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[†]Research Paper

Influencing interface morphology and modified asphalt binders on interlayer bonding performance

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ABSTRACT

Interlayer bonding strength is a critical factor influencing the durability and performance of asphalt pavement systems. This study investigates the combined effects of tack coat type, application rate, and substrate surface texture on the interfacial shear strength (ISS) between asphalt layers. Four surface conditions, new wear, binder, aged-worn, and milled, were simulated to represent varying field scenarios. The interface morphology was quantitatively analysed using both the sand patch method and 3D laser scanning. Seven tack coat formulations were evaluated, including a conventional tack coat, hard-grade cutback, and a novel hybrid material modified with Styrene-Butadiene-Styrene (SBS) and polylactic acid (PLA) labels MS4-70 and MSP5-70, respectively. The Tack coats were applied at three residual rates (0.1, 0.23, and 0.35 L/m^2). Direct shear testing was conducted to assess ISS under various conditions. The results reveal that surface roughness and tack coat type significantly impact bonding performance. Milled surfaces showed the highest texture and yielded superior shear performance due to enhanced mechanical interlock and bonding area. Conversely, the wear surface, characterised by a dense gradation and smooth profile, exhibited the lowest ISS values. The hybrid MSP5-70 tack coat represents a new generation of modified bonding that consistently produces the highest ISS values compared to conventional tack coats (CRS-1, CSS-1h, and RC70). These findings underscore the importance of tailored tack coat formulations and texture-specific application strategies for enhancing pavement structural integrity.

1. Introduction

Asphalt pavement characterised as a conventional layered system, is comprised of several structural layers that are interconnected at their interfaces, thereby forming a cohesive monolithic structure [1, 2]. Factors such as the type and amount of bonding materials, traffic load effects, changes in ambient temperature, interlayer cleanliness, climatic conditions, and details of the construction process play a crucial role in interlayer bonding, which significantly influences the mechanical properties and lifespan of pavements [3]. Insufficient interlayer adhesion may result in multiple pavement failures, including slippage cracking, delamination, and top-down cracking, potentially decreasing the pavement's lifespan by about 40% or more [4]. Recently, several countries have developed improved methods for testing interlayer bonds in asphalt layers. Common testing devices include shear, pull-off, and torsion tests. The shear test is the most commonly utilized method to assess interlayer bonding properties. Studies have examined the impacts of test temperature, tack coat types, application rates, interface conditions, and external loads on interface strength. For instance, Biglari et al., (2019) utilised the LPDS (layer-parallel direct shear) apparatus for conducting interface shear tests, assessing the influence of temperature and bonding material on interface strength [5]. Likewise, Ai et al., (2022) employed a custom device to explore how temperature, interface characteristics, and external load affect interface strength. Their findings indicated that roughness was the most influential factor, followed by external load and tack coat rate [6]. One of the primary challenges in using tack coat materials is choosing the right type of tack coat and determining the appropriate amount for application at the interface, which is necessary to ensure adequate bonding between layers. Covey et al.,(2017) identified a positive relationship between the rheological properties of bonding materials and interlayer shear strength. These bonding materials act as adhesive agents in the tack coat, making their rheological characteristics crucial to the assessed ISS value [7]. Numerous studies suggest that tack coats with a harder residue provide enhanced bond strength compared to those with a softer binder [8, 9]. A harder residue can be achieved by using a higher performance grade (PG). During the peak season of pavement construction projects, which usually occurs in the summer, tack coats often soften and become sticky when temperatures rise above 50 ∘C [10]. As a response,Li et al., (2019) have developed a new modified asphalt tack coat that shows excellent trackless properties at 60 ∘C, enhanced by a polymer modifier content. These materials are produced by mixing polymer modifiers like Styrene-Butadiene-Styrene (SBS), hard asphalt, and polyethene (PE) into the base asphalt [11]. Using polyurethane latex as a modifier for emulsified asphalt Wang et al., (2023) [12] found that, after a short emulsification period, the modified emulsified asphalt tack coat's shear strength surpassed 1 *MPa*. Although styrene-butadiene-styrene (SBS) and styrene-butadiene rubber (SBR) are commonly used in the production of polymer-modified asphalt, there are often significant challenges when attempting to modify emulsified asphalt [13, 14] . For example, compared to other modifiers, the emulsification of SBS is typically harder. In their study, Hou et al., (2018) examined a modified tack coat used in composite pavement, revealing a 69% increase in the interlayer's shear strength. They also found that the shear strength of the modified tack coat surpassed that of the control bitumen [15].

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Nomenclature

ISS	Interfacial Shear Strength	*Sku*	Kurtosis
SBS	Styrene-Butadiene-Styrene	*Sdq*	Root Mean Square Slope
PLA	Polylactic Acid	*Sdr*	Developed Interfacial Area Ratio
MTD	Mean Texture Depth	*S*	Spatial Surface Area
3*D*	Three-Dimensional	S'	Horizontal Projected Area
HMA	Hot Mix Asphalt	*DC*	Degree Of Curvature
NMAS	Nominal Maximum Aggregate Size	S	Spatial Surface Area
AC	Asphalt Content	*SCRB*	State Corporation For Roads And Bridges
VS	Volume Of Sand	$CRS-1$	Cationic rapid setting emulsion
As	Total Material-Covered Surface Area	$CSS-1h$	Cationic slow setting -hard asphalt
Sa	Arithmetic Mean Height	*RC*70	Rapid curing cut back at viscosity 70
Sq	Root Mean Square Height	$HRC-70$	Rapid curing -hard asphalt at viscosity 70
Sz	Maximum Height	$MS4-70$	Rapid curing - 4% modified SBS asphalt at viscosity 70
Ssk	Skewness	$MSP5-70$	Rapid curing - modified asphalt with SBS and PLA at a viscosity 70

The adhesion qualities of the binder, as well as the interlock and, consequently, the geometrical surface characteristics of the interface, are essential variables in the binding between asphalt pavement layers. Regardless of the mechanical characteristics of the aggregate or the binder (or tack coat) film at the interface of the asphalt pavement layers, those geometrical surface qualities and shape are important factors for the interlock [16]. The importance of interface morphology in affecting interlayer bonding performance in pavement systems has been extensively studied. According to A. Raposeiras et al., (2013), ISS values rise as surface roughness increases. Additionally, it was discovered that when aggregate particles larger than 8 *mm* are utilized at a rate of 40% to 50%, they contribute the most to shear strength [17]. The type of asphalt mixture significantly impacts the bonding strength of pavement layers. West et al., (2005) compared the bonding characteristics of the coarse- and fine-graded mixtures and discovered that the coarse-graded mixture with a 19 *mm* nominal maximum aggregate size (NMAS) had a lower shear strength than the fine-graded mixture with a 4.75 *mm* NMAS [18]. The impact of asphalt mixture surface macro-texture on adhesion between pavement layers was examined by A. C. Raposeiras et al., (2012) , who discovered that the maximum shear strength is achieved with a rough texture of 0.17 *mm* [19]. Furthermore, other researchers have employed alternative ways to assess the interface bonding status. Liu et al., (2017) [20] and Jaskula et al., (2021) [21] noted that creating roughness on the lower layer surface using techniques such as slotting, chiselling, and milling can significantly improve interlayer shear strength. Al-Qadi et al., (2008) [22] and Mohammad, (2012) [23] found that milled surfaces generally provide better bonding conditions compared to smooth, unmilled surfaces. The increased macro-texture from milling enhances tack coat absorption and physical interlock, contributing to higher shear resistance. Bahia et al., (2019) [24], Their Wisconsin DOT-sponsored study highlighted that surface texture significantly affects ISS, with high-texture (milled) surfaces producing better bonding than their low-texture counterparts. Using the LISST (Louisiana Interlayer Shear Strength Tester), they quantified surface roughness via Mean Texture Depth (MTD) and observed that high MTD values generally correspond to higher ISS. However, the impact of tack coat application rate was less consistent, and in some cases, a lower application rate produced slightly higher ISS values. Moreover, Heo, (2021) emphasised that the texture depth created by milling plays a critical role; higher mean profile depth (MPD) correlated positively with increased ISS, especially at moderate to high temperatures. These findings suggest that the effectiveness of milling is not solely a result of roughness but its interaction with tack coat properties and environmental conditions [25]. The advancement of measurement technologies, especially non-contact scanning methods, has greatly enhanced studies on pavement morphology. These enhancements have proven essential in the research of pavement texture and the skid resistance of road surfaces, with substantial contributions from [26–28]. Hoła et al., (2015) employed a 3D laser scanner to get the three-dimensional roughness parameters of the concrete layer surface. A linear link was established between surface texture aspect ratio (Str), peak material volume (Vmp), and the pull-off adhesion of the concrete layer, with a correlation coefficient of 0.7 [29]. Tang et al., (2021) used an Olympus Microscope to take pictures of the lower layer's surface morphology and then used MATLAB to make a 3D model of it. Their results showed that there was a positive relationship between the roughness of the surface, the shear strength, and changes in the tack coat rate [30]. Among these developments, Song et al., (2022) used three-dimensional (3D) scanning to evaluate interlayer fracture behaviour and reconstruct interface morphology. They found that as texture depth (TD) increased, so did the stress intensity factor (KIC) and the critical strain energy release rate (J-integral) [31]. The objective of this study was to quantify the effects of tack coat type, tack coat application rate, and surface type and morphology on the interface shear strength. To achieve this objective, seven types of tack coat materials were applied at three application rates on four types of surfaces. The surface-texture depth of the underlying layers was also measured and correlated to the shear properties through the innovative application of the non-contact and non-contact methodologies (3D laser scanning).

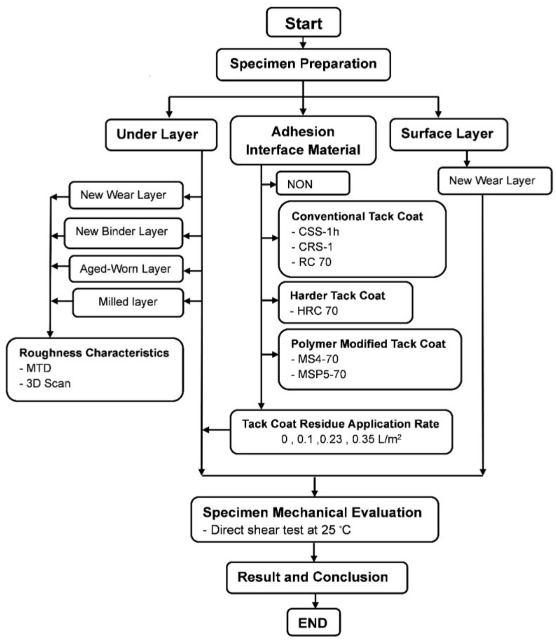


Figure 1. Framework for this study.

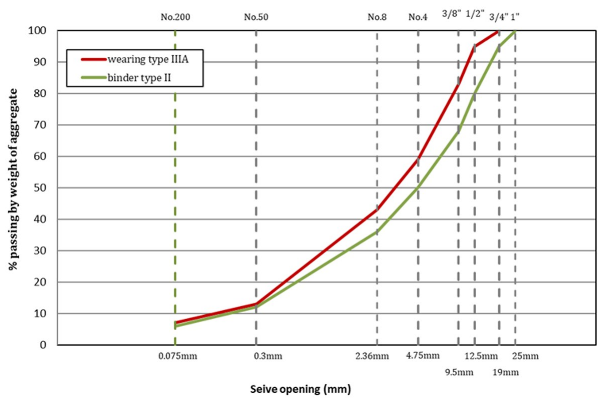


Figure 2. Aggregate selected graduation.

Table 1. Properties of asphalt cement.

Property	ASTM Designation	Result	SCRB Specification
Penetration at 25 C°	D 5	043	(40–50)
Ductility at 25 C°	D 113	> 100	> 100
Softening Point C°	D 36	049	———
Brookfeld Viscosity at 135 C°, cP	D 4402	688	Min. 400
Brookfeld Viscosity at 165 C°, cP	D 4402	167	———

2. Methodology

This study involved the preparation of four status double-layered asphalt systems. The underlying consisted of either a wearing or a binder course with different construction conditions, such as new HMA, aged, and milled underlayers that were covered with a wearing course mixture on top of it. To assess the properties of interlayer bonds, one temperature was considered during testing, seven tack coat kinds, the tack coat applying amount, and interface roughness by using the sand patch and a 3D laser scanner were employed to obtain and rebuild the interface morphologies. The direct shear bond test was locally manufactured. The comprehensive research framework for this study is illustrated in Fig. 1.

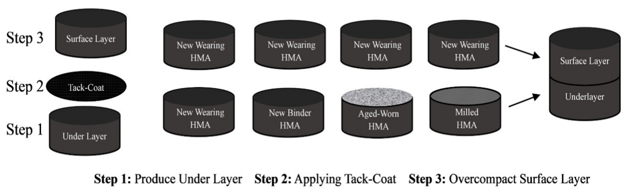


Figure 3. Steps of specimen preparation.

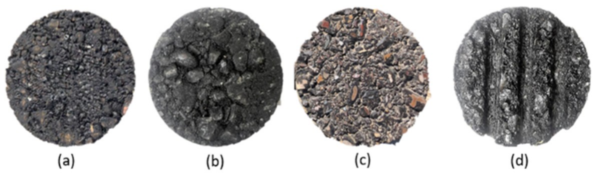


Figure 4. Underlayer Surface Conditions for the current experimental study (a) new wear course,(b) new binder course,(c) aged-worn wearing course, and (d) milled.

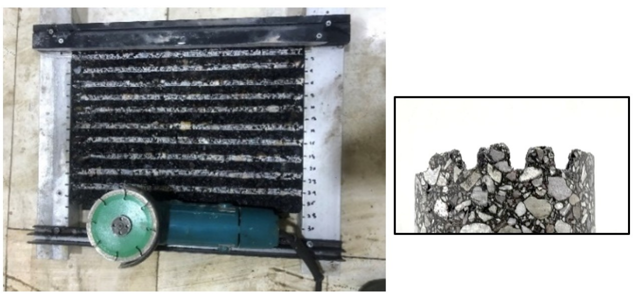


Figure 5. Simulated to prepare the milled HMA surface.

3. Material design

3.1 Asphalt cement and aggregate

In this study, asphalt cement grade 40-50 provided by the Al-Dura refinery was used to prepare specimens; the binder's physical properties meet the Iraq-SCRB (State Corporation for Roads and Bridges) specification presented in Table 1. In addition, coarse- and fine-grained aggregates and limestone produce the asphalt mixture. The nominal maximum aggregate size (NMAS) for wearing and binder course layers was 12.5 *mm* and 19 *mm*, respectively, based on the SCRB specification for the upper and underlying systems. The selection of coarse and fine-grained materials for wearing and binder coarse materials used in the existing experimental setup at the centre of the SCRB specification, as presented in Fig. 2.

3.2 Interface adhesion material (tack coat)

This study evaluated the interlayer bonding performance of asphalt pavements using six different tack coat formulations. Two of these materials were conventional emulsions: Cationic Rapid Setting (CRS-1) and Cationic Slow Setting (CSS-1h) emulsions, commonly used in pavement construction. Table 2 shows the physical properties of the emulsions. The remaining four formulations were laboratory-prepared using base asphalt binders diluted with benzene to simulate cutback asphalt characteristics. One formulation involved blending a penetration grade of 85–100 asphalt with a specific ratio of benzene to produce a conventional cutback binder comparable to RC-70, which is extensively utilised in Iraq, while another used a harder binder with a penetration grade of 40–50 to formulate a stiffer version referred to as HRC-70. Furthermore, two polymer-modified tack coats were developed by incorporating Styrene-Butadiene-Styrene (SBS) polymer at a concentration of 4% by weight. The type of SBS is from Kraton Corporation, and the modified binders were prepared at the ALTCOM company, ensuring consistency in mixing and formulation procedures. These modified binders were also diluted with benzene to ensure sprayability and uniform application, resulting in a new material called MS4-70. The novelty of this study is the preparation of a unique cutback by mixing hard asphalt cement (penetration grade 40-50) with 4% SBS polymer and 5% PLA (polylactic acid) to make a new hybrid modifier binder. The binder was then diluted with benzene to make it easy to spread. The new tack coat is named MSP5-70. Table 3 displays the physical properties of the cutbacks. The overall cutbacks spread at 75 °C, while the $CSS^{-1}h$ and CRS^{-1} emulsions spread at 35°C. Adhering to the SCRB limitations, specific tack-coat residue application rates of 0.1, 0.23, and 0.35 L/m^2 were chosen. All rates were calculated based on the residual rate and applied to the interface using a brush.

4. Preparation of specimen

4.1 Proportion design of mixture

Employing the Marshall method to design the proportions of two types of asphalt mixtures, the optimum asphalt contents have been determined to be 4.4% for the binder layer and 4.7% for the wear layer. Table **??** illustrates the volumetric properties of the aforementioned asphalt specimens at their respective optimum asphalt contents.

4.2 Preparation of specimen

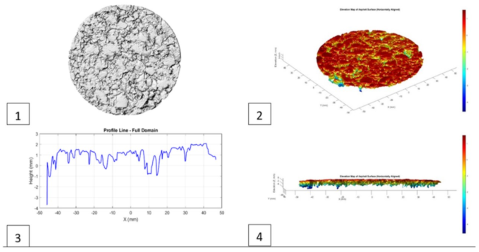
The test specimens were produced under EN 12697-33, utilising a roller compactor and compacted into two layers to form slab specimens (400 *mm* by 305 *mm*). The underlying layer was either binder or wear, while the upper layer was wear. The underlying layer was 42 mm high, whereas the overlying layer was 38 *mm* high. In order to achieve the desired layer density at the optimal asphalt content, roller compaction started with a static load of 5 *kN* applied for 15 cycles, which subsequently increased by 2.5 *kN* for every following 15 cycles to ultimately reach a maximum of 12.5 *kN* over the course of a total of 60 cycles. The loose mixture's compaction temperature was consistently maintained at 135 °C. The underlying layer (wearing or binder) was first compacted and then extruded to create the two-layer shear test specimens. Once this layer cooled to room temperature, various construction conditions, such as aged-worn and milled, were used to simulate the field condition. In the subsequent steps to prepare the layers, tack-coat material was applied uniformly to the surface of the underlying layer at varying rates. After a curing period of approximately 2 hours, the loose upper mixture, referred to as the wear coarse mixture, was compacted onto the top of the underlying layer. Upon completion of the pavement layer compaction, six samples were extracted from each slab using a pavement core drilling machine with a diameter of 100 *mm*, which is ready for laboratory evaluation testing.Underlayer Surface Conditions Preparation. In order to simulate field conditions, the effects of pavement conditions—such as new, aged, and milled— on the current pavement surfaces laboratory prepared were examined, as illustrated in Fig. 4.

(a.) New underlayer

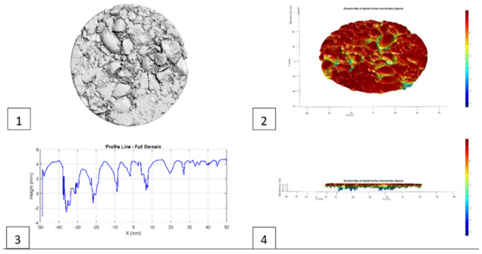
New (unaged) HMA underlayer samples were prepared and compacted from either a wearing or binder mixture, as illustrated in Fig. 4a and b 4. The loose asphalt mix was heated in an oven to 135 °C to prepare these samples, then placed in a slab mould and compacted with a roller compactor.

(b.) Aged-worn underlayer

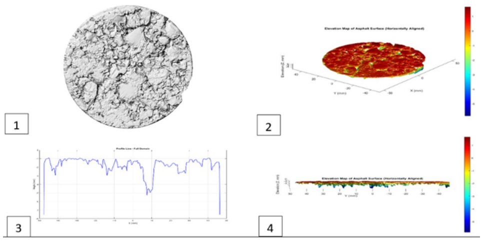
In order to simulate a pavement surface that has aged, likely due to traffic and environmental factors, aged-worn HMA bottom layers were created by ageing and polishing new HMA layer samples. To achieve this, the sample's



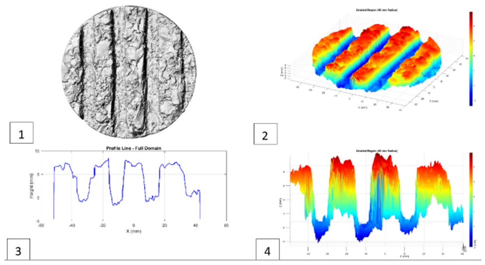
(a) Wear 3D interface morphology: (1) surface mesh (2) top surface map (3) 2D centre profile (4) side surface map.



(b) Binder 3D interface morphology: (1) surface mesh (2) top surface map (3) 2D centre profile (4) side surface map.



(c) Aged-worn surface 3D interface morphology: (1) surface mesh (2) top surface map (3) 2D centre profile (4) side surface map.



(d) Milled surface 3D interface morphology: (1) surface mesh (2) top surface map (3) centre profile (4) side surface map.

Figure 6. 3D reconstruction of interface morphology.

Table 2. Emulsified asphalt test results and specifications.

Property		**CRS-1**		**CSS-1h**	
		Result	Specification limit AASHTO M-208	Result	Specification limit AASHTO M-208
Saybolt-Furol viscosity at 25 C°		———	———	25	20-100
Saybolt-Furol Viscosity at 50 C°		30	20-100	———	———
Residue by distillation (%)		68	Min 60	58.1	Min 57
Tests on residue from distillation test	Penetration, 25 C°	115	100-250	43.8	40-90
	Ductility, 25 C°	50.0	40 Min.	45.0	40 Min.
	Solubility in trichloroethylene, (%)	98.3	97.5 Min.	98.0	97.5 Min.

Table 3. Cutback asphalt test results.

Property		**RC-70**	**HRC-70**	**MS4-70**	**MSP5-70**
		Result	**Result**	**Result**	**Result**
Kinematic Viscosity at 60 C°(CSt)		102	103	125	132
Residue by distillation (%)		66	60	49	46
Tests on residue	Penetration, 25 C°	92	46	31	16
Tests on residue	Softening Point C°	42	47	64	69
Tests on residue	Viscosity at 135C°poise	0.413	0.688	1.88	3.32
from	Ductility, 25 C°	> 100	> 100	67	59
distillation test	Solubility in trichloroethylene, (%)	42	49	66	71

surface was polished using a circular grit sandpaper that was affixed to a 100 *mm* random orbital sander disc. The sander maintained an average speed of 1500 oscillations per minute for five minutes, ensuring that the top surface was polished uniformly. Dust was subsequently eliminated through the use of pressurized air. Polished samples were maintained in an oven at a temperature of 85°C for a duration of 120 hours (5 days) to simulate the oxidative ageing of asphalt mix experienced for 5 to 7 years in service, as stipulated by AASHTO R 30 [32]. Figure 4c presents a sample of the aged-worn hot mix asphalt (HMA) bottom layer.

(c.) Milled HMA bottom layer
Laboratory-prepared milled HMA underlayer samples were created to simulate the milling texture on the surfaces of wear HMA samples, utilizing a process outlined by Julián Rivera in 2021 [33]. The milling process commences with the application of a grid pattern on the sample, followed by cutting through the indicated regions utilizing a wet rock saw at defined depths and intervals for standard milling, as specified in Wirtgen, (2021) [34]. Figure 5 illustrates a simulated milled Hot Mix Asphalt (HMA) surface.

5. Testing method

This section outlines the equipment and the testing principle. Initially, various methods are employed to analyse the texture of the underlying. Ultimately, the conditioned specimens undergo testing with the shear bond testing apparatus.

5.1 Texture evaluation

5.1.1 Mean texture depth (MTD) (sand patch method)

This test was conducted in accordance with ASTM E 965 and aims to assess the macro-texture of the surface of the underlying layers, as expressed as the ”Mean Texture Depth”MTD. It is considered A suitable method for measuring the surface texture depth of asphalt pavement with a texture depth exceeding 0.25 *mm*. It involves calculating the ratio of a specific volume of sand to the total material-covered surface area, as calculated using Eq. 1.

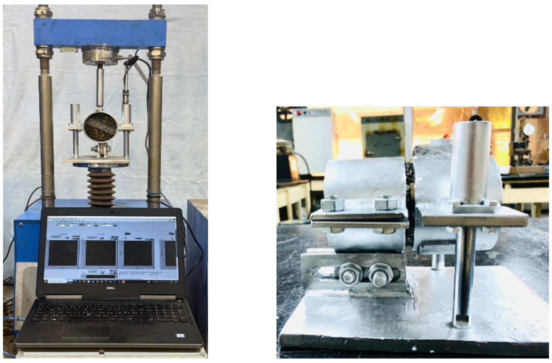
$$MTD = VS/As \tag{1}$$

5.1.2 3D Surface topography measurement

This study utilised a high-resolution intraoral scanner (Medit *i*600) with high precision (0.01 *mm*) to generate a 3D morphology of the lower asphalt paving layer. The device's advanced 3D-in-motion video scanning technology and full-colour imaging capabilities allowed for accurate, non-contact surface capture. The scanned data were exported and further analysed using MATLAB according to ISO 25178 to extract surface roughness parameters, which are catalogued in Table **??**. The 3D reconstructed surface morphology is illustrated in Fig. 6. This method provided a detailed digital representation of the interface morphology, which was subsequently used to evaluate the influence of surface roughness on interlayer bonding performance and these parameters.

5.2 Shear bond test

The device used to evaluate bonding strength consists of two parts of cylinders (100 *mm* in diameter) with a gap between the two cylinders of less than (8 *mm*). One of the cylinders is fixed at its bottom to a plate, while the second part moves in a vertical direction, as shown in Fig. 7. After being batched, the specimens were placed in an environmental chamber for two hours to guarantee they attained the testing temperature. Then, they were quickly put on the direct shear apparatus. The direct shear load was applied vertically, perpendicular to the interlayer, using a Universal multispeed load. A constant shear loading rate was set at 50 mm/min. The data acquisition system automatically recorded the shear forces and displacements. The interface bond shear strength is calculated by dividing the maximum load before failure by the cross-sectional area of the specimen.



(a) Universal load device. (b) Side view of the direct shear test .

Figure 7. Direct shear bonding testing.

6. Results and discussion

6.1 Evaluation of interlayer morphology characteristics

6.1.1 Roughness

The statistical analysis results for the roughness characteristics of the interfaces are illustrated in Fig. 8 and 9, with each subfigure devoted to the texture parameter statistics for interlayer surfaces in the four double-layered asphalt systems evaluated. The subsequent observations may be made: Across all systems, the milled surface exhibits the highest roughness values among all types, with a mean texture depth (MTD) of 1.88 *mm*, mean height (Sa) of 2.41 *mm*, root mean square height (Sq) of 4.47 *mm*, and a maximum height (Sz) of 7.03 *mm*. These elevated values indicate a deeply textured surface, which enhances mechanical interlock and improves the effectiveness of tack coat bonding. Contrastingly, the wear surface exhibits the lowest roughness, with MTD, Sa, Sq, and Sz values of 0.602 *mm*, 0.99 *mm*, 2.00 *mm*, and 2.96 *mm*, respectively. This indicates a smooth and potentially polished condition that may restrict bond strength due to its dense-graded structure and abundance of fine particles, and it tends to exhibit a smoother and uniform surface texture. Both the binder and aged-worn surfaces exhibit intermediate roughness characteristics; the binder layer exhibits slightly higher values than the aged-worn one because it is characterised by skeletal structures with larger aggregate particles, which are more likely to have a rougher texture with deep concavities and noticeable spikes. Specifically, the binder layer's Sz is 3.93 *mm*—about 33% higher than the wear layer, while the aged-worn surface has a Sz of 3.54 *mm*. These findings suggest that milled surfaces are the most favourable for achieving high bond strength due to their superior texture, while worn and aged surfaces may require additional surface preparation or enhanced tack coat materials to ensure sufficient adhesion. The Ssk (Skewness) parameter represents the extent of asymmetry in the distribution of surface height. In the case of aged, binder, and wear structures, the surfaces of the interlayers display a peak-like distribution, signifying skewness toward positive. Meanwhile, in milled constructions, the distribution of interlayer surfaces appears valley-like and skewed towards the negative, indicating protrusions that enable aggregate particles to push into the lower surface, resulting in distinct concave depressions. The Sku (Kurtosis) parameter, which reflects the sharpness or peakiness distribution of the surface height, demonstrates that the interlayer surfaces of the three asphalt structures have values exceeding 3, except for the milled structure. This indicates a distinct sharpness in surface morphology, which is characterised by a peaked distribution that is centred around a mean level. The interface of the binder structure is distinguished by its extreme sharpness, which implies a substantial concentration of heights around a central peak in comparison to the other structures. Examination of the Sdq (Root Mean Square Slope) parameter of the interlayer surfaces of all asphalt systems reveals that all values are greater than zero, indicating that there are no entirely flat interfaces. This finding suggests an unequal textural inclination across all surfaces investigated. Importantly, texturing tilt varies significantly between each structure's interlayer surfaces. This variance is principally determined by the layer's structural gradation, which results in a texture roughness gradient that goes from rough to flat in the order of milled, binder, aged-worn, and wear. Additional insights from the Sdr (Developed Interfacial Area Ratio) analysis reveal that interlayer surfaces show an expanded area. This effect highlights the distinct texture features of the milled interface, which demonstrates the most notable texture variation, with a binder, aged-worn, and wear following in order of decreasing texture significance.

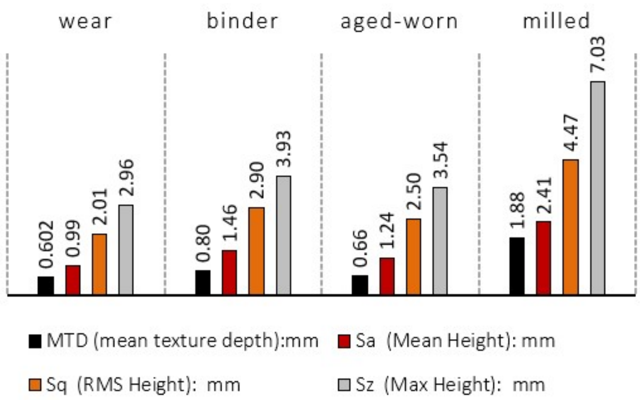


Figure 8. Height interfaces roughness parameter.

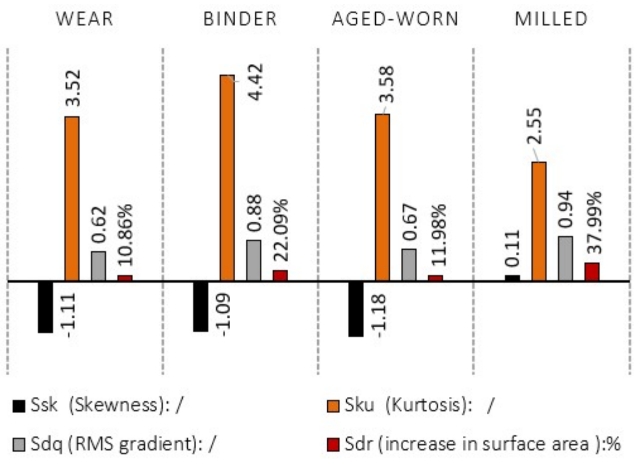


Figure 9. Spatial surface interface roughness parameter.

6.1.2 Surface area

The spatial surface area (S) of interfaces in various specimens was determined, and the findings are shown in Table **??**. The interface's surface characteristics influence the interlocking component of interface bonding between double-layered specimens. As a result, it is required to quantify the effects of successive layers' surface features on interface bonding and investigate the contact state between interlayer surfaces. The degree of curvature (DC) of the interlayer surface features was discussed. The degree of curvature parameter is expressed in Eq. 2, and the calculation results are illustrated in Table ??.

$$DC = (S - S')/S' \quad (2)$$

Where DC represents the curvature degree of the specimen's interface; S represents the spatial curved surface area of the interface in mm^2, while S' denotes the horizontal projected area of the interface, also measured in mm^2. The analysis of the curvature degree of the milled surface morphology produced the highest curved surface area (12241.9 mm^2) and degree of curvature (0.69%), indicating a highly textured profile that provides superior mechanical interlock and a greater actual bonding area. This makes milled surfaces the most favourable for achieving strong interlayer adhesion. In contrast, the binder surface displayed a moderately high surface area (10148.3 mm^2) and curvature (0.40%), benefiting from natural binder texture. The likely causes stem from a greater amount of coarse aggregates present in asphalt mixtures that have a high air void content. The aged-worn surface had slightly more roughness than a new surface (8817.5 mm^2, DC = 0.22%). Finally, the wear surface (new surface) was the smoothest of all, with the lowest curved area (8670.0 mm^2) and curvature (0.19%), offering limited mechanical interlock. On the other hand, wear has a dense gradation with lower porosity. The NMAS (nominal Maximum Aggregate Size) of the underlayer, as well as the variations in the proportions of fine ($\leq$4.75 mm) and coarse ($>$4.75 mm) aggregates for each type of asphalt mixture, constitute the primary factors.

6.2 Evaluation of interlayer shear bond strength

This study investigated the interlayer bond shear strength (ISS) under different tack coat types, application rates, and surface conditions factors critical to pavement performance and durability.

6.2.1 Effects of tack coat type

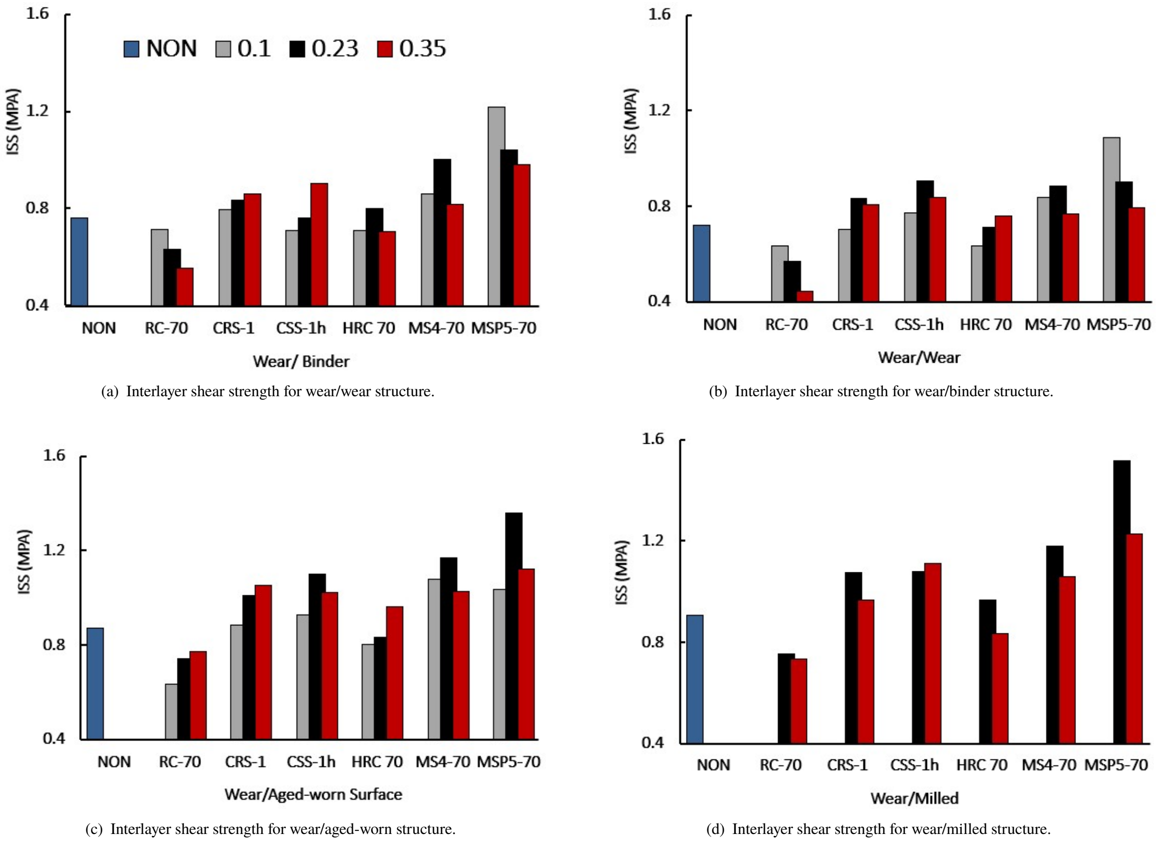
The shear bond strength between asphalt pavement layers plays a crucial role in ensuring pavement performance and durability. The interlayer shear strength (ISS) under varying tack coat types and residual application rates across four surface interface conditions are present in Fig. 10a through Fig. 10d. The choice of tack coat material has a profound impact on the bond strength. The results show a clear advantage of polymer-modified tack coats over conventional tack coats. Conventional tack coat materials (RC 70, CSS, CRS) showed moderate performance improvements with increasing application rates. However, their ISS values remained lower than polymer-modified alternatives, especially under challenging surface conditions. Their relatively lower elasticity and cohesive strength may limit their ability to accommodate movement or absorb surface irregularities, particularly on milled or aged layers. The CSS is the best conventional tack coat for shear resistance, followed by the CRS and, lastly, the $RC-70$. Other pavement systems exhibit a comparable trend. Consequently, using a slower-setting asphalt emulsion with a harder base binder grade in moderation on an HMA surface enhances the ISS values more effectively than alternative tack coat varieties. When used, the harder tack coat HRC-70 notes greater shear resistance than conventional tack coat RC-70 by 15%. This phenomenon results from the tack coat material softening due to rising temperatures, which in turn diminishes interlayer adhesion. Furthermore, the softened tack coat material induces a lubricating effect at the interface, thereby reducing the frictional component of interlayer bonding. Clearly, results show a substantial improvement in bond shear strength (ISS) when conventional tack coats are used compared to the absence of any tack coat (NON). This difference is consistent across all tested surface interfaces and application rates except when using RC-70, which shows lower ISS by about 10%. When modified cutback by adding polymer modifier (SBS), the application of MS4-70 on HMA surfaces resulted in a higher ISS value (1.18 MPa) as compared to HRC-70 due to improved viscoelastic behaviour, adhesive strength, and film durability that contribute to superior interlayer bonding. The MSP5-70 tack coat demonstrated the highest shear strength across a variety of surface types. This tack coat is composed of a polymer that has been modified with hard base asphalt cement. The Viscosity of the residual binders at the test temperature is directly correlated with these results. The Viscosity of residue MSP5-70 is measured to be 3.32 poises at 135°C, whereas the Viscosity of MS4-70 is 1.88 poises, and the harder asphalt base is 0.68 poises. Consequently, the Viscosity of the tack coat influences the bonding properties at the interlayer interface. Polymer-Modified (MS4-70, MSP5-70) significantly outperformed traditional materials. The polymers enhance the elastic recovery, cohesive strength, and adhesion of the tack coat, resulting in improved bond strength, especially on rougher or more absorptive surfaces. Using PLA 5% instead of NON increases ISS by 52-67% depending on the surface as Compared to MSBS4-70, the gain is 20–26%, confirming PLA 5% as the most effective tack coat in this comparison.

6.2.2 Effect of residual application rate

This study considered residual application rates of 0.1, 0.23, and 0.35 L/m^2. Figure 10 illustrates how the residual rate and the type of interface affect shear strength. The figure shows that for all types of tack coats, different residual rates greater than 0.23 L/m^2 don't have much of an effect on shear strength, except for traditional tack coats. For residual rates on the low to intermediate end (e.g., 0.15 - 0.23 L/m^2), bonding benefits are evident. Implementing a tack coat to enhance bonding strength appears to be more beneficial at the lower end of this range compared to the higher end. Excessive tack coat can lead to shear slippage at the interface, whereas insufficient application may cause debonding issues. It is essential to determine the ideal amount of tack coat for optimal performance. Different pavement surface conditions, such as new, old, or milled, necessitate varying tack application rates to establish an effective interface bond. Generally, the new wear underlayer requires less tack coat than the new binder layer. The requirement of a tack coat is less for tight or dense layers due to low interface roughness, high fine aggregate content, and low air void content. Also, it is evident that the ISS values measured for samples having aged-worn HMA as their bottom layers with polished textures were more sensitive to an increase in the tack coat application rate and provided a more in-contact surface with the top layer and bonding agent than the new HMA, which contributes to a higher ISS value. Nevertheless, the ISS values exhibited a consistent decline as the tack coat application rate increased throughout the testing of samples with a milled HMA underlayer layer. This indicates the influence of surface type on the ISS values recorded for HMA samples. Attributable to an increased surface area resulting from grooving. However, for the milled surface, the ISS results demonstrated enhancement with an increased application rate of 0.23 L/m^2. Indeed, at a low application rate, the binding agent was absorbed by the surface, resulting in an insufficient quantity of bonding agents to enhance the interlayer bond. Nonetheless, an additional increase in the tack coat application rate resulted in greater availability of bonding agents for adhesion, notwithstanding some absorption by the surface texture. A consistent trend across all surface types shows that increasing the tack coat application rate generally enhances the interlayer shear strength. The highest ISS values were typically observed at the 0.23 L/m^2 rate, followed by 0.35 L/m^2 and 0.1 L/m^2. This indicates the vital role of sufficient tack coat quantity in ensuring optimal bonding; however, in a few cases (especially with conventional tack coat RC 70 on new surfaces), the improvement from 0.1 to 0.23 L/m^2 significantly improved performance. The Optimal application rates lie at 0.23 L/m^2 for most materials, balancing performance with economic and constructability considerations.

6.2.3 Effect of surface type

The interface's varying roughness levels result in a differential contact area between the tack coat and the interface. Consequently, the interface adhesion properties exhibit variation. This study examined the impact of varying surface roughness on surface bonding properties. Figure 11 shows the average peak shear strength for different interlayer surfaces at optimum application rates. The samples compacted without a tack coat exhibited the highest ISS value, particularly those constructed with milled HMA (0.91 MPa). This was succeeded by samples featuring an aged-worn HMA underlayer (0.87 MPa), binder HMA (0.76 MPa), and wear HMA (0.72 MPa), respectively. The new wear surface produced the lowest ISS value of 0.64 MPa, an 11% reduction compared to the minimum ISS of 0.71 MPa recorded for the binder HMA underlayer. This was mostly attributable to the significantly smoother texture of the wear underlying layer relative to the other HMA bottom layer samples. While the new Binder Surface exhibited slightly better results than wearing surface interfaces, possibly due to a more favorable texture interlock. At optimum application rates, most materials reached ISS values of more than 1 MPa, especially when using modified binders. Aged and worn Hot Mix Asphalt (HMA) surfaces are recognised to contain oxidised asphalt binder, which exhibits a higher shear strength compared to unaged binder. Thus, the aged asphalt binder film covering aggregate at the surface formed a strong connection at the interlayer, resulting in the greatest ISS value, which was the reason for the high ISS value seen for the sample with aged-worn HMA. Because the new HMA had unaged binder film on its aggregates at the sample's surface, the interlayer bond was not as strong as it was in the case of the aged and worn HMA bottom layer. The Milled Surface interfaces demonstrated the highest ISS values across nearly all binder types and rates. The rough, irregular surface left after milling increases both the mechanical interlock and surface area for bonding. The tack coat at the interface significantly passes through the groove, expanding the contact bonding area and simultaneously functioning as an anchor. Polymer-modified tack coats recorded peak performance here, with values exceeding 1.5 MPa at 0.32 L/m^2 application rate.



(a) Interlayer shear strength for wear/wear structure.

(b) Interlayer shear strength for wear/binder structure.

(c) Interlayer shear strength for wear/aged-worn structure.

(d) Interlayer shear strength for wear/milled structure.

Figure 10**.** Interlayer shear strengths (ISS) under varying tack coat types and residual application rates.

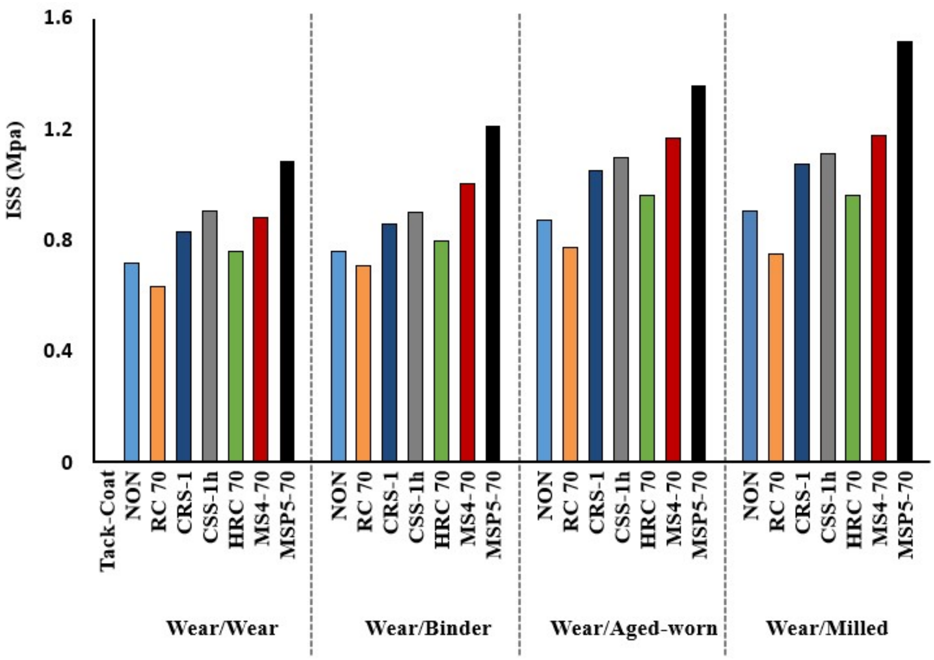


Figure 11**.** Interlayer shear strength of different layers at optimum tack coats.

7. Conclusions

This research highlights the multifaceted influence of tack coat type, application rate, and substrate texture on asphalt interlayer bonding. The use of 3D scanning provided a novel perspective on interface morphology, confirming that texture features such as curvature, peak-valley distribution, and surface area play a pivotal role in mechanical interlock and adhesive performance. Furthermore, various indicators were proposed to quantify the bond characteristics of the interface. The subsequent conclusions can be derived:

- The morphology of the surface skeleton and variations in mineral sizes within the asphalt mix greatly influence interface texture. The composition of the underlayer is crucial for morphological alteration, affecting interlocking contributions and, subsequently, interlayer shear strength.
- Milled surfaces—due to their high texture depth, irregularity, and surface area—offer the best conditions for tack coat penetration and bon-

ding, resulting in the highest interlayer shear strength. Conversely, wear surfaces with dense gradation and smooth textures yielded the weakest bond strength due to limited texture and mechanical interlock. Binder and aged-worn surfaces demonstrated intermediate performance, which was affected by aggregate gradation and surface oxidation, respectively.

- It was discovered that the interfacial shear strength (ISS) values that were measured for specimens that were prepared to utilize any surface textures that contained RC-70 tack coat in their interlayers could be lower than those that were prepared without any tack coat.
- Hard binder grade (HRC-70) tack coats were found to be the most efficient for achieving better ISS values than using a conventional cutback for all types of pavement surfaces but less than emulsion tack coats (CRS-1 and CSS-1h).
- Modifying the tack binder in a hybrid manner is essential for enhancing the shear strength at the interface of asphalt layers. Additionally, the high Viscosity of the tack binder contributes to improved shear strength at elevated temperatures.
- The novel hybrid-modified tack coat (MSP5-70) comprising hard asphalt, styrene-butadiene-styrene (SBS), and polylactic acid (PLA) proved the most effective, outperforming both conventional and SBS-only modifiers, especially on rougher substrates like milled surfaces. It improved interlayer shear strength by up to 67% compared to untreated interfaces and by over 25% compared to other polymer-modified binders. Its superior performance is attributed to increased Viscosity, elastic recovery, and cohesive energy at the interface, which are qualities critical in high-temperature construction environments.
- The residual application rate of the tack coat has an important effect on the shear strength developed by the bonded interface of the asphalt layers. It was found that the application of tack coat at low and moderate rates (0.1 and 0.23 L/m^2) resulted in enhanced ISS outcomes when compared to samples treated with high levels of tack coat, which included various surface textures.
- The type of surface significantly influenced the ISS values measured. The highest ISS values were recorded for specimens made with milled, aged-worn surfaces, followed by new binder Hot Mix Asphalt (HMA) and the wear bottom layers. These findings support the strategic use of hybrid tack coats and texture-appropriate application rates to enhance the longevity and cohesion of asphalt pavements significantly.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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