Optimizing Geosynthetic Interlayer Systems for Reflective Cracking Mitigation: Mechanical Performance, Economic Analysis, and Environmental Benefits

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Abstract.

This study investigates the mechanical performance of various geosynthetic interlayer systems used in asphalt overlays to mitigate reflective cracking under monotonic loading conditions. Through a series of laboratory tests using a Crack Widening Device, the influence of reinforcement type (geotextile and geogrid) and placement depth (one-third, one-half, and two-thirds from the bottom of the specimen) was evaluated. Results demonstrate that reinforcement positioned closer to the crack initiation zone significantly enhances crack resistance, with the one-third placement yielding the highest fracture energy (G_{IC}) and toughness improvement factor (TIF). Geotextile (Paving fabric-PF) reinforced specimens consistently outperformed both unreinforced controls and Carbophalt GB (glassgrid), particularly when embedded near the bottom. Conversely, reinforcements placed near the top surface showed diminished effectiveness due to delayed engagement with the fracture front. These findings underscore the importance of strategic interlayer positioning and material selection in extending pavement service life and optimizing overlay rehabilitation designs.

Keywords: crack widening device, reflective cracking, paving fabric, bituminous interface, fracture toughness.

1 Introduction

Flexible pavements are subjected to continuous traffic loading and climatic variations that cause a range of structural distresses over time. Among these, reflective cracking is one of the most prevalent and detrimental forms of deterioration in hot mix asphalt (HMA) overlays (Buttlar et al., 1999; Cleveland et al., 2002). These cracks typically initiate from pre-existing joints or cracks in the underlying layers and propagate through the overlay due to repeated load-induced tensile and

shear stresses, as well as temperature fluctuations (Eltahan & Lytton, 2000; Blankenship et al., 2004). Once formed, reflective cracks compromise pavement integrity by allowing moisture infiltration, accelerating delamination, and reducing service life (Elseifi & Al-Qadi, 2003).

Although the placement of HMA overlays remains a common and cost-effective rehabilitation approach (Kumar et al., 2017; Kumar & Saride, 2017), their durability is often limited by the early onset of reflective cracking. Current overlay design frameworks typically overlook this failure mechanism, necessitating the adoption of additional treatments (Baek & Al-Qadi, 2008). Over the last two decades, geosynthetic interlayers—including paving fabrics, geogrids, and geocomposites—have been widely studied for their ability to mitigate reflective cracking and enhance the structural performance of asphalt overlays (Austin & Gilchrist, 1996; Zornberg & Gupta, 2010).

Geosynthetics provide multiple benefits such as stress dissipation, strain distribution, and reinforcement, depending on their configuration, tensile properties, and interaction with the surrounding asphalt matrix (Chen et al., 2015; Virgili et al., 2009). Research has shown that these materials can reduce the demand for thicker HMA layers, thereby lowering construction costs and supporting environmental sustainability through reduced material usage and emissions (Farshad 2005; Spadoni et al., 2021). However, their performance is highly dependent on interface bonding, material stiffness, and notably, the vertical placement of the interlayer within the overlay system (Sobhan & Tandon, 2008; Pasquini et al., 2013, 2015). For example, reinforcement placed at one-third the overlay thickness from the bottom has been shown to improve crack mitigation by engaging earlier with propagating cracks (Ho et al., 2024; Torre et al., 2015).

Despite the widespread use of geosynthetics, standardized methods for evaluating their crack resistance contributions remain limited. Several testing protocols-such as four-point bending

(Ferrotti et al., 2012), University of Granada – Fatigue Asphalt Cracking Test, UGR-FACT (Navarro & Gamez, 2014), and the Texas Overlay Tester (Padilla et al., 2016) - are widely recognized but often constrained by specimen size, complexity, or limited adaptability for reinforced overlays.

To address these challenges, the current study investigates the mechanical performance of geotextile and geogrid interlayers embedded at various depths (one-third, one-half, and two-thirds from the bottom) within asphalt overlays. Tests were conducted under displacement-controlled loading rates at 2 mm/min using a Crack Widening Device. By analyzing force-crack width behavior from initiation to failure, this study aims to quantify the influence of reinforcement type, placement depth, and loading rate on the reflective crack resistance of asphalt composites. The findings contribute to a more mechanistic understanding of geosynthetic reinforcement strategies, offering guidance for the design of durable, cost-effective, and sustainable pavement rehabilitation solutions.

2   Methodology

The objective of this study was to evaluate the performance of geosynthetic interlayers in asphalt composite structures under varying placement depths. The investigation focused on analyzing the evolution of force-displacement behavior during crack propagation. Laboratory testing involved two types of specimen configurations: reinforced samples incorporating geosynthetics between asphalt layers, and unreinforced control specimens. To simulate realistic pavement rehabilitation scenarios, identical hot mix asphalt was used for both the upper and lower layers of all specimens. To examine the role of interfacial friction in enhancing crack resistance, geosynthetic materials were embedded at three distinct vertical positions within the specimens - one-third, one-half, and two-thirds from the bottom. This systematic approach enabled a detailed assessment of how

reinforcement depth influences crack mitigation through frictional interaction with the surrounding asphalt matrix. In the control group, a tack coat emulsion was applied at a corresponding depth, allowing direct comparison between conventional bonding treatments and geosynthetic reinforcement.

Among available laboratory techniques for evaluating these parameters, this research employed a Crack Widening Device specifically developed at École de Technologie Supérieure (ÉTS). This apparatus enabled precise measurement of force-displacement responses and provided insight into the mechanical contributions of interlayer reinforcements and their potential to enhance pavement durability under different loading conditions.

2.1 Materials

This study utilized a hot mix asphalt (HMA) design tailored to meet the specifications of Transport Quebec, focusing on a mixture commonly applied in Quebec, Canada. The selected mix, ESG-10, features a nominal maximum aggregate size of 10 mm and is suitable for both surface and binder course applications. ESG-10 demonstrated superior mechanical performance, exceeding the provincial standards for water sensitivity and rutting resistance, as summarized in **Table 1**. The asphalt binder used in the mixture was a performance-graded PG 64E-28.

To evaluate the performance of reinforced asphalt interfaces, two types of reinforcement materials were incorporated into the double-layered specimens: a geotextile (designated as PF) and a geogrid (Glassgrid). The PF reinforcement consists of a needle-punched nonwoven fabric saturated with PG 64-34 asphalt binder, enhancing bonding and waterproofing characteristics. The principal mechanical properties of the PF, as specified by the manufacturer, are provided in **Table 2**.

Table 3 outlines the characteristics of the geogrid materials. The designation "GB" refers to a category of bitumen-coated reinforcement grids composed of carbon fibers or hybrid

configurations of carbon and glass fibers, offering improved tensile performance and structural

integrity at the interface.

Table 1. The specification of Hot Mix Asphalt

Mixture		ESG-10[1]
Binder Type		PG 64E-28
Binder Content (% mass)		5.45
Water Sensitivity (LC 26-011) (%)	Measured	97.3
	Required	≥ 70
Rutting Test (LC 26-4101) (%)	Measured	After 1000 = 6.6 After 3000 = 8.2
	Required	(After 1000 cycles) ≤ 10 (After 3000 cycles) ≤ 15

[1]**ESG-10=** a mix for the surface course and binder course with a maximum aggregate size of 10 mm

Table 2. The mechanical properties of Geotextile paving fabric (**PF**) (supplied by the company)

Specification	Test Method	Unit	Value
Grab tensile elongation	CAN 148.1 No. 7.3	%	45–105%
Grab tensile strength	CAN 148.1 No. 7.3	N	550
Mullen burst	CAN 4.2 No. 11.1	kPa	1585
Bitumen retention	ASTM D6140	L/m^2	1.15

Table 3. The mechanical properties of geosynthetics

Name	Name in abbreviation	Type/Transversal Strength (kN)	Type/Longitudinal Strength (kN)	Covered Layer	Elongation		Mesh size (square shape) (mm)
					Transversal Direction	Longitudinal Direction	
Carbophalt G 120/200	GB	Glass fibers / 120	Carbon fibers/200	Plastic foil	<3%	<1.5%	20

All asphalt slabs—both reinforced and unreinforced—were prepared in the laboratory to final

dimensions of 500 mm × 180 mm × 100 mm, following geosynthetic manufacturers' guidelines.

The bottom ESG-10 asphalt layer was compacted using a French roller compactor in accordance

with LC 26-410 (MTQ standards). For interlayers placed at mid-depth, the compacted thickness

was set at 50 mm, while 63 mm was used to achieve one-third and two-thirds vertical placement targets. Slabs were then cured for 48 hours under ambient laboratory conditions.

Interlayer installation varied by reinforcement type. For unreinforced slabs and those with GB geogrids, a cationic asphalt emulsion (CSS-1h) was applied at 0.18 L/m² using a syringe and spatula. After three hours of fan-assisted drying, the geogrid was placed and lightly heated with a propane torch from a 10 cm distance at a constant speed to activate the bitumen uniformly. For paving fabric (PF), hot asphalt binder (PG 64-34) was applied at 168 °C at a dosage of 0.11 L/m², followed immediately by placement of the pre-cut geotextile.

After interlayer application, the top ESG-10 layer (50 mm or 37 mm, depending on reinforcement depth) was compacted at 135 °C. Final slabs were cut into 80 mm × 80 mm × 80 mm specimens, with edges precisely trimmed to eliminate boundary effects and ensure consistent mechanical response during testing (**Fig. 1**).

To ensure optimal test accuracy, the top and bottom faces of each specimen were finely sanded prior to loading. This polishing process created a uniform surface finish, promoting consistent contact with the testing machine's loading head and base support. Such preparation minimized seating irregularities and contributed to the reliability of the mechanical measurements.

Furthermore, for accurate assessment of crack resistance in asphalt specimens reinforced with geogrids, it is essential that the test configuration accommodates at least three open apertures along the crack path (Solatiyan et al., 2023). Meeting this criterion improves interaction between the crack tip and the reinforcement, resulting in more meaningful and reproducible data.
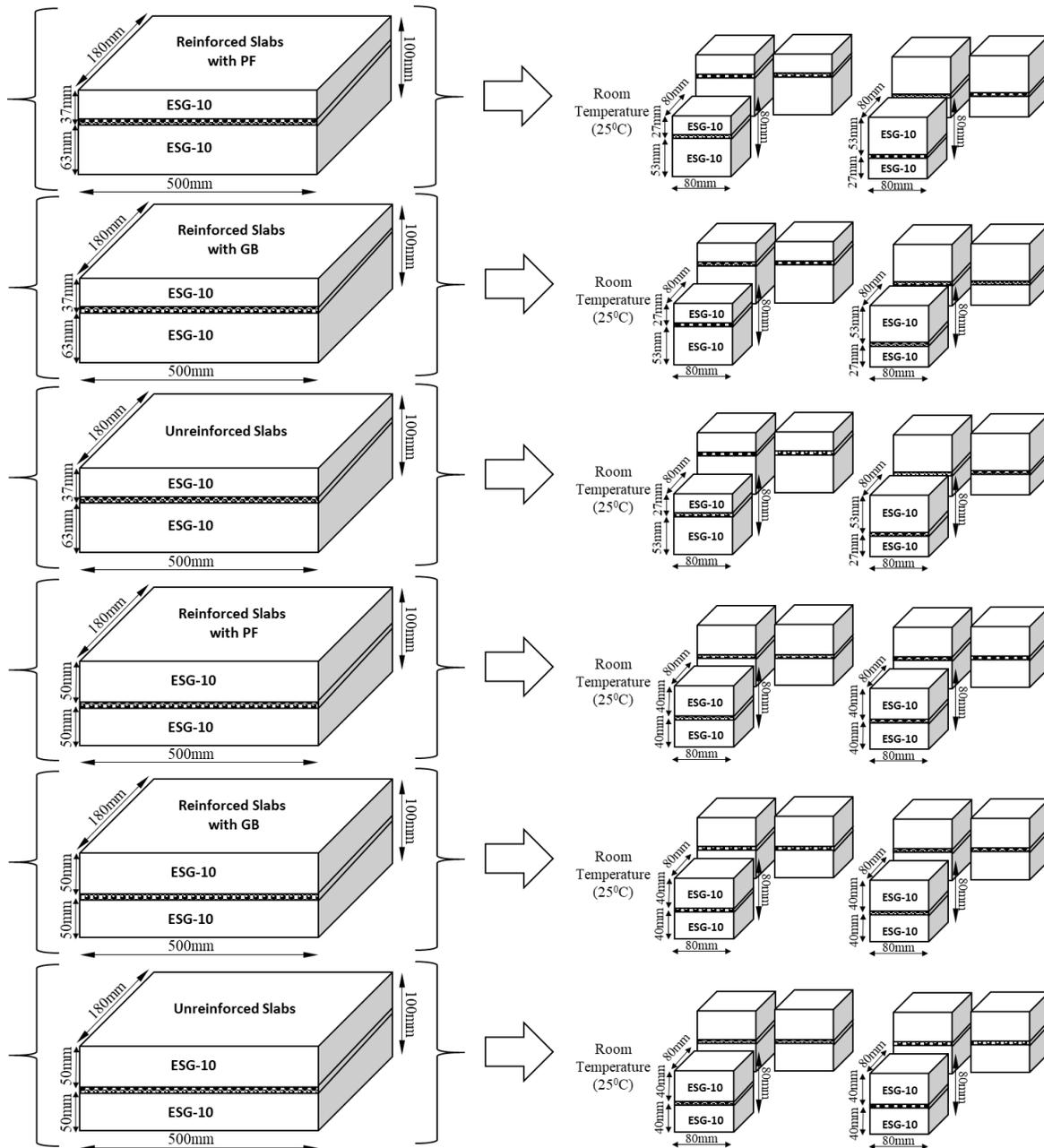
Fig. 1. Schematic of shape, size, and dimensions of specimens

2.2 Test Setup

A custom-designed crack propagation testing apparatus was developed and meticulously calibrated to simulate the mechanical degradation of asphalt layers due to traffic loading and environmental stresses. This device facilitates the controlled initiation and progression of cracks from a predefined notch to the surface of the specimen, enabling a detailed evaluation of fracture

behavior in both reinforced and unreinforced bituminous structures. One of the apparatus's distinguishing features is its ability to maintain a constant loading rate, even at large deformations, through the incorporation of a stabilizing edge projection that ensures uniform force application throughout the test. The configuration and operation of the device are discussed in detail in subsequent sections, with **Fig. 2** providing a visual schematic of the apparatus and its testing arrangement.

Structurally, the device features a triangular base that supports two guided sliding arms, which securely hold the asphalt specimen during testing. A spring-loaded screw mechanism maintains contact between the sliding arms until the test begins, after which the spring disengages and no longer contributes resistance. The test is initiated by applying a pre-set vertical compressive load (up to 100 N) through a servo-hydraulic MTS actuator, following which the sliding components move at a controlled displacement rate.

These components travel along a 45° inclined plane, translating vertical displacement into synchronized horizontal movement. As the sliding elements progress, their edges engage with a pre-formed notch-6 mm wide and 15 mm deep-cut either at the top or bottom face of the specimen, depending on the placement depth of the reinforcement. This movement initiates and drives a controlled crack that propagates through the interlayer system until it reaches the surface. Reinforcements or tack coat emulsions were embedded at one-third, one-half, and two-thirds of the specimen height, enabling comparative analysis of crack resistance at varying depths, as shown in **Fig. 3**.
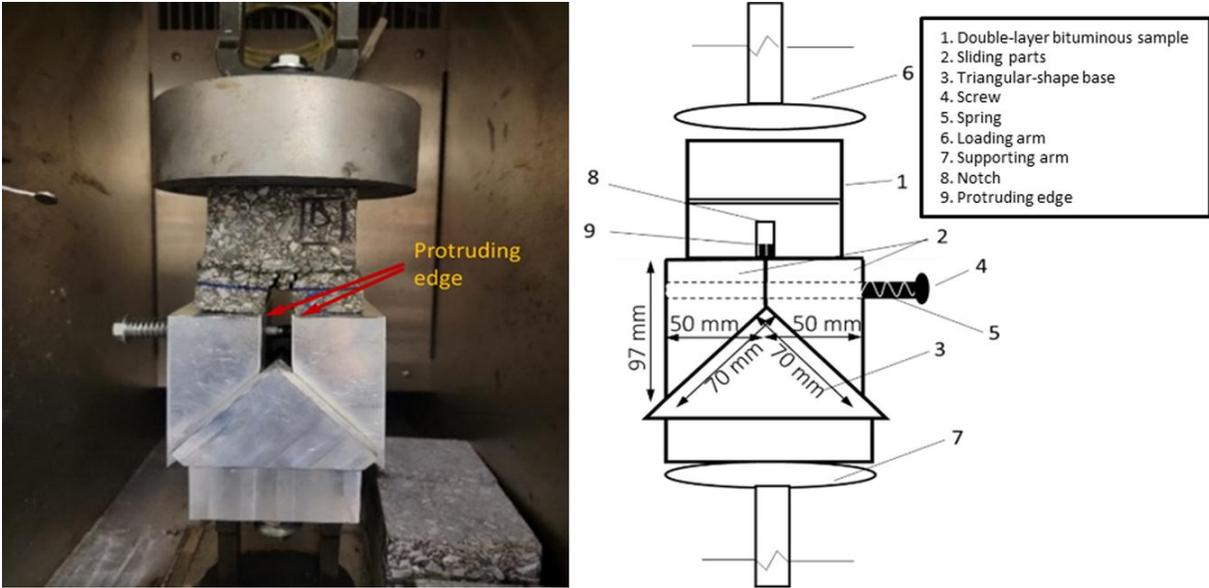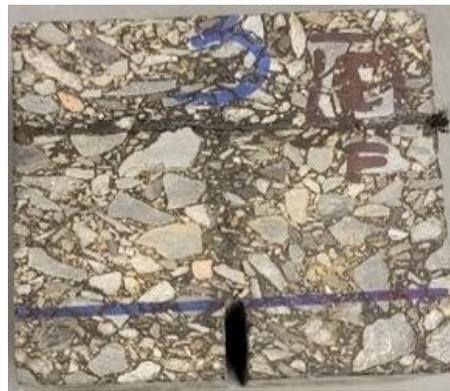
Fig. 2. A view of crack widening device and how it works.

1. Double-layer bituminous sample
2. Sliding parts
3. Triangular-shape base
4. Screw
5. Spring
6. Loading arm
7. Supporting arm
8. Notch
9. Protruding edge

a)   At One-third from the bottom

b)   At Two-third from the bottom

c)   At One-half from the bottom

Fig. 3. Detail of reinforcement/emulsion position in the samples.

3   Results and Discussion

This study primarily investigates the force–crack width response of bituminous specimens reinforced at various depths. Emphasis is placed on identifying the mechanical effects of reinforcement position during crack propagation. All reported results represent the average of two replicate tests conducted for each interlayer configuration to ensure consistency and reliability in the analysis.
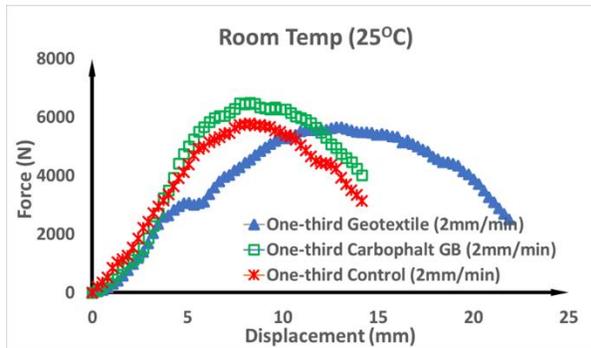
3.1   The performance of reinforcement/emulsion

As highlighted by Ho et al., (2024), reinforcement materials perform most effectively at room temperature (~25 °C), where stable thermal conditions enhance interfacial bonding and enable full mobilization of mechanical properties. The force–displacement responses clearly demonstrate that both reinforcement type and placement depth significantly influence crack resistance in asphalt composites under monotonic loading (**Fig. 4**).

Among the reinforcement strategies tested, placing materials at one-third of the specimen height (closest to the crack origin) produced the most notable improvements. Carbophalt GB achieved the highest peak force (~6,700 N), attributed to its stiff glass–carbon fiber composite and bitumen coating, which ensures early load transfer. However, its post-peak response was brittle, with a rapid decline in load-carrying capacity. In contrast, the geotextile (PF) showed a more ductile response, maintaining load over displacements exceeding 20 mm, reflecting its ability to bridge cracks and dissipate energy due to its flexible, binder-saturated structure. The control sample, bonded with emulsion, reached a similar peak force but failed earlier, confirming its lower toughness and limited post-crack resistance.
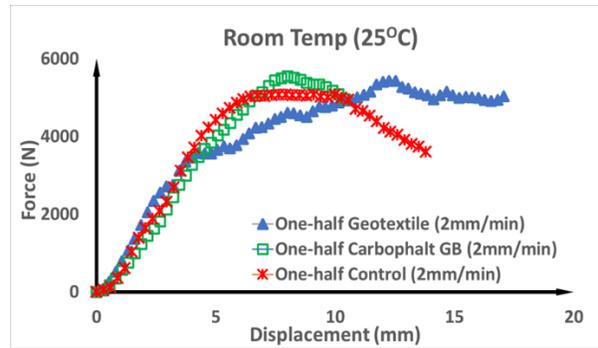
At mid-depth (one-half height), the reinforcement effects were less distinct, with peak forces clustering between 5,000 and 5,800 N. PF continued to outperform others in ductility, while GB retained a high peak but dropped off quickly. The control again lagged in post-peak toughness. At

two-thirds height, reinforcement benefits diminished, as cracks had more distance to propagate before reaching the interlayer. PF still exhibited the most extended load-bearing behavior, but peak forces were lower across all samples, confirming reduced reinforcement effectiveness at this placement depth.

These findings underscore that reinforcement placed near the crack initiation zone significantly improves crack resistance. Flexible geotextiles like PF, with strong adhesion and energy absorption, offer superior performance when placed near the bottom interface. Stiffer materials like Carbophalt GB excel in initial strength but risk brittle failure if not optimally positioned. Emulsion-bonded control samples, while modestly effective, consistently underperformed compared to geosynthetics. Overall, reinforcement configuration-both material and placement depth-plays a critical role in improving overlay durability, aligning with prior research and offering clear guidance for pavement design and rehabilitation practices.

a)   One-third

b)   One-half (Mid-depth)
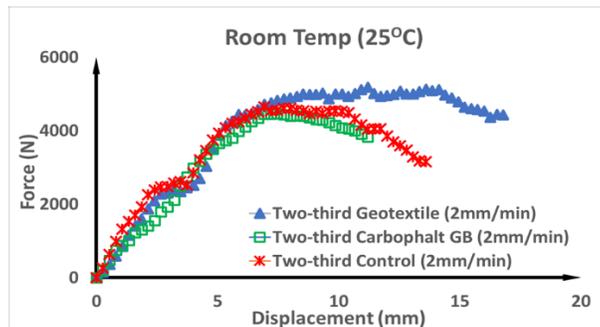
c)   Two-third

3.2 The optimum location for the reinforcement/emulsion in asphalt pavement system

The mechanical performance of reinforced asphalt composites is strongly influenced by the vertical positioning of the interlayer within the structure, particularly in relation to the crack initiation zone (**Fig. 5**). When geotextile or Carbophalt GB reinforcement was placed at one-third of the specimen height measured from the bottom - closest to the initial notch and representative of early crack development in overlays - the material exhibited the highest load-bearing capacity and most extended displacement before failure. This placement allowed the reinforcement to engage directly with the advancing crack front, promoting effective crack-bridging action and enhanced energy dissipation. As a result, the specimens demonstrated improved resistance to crack propagation and a more ductile failure profile.

In contrast, when the same reinforcement materials were embedded at mid-depth (one-half height) and especially at two-thirds height - closer to the surface and farther from the bottom notch - both the peak force and post-peak deformation capacity declined noticeably. This behavior is attributed to the delayed or reduced interaction between the reinforcement and the crack path; since the crack initiates at the bottom and propagates upward, placing the reinforcement too far from the tensile stress concentration zone limits its effectiveness. For Carbophalt GB in particular, the difference in performance between the one-third and two-third placements was substantial, underscoring the critical role of reinforcement proximity to the fracture origin.

The control specimens, which were unreinforced but bonded with an emulsion interface, followed a similar trend. Peak forces were highest when the emulsion layer was applied closer to the bottom of the specimen, suggesting that even in the absence of physical reinforcement, interface location contributes to load transfer and crack resistance. However, the reinforced specimens consistently outperformed the unreinforced ones, validating the structural contribution of geosynthetic

interlayers beyond bonding alone.

These observations confirm that reinforcement effectiveness in asphalt overlays is governed not only by material properties but also by spatial configuration relative to the anticipated crack path. Placing reinforcements near the crack initiation zone activates their tensile and interfacial properties earlier during loading, resulting in enhanced fracture resistance. Conversely, upper placements reduce early-stage engagement, weakening crack mitigation potential. This highlights the importance of aligning reinforcement positioning with fracture mechanics principles when designing pavement rehabilitation strategies.
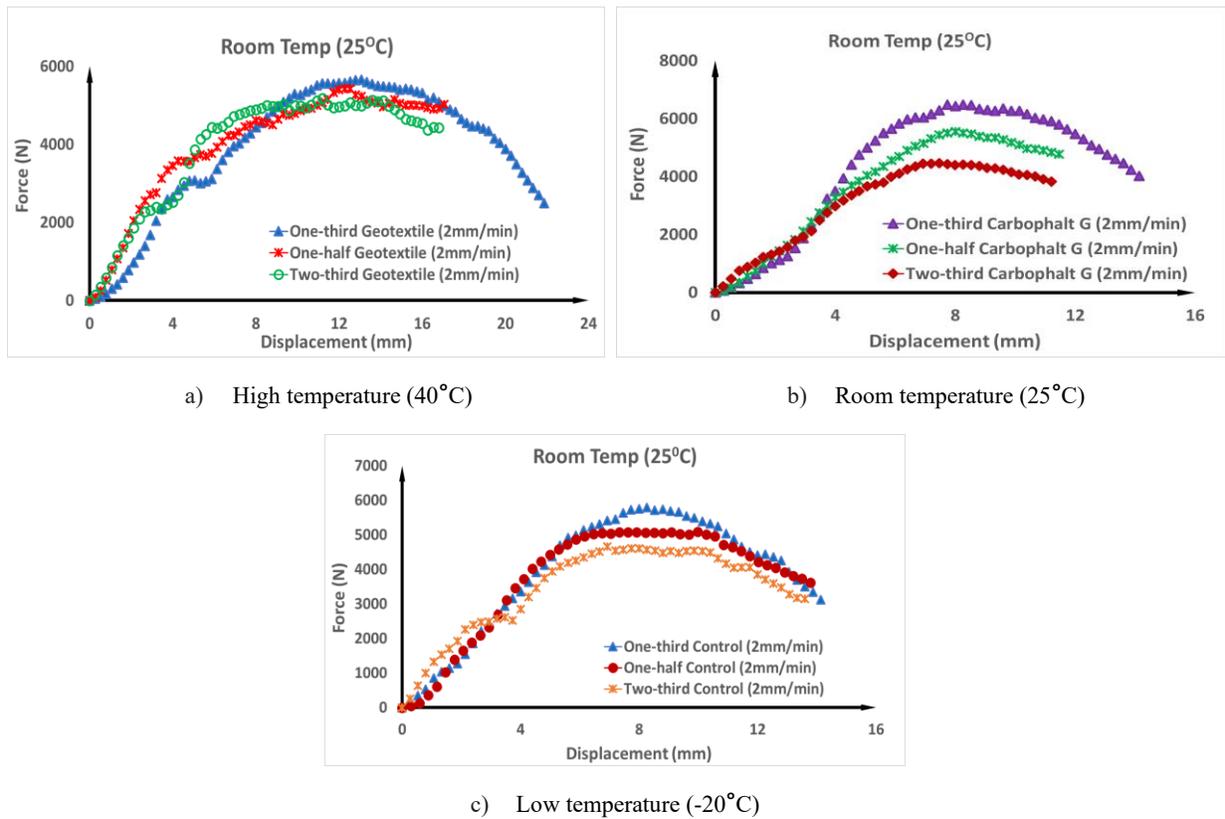
a)   High temperature (40˚C)   b)   Room temperature (25˚C)

c)   Low temperature (-20˚C)

Fig. 5.   The optimum location of reinforced and unreinforced samples.

3.3   Toughness Improvement Factor

The Toughness Improvement Factor (TIF) is a dimensionless parameter that quantifies the enhancement in crack resistance provided by reinforcement in asphalt composites, relative to an unreinforced control which is considered as baseline with the value at 1. It is defined as the ratio

of the energy absorbed by a reinforced specimen during fracture to that absorbed by an unreinforced specimen under identical test conditions. Mathematically, it can be expressed as:

$$TIF = \frac{U_{reinforced}}{U_{control}}$$

where $U_{reinforced}$ and $U_{control}$ denote the total energy absorbed (i.e., the area under the force-displacement curve) for the reinforced and unreinforced samples, respectively. This area corresponds to the mechanical work done during loading, encompassing both elastic deformation and post-peak fracture energy dissipation. A TIF value greater than 1 indicates improved performance due to reinforcement, as it reflects increased capacity to absorb and redistribute stress before failure.

The integration of reinforcement modifies the shape and extent of the force-displacement response, typically raising the peak force and extending the displacement at which failure occurs. This results in a larger area under the curve, and thus a higher toughness. In contrast, when reinforcement is placed in locations that limit its interaction with the crack front-such as farther from the crack initiation zone-the energy absorbed tends to decrease, resulting in a lower TIF. Accordingly, TIF is not only a comparative performance index but also a meaningful indicator of the reinforcement's effectiveness in resisting crack propagation and enhancing the structural integrity of asphalt composites. Its direct link to the force–displacement relationship makes it a valuable tool in optimizing the design and placement of geosynthetic interlayers, particularly in pavement rehabilitation contexts where reflective cracking is a concern.

Fig. 6 described the performance trends observed in the Toughness Improvement Factor (TIF) data align closely with the force–displacement behavior of asphalt composites reinforced with geotextile and Carbophalt GB. These trends underscore the critical influence of interlayer placement depth on reinforcement effectiveness. When the reinforcement was installed at one-

third the specimen height from the bottom-placing it closest to the initial crack location-both geotextile and Carbophalt GB specimens exhibited markedly improved toughness. Specifically, geotextile-reinforced specimens achieved a TIF of 1.54 in this configuration, indicating over 50% improvement in energy absorption capacity compared to the unreinforced control, while Carbophalt GB showed a more modest gain (TIF ≈ 1.12). This superior performance stems from the reinforcement's proximity to the notch tip, where crack initiation begins. Being near the fracture origin enables the interlayer to engage immediately during crack development, enhance stress redistribution, and bridge the crack path effectively-resulting in higher peak forces and extended post-peak deformation.

As the reinforcement was placed higher-at mid-depth (one-half) and especially near the top (two-thirds)-a clear decline in TIF was observed. For geotextiles, TIF dropped to 1.44 at one-half and further to 1.36 at two-thirds. Carbophalt GB showed a more pronounced deterioration, with TIF falling below 1 (0.89 at mid-depth and 0.76 at two-thirds), indicating a reduction in toughness compared to the unreinforced control. This degradation occurs because the reinforcement is positioned farther from the zone of maximum tensile stress, limiting its interaction with the crack tip during its critical early propagation stage. As a result, the interlayer engages only after significant damage has already occurred, reducing its ability to delay crack growth or enhance energy dissipation.

The control specimens, which relied solely on emulsion bonding at the interface, also followed this pattern. Although all control TIF values are normalized to 1 for comparison, the underlying displacement and peak load behaviors revealed that when the emulsion interface was placed at one-third height, the specimen demonstrated improved crack resistance relative to higher placements. This highlights that even without structural reinforcement, interface positioning has a

measurable effect on fracture behavior.

In summary, a clear cause-and-effect relationship emerges: placing the reinforcement closer to the bottom of the specimen - where cracks typically initiate in real pavement scenarios - results in earlier and more effective mechanical engagement. This positioning maximizes crack bridging, delays fracture progression, and enhances overall toughness. Conversely, when the reinforcement is situated farther from the crack origin, its capacity to resist crack propagation diminishes significantly. These findings highlight the necessity of thoughtful interlayer positioning in asphalt pavement rehabilitation, particularly when the objective is to mitigate reflective cracking and extend service life through improved structural performance.
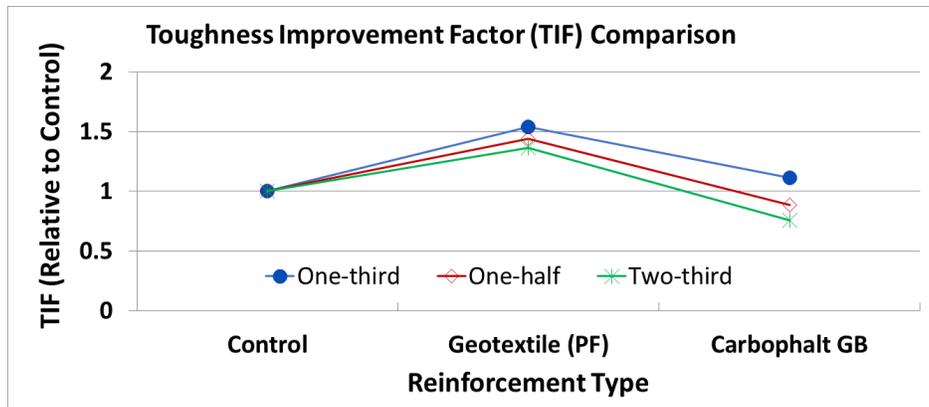

Fig. 6. Toughness Improvement Factor Comparison.

3.4 Fracture toughness GIC

Fracture toughness, commonly denoted as G_{IC}, often referred to as Mode I fracture toughness, is a fundamental material property that quantifies a structure's resistance to crack initiation and propagation. In asphalt composites, G_{IC} is typically defined as the energy required to propagate a crack per unit area of the fracture surface. It is calculated using the equation:

$$G_{IC} = \frac{W}{A}$$

where W is the energy absorbed during fracture (i.e., the area under the force–displacement curve,

in N·mm or J), and A is the ligament area (in mm²) across which the crack propagates. Higher G_{IC} values indicate enhanced fracture resistance and improved toughness of the asphalt system.

Fig. 7 reveals clear trends in how reinforcement type and vertical positioning affect the fracture toughness of asphalt specimens. Across all configurations, the geotextile (PF) reinforcement consistently exhibits the highest fracture energy values, indicating its superior crack-bridging capacity and energy dissipation. When placed at one-third height from the bottom (closest to the crack initiation zone), geotextile reinforcement achieved the highest G_{IC} value of 39.81 J/m². This placement allows the geosynthetic to actively engage with the crack tip during propagation, enhancing the composite's ductility and delaying failure.
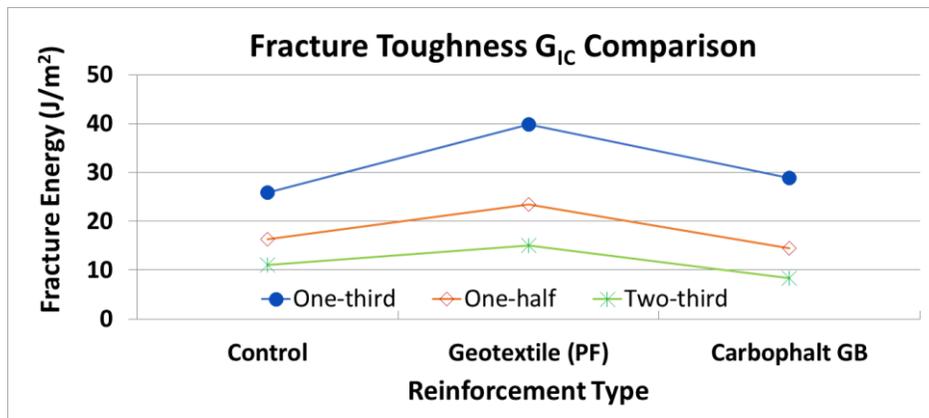

Fig. 7. The influence of loading rate on performance of reinforced and unreinforced samples

The control (unreinforced) specimens, while expected to perform least effectively, surprisingly outperformed the Carbophalt GB (glassgrid) specimens at all depths except at the one-third position. Specifically, control specimens yielded a G_{IC} of 25.85 J/m² at one-third depth, outperforming Carbophalt GB at one-half (14.50 J/m²) and two-thirds (8.40 J/m²). This suggests that although glassgrids provide structural reinforcement, their effectiveness in crack resistance is highly sensitive to placement depth. When situated farther from the crack tip (e.g., two-thirds height), the glassgrid's ability to arrest crack growth diminishes significantly due to delayed engagement with the fracture zone.

Furthermore, the fracture toughness of all materials decreased progressively with increasing reinforcement depth. At two-third depth-closer to the surface and farther from the notch-the reinforcement is less effective in mitigating crack propagation originating from the bottom, as seen in rehabilitation scenarios. At this depth, the geotextile still outperformed the other systems with a G_{IC} of 15.11 J/m², while control and Carbophalt GB followed with 11.08 and 8.40 J/m², respectively.

In conclusion, the effectiveness of geosynthetic reinforcement in improving fracture toughness is highly dependent on its proximity to the crack initiation zone. The geotextile reinforcement demonstrates robust toughness enhancement across all depths, particularly when placed at one-third from the bottom. These findings underscore the importance of strategic interlayer positioning to maximize the mechanical benefits of reinforcement in mitigating reflective cracking in asphalt overlays.

4   Conclusion

This study investigated the mechanical performance of asphalt overlays reinforced with geosynthetics, focusing on the effect of reinforcement type and vertical placement under monotonic loading. Results confirmed that placing reinforcement at one-third from the bottom-closest to the initial crack-significantly improved crack resistance, energy absorption (fracture energy, G_{IC}), and toughness. Among the reinforcements tested, paving fabric (PF) demonstrated the most consistent improvement across all metrics, while Carbophalt GB showed moderate gains. Unreinforced control specimens exhibited the lowest resistance to crack propagation, underscoring the effectiveness of geosynthetic interlayers.

As the reinforcement was positioned farther from the crack origin, its contribution to resisting fracture diminished. This emphasizes the importance of strategic placement, especially in

reflective crack mitigation.

To further this research, it is recommended to explore cyclic and fatigue loading scenarios, temperature-dependent performance, and numerical modeling for predictive analysis. Additionally, field validation and studies on alternative or hybrid reinforcement materials could offer practical insights for sustainable pavement rehabilitation.

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