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The mechanical performance of reinforced bituminous interfaces with paving fabric under freeze-thaw conditioning

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ABSTRACT

The application of paving fabric at the interface of bituminous layers as a rehabilitation strategy has proved its effectiveness in extending the pavement service life by delaying the manifestation of reflective cracking on the surface. However, this enhanced performance relies on the adhesion bond supplied at the interface, which in the case of debonding, the structural benefits provided by the interlayer can be compromised. Gaining authentic knowledge about the bonding condition at a reinforced interface exposed to different conditioning impacts helps to improve the reliability of the input data, which has not been adequately considered in the mechanistic-based design methods proposed for reinforced bituminous structures. This research was dedicated to understanding the mechanical behavior of double-layer bituminous layers composed of two different hot mixtures and reinforced with paving fabric when subjected to freeze-thaw cycling. To attain this objective, the initial step involved determining the optimal dosage of bitumen for use as a tack coat at the interface of the paving fabric, which was established as 0.0014 m3/m2 through asphalt retention tests. Subsequently, the results from the shear test, conducted using the slant shear device, were utilized to establish three comparative criteria at the interface, aimed at elucidating distinctions when compared to unreinforced cases. These criteria include the energy absorbed by the interface during shearing, shear stiffness, and the coefficient of interface bonding (CIB). This study revealed that by increasing the number of freeze-thaw cycling, the reinforced interface keeps the shear stiffness and the CIB values unchanged. However, in terms of energy absorption capabilities, the unreinforced interfaces showed better performance. This study showed that using the CIB value to quantify the bonding strength at the interface and energy dissipation and initial shear stiffness to quantify the evolution of interface bonding over number of F-T cycles are all proper representatives to include into mechanistic-empirical design methods for reinforced structures in order to present realistic models.

1. Introduction

Asphalt binders exhibit diverse behaviors influenced by temperature, load severity, and loading speed. These characteristics play a crucial role in the overall performance of bituminous layers [12]. While previous studies have examined these factors, the unique challenges posed by freeze-thaw cycles on the mechanical behavior of bituminous interfaces, especially those reinforced with geosynthetics, remain underexplored.

The placement of interlayer systems in the form of geosynthetic materials along with a fresh asphalt overlay on a deteriorated bituminous surface has proved its effectiveness in extending the service life of a pavement structure [23]. However, this functional upgrade is mostly governed by the bond strength provided between consecutive bituminous layers in the presence of the interlayer [26]. The application of a layer of tack coat between the geotextile and the bottom bituminous layer enhances the structural integrity of the system, which was initially compromised by the asynchronous execution of the layers. Nevertheless, the outrageous environmental conditions accompanied by excessive traffic loads lead to a gradual disappearance of bond strength with varying degrees depending upon the type of geosynthetic, type and dosage of the tack coat, and the surface texture of the materials in contact at the interface level [23]. On the other hand, debonding at the interface level may result in the manifestation of premature fatigue failure, longitudinal cracking, and surface delamination due to tack coat failures [5].

The influence of tack coat (type, dosage, curing time), temperature, loading rate, and geosynthetic characteristics (thickness and coverage ratio) on interface bonding condition have already been studied [4,6,7,

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9,14,18,21]. Nonetheless, a legitimate measurement of the interface bond strength subjected to freeze-thaw (F-T) cycles and its moisture susceptibility ought to be conducted to gain a better knowledge in selecting realistic interface inputs for mechanistic- based design methods.

The shear strength has frequently been adopted by researchers to assess the bonding strength at a reinforced interface with a layer of geosynthetic compared with an unreinforced one. On this ground, a variety of test methods have been proposed to reproduce the field loading condition, which most of them were originated from the Leutner shear test device [10]. The device, which was first developed in the late 1970s, accommodates cylindrical shape specimens between a lower and upper semicircle ring. A shear displacement rate of 50 mm/min is applied from the upper body and the resulting shear stress is collected during the test. In spite of the simplicity and ease of specimen installation, the test procedure suffers from the lack of a confining pressure supported by the normal load applied at the top. It is believed that the friction between the layers surrounding the interface constitutes an important share of the shear strength when the normal load is applied at the top surface [20]. If this effect does not properly address in the laboratory shear test devices, it will result in unreal material response and restricts its application in pavement analysis and design [8]. On this basis, another set of shear test devices were developed to include the normal load effect. The slant shear device [24], the Ancona Shear Testing Research and Analysis (ASTRA) [7], the Louisiana Interface Shear Strength Tester (LISST) [3], the NCAT bond strength device [28], the Sapienza Horizontal Shear Test Machine (SHSTM) [10], the Coaxial Shear Test (CAST) [22], and the Advanced Shear Tester (AST) device [32], are some test setups in which the interface plane simultaneously undergoes a constant or variable normal stress and a shear stress. Among them, the slant shear device, in spite of its simple structure, is able to resemble the realistic field loading condition in an optional temperature and loading rate [25].

Freeze-thaw cycling has a principal destructive impact on flexible pavements [17,2] which progressively leads to an adhesive failure between aggregates and surrounding binder, known as stripping. As the number of freezing and thawing increases, the separation between two bodies accumulates over the time, which in turn speeds up the degradation of the pavement structure due to thermal cracking, fatigue cracking and permanent deformation [1,11,13]. Concerning that, the expanded air void content due to the F-T cycles is considered as the root cause of accelerated deterioration process of the pavement structure [27]. In addition, under water saturated condition, it was also demonstrated that water could easily penetrate into the aggregate-binder space and undermine the bond strength at the interface [11,13]. In an experimental study, the addition of rubber powder and polyester fibers in the asphalt mixture resulted in a better anti-freezing performance than the corresponding neat mixtures [19,29,30,31]. However, only a few studies have been focused on the impact of the F-T cycle on the performance of the reinforced bituminous layers with geosynthetics. This study was taken up to understand how the freeze-thaw cycles could affect the bonding condition at a bituminous interface reinforced with a layer of paving fabric.

2. Materials and methods

This research was launched to assess the bond strength at the interface of a layer of paving fabric and its surrounding bituminous layers under freeze-thaw conditioning. Achieving this goal, cubic shape double-layered specimens, both unreinforced and reinforced with paving fabric surrounded by two different types of mixtures, in terms of aggregate size, were manufactured in the laboratory in order to resemble the field condition. It was assumed that different types of mixture in contact with geotextile might receive varying degrees of influence from the F-T cycling. The slant shear tester (AST) device was utilized to quantify the shear strength at the reinforced and unreinforced interfaces under the effect of different interfacial conditions. To observe the evolution of shear strength as the number of freeze-thaw cycles increased, the testing process iterated at 1 and 5 cycles. While a higher number of cycles could potentially offer a more detailed understanding of shear strength evolution, practical considerations played a pivotal role in determining the chosen iteration range. Handling conditioned samples at a higher cycle number presented challenges, including the risk of external hand-made cracking during displacement and the potential for clogging air voids in the sample structure due to suction pressure. These practical constraints necessitated a careful balance between obtaining meaningful data and ensuring the feasibility of the experimental setup. The decision to limit the iteration to 5 cycles aimed to strike this balance and provide insightful data while mitigating potential issues associated with handling samples at higher cycle numbers. The following subsections give more details on the specification of the materials and the test procedure followed in this research.

2.1. Materials and specimen preparation

In order to investigate the effect of the surface texture on mechanical properties at the interface, paving fabric was introduced in two types of structures, named S_1 and S_2, composed of two different hot asphalt mixtures in terms of aggregate size complying with *Transport Quebec's standard (LC 4202) (MTQ, 2018)*. The structure S_1 included a surface layer with a nominal maximum aggregate size (NMAS) of 10 mm (ESG-10) placed over another bituminous course of the same specification. On the other hand, the structure S_2 was formed by the implementation of the surface course (ESG-10) over a bituminous binder course with an NMAS of 14 mm (ESG-14). Corresponding to those two unreinforced structures, reinforced structures were built with the same mixes on top and bottom but with the addition of a layer of paving fabric at the interface of the mixtures, as shown in Fig. 1. The mechanical specifications and the designed sieve curves for each type of mixtures are presented in Table 1 and Fig. 2, respectively.

The formation of each type of structure was first launched by the production of the bottom bituminous layer at a mixing temperature of 168 °C, in a mold of size 500 × 180 × 100 mm. Thereafter, the mixture was compacted by means of the French Roller Compactor (FRC), according to European Standard EN 12697–33, at 165±2 °C complying with the type of bitumen. After 24 hours, two distinct procedures were pursued for the preparation of the interface on the top surface of the prepared slabs:

- For the unreinforced structure, a layer of cationic emulsion type SS-1 h with the dosage of 180 g/m^2 of the residual bitumen was applied on the surface with the help of a syringe and uniformly distributed via the edge of a spatula. The top layer application was performed after 3 hours required for complete breakage of the emulsion.
- For the structure reinforced with paving fabric, the bitumen type 58 H-34 with the optimum dosage (as found earlier) was utilized at compaction temperature (i.e. 160 ºC), which was promptly followed by the placement of the fabric on the surface.

The production procedure was moved forward by applying the top hot mixture on the prepared surface. This application was conducted after 3 hours in the case of unreinforced structure and immediately after installation of the paving fabric in the case of reinforced structure. Afterwards, the double-layer structure was compacted through the FRC method at 165±2 °C.

The mean texture depth, indicated in Table 1, for each mixture used as the bottom slab in the double-layered structure, was obtained by scanning probe microscopy method, as shown in Fig. 3. In this method, the 3D dimensional surface data (i.e. x, y, and z) was first gathered. Then, to determine a representative quantity as a surface roughness, the "Gwyddion" software was utilized. Within Gwyddion, there are several ways of doing statistical analysis. One way is to use functions from "Data

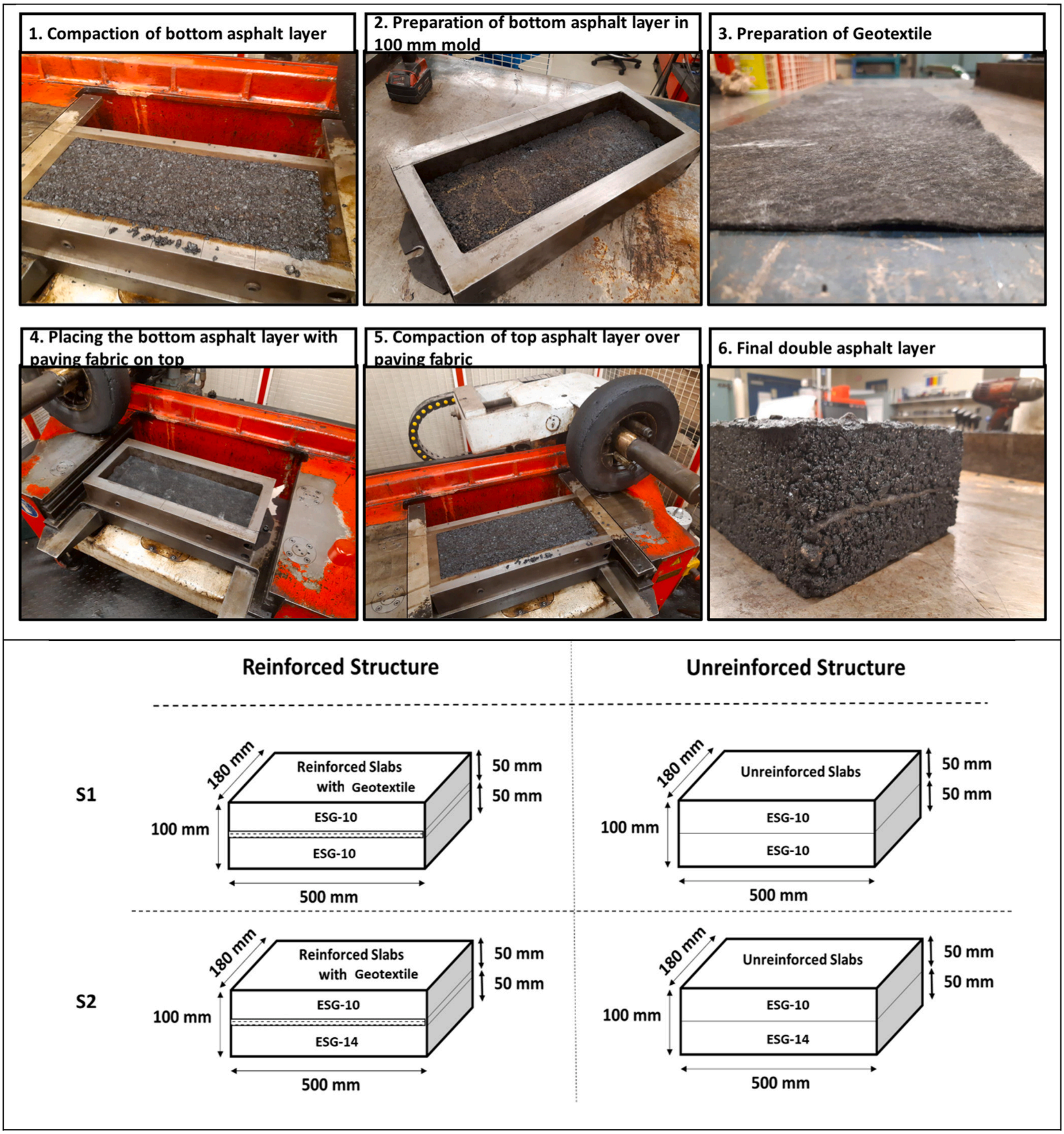

Fig. 1. Size, shape and configuration of double-layer structures.

Process menu" in which standardized one-dimensional roughness parameters can be evaluated. One of these parameters is the "Arithmetical mean deviation" which is the average deviation of all points' roughness profile from a mean line over the evaluation length according to Eq. 1:

$$R_a = \frac{1}{N}\sum_{j=1}^{N}\left|z_j - z_{avg.}\right| \tag{1}$$

where,

R_a = Surface roughness in mm;
z_j = Height of an arbitrary point on the surface from the origin;
$z_{avg.}$ = Mean height of all the points on the surface;
N = Number of points scanned from the surface.

Fig. 3 demonstrates a 3D colored plot presented by scanning probe microscopy for both of the mixes. As can be seen, on average, the ESG-14 had substantially higher surface roughness (i.e. 2.76 mm) compared with the ESG-10 (i.e. 1.58 mm) especially at two ends where the wheel of French roller compactor, utilized for the compaction of the slabs, has been stopped and started the movement in each cycle of the compaction process.

For reinforced double layer structures, geotextile impregnated with bitumen type 58 H-34 was utilized. In order to determine the proper

Table 1
Mechanical specification of mixtures.

Specifications	ESG-10	ESG-14
Binder Type	PG 64E-28	PG 64 H-28
Binder Content (mass %) (LC 26–004)	5.33	4.65
Mean Texture Depth (R_a) (mm)	1.58	2.76
Rut Depth (%) (LC 26–4101)	4.3 (1000 cycles) 6.1(3000 cycles)	4.9 (30,000)
Air Void (%) (LC 26–320)	6.7	7.0
Maximum Theoretical Specific Gravity (Gmm) (LC 26–045)	2.536	2.577
Water Sensitivity (%) (LC 26–001)	87	91

dosage of bitumen required as tack coat between the geotextile and the bottom slab layer, the asphalt retention test was performed according to ASTM D6140 (ASTM 2014). This test is a critical evaluation for understanding the effectiveness and performance of paving fabric within asphalt pavement structures. This test assesses the geotextile's ability to retain asphalt and prevent its drainage or displacement under various loading conditions. The asphalt retention test is necessary to:

- **Performance Validation:**
  The asphalt retention test validates whether the geotextile effectively retains the asphalt binder within the pavement matrix. Proper retention ensures that the asphalt mix remains intact and functional over the lifespan of the pavement.
- **Preventing Drainage and Rutting:**
  Uncontrolled drainage of asphalt binder from the mix can lead to the loss of essential components, affecting the mechanical properties

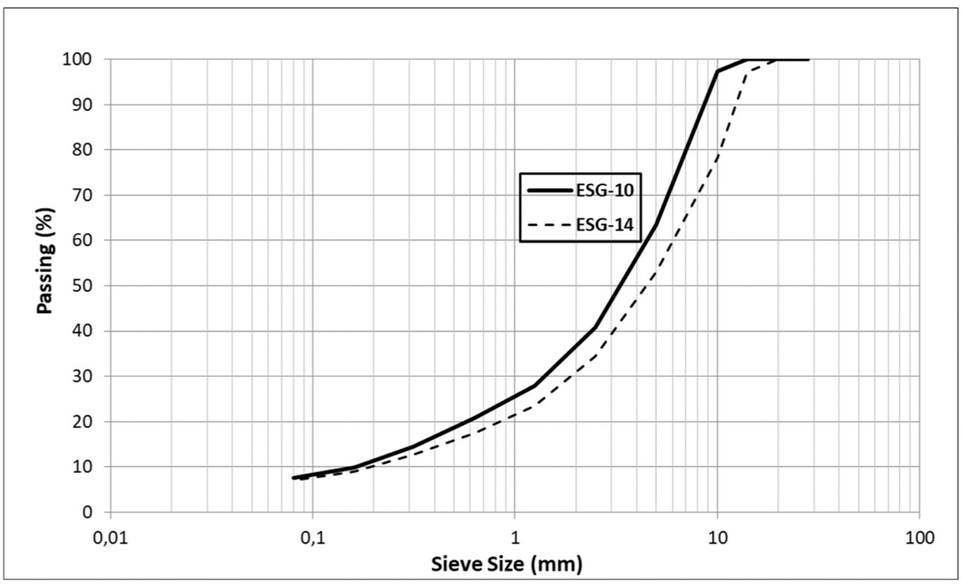

Fig. 2. Gradation curves of mixes.

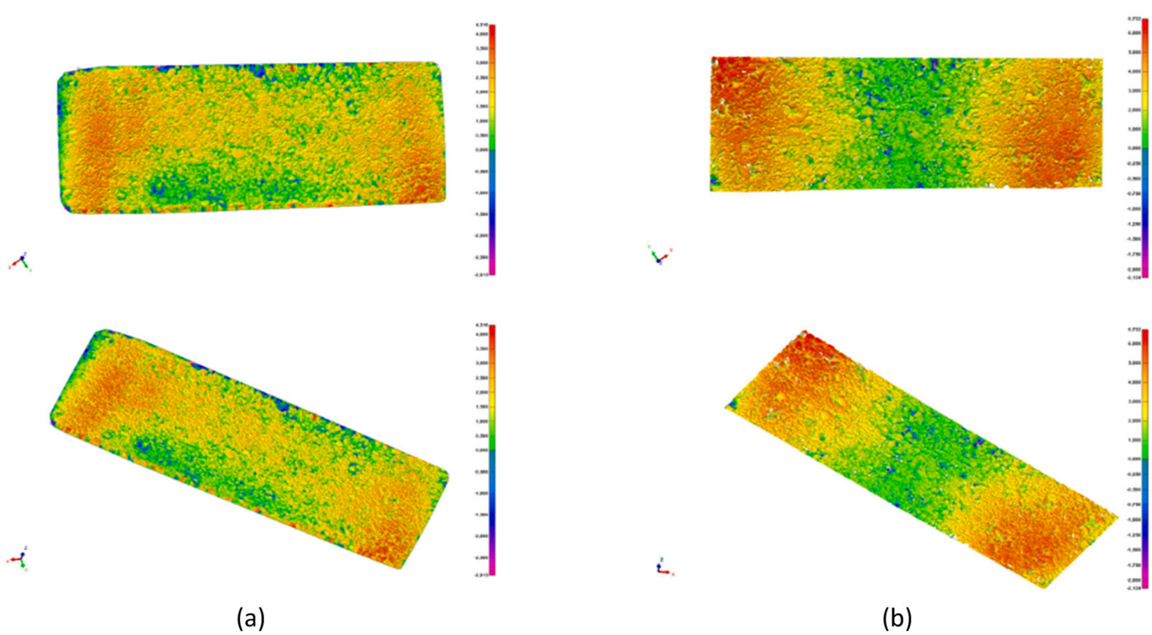

Fig. 3. Surface texture presentation obtained from scanning probe microscopy method for (a) ESG-10; (b) ESG-14.

of the pavement. This can result in premature pavement distress, including rutting and cracking. The asphalt retention test ensures that the geotextile prevents excessive rutting.

- **Optimal Material Selection:**
  The test aids in selecting the right type of geotextile for the specific asphalt mixture and project requirements. Different geotextile materials and configurations have varying asphalt retention capabilities, and the test helps optimize material selection.
- **Preventing Oxidation and Aging:**
  Asphalt oxidation and aging can occur when the excessive binder is exposed to air and moisture. A geotextile that retains the right amount of asphalt binder can protect it from these factors, preserving the binder's performance characteristics.
- **Cost-Effectiveness and Maintenance Reduction:**

From economic point of view, proper asphalt retention reduces the need for frequent maintenance and repairs due to pavement distress as well as the reduction of required asphalt binder to provide adhesion between the paving fabric and adjacent bituminous layers. This contributes to cost-effectiveness and extends the service life of the pavement.

To perform the test, from the roll of geotextile, four specimens in cross machine and four specimens in machine direction were cut to a rectangular shape of size 100 by 200 mm. Then the samples were submerged in three types of bitumen: PG 58E-34, PG64E-28, and PG 64 H-28 at 135 °C and maintained for 30 minutes. Thereafter, the bitumen was removed from the oven and with the aid of clips, the samples were hung for 30 minutes from each end to receive a uniform state of saturation all over the fabric. After letting the samples cool down for 30 minutes, the extra bitumen was trimmed and each specimen was weighed to the nearest 0.1 g. This procedure is demonstrated in Fig. 4. The mean value of asphalt retention capability of geotextile was calculated through following equation:

$$R_A = \frac{W_{Sat} - W_g}{1000.\quad (A_g \quad \times G)}$$

where,

R_A = asphalt retention in m^3/m^2;
W_{Sat} = weight of saturated sample in g.;
W_g = weight of the sample before saturation in g.;
A_g = area of sample before saturation in m^2;
G = specific gravity of bitumen in g/m^2

Based on the abovementioned test method, the bitumen PG 58E-34 offered better retention test result compared with the two other types of bitumen and is the most cost-effective option available on the market. Therefore, the optimum dosage of tack coat was selected 0.0014 m^3/m^2 in which the amount of bitumen wasted during its application was also considered.

The main physical properties of the needle-punched nonwoven fabric used as geotextile in paving fabric structure are presented in Table 2.

From each of the structure, constructed as mentioned above, 10 cubic shape specimens of size 80 × 80 × 80 mm were cut with a masonry cutter and further processed by polishing the end surfaces. The final dimension and number of specimens derived from each type of structure are schematically shown in Fig. 5. As shown, the number of test

Table 2
Main technical specification of Fabric (data from the supplier).

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

Fig. 4. Asphalt retention test procedure.

repetition for each structure was selected two and the test was performed in three different interface conditions: dry, one F-T cycle and five F-T cycles. In total, 24 specimens were tested.

2.2. Test method

In order to find out the effect of freeze-thaw cycling on bonding strength at a reinforced interface with various dosage of tack coat, the slant shear test device (Solatiyan et al., 2020c) was adopted and the results were compared with corresponding unreinforced interfaces. It was conjectured that the slant shear device could simulate the loading condition as is in the field and help to better distinguish the differences in bonding strength at the interface level while subjected to F-T conditioning. The main features of this device, which makes it distinguished compared to similar devices are its simplicity, ease of setup, and to apply normal and shear stresses at the same time at the interface level. The latter becomes of great importance under heavy wheel loads or low-speed vehicles, in which the surface texture effect plays a crucial role in providing friction between the layers in contact. A schematic view of the device is illustrated in Fig. 6.

The device includes two aluminum pieces, bottom movable part and top adjustable one in height. The system is able to move through a handmade metal ski installed over a rail. Because of its size, the device is consistent with the thermal chamber of an MTS servo-hydraulic loading system, which provides the possibility of doing the test in an arbitrary temperature. In addition, the least effort required for specimen preparation and independency of specimens to gluing, present a suitable device for doing a large number of tests in a short period of time.

The testing device underwent rigorous calibration during its development, ensuring results with less than a 15 % discrepancy. For this research, the average of two samples was considered for each type of structure and dosage of tack coat. The decision to use two specimens was rooted in the device's established reliability, maintaining results within an acceptable margin of error. In order to record the horizontal displacement during the test, a linear variable differential transducer or LVDT was utilized. The test was carried out at room temperature 20 $\pm$ 1 °C and a displacement rate of loading equals to 2 mm/min. The selection of loading rate is attributed to several reasons:

- A slower loading rate resembles better the gradual and sustained loading caused by daily fluctuation in temperature that asphalt pavements encounter during their service life.
- Viscoelastic materials like asphalt exhibit time-dependent deformation behavior, where their response can change with varying loading rates. A slower loading rate allows for more accurate observation and measurement of these deformation characteristics, helping to capture the viscoelastic behavior effectively.
- A higher loading rate introduces dynamic effects that could obscure the viscoelastic behavior being studied. Slower loading rates tend to minimize these dynamic influences, allowing to focus on the material's true viscoelastic response.

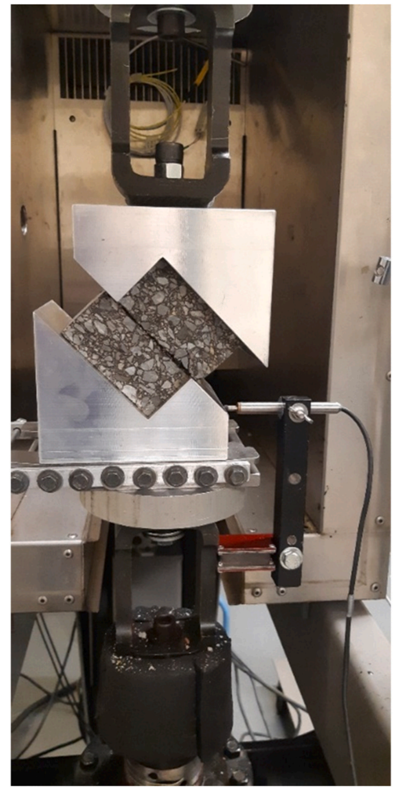

Fig. 6. A schematic view of the slant shear device.

- Choosing 2 mm/min is within the feasible range of the slant shear device and presents a minimum discrepancy of the results obtained from the samples of the similar structures.

Furthermore, a gap width of 5 mm at the interface level was chosen to accommodate the thickness of both the geotextile and the bitumen used as a tack coat. This specific gap width has been previously employed in the Sapienza Horizontal Shear Test Machine [10].

2.3. Freeze-thaw conditioning

Freeze-thaw conditioning was carried out complying with ASTM-D 4867 at one and five cycles to see how the bonding strength at the interface evolves as the number of cycles increase. On this basis, two cubic shape specimens of size 80 mm by 80 mm, from each type of structure and each dosage of tack coat were prepared. Thereafter, each sample was saturated by the vacuum pressure device at 20 kPa for 5 minutes to receive the saturation level between 55 and 80 percent, as indicated by the standard. Afterwards, the saturated specimens covered tightly by two plastic films and then placed inside a leak-proof plastic

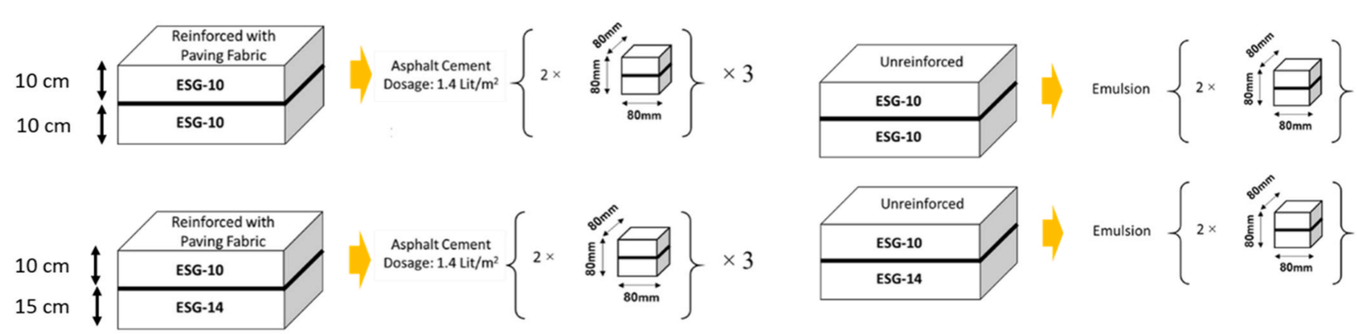

Fig. 5. Size and number of specimens derived from each double-layer slab.

bag including 3 mL of distilled water measured by a syringe. Lastly, the plastic bag was sealed firmly by wrapping up with a masking tape. For each cycle, the sealed specimens were submitted into a freezer at -18 ± 2 °C for a duration of 15 h and then transferred into a water bath, already set at 60 ± 1 °C. After 3 minutes conditioning in water, the plastic bag and the covering films were removed from the specimens and soaked for 24 hours inside the water bath, as shown in Fig. 7.

3. Results and discussion

The influence of different interfacial conditions on bonding strength at the reinforced and unreinforced interfaces are presented and discussed in this section. Fig. 8 demonstrates the force-displacement curve at the interface level averaged on two repetitions for each type of structure and for different conditioning states. The failure criteria were determined as the point at which the shear strength of the interface decreases to 70 percent of the maximum shear strength observed at the interface during the test. As can be seen, the unreinforced structures (i.e. UN10/10 and UN10/14) presented highest shear strength compared to similar reinforced structures. In this regard, both unreinforced and reinforced interfaces surrounded by ESG-10 and ESG-14 performed better compared to the one formed by ESG-10 over ESG-10 in dry

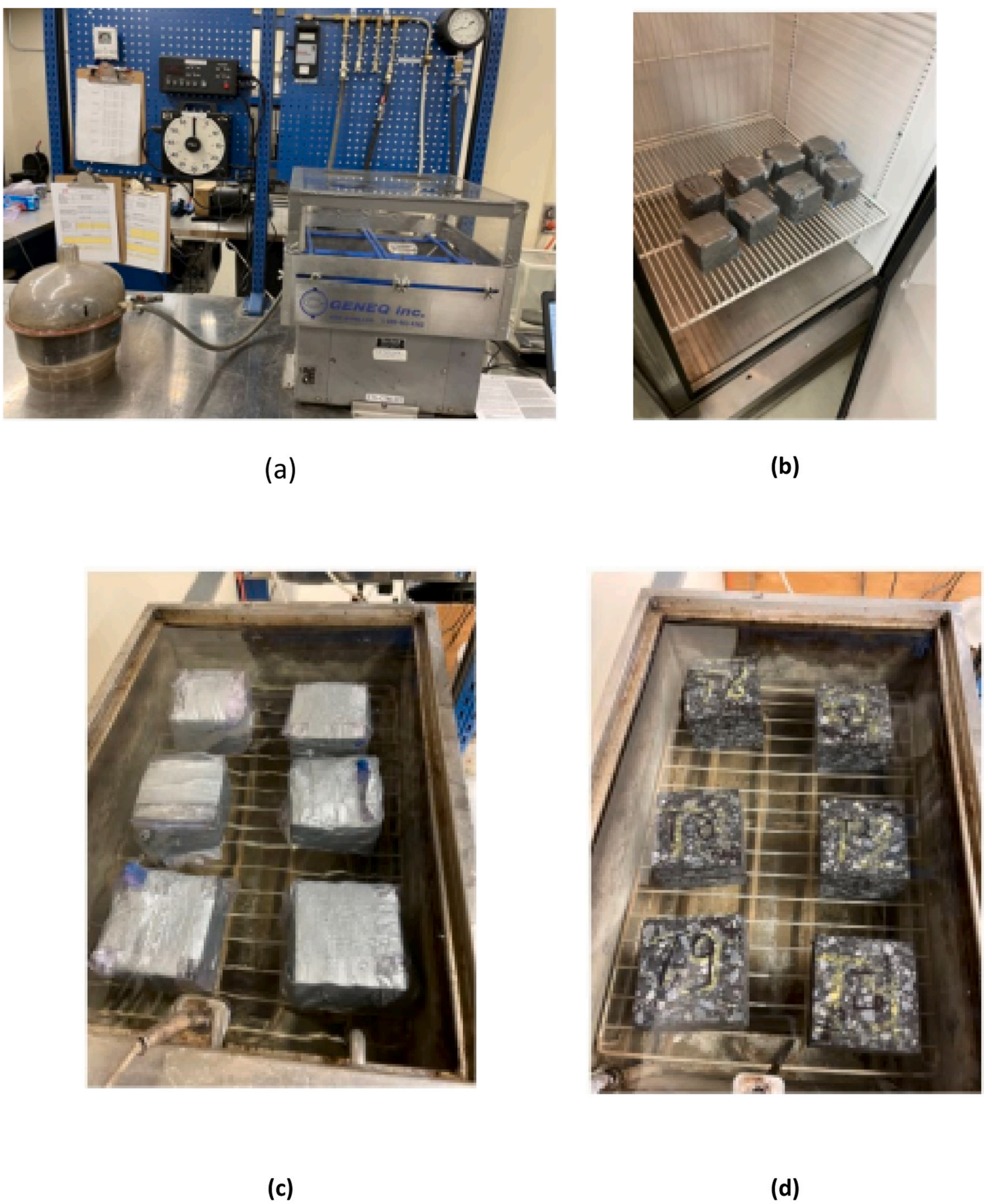

Fig. 7. Freeze-thaw conditioning of the specimens (a) saturation of specimens by vacuum pressure; (b) wrapping the saturated specimens and placement in the freezer for 15 h; (c) Transferring the specimens in a water bath at 60 ºC; (d) removing the plastic bags from specimens and conditioning for 24 h.

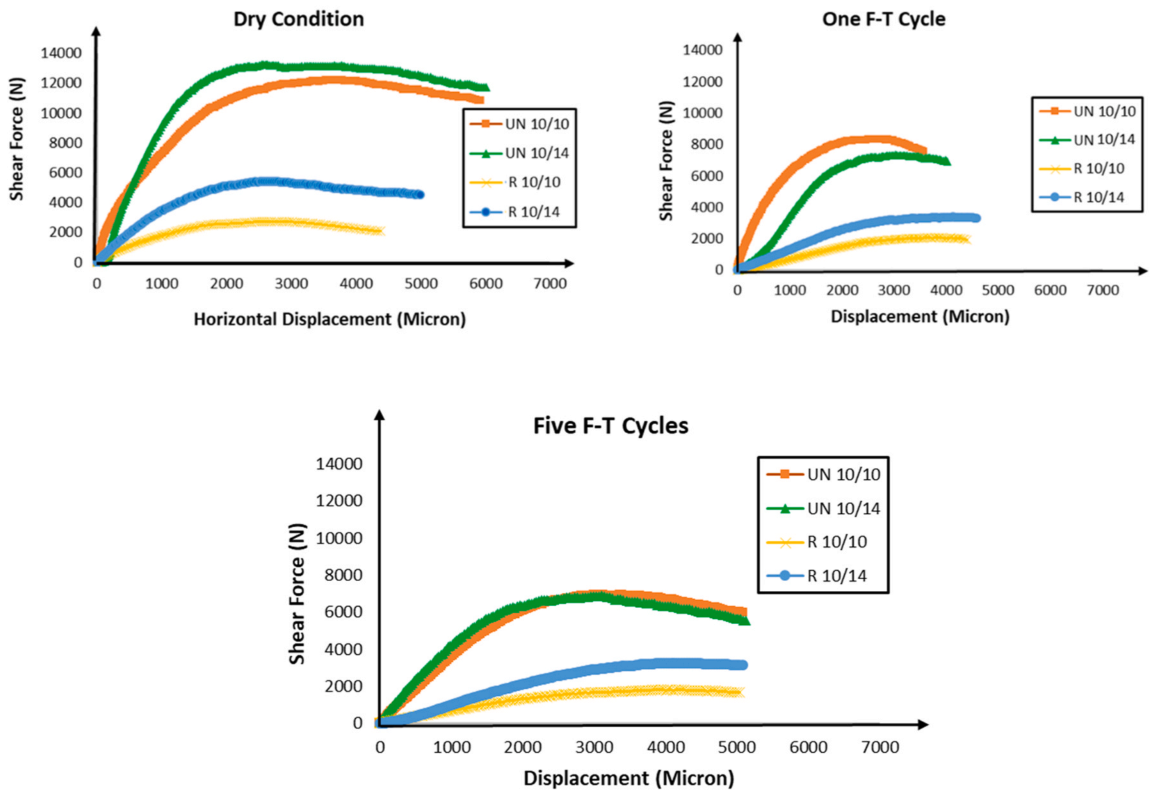

Fig. 8. Force-displacement curves at interface level for reinforced and unreinforced specimens in different conditioning states.

condition. These results can be explained by the fact that the rougher surface provided in the presence of ESG-14, as indicated by the mean texture depth in Table 1, increases the real contact area, and potentially improves stress transfer between the layers. This can impact the overall load distribution and shear behavior. On the other hand, greater surface roughness enhances the frictional resistance between the layers, which affects the shear stress that develops along the interface during the shearing test. Higher frictional resistance due to increased roughness can lead to higher shear strengths and energy absorption at the interface. However, the role of roughness becomes of less importance for the unreinforced interface while conditioning at different number of cycles. This is primarily stems from the intrusion of water through microcracks and irregularities on the surface during freeze-thaw cycles. Higher surface roughness provides more opportunities for water to penetrate and lead to the formation of ice within these crevices, potentially influencing crack formation and propagation and interface behavior. Furthermore, freeze-thaw cycles can exacerbate debonding due to the expansion and contraction of ice. Another point of interest is that the unreinforced interface loses almost 30 % in shear strength under conditioning while this impact is limited to 15 % for reinforced ones. This is mainly due to the low chances of water to penetrate the irregularities of the interface in the presence of paving fabric and subsequent reduction in ice lenses formation.

To gain a better insight into differences caused by conditioning, three major criteria were considered for the comparison on mechanical performance among the structures: 1. absorbed energy by the interface during shearing in joule, calculated by the area surrounded by force - displacement curve; 2. Initial stiffness at interface level in N/mm obtained from initial slope line drawn from the origin of force-displacement curve; and 3. coefficient of interface bonding (CIB) in N/mm^3 derived from the quotient of maximum interlayer shear strength (ISSmax) and the corresponding interlayer shear displacement (ISD)($CIB = \frac{ISS_{max}}{ISD}$). In the following subsections, the results obtained for each of these criteria are discussed in detail.

3.1. Result and discussion on absorbed energy by the interface

Fig. 9 illustrates the absorbed energy by the interface during shearing test for the structures S_1 and S_2 (Fig. 1) computed by the Riemann sum.

As can be observed, the interfaces in the structure type S_1 (ESG-10 over ESG-10) had substantially lower absorbed energy compared with the structure type S_2 (ESG-10 over ESG-14) when comparing both of the structures in each interface condition. This could be explained by the higher frictional effect coming from the coarse materials, in S_2, in contact with the interface as discussed earlier. Furthermore, in both of the structures, the absorbed energy by the interface in the dry condition is the highest, followed by one F-T cycle and then five F-T cycles. However, reinforced interfaces were almost insensitive to F-T cycles. In this connection, the F-T cycles in both type of structures had higher adverse influence on unreinforced interfaces while in reinforced interfaces with the paving fabric the detrimental effects from the conditioning were restrained when compared with the dried condition.

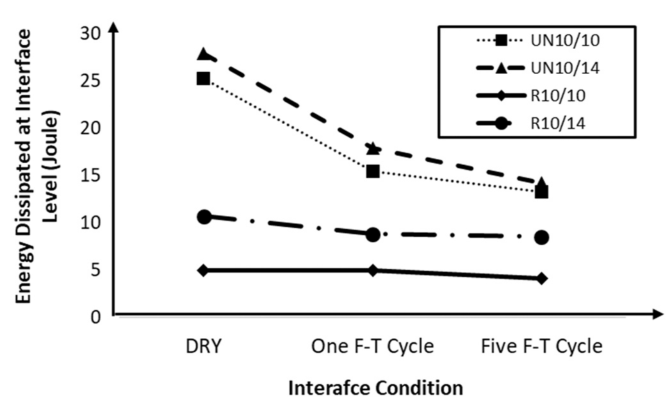

Fig. 9. Energy dissipated at interface level during shearing test for each interface condition.

3.2. Result and discussion on shear stiffness by the interface

As a second criterion to evaluate the effect of the F-T cycling on the interface performance, the initial tangent on force-displacement curve made from the origin was considered as shear stiffness. This factor is the ability of the interface to restrain debonding under shear stresses. A comparison of the evolution of this factor over different number of cycles for different types of reinforced and unreinforced structures is displayed in Fig. 10. It can be perceived that in unreinforced structure, the interface loses its stiffness as the number of F-T cycle grows. However, in the case of reinforced structures, after a significant initial drop in shear stiffness after one F-T cycling, the shear stiffness remained almost unchanged with respect to the number of cycling. Another interesting point is that, in both of the structures (i.e. S_1 and S_2), in reinforced structure, the higher mean texture depth provided on the ESG-14 surface, as observed in Fig. 3, played a major role in increasing the shear stiffness at interface level compared to the ESG-10 due to increased friction between the bituminous surface and the fabric, while in unreinforced structures, this factor was not of great importance.

3.3. Result and discussion on coefficient of interface bonding (CIB)

Considering the fact that reinforced interfaces are able to undergo high shear displacement before failure, the coefficient of interface bonding (CIB) was defined to have the influence of both shear stress and shear displacement at failure point into account while ranking the structures based on the bonding condition supplied at the interface level. This parameter is simply computed from the quotient of maximum interlayer shear strength (ISS_{max}) and the corresponding interlayer shear displacement (ISD) ($CIB = \frac{ISS_{max}}{ISD}$) and could be used as an input in mechanistic-empirical design methods to realistically define the bonding condition at any type of bituminous interface [25]. On this ground, the higher CIB values implies strong bonding quality, while less CIB refers to poor bonding. Fig. 11 provides a comparison on CIB values for both unreinforced and reinforced interfaces in different conditioning states. As can be seen, in dry condition, both of the unreinforced structures, S_1 and S_2, had similar CIB values. However, in reinforced one, the structure S_2 showed enhanced bonding quality compared with the structure S_1. This trend remained almost the same under one- and five-times F-T cycling. On this basis, two important considerations can be observed in different interface conditions: first, the placement of the paving fabric between bituminous layers type S_1 lowered the bonding quality 4–6 times of that in corresponding unreinforced structure of type S_1, and almost to half of the bonding quality in similar unreinforced structure type S_2. Second, the bonding quality at reinforced interfaces showed less sensitivity to F-T cycling while in unreinforced ones, the bonding quality continuously decreased as the number of cycles increased.

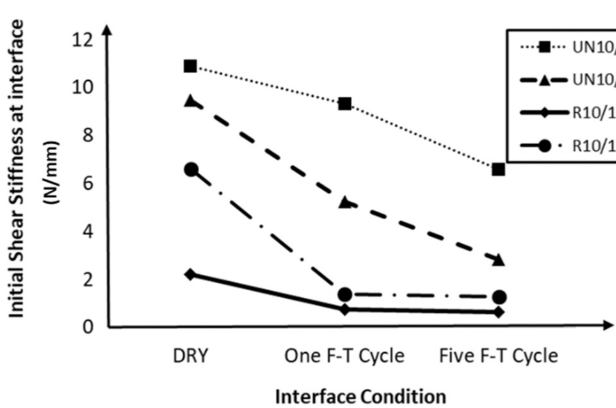

Fig. 10. Evolution of shear stiffness over the number of cycles in different interface conditions for reinforced and unreinforced structures.

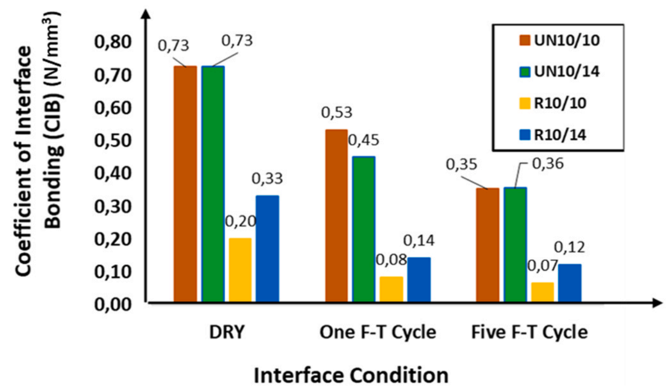

Fig. 11. Degradation of bonding quality at the interface based on CIB values.

4. Conclusion

The results of the shear test were utilized to evaluate the effect of freeze-thaw cycling on bonding quality supplied at a bituminous interface. To this end, the slant shear tester device, which could better simulate the actual loading state, as is the case in the field, was adopted to establish three comparative failure criteria at reinforced and unreinforced interfaces: absorbed energy by the interface, the shear stiffness developed at the interface, and the coefficient of interface bonding (CIB). Two types of double-layered bituminous slabs composed of two different hot mixtures containing an unreinforced and reinforced interface with paving fabric were fabricated in the laboratory to seek for the changes in the failure criteria under dry, and two different numbers of freeze-thaw cycles compared with unreinforced slabs. Following key findings can be drawn from this study:

- For unreinforced and reinforced structures, the F-T conditioning had high adverse effect on the shear stiffness and the bonding quality at the interface. Nevertheless, this negative effect was restrained in reinforced interface as the number of F-T cycling grows.
- In terms of the ability of the interface to energy absorption, the unreinforced interfaces showed higher performance in dry condition. However, under F-T cycling, this advantage becomes of less importance. Moreover, in both reinforced and unreinforced structures, the interface formed from a fine hot mix and a coarse hot mix, presented higher ability to absorb the energy while shearing.
- Three indices utilized in this study were sensitive to the changes in the interface condition both in reinforced and unreinforced structures. In this regard, the drop in energy dissipation or initial shear stiffness provided a better tool to quantify the evolution of shear strength over number of F-T cycles while CIB value presents a single value of the resistance of the interface per unit length regardless of the length. By defining the bounding quality between bituminous layers based on the CIB value, the stress and strain distributions between layers can be more realistically reflected in empirical based design methods.
- In reinforced structures with paving fabric, the changes in the shear stiffness and the CIB values to the F-T cycling were not significant.
- In order to gain the highest advantage from introducing paving fabrics between bituminous layers, the increased friction provided between the fabric and the coarse surface plays a pivotal role in reinforced case.

In considering the implications of our findings, it is crucial to acknowledge certain limitations inherent in this study. The laboratory conditions under which the investigation was conducted, while providing controlled environments, may not fully replicate the complexities of real-world field scenarios. Variations in traffic loads, temperature fluctuations, and environmental factors were not fully accounted for. Furthermore, our focus on a specific tack coat dosage (0.0014 m^3/m^2) limits the generalizability of our results to a broader range of dosages. Additionally, the homogeneous composition of the bituminous layers, consisting of two different hot mixtures, may not fully capture the diversity encountered in practical applications. The study primarily explored freeze-thaw cycling, leaving aspects of long-term durability, aging mechanisms, and external factors such as surface preparation unexplored. These limitations highlight opportunities for future research to refine our understanding of interface bonding in diverse pavement structures and real-world conditions.

While our findings contribute to advancing the field of pavement engineering, there remains a need for further exploration into optimizing materials and design methods. Future research endeavors could benefit from the approach outlined in [15], which utilizes data-driven machine learning techniques to precisely predict the inhibition efficiency of carbon dots (CDs) and optimize their synthesis route. By adapting similar methodologies, researchers can enhance the reliability of predictive models and contribute to the development of more sustainable and effective design guidelines for reinforced bituminous structures.

Additionally, future research endeavors could draw inspiration from the study conducted by [16], which investigated the mechanical properties and effects of volume fraction for various types of fibers in hybrid fiber-reinforced concrete (HFRC). By incorporating similar fiber reinforcement strategies into bituminous layers, the mechanical behavior of these layers under freeze-thaw conditioning could be evaluated, potentially leading to enhancements in their performance and longevity.

CRediT authorship contribution statement

Moubarak Savadogo Ibrahim: Investigation, Data curation. **Michel Vaillancourt:** Writing – review & editing, Methodology, Investigation. **Ehsan Solatiyan:** Writing – original draft, Formal analysis, Data curation, Conceptualization. **Alan Carter:** Writing – review & editing, Project administration, Methodology.

Declaration of Competing Interest

None.

Data availability

The data that has been used is confidential.

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