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A Comprehensive Review of Interlayer Bond Strength in Asphalt Pavement Systems

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ABSTRACT

Flexible pavements consist of numerous layers, and the integrity of the interface between them is crucial for structural performance and service life. Inadequate interlayer bonding can cause premature failures such as slippage, rutting, delamination, and fatigue cracking. This review comprehensively synthesises the factors that influence the strength of interlayer bonds in asphalt pavement systems. It examines the impact of surface texture, moisture, temperature, contamination, application rate, curing time, and tack coat type. The emphasis is on mechanical evaluation methods, such as shear, tensile (pull-off), torsion tests, and emergent non-destructive and fatigue-based techniques. Advanced modelling techniques such as finite element analysis (FEA) and machine learning (ML) are also considered for predicting interlayer shear strength (ISS). Key findings emphasise the importance of polymer-modified emulsions, surface cleanliness, and proper tack coat application in improving bond performance. The review identifies gaps in standardisation, field testing consistency, and predictive modelling. This work combines material science, pavement mechanics, and simulation tools to support building standardised practices for analysing and optimising interlayer bonding. It also outlines future research needs focusing on fatigue behaviour, field validation, and predictive modelling frameworks.

1. Introduction

A pavement structure comprises multiple layers, assuming all layers work together as one layer or a single monolithic unit. The boundary between these two consecutive layers is known as the layer interface, and the adhesion conditions at the layer interface highly influence the stress distribution. If the adhesion bonding is not achieved between the existing pavement and the new asphalt pavement layer or successive layers, delamination or separation occurs into constituent layers, which may cause several structural distresses (slippage and fatigue cracking).

Slippage, cracking, debonding, and pavement deformation are common diseases caused by inadequate bonding properties, which are typically induced by vehicle turning and braking. These issues are not only structural, but they also compromise safety and durability. Previous research suggests that a weakened bond at a single interface can decrease pavement lifespan by two-fifths to five-sixths, or possibly as low as one-sixth [1].

To create a strong connection between layers, a tack coat is used, usually made of a liquid asphalt emulsion or modified binder. This helps to enhance the adhesion between the surface of the underlying layer and the new asphalt layer. The bonding material improves the cohesion and structural integrity of the pavement system by reducing slippage and enabling the pavement to respond uniformly to traffic loads [2].

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Several factors influence the effectiveness of a tack coat, including the type of material used, the application rate, surface texture, temperature, moisture content, curing time, and cleanliness. Collectively, these parameters determine the overall performance and durability of the pavement system. Researchers have employed various testing methods to evaluate the interlayer bond strength, including direct shear, pull-off, wedge-splitting, and torsional test techniques [3]. Furthermore, several advanced techniques, such as Finite Element (FE), X-ray Computed Tomography (CT), Falling Weight Reflectometer (FWD), and Digital Image Correlation (DIC), were created for thoroughly examining bonding properties.

This review aims to provide a comprehensive and critical understanding of interlayer bond strength mechanisms in flexible asphalt pavements. Unlike previously evaluations, which focused on individual characteristics, this study synthesises a variety of influencing factors, such as tack coat types, surface texture, environmental conditions, testing methodologies, and simulation tools. Furthermore, it identifies significant gaps in current literature, such as limited utilisation of bio-based or trackless tack coatings, the absence of standardised test interpretation methodologies, and insufficient investigation of fatigue performance under cyclic loading. This work contributes to a thematic reorganisation of parameters influencing interlayer shear strength and provides useful insights for future experimental research and standard development efforts.

2. Mechanisms of Bond

The bond mechanism between layers in asphalt pavement is influenced by adhesion and cohesion forces. The mechanism of interlayer is shown schematically in Figure 1 . Adhesion results from the interaction between the asphalt binder and aggregate at their interface. In contrast, cohesion pertains to the internal strength of the asphalt binder. Together, these two mechanisms help prevent the separation of pavement layers [4].

During construction, it's commonly believed that a completely bonded interface is created by applying a tack coat. In practice, however, the bonding condition usually falls between fully bonded and fully sliding. This semi-bonded state can compromise pavement integrity under traffic loads.

Nonetheless, it is widely acknowledged that normal and shear forces are a part of the general forces and mechanisms at the interface due to vehicular movement. Shear forces predominate during vehicle braking and turning, whereas normal forces arise from vertical traffic loading. [5]. Uzan et al., [6] Estimated a maximum shear stress near the midpoint of the surface layer. The interface will break and debond when it cannot withstand the applied forces, regardless of the position and amount of the maximum stresses.

Interface failures can take two main forms: (1) monotonic failure caused by a single excessive load and (2) fatigue failure resulting from repeated loading cycles over time. In fatigue situations, minor displacements accrue, resulting in a gradual weakening of the interlayer bond. Hakimzadeh et al. [7] Demonstrated that insufficient adhesion at the interface can significantly accelerate damage propagation between layers, especially under thermal cycling and dynamic traffic loads. Therefore, understanding the bond mechanism is essential for predicting pavement performance and preventing early failures.

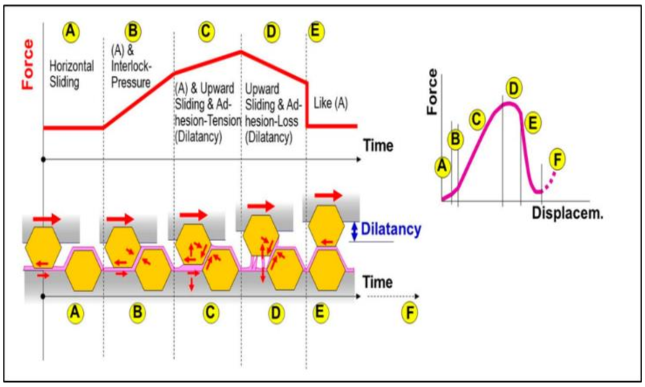

Figure 1. Schematic of the interlayer mechanism bonding [8]

3. Problems and Consequences of Poor Bonding

One of the most common and crucial failure mechanisms in asphalt pavements is weak interlayer bonding, which leads to severe performance decline. There are many different types of failure modes, such as slippage and delamination, shown in Figure 2. The most common of these problems is slippage failure. Huang [9] defines slippage failure as a crescent-shaped crack with the two ends extending toward traffic. This failure typically happens when the interfaces between the two layers in contact have inadequate bonding. D. H. Chen [10] Also agrees with this statement. In areas where vehicles generate significant horizontal forces, abrupt curves, and congested intersections involving continuous acceleration and deceleration, slippage failures may commonly occur [11]. Furthermore, inadequate pavement interlayer bonding appears to contribute to surface layer delamination [12]. Researchers worldwide have documented some actual situations, including issues associated with poor bonding [10].

(a) slippage failure

(b) Delamination

Figure 2. interface failure modes [13].

4. Components Contributing to The Interface Strength Failure Mechanism

Under repeated vehicle loads, the bearing capacity is declining, and cumulative interlayer damage seems quite severe. The interface shear stress exceeds the tack coat's shear strength when the cumulative effect of traffic load reaches a particular value [14]. Interlayer damage is more common for many reasons; however, the exact mechanism causing interlayer failure is unclear. It will result in the interlayer bonding property failing, shortening the pavement structure's overall service life.

According to the cracking spreading of fracture mechanics, interlayer failure modes can be characterised based on the external appearance of damage. These modes occur in both in-plane shear and tensile during the asphalt layer's service life; the failure mode is shown in Figure 3 [15].

The sliding (shear) failure in interface mechanics refers to the relative horizontal displacement between the interface's upper and lower layers. Interface damage under horizontal shear stress is similar to slide failure. The interface is more susceptible to shear failure because of less internal friction, particularly when the vehicle starts or brakes.

A variety of reasons cause interlayer shear failure, which can be categorised as follows:

(1) increased shear stress due to unreasonable pavement structure and alignment design [16];

(2) An abrupt change in shear stress is caused by the inadequate bonding characteristic of tack coat materials [17]. Consequently, an analysis of the interlayer shear strength mechanical mechanism is required.

Pull-off (tensile) failure occurs when the upper and lower layers separate vertically. The energy release rate is the primary distinction between sliding and pull-off failures. Beyond that, the building of the various layers of asphalt pavements isn't connected. Pull-off tests are commonly used to assess interlayer damage produced by vertical stress [7].

Poor bonding is not entirely understood because various factors vary depending on traffic load, paving materials, and environment. Many studies have found that the asphalt type in the wearing course. [18], tack coat material, inadequate compaction of the base course, subbase course, or subgrade [19], segregation in the base course, and improper or excessive application of tack coat under vehicle loads impact the bonding of pavement layers [20].

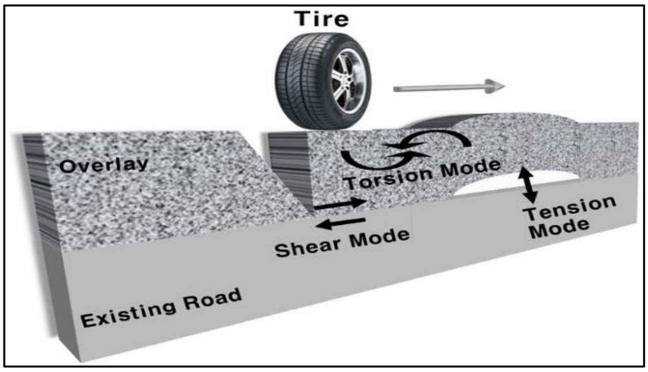

Figure 3. pavement interface failure mode.[21]

5. Parameters That Affect The Interlayer Bonding Characteristic

5.1 Property of Tack Coat

5.1.1 Tack Coat Types

The type of tack coat used significantly influences the bond strength between pavement layers. Different formulations provide different performance levels based on viscosity, curing properties, and interaction with aggregate surfaces. Tack coats are typically categorised into four primary types: hot asphalt binders, asphalt emulsions, cutback asphalts, and polymer-modified (or trackless) tack coats.
Every type presents distinct advantages and limitations. For instance:

- Hot asphalt cement offers great bond strength but needs high-temperature handling, raising safety and energy issues.
- Asphalt emulsions are popular because they can be easily applied at ambient temperature. However, their effectiveness may differ based on the emulsion's setting rate and the surface conditions.
- Cutback asphalts comprise solvents that are required to evaporate following application, which raises significant environmental and health concerns.
- Trackless tack coats, which are frequently modified by polymers, provide superior bond performance and significantly reduce tracking during construction. This characteristic renders them particularly desirable for high-traffic roadways.

5.1.1.1 Hot Asphalt Cement

Asphalt is a class of black or dark-colored (solid, semisolid, or viscous) cementitious substances, composed principally of high molecular weight hydrocarbons. It can be used as a tack coat material. PG 64-22, PG 76-22, PG 76-22M, and PG 58-28 are the common binder types used as tack coat material. The primary benefit of utilising asphalt binder is that it does not require curing time. However, the high temperature requirement to make enough asphalt fluid through the distributor is a serious safety concern for the workers. Also, it is costly as it requires high energy to maintain the binder fluidity at high temperatures for uniform application [22].

5.1.1.2 Asphalt Emulsion

Asphalt emulsion consists of three primary components: asphalt, water, and a small amount of an emulsifying agent. All these components are combined in a colloid mill, which breaks the asphalt into tiny droplets. The surfactant emulsifier keeps the asphalt droplets stable in suspension and controls the breaking time. It is used more frequently than hot asphalt cement or cutback due to its application at lower temperatures, which promotes greater uniformity, energy efficiency, and improved safety in application [23]. Asphalt emulsions are often categorised into three types based on the electronic charge around the asphalt cement particles: anionic, cationic, and nonionic. Anionic and cationic asphalt emulsions are the main emulsified tack coat compounds utilised. Emulsions are additionally categorised based on their evaporation duration. For instance: rapid-set (RS), medium-set (MS), slow-set (SS), and quick-set (QS).

5.1.1.3 Cutback Asphalt

Asphalt cutback is a blend of asphalt binder and some petroleum distillates. When applied as a tack coat, the distillates evaporate or cure out, and only leave the residual asphalt as the bonding agent in the tack coat. Despite strong adhesion performance, health, safety, and environmental concerns restrict their contemporary use [24].The solvent evaporation rate depends on the kind of solvent and the proportion of remaining asphalt in the asphalt cutback. Based on evaporation rates, asphalt cutbacks are categorised into three types: Rapid-curing (RC), Medium-curing (MC), and Slow-curing (SC).

5.1.1.4 Trackless Tack Coat

Trackless tack coat is composed of polymer modifier and hard base asphalt and is designed to reduce the tracking problems associated with traditional tacks. When the new layer is put on, the heat activates the material from a hot lift of asphalt, and it bonds with the new overlay. [25]. It was reported that trackless tack coats have higher shear strength than conventional tack coats, CRS-1 and SS1[26]. The bonding performance of trackless tack coat decreases with increased temperature and is superior to CRS-1 at 40°C [27] . The high temperature grade for CRS-1 was PG 58, whereas for trackless tack coat it was PG 82. Although it has high brittleness, which resembles its high interface shear strength, it may be vulnerable in cold regions due to its low top-down cracking resistance [28].

5.1.1.5 Additives Used for Tack Coat

In recent years, additives in tack coat formulations have made considerable progress, enhancing performance related to adhesion, cohesion, and resistance to environmental stressors. These additives can be mixed with asphalt emulsions or hot binders to alter their rheological and adhesive properties.

Polymer-modified asphalt emulsions can be made using various polymers, such as ethylene-vinyl acetate (EVA), polyvinyl acetate (PVA), polyphosphoric acid (PPA) [29], styrene-butadiene-styrene (SBS), styrene-butadiene rubber (SBR), epoxy resin, and natural rubber latex (NRL). The effect of polymer on bonding performance is:

- The SBS (Styrene–Butadiene–Styrene) improves elasticity and bond strength during cyclic loading [30].
- SBR (Styrene–Butadiene Rubber) offers enhanced wetting properties and significantly improves bonding in humid conditions [31].
- EVA (Ethylene Vinyl Acetate) improves rigidity and thermal resistance [32].
- HDPE (High-Density Polyethylene): Enhances the cohesion and durability of tack coats in wet environments.
- Epoxy and latex modifiers offer enhanced adhesion and chemical resistance, particularly under extreme traffic and temperature variations [33].

A study by Qinqin Zhang et al., [34] explored the thermal performance of SBR-modified asphalt emulsions compared to a standard emulsion. The findings revealed a significant increase in the softening point, which is associates with the thermal stability and heat resistance of asphalt. A temperature rise of 5 ◦C was observed in dactylitis, alongside a decreased softening point. D. Hou et al., [35] Examined the efficacy of a modified asphalt formulated with trackless tack coat materials (TTCM). The findings indicated that TTCM enhanced the interface shear strength (ISS) by 69% at 20 °C. TTCM may be an alternative and potential candidate for high-temperature pavement coatings compared to traditional tack coats. Consequently, a polymer-modified asphalt emulsion may seal the base layer while producing high binder content at the interface with elevated application rates. [36].

Feipeng et al. developed an asphalt emulsion suitable for micro-surfacing using an SBS-modified asphalt binder. Ghaly and his team [37] evaluated the impacts of latex-modified tack coat asphalt emulsion alongside cutback asphalt grade 60/70. The modified tack coat demonstrated a higher ISS than the cutback and tack coat asphalt emulsion. Additionally, a slight increase in shear strength was observed at low viscosity when contrasted with high viscosity.

Table 1: A Summary of Different types of tack coats, classifications, and comparisons.

Hot Asphalt binder	AC-20, AC-30, PG 64-22, and PG 76-22,	Bond strength is high, but difficult to spray, and requires high heating
Asphalt Emulsion	Slow set (SS-1, SS-1h, CSS-1, and CSS-1h) Rapid set (RS-1, RS-2, CRS-1, CRS-2, and CRS-2P)	Personnel safety, ease of handling, savings on energy, and environmental friendliness
Cutback Asphalt	RC 70, RC 250, RC 8000, and VG 10	It is costly, uses more energy, and causes pollution.
Trackless and tack coat additive	modified with Polymer: CRS-2P, Coat, Latex-modified: SS-1h, CRS-2L Polymers types: EVA, PVA, SBS, SBR Latex, and natural rubber	strong bonds, environmental friendliness, resolving issues, and savings in energy

5.1.2 Tack coat applying rate

The selection of an optimum tack coat material and its application rate significantly contribute to the interlayer shear strength. The optimum application of tack coat is required because high application can introduce a slip plane, decreasing the bonding between layers, and an insufficient application rate generally leads to inadequate coverage, resulting in diminished adhesive contact between layers.

Studies have established that optimal residual application rates typically range between 0.20 and 0.7 L/m², with necessary adjustments based on surface texture condition and type of tack coat. Pavement surfaces with different texture conditions, such as old, milled, and new pavement, require different tack coat application rates. For milled or aged surfaces, larger application rates are typically needed. [22].

The rate at which tack coat materials are applied has been thoroughly investigated. Many studies have demonstrated the impact of rate application and enhancements on ISS values. (Tseng & Jameson, [38] Raising the application rate from 0.20 to 0.40 L/m² showed an almost 20% enhancement in interlayer shear strength on textured surfaces. Additionally, the application rate enhances the shear strength and increases the contact area .However, an excessively thick film of tack coat might establish a sliding level within the interlayer and weaken the bond. As a result, an optimal adhesive application rate is required to achieve a high bond strength between pavement layers. [39].

Song et al., [40] Studied the shear strength for three underlying materials and four tack coat rates. Low interface roughness caused the tack coat to lose contact bonding at 25 °C; a higher quantity of tack coat led to reduced shear strength. When emulsions with slow-setting properties serve as the tack coatings, Covey et al., [41] found that applying too much tack coat material leads to slippage.

5.1.2 Curing Time

The duration after applying the tack coat and before constructing a new layer is called "curing time". This period is essential for the evaporation of water or solvent present in the binder and achieving adequate adhesive properties interface. There is no agreement in the literature about how much curing time should be given for proper curing. Hasiba,[42] Reported that a conventional paver requires a two-hour curing time, whereas Hachiya et al., [43] suggested a curing time of 24 hours. The optimal curing time depends on binder type, ambient temperature, humidity, and surface texture. This factor signifies a complete coating breakdown [44].

Nonetheless, a universally accepted standard for optimal curing time remains absent, leading contractors to often proceed without adequate verification, especially when facing time constraints. This approach yields inconsistent field results in performance. To address this issue, recent research has proposed utilising indirect indicators, including surface temperature, changes in tack coat colour, or dielectric sensors, to ascertain appropriate curing thresholds in real time.

The curing period significantly influences the interlayer bonding, especially when the current asphalt layer is contaminated. J.-S. Chen & Huang, [45] Findings indicated that varying cure times did not significantly influence the bonding property. However, shear strength gradually increased with longer cure times until it reached a stable value. [46] Found that the curing period positively affected the bonding properties between layers. As anticipated, curing at moderate to high temperatures enhanced interlayer bonding strength.

Table 2: A summary of the Tack Coat Property

Factor Affecting	Remarks
Tack Coat Type	Polymer-modified bitumen emulsion, called Trackless Tack, consistently has higher ISS values than cutback bitumen, straight-run bitumen, and conventional bitumen emulsion. Binder viscosity is ordinarily correlated to measured ISS.
Tack Coat Application Rate	ISS generally peaks at an optimal application rate of the tack coat. The optimal rate depends on the texture of the interface, which is affected by milling processes, asphalt size and density, contamination, and underlying material age. More texture requires a higher tack coat rate to achieve optimal ISS.
Curing time	Curing time greatly impacts the bonding properties between layers. As curing time increases, the shear strength shows a slight rise and stabilises after reaching a specific value.

5.2.Environmental Effects

5.2.1 Interface Moisture

Sensitivity to moisture is one of the main reasons for pavement degradation, involving stripping and potholes. Moisture causes the binder-to-aggregate bonds to weaken; the pavement interlayer may be considered sensitive to water and cause premature deterioration of the interlayer. In comparison to dry conditions [47]. Moisture's effect on interlayer shear strength depends on the quantity of water present and duration.

The authors recommended that the surface be dry and clean to prevent water from adversely affecting the bonding at the interface, according to Sholar et al.,[48] An extensive amount of water can weaken the tack coat's shear strength, particularly during construction, when precipitation can severely poor the coating's interlayer shear strength. Although there is no set limit on the amount of moisture present when applying a tack coat, all studies advise using a dry and clean surface. Raab, [49] Discovered that shear stress and stiffness can be reduced by over 30% due to moisture effects when the air void ratio is at 5% with a five-hour water exposure treatment.

Ghabchi et al.,[50] Found that in the absence of a tack coat, moisture causes decreased interface shear strength values. When sprayed at optimal residual application rates, a tack coat increases the degree of resistance to moisture-induced damage. Therefore, tack coats can significantly prevent moisture-induced damage by working exclusively as moisture barriers.

W. Zhang, [44] indicates that ISS values measured at the interface between an asphalt overlay and a concrete slab may decline due to moisture conditioning. On the other hand, there are opposing results concerning the effect of moisture on the ISS values observed at the interface of two asphalt layers. Recently, Alnuami & Sarsam, [51] studied the moisture effect on the interfacial bond strength of the multilayer pavement under two types of tack coats, RC-70 and CMS. They found that the specimens with the RC-70 tack coat had greater permanent deformation and lower shear strength than the CMS.

5.2.2 Pavement Aging

Ageing of asphalt pavements typically leads to stronger interlayer bonds, mainly by affecting asphalt content, gradation, density, and compaction methods. Ageing samples in the laboratory usually improves interlayer strength. The interlayer strength in field cores can either rise or stay the same over time, depending on the cores taken in between wheel paths.

Based on several studies, tack coats with a harder residue have a greater adhesion than those with a soft binder [52]. The aged or the use of a higher performance grade (PG) binder might produce a harder residue.

A direct correlation exists between pavement service duration and interlayer bonding strength Das et al.,[53] found that an increase in pavement service time, regardless of pavement type, resulted in increased interface bonding strength caused by ageing. Ageing increases interlayer bond strength with or without a tack coat, according to a further study by Raab et al.,[54]. However, when a tack coat was applied, the improvement was shown to be more significant. The ISS values were observed to increase similarly for both site ageing and long-term oven ageing.

The mechanism is due to the stiffening of the binder as a result of oxidative ageing, which enhances the mechanical interlock and resistance at the interface. Therefore, it has a positive effect on the ISS for pavement interlayers treated using a tack coat. Consequently, the failure of the tack coat is more likely to appear at an early stage of the pavement, when the interlayer residue has not yet undergone ageing. Nonetheless, most research regarding the effectiveness of tack coats in enhancing ISS is performed on field cores, which are often older and exhibit higher ISS values than newly constructed pavements.

5.2.3 Temperature

Temperature plays a crucial role in asphalt performance, as it directly influences the rheological characteristics of the asphalt binder and tack coat [55]. That indicates a linear relationship between temperature and ISS; specifically, as the temperature increases, the ISS decreases [44]. The NCHRP report 712 noted that ISS showed a significant increase with the temperature rising from 10 to 60 ◦C. The bonding performance of the trackless emulsion exceeded that of the CRS-1 emulsion at temperatures exceeding 40 ◦C, as established by ISS [56]. Additionally, another study showed that temperature has a significant impact on the bond strength. West, Zhang, & Moore,[57] It was observed that binding strengths at 15 ◦C were 2.3 times greater than those at 25 ◦C. Amelian & Kim,[58] observed a rapid decrease in shear strength following the peak shear strength at a low temperature, whereas the decrease in strength at an intermediate temperature was gradual. The results demonstrate that the tack coat material has greater sensitivity at lower temperatures compared to higher temperatures. Based on several studies [35], [58], it was observed that interlayer shear strength decreased as temperature increased for all surface types. In addition, D. Hou et al.,[35] found that high-viscosity tack coats had higher shear strengths than low-viscosity ones at higher temperatures. At lower temperatures, increasing the tack coat application rate increased ISS results, but this was not the case at higher temperatures. Similar findings were reported by Recasens et al.,[59]. These results highlight the importance of considering ambient temperature when selecting tack coat materials and application strategies, especially in areas with significant wide thermal changes.

Table 3: A summary of the Environmental Effects

Factor Affecting	**Remarks**
Interface moisture	Moisture condition has the potential to reduce the shear strength of the interlayer. Therefore, to prevent water and dust from negatively affecting the bonding at the interlayer, a dry and clean surface is advised before applying the hot-mix asphalt.
Pavement aging	Pavement ageing enhances interlayer bond strength, both with and without a tack coat, thereby extending the service time of the interface bond strength.
temperature	The most influential of all parameters is due to its impact on the viscosity of the tack coat material. Increasing test temperature from 20-60°C has resulted in typical drops in measured bond strength of 90-95%.

5.3. Surface and Construction Characteristics

5.3.1 Aggregate And Surface Texture

Surface type and texture both contribute significantly to interlayer shear strength, as shown in Figure 4. The characteristics of the top layer mixture and the face texture of the underlayer have an essential effect on the bonding strength and tack coat qualities. [36]. Moreover, higher texture depth and the interlayer contact area enhance the stiffness and interface bonding.

Several studies demonstrate that the strongest bonds are found when the mixes have an intermediate texture [60]. Thus, optimal texturing offers sufficient friction between layers and enhances load transfer between them, which limits slippage during traffic loading [61]. Accordingly, the gradation of aggregates and the type of mixture are considered key factors that influence the tack coat shear strength [62]. Raposeiras et al.,[63] Investigated the impact of surface macrotexture on several asphalt mix types. They found that the best resistance values were achieved with coarse gradation mixes, while the lowest values were obtained with dense gradation mixes with a serrated surface.

The nominal maximum aggregate size (NMAS) influences the shear strength, as reported by [64] . Using round aggregates, Raab [65] found that the best shear strength is achieved by combining a small aggregate in the upper layer with a big aggregate in the underlying layer to improve aggregate interlock between layers. However, West, Zhang, & Moore,[57] show that the fine-graded mixture (NMAS 4.75 mm), demonstrated higher shear strength than the coarse-graded mixture, which has a 19 mm NMAS.

In order to associate aggregate gradation with the British pendulum number (BPN), Y. Hou et al., [66] investigated the quantitative relationship between area fractal dimension and gradation. Furthermore, using their proposed mass fractal characteristic function, the formula for calculating the area fractal dimension of aggregate distribution characteristics was deduced through using five surface textures of asphalt mix types—AC, rubber AC, RAC, micro-surfacing MS, OGFC, and SMA.

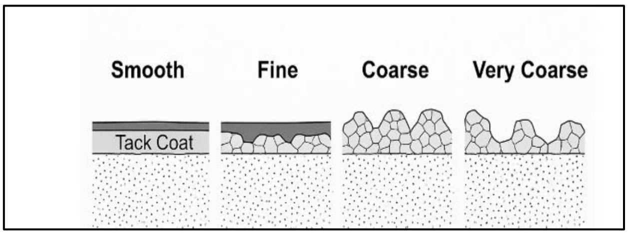

Figure 4. Surface Texture

5.3.2 Milling

Milling has become a common technique in Hot Mix Asphalt (HMA) rehabilitation projects, either to completely remove deteriorated layers or to prepare a milled surface for a new overlay. The milled surface produces a rough surface texture that increases surface area at the contact between the old and new surfaces, thereby enhancing mechanical interlock and improving bond strength. In addition to enhancing texture and ride quality, milling is crucial for recycling existing asphalt, which makes it an economical and environmentally friendly technique for pavement rehabilitation plans. It is important to look into how it might affect pavement performance and lifetime in order to ensure efficient and sustainable road maintenance procedures. For this, some research focused on the effect of pavement milling on the remaining roadway surface and pavement performance [67].

Many research studies have shown that milled pavement surfaces consistently exhibit a higher ISS than non-milled pavement surfaces [22]. Furthermore, it is well-recognised that surface roughness and texture depth significantly relate to the material's properties [68].Rivera et al.,[69] Assessed the quantity of tack coat and its impact on the texture of milled pavement layers, along with the influence of the surface area of milled pavement on the volume of tack coat required. They discovered that the texture produced by the milling processes matched the texture obtained via the sand patch test, and these grooves led to excessive tack coat laying, resulting in overdosing. These findings underscore the significance of optimising both milling depth and tack coat rate to prevent inconsistencies in bonding quality.

(a) Standard Milling (b) Fine Milling (c) Micro-Milling
Figure 5. Type of milling [69]

5.3.3 Surface Cleanness

Surface cleanliness is essential for attaining effective interlayer adhesion in asphalt pavement systems. Most literature suggests the tack coat should be applied on a clean surface. Contaminants like dust, dirt, sand, or clay residues can prevent proper adhesion by forming a barrier between the tack coat and the substrate. This leads to debonding by delamination or sliding of the pavement surface. There are several ways to clean the pavement surface: mechanical brooming, flushing the surface with water, or blowing off debris using high-pressure air [70]. FDOT,[71] Specifically, before applying any bituminous material, dust, sand, dirt, loose material, caked clay, and other foreign materials should be removed to ensure comprehensive adhesion throughout the entire surface width and prevent weak bonding zones. Hristov,[72] assessed three distinct categories of interlayer surface condition: clean, moderate, and high contamination. He discovered that moderate contamination did not significantly impair interlayer bonding; however, severe contamination weakened the interlayer bond, adversely affecting premature interlayer failure, which should be prevented in field applications. L. Mohammad et al.,[73] Indicated that most research demonstrated significant variances in bond strength between clean and dusty settings. Contaminated surfaces negligible effect on interface bonding when the tack coat is adequately cured. Nonetheless, the emulsion demonstrated ineffective adherence to the layers when it was not fully cured. In addition, Salinas et al.,[74] show that air-blast cleaning considerably improves interface bonding, but this method is time-consuming, which reduces job efficiency; it is also uncomfortable in the field, especially in metropolitan areas where dust clouds could be dangerous.

Table 4: A summary of the Surface and construction characteristics

Factor Affecting	Remarks
Aggregate and Surface texture	Aggregate gradations are crucial for achieving layer interlocking, which enhances texture depth. Mixtures with a high air void content enhance interlock yet reduce shear strength.
Milling	Milled pavement surfaces demonstrated greater shear strength compared to unmilled surfaces due to mechanical interlock and increased surface area.
Surface cleanness	Clean and dry interfaces are optimal for achieving good interface performance. Some studies have shown no advantage or even improved performance for wet and/or dirty interfaces. This is considered to be an anomaly and does not represent field conditions.

6. Bonding Evaluation Techniques

To evaluate the durability and quality of interlayer bonding in asphalt pavements, a variety of laboratory and field test methods are required. These methods simulate stress and load conditions during pavement service. Most bond performance evaluation methods focus on shear, tensile, and torsion modes; the debonding at the pavement interface typically occurs under shear or tension due to traffic loads.

Bonding Evaluation Techniques can be classified into three general categories :

- Static Tests, evaluation of bonding under monotonic/static load to simulate braking situations.
- cyclic/dynamic test, to simulate a continuous moving traffic load and
- Non-destructive tests evaluation the bonding without damaging the pavement structure.

6.1 Testing for Static Bonds

Static bond test tools have recently been widely utilised to evaluate interlayer characteristics. During static bond testing, a load or displacement is applied monotonically between two pavement layers until fails, and the resistance that results is measured. Direct shear, tensile, and torque tests are the most commonly used evaluation techniques that are shown in Figure 6. [16].

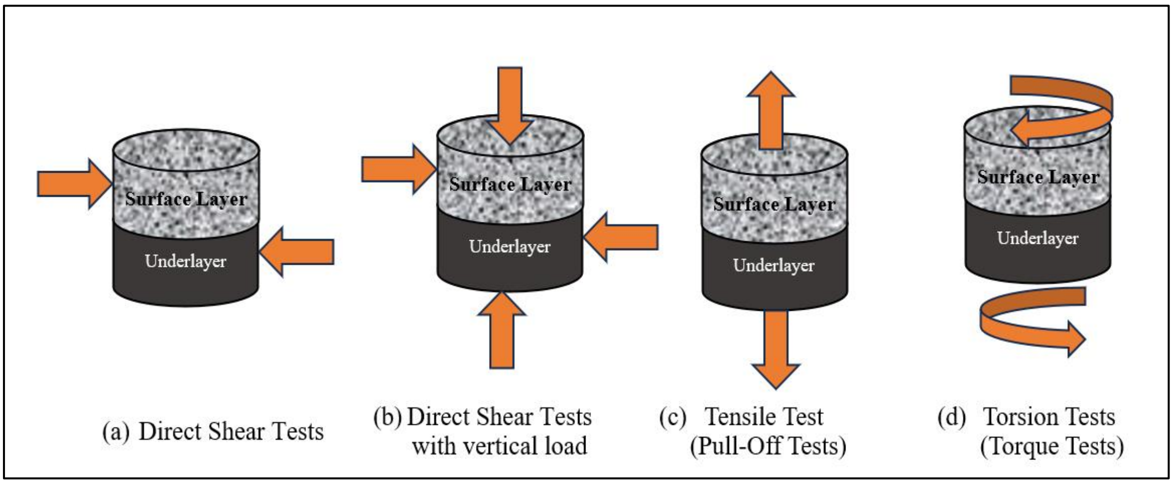

Figure 6. Static Bonding Tests

6.1.1 Shear Tests

The shearing technique is now widely favoured for evaluating interface problems

because of its effectiveness and simplicity, making it a popular method for assessing interface bonding. A constant level of shear displacement and shear load at the interfaces of double-layered samples, simulating slippage conditions under traffic loads.

Numerous countries have developed different types of shear test apparatuses, which can be divided into two categories: direct shear tests with normal stress and those without normal stress.

The primary interlayer direct shear apparatus was created by Leutner in 1978 for use in shear experiments. The test required that shear force be applied at a consistent rate through a fixed plane until deformation occurred. Additionally, the continuous observation of the resulting shear force was considered as a function of the displacement that occurred [75].

However, the Leutner test has been significantly modified to improve accuracy and adapt to different testing conditions. These enhancements led to development testing methods such as the Florida Direct Shear Test, Layer-Parallel Direct Shear (LPDS) Test, Louisiana Interlayer Shear Strength Tester (LISST), and NCAT Shear Test, which utilise applied shearing load for assessing the performance of multilayered pavement [75].

The Florida Direct Shear Test was developed by the Florida DOT in 2003 to assess the bond strength performance of pavement work conducted under dry and wet situations. It uses either highway cores or laboratory-fabricated samples that do not require trimming for device placement. The gap width between shear plates is 4.8 mm. The climatic chamber facilitates testing samples at various temperatures, while a vertical load is supplied using a controlled strain mode at a loading rate of 50.8 mm/min until failure occurs [76].

The Swiss Federal Laboratory developed the Layer-Parallel Direct Shear (LPDS) Test for Materials Testing and Research. This device is considerably similar to Leutner shear test devices; some changes can still be seen. It is employed to assess the quality of the pavement mixture and the interlayer shear characteristics of the tack coat material by measuring the normal average shear stress and maximum shear stiffness. A cylindrical composite specimen with a diameter of 100 mm and a 2 mm gap between shearing plates can be used to test field and lab cores [15], [46].

Another direct shear test technique for determining interlayer shear strength is the Ancona Shear Testing Research and Analysis (ASTRA) test, which an Italian research team developed [77] The ASTRA test involves applying horizontal stresses to the sample's upper layer and continuously increasing the horizontal displacement until it fails.

Additionally, a constant vertical load is used for confinement. During testing, the whole apparatus is kept in a controlled chamber. The maximum interface shear stress is measured to assess shear resistance. This resistance evaluates how much the tack coat improves the ISS value. Both field cores and samples processed in a lab can be used for the test.

The Louisiana Transportation Research Centre (LTRC) developed the Louisiana Interlayer Shear Strength Tester (LISST) for assessing pavement interface characteristics [78]The tester includes a specially designed mould with two shearing plates: a fixed response frame and a moving shearing frame, which maintains a 12.7 mm gap. In addition to shear stress, the actuator connected to the mould is capable of applying a normal load. This mould accommodates double-layered samples with 100mm and 150mm diameters, with a horizontal force of 50 lbs/min exerted on the asphalt mix specimen at a designated temperature until failure occurs.

The Alabama DOT-National Centre for Asphalt Technology created the National Centre for Asphalt Technology (NCAT) bond strength device. This apparatus is connected to a Marshall press or a universal testing machine to load specimens. A specimen with a diameter of 150 mm can be examined with layer heights larger than 50 mm but less than 150 mm [79]. Uses the shearing process to calculate the bond strength between the pavement interlayer.

Table 5: Common loading rate and sample size compilation for shear test

Device	Loading Rate	Specimen
FDOT shear test device	Loading rate: 50.8mm/min	Dia: 150 mm
Layer Parallel Direct Shear Test	Loading rate: 50.8 mm/min	Dia: 150 mm Height: 130mm
ASTRA shear test device	Normal stress: 0.4 Mpa	Prismatic: 100 x 100 mm2 Cylindrical: 94 to 100 mm
Louisiana interlayer shear strength test	Loading rate: 2.54 mm/sec	Height: 100 mm Dia: 150 mm
NCAT simple shear test device	Loading rate: 50.8 mm/min	Dia: 150 mm Height: 115 mm

6.1.2 Tensile Tests (Pull-Off Tests)

Tensile load is another method for assessing bond strength using apparatus such as the Wedge-Splitting Test, the Switzerland Pull-Off Test, the Louisiana Tack Coat Quality Tester (LTCQT) device, and the UTEP Pull-Off Test. In these experiments, tensile stress is applied to a double-layered specimen, causing the top surface layer to pull off vertically and break the interface.

As early as 1999, the Swiss Federal Laboratories for Materials Testing and Research (EMPA) developed the pull-off test device in situ to determine the tensile bond strength between an asphalt surface and a concrete underlayer. The apparatus consists of a disc with a diameter of 100 mm that is bonded to the specimen's top layer and glued to a concrete plate at the bottom. The specimen is then gradually subjected to a tensile rate of 100N/s until it fails.

The Wedge-Splitting Test was created by a Technical University in Austria. It uses specific fracture energy and maximum horizontal stress to assess the fracture-mechanical behaviour of layer bonding. To calculate fracture energy, a dual-layered sample with a groove and starter notch along the interface is subjected to a vertical force through a wedge at a constant failure rate [80].

Following that, the Louisiana Tack Coat Quality Tester (LTCQT) and UTEP Pull-Off Device were designed to measure the tensile strength of interlayer bonds.

The Pull-off test, created at the University of Texas at El Paso, is known as the UTEP Pull-off test [81]. This device is designed to evaluate and measure the bonding properties of the tack coat material applied on-site, as the current approach for assessing the quality of a certain tack coat is highly subjective. Once the tack coat has cured, the UTEP pull-off device is placed on the tacked surface, ensuring the contact plate is in contact with the tack coat material. An applied dead load of 18.1 kg (40 lb) is maintained for 10 minutes to achieve full contact between the contact plate and the adhered surface. The dead load is eliminated after 10 minutes, and the contact plate is released by pulling due to the applied torque on the device [33].

The Louisiana Tack Coat Quality Tester (LTCQT) instrument was designed to measure the interlayer bonding strength of the tack coat in the field. It was created by collaborating with the Louisiana Transportation Research Centre and Instrotek Inc. for NCHRP 9-40. Several parameters must be satisfied. The loading rate is set at 0.2 mm/s until the maximum tensile load is reached. The device's contact plate must maintain contact with the tack surface for 3 minutes at an applied pressure of 10.8 kPa. The results demonstrate that the LTCQT effectively evaluates bond strength quality and distinguishes the behaviours of the tack coatings tested in the field [82].

Table 6: Common loading rate and sample size compilation for tensile test

Device	Loading Rate	Specimen
Switzerland Pull-Off Test	Loading rate: 100 N/s	Dia: 100 mm
Wedge-Splitting Test	load rate: to 0.5 mm/min	Rectangular: 100 x 100 mm Height: 100 mm
Louisiana tack coat quality test (LTCQT)	Loading Rate: 0.2mm/s	Height: 56 mm Dia: 150 mm
University of Texas El Paso (UTEP) pull of test		NA Dia: 127 mm

6.1.3 Torsion Tests (Torque Tests)

The torque test aims to determine the maximal shearing torque applied to cored specimens, thereby separating the surface system from its substrate. To evaluate the bonding strength of the tack coat materials, torque is applied to the upper part of the specimen, resulting in the twisting and failure of the bond layer.

One of the most widely used torque assessments is the torque bond test (TBT), originally developed in Sweden for assessing bond characteristics in situ. It has been integrated into the UK's certification process for thin surfacing systems [83]. This particular test can be applied to field specimens fabricated in a laboratory using a specific apparatus. Specimens can either be 100 mm or 150 mm in diameter. During the test, the specimen is affixed to a metal plate, and torque is applied until either the specimen fails or a test value of 300 Nm is achieved.

The Texas Transportation Institute established the Torsional Shear Test (TTI), in which a twisting moment at a constant rate of 2.9 E-04 radian/sec and a normal load are applied to the specimen at a consistent rate until failure occurs. Plastic shear strength is measured to evaluate the strength of the tack coat.

UTEP Pull-Off Test uses the torque force to identify the interlayer shear strength of the tack coat by detaching the contact plate and the tack-coated pavement.

The ATacker device [84] could also be used to measure torque strength in a laboratory and on-site. It was developed by Instrotek to evaluate the performance of tack coats. The A-tacker consists of a contact plate to be placed in contact with the tack coat, a torque shaft for applying the load, and a force gauge to measure the necessary pull-off force. Weights are loaded on the top of the frame to resist the pull-off force. The torque is manually applied with the help of a shaft in the torque wrench.

6.2 Cyclic / Dynamic Bond Test (Shear Fatigue Test)

A comprehensive review of the existing literature indicates that most studies on interface bonding performance have concentrated on its monotonic behaviour. At the same time, less emphasis has been placed on its performance under fatigue conditions. In practice, pavements are subjected to substantial cyclic loads from traffic over their lifetime. Static loading situations do not accurately reflect the actual loading conditions in pavements brought on by the repetitive movements of vehicles. As a result, the characterisation of bonding behaviour is flawed. Nevertheless, interest in research focused on interface fatigue behaviour has grown significantly in recent years.

Romanoschi & Metcalf,[85] They created a testing setup to evaluate the shear fatigue properties of bonding surfaces. During their observations, they found a clear linear correlation between permanent shear displacement and the number of loading cycles, noticing a quicker growth rate when higher stress levels were applied. Following this, Diakhate et al.,[86] conducted experimental characterisation of shear fatigue behaviour at interfaces via laboratory tests to develop an interface fatigue equation. They built a model to closely connect shear fatigue parameters with those derived from the direct shear test. Another study by Diakhaté et al.,[87] employed accelerated shear fatigue testing to suggest a different approach for forecasting the conventional interface fatigue law. They also discovered that excluding a tack coat reduced bonding fatigue performance. Tozzo et al., [88] Successfully developed an innovative model that incorporates all possible stress combinations in analysing interface fatigue damage.

Furthermore, Tozzo et al., [89] utilised fundamental monotonic tests to predict interface failure under cyclic loads by connecting dynamic and monotonic outcomes. The latter study demonstrated a strong correlation between interlayer shear strength from the monotonic shear test and the results of fatigue tests. This indicates that interlayer bond energy is a reliable predictor of the shear strength of tack coats and has a considerable correlation with the outcomes of fatigue tests [90].

Table 7: Overview of interface bond testing methods

Test	Advantage	Limitation
Shear test	The operation is uncomplicated and closely related to the damage of the interlayer on-site.	Generating pure shear stress at the interface is challenging, and there are no consistent conclusions regarding the application of normal and shear stress.
Torque test	Performed either on-site or in a lab, using a less destructive prototype field test device.	Only applicable to the uppermost pavement interface, improper torque rate caused by manual operation.
Tensile test	Tests were performed in existing and additional laboratories to study the bond strength of tack coats.	It is not feasible at elevated interlayer bonding resistance.
Shear Fatigue Test	accurately reflect the actual loading conditions in pavements brought on by the repetitive movements of vehicles.	Requires devices that apply repeated loads, and the examination takes a long time.

6.3 Non-Destructive Testing

In recent years, Researchers have designed various non-destructive techniques to investigate the qualities of the tack coat. Additional parameters, such as roughness and texture, significantly contribute to characterising interface behaviours. Currently, the main method for determining the surface Mean Texture Depth (MTD) of road pavements is the volumetric patch approach. [91]Alternative technologies, including the profile comb, laser profilometer, 3D scanner, and X-ray Computer Tomography (CT), can be employed to examine surface profiles [92].

Furthermore,[93] utilised FTIR to identify the chemical functional groups in the tack coat substance. The results indicated that the quantities of the element were higher at the top of the overlay adhesive compared to the bottom.

The Falling Weight Reflectometer (FWD) is frequently employed to evaluate flexible pavements and estimate their lifespan. The FWD exerts impact pressure upon the pavement surface to replicate traffic loading and to measure pavement deflection at various radial points from the load Centre. Al Hakim et al., [94] Developed a novel back-analysis approach to evaluate the bonding between asphalt pavement layers and the stiffness of this layer, utilising FWD test results.

7. Modelling and simulation for Bond strength

Traditional experimental methods may not fully capture the effects of material properties, environmental factors, and construction techniques, owing to the complex behaviour of interlayer bonding in flexible pavements. As a result, numerical simulations and computational models have become crucial for quality assurance, optimising design parameters, and predicting interlayer bond strength.

7.1 Empirical and Data-Driven Modelling

Over time, prediction modelling of interlayer bond strength has progressed from traditional regression techniques to advanced data-driven methodologies like machine learning and neural networks. These models are intended to aid laboratory testing by revealing hidden correlations among the factors impacting bond performance. Empirical and statistical models, such as those published by Hakim, [95] and Bui et al., [96] use regression analysis to correlate bond strength with factors such as tack coat application rate, temperature, curing length, and normal stress. While these models are generally basic and interpretable, they frequently suffer from poor generalizability, particularly in real-world multivariable circumstances.

To overcome these challenges, researchers have increasingly used artificial intelligence techniques. In recent years, neural networks (ANN) and machine learning (ML) have been widely used across various fields, including aerospace, electronics, finance, and medicine. This is owing to their robust ability to detect patterns and model nonlinearity, which reduces the need for precise mathematical models to analyse issues involving multi-factor interactions.

[97] Employed an artificial neural network (ANN) to evaluate interlayer shear bond properties through the analysis of empirical data. The findings indicated that ANN techniques successfully assess interlayer shear bonding properties. Subsequently, Raab et al., [98] employed three artificial neural network models to evaluate and forecast changes in interlayer bonding properties over time. Using temperature, normal pressure, and aggregate size as main experimental variables, [99] three metaheuristic algorithms were used in tandem with an adaptive neuro-fuzzy inference system (ANFIS) model. Their results revealed that the proposed models were rather successful in exactly estimating interlayer shear strength. Interlayer shear strength was recently projected using artificial neural networks (ANN) and random forests (RF), thereby obtaining an explanation of more than 95% of the experimental data [100]. The discussed studies focused on several important parameters: temperature, normal stress, type of tack coat, aggregate size, and deformation rate. It is important to underline that the analysis disregarded particular elements, such as the pace of application of the tack coat. Thus, additional progress of these approaches is necessary to generate accurate models with machine learning techniques. For pavement structural design and quality control aims, these models might increase the generalizability and precision of ISS prediction. This will improve knowledge in the complex interface characterisation and design field.

7.2 Numerical and Finite Element Analysis

As computer technology has advanced, various programs have been created to numerically simulate the mechanical behaviour of asphalt pavement, accurately addressing structural issues. Additionally, these programs can effectively meet design standards and mechanical requirements. Consequently, simulation or structural analysis utilising specialised software has been examined to assess bond strength based on input variables including bond strength, material strength, and textural features [101].

One of the most extensively utilised methods is the finite element (FE) method, which is used to study how the shear bond properties of tack coatings affect pavement performance. A finite element modelling approach incorporated laboratory-measured bond properties to elucidate the constitutive behaviour at the interface.

Nti et al.,[102] Investigation through finite element simulation shows that the performance of tack coat materials at the interface is primarily affected by the pavement structure, with minimal differences in field stresses observed among various tack coat materials.

Numerous studies have illustrated the effects of inadequate contact bonding via FEM-based simulations. Kruntcheva et al.,[103] Demonstrated that inadequate bonding of interface conditions resulted in a 20% to 35% decrease in pavement lifespan compared to fully bonded conditions, based on assessing five interface bonding situations. Ozer et al., [104] Report that inadequate interfacial bonding raised the risk of fatigue failure and led to adverse impacts as pavement temperatures increased, based on findings from the 3-D finite element analysis. Hu & Walubita,[61] Developed a 3D finite element model to simulate fully bonded and unbonded interfacial situations. Strains for both situations were evaluated for flexible, semi-rigid, and rigid substrate materials. The study determined that bonding conditions do not substantially affect reactions at the upper layer of the wearing course. However, they significantly influence tensile strains at the lower layer of the wearing course. Li et al., [105] Used FEM to study the effects of different tack coat materials on the fatigue performance of asphalt pavements. They discovered that when the tack coat material's stiffness grew, the asphalt pavements' fatigue life decreased.

7.3 Specialised Software Tools

Alongside FEM, specialised pavement analysis software tools—such as ABAQUS, BISAR, and FlexPAVE—have been employed to evaluate interlayer bonding. These programs simulate thermal gradients, dynamic loads, and ageing effects to forecast long-term performance and structural deterioration. Utilising ABAQUS, Rahman et al.,[106] a three-dimensional (3D) pavement model. Their findings indicated that loads combined with environmental influences could lead to interface debonding or failure. Similarly, Cho et al., [107] examined how the debonding mechanism impacts the fatigue cracking behaviour of asphalt pavements through the FlexPAVE simulation program. The study revealed that debonded surface layers in asphalt could reduce the pavement structure's fatigue performance lifetime by 90%.

Furthermore, Q. Zhang et al.,[108] developed the pertinent calculation formula after performing a two-dimensional (2D) simulation of the indirect tensile test for asphalt pavement interlayers through finite-element analysis. Gong et al.,[109] Employed BISAR software to assess and compute the stress and strain of the pavement structure in response to variations in the interlayer bonding coefficient K. It was determined that when the interlayer bonding coefficient ranges from 108 N/m³ to 1012N/m³, the associated interlayer interface is completely smooth and continuous. Simultaneously, they demonstrate that alterations in the interlayer contact conditions substantially influence the stress and strain inside the pavement structure. Nian et al., [110] Introduced a finite element incremental structural computation approach that accounts for the nonlinear contact between layers, based on the current contact state of elastic layered systems. This analysis method is demonstrated to be more rational than the elastic layered system theory, which posits that the contact interface is either fully sliding or continuous.

8. Conclusion

This review emphasised the critical importance of interlayer bond strength in assuring flexible pavements' structural integrity and durability. Key aspects influencing bond performance, including tack coat type and application rate, surface condition, moisture, temperature, and aggregate texture, were thoroughly investigated. The findings show that improper bonding can cause premature failures such as slippage, rutting, and fatigue cracking, raising maintenance costs and decreasing service life.

Shear testing is still the most used approach for evaluating interface strength since it is practical and matches real-world failure scenarios. However, new insights from fatigue-based testing, non-destructive evaluations, and numerical simulations (e.g., FEM) provide a more detailed understanding of long-term performance under traffic-induced cyclic loads.

Recent improvements in machine learning and statistical modelling show promise in estimating interlayer shear strength under various field settings. At the same time, there are still gaps in incorporating variables such as tack coat ageing and application speed.

Furthermore, the review shows unresolved problems such as the lack of standardised tack coat application methods, the limited use of fatigue-based evaluation, and insufficient integration of AI models for predictive analytics. Future research should concentrate on filling these gaps by creating strong mechanistic models validated with field performance data and establishing internationally recognised testing standards that appropriately reflect real-world situations.

Practical Implications

1. Select appropriate tack coat materials based on project requirements, environmental conditions, and traffic loads.
2. The tack coat application rate should be adjusted based on the surface texture and cleanliness. Insufficient rates may cause slippage, while excessive use can create a slip plane.
3. High shear strength and properly adhesion are crucial to avert slippage and delamination, particularly in areas with higher traffic volumes and temperature variations.
4. In the process of Interface Surface Preparation, it is essential to ensure mechanical interlock; therefore, emphasis must be placed on maintaining clean, dry, and textured surfaces before application.
5. Proper moisture control and surface preparation are crucial for long-lasting pavement performance, alongside material selection.
6. Polymer-modified and trackless tack coatings are preferred in regions with high moisture or temperature variability because of their higher adhesion and water resistance.

9. Recommendations for Future Research

1. Standardise testing methods, like shear and tensile tests, to enhance comparability across studies and set minimum performance guidelines.
2. Develop field-ready evaluation tools, including non-destructive methods and fatigue testing protocols.
3. Utilise machine learning models trained on extensive datasets to predict interlayer bond strength across diverse pavement designs.
4. Assess the long-term field performance of innovative tack coat formulations under varying temperature and traffic conditions.
5. Create international guidelines for tack coat application rates considering surface roughness, age, and environmental conditions.

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