Development of a Novel Lightweight Asphalt Concrete Mixture with Improved Insulation and Strength Characteristics

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Abstract

This study investigates the effects of substituting 70% of natural aggregate particles with Foamed Glass Synthetic Lightweight Aggregate (FG-SLA) in Hot Mix Asphalt (HMA), focusing on changes in the mixture's cracking resistance, tensile strength, resistance to moisture-induced damage, and thermal conductivity. The results show that the inclusion of FG-SLA significantly reduces thermal conductivity, offering a potential benefit in improving frost protection. The substitution also led to improved cracking resistance in the mixture. Additionally, it enhances the mixture's resistance to moisture-induced damage, as indicated by higher tensile strength ratios compared to the control mixture. However, a decrease in the dry tensile strength of the lightweight HMA can be recognized, highlighting a trade-off between moisture resistance and mechanical strength. These findings underscore the potential of FG-SLA in improving HMA performance, especially in applications where thermal properties and moisture resistance are critical. Although the results from this preliminary study are found to be promising, further research is needed to better understand the effects of varying levels of FG-SLA substitution, as well as its broader implications on thermal conductivity, mechanical properties, and economic feasibility.

1. Introduction

Asphalt concrete is a widely used material in the construction industry, which can be produced through a wide range of technologies in the form of either Hot Mix Asphalt (HMA), (half-) Warm Mix Asphalt (WMA), and Cold Mix Asphalt (CMA). Conventional HMA, as the predominant type, consists primarily of natural aggregates, asphalt binder and in some cases additives. The high demand for natural aggregates use in construction industry has been straining the natural resources by depleting the sources for quality aggregates. Globally, gravel consumption is responsible for 0.17 – 1.8 % of the world's carbon footprint, and in the province of Quebec, aggregates emit 2.28 – 3.59 kgCO2eq/t (de Bortoli, 2023). Given the widespread use of natural aggregates, many nations are facing aggregate shortages (Danielsen & Kuznetsova, 2014), prompting research into alternative aggregates, particularly those formed from recycled materials. Therefore, partial replacement of natural aggregates with recycled materials, mainly reclaimed Asphalt Pavement (RAP) and to a lesser extent Recycled Asphalt Shingles (RAS), has been pursued by several agencies and research institutions over the course of past few decades. Such replacement can potentially alleviate the adverse impacts on habitats and ecosystems in proximity to aggregate extraction operations.

As there has been a push to incorporate alternative sustainable materials within construction practices, the use of aggregate from recycled materials in asphalt mixtures has become increasingly relevant. However, the majority of research in this area has been focused on the incorporation of RAP, RAS, and Crumb Rubber (CR) in producing new asphalt mixtures (Picado-Santos et al., 2020; Mashaan et al., 2014). In addition to these commonly used recycled materials, there is a great potential in using synthetic aggregates to achieve other functionalities from conventional asphalt concrete mixtures. For instance, aside for the traditional paving activities, projects that deal with weak or collapsing subgrade soils as well as frost susceptible job sites can benefit from mixes that are capable of improving the thermal resistance and reducing the pavement deadweight surcharge. These are typically addressed solely through solutions in granular layers such as using Expanded Poly Styrene (EPS or XPS), synthetic lightweight aggregates (SLA) for road embankments and granular base layers applications (Khan & Mrawira, 2008). Extensive research has been conducted into SLA as it offers the ability to dramatically reduce the specific gravity of the layers. However, these efforts have been more focused on producing lightweight Portland cement concrete materials and granular layers (Mallick et al., 2004; Khan & Mrawira, 2008; Zhang et al.; 2018, Mohajerani et al., 2017). Limited research can be found in the existing literature on Lightweight asphalt concrete mixtures (Mallick et al., 2004). A lightweight asphalt concrete material is expected to reduce loads on pavement sub layers or structures such as bridges or weak subgrade soils compared to conventional HMA mixtures. SLA also possesses a characteristically low thermal conductivity, such a property lowers the overall thermal conductivity of an HMA layer, which helps protect pavement sublayers from freeze-thaw cycles. However, a major drawback with most of the lightweight aggregates would be their relatively low strength and relatively high absorption (Ullah et al., 2021). These two common characteristics prevent successful utilization of SLA in more robust layers, such as asphalt concrete layers in a pavement structure. However, the particular SLA that is the subject of this study is produced from foamed waste glass using a proprietary patented protocol that overcomes these common issues while maintaining other desirable features that SLA typically offer. The specific properties of the Foamed Glass SLA (FG-SLA) will be discussed in the following sections.

Multiple techniques for the production of FG-SLA exist, which result in different material properties. Yousefi et al. (2019) outlines a process for producing FG particles from recycled glass which begins by grinding glass particles, initially up to 10 mm in diameter, into an ultra-fine powder. This powder is then mixed with a foaming agent—specifically silicon carbide (SiC)—and the blend is fed into a kiln operating at temperatures ranging from 700°C to 1000°C. Under these conditions, the glass melts, and the foaming agent decomposes, releasing gases that create a network of air bubbles throughout the molten material. As the mixture cools, these bubbles become encapsulated within a rigid structure, resulting in foamed glass particles composed of approximately 92% air voids and 8% solid glass (Yousefi et al., 2019). Each bubble is enclosed by a thin, impervious glass layer, contributing to the material's lightweight and insulating properties (Yousefi, 2019) and relatively lower absorption.

Previous studies on the use of SLAs in asphalt applications indicate promising potential for enhancing the performance of HMA by partially substituting traditional natural aggregates. A variety of alternative aggregates have been studied, including waste fly ash and plastic composites (Mallick et al., 2004), expanded shale (Khan & Mrawira, 2008), ceramsite (Zhang et al., 2018), and crushed waste glass (Mohajerani et al., 2017). These investigations have primarily focused on optimizing the substitution levels and evaluating their effects on the mechanical and thermal properties of HMA mixtures. Many of these studies identified an optimal natural aggregate replacement range of 15% to 20% for maintaining desirable strength characteristics (Khan & Mrawira, 2008; Mohajerani et al., 2017; Ullah et al., 2021). Despite this breadth of research, there remains a noticeable gap in the literature concerning the use of FG-SLA in HMA mixtures. Although FG has been explored for use in subgrade applications, its influence on the performance of asphalt concrete has not been extensively documented. Additionally, while some studies have applied empirical methods—such as the Lee method used by Abbas & Alhamdo, 2023, which involves heating one side of a specimen in a controlled environment to measure heat transfer—for determining thermal conductivity, such techniques have yet to be widely used for mixtures incorporating FG-SLA (Abbas & Alhamdo, 2023).

This study investigates the impact of partially replacing natural aggregates with FG-SLA in HMA, with particular attention to thermal insulation and mechanical performance. The primary objective is to assess how a high-volume substitution—specifically 70% by volume—of foamed glass SLA affects the thermal conductivity and mechanical strength of the HMA mixture. To evaluate mechanical viability at this high substitution level, performance tests including the Indirect Tensile Strength (ITS) test and the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) were conducted.

2. Materials and Mix Design

2.1 Asphalt Binder

The asphalt binder utilized in this study is a Styrene-Butadiene-Styrene (SBS)-modified binder with a Performance Grade (PG) of 64-28J, which is widely used in road construction across Ontario. Its selection supports the study's objective of assessing potential enhancements in asphalt performance over a broad temperature range, with a particular focus on improving resistance to low-temperature cracking in colder climates.

2.2 Natural and Foamed Glass Aggregates

The natural aggregates were sourced from local suppliers in southern Ontario and incorporated into the HMA mixture alongside the FG-SLA. This aggregate conformed to SP 19.0 – R15 Category D specifications and exhibited a bulk specific gravity (G_{sb}) of 2.685 with a water absorption of 0.83%. The aggregate blend was designed to meet the gradation requirements of Superpave 19.0 mm and consisted primarily of crushed stone. These conventional aggregates provided the necessary structural integrity and helped maintain compliance with Ontario Provincial Standard Specification (OPSS) 1151 standards (*MTO Technical Publications,* 2021).

FG aggregate, also known as SLA, was used in this study as a lightweight, porous alternative to conventional natural aggregates. Due to the limited availability of particles passing the 19 mm sieve — since the material was originally produced for Granular B layer applications— larger-sized FG-SLA was crushed and sieved to produce finer fractions suitable for use in HMA mixtures. Figure 1 shows a sample of the original FG-SLA before crushing and after crushing and blending with natural aggregates. This crushing process, while necessary for gradation control, could have disrupted the fully impervious glass shell surrounding each particle, thereby altering key physical properties such as water absorption and density. These aspects were considered and verified during the experimental campaign in this study. Figure 2 shows the particle size distribution of the FG-SLA after crushing.

Figure 1. Original FG-SLA Particles (Left) and Blend of Crushed FG-SLA and Natural Aggregates (Right)

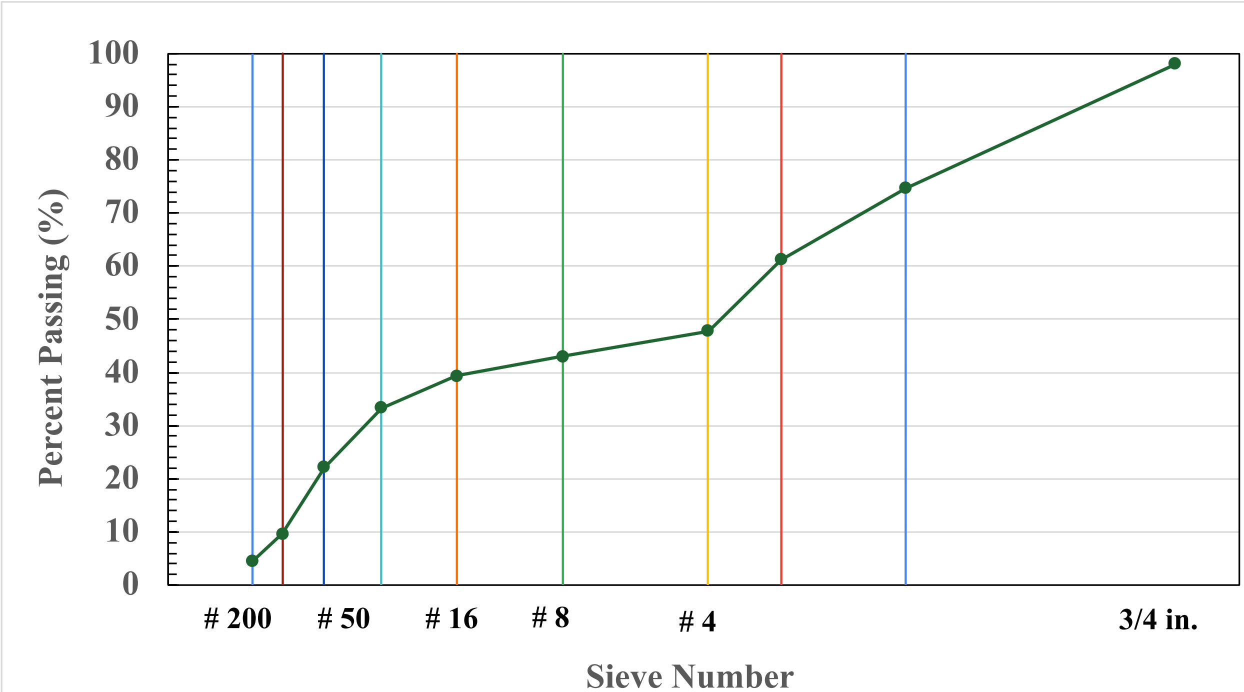

Figure 2. Percent Passing of Crushed FG-SLA

The Engineering properties of the specific FG-SLA used in this study is summarized in Table 1. These measurements were done by Schneider (2017) on the very same materials used in this study.

Table 1. Engineering Properties and Characteristics of FG-SLA (Schneider, 2017)

Property	**Value**
Thermal Conductivity, Dry	<0.08 [W/mK]
Thermal Conductivity, Wet	0.11 [W/mK]
Design Value of Compressive Strength	275 [kN/m^2]
Compressive Strength (10% compression)	>=570 [kN/m^2]
Density	150 kg/m^3
Granular Size	Approx 10 – 60 mm
Internal Water Absorption	0 [Vol%]
Elastic Modulus	65,400 [Kpa]

Water absorption is a critical parameter in HMA design, as highly absorptive aggregates can draw in binder, affecting both coating and overall cost of materials production. To assess this, the water absorption of the crushed FG-SLA was determined using the procedure outlined in ASTM C127 (2024). The absorption of the crushed FG-SLA was measured to be 33%, representing a significant increase compared to the original material's negligible absorption. It is worth mentioning that there currently is a gap regarding a specific standard method for measuring the density of such material for paving material applications. Furthermore, maintaining Saturated Surface-Dry (SSD) condition is still an aspect that needs to be further revised, given the nature of the accessible pores' distribution for the FG-SLA. These factors might have contributed to the accuracy of absorption estimation and will need to be further investigated in future studies.

To verify the aggregate's density, initially reported to be 150 kg/m³ for the original particles, a volumetric displacement method was used. A 250 mL graduated cylinder was filled with water to the 150 mL mark and tared. Crushed FG-SLA was then added until the water level reached 250 mL, and the mass of the added aggregate was recorded. This procedure was repeated across multiple samples to ensure consistency. The density was calculated using the equation:

$$\rho = \frac{C}{0.00015} \tag{1}$$

Where:
ρ = Density [kg/m^3]
C = Weight of Aggregate Added to Graduated Cylinder [kg]

The measured density of the FG-SLA was found to be 427 kg/m³, higher than the original particles' (prior to crushing) value, but still significantly lower than that of natural aggregate particles. This change highlights the importance of producing the right size of the FG-SLA for this novel application to avoid the need for verifying aggregate properties after processing, as mechanical alteration can substantially affect both performance and mix design parameters.

2.3 **Mix Design and Volumetric Properties**

Two mixes were produced according to the Superpave mix design method. Mix-A contained 100 % natural aggregate and was used as the control mix. Designated Mix-B contained 70% FG-SLA and 30% natural aggregates by volume and was the subject of this study. This ratio was selected to evaluate the properties of HMA at a significantly higher SLA substitution level than what was identified to be optimal by other studies (Ullah et al., 2021). The significantly lower density of the FG- SLA necessitated modifying the conventional mass-base calculations in the mix design process. To this end, mass-volume conversions using the experimentally measured densities for the mixture ingredient were carried out to maintain an equivalent mixture as compared to the control asphalt concrete mix.

Mix-A contained a binder content of 4.8% by mass, while the binder content of Mix-B was set at 6.65 % by mass to account for the high absorption of the FG-SLA. The theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}) of Mixes A and B were determined in accordance with AASHTO T 209-12 (2020) and AASHTO T 166-22 (2022b), respectively, to evaluate the volumetric properties of the mixtures. Mix-A, which contained only natural aggregates, exhibited a G_{mm} of 2.5411 and a G_{mb} of 2.3497. In contrast, Mix-B, which incorporated 70% by volume of FG-SLA, showed significantly lower values, with a G_{mm} of 2.0129 and a G_{mb} of 1.7475. These results indicate that the G_{mm} and G_{mb} of Mix-B were approximately 79% and 74%, respectively, of those of Mix-A, demonstrating the substantial reduction in mixture density due to the inclusion of FG-SLA.

3. Methodology

3.1 IDEAL-CT Method

The IDEAL-CT formally designated as ASTM D8225 (2019) was used to evaluate the cracking resistance of the HMA mixture containing 70 % SLA substitution and a control mixture using only natural aggregate. For a particular HMA mixture to be feasible in a large-scale application, it must be able to withstand any service loads without exhibiting premature failure, such as cracking. The IDEAL-CT method was performed on disk-shaped HMA specimens compacted using the Superpave gyratory compactor (SGC), with a diameter of 150 mm and a thickness of 62±2 mm. The Load-Line Displacement (LLD) rate during the test was kept at 50 mm/minute with a tolerance of 2 mm/minute. During the test, both the load and displacement were recorded. The post-peak slope of the load-displacement curve between 85 % and 65 % of the peak load was taken as m_{75}, and used to calculate the Cracking Tolerance index (CT_{index}). Generally, a higher CT_{index} corresponds to a more crack resistant HMA mixture. For most HMA applications, the mixtures must have a CT_{index} of at least 50, though some applications may demand a higher CT_{index} (Chen et al., 2021).

The CT_{index} was calculated using Equation 1:

$$CT_{index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \qquad (2)$$

Where:

CT_{index} = Cracking Tolerance Index [-]
l_{75} = Displacement at 75% of the Post-Peak Load [mm]
G_f = Failure Energy [J/m^2]
t = Specimen Thickness [mm]
D = Specimen Diameter [mm]
m_{75} = Post-Peak Slope [-]

3.2 ITS Test and Moisture Susceptibility Analysis

The ITS test was performed in accordance with AASHTO T 283-22 (2022a), *Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage*, to evaluate the tensile strength and moisture susceptibility of HMA mixtures incorporating FG-SLA. This standard simulates the effects of water saturation and freeze-thaw cycles on asphalt mixtures, reflecting real-world conditions such as rainfall and snowfall that pavements are routinely exposed to. Two sets of cylindrical SGC compacted specimens were prepared—one tested under dry conditions, and the other subjected to vacuum saturation, one freeze-thaw cycle, and subsequent soaking in warm water before testing. Each specimen was loaded diametrically at a constant deformation rate of 50 mm/min until failure, and the peak load was recorded. The ratio of the tensile strength of the conditioned specimen to that of the dry specimen is referred to as the Tensile Strength Ratio (TSR), which serves as an indicator of the mixture's resistance to moisture-induced damage, such as stripping. According to OPSS 1150, a minimum TSR value of 0.80 is required for HMA mixtures. If the TSR falls below this threshold, the addition of anti-stripping agents may be necessary to enhance moisture resistance (*MTO Technical Publications,* 2021).

4. Results and Discussion

4.1 IDEAL-CT Results

The cracking resistance of the asphalt mixtures was evaluated using the IDEAL-CT method, reported in terms of the CT_{index}. Three replicates were tested for each mix type: Mix A, containing only natural aggregates, and Mix-B, incorporating FG-SLA. Table 2 summarizes the CT_{index} results obtained for the two mixes in this study. Mix-A yielded an average CT_{index} of 50, which aligns with the commonly accepted performance threshold for adequate cracking resistance. Mix-B demonstrated a significantly higher average CT_{index} of 671.41, representing a 13.66-fold increase over the natural aggregate mix. The individual CT_{index} values for Mix 2 ranged from 502.91 to 827.96, all well above the commonly acceptable minimum requirement. Figure 3 illustrates a comparison between the IDEAL-CT results of mix A and mix B.

Table 2. Summary of IDEAL-CT Test Results for Mixes A and B

Specimen	***CT_{index}***	***Average***
Mix A (1)	31	
Mix A (2)	32	49
Mix A (3)	85	
Mix B (1)	445	
Mix B (2)	503	450
Mix B (3)	401	

This notable improvement in cracking resistance is likely due to the cellular structure and lightweight nature of the FG-SLA, which may enhance the flexibility and energy dissipation capacity of the asphalt mixture as well as the enhanced aggregate-mastic bond due to absorption of additional binder to the FG-SLA pores. The inclusion of FG-SLA appears to improve internal stress distribution, reducing the likelihood of crack formation and propagation. These results indicate that the use of FG- SLA in HMAs can greatly enhance their resistance to cracking compared to conventional mixtures made with natural aggregates.

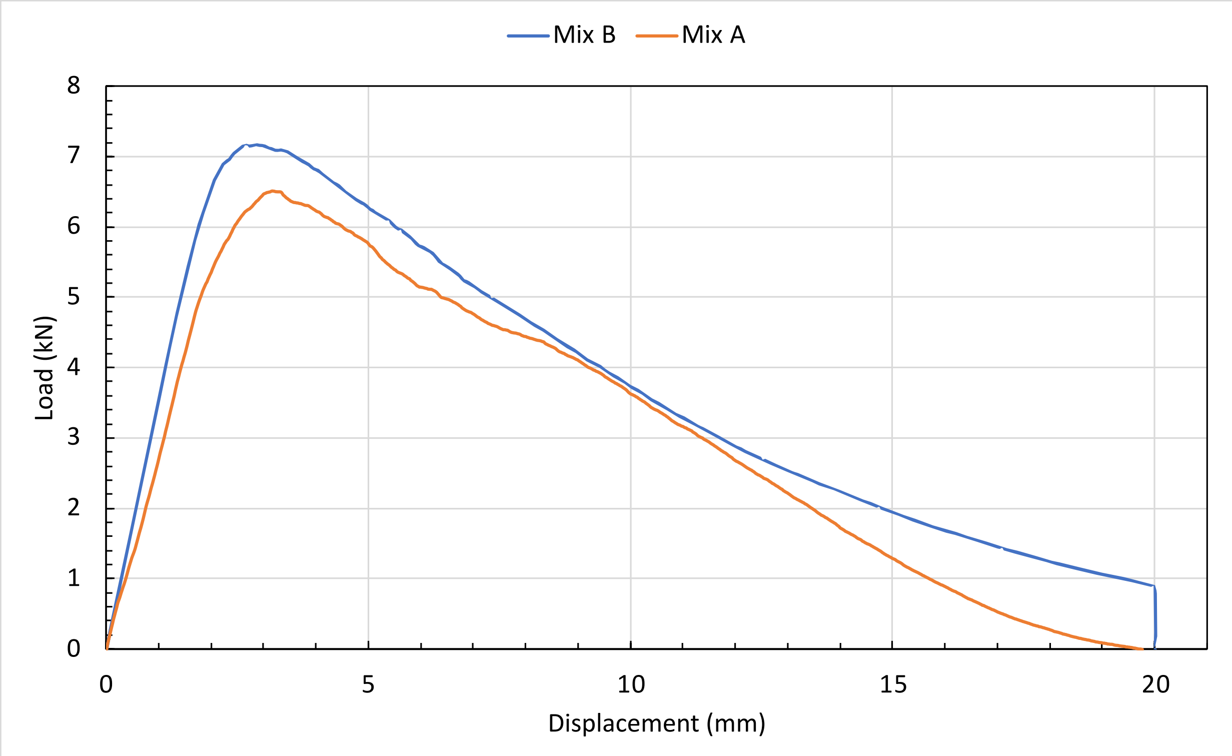

Figure 3. Sample Comparison of IDEAL-CT Results for Mixes A and B

4.2 ITS and TSR Result

The tensile strength results for Mixes A and B reveal significant differences between the dry and wet conditions. The dry tensile strength of Mix B is approximately 66% of that of Mix A, while the wet tensile strength of Mix B reaches about 77% of Mix A. Despite the lower overall tensile strength, Mix B exhibits a better resistance to moisture-induced damage, as indicated by its higher moisture susceptibility performance. Importantly, Mix-B satisfies the minimum TSR value of 0.80 required by OPSS 1150, whereas Mix-A does not. This suggests that the inclusion of FG-SLA could improve the mixture's performance in wet conditions, making it more resistant to moisture-related degradation. The enhanced TSR of Mix B can be attributed to the surface characteristics of the coarse FG-SLA particles, which likely improve binder adhesion. Additionally, the aggregate crushing process may have modified the surface morphology of the FG-SLA, increasing its bonding potential with the binder.

These findings are further supported by the physical properties of the SLA, such as its lower density and higher water absorption capacity. These characteristics influence the internal aggregate skeleton behavior, moisture retention, and bonding strength of the mixture. The increased water absorption of the FG-SLA may help manage moisture more effectively, contributing to improved tensile strength under wet conditions and enhancing the overall performance of Mix B. Figure 4 shows the summary of ITS results and their corresponding TSR values for Mixes A and B.

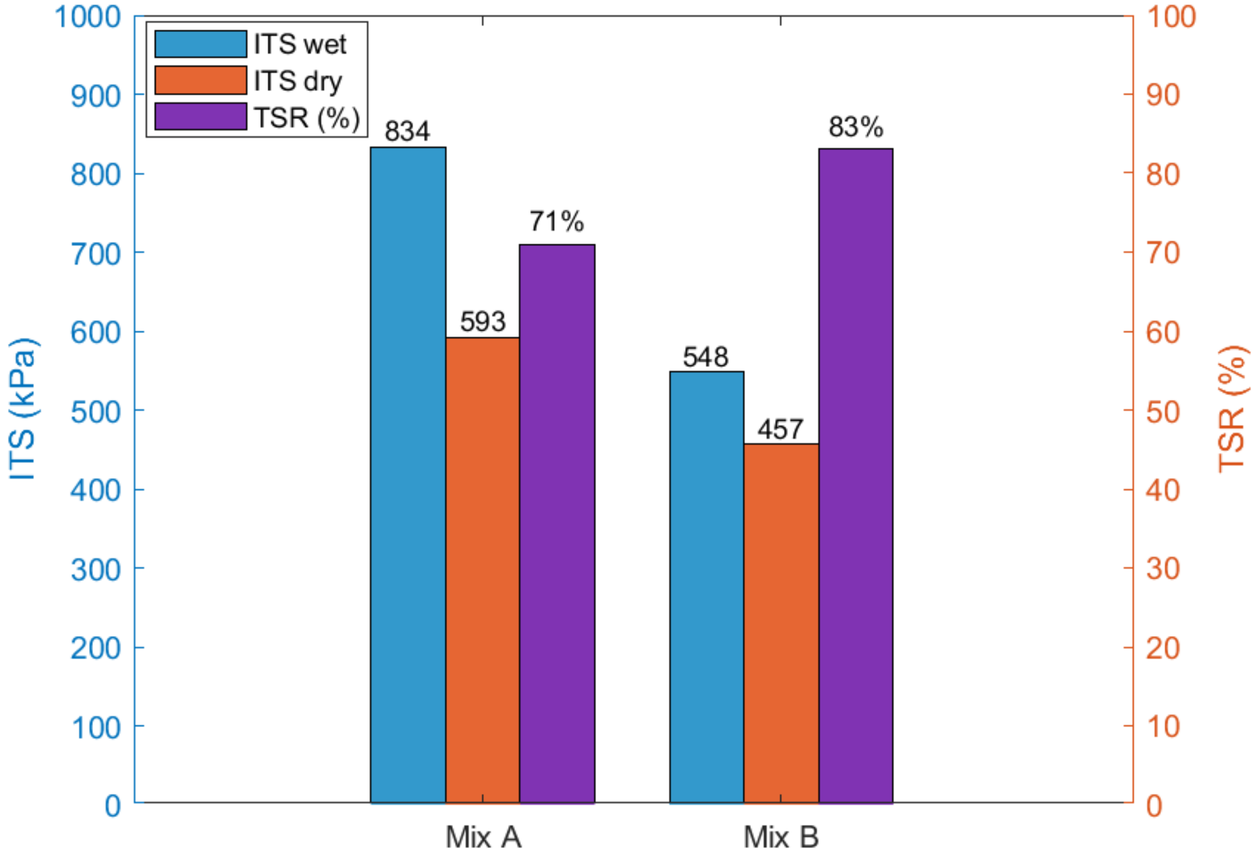

Figure 4. Sample comparison of ITS and TSR results for Mixes A and B

4.3 Theoretical Thermal Conductivity Result

The thermal conductivity of asphalt mixtures plays a crucial role in determining their thermal behavior and energy efficiency, which is especially important in understanding how these mixtures perform under varying environmental conditions. The Hashin-Shtrikman (HS) bounds method was applied to estimate the effective thermal conductivity of the HMA mixtures. This method, originally adapted for use on transversely isotropic two-phase composite materials by Calvo-Jurado & Parnell, calculates the upper and lower bounds of thermal conductivity by considering the thermal properties of both the binder and the aggregate, as well as their volume fractions and aspect ratios (Calvo-Jurado & Parnell, 2014).

The thermal conductivity values for the natural aggregates were determined by averaging data from materials like granite, quartzite, sand, basalt, and limestone (Cermák & Rybach, 1982). The asphalt binder used in this study is an SBS polymer-modified binder, which is known to have a lower thermal conductivity than conventional binders. In this analysis, the aspect ratio for each material was assumed to be 1, representing the roughly spherical shape of the particles.

For Mix A, which contains natural aggregates, the thermal conductivity of the aggregate phase was calculated as a volume-weighted average, resulting in a value of 2.67 W/mK. In contrast, Mix B, which incorporates FG-SLA, has a much lower thermal conductivity for the FG-SLA phase (0.11 W/mK). The volume fractions and thermal conductivities for the binder, aggregates, and FG-SLA are presented in Table 3:

Table 3. Thermal Properties and Volume Fractions of Aggregate and Binder (Schneider, 2017, Cermák & Rybach, 1982, *McAsphalt, 2025*)

Material	***Thermal Conductivity***	***Volume Fraction (Mix A)***	***Volume Fraction (Mix B)***	***Aspect Ratio***
Binder	0.40 [W/mK]	0.1194	0.0725	1
Natural Aggregate	2.67 [W/mK]	0.8806	0.2782	1
FG-SLA, Wet	0.11 [W/mK]	0	0.6493	1

To simplify the calculations, the HMA mixtures are assumed to be randomly distributed. Because the HS method is only applicable for a two-phase material, the volume-weighted average of the aggregates' thermal conductivity is used to determine the thermal conductivity of the aggregate phase for Mix-B as 0.88 W/mK. Equations 3 and 4 are used to determine the lower and upper bounds, respectively of the thermal conductivity as per the HS method:

$$k_{-} = k_0 + \emptyset_1((k_1 - k_0)^{-1} + \frac{1}{3k_0}(1 - \emptyset_0))^{-1} \qquad (3)$$

$$k_{+} = k_1 + \emptyset_0((k_0 - k_1)^{-1} + \frac{1}{3k_1}(1 - \emptyset_1))^{-1} \qquad (4)$$

Where:
k_{-} = HS Lower Bound [W/mK]
k_{+} = HS Upper Bound [W/mK]
k_0 = Binder Thermal Conductivity [W/mK]
k_1 = Aggregate Thermal Conductivity [W/mK]
$\emptyset_0$ = Binder Volume Fraction [-]
$\emptyset_1$ = Aggregate Volume Fraction [-]

Table 4 summarizes the lower and Upper HS bounds for the thermal conductivities of Mixes A and B:

Table 4. Upper and Lower Bounds for the Thermal Conductivities of Mixes A and B

	Lower Bound	***Upper Bound***	***Median***
Mix A	1.15 [W/mK]	2.39 [W/mK]	1.77 [W/mK]
Mix B	0.72 [W/mK]	0.84 [W/mK]	0.78 [W/mk]

The reduced thermal conductivity in Mix B, primarily due to the inclusion of FG-SLA, offers potential advantages in enhancing moisture resistance and long-term durability, as lower thermal conductivity is typically associated with better thermal stability. This is supported by higher TSR value of Mix B compared to Mix A, indicating superior moisture resistance. The findings from the thermal conductivity analysis align with the results from the ITS and moisture sensitivity, where Mix B demonstrated improved resistance to moisture-induced damage despite having a lower tensile strength in the dry state. Furthermore, the lower thermal conductivity in Mix B is corroborated by the Ideal-CT, which shows better resistance to crack propagation and moisture-induced damage. The relationship between thermal conductivity, tensile strength, and moisture resistance highlights the potential of FG-SLA to improve the overall performance of HMAs, particularly in applications where frost-protection and/or lightened pavement structures are needed and critical in presence of problematic subgrade soils. The fact that the lightweight asphalt concrete mixture in this study could render these functionalities while maintaining a superior moisture damage resistance and cracking resistance underscores the promising prospect for further exploring this option for special pavement engineering applications.

5. Conclusions

Designing flexible pavements over very weak/collapsing subgrade soils or in cold regions where frost protection is critical requires specific provisions as compared to the conventional pavement design and construction practices. Use of speciality asphalt concrete mixes with lighter weights and better thermal insulation properties has seen limited attention in the past, mainly due to the fact that lightweight aggregates typically suffer from extremely high absorptions, lower mechanical properties, and not very different insulating characteristics. This study investigated the impact of incorporating a specific SLA, i.e. FG-SLA, as a partial replacement of the natural aggregates' skeleton in the conventional asphalt concrete mixes. Substantial amount of FG-SLA (i.e., 70%) was incorporated into producing an equivalent asphalt concrete mixture. The tensile strength and moisture resistance characteristics of HMA mixtures, alongside their theoretical thermal conductivity using the Hashin-Shtrikman bounds method were evaluated. The following conclusions can be drawn:

- The results indicate that the inclusion of FG-SLA reduces the thermal conductivity of the HMA mixture by 56 % while enhancing its resistance to moisture induced damage by 17 %.
- The Lightweight asphalt concrete mixture using FG-SLA exhibited a significant cracking resistance improvement in terms of CT_{index}. This was evident by the ductile fracture pattern observed during the IDEAL-CT tests as compared to the control mix specimens.
- The inclusion of FG-SLA resulted in a 12% increase in the TSR value as compared to the control mixture. Alternatively, the wet and dry tensile strength values of the FG-SLA mixture were 66% and 77% of the control, respectively.
- The findings suggest that FG-SLA has the potential to enhance the thermal stability and durability of HMA mixtures, making it a promising alternative in applications where frost protection, surcharge weight reduction, and moisture resistance are critical.

6. Future Research Recommendation

The limited research on FG-SLA in asphalt mixtures highlights the need for further studies to evaluate its long-term performance, economic viability, and potential environmental benefits. The cost and availability of FG-SLA should be considered in future research to assess its broader implementation within the construction industry. This study highlights the potential of using high volumes of FG-SLA in HMA mixtures but suggests that lower substitution levels may offer improved strength. Future research should investigate a wider range of replacement levels, use empirical methods to measure thermal conductivity, and assess the impact of crushing FG-SLA on material performance to optimize its practical application in asphalt mixtures.

References

Aabøe, R., Øiseth, E. et Hagglund, J. 2005. "Granulated Foamed Glass for Civil Engineering Applications." In 2005 Workshop NR2 - Recycled Materials in Road & Airfield. Oslo, Norway.

AASHTO T 166: Standard Method of Test for Bulk Specific Gravity (G_{mb}) of Compacted Asphalt Mixtures Using Saturated Surface-Dry Specimens," American Association of State Highway and Transportation Officials, 2022b.

AASHTO T 209, "Standard Method of Test for Theoretical Maximum Specific Gravity (G_{mm}) and Density of Asphalt Mixtures," American Association of State Highway and Transportation Officials, 2020.

AASHTO T 283, "Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage," American Association of State Highway and Transportation Officials, 2022a.

Abbas, F. A., & Alhamdo, M. H. (2023). Enhancing the thermal conductivity of hot-mix asphalt. *Results in Engineering*, *17*, 100827. https://doi.org/10.1016/j.rineng.2022.100827

ASTM C127-24, "*Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*." 2024, https://doi.org/10.1520/c0127-24

ASTM D8225-19, "*Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature*." 2019, https://doi.org/10.1520/d8225-19

Calvo-Jurado, C., & Parnell, W. J. (2014). Hashin–Shtrikman bounds on the effective thermal conductivity of a transversely isotropic two-phase composite material. *Journal of Mathematical Chemistry*, *53*(3), 828–843. https://doi.org/10.1007/s10910-014-0452-8

Cermak, V. and Rybach, L., 1982. Thermal properties: Thermal conductivity and specific heat of minerals and rocks. In: G.Angeneister (Ed.), Landolt-B"rnstein Zahlenwerte and Funktionen aus Naturwissenschaften und Technik, Neue Serie, Physikalische Eigenschaften der Gesteine. Springer Verlag, Berlin, Heidelberg and New York, V/1a, 305-343.

Chen, H., Zhang, Y., & Bahia, H. U. (2021). The role of binders in mixture cracking resistance measured by ideal-CT test. *International Journal of Fatigue*, *142*, 105947. https://doi.org/10.1016/j.ijfatigue.2020.105947

Danielsen, S. W., & Kuznetsova, E. (2014). Environmental impact and sustainability in aggregate production and use. *Engineering Geology for Society and Territory - Volume 5*, 41–44. https://doi.org/10.1007/978-3-319-09048-1_7

de Bortoli, A. (2023). Understanding the environmental impacts of virgin aggregates: Critical literature review and primary comprehensive life cycle assessments. *Journal of Cleaner Production*, *415*, 137629. https://doi.org/10.1016/j.jclepro.2023.137629

Khan, A., & Mrawira, D. (2008). Influence of selected mix design factors on the thermal behavior of lightweight aggregate asphalt mixes. *Journal of Testing and Evaluation*, *36*(6), 492–499. https://doi.org/10.1520/jte101687

Mallick, R. B., Hooper, F. P., O'Brien, S., & Kashi, M. (2004). Evaluation of use of synthetic lightweight aggregate in hot-mix asphalt. *Transportation Research Record: Journal of the Transportation Research Board*, *1891*(1), 1–7. https://doi.org/10.3141/1891-01

Mashaan, N. S., Ali, A. H., Karim, M. R., & Abdelaziz, M. (2014). A review on using crumb rubber in reinforcement of Asphalt Pavement. *The Scientific World Journal*, *2014*, 1–21. https://doi.org/10.1155/2014/214612

McAsphalt, *The right mix*. McAsphalt. (n.d.). https://mcasphalt.com/

Mohajerani, A., Vajna, J., Cheung, T. H., Kurmus, H., Arulrajah, A., & Horpibulsuk, S. (2017). Practical recycling applications of crushed waste glass in construction materials: A Review. *Construction and Building Materials*, *156*, 443–467. https://doi.org/10.1016/j.conbuildmat.2017.09.005

MTO Technical Publications. (n.d.). https://www.library.mto.gov.on.ca/SydneyPLUS/TechPubs/Portal/tp/TechnicalPublications.aspx

Picado-Santos, L. G., Capitão, S. D., & Neves, J. M. C. (2020). Crumb rubber asphalt mixtures: A literature review. Construction and Building Materials, 247, 118577. https://doi.org/10.1016/j.conbuildmat.2020.118577

Schneider, A. C., & Baaj, H. (2017). *Sustainable alternative materials in unbound granular layers of pavement structures* (thesis). University of Waterloo, Waterloo, Ontario.

Ullah, S., Raheel, M., Khan, R., & Tariq Khan, M. (2021). Characterization of physical & mechanical properties of asphalt concrete containing low- & high-density polyethylene waste as aggregates. *Construction and Building Materials*, *301*, 124127. https://doi.org/10.1016/j.conbuildmat.2021.124127

Yang, Q., Lin, J., Wang, X., Wang, D., Xie, N., & Shi, X. (2024). A review of polymer-modified asphalt binder: Modification mechanisms and mechanical properties. *Cleaner Materials*, *12*, 100255. https://doi.org/10.1016/j.clema.2024.100255

YOUSEFI, Y. (2014). *Engineering and environmental assessment of foam glass lightweight aggregate for pavement application* (thesis). *Engineering and Environmental Assessment of Foam Glass Lightweight Aggregate for Pavement Application*. University of Waterloo, Waterloo, Ontario.

Zhang, M., Qian, Z., Zhou, Y., & Liu, Y. (2018). Test and evaluation for effects of aggregates fragmentation on performance of lightweight asphalt concrete. *Construction and Building Materials*, *169*, 215–222. https://doi.org/10.1016/j.conbuildmat.2018.02.058