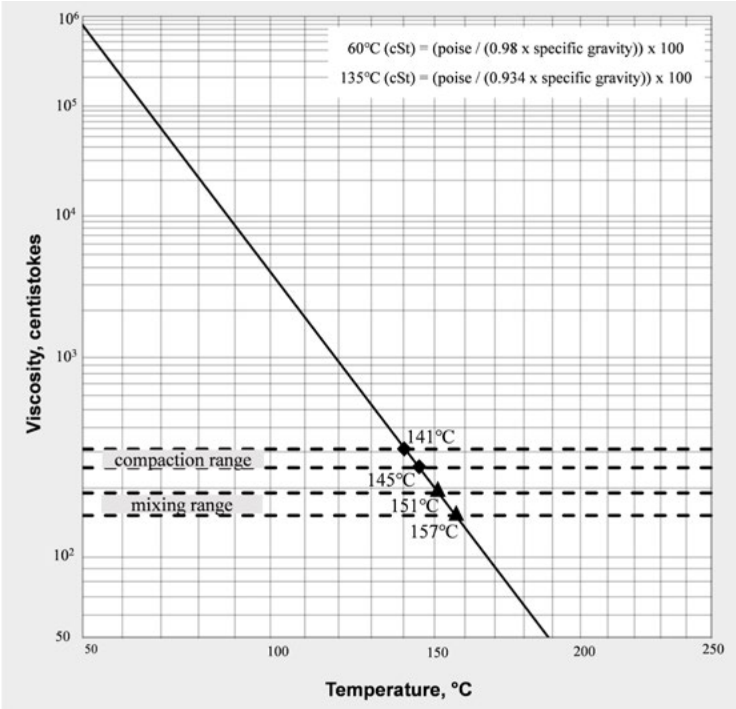

Figure 3. Mixing and compaction temperature chart.

3.5. Performance testing

To understand the impact of replacing a portion of the fine aggregates and filler in asphalt concrete with OSP, the study followed the Marshall Method of Mix Design to prepare asphalt concrete specimens for the Experimental Group and two Control Groups. The specimens were subjected to Marshall stability, Marshall flow, immersion–compression, indirect tensile strength, TSR, boil, and Cantabro abrasion tests. By comparing the Experimental Group and the two Control Groups, the study aimed to evaluate the effects of adding OSP on the performance of asphalt concrete.

4. RESULTS AND ANALYSIS

4.1. Basic properties testing

4.1.1. Sieve analysis

The aggregates used in this study included 3/4”, 3/8”, 1/4”, sand, and OSP. Sieve analysis tests revealed that 43.2% of the OSP passed the No. 200 (0.075 mm) sieve, with a fineness modulus of 0.73. This indicates that the particle size was sufficiently fine to replace both the fine aggregates and the entire filler in asphalt concrete.

During the treatment process, OSP was crushed and sieved. Sieve analysis conducted in this study confirmed that its particle size meets the requirements for mineral filler in asphalt mixtures (27).

4.1.2. Physical properties

The physical properties of the coarse aggregates, fine aggregates, OSP, recycled fines, and hydrated lime (anti-strip additive) used in this study all met the specifications. However, it is important to note that the maximum specific gravity among the aggregates was 2.620 for sand, while the minimum was 2.407 for OSP, resulting in a difference of 0.253, which exceeded the acceptable limit of 0.2. Therefore, adjustments to the percent passing during aggregate blending were necessary. The test results shown in Table 5.

Table 5. Physical properties.

Material / Test item	Aggregates				OSP	Recycled fines	Hydrated lime
	3/4"	3/8"	1/4"	Sand			
Specific gravity	2.618	2.599	2.607	2.620	2.407	2.492	2.334
Water absorption rate (%)	0.44	0.54	1.04	1.13	---	---	---

4.1.3. Asphalt binder

The basic properties of the AC-20 asphalt binder grade used in this study, as shown in Table 6, all met the requirements for AC-20 in ASTM D3381 (35).

Table 6. Basic properties of AC-20 asphalt binder.

Test	Test value	Requirements for AC-20 (35)
Penetration (25°C), 100 g, 5 s	60	≧ 40
Flash point, Cleveland open cup (ºC)	>230	≧ 232
Viscosity (60ºC, poise)	2250	2000 ± 400
Viscosity (135ºC, poise)	435	≧ 210
Viscosity (60°C, poise) (Tests on residue from thin-film oven test)	3860	≦ 10,000
Ductility (25°C), 5 cm/min, (cm) (Tests on residue from thin-film oven test)	75+	≧20
Specific gravity	1.033	-

4.2. Scanning electron microscope (SEM) and visual observations

To address the differences in particle morphology, this study performed its analysis with SEM imaging and visual observations in Figure 4 and Figure 5, respectively. The results of SEM are as follows:

1. OSP

- The particles appear flaky or irregularly fragmented, with incomplete boundaries, cracks, and fracture marks. Internal textures, pores, and translucent areas are visible, indicating a loose structure.
- Compared with recycled fines and hydrated lime, OSP exhibits more pores between particles as well as microcracks within individual particles. Due to its higher porosity, asphalt binder is more easily adsorbed or infiltrated into the particle interiors, which reduces the effective asphalt content for coating the aggregate surface. Consequently, to achieve the proper air voids in the mix design, a higher asphalt content is required. Thus, incorporating OSP leads to a relatively higher asphalt content.

2. Recycled fines

- The particles are generally more intact, with clearly defined edges. Although some irregularities exist, the overall morphology is relatively dense. The particle surfaces appear as dark, block-like structures with low translucency, reflecting a compact internal structure. This suggests that recycled fines, having undergone multiple cycles of compaction and crushing, possess relatively low porosity.

3. Hydrated lime

- The particles show higher translucency and appear fine, flaky, and flocculent in structure. They are densely stacked, with almost no large pores, and display a uniform distribution, indicating that hydrated lime has high fineness and strong filling capability.

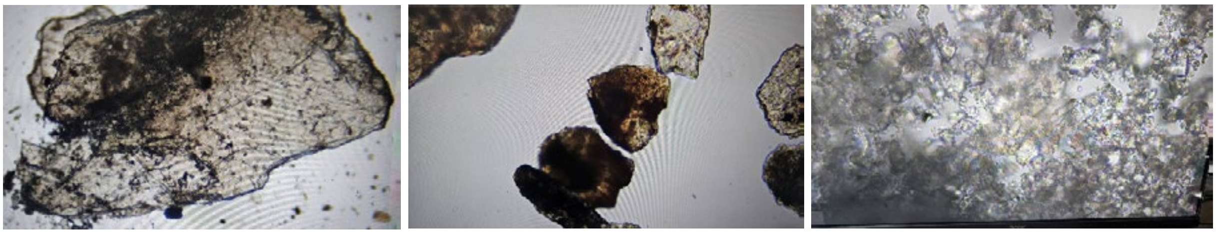

Figure 4. SEM: OSP (100x) (left); recycled fines (100x) (middle); hydrated lime (400x) (right).

The results of visual observations are as follows:

1. OSP

- The material appears whitish with brownish tones. Particle sizes vary considerably, with some flaky and some blocky forms. Clear gaps are visible between particles, along with fractured edges, indicating a relatively fragile structure prone to generating irregular fragments.
- Consistent with SEM observations, OSP exhibits more cracks and pores, and when stacked, the higher porosity results in lower filling capacity compared with recycled fines and hydrated lime.

2. Recycled fines

- The material is dark gray in color, consisting of very fine powder. Particles are uniform, with high fineness, visually resembling “powdery agglomerates.” The porosity between particles are minimal, and the overall appearance is compact.
- Consistent with SEM observations, recycled fines have been finely ground, with almost no visible cracks or pores.

3. Hydrated lime

- The material is whitish in color. The particles are slightly coarser than recycled fines but remain powdery in form. The texture is loose, and visually it tends to appear “agglomerated yet easily dispersible.”
- Consistent with SEM observations, hydrated lime consists primarily of fine powder-like particles, exhibits good filling capacity, and contains low porosity.

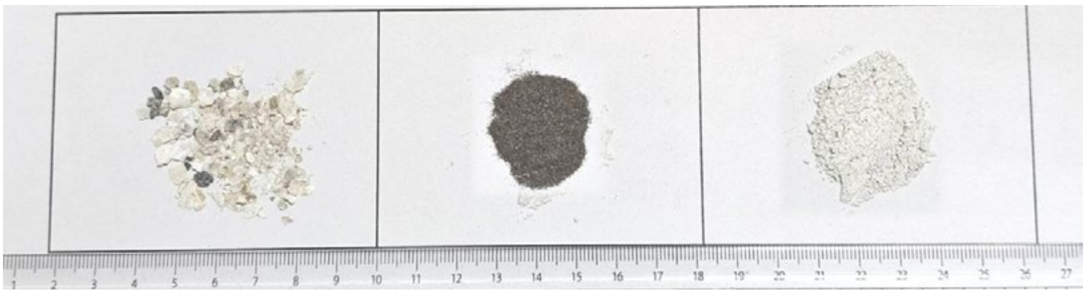

Figure 5. Visual observations (cm): OSP (left); recycled fines (middle); hydrated lime (right).

The OSP particles exhibited rough surfaces and irregular shapes; recycled fines were more uniform and exhibit high fineness, appearing as very fine powder; while hydrated lime particles were even finer and tend to be spherical. These differences in particle morphology affected packing density and the coating behavior of the asphalt binder, which in turn influenced the deformation resistance of the asphalt mixtures (33). Moreover, OSP particles have rough surfaces and relatively high porosity, which facilitate the distribution and coating of asphalt binder and thereby improve the interfacial adhesion of the asphalt mixture (14, 21).

4.3. PERFORMANCE TESTING RESULTS

In order to minimize possible experimental errors, for each performance test, the study produces three specimens for the Experimental Group, Control Group A and Control Group B respectively, and calculates the average of the three specimens as the results of each group for comparison.

4.3.1. Marshall stability test

Marshall stability is the peak resistance load obtained during a constant rate of deformation. Marshall stability represents the asphalt concrete's resistance to failure, and the test results are shown in Figure 6(a). The reference value of Marshall stability is ≥ 8006 N (816 kgf) (27). The results indicate that the asphalt concrete of Control Group B exhibited the highest stability, while the Experimental Group and Control Group A showed similar stability values. The stability values for all groups met the requirements of AI MS-2 7th.

The similarity in Marshall stability among the three groups can be attributed to the control of gradation using the maximum density line, ensuring sufficient compaction of the aggregates and promoting interlocking effects between them. However, OSP likely has a lower crushing strength than natural aggregate, which reduces the asphalt mixture's resistance to load (14, 20). This may explain the slightly lower stability of the Experimental Group compared to Control Group A and Control Group B. Nevertheless, the reduction in Marshall stability remains within the limits specified by the standards, indicating that OSP as a substitute has only a limited impact on the overall structural strength of the pavement. Additionally, the addition of hydrated lime to asphalt binder contributes to stiffening, resulting in the superior performance of Control Group B in terms of stability.

4.3.2. Marshall flow test

Marshall flow is a measure of the deformation (elastic plus plastic) of the asphalt concrete specimen determined during the stability test. A high flow value indicates that the asphalt concrete is susceptible to permanent deformation under traffic loads, while a low value suggests a propensity for cracking. The reference value of Marshall flow is 8–14 (0.25 mm) (27). The test results, as depicted in Figure 6(b), indicate that the Experimental Group and Control Group A had higher flow values compared to Control Group B. This may be because OSP likely has a lower crushing strength than natural aggregate in Experimental Group. Control group B has the lowest flow value due to the stiffening when adding hydrated lime to the asphalt binder. This implies that when using OSP as a substitute for aggregates, caution should be exercised to avoid excessive traffic loads. However, the average flow values of all three groups met specifications.

Previous literature has indicated that OSP possesses a lower crushing strength than natural aggregates, primarily due to its porous structure (14, 20). This characteristic reasonably explains why the Experimental Group exhibited lower Marshall stability (Figure 6(a)) and higher Marshall flow (Figure 6(b)) than Control Groups A and B. Additionally, the replacement levels of OSP and filler (Table 4), as determined by the maximum density line, may also influence the results of Marshall stability and Marshall flow.

4.3.3. Immersion–compression test

The ratio between the stability of the conditioned subset of specimens and the unconditioned subset of specimens is the index of retained stability. The retained stability index is used to assess the moisture damage resistance between asphalt binder and aggregates. The reference value of immersion–compression test is ≥ 75% (36). The test results, depicted in Figure 6(c), indicate that the Experimental Group and Control Group B demonstrated comparable and superior moisture damage resistance, respectively, compared to Control Group A. This suggests that OSP enhances the bonding between asphalt binder and aggregates, thereby improving the moisture damage resistance of the asphalt concrete.

4.3.4. Indirect tensile strength test

Indirect tensile strength test is used to analyze mixtures to assess their low temperature cracking performance. The indirect tensile strength test is also utilized to assess the bonding condition and tensile resistance under moisture damage. Mixture with indirect tensile strength less than 200 kPa was defined to have poor rut resistance, while with indirect tensile strength greater than 320 kPa was defined to have good rut resistance properties (37-39).

The test results, illustrated in Figure 6(d), indicate that Control Group B exhibited the highest indirect tensile strength, followed by the Experimental Group. This suggests that adding hydrated lime anti-strip additive to asphalt concrete or using OSP to replace a portion of the fine aggregate and entire filler can effectively enhance the material's resistance to tensile failure. Conversely, Control Group A showed the lowest indirect tensile strength.

4.3.5. Tensile strength ratio (TSR)

TSR compares the average indirect tensile strength of wet specimens to that of dry specimens. It assesses the degree of stripping between asphalt binder and aggregates caused by pore water pressure. TSR is calculated by dividing the average indirect tensile strength of the three conditioned (wet) specimens by the average indirect tensile strength of the three unconditioned (dry) specimens. According to AASHTO T 283 test (28, 40), the moisture sensitivity evaluation on mixtures without anit-strip agent indicates the minimum requirements for moisture sensitivity of 80% TSR with visual confirmation. Furthermore, the contractor's TSR result is verified if the TSR result is above 0.80 (41). Most agencies use a minimum value of TSR = 80% in the moisture sensitivity test (42). In addition, the target minimum value for TSR is 75%. Mixes with a TSR value meeting the target minimum are considered suitable for mix production and will not require the use of a liquid anti-strip additive (43).

In this study, three specimens were prepared for the Experimental Group and two control groups to determine the average TSR values. As depicted in Figure 6(e), the TSR values for the Experimental Group and Control Group B were both above 80%, indicating that both OSP and hydrated lime anti-strip additive could reduce the stripping effects of pore water pressure. OSP effectively improves the adhesion between aggregates and asphalt binder. This is attributed to its rough surface texture and the main component of OSP after calcination, CaO, with strong adsorption properties, which enhances adhesion. When CaO adheres to aggregates, it can reduce the surface tensile strength between asphalt binder and aggregates, allowing the asphalt binder to fully wrap aggregates. However, the TSR value for Control Group A was above 80%, at about 80.7%. This suggests that asphalt concrete using natural aggregates without hydrated lime anti-strip additive has a relatively lower indirect tensile strength under moisture exposure.

Existing literature has demonstrated that fillers rich in CaO exhibit stronger adsorption capabilities. This enhances the adhesion between aggregates and asphalt binder and reduces moisture susceptibility. Abuawad *et al.* (4) and Arabani *et al.* (12) suggested that the addition of OSP can increase the asphalt mixture's resistance to moisture damage, improve interfacial bonding characteristics, and thereby enhance durability, which explains the superior moisture damage resistance observed in the Experimental Group (Figure 6(c) and Figure 6(e)).

4.3.6. Boil test

The boil test is a quick and easy visual indication of chemical incompatibility between the asphalt binder and aggregate. The specimens are produced manually using mixing facility in the laboratory to prepare each group of 2,000 g loose asphalt mixture. A specimen of loose asphalt mixture is placed in boiling water for 10 minutes and then removed. The extent of retained asphalt coating on the aggregate is then evaluated relative to a nonconditioned specimen. The boil test is an example of a loose mix test that is used to characterize the bonding between the asphalt and aggregate (adhesion). When the aggregates are mixed in the laboratory with the designated grade of asphalt, the coating area shall be greater than 95% (44). The test results depicted in Figure 6(f) indicate that the Experimental Group and Control Group B exhibited minimal stripping after boiling, with the asphalt mixture retaining its glossy appearance. This demonstrates that OSP could enhance the moisture damage resistance of asphalt concrete. In contrast, Control Group A showed more stripping, particularly at the location marked by a red circle in Figure 6(g).

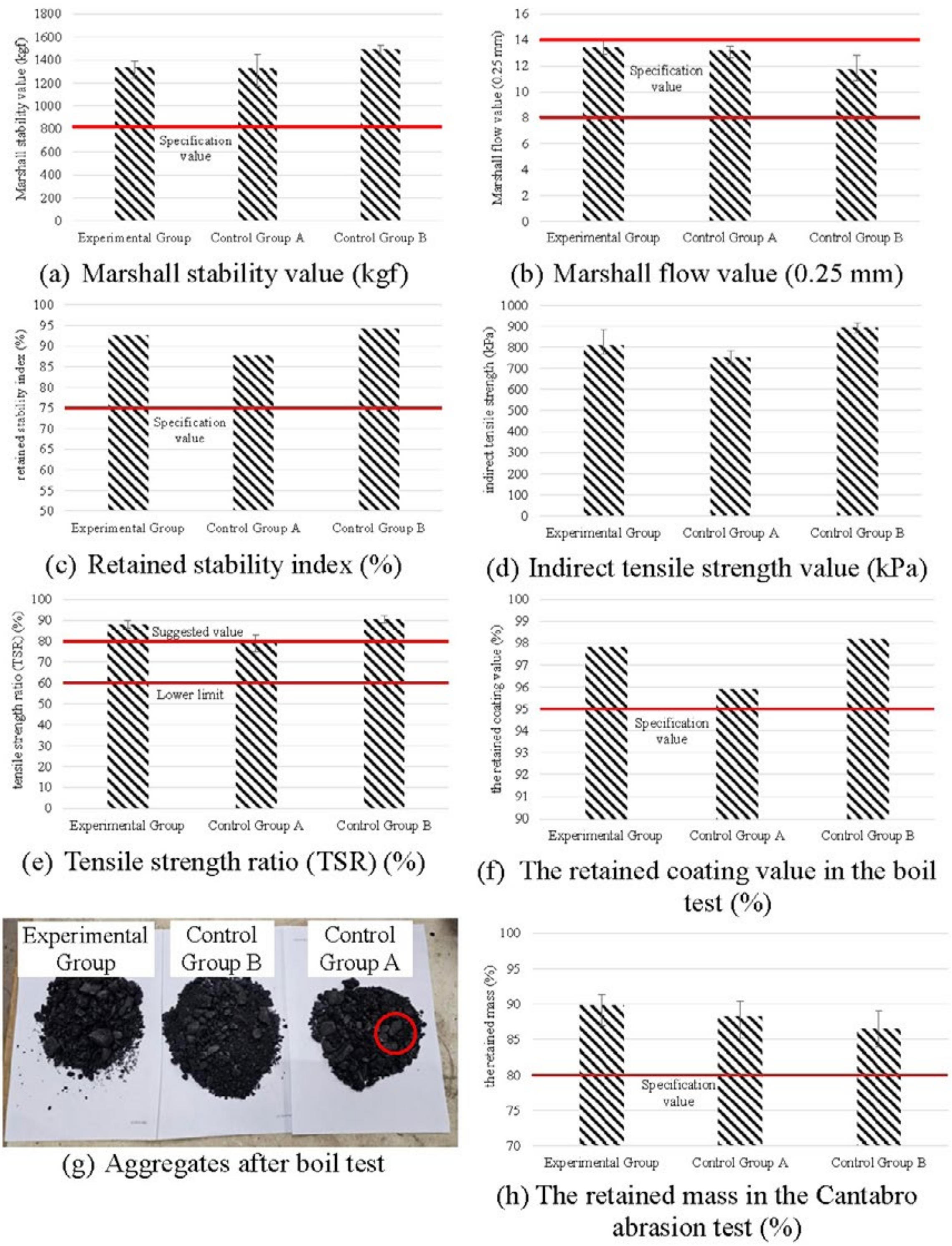

Figure 6. Performance testing.

4.3.7. Cantabro abrasion test (45)

The Cantabro abrasion test determines the particle loss of the laboratory-compacted cylindrical specimens of asphalt mixtures after completion of a specified number of revolutions. The particle loss is assessed by the loss of mass of asphalt samples after turns in the Los Angeles machine. The results are expressed as retained mass (%). According to EN 12697-17 (45), the recommended maximum mass loss is 20%, which corresponds to a retained mass of at least 80%. Therefore, the acceptance threshold is indicated at 80%. This test enables the estimation of the abrasion resistance of asphalt mixtures under traffic loads and friction.

The percent of weight loss is said to be an indication of durability and is related to the quantity and quality of binder utilized. The results, as shown in Figure 6(h), indicate that the Experimental Group exhibited the best performance in resisting aggregate abrasion. This is likely attributed to the addition of OSP. In order to meet mix design requirements, a slightly higher asphalt content was used, which provided more asphalt binder to coat the aggregate. Moreover, the rougher surface and greater porosity of OSP particles facilitated the distribution and coating of asphalt binder (21), which enhances the bonding between asphalt binder and aggregates, thereby improving the bonding between aggregates and enhancing their resistance to abrasion. This not only reduced the abrasion of the asphalt mixture but also confirmed the capacity of OSP to improve the distribution and coating of asphalt binder.

4.3.8. Asphalt content

Due to the rough and highly absorptive surface of OSP particles, a higher asphalt content is required (12). Therefore, to meet the requirements for mix design, the Experimental Group was formulated with a slightly higher asphalt content. The increased asphalt content not only improved the coating and adhesion between aggregates and asphalt binder but also enhanced the abrasion resistance in the Cantabro abrasion test (Figure 6(h)). These findings are consistent with the results of Hu *et al.* (21), who reported that increasing asphalt content improved the durability of OSP-modified asphalt mixtures.

5. CONCLUSIONS AND FUTURE WORK

To understand the effect of the addition of OSP on asphalt concrete performance, this study replaced 6% of the fine aggregate and entire mineral filler required in the mix design with OSP in the Experimental Group. Control Group A consisted of asphalt concrete with natural aggregates without hydrated lime anti-strip additive, while Control Group B included asphalt concrete with natural aggregates and hydrated lime anti-strip additive. Various performance tests were conducted on specimens from each group, yielding the following findings:

- This study has included an in-depth discussion of the research findings, comparing them with previous literature (4, 5, 8, 10, 12, 14, 20, 21, 33). This discussion highlights both the consistency of our results with existing studies and the novel contributions of this research.
- The properties of OSP are similar to hydrated lime and met the specifications for fine aggregates, allowing it to replace natural aggregates and entire filler in asphalt concrete. This study controlled the aggregate gradation using the maximum density line and limited the 6% replacement of OSP to fine aggregate. Although the replacement rate of OSP is limited due to aggregate gradations, it is already demonstrated that the addition of OSP performs well in asphalt concrete. The specific replacement rate will vary depending on various engineering designs and requirements. In addition, it is important to note that OSP has a lower specific gravity than natural aggregates, requiring adjustment of the aggregate's percent passing during aggregate blending.
- Results from the retained strength test, indirect tensile strength test, TSR test, boil test, and Cantabro abrasion test all indicated superior performance of the Experimental Group, all

complied with the requirements of AI MS-2 7th, compared to Control Group A. Particularly, the results of the retained strength test, TSR, and boil test demonstrated that the properties of OSP similar to those of hydrated lime anti-strip additive, enhancing the moisture damage resistance when added to asphalt concrete. However, the relatively lower Marshall stability can be attributed to the lower crushing strength of OSP; the slightly higher flow value suggests caution when using OSP in situations with high traffic loads.

- This study focused on investigating the engineering performance of OSP in DGAC. This study analyzed three representative combinations, commonly used in pavement engineering, in the mix design, with the aim of maintaining the representativeness of DGAC while ensuring the feasibility of the related experiments. The results provide valuable comparative and validation insights. OSP meets the performance requirements of asphalt mixtures. Although OSP has lower strength than natural aggregates, leading to a slight decrease in Marshall stability, its performance in moisture damage resistance, abrasion resistance, and interfacial bonding strength improvement demonstrated clear advantages. This reflects that OSP is not merely a replacement material; rather, its particle characteristics strengthen the coating ability between aggregates and asphalt binder. These findings are consistent with the relevant literature and lead to further important insights.
- More importantly, OSP is a by-product generated in large quantities by the aquaculture industry. Its reuse brings significant environmental benefits, as discarded OSP can cause storage and odor problems and even lead to secondary pollution. Utilizing OSP as a recycled material in pavement engineering not only reduces the consumption of virgin materials and the associated environmental impacts, but also aligns with the global trend toward net-zero emissions by 2050.
- Considering material recycling and sustainability, the use of OSP as a substitute material indeed shows potential for application in DGAC. The results of this study show that OSP can improve the stripping resistance and durability of asphalt mixtures. Future research may further explore OSP’s particle structure, particle size distribution, interfacial behavior, mineralogical characteristics, and additional combinations in the mix design covering different asphalt contents and OSP replacement levels, as well as to assess their long-term performance after incorporation. These additions provide a foundation for the future expansion and development of this research.

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Authorship contribution statement

FJia-Ruey Chang: Conceptualization, Data curation, Formal analysis, Funding acquisition, Methodology, Project administration, Resources, Supervision, Validation, Writing - review & editing.

Yi-Yu Lo: Conceptualization, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

Statement on the use of Artificial Intelligence

Not applicable.

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