A REVIEW OF MACRO-TEXTURE EVOLUTION AND SKID RESISTANCE DEGRADATION ANALYSIS OF HIGH-SPEED BITUMINOUS WEARING COURSES

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Abstract -*The surface characteristics of high-speed bituminous wearing courses play a decisive role in ensuring traffic safety, particularly under wet operating conditions. Among these characteristics, macro-texture significantly governs water drainage capability and tire–pavement interaction, thereby influencing skid resistance performance over time. However, progressive surface wear, aggregate polishing, binder aging, and environmental exposure contribute to macro-texture evolution and consequent degradation of skid resistance. This review synthesizes existing scientific literature on the mechanisms governing macro-texture development, measurement methodologies, and the temporal deterioration of frictional properties in high-speed asphalt pavements. Emphasis is placed on commonly adopted texture parameters such as Mean Profile Depth (MPD), friction indicators obtained from British Pendulum Tester and continuous friction measuring equipment, and their reported correlations. The review critically evaluates empirical, mechanistic, and data-driven models proposed for predicting skid resistance degradation. Variability in findings due to traffic intensity, aggregate mineralogy, climatic conditions, and measurement techniques is examined to identify inconsistencies and knowledge gaps. Furthermore, advancements in non-contact laser profiling and high-speed friction measurement technologies are discussed. The study highlights the need for standardized evaluation protocols and integrated multi-scale texture analysis frameworks to enhance predictive reliability and pavement safety management strategies.*

Key Words: Macro-texture evolution; Skid resistance degradation; High-speed bituminous wearing courses; Pavement surface friction; Mean Profile Depth (MPD); Texture–friction correlation.

1. INTRODUCTION

1.1 Background and Significance

1.1.1 Importance of Macro-Texture and Skid Resistance in High-Speed Road Safety

Surface friction characteristics of bituminous wearing courses are fundamental to highway safety, particularly on high-speed corridors where braking demand and hydroplaning risk are significantly amplified. Macro-texture, defined as surface irregularities with wavelengths typically between 0.5 mm and 50 mm, plays a critical role in facilitating water drainage from the tire–pavement interface. Adequate macro-texture reduces the thickness of the water film during rainfall events, thereby improving tire contact and minimizing loss of friction (PIARC, 2012). In high-speed traffic conditions, insufficient macro-texture has been directly associated with increased wet-weather accident rates due to compromised skid resistance (Flintsch et al., 2003). Consequently, maintaining texture depth within functional thresholds is essential for ensuring pavement serviceability and road user safety.

1.1.2 Relationship Between Surface Texture and Stopping Distance at High Speeds

Stopping distance is strongly governed by the available friction force at the tire–road interface. At elevated speeds, friction demand increases nonlinearly, and the presence of water further reduces effective contact area. Macro-texture enhances hysteresis friction and promotes rapid water evacuation, thereby sustaining friction coefficients under dynamic loading (Persson, 2001). Empirical studies demonstrate that reductions in surface texture depth correlate with extended braking distances, particularly above 80 km/h, where hydrodynamic effects become dominant (Hall et al., 2009). Thus, the evolution of macro-texture over pavement life has direct implications for vehicular deceleration performance and accident prevention.

1.2 Definitions and Key Concepts

1.2.1 Macro-Texture vs Micro-Texture

Pavement surface texture is typically classified into micro-texture and macro-texture based on wavelength and amplitude characteristics. Micro-texture refers to fine-scale asperities of aggregate particles (wavelength < 0.5 mm) and primarily governs adhesion-related friction at low speeds. In contrast, macro-texture is associated with aggregate arrangement and mixture design features that influence water drainage and hysteresis effects at higher speeds (Moore, 1975). While micro-texture is highly dependent on aggregate mineralogy and polishing resistance, macro-texture is more influenced by gradation, air void structure, and compaction quality (Kane et al., 2013). Both scales interact synergistically to determine overall skid resistance performance.

1.2.2 Skid Resistance Metrics and Measurement Parameters

Skid resistance is quantified using various standardized indicators that capture frictional performance under controlled conditions. The British Pendulum Number (BPN) provides a portable assessment of surface friction, primarily reflecting micro-textural characteristics (ASTM E303, 2020). Continuous Friction Measuring Equipment (CFME), such as SCRIM and Locked-Wheel Testers, evaluates friction under dynamic conditions representative of traffic speeds (Wambold et al., 1995). Texture-related parameters, including Mean Profile Depth (MPD) obtained through laser profilometry, are widely adopted to characterize macro-texture quantitatively (ISO 13473-1, 2019). Correlative relationships between MPD and friction coefficients have been extensively investigated, although variability persists due to operational and environmental factors.

1.3.Recent Developments in Pavement Materials and Assessment Technologies

Technological progress in non-contact laser profilometry and high-speed friction testing has significantly improved measurement precision and spatial coverage. Three-dimensional texture scanning enables multi-scale surface characterization beyond traditional sand patch methods (Kogbara et al., 2016). In parallel, data-driven modelling approaches and mechanistic–empirical frameworks are increasingly employed to predict friction deterioration trends under traffic loading and climatic exposure. These developments necessitate a systematic review to evaluate methodological robustness, identify convergence in findings, and highlight areas requiring further refinement.

1.4 Objectives and Scope of the Review

This review aims to critically synthesize existing literature on the evolution of macro-texture and its influence on skid resistance degradation in high-speed bituminous wearing courses. Specifically, it examines: (i) mechanisms governing texture alteration under traffic and environmental actions; (ii) measurement techniques and texture–friction correlations; (iii) degradation modelling approaches; and (iv) technological advancements in monitoring systems. The scope is confined to peer-reviewed studies focusing on asphalt-based wearing surfaces subjected to high-speed traffic conditions. Experimental results are discussed comparatively rather than presented as original research findings. Through structured analysis, the review seeks to identify knowledge gaps and propose directions for improved predictive and maintenance frameworks.

2. METHODOLOGY OF LITERATURE SELECTION

2.1 Search Strategy

2.1.1 Database Selection

A systematic and structured literature search was conducted to ensure comprehensive coverage of scholarly contributions related to macro-texture evolution and skid resistance degradation in high-speed bituminous wearing courses. Major bibliographic databases including Web of Science, Scopus, and Google Scholar were selected due to their extensive indexing of peer-reviewed journals in pavement engineering and transportation infrastructure. These platforms are widely recognized for their reliability in systematic reviews and bibliometric analyses (Mongeon and Paul-Hus, 2016). The selection of multiple databases minimized publication bias and enhanced retrieval of interdisciplinary studies encompassing materials science, highway engineering, and surface characterization technologies.

2.1.2 Time Span of Literature Coverage (1990–2025)

The review considered publications from 1990 to 2025 to capture the evolution of pavement texture research over approximately three decades. The early 1990s marked the increasing adoption of mechanistic friction analysis and improved texture measurement techniques, while the post-2000 period reflects advancements in laser profilometry and high-speed friction testing technologies. Including recent literature ensures incorporation of developments in digital surface characterization and predictive modelling approaches. Temporal coverage across this span enables assessment of long-term research trends and methodological shifts in pavement surface evaluation (Tranfield, Denyer and Smart, 2003).

2.2 Inclusion and Exclusion Criteria

2.2.1 Types of Publications Considered

The review primarily included peer-reviewed SCI-indexed journal articles to ensure methodological rigor and academic reliability. Key journals in pavement engineering, materials science, and transportation safety were prioritized. Additionally, relevant international standards (e.g., ASTM, ISO) and selected high-impact conference proceedings were included where they contributed foundational knowledge on measurement techniques or standardized procedures. Non-peer-reviewed reports, unpublished theses, and opinion-based articles were excluded to maintain scientific credibility and consistency in evidence synthesis.

2.2.2 Keywords and Search Strings

Structured keyword combinations were employed using Boolean operators to refine search results. Primary keywords included: “macro-texture evolution,” “skid resistance degradation," "bituminous wearing course," "Mean Profile Depth (MPD)," "pavement friction," and "high-speed asphalt surface." These were combined using logical connectors such as AND/OR to improve retrieval specificity. The development of keyword clusters followed established systematic review protocols to enhance transparency and reproducibility (Kitchenham and Charters, 2007). Synonyms and related technical terms were incorporated to account for terminological variation across regions and disciplines.

2.2.3 Language and Quality Filters

Only articles published in English were considered to ensure consistency in interpretation and analysis. Quality filtering involved screening for journal impact, citation frequency, and methodological clarity. Studies lacking clear experimental procedures, measurement descriptions, or statistical validation were excluded. Duplicate records across databases were removed during the screening stage. Abstract and full-text reviews were conducted sequentially to confirm thematic relevance to macro-texture and skid resistance relationships.

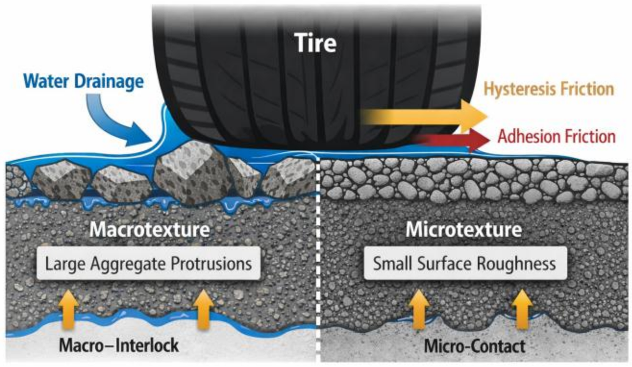
3. FUNDAMENTAL CONCEPTS

3.1 Pavement Surface Texture

3.1.1 Classification: Micro, Macro and Mega Texture

Pavement surface texture is a multi-scale characteristic that significantly influences tire–pavement interaction and hydraulic behaviour. It is commonly classified into micro-texture, macro-texture, and mega-texture based on wavelength ranges. Micro-texture (wavelength < 0.5 mm) corresponds to the fine asperities of aggregate particles and primarily governs adhesion-related friction at low speeds. Macro-texture (0.5 mm–50 mm) arises from aggregate arrangement and mixture structure, controlling hysteresis friction and water drainage capacity. Mega-texture (50 mm–500 mm) relates to surface irregularities associated with construction practices or surface distress, influencing ride quality and dynamic loading (PIARC, 2012). This hierarchical classification enables functional interpretation of texture effects across varying traffic speeds and environmental conditions.

The interaction between these texture scales is not independent; rather, they operate synergistically. While micro-texture contributes to direct rubber adhesion, macro-texture facilitates rapid water escape and enhances contact under wet conditions. Mega-texture, although less directly linked to friction generation, may affect vehicle stability at very high speeds due to induced vibrations (Hall et al., 2009).



Schematic illustration showing the difference between microtexture and macrotexture at the tire-pavement interface.

Figure 1 — Microtexture vs Macrotexture Schematic

3.1.2 Measurement Scales and Units

Texture characterization is performed using both volumetric and profile-based measurement techniques. Traditional volumetric approaches such as the sand patch test provide Mean Texture Depth (MTD), expressed in millimetres. Modern laser-based profilometers measure Mean Profile Depth (MPD), a standardized macro-texture indicator derived from longitudinal surface profiles (ISO 13473-1, 2019). Three-dimensional scanning systems further enable areal texture parameters, offering enhanced resolution and repeatability compared to manual methods. Measurement scale selection depends on functional requirements; macro-texture parameters are particularly critical for high-speed pavements due to their influence on drainage efficiency and hydrodynamic pressure distribution.

3.2 Skid Resistance and Friction

3.2.1 Definition of Skid Resistance

Skid resistance refers to the ability of a pavement surface to develop sufficient frictional force to resist sliding of vehicle tires under braking or cornering manoeuvres. It is a dynamic property influenced by surface texture, tire characteristics, speed, temperature, and moisture conditions. From a tribological perspective, pavement friction consists of adhesion and hysteresis components, with their relative contributions varying according to surface roughness scale and operational speed (Persson, 2001). At higher speeds, hysteresis friction associated with macro-texture becomes increasingly dominant due to deformation of the tire tread over surface asperities.

Skid resistance is therefore not a static material property but a system-level response governed by tire–pavement–environment interaction. Its degradation over time is typically associated with aggregate polishing, binder wear, and traffic-induced surface smoothing.

3.2.2 Measurement Methods

Various standardized devices are employed to quantify skid resistance under controlled conditions. The British Pendulum Tester (BPT) measures friction at low speeds and provides the British Pendulum Number (BPN), primarily reflecting micro-textural properties (ASTM E303, 2020). For network-level assessment at operational speeds, Sideway-force Coefficient Routine Investigation Machine (SCRIM) evaluates friction under continuous motion, offering representative field performance data (Wambold et al., 1995). The Locked-Wheel Skid Tester simulates emergency braking conditions by measuring friction at a specified slip ratio, widely used in highway performance monitoring. The Dynamic Friction Tester (DFT) measures friction across variable rotational speeds, allowing characterization of speed-dependent friction curves.

Each method captures distinct aspects of the friction mechanism, and discrepancies between results may arise due to differences in test speed, slip conditions, and water application rates. Consequently, harmonization of friction indicators remains a continuing challenge in pavement performance evaluation.

3.3 High-Speed Bituminous Wearing Courses

3.3.1 Composition and Typical Materials

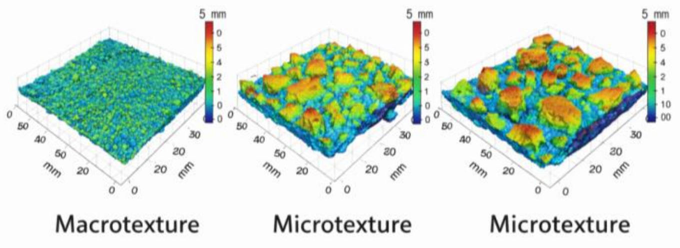
High-speed bituminous wearing courses are engineered asphalt mixtures designed to withstand heavy traffic loading while maintaining adequate surface friction and durability. Typical compositions include dense-graded asphalt concrete (AC), stone mastic asphalt (SMA), and open-graded friction courses (OGFC). These mixtures consist of mineral aggregates, bituminous binders (often polymer-modified), mineral fillers, and air void structures optimized for structural and functional performance (Roberts et al., 1996). Aggregate mineralogy and gradation significantly influence both macro-texture formation and resistance to polishing.

Polymer-modified binders enhance rutting resistance and durability, whereas gap-graded mixtures such as SMA promote stone-on-stone contact, contributing to improved macro-texture retention. Open-graded surfaces facilitate superior drainage but may exhibit different long-term texture evolution patterns.

3.3.2 Characteristics Relevant to Surface Texture and Friction

The functional performance of high-speed wearing courses depends on structural integrity, aggregate interlock, and resistance to surface wear. Macro-texture is strongly affected by aggregate size distribution, compaction level, and binder content. Over time, traffic loading may cause aggregate embedment or polishing, leading to reduced texture depth and frictional performance. Environmental factors such as temperature fluctuations and oxidation further influence binder stiffness and aggregate exposure (Kane et al., 2013).

For high-speed highways, optimal balance between durability and surface roughness is critical. Excessively smooth surfaces increase hydroplaning risk, whereas overly rough surfaces may generate noise and vibration issues. Therefore, mixture design and maintenance strategies must consider long-term macro-texture stability to sustain skid resistance throughout the pavement service life.



Laser-scanned surfaces of different asphalt pavement textures showing spatial variation in macrotexture morphology.
Source: Laser scanning images of textured asphalt surfaces.

Figure-2: Pavement Texture 3D Scan Example

4. MACRO-TEXTURE EVOLUTION OF BITUMINOUS SURFACES

4.1 Mechanisms of Texture Change

Macro-texture evolution in bituminous wearing courses is governed by mechanical, material, and environmental processes acting simultaneously over the pavement service life. These mechanisms alter aggregate exposure, surface morphology, and void structure, ultimately affecting hydraulic conductivity and frictional response.

4.1.1 Traffic Loading

Traffic loading is the primary driver of macro-texture modification. Repeated wheel passes induce abrasion, aggregate rearrangement, and localized compaction, particularly in high-volume corridors. Under heavy axle loads, aggregate particles may undergo micro-fracture or embedment into the binder matrix, reducing effective surface protrusion and texture depth. Shear stresses at the tire–pavement interface also promote surface smoothing over time (Flintsch et al., 2003). The rate of texture reduction is strongly correlated with cumulative Equivalent Single Axle Loads (ESALs), with accelerated degradation observed in slow lanes and braking zones.

4.1.2 Aggregate Polishing

Aggregate polishing is a progressive reduction in surface roughness caused by mechanical abrasion from tire contact.

The polishing resistance of aggregates depends on mineral hardness, angularity, and petrographic composition. Siliceous aggregates typically exhibit better long-term resistance compared to softer calcareous materials. As polishing progresses, micro-texture diminishes first, followed by gradual macro-texture alteration due to smoothing of exposed aggregate surfaces (Kane et al., 2013). This phenomenon significantly reduces friction under wet conditions, where adhesion components become limited.

4.1.3 Binder Degradation and Oxidative Hardening

Bituminous binders undergo oxidative aging due to exposure to oxygen, ultraviolet radiation, and thermal cycles. Oxidative hardening increases binder stiffness, potentially leading to micro-cracking and raveling at the surface. Over time, binder film thinning and aggregate debonding may occur, modifying surface morphology and contributing to texture variability (Petersen, 2009). While binder aging can initially increase aggregate exposure due to stiffening, long-term deterioration often results in material loss and surface irregularities that alter macro-texture characteristics.

4.1.4 Environmental and Climatic Influences

Environmental conditions significantly influence macro-texture stability. Temperature fluctuations induce thermal stresses and expansion–contraction cycles, affecting binder–aggregate adhesion. In colder climates, freeze–thaw cycles promote surface scaling and micro-cracking, whereas high-temperature regions may experience accelerated binder softening and rutting. Moisture infiltration further exacerbates stripping and surface wear. Climatic exposure, combined with traffic action, creates region-specific patterns of texture evolution (Al-Qadi et al., 2008). Therefore, macro-texture degradation cannot be fully understood without considering environmental context.

4.2 Texture Parameters and Indicators

Quantitative evaluation of macro-texture requires reliable surface characterization parameters that reflect functional performance.

4.2.1 Mean Profile Depth (MPD)

Mean Profile Depth (MPD) is one of the most widely adopted macro-texture indicators derived from longitudinal surface profiles. It is calculated from high-resolution laser measurements over standardized sampling lengths and expressed in millimetres. MPD provides improved repeatability compared to volumetric sand patch methods and is standardized under ISO 13473-1 (2019). Numerous studies have demonstrated significant correlation between MPD and wet friction performance at high speeds, making it a critical parameter in pavement management systems.

4.2.2 RT, RMS and Other Texture Metrics

Beyond MPD, additional statistical parameters such as Root Mean Square (RMS) height, texture roughness index (RT), and skewness descriptors are used to characterize surface morphology. RMS values represent the standard deviation of surface elevation data and provide information about amplitude variability. These metrics enable multi-dimensional interpretation of texture structure, particularly when using three-dimensional surface mapping techniques (Kogbara et al., 2016). Although MPD remains dominant for network-level evaluation, advanced metrics facilitate deeper understanding of texture distribution and degradation patterns.

4.2.3 Laser Scanning and Profilometry Methods

Modern texture assessment relies heavily on non-contact laser profilometers capable of high-speed data acquisition. These systems generate continuous surface profiles and allow computation of standardized parameters under operational traffic speeds. Three-dimensional laser scanners further enable areal texture analysis, overcoming limitations of traditional line-based measurements. Compared to manual sand patch testing, laser methods provide higher spatial resolution, improved safety, and better reproducibility (PIARC, 2012). However, data interpretation requires careful filtering and calibration to ensure consistency across equipment types.

4.3 Time-Dependent Texture Evolution

Macro-texture is not static but evolves dynamically under cumulative mechanical and environmental influences.

4.3.1 Patterns Observed in Long-Term Field Studies

Longitudinal field investigations reveal that macro-texture typically experiences an initial stabilization phase following construction, followed by gradual decline due to polishing and wear. In some cases, early-life densification may slightly reduce texture depth before equilibrium is reached. Subsequent degradation often follows nonlinear trends, influenced by traffic growth and mixture characteristics (Hall et al., 2009). Certain open-graded surfaces demonstrate relatively stable macro-texture retention compared to dense-graded mixtures, though they may be susceptible to clogging effects over time.

4.3.2 Effects of Pavement Age and Traffic Intensity

Pavement age and traffic intensity are strongly associated with macro-texture reduction rates. Higher traffic volumes accelerate aggregate polishing and structural rearrangement, leading to measurable decreases in MPD values within the first few service years. Conversely, low-volume roads often retain texture characteristics for extended periods. Empirical analyses indicate that degradation curves are influenced by cumulative load repetitions rather than chronological age alone (Flintsch et al., 2003). Therefore, predictive models must integrate traffic loading parameters alongside environmental variables to accurately estimate long-term macro-texture performance.

5. SKID RESISTANCE DEGRADATION ANALYSIS

5.1 Relationship Between Macro-Texture and Skid Resistance

The interaction between pavement surface texture and tire rubber governs the frictional performance of bituminous wearing courses. While micro-texture controls adhesion at low speeds, macro-texture becomes increasingly significant under high-speed and wet conditions.

5.1.1 Theoretical Foundations

From a tribological perspective, pavement friction comprises adhesion and hysteresis components. Adhesion arises from molecular bonding between tire rubber and aggregate asperities, whereas hysteresis friction is generated through viscoelastic deformation of rubber over surface irregularities (Persson, 2001). At higher speeds, the presence of water reduces adhesive contact, and macro-texture facilitates drainage, limiting hydrodynamic lift and maintaining effective contact area. Theoretical models of tire–pavement interaction indicate that insufficient macro-texture increases water film thickness, thereby reducing available friction and elevating hydroplaning risk (PIARC, 2012). Consequently, macro-texture is functionally linked to friction sustainability under dynamic loading.

5.1.2 Empirical Correlations Reported

Numerous field investigations have quantified correlations between macro-texture indicators, such as Mean Profile Depth (MPD), and measured friction coefficients. Studies report positive relationships between MPD and high-speed friction values, particularly under wet testing conditions (Flintsch et al., 2003). However, the strength of correlation varies depending on traffic speed, testing device, and surface condition. Some researchers observe nonlinear behaviour, where friction improvement plateaus beyond a threshold texture depth (Hall et al., 2009). These empirical findings highlight that macro-texture is a necessary but not independently sufficient predictor of skid resistance.

5.2 Skid Resistance Measurement Techniques

Accurate evaluation of skid resistance requires standardized measurement systems capable of simulating real traffic conditions.

5.2.1 Portable Devices

Portable devices, such as the British Pendulum Tester (BPT), provide rapid point-based assessment of surface friction. The British Pendulum Number (BPN) reflects low-speed friction characteristics and is particularly sensitive to micro-texture properties (ASTM E303, 2020). Although widely used for spot evaluations and laboratory specimens, portable devices may not fully represent friction performance at highway speeds. Their advantages include simplicity, cost-effectiveness, and minimal operational requirements.

5.2.2 High-Speed Continuous Friction Measuring Equipment (CFME)

Continuous Friction Measuring Equipment (CFME), including SCRIM and locked-wheel testers, evaluates friction under operational speeds and controlled slip conditions. These systems provide network-level data and enable spatial variability analysis along highway sections (Wambold et al., 1995). Compared to portable devices, CFME better captures macro-texture effects under wet conditions. However, differences in slip ratio, tire type, and water application protocols can produce variability between measurement systems, necessitating calibration and harmonization procedures.

5.3 Factors Affecting Skid Resistance Degradation

Skid resistance degradation is influenced by material characteristics, environmental exposure, and mechanical distress mechanisms.

5.3.1 Polishing Resistance of Aggregates

Aggregate mineralogy plays a critical role in long-term friction retention. Hard, angular aggregates with high polishing resistance maintain surface roughness over extended traffic exposure, whereas softer aggregates tend to smooth rapidly. Polishing reduces micro-texture first, followed by gradual reduction in macro-texture contribution to friction (Kane et al., 2013). Laboratory polishing tests and petrographic analysis are often used to evaluate aggregate suitability for high-speed pavements.

5.3.2 Environmental Interaction

Moisture and temperature significantly affect frictional behaviour. Under wet conditions, water acts as a lubricant, reducing adhesion and amplifying the importance of macro-texture. Elevated temperatures may soften the binder, potentially leading to aggregate embedment and surface smoothing. Conversely, freeze–thaw cycles can induce micro-cracking and surface scaling, altering texture morphology (Al-Qadi et al., 2008). Environmental exposure thus accelerates degradation processes and modifies friction performance seasonally.

5.3.3 Surface Wear Modes

Mechanical wear mechanisms such as abrasion, cracking, and raveling directly alter surface morphology. Abrasion caused by tire contact progressively smooths aggregate surfaces. Cracking and raveling may initially increase surface roughness but eventually lead to material loss and structural deterioration. These distress modes interact with traffic intensity and mixture design, influencing the rate and pattern of skid resistance decline (Roberts et al., 1996).

5.4 Temporal Trends in Skid Resistance

Skid resistance evolves over the pavement life cycle and is typically characterized by an initial period of adjustment followed by gradual decline.

5.4.1 Longitudinal Monitoring Studies

Long-term monitoring programs indicate that skid resistance often decreases rapidly during the early service period due to aggregate polishing, then stabilizes before declining again as structural wear progresses (Hall et al., 2009). High-traffic sections exhibit faster degradation rates compared to low-volume roads. Seasonal fluctuations are also reported, with lower friction observed during wet or high-temperature periods.

5.4.2 Statistical and Empirical Degradation Models

Various statistical and empirical models have been proposed to predict friction decline over time. Regression-based models frequently relate friction coefficients to cumulative traffic loading, age, and environmental variables. Mechanistic–empirical approaches incorporate texture evolution parameters to enhance predictive capability (Flintsch et al., 2003). Although these models demonstrate reasonable accuracy within specific datasets, generalization across regions remains challenging due to variability in materials and climate.

5.5 Comparative Evaluation of Findings

5.5.1 Similarities and Discrepancies in Reported Degradation Rates

Comparative analysis of published studies reveals consistent agreement that traffic loading and aggregate polishing are primary drivers of friction decline. However, reported degradation rates vary substantially. Some investigations indicate rapid early-life friction loss, whereas others observe more gradual trends. Differences in testing methodologies, climatic exposure, mixture types, and traffic compositions contribute to these discrepancies (PIARC, 2012).

5.5.2 Possible Reasons for Variation

Variability in findings can be attributed to inconsistencies in measurement equipment calibration, slip ratios, and water application rates. Regional differences in aggregate mineralogy and maintenance practices further influence outcomes. Additionally, the absence of standardized macro-texture thresholds across jurisdictions complicates cross-study comparisons. These variations highlight the necessity for harmonized testing frameworks and multi-parameter analysis to improve predictive reliability.

6. MODELING AND PREDICTION APPROACHES

Predictive modeling of macro-texture evolution and skid resistance degradation is essential for pavement management systems and safety-based maintenance planning. Over the past decades, approaches have evolved from simple empirical regressions to mechanistic–empirical frameworks and, more recently, data-driven analytical techniques.

6.1 Empirical Models

6.1.1 Regression and Curve-Fitting Approaches

Empirical models represent the earliest and most widely adopted methods for predicting skid resistance degradation. These models typically employ regression analysis to relate friction indicators (e.g., friction number or sideway-force coefficient) to explanatory variables such as pavement age, cumulative traffic loading, and initial texture depth. Linear, exponential, and logarithmic decay functions are commonly used to describe friction reduction trends (Flintsch et al., 2003).

Curve-fitting approaches are particularly useful for network-level performance forecasting, where large datasets are available from routine monitoring. However, empirical models are inherently site-specific and rely heavily on calibration datasets. Their predictive accuracy diminishes when extrapolated beyond the original environmental or material conditions. Despite these limitations, empirical formulations remain practical tools in pavement management systems due to their simplicity and ease of implementation.

6.2 Mechanistic–Empirical Models

6.2.1 Theoretical and Physics-Based Explanations

Mechanistic–empirical (M–E) models integrate physical principles governing tire–pavement interaction with statistically calibrated parameters. These approaches consider tribological mechanisms such as adhesion and hysteresis friction, viscoelastic deformation of rubber, and hydrodynamic pressure effects under wet conditions (Persson, 2001). By incorporating macro-texture parameters such as Mean Profile Depth (MPD) into theoretical friction formulations, M–E models aim to provide more generalized predictive capability.

Such models often include traffic-induced polishing rates, aggregate mineral hardness, and environmental exposure as mechanistic inputs. Compared to purely empirical regressions, mechanistic–empirical approaches offer improved interpretability and transferability. Nevertheless, accurate calibration requires comprehensive field data, and the complexity of tire–pavement interactions introduces uncertainties in parameter estimation (Hall et al., 2009).

6.3 Machine Learning and Advanced Analytics

6.3.1 Data-Driven Prediction Methods

With the expansion of high-resolution surface monitoring and continuous friction measurement systems, large datasets have become available for advanced analytical modeling. Machine-learning algorithms—including Artificial Neural Networks (ANN), Support Vector Machines (SVM), and Random Forest models—have been explored for predicting skid resistance based on multi-parameter inputs such as texture metrics, traffic intensity, and climatic variables (Kogbara et al., 2016).

Data-driven models can capture nonlinear relationships that traditional regression methods may fail to identify. They are particularly advantageous when handling high-dimensional datasets derived from laser scanning technologies. However, their effectiveness depends strongly on dataset quality, feature selection, and model training protocols.

6.3.2 Prospects and Limitations

The primary advantage of machine-learning approaches lies in their ability to improve predictive accuracy through adaptive learning. They can integrate multi-scale texture descriptors and real-time monitoring data for proactive pavement maintenance strategies. However, these models often function as "black boxes," limiting physical interpretability. Additionally, overfitting risks and lack of standardized validation frameworks remain critical challenges. Broader adoption requires transparent reporting of model architecture, validation procedures, and cross-regional testing.

6.4 Critical Assessment of Models

6.4.1 Performance Evaluation

Model performance is typically evaluated using statistical indicators such as coefficient of determination (R^2), root mean square error (RMSE), and mean absolute percentage error (MAPE). Empirical models generally provide acceptable short-term predictions within calibrated conditions, whereas mechanistic–empirical models demonstrate improved conceptual robustness. Machine-learning models frequently achieve higher predictive accuracy but require extensive datasets for stable generalization (PIARC, 2012).

Comparative studies suggest that no single modeling approach is universally superior; effectiveness depends on data availability, required prediction horizon, and practical implementation constraints.

6.4.2 Areas Requiring Improvement

Despite considerable progress, several gaps remain in predictive modeling of macro-texture and skid resistance degradation. First, integration of multi-scale texture parameters into unified modeling frameworks is limited. Second, long-term datasets capturing combined traffic and environmental effects are insufficient in many regions. Third, harmonization of friction measurement standards is needed to improve model transferability across jurisdictions. Future research should emphasize hybrid modeling approaches that combine mechanistic understanding with data-driven adaptability to enhance predictive reliability and operational applicability.

7.CONCLUSION

This review critically synthesizes existing literature on macro-texture evolution and skid resistance degradation in high-speed bituminous wearing courses, highlighting their interdependent roles in pavement safety performance. The findings confirm that macro-texture is a decisive factor in maintaining adequate friction under high-speed and wet conditions, primarily through enhanced water drainage and hysteresis-based friction mechanisms. Traffic loading, aggregate polishing, binder aging, and environmental exposure collectively govern texture modification over the pavement life cycle. While empirical studies consistently demonstrate a positive correlation between texture depth indicators—such as Mean Profile Depth (MPD)—and high-speed friction performance, variability persists due to differences in materials, climate, and testing methodologies.

Advancements in laser-based profilometry and continuous friction measuring systems have improved the accuracy and spatial coverage of surface characterization. Moreover, predictive modeling approaches have evolved from regression-based empirical formulations to mechanistic–empirical and data-driven frameworks. However, inconsistencies in measurement protocols and limited long-term datasets constrain model generalization across regions. The review underscores the need for standardized evaluation procedures, integration of multi-scale texture descriptors, and hybrid predictive models that combine physical understanding with advanced analytics. A comprehensive and harmonized approach to texture and friction monitoring is essential to enhance safety management strategies for high-speed asphalt pavements.

8.LIMITATIONS OF THE REVIEW

This review is limited to English-language publications and primarily focuses on peer-reviewed journal articles, potentially excluding relevant regional studies or technical reports. Variability in friction measurement equipment and reporting formats across jurisdictions restricts direct quantitative comparison of degradation rates. Additionally, the synthesis relies on published datasets without independent validation, and differences in climatic and material conditions may influence generalizability of conclusions. Emerging machine-learning applications were discussed conceptually due to limited long-term field validation studies. Future reviews incorporating meta-analytical techniques and broader multilingual databases could provide more comprehensive global insights.

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