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ABSTRACT

Slip-related injuries and vehicle skids in low-friction environments highlight the urgent need for advanced anti-slip materials to improve safety and prevent accidents. This review summarizes the fundamental mechanisms of slipping, drawing on contact mechanics and a proposed friction behavior model for surface interfaces. Strategies to enhance anti-slip performance such as surface texturing, chemical modification, and filler incorporation are discussed. Standardized evaluation methods, including friction testing, the British Pendulum Test, and the ramp test, are reviewed alongside other common assessment techniques. The practical applications of anti-slip materials are explored, with emphasis on high-risk areas like roadways and winter footwear. Challenges in achieving durable, high-performance solutions are outlined, and future research directions are suggested. By integrating current advancements and practical considerations, this review supports the development of next-generation anti-slip systems aimed at enhancing safety and functionality across diverse applications.

1 | Introduction

Anti-slip materials are crucial in enhancing safety and reducing accidents across various environments by improving traction and preventing slipping. Slip-and-fall is the second most common cause of fatal work-related injuries, the third most common nonfatal workplace injury, and among older adults remains the leading cause of both fatal and nonfatal injuries [1]. Additionally, between 1994 and 2012, approximately 16% of all annual fatal vehicle crashes in the U.S. were attributed to adverse weather conditions and vehicles skidding. Among these, rain was responsible for more fatalities than snow or ice, although icy conditions notably increased crash risk during the winter months [2]. In the context of road safety, particularly in wet and icy conditions, the importance of anti-slip materials becomes even more pronounced. Skid resistance- the force that occurs when a tire and pavement interact while the tire is not rotating- is a key factor in preventing accidents [3, 4]. Studies indicate that approximately 20% of all accidents occur in wet or icy conditions, with the slipperiness of wet roads playing a significant role in these incidents. This underscores the necessity for materials that enhance the anti-slip properties of road surfaces, thereby improving safety for all road users [5, 6]. In addition to road safety, the risk of slipping on inclined icy surfaces remains a common cause of accidents and injuries. To prevent such incidents, the development and utilization of modified materials for tires and shoe soles have been proposed as effective measures. This approach aims to enhance traction and reduce the likelihood of slips in hazardous conditions [7].

In industrial environments, anti-slip coatings are essential for improving safety on surfaces like walkways, decks, and areas around heavy equipment where slipping risks are high. Their main purpose is to prevent accidents, especially in wet, oily, or icy conditions [8]. In structural systems, anti-slip features also help maintain stability, such as in prestressed cable structures where the grip of steel clamps depends on surface treatments and bolt tension [9]. These materials also improve reliability in mechanical systems; bio-inspired crimping structures, for instance, help hoses stay securely connected under pressure [10]. In cold and harsh environments, anti-slip solutions like insulation, heated surfaces, and protective gear help reduce temperature-related slipping risks [11]. Anti-slip materials can help mitigate these risks by incorporating advanced surface designs and innovative strategies. Their application is vital in meeting safety standards, preventing injuries, and maintaining an efficient working environment in numerous sectors [12, 13]. Following section focuses on the physical concepts behind the slipping phenomenon viewed through the lens of contact mechanics. By understanding how surfaces interact to initiate slipping and identifying the key parameters at the interface, we can better focus on enhancing the performance of anti-slip materials in real-world applications.

Slipping is governed by complex physical mechanisms involving multiple interactions at the interface of contacting materials. In the design of anti-slip materials, it is crucial to leverage these mechanisms effectively to enhance grip and reduce slippage. This review provides a mechanism-based framework, organizing anti-slip strategies by their underlying physical principles and contact mechanics concepts rather than by application alone. We explore key approaches, including surface texturing, chemical treatments, and filler incorporation. Techniques such as laser patterning, biomimetic designs, surface grooving, and multi-scale texturing are highlighted for their demonstrated improvements in slip resistance.

To support the design and evaluation of these materials, we consolidate common test methods and provide comparative insights into their applicability, strengths, and limitations. The review also highlights a wide range of applications, from everyday uses to industrial and construction environments, including pavements, road coatings, flooring systems, and winter footwear. Finally, we address the challenges of designing anti-slip surfaces for high-traffic areas and outline future research directions, such as hybrid designs, adaptive surfaces, and sustainable materials. Through this comprehensive analysis, the paper aims to provide a deep understanding of the strategies and considerations involved in the development, evaluation, and application of anti-slip materials, ultimately contributing to safer and more reliable solutions for preventing slips, trips, and falls. Figure 1 presents an overview of the topics discussed in this review.

FIGURE 1 | Schematic representation of the structure of this review, providing a comprehensive overview of material-based strategies toward anti-slip purposes.

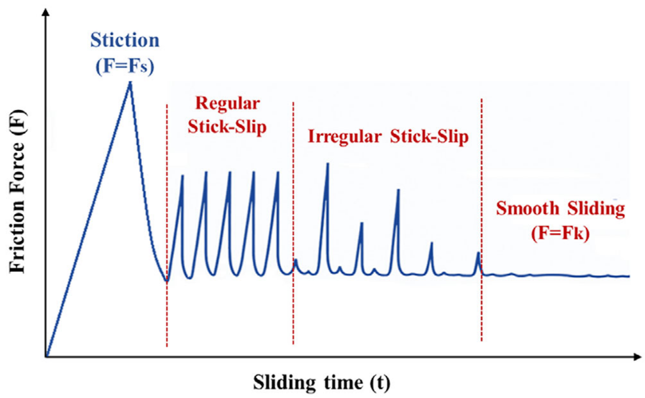


FIGURE 2 | Schematic representation of a typical friction force evolution in time, showing the different phases of friction during sliding.

2 | Contact Mechanics and Sliding Friction

Slipping in physics occurs when the frictional force between two surfaces becomes insufficient to prevent relative motion, resulting in sliding. This highlights the need to understand the interfacial interactions and frictional mechanisms that govern the transition from static to kinetic friction. Macroscopic frictional behavior has traditionally been described by Amontons' laws [14]. In their classical form, these laws state: (1) the frictional force Ff is proportional to the normal load N, such that Ff = μN, where μ is the coefficient of friction (COF); and (2) this frictional force is independent of the apparent contact area. These laws imply a constant coefficient of friction (μ) that is independent of sliding speed and other dynamic variables for a given material pairing. However, in reality, μ is not an intrinsic material constant but rather a system-dependent parameter influenced by surface conditions, material pairing, contact history, and kinematics [15]. One critical distinction often observed in practice is that the maximum static friction, the threshold required to initiate slip, generally exceeds the kinetic friction, which is the force required to maintain motion [16]. This arises from the formation of strong interfacial bonds during stationary contact, which require additional force to break. Once sliding begins, these bonds continually form and rupture, resulting in a slightly reduced and more stable kinetic friction. This difference leads to the phenomenon of stick–slip motion, where alternating periods of sticking and sudden sliding occur, especially in systems with elastic components and insufficient damping. The diagram in Figure 2 illustrates how the friction force evolves over sliding time, depicting different phases of friction behavior [17]. It begins with stiction, during which the friction force rises until it reaches the peak of static friction (Fs). Once this threshold is overcome, the system enters a phase of regular stick–slip, characterized by periodic cycles of force build-up and sudden release as the interface alternates between sticking and slipping. As sliding continues, the friction behavior becomes less uniform, transitioning into irregular stick–slip, with fluctuations in force becoming smaller and less predictable. Eventually, the system reaches a state of smooth sliding, where the friction force stabilizes at a constant kinetic friction level (Fk) [17]. This progression from static friction through stick–slip to steady-state sliding is commonly observed in tribological systems and reflects the complex interplay of interfacial shear strength and sliding dynamics. While some deformation effects are described, they are considered in terms of their contribution to friction and anti-slip performance, not as wear processes.

At the microscopic scale, friction arises from the interactions between tiny contact points—known as asperities—where surfaces touch. No surface is perfectly smooth; even highly polished materials have minute topographical irregularities. Consequently, the true contact area is only a small fraction of the apparent, or nominal, contact area [18]. Seminal studies by Bowden and Tabor [19] revealed that the real contact area increases approximately linearly with the applied normal load, as asperities undergo plastic or elastic deformation to form load-bearing micro-junctions. Each junction sustains a shear force proportional to its area, characterized by an interfacial shear strength. Consequently, the total friction force can be modelled as the summation of shear forces across all these micro-contacts, yielding a friction force that scales with the real contact area. Contact mechanics provides the theoretical foundation for analysing the deformation behavior of asperities under load [20]. For ideally smooth and linearly elastic solids, Hertzian theory describes the contact between two curved bodies. In the case of a sphere of radius R pressed into a flat surface with a normal load W, the resulting contact area is circular, with radius a given by [21]:

$$a^3 = \frac{3WR}{4E} \tag{1}$$

where E is the effective elastic modulus of the contacting bodies. The contact area increases sub-linearly with the applied load, aligning with empirical observations from asperity models. Within this contact patch, the normal pressure distribution is typically parabolic (maximum at the center), and any applied tangential force introduces interfacial shear stresses [22]. As shown by Mindlin's solution [23] for tangential loading, small tangential forces are accommodated via elastic deformation in a partial slip regime. This means that most of the contact area remains in a "stick" state while a peripheral annulus undergoes microslip [22]. This phenomenon occurs because the local tangential stress exceeds the shear limit at the edges before the core, creating a ring of slip around a central stick region. As the tangential force increases, this slip zone gradually expands inward until full sliding occurs [24]. At this point, the tangential stress across the entire contact area exceeds the local shear strength, leading to gross (full) sliding. The static friction force (Q_s) can thus be estimated as [25]:

$$Qs \approx Areal \cdot \tau \tag{2}$$

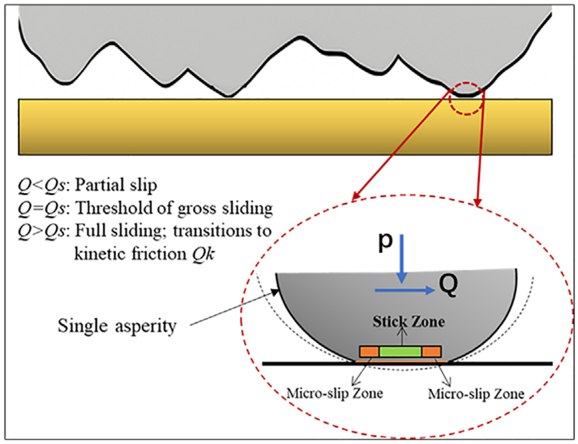


FIGURE 3 | Idealized schematic of a single asperity under normal load (P) and external tangential load (Q); Stick-slip transition (Q_s: Threshold static friction force Q_k: kinetic friction force).

where τ is the interfacial shear strength, and Areal is the real contact area. This model provides valuable insights into stick–slip dynamics, which implies that if the system surpasses Q_s, a sudden drop to the kinetic friction force (Q_k) arises, allowing the interface to re-stick until the force rebuilds, thereby causing oscillatory motion. Figure 3 shows the schematic of a single asperity under normal load P and tangential load Q. The contact area supports elastic shear deformation up to a threshold. As Q increases, a micro-slip zone emerges at the periphery. Upon reaching the static friction limit, gross sliding propagates across the contact. This behavior, when extended to a rough surface comprising many such asperities, governs the transition from stick to slip [26]. Conversely, when asperities undergo plastic deformation, a "ploughing" effect adds to the overall friction. In this scenario, energy is dissipated both through interfacial shear and the deformation of the surface material itself. Harder materials typically show lower friction because their limited real contact area reduces adhesion, while softer materials deform more readily, increasing contact and resistance to sliding [27, 28].

Asperities, which are central to slip-related friction mechanisms, have been examined. Closely related yet distinct is surface roughness, another factor that strongly influences frictional behavior at an interface. While asperities refer to the individual microscopic peaks that make actual contact between surfaces, surface roughness describes the overall surface texture, quantified through standardized parameters. For instance, the arithmetic average roughness (R_a) provides a general measure of a surface's smoothness, whereas the average maximum height of the roughness profile (R_z) captures the height difference between the highest peaks and lowest valleys. This makes R_z particularly valuable for assessing surface characteristics that directly affect functional performance, such as friction and wear [29].

The influence of the roughness parameters on friction behavior can be two-fold, depending on the dominant interaction mechanism. On one hand, increasing microscale roughness (e.g., higher R_a values) can reduce the real contact area and diminish molecular adhesion, thereby lowering friction, especially in clean, dry, or adhesion-sensitive interfaces [30]. On the other hand, moderate or controlled roughness can enhance

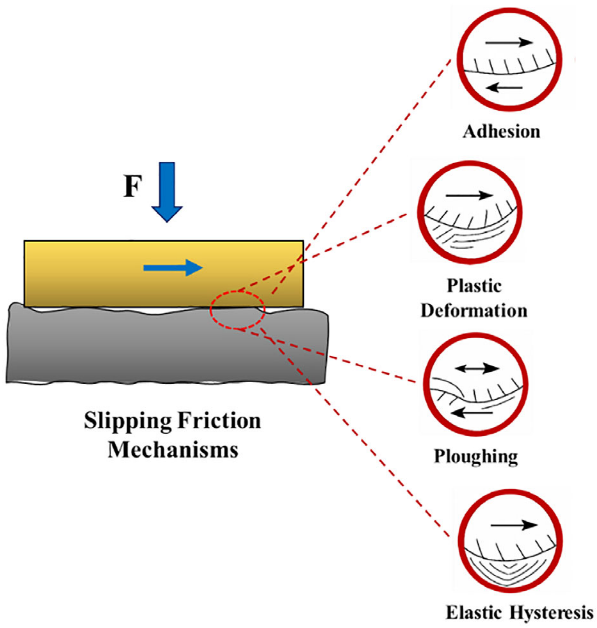


FIGURE 4 | Schematic representation of the primary mechanisms involved in slipping friction.

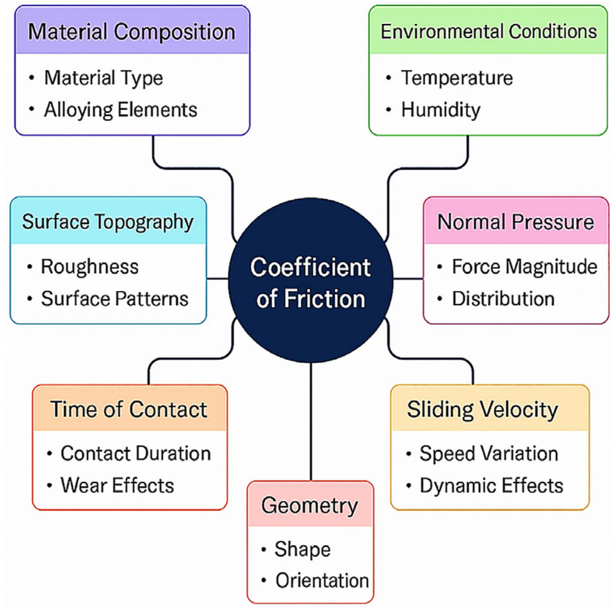


FIGURE 5 | Key parameters affecting COF under slippery conditions.

friction by promoting mechanical interlocking and increasing energy dissipation through viscoelastic deformation. This effect is especially relevant for soft materials such as polymers and rubber, which readily conform to surface irregularities [31]. In dry or mildly contaminated conditions, friction increases with roughness until a plateau is reached, beyond which additional roughness may not improve grip and may even be detrimental due to reduced contact efficacy [32, 33]. In addition to the above mentioned, adhesion at micro- and nano-scale contact junctions significantly contributes to friction. Van der Waals forces [34] and in humid conditions, capillary bridges [35] can promote adhesion between closely spaced surfaces. In cases like pressure-sensitive adhesives or gecko footpads [36], substantial frictional resistance can develop even in the absence of a significant normal load. Geckos exploit hierarchical fibrillar structures on their toe pads to maximize contact and generate sufficient van der Waals forces to support their body weight while climbing [36]. Adhesion-dominated friction deviates from Amonton's law, as it allows for friction at or near zero applied load. While often detrimental in engineering applications, leading to stiction [37], such mechanisms are purposefully harnessed in biomimetic adhesives and certain anti-slip materials.

As discussed, multiple interacting mechanisms contribute to the slipping phenomenon, each shaping the frictional behavior of the surfaces in contact. In essence, when two surfaces slide against one another, friction arises from a blend of interrelated processes rather than a single, dominant cause. Figure 4 illustrates these mechanisms. First, adhesion occurs at asperities, where intermolecular forces create junctions that must be sheared apart during motion, leading to energy dissipation. At the same time, these asperities deform under load—some elastically, temporarily storing and releasing energy, and others plastically, irreversibly dissipating it. In addition, ploughing arises when hard asperities cut into softer regions, forming grooves that increase resistance and generate wear debris. Slipping may also involve dynamic stick–slip behavior, in which periods of sticking are followed by sudden releases, producing fluctuating friction forces, vibrations, and noise. Collectively, these mechanisms, adhesion, deformation (elastic and plastic), and stick–slip, govern the frictional response of surfaces under sliding, transforming mechanical motion into dissipated energy and heat. We focus here on the frictional behavior relevant to slip prevention, not material wear.

3 | Anti-Slip Materials and Strategies

Designing anti-slip surfaces requires a multifaceted approach that balances slip resistance, durability, and environmental sustainability. Recent advancements have focused on developing materials and coatings that enhance friction and maintain consistent performance under diverse conditions. The anti-slip performance of materials is strongly influenced by the interplay of surface properties and their effect on the coefficient of friction (COF). Figure 5 illustrates the key factors influencing the coefficient of friction in contact with slippery surfaces [38]. Friction is a fundamental parameter in anti-slip applications, representing the resistance to sliding between two contacting surfaces. A higher COF indicates greater resistance to motion, which is essential for reducing slips and improving safety in a wide range of environments [39]. For instance, in flooring materials, an elevated COF can drastically reduce the likelihood of slip-related accidents. This concept is especially vital in high-risk settings such as workplaces and public spaces, where specialized surface treatments are employed to improve traction and ensure safety for occupants [40, 41]. Moreover, based on research done by Chang et al. on evaluating the relationship between floor surface slip resistance and human gait, it was proved that both static and dynamic COF play roles in predicting slip outcomes [39]. These insights are crucial for designing surfaces and materials that prevent sliding in both industrial and everyday settings. Despite the diversity of measurement methods and testing setups, a consistent trend emerges: increasing the COF typically improves the surface anti-slip properties [42, 43].

Various materials have been explored to manipulate the COF for effective anti-slip solutions. For example, elastomers are known for their adaptable friction behavior, performing well across various surfaces and speeds. Rubber, in particular, is widely used in applications like footwear soles and flooring due to its high elasticity and ability to adapt to surface irregularities, which helps prevent slipping [12]. Anti-slip behavior can be systematically addressed by organizing materials according to rubber type and additive composition. This highlights how formulation choices influence elasticity, adhesion, and frictional performance in practical applications. In other words, while elastomers inherently offer good slip resistance, their performance can be enhanced through compositional modifications. Elastomers used in engineering applications are commonly categorized into conventional rubbers and thermoplastic elastomers, with the latter comprising blends or dynamically vulcanized systems that combine rubber elasticity with thermoplastic processability. As reviewed by Fazli and Rodrigue [44], the mechanical response of thermoplastic elastomers is managed by the morphology and interfacial adhesion between rubber and thermoplastic phases, which can be adapted through formulation and compatibilization strategies. Such material-level design considerations complement surface texturing and coating approaches by enabling control over bulk viscoelastic behavior relevant to frictional and thus anti-slip performance. Li et al. developed anti-slip thermoplastic vulcanizate elastomers (TPVs) by combining solution-polymerized styrene–butadiene rubber (SSBR) with thermoplastic elastomers (SEPSs/SEBSs) via dynamic vulcanization. As illustrated in Figure 6a,b, increasing the SSBR content in the TPVs raised both static and dynamic friction, demonstrating that SSBR significantly improves slip resistance, particularly since Thermoplastic Elastomers (TPE) alone exhibit relatively poor grip. They also observed that higher rubber content enhanced the material's viscoelasticity, further improving its gripping performance [45]. This improvement can be explained by the friction theory model, which links adhesion and hysteresis friction to the material energy loss, quantified by the tangent of the loss angle (tan δ: defined as the ratio of the loss modulus to the storage modulus). According to this model, friction arises from two main factors: (i) adhesive forces between the surfaces and (ii) energy dissipation within the material caused by deformation, known as hysteresis. Therefore, the higher energy loss results in a higher tan δ and thus a greater friction coefficient [46]. Figure 6c illustrates tan δ changes vs. temperature for the samples. The results proved that a higher SSBR/TPE ratio led to higher tan δ and thus a higher COF for temperatures higher than $-15°C$ [45]. Referring to the friction mechanisms discussed in Section 2, the use of elastomers can leverage both adhesion and elastic hysteresis friction to enhance anti-slip performance. Other material factors, like softness and surface roughness, also play an important role. Mohan et al. found that softer rubber soles with rougher surfaces reached higher friction values (~1.0 dry, ~0.88 wet) than harder, smoother ones [47] showing how material compliance and texture are key to improving grip through both mechanical interlocking and elastic deformation mechanisms.

In another approach, Nishi et al. [48] examined rubber outsoles incorporating activated carbon or sodium chloride. As the soles wore down, microscopic depressions formed, trapping air and water. This generated negative Laplace pressure, which increased the real contact area and enhanced grip on wet or icy surfaces through hydrodynamic effects. Overall, optimizing the composition and surface design of elastomers can greatly improve their slip-prevention performance. These strategies have also been effectively applied to composite materials, where embedding hard particles in a softer matrix produces textured surfaces that enhance friction through mechanical interlocking and increased surface roughness. Studies on surface-engineered coatings further support this approach, demonstrating how particle distribution, matrix characteristics, and surface morphology collectively influence slip resistance [49, 50]. Beyond synthetic composites, natural polymers from plant and animal sources are emerging as sustainable alternatives for anti-slip applications. One patented formulation, for instance, combines animal protein, plant-derived polymers, and alkali metal hydroxides to produce an effective anti-slip surface, showcasing the potential of bio-based materials in this field [51].

For more demanding environments, metal-based coatings have been developed to provide both high slip resistance and reliable performance under heavy use. These coatings are especially suited for industrial settings, where reliable performance under heavy stress is crucial [52, 53]. Together, these studies emphasize the critical role of material selection—whether elastomers, composites, or coatings—and surface engineering in optimizing frictional performance for specific applications. The following sections delve into strategies and innovations in anti-slip materials, showcasing practical solutions based on the fundamental principles outlined in Section 2. These approaches prioritize a balance of functionality, durability, and adaptability. To translate these concepts into real-world applications, various techniques such as surface texturing, chemical treatments, and the incorporation of functional fillers have been developed, enabling researchers and industries to tailor anti-slip materials to meet the unique demands of different environments and conditions.

3.1 | Surface Texturing for Enhanced Friction and Grip

3.1.1 | Laser Surface Texturing

Surface texturing involves creating micro- or nano-scale patterns on a material surface to increase roughness, thereby improving friction and grip. This method has proven effective in modifying the surface topography. By introducing micro and nano-scale structures on the surfaces of processed components, surface texturing aims to enhance frictional performance [54, 55]. Techniques such as laser surface texturing (LST) have been employed to fabricate textures, effectively improving frictional behavior. Adjusting the surface topology can effectively modify the static and dynamic friction coefficients, without altering the surface chemical composition [56]. LST is a precise, versatile method for making controlled micro-scale features such as dimples, grooves, micro-cavities, that can be tuned to alter frictional behavior. Numerous experimental researches mention LST's ability to deliberately change contact mechanics and friction by controlling texture geometry, density, and orientation [57]. In lubricated regimes, these micro-pockets act as hydrodynamic

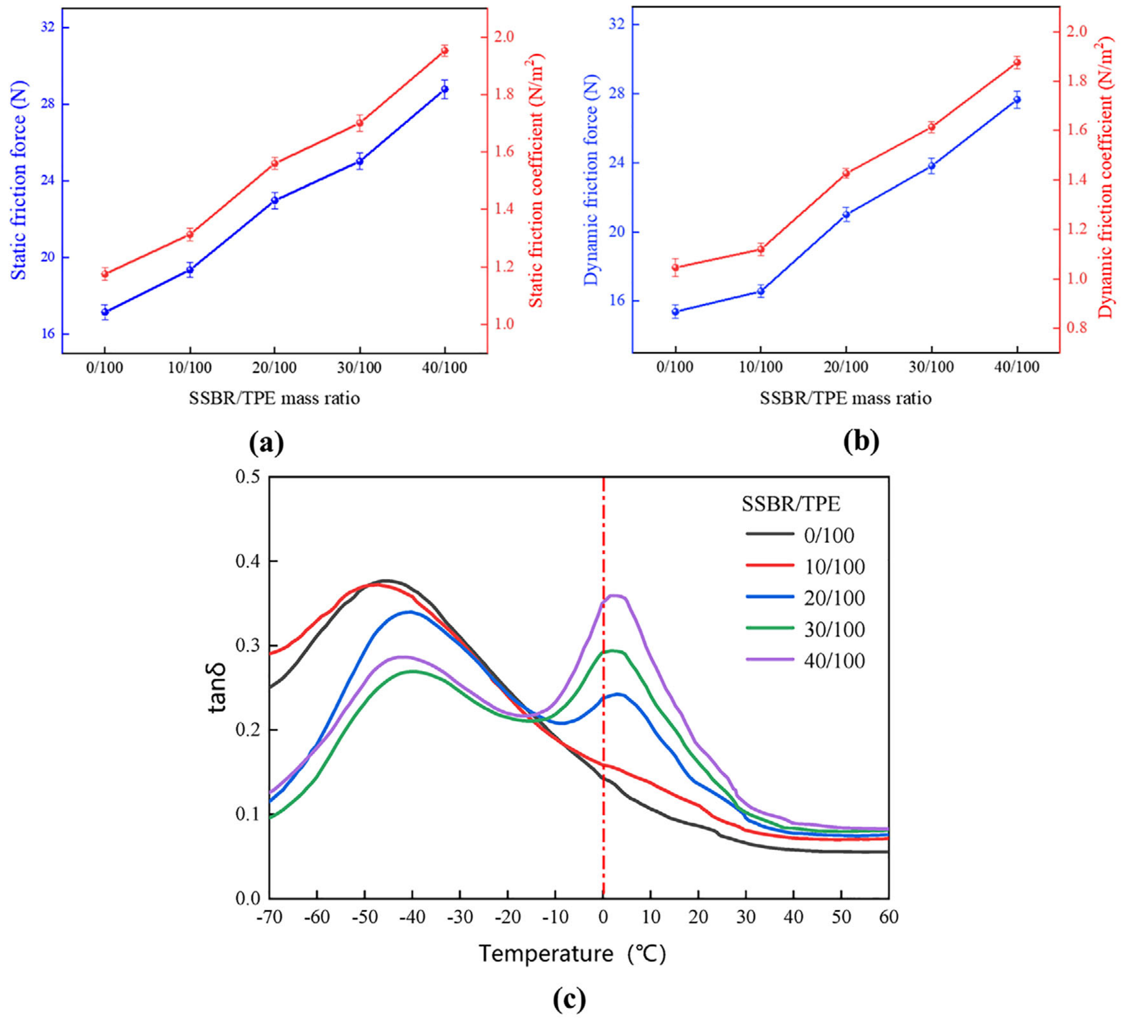


FIGURE 6 | (a) Static and (b) dynamic friction coefficients of TPEs with varying SSBR (styrene butadiene rubber) content, showing improved slip resistance with increased SSBR. (c) Variation of tan δ with temperature, indicating that higher SSBR/TPE ratios lead to greater energy dissipation and higher friction coefficients. Reproduced under the terms of the CC BY 4.0 license [45]. Copyright 2024, MDPI, Basel, Switzerland.

micro-bearings or micro-reservoirs that generate local pressure and reload lubricant, which can substantially reduce friction when properly designed. Conversely, with careful texture design, LST can be used to increase and stabilise high friction in dry conditions. In this case, texture patterns could raise static friction coefficients and create high-friction contacts for joints and fastening surfaces [58]. Many recent studies emphasize that the tribological outcome (e.i, frictional behavior) of laser textured surface depends strongly on texture geometry and patterns [57]. Therefore, careful design and optimisation are essential to achieve the intended anti-slip and frictional behavior. For instance, Dunn et al. [58] investigated LST to enhance friction in high-contact-pressure applications. Their results showed that increasing pulse overlap and using specific texture geometries could raise the static COF significantly, with reported increases of up to +80%–120% over untextured surfaces depending on the contact pressure. Additionally, Schille et al. [57] used high-rate laser technology for surface texturing at unprecedented processing rates. Their findings revealed that the highest static COF ($\mu_{(20)}$ = 0.68) was achieved for the cross-pattern laser texture, representing a +126% increase over the fine-ground reference surface. Moreover, self-organized cone-like protrusions reached a static COF of $\mu_{(20)}$ = 0.44, indicating a moderate friction-enhancing effect. These laser-textured surfaces also show strong potential for improving the adhesive strength and long-term stability of bonded joints and hard coatings. Figure 7a–c shows different surface topographies created using an ultrashort pulse laser with varied scanning patterns. Similarly, in another study, they used laser surface texturing on alloy steel 42CrMo$_4$+QT (AISI 4140) and demonstrated that dimple-shaped microstructures could nearly double the static and kinetic friction coefficients, achieving μs ≈ 0.53 and up to $\mu_k \approx 0.82$ under dry conditions [59]. These studies show that LST can substantially increase friction and even double the COF, when texture geometry and laser parameters are carefully optimized. The method also offers added benefits such as improved coating adhesion and surface stability. However, its effectiveness is highly sensitive to process conditions, meaning that poorly designed or improperly tuned textures may yield limited or inconsistent results. Thus, LST success depends on precise control of texture design and processing that can be challenging.

Building on this, additional studies reinforce the broader effectiveness of laser-based surface texturing as a friction-enhancing

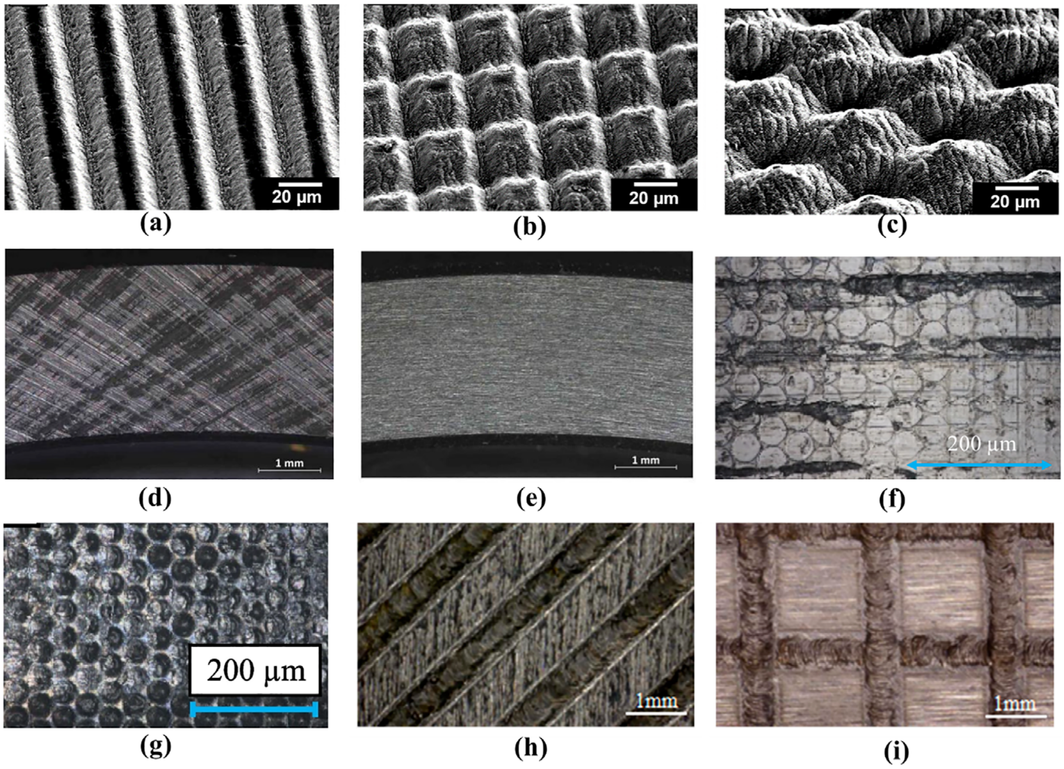


FIGURE 7 | Different surface topographies created using an ultrashort pulse laser beam with varied scanning patterns, including (a) line pattern, (b) cross pattern, and (c) a combination of alternating line and crosswise laser beam scans. Reproduced under the terms of the CC BY 4.0 license [57]. Copyright 2024, MDPI, Basel, Switzerland. Counterpart surfaces in contact with laser-textured high-friction rings: (d) before slippage test; no visible indentations; (e) after slippage test; uniform surface with no dominant features. Reproduced under the terms of the CC BY 4.0 license [60]. Copyright 2022, MDPI, Basel, Switzerland. Post-test surface condition of laser-textured specimens: (f) Honeycomb walls remain on the clamping element surface after testing (g) Laser-structured surfaces filled with wear debris from the counter element, while the honeycomb walls show no observable damage. Reproduced under the terms of the CC BY 4.0 license [59]. Copyright 2025, Springer Nature. Surface morphology made by the laser scanning processing method showing (h) micro-grooves (i) and reticular grooves. Reproduced under the terms of the CC BY 4.0 license [61]. Copyright 2023, MDPI, Basel, Switzerland.

and anti-slip strategy. Góra et al. [60] similarly showed that LST enables the fabrication of high-friction mechanical rings with textures specifically engineered for robust grip in industrial components. Figure 7d,e show the counterpart surfaces in their study, in contact with laser-textured high-friction rings before and after slippage tests, respectively. More recently, Schlegel and Hartmann [59] applied laser-generated honeycomb-like textures to the circumferential surfaces of cemented-carbide rods and showed that the resulting structures increased the slip-load capacity by up to a factor of 2.4 compared with untextured surfaces. Figure 7f,g present post-test conditions of laser-textured specimens, where honeycomb walls remain intact and wear debris from the counter element fills the textured areas without damaging the structure. This study highlighted the strong mechanical interlocking achievable through controlled micro-patterning. Figure 7h,i illustrate another example of micro-grooves and reticular grooves produced by the laser scanning processing method. Taken together, these findings collectively confirm that micro-scale laser-generated textures enhance friction primarily by promoting increased asperity engagement under load, making LST a reliable method for improving contact performance in both dry and boundary-lubricated environments. Furthermore, femtosecond-induced structures using Laser-induced periodic surface structures (LIPSS) have expanded this capability to polymers, where finely controlled micro-grooves improve traction by tailoring roughness and wetting behavior [57].

Overall, laser-based surface texturing offers a highly precise and controllable method for increasing friction and grip by creating micro- and nano-scale features. It can promote strength. Its key advantages are the static friction increase, promotion of asperity interlocking under load, and thus improvement of mechanical anchoring without altering the bulk material; these advantages can make laser-based surface texturing an appropriate method for anti-slip applications. However, its effectiveness depends strongly on careful optimization of laser parameters and texture design. Despite these limitations, LST can be a promising method for those applications where secure contact and high grip are essential, including high-pressure mechanical joints, industrial gripping elements, cutting and drilling tools, anti-slip metallic or polymer surfaces, and precision components requiring reliable dry-contact performance.

Other surface texturing techniques, such as incorporating grooves or patterns into material designs, can significantly influence frictional properties. For instance, Iwashita et al. [62] conducted a numerical study on the friction of viscoelastic objects with grooves and found that the static friction coefficient decreases as groove width and depth increase. This finding demonstrates the potential of customizing surface structures to control friction effectively. Additionally, Qu et al. [63] found that g grooves to rubber surfaces reduce friction-induced vibrations, thereby improving overall frictional performance. In another study, Wu et al. [64] fabricated various groove textures on steel using a laser and tested their frictional behavior under different high temperatures and working conditions. The results revealed that introducing groove surface textures on steel significantly reduced friction coefficients, wear, and modified friction coefficients, and improved energy efficiency under high-temperature conditions. The effectiveness of these reductions varied depending on specific texture parameters and experimental settings. Key mechanisms for improvement included enhanced hardness, efficient storage of wear debris, release of thermal stress, and reduction of friction-induced temperature increases. Key mechanisms for improvement included enhanced contact stability, efficient dissipation of thermal stresses, and reduction of friction-induced temperature increases. These findings highlight the potential of surface texturing in optimizing frictional performance and energy efficiency in high-temperature applications [64].

In addition to precision laser texturing, a broad range of non-laser surface texturing approaches have been reviewed for their influence on friction behavior. Vishnoi et al. [54] provided a comprehensive overview of surface texturing techniques, including mechanical abrasion, abrasive blasting, grinding, shot peening, chemical and electrochemical etching, micromachining, and laser-based methods, and discussed how these approaches modify surface roughness across multiple length scales to influence friction. The review emphasizes that tribological performance is governed by texture scale, surface morphology, and contact conditions rather than the use of a single fabrication technique. Complementarily, Costa et al. [65] focused on surface textures designed to increase friction and report that both ordered and irregular textures can enhance friction through mechanisms such as increased real contact area and mechanical interlocking, depending on material pairing and environmental conditions. Together, these reviews highlight that surface removal-based and damage-induced texturing methods represent viable alternatives to highly controlled laser patterning, particularly in applications where frictional performance and practical implementation are prioritized over strict geometric regularity. Since slip resistance fundamentally depends on frictional performance at the interface, surface texturing strategies that enhance friction are directly relevant to the design of anti-slip surfaces, even though their effectiveness must be evaluated under application-specific conditions.

3.1.2 | Biomimetic Surface Texturing

Biomimetic surface design has rapidly become a leading strategy for developing advanced anti-slip and high-adhesion materials. Unlike traditional laser-textured surfaces discussed so far, biomimetic structures replicate naturally evolved micro/nano-architectures that provide organisms with exceptional friction, adhesion, and wet-surface adaptability. Biomimetic approaches draw inspiration from nature to develop advanced materials with enhanced adhesion and friction properties. A prime example is the development of nanopillar arrays inspired by the adhesive toe pads of tree frogs. These toe pads feature densely packed keratin nanopillars that allow frogs to adhere to various surfaces, including wet and smooth ones. Researchers have replicated this hierarchical, anisotropic structure to create synthetic surfaces with improved adhesion and friction [66]. The adhesive toe pads of tree frogs consist of soft epithelial cells arranged in a hexagonal array of micropillars, separated by fluid-filled channels, forming a hierarchical structure that enables strong wet adhesion and friction [67]. The softness of the pad outer layer allows the surface to conform intimately to rough or uneven substrates, maximizing real contact area [68]. Moreover, the mucus secreted by the toe pad fills the micropillar channels, enabling capillary-assisted wet adhesion and facilitating reliable grip even in wet conditions [69]. Bio-inspired synthetic surfaces have replicated this hierarchical design and demonstrated enhanced adhesion and friction under wet conditions. For instance, hybrid surface patterns mimicking frog toe pads have been fabricated using polydimethylsiloxane (PDMS) micropillars embedded with polystyrene (PS) nanopillars, enhancing adhesion and friction due to the combination of material properties and structural hierarchy [70]. Figure 8a–c shows SEM images of the pillar array (Comp+), a representative friction curve for PDMS arrays, and the transition distance from static to dynamic friction (Ds) for Comp+ and PDMS arrays, respectively. The enhanced adhesion of Comp+ micropatterns required a greater lateral displacement to trigger detachment at the pillar edge during shearing. Consequently, Ds for Comp+ is twice that of the pure PDMS pillars [70]. Additionally, two-level micropillar arrays with nanocavities, inspired by tree frog toe pads, have been shown to produce boundary friction approximately 20 times greater than flat surfaces, which are presented in Figure 8d,e [71].

Figure 8 illustrates the examples of nature-inspired approaches, particularly for increasing friction. The biomimetic designs have practical applications in climbing robots, and medical devices where controlled adhesion is essential. By emulating the natural adhesive mechanisms of tree frogs, these surfaces maintain strong adhesion in diverse environmental conditions [67].

Geckos also achieve remarkable adhesion and friction via a multi-scale hierarchical system consisting of macroscopic lamellae, microscale setae, and at the tip of each seta, hundreds of sub-micrometric spatular tips. These nanotips maximize contact at the molecular level, enabling adhesion via van der Waals forces [34]. Early direct experimental evidence showed that gecko setae adhere equally well to hydrophobic and hydrophilic substrates, supporting a van der Waals mechanism rather than capillary or suction-based adhesion [74]. In fact, the hierarchical structure provides the necessary compliance to conform perfectly to rough and irregular surfaces and to ensure the intimate contact required for the van der Waals forces to operate effectively [75]. These principles have been translated into engineered 'gecko-inspired' adhesives and grippers used in soft robotics [76, 77], reversible adhesive pads and medical patches [78], where achieving strong attachment even on challenging or irregular surface, without the use of chemical glues, may be desirable.

Across the reviewed studies, a consistent pattern emerges: gecko-inspired surfaces excel not merely because they "stick," but

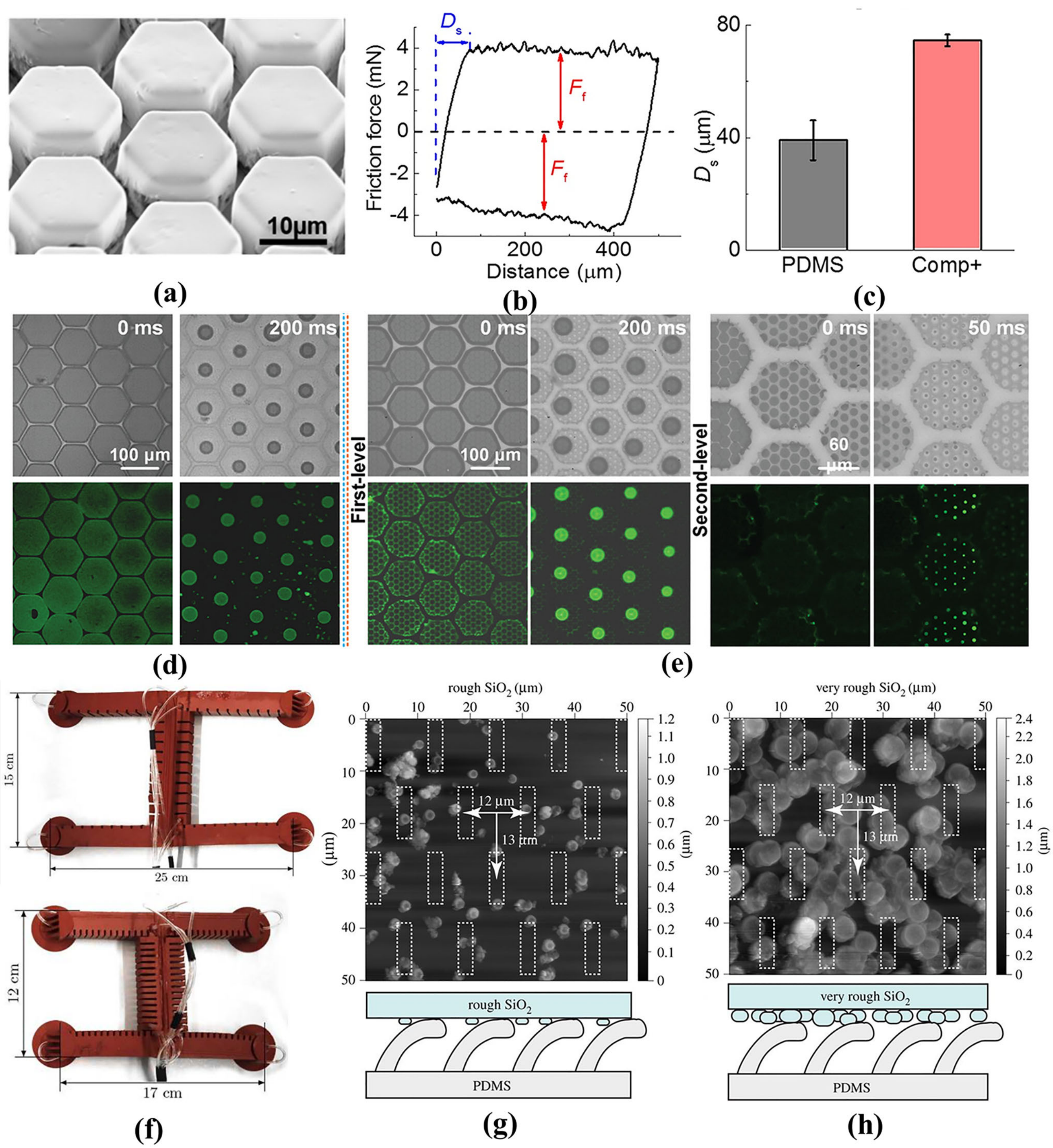


FIGURE 8 | Resulting composite pillars with PS nanopillars embedded in a PDMS matrix. (a) SEM image of the composite pillar array (Comp+). (b) Representative friction curve for PDMS arrays, showing friction forces (Ff) in trace and retrace directions and the transition distance from static to dynamic friction (Ds). (c) Ds for Comp+ and PDMS arrays. Reproduced under the terms of ACS AuthorChoice [70] Copyright 2017, American Chemical Society. (d) On the bioinspired single-level pillar surface, liquid self-splitting occurs progressively. (e) On the bioinspired hierarchical (two-level) pillar surface, self-splitting occurs sequentially on the upper and lower tiers as the liquid volume decreases. Reproduced under the terms of the CC BY 4.0 license [71]. Copyright 2020, Wiley-VCH GmbH. (f) Large and small prototype of the gecko-inspired soft robot. Reproduced under the terms of the CC BY 4.0 license [72]. Copyright 2019, Schiller, Seibel, and Schlattmann. Atomic force microscopy images of (g) rough and (h) very rough surfaces with overlaid gecko-inspired flap tip dimensions illustrate how surface geometry influences interlocking. The schematic shows that on the rough disc the PDMS flaps can interlock effectively, whereas on the very rough disc the larger asperities reduce interlocking and make the surface behave more "smooth" to the flaps. Reproduced with permission [73]. Copyright 2015, The Royal Society.

because their hierarchical, compliant microstructures actively manage friction, suppress slip, and adapt to a wide range of surface conditions. Schiller et al. [72] demonstrated that such fibrillar systems provide stable attachment and high friction on vertical and uneven substrates, enabling reliable locomotion in climbing and perching robots (Figure 8f). Building on the importance of compliant microstructures, Das et al. [73] showed that gecko-mimetic PDMS microflaps and fibrillar arrays substantially increase shear friction while suppressing stick–slip instabilities across smooth and rough surfaces (Figure 8g). These findings highlight that gecko-like adhesives provide not only strong attachment but also tunable, predictable frictional behavior, making them suitable for precision manipulation and vibration-resistant interfaces.

Extending these principles toward practical devices, Pang et al. [79] developed the hierarchical adhesive gripper, achieving a ~1.5× increase in normal adhesion and significant reduction in incipient slip when handling irregular or low-friction objects. This demonstrates the potential of gecko-inspired friction systems in industrial automation, warehouse robotics, and manufacturing, where adaptive and secure gripping is critical. Complementing these robotic applications, Finally, Liu et al. [80] stated that gecko-inspired adhesion and friction can be maintained on wet or liquid-contaminated surfaces by integrating hierarchical compliance with capillary-assisted mechanisms, broadening applications to marine robotics, outdoor tools, and search-and-rescue devices. Collectively, these studies illustrate that gecko-inspired surfaces provide adaptive, reversible, and energy-efficient friction enhancement, capable of conforming to complex geometries, distributing loads effectively, and maintaining grip under diverse environmental conditions. This combination of properties positions gecko-inspired designs as highly promising for next-generation technologies in robotics, wearable devices, biomedical interfaces, and engineered anti-slip surfaces.

Despite many advantages, gecko-inspired adhesion and friction surfaces still face significant limitations that need to be carefully addressed depending on the application. The underlying adhesion mechanism (based on van der Waals forces) requires extremely close contact, even thin layers of water, dust, or contaminants can significantly weaken adhesion. Studies have reported reduced adhesive performance on wet or heavily contaminated surfaces [81]. Moreover, humidity effects are complex; in some cases, increased humidity softens setal material and increases adhesion, in others, water films disrupt adsorption and reduce performance, meaning reliability across different environmental conditions is uncertain [82]. Therefore, this sensitivity complicates applications in wet, dirty, dusty, or variable environments for outdoor, industrial, medical with bodily fluids, applications. In addition, synthetic fibrillar adhesives often use soft polymers (e.g., PDMS), which can degrade over time, lose stiffness, structurally fatigue, or suffer wear, particularly under high load or repetitive friction cycles. Besides, replicating the exact multi-scale geometry (millions of fine hairs, nanoscale spatula) over large areas is technically challenging and costly. Scaling up manufacturing while maintaining fidelity and uniformity also remains a barrier. In addition, for applications requiring robust traction under rain, oil, water, or contamination, their consistent high adhesion on wet, humid, or fluid-lubricated surfaces remains elusive. Experiments show a performance drop when substrates are wet, or when water layers exceed nanometer scales [83].

Overall, gecko-inspired adhesion and friction surfaces represent a powerful and versatile class of engineered grip/anti-slip solutions, with clear advantages over conventional adhesives or mechanical fasteners, especially when reversibility, conformality, high friction, and clean detachment are desired. Their hierarchical, compliant microstructure offers adaptability across varied surface geometries and materials. make it smooth However, for practical deployment, especially in industrial, outdoor, biomedical, or heavy-duty contexts, their environmental sensitivity, material durability, and fabrication scalability must be carefully considered. Hybrid solutions that combine gecko-inspired geometry with robust materials, surface coatings, or complementary adhesion mechanisms (e.g., capillary, electroadhesion, mechanical interlocking) may be necessary to overcome these limitations.

3.2 | Chemical Treatment

Chemical treatments are widely used to alter the surface topography and surface chemistry of the materials. These treatments work by creating microscale or nanoscale changes to the material surface, which significantly enhance traction under various conditions. For instance, Quirino et al. [84] investigated the effects of acid-based anti-slip treatments on glazed ceramic tiles, which are known to be extremely slippery when wet. They applied two common treatments, hydrofluoric acid, and ammonium bifluoride, and systematically evaluated their impact on slip resistance, surface morphology, and maintenance properties. They found that hydrofluoric acid dissolves portions of the glaze, creating microscopic holes, while the tile treated with ammonium bifluoride deposits a layer of submicron particles on the surface. These microscopic changes slightly increased the slip resistance of the tiles under wet and dry conditions. However, the study also highlighted significant drawbacks: hydrofluoric acid-treated tiles became more fragile, and the particle layer from the ammonium bifluoride treatment lacked strong adhesion, reducing the longevity of the anti-slip modification. Despite these limitations, the modifications provided practical improvements for safety in wet environments, particularly in high-traffic areas like kitchens and bathrooms [84]. In another study, Kim [85] investigated the slip-resistance performance of organic coatings applied to ceramic tiles under varying environmental conditions, using three additional floor-coating agents: epoxy, acrylic polymer, and acrylic. Figure 9a,b present the ceramic-tile surfaces before and after chemical treatment. The study demonstrated a clear relationship between coating type and environmental conditions in achieving optimal slip resistance. Among the tested materials, the acrylic-based coating performed best on dry surfaces, increasing surface roughness by up to 95%. Epoxy coatings proved most effective in damp environments, and acrylic polymer coatings performed reliably in both damp and foamy conditions, making them suitable for high-risk areas. In contrast, acrylic coatings offered only moderate benefits in arid settings and performed poorly in foamy environments. These findings highlight the superior performance of acid-based etchant treatment at improving slip resistance

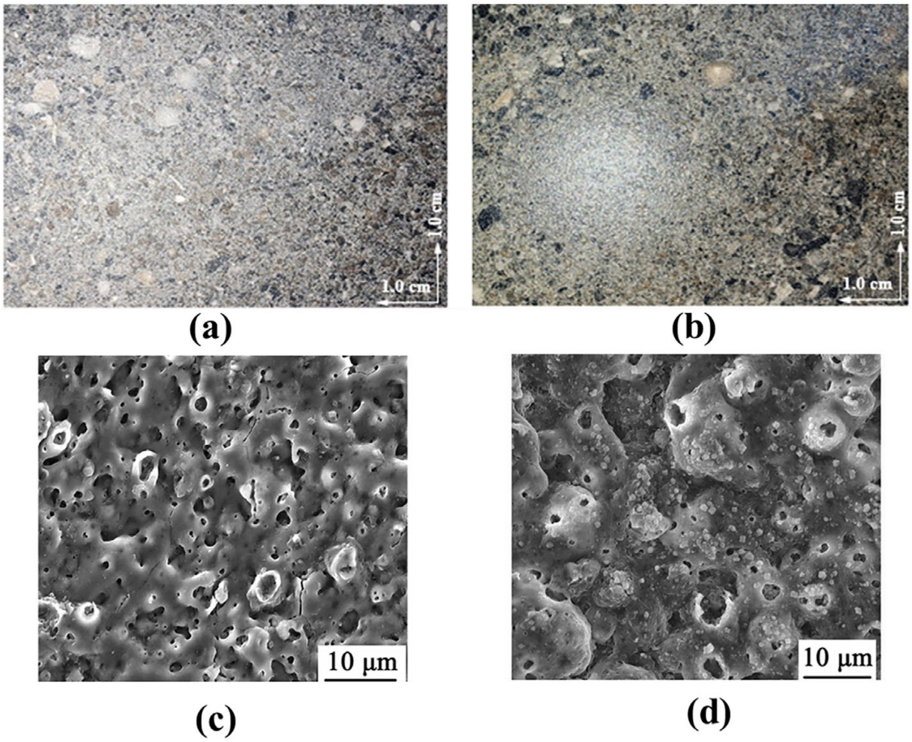


FIGURE 9 | (a) Untreated ceramic tile surface, (b) tile treated with acrylic-based coating. Reproduced with permission from Results in Engineering. Copyright 2025 Elsevier B.V [85]. (c) PEO coatings without and (d) with h-BN particles, illustrating the presence of micropores due to the PEO process. Reproduced under the terms of the CC BY 4.0 license [92]. Copyright 2022, Springer Nature.

performance, and also underscore the importance of selecting coating agents according to specific environmental conditions [85].

In addition, advanced coatings and chemical surface modifications offer further improvements in slip resistance. Silicone-based slippery polymer coatings, for example, feature humidity-dependent nanoscale topography, enabling them to adjust surface properties in response to environmental humidity and influence frictional behavior [86]. Similarly, modifying thermoplastic rubber (TPR) soles with trichloroisocyanuric acid in a methyl ethyl ketone medium introduces chlorinated and oxidized moieties. These changes enhance the slip resistance of TPR soles under wet conditions by increasing surface roughness and improving hydrophilicity [87]. Moreover, plasma treatments, including plasma oxidation and plasma electrolytic oxidation (PEO), have been extensively studied for their effectiveness in enhancing surface properties. Plasma oxidation involves exposing a material surface to a plasma environment, introducing functional groups that increase surface energy and promote better adhesion. This method has been applied to various polymers to improve their bonding characteristics, which can indirectly enhance slip resistance by allowing for the application of more effective anti-slip coatings [88].

PEO, also known as micro-arc oxidation, is a process used to form ceramic oxide coatings on metals such as aluminium, magnesium, and titanium. While these coatings are traditionally recognized for improving wear resistance and hardness, their surface microstructure, particularly roughness and porosity, can play a crucial role in enhancing slip resistance. PEO coatings, for example, are known for their strong adhesion to substrates and relatively low stiffness, resulting in a lower strain energy release rate. Despite their lower stiffness, PEO coatings are generally harder than those produced by anodization [89]. In addition to PEO, various surface modification techniques, such as mechanical, electrochemical, and localized heat treatments, have been utilized to achieve optimal surface morphology in materials like titanium alloys. These methods help enhance surface roughness and energy, which in turn improves mechanical adhesion [90]. While PEO is primarily utilized to enhance light metal alloy wear properties, there is limited direct research on its application specifically for anti-slip purposes. However, the increased surface roughness resulting from PEO treatments can potentially contribute to improved slip resistance. For instance, Rapheal et al. [91] studied thin films produced on MRI 230D Mg alloy using PEO, which demonstrated enhanced surface hardness and roughness characteristics that could increase friction and grip, potentially benefiting anti-slip applications. Additionally, Figure 9c,d, illustrate the PEO coatings with microporous structure typical of the PEO process without and with h-BN particles, respectively. In Figure 9c, larger and more defined pores are visible, while Figure 9d shows a more refined surface with smaller, partially filled pores, indicating that h-BN incorporation helps reduce porosity and improve coating uniformity. These studies highlight the potential of optimizing PEO coating microstructures to improve surface roughness and contact interactions, contributing to better frictional performance and anti-slip behavior.

A comprehensive selection of chemical or surface-modification treatments for improving slip resistance must therefore move beyond the immediate frictional improvements reported in previous studies [84–92] and instead rely on a systematic evaluation of substrate compatibility, environmental exposure, and long-term functional stability. Although strong acid etching (e.g., HF or mixed mineral acids) can significantly increase micro-roughness and short-term slip resistance, several studies have shown that aggressive chemical attack may weaken surface cohesion, accelerate wear, and increase maintenance demands in high-traffic environments, making such treatments unsuitable for many applications [84–86]. In contrast, plasma-based modification and oxide-ceramic coatings, such as PEO, demonstrate substantially greater durability and environmental stability. Moreover, the tunable microstructure achievable in such coatings, where pore size, layer thickness, and incorporated phases can be controlled through electrolyte composition and processing parameters, allows engineers to modify the frictional response to specific loading conditions. However, environmental factors, such as moisture and particulate contamination strongly influence the real-world performance of anti-slip treatments [87–90]. Needless to mention, safety and sustainability constraints also shape treatment choice. For instance, highly reactive agents like HF present serious occupational hazards, require strict disposal and handling procedures, and may therefore be impractical in many industrial or public settings, whereas plasma-based treatments avoid such chemical risks and produce longer-lasting performance with lower maintenance overhead [91, 92]. Taken together, this broader evidence base reinforces that the most effective anti-slip strategy is not a single universal method but a context-dependent choice that balances friction performance, durability, maintenance requirements, environmental exposure, and safety constraints.

3.3 | Filler Incorporation

Incorporating fillers into polymer matrices can significantly improve anti-slip properties by altering surface characteristics and enhancing mechanical performance. For example, silicone rubber composites filled with aluminium hydroxide (ATH), yimonite (YMT), boron nitride (BN), and mica showed that ATH-filled composites had the best mechanical properties, with an elongation at break of 230% and a tensile strength of 2.9 MPa, contributing to enhanced grip and slip resistance [93]. Similarly, rubber compounds incorporating activated carbon or sodium chloride have shown enhanced friction forces and reduced slip rates when used in footwear outsoles, highlighting the effectiveness of these additives. Figure 10a presents images of the rubber specimens, a visual comparison contrasts untreated rubber with samples filled with activated carbon and sodium chloride, and Figure 10b illustrates the corresponding friction coefficients (μ) for each sample. The results revealed that these additives significantly boost friction, rubber with activated carbon or NaCl exhibits noticeably higher μ values, demonstrating how filler-induced micro-depressions enhance traction by trapping air and water at the interface [48]. Further studies have explored the use of nanofillers to improve the mechanical and tribological properties, the frictional performance, and surface properties of polymer composites. For example, the incorporation of carbon nanotubes (CNTs) and graphene into polymers has been investigated to enhance scratch and shear resistance, surface cohesion, and stability under sliding. These nanofillers contribute to increased cohesive strength and shear resistance, which are crucial for maintaining frictional performance under various conditions [94]. The strategic incorporation of various fillers, including nanofillers, into polymer matrices can effectively enhance anti-slip properties by improving mechanical strength, surface characteristics, surface roughness, contact adhesion, and mechanical integrity. These enhancements are vital for developing materials with superior grip and reduced slip rates in diverse applications. For instance, Yuan et al. [95], investigated the effect of ceramic particle characteristics in epoxy resin-based anti-skid layers, specifically for urban pavements. Key findings from this study indicate that the embedding behavior of ceramic particles is significantly influenced by the cementitious mix ratio. A ratio of adhesive to powder filler to sand filler of 1:0.5:1 or 1:0.5:1.5 was found to promote the effective embedding of aggregate particles in the resin layer. Figure 10c shows the effect of composite filler on the viscosity of the thin layer: by maintaining a lower powder filler content and adjusting viscosity primarily through the filler lead to a more stable and predictable rheology. The study also revealed that higher cementitious viscosity reduced the embedding depth of the ceramic particles, which could affect the surface roughness and slip resistance of the final layer (Figure 10d). Further image analysis techniques were employed to assess the geometric properties of the aggregate particles. It was determined that the shape characteristics of the aggregates, including the roundness factor, prism factor, and axial coefficient, play an essential role in the embedding depth, with the roundness factor having the greatest impact. The correlation analysis highlighted the importance of aggregate shape in optimizing the performance of anti-skid coatings [95].

Overall, incorporating fillers into polymer matrices for anti-slip applications offers significant advantages, including enhanced mechanical strength and surface roughness, which collectively improve traction, durability, and friction stability under varying conditions. Moreover, the selection and combination of micro-, macro-, and nano-scale fillers allow for tailored anti-slip surfaces using microstructural surface texturing to maintain high friction and stability. However, these benefits come with limitations. Achieving uniform dispersion and proper filler–matrix compatibility, for instance, is critical to avoid agglomeration, inhomogeneity, or weak interfaces. On the other hand, excessive filler content may reduce elasticity or increase brittleness. Besides, processing parameters, filler loading, and particle morphology must be carefully controlled to ensure consistent performance. Therefore, optimizing the type, loading, dispersion, and surface characteristics of fillers is essential to achieve reliable, durable, and effective anti-slip surfaces [12].

In more practical daily use, the strategies for designing anti-slip surfaces are varied and adaptable to different conditions, including dry, wet, and icy environments. Table 1 summarizes specific methods and mechanisms tailored to slippery surfaces to exemplify the application of these strategies. Advanced micro- or nano-level texturing is a proven strategy for creating surfaces that enhance traction by trapping air and water, thereby increasing grip through contact points and surface roughness [42, 96–98].

The interaction between ice and textured material surfaces is governed by mechanical interlocking effects, where raised patterns enhance friction by increasing contact with ice. The interac-

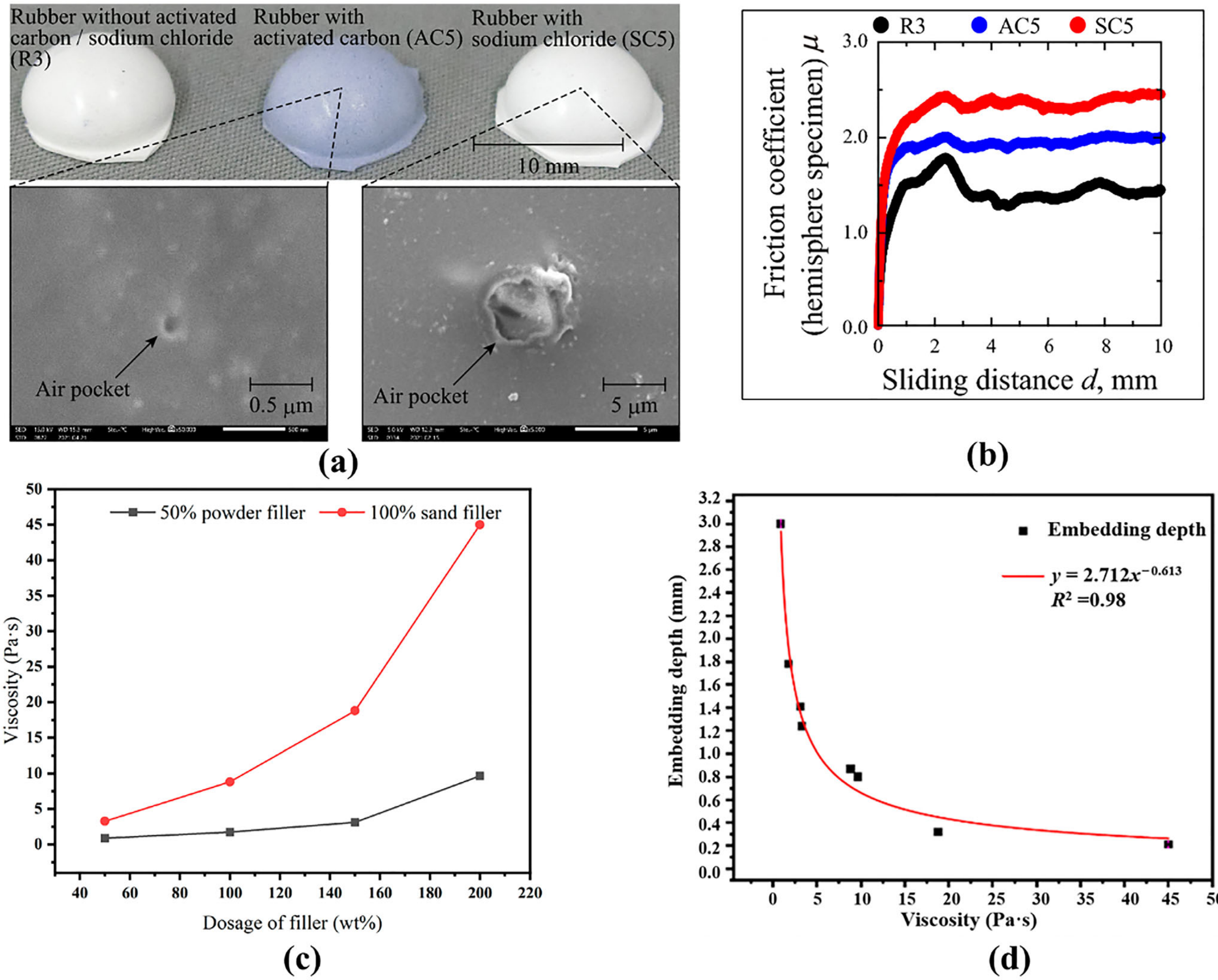


FIGURE 10 | (a) Visual comparison of rubber specimens with and without activated carbon and sodium chloride fillers. (b) Corresponding friction coefficients (μ) for each formulation, highlighting the influence of the additives on friction performance. Reproduced under the terms of the CC BY 4.0 license [48]. Copyright 2022, Springer Nature. (c) Composite ceramic fillers content influencing the thin-layer viscosity. (d) Effect of cementitious viscosity on embedding depth of ceramic particles, potentially affecting surface roughness and slip resistance. Reproduced under the terms of the CC BY 4.0 license [95]. Copyright 2024, MDPI, Basel, Switzerland.

tion between ice and textured material surfaces is particularly challenging due to the low shear strength of ice and, in wet conditions, the presence of a thin lubricating water layer that reduces friction. On dry ice, traction is mainly governed by mechanical interlocking, where raised micro- or nano-scale patterns enhance contact and resist sliding. Mielonen et al. studied microtextured polymer surfaces with micropillar patterns on polypropylene and rubber compounds. Their results demonstrated that introducing a secondary level of texture significantly improved polymer-ice interlocking, leading to higher ice traction. Further innovation involved nanomaterials like hexagonal graphene nanoplatelets (GNPs), forming hierarchical surface textures that enhance ice traction by 64% while improving wear resistance [96]. Building on these advancements, researchers developed a novel hybrid composite material combining soft fibers (poly(p-phenylene-2,6-benzobisoxazole)) and hard fibers (carbon fiber) to enhance COF on ice. At an optimal poly(p-phenylene-2,6-benzobisoxazole) fiber volume fraction of 8%, the composite exhibited significantly improved friction and abrasion resistance, making it suitable for long-term applications in icy environments [97]. Flexible polymer matrices, such as TPE or rubber-based composites, complement these texturing strategies by conforming to micro- and nano-scale ice surface irregularities, increasing real contact area and further reducing slip [99, 100]. Recent research studies highlight that optimizing ice traction requires a synergistic approach, combining hierarchical surface texturing, filler reinforcement, and appropriate matrix elasticity to maximize mechanical interlocking while maintaining durability under repeated wet or dry ice conditions. These design principles are particularly relevant for applications such as winter footwear soles, polymer ramps, anti-slip outdoor coatings, and composite panels, where reliable traction under both dry and wet ice is critical for safety and performance. For instance, Bagheir et al. [101], showed that composite outsole materials in winter footwear can significantly reduce slip and fall incidents, demonstrating the effectiveness of material and structural design for pedestrian safety on ice. Gao et al. [102], further demonstrated that outsole surface properties, such as roughness and hardness, strongly influence friction on

TABLE 1 | Overview of materials and strategies to develop anti-slip property.

Material	Mechanism of anti-slippery	Example of application	Refs.
Textured and Patterned Surfaces; Micro- and Nano-Texturing	Creating surface asperities at micro- or nano-scale to increase contact area and friction, interlocking with the contact surface and enhancing grip.	Winter footwear soles, anti-slip decking materials, high-tech flooring, advanced shoe soles	[42, 96–98, 104]
Grit-Embedded Surfaces, Anti-Slip Grit Additives	Embedding hard particles (e.g., ceramics, silica) into softer matrices to create roughened surfaces that physically lock into irregularities of the slippery surfaces	Anti-slip tapes and coatings for walkways and steps	[98, 105]
TPE	Flexible materials that deform under pressure to maximize the real contact area, improving grip and friction on slippery surfaces	Winter boots, flexible anti-slip mats	[99, 100]
Composite Structures with Embedded Particles	Combining hard fillers (e.g., ceramic particles) in a flexible matrix to create durable, anti-slip coatings that balance slip resistance with wear resistance.	Anti-slip road coatings, industrial floor coatings	[95, 106]

ice, emphasizing the importance of microstructural and material optimization to maintain reliable traction under both dry and wet icy conditions. Similarly, Islam et al. [103] investigated tread patterns and elastomeric composite outsoles, showing that specific material formulations and hierarchical surface textures can achieve high static and dynamic friction on ice, even in the presence of thin water layers. Collectively, these studies support the use of hierarchical texturing, filler reinforcement, and optimized polymer matrices to ensure durable and effective anti-slip performance in challenging icy environments.

Despite their effectiveness, the mentioned approaches for anti-slip surfaces on ice have several inherent limitations. For instance, micro- and nano-textures that enhance mechanical interlocking may also increase ice adhesion under static freezing conditions, potentially reducing performance when meltwater layers are present. Moreover, as the composite materials used for these applications are sensitive to abrasion, their anti-slip performance may degrade over time [101]. In the manufacturing process, precise control of surface texture, filler distribution, and matrix curing is essential to achieve reproducible properties; however, this level of control increases process complexity and overall production costs. On the other hand, environmental and health considerations, particularly with nanoparticle fillers, may also restrict large-scale deployment. Finally, while these strategies offer significant anti-slip advantages, careful optimization of filler type, loading, texture geometry, and matrix properties is essential to balance friction, durability, and safety across varying conditions.

4 | Evaluation of Anti-Slippery Performance

Evaluating anti-slip performance is essential for ensuring safety across a wide range of surfaces and applications. This evaluation typically involves quantifying slip resistance through the measurement of the coefficient of friction, both static and dynamic. The static COF refers to the ratio of the tangential force required to initiate motion to the normal force, while the dynamic (DCOF) pertains to the force needed to maintain sliding. These values offer insights into traction and are particularly useful when comparing materials under controlled conditions [107]. Although often used interchangeably, COF and slip resistance address different aspects of performance. COF is measured under standardized, controlled conditions, whereas slip resistance is more indicative of behavior in real-world scenarios and is often expressed on a scale from 0 to 1, with lower values indicating higher slipperiness [108]. To bridge the gap between laboratory and real-world evaluations, researchers have refined laboratory tribometers and introduced new testing protocols that more closely simulate real-world slip conditions. The most widely used techniques for assessing COF and slip resistance will be detailed in the following sections. The most used measurement techniques related (friction testing) to these concepts will be discussed in the following subsections.

It is important to emphasize that slip resistance and frictional behavior are strongly influenced by the test environment and various parameters such as variations in temperature, phase state of water, and surface contamination. These factors directly modify the interfacial and boundary conditions governing contact mechanics. For instance, one study demonstrated that friction is governed by mixed or lubricated regimes for icy and snow-covered surfaces, associated with pressure and friction-induced meltwater layers, resulting in a strong dependence on sliding speed and temperature [109]. In contrast, dry and wet flooring systems are predominantly controlled by adhesion and mechanical interlocking related to surface roughness. This behavior has been extensively reviewed in studies on footwear-ground friction that highlight how counterface texture and asperity interactions manage friction under different environmental conditions [110]. These distinctions underline that slip resistance measurements are inherently regime-specific, and their interpretation must account for the environmental conditions under which friction is generated. In the following, we discuss common test methods, highlighting their typical applications and relevance in evaluating slip resistance under different environmental conditions.

4.1 | Friction Testing

A variety of instruments and test methods are used to measure slip resistance. In laboratory settings, common tribometer configurations include simple setups like block-on-plane, pin-on-disk, or ball-on-plate apparatus, where a piece of the candidate material is dragged or rotated against a surface under controlled load and speed. In a notable study, Hidalgo et al. [111] used a custom-designed pin-on-disk tribometer built to international standards to examine the frictional, lubrication, and wear behaviors of various materials. This device allowed precise adjustments to key test parameters, such as applied load, rotational speed, and environmental conditions, enabling researchers to analyze material combinations under specific scenarios. The versatility of this tribometer highlighted its ability to adapt to diverse testing requirements, making it a reliable tool for detailed tribological assessments [111]. Similarly, Verma et al. [112], utilized a pin-on-disk tribometer to study the tribological performance of materials under dry conditions. The research focused on understanding material interactions in the absence of lubrication, an essential consideration for applications where lubrication is either impractical or undesirable. The findings provided crucial insights into material suitability for high-friction environments, such as dry climates or specialized safety equipment [112]. These studies highlight how useful and versatile tribometers are for COF testing. By providing consistent and reliable results, tribometers are crucial for selecting the right materials and evaluating their performance. This information is especially valuable in fields like industrial engineering and safety, where understanding surface interactions is key.

When applied to anti-slip technologies, tribometer testing helps identify and optimize materials that can provide the necessary friction to prevent slips, especially on slippery surfaces like ice or wet conditions. The results ensure that materials are well-suited for real-world use, enhancing safety and performance. Figure 11 represents a visual and conceptual understanding of the different tribometers. The working principles of the four types of tribometers are fundamentally similar in that they all involve controlled contact between surfaces to measure friction and wear; however, their specific configurations and applications vary. In the Pin-on-Disk Tribometer (Figure 11a), a stationary pin is pressed against a rotating disk under a set load, allowing for the measurement of friction and wear under sliding conditions. The Ball-on-Disk Tribometer (Figure 11b), operates similarly but uses a ball instead of a pin, enabling localized friction and wear analysis, particularly for coatings and thin films [113]. The four-ball tribometer uses three stationary balls and one rotating ball to assess lubricant performance, particularly under extreme-pressure conditions, making it well suited for lubricant testing (Figure 11c) [114]. Finally, the block-on-ring tribometer (Figure 11d), uses a block pressed against a rotating ring to measure friction and wear, often applied in ring-and-seal systems [109]. While all these tribometers aim to measure friction and wear, each is designed to accommodate specific materials, environments, and applications with variations in contact mechanisms such as stationary vs. rolling contact and point vs. line contact. Despite the variety of devices, an ongoing challenge noted in tribology research is correlating these friction measurements with actual slip outcomes since the relationship between measured COF and experienced slipperiness is complex [115].

Building on the importance of reliable friction testing methods, the dynamic friction tester (DFT) offers a more advanced approach to evaluating surface friction, especially under dynamic conditions. Unlike traditional tests, which measure slow sliding contact, the DFT assesses friction at various speeds, making it particularly useful for studying the interaction between tires and pavements, for instance, where high-speed friction is more relevant: indeed, testing friction at different speeds allows for a better understanding of how surfaces perform under real-world conditions. Additionally, the DFT is versatile and can be used in the field and the laboratory, providing flexibility for a wide range of applications. The DFT is also valuable for evaluating how different polishing techniques or material mixtures affect friction [116–118]. As shown in Figure 12, the tester features a rotating disk equipped with three spring-loaded rubber sliders, which encounter the surface as the disk slows down due to the friction between the sliders and the surface [119]. A water supply system is incorporated to simulate wet conditions, while the torque is measured to assess the friction generated by the interaction between the sliders and the surface during the spin-down process. The collected data is then analyzed to calculate the friction at various speeds, providing a detailed and comprehensive assessment of the surface's frictional performance [120].

4.2 | British Pendulum Test (BPT)

Numerous laboratory methods exist for measuring slip resistance, but the BPT remains one of the most widely recognized and used. Its enduring popularity is due to its accuracy, affordability, portability, and ease of use [121]. The result of this test is referred to as the British Pendulum Number (BPN) or the Pendulum Test Value (PTV) [122]. The BPT procedure involves using a pendulum tester equipped with a standard rubber slider to assess the frictional properties of a surface. Before testing, the surface must be thoroughly cleaned and wetted. The pendulum slider is carefully positioned to make light contact with the surface, then raised to a locked position and released to swing across the test area [123]. A drag indicator records the BPN, with higher readings indicating greater friction. The degree of oscillation lag corresponds directly to the frictional interaction between the slider and the surface, producing a quantitative measurement. The BPT also offers practical thresholds for interpreting slip risk according to BS 7976-2 standard. Surfaces with a PTV of 36 or above are considered to have very low slip risk. Values between 25 and 35 indicate moderate slip risk, while surfaces with a PTV below 25 are deemed highly prone to slippage [124]. This makes the BPT an essential tool for evaluating slip resistance in diverse applications, from flooring and pavements to industrial surfaces.

Cui et al. [125], focused on the interpretation of BPT measurements, aiming at enhancing the evaluation of floor slip

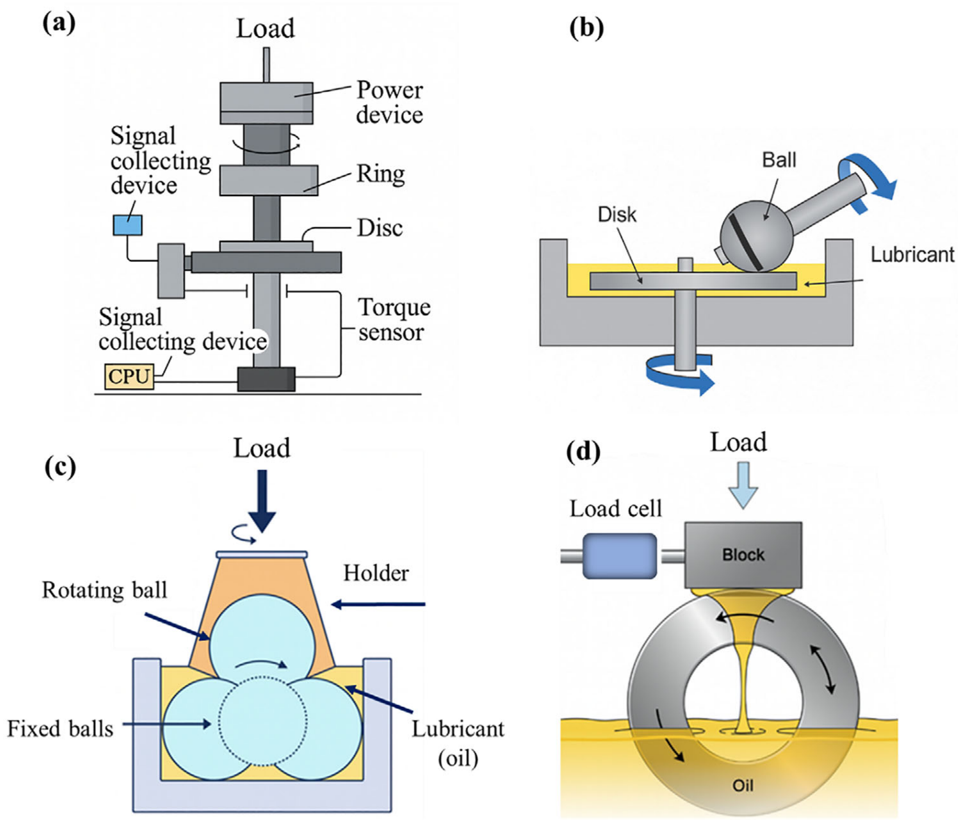


FIGURE 11 | Schematic representation of various types of tribometers: (a) Pin-on-Disk Tribometer; A stationary pin pressed against a rotating disk to evaluate friction and wear properties. (b) Ball-on-Disk; Similar to the pin-on-disk configuration, but a ball replaces the pin to facilitate point contact analysis (c) Four-Ball Tribometer; A setup with four balls arranged in a tetrahedral configuration, designed to assess lubricant properties under high-pressure conditions (d) Block-on-Ring; A system in which a block is pressed against a rotating ring to measure friction and wear characteristics.

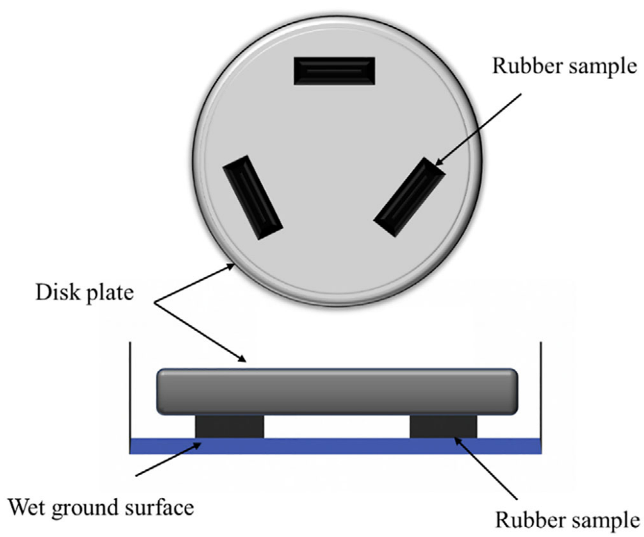
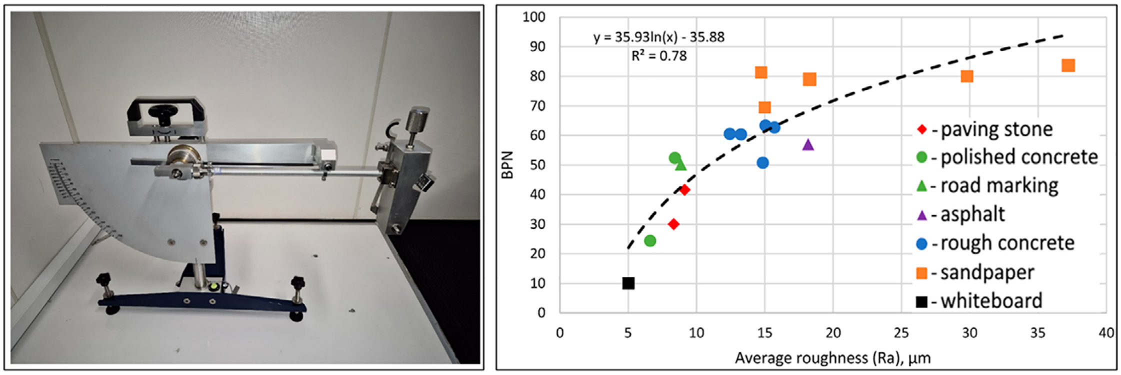


FIGURE 12 | Schematic of Dynamic Friction Tester (DFT).

resistance. They analyzed the correlation between BPT values and actual slip incidents, proposing adjustments to improve the test predictive accuracy. Their findings suggested that incorporating additional surface condition parameters could lead to more reliable assessments of slip potential. In another study, Cui et al. [126], introduced an improved BPT using a curved slider. This modification aimed to better simulate the contact mechanics between footwear and floor surfaces. The study demonstrated that the curved slider provided more consistent and representative measurements of slip resistance, particularly on textured surfaces, thereby enhancing the test's applicability to real-world conditions [126]. Figure 13a illustrates the British Pendulum Tester apparatus, used to evaluate various pavement textures. The results presented in Figure 13b were obtained by Baimukhametov et al. [127] using the BPT device to investigate the correlation between surface roughness and slip resistance. These studies underscore the BPT significance in evaluating slip resistance and highlight ongoing efforts to refine the method for more accurate and reliable assessments.

4.3 | Ramp/Inclined Plane Test

Slip resistance tests are also fundamental for evaluating the safety of walking surfaces by measuring the frictional properties of footwear and flooring materials. A variety of devices and methods have been developed to accurately measure slip resistance under realistic conditions [128, 129]. The portable slip simulator is designed to replicate real-world walking conditions. This device allows for in situ measurements of pedestrian slip resistance, providing DCOF results that correlate strongly with those obtained from force platforms. Aschan et al. [129] demonstrated that the portable slip simulator offered precise and user-friendly



(a) (b)

FIGURE 13 | (a) British Pendulum Tester device (b) Representative results of correlation between BPN value and average roughness. Reproduced under the terms of the CC BY 4.0 license [127]. Copyright 2024, MDPI, Basel, Switzerland.

measurements, with DCOF values showing a strong correlation with reference values.

The ramp test, also known as the inclined plane test, is a widely used method to evaluate slip resistance by determining the angle at which a person or object begins to slip on an inclined surface. During the test, the surface is gradually tilted until slipping occurs, and the critical angle, referred to as the slip angle, is recorded. This angle serves as a quantitative measure of the surface's slip resistance, with higher slip angles indicating greater resistance to slippage. The ramp test is particularly valuable for assessing flooring materials in environments prone to challenging conditions, such as wet or oily surfaces in kitchens, industrial facilities, and public spaces [130]. For instance, Reyes et al., [131], studied the application of the inclined plane test for measuring geosynthetic interface friction and examined the stability of sloping geosynthetic liner systems under low normal stress. The test provided critical insights into the frictional behavior of different geosynthetic materials, enabling better evaluation of their suitability for use in engineering applications such as landfill liners, retaining walls, and slope stabilization systems. This highlights the ramp test versatility in assessing material performance across a variety of real-world scenarios [131]. Furthermore, Sariisik et al., [132], described various slipping test methods and applied the ramp slip meter to travertine surfaces. Their study provided an overview of different slip resistance testing methods and demonstrated the application of the ramp slip meter in evaluating the slip resistance of travertine, a commonly used flooring material [132]. Similarly, the simulated walking on an inclined surface method assesses slip resistance by simulating the angle at which a person might slip on an inclined surface. This approach is particularly useful for evaluating flooring materials in environments where surfaces may become wet or oily, such as kitchens or industrial settings. Studies have applied this method to various flooring materials to determine their suitability for such conditions [32]. Figure 14 illustrates the ramp tester device along with representative results that demonstrate a clear correlation between slip resistance and DFOC. The related study aimed to explore the relationship between the slip angle in a ramp test and the static and dynamic coefficients of friction measured by the device on glycerol-contaminated floor sheets. Results show that DCOF values, particularly at sliding velocities below 0.3 m/s, are highly correlated with the slip angle (Figure 14b), indicating the device can effectively simulate slip resistance in ramp tests. This validates the device as a reliable tool for assessing slip resistance and preventing slip-induced falls [114].

In addition to material and specimen-level tribological tests, whole-shoe testing is essential for evaluating slip resistance in safety footwear, as it accounts for the combined effects of outsole material, tread design, shoe construction, and human-surface interaction. Ramp-based whole-shoe testing protocol was developed by Hsu et al. [133] and studied to evaluate footwear performance on inclined surfaces under realistic walking conditions. These studies quantify slip resistance based on the maximum slope angle at which participants can walk without slipping, and thus capturing the combined effects of outsole material, tread design, shoe construction, and human gait dynamics. Such whole-shoe ramp tests have been successfully applied to assess footwear performance on contaminated, icy, and outdoor walking surfaces, providing application-level insight that complements laboratory-scale friction measurements and material-level ramp tests [134, 135]. Such ramp tests help bridge the gap between fundamental tribological characterization and real-world slip scenarios. In parallel, standardized wholeshoe testing methods provide a system-level evaluation of footwear slip resistance that complements laboratory tribological measurements. The SATRA TM144 wholeshoe slip resistance test, which forms the basis of international standards such as ISO 13287 and ASTM F2913, is widely used to assess the frictional performance of footwear on representative flooring surfaces. Gauvin et al. [136] applied the SATRA TM144/STM603 tester with an ice tray to evaluate slip resistance on icy surfaces, and compared mechanical test results with human-centred Maximum Achievable Angle (MAA) methods. Their study demonstrated that while the SATRA wholeshoe method provides reproducible and industry-accepted measurements, differences with human-centred tests underline the importance of considering real-world walking conditions when interpreting mechanical test results [136].

4.4 | Wehner–Schulze (W/S) Friction Test

The Wehner–Schulze friction device is a specialized tool designed to evaluate flat circular surfaces with a diameter of 225 mm, combining both polishing and skid-resistance measurements in

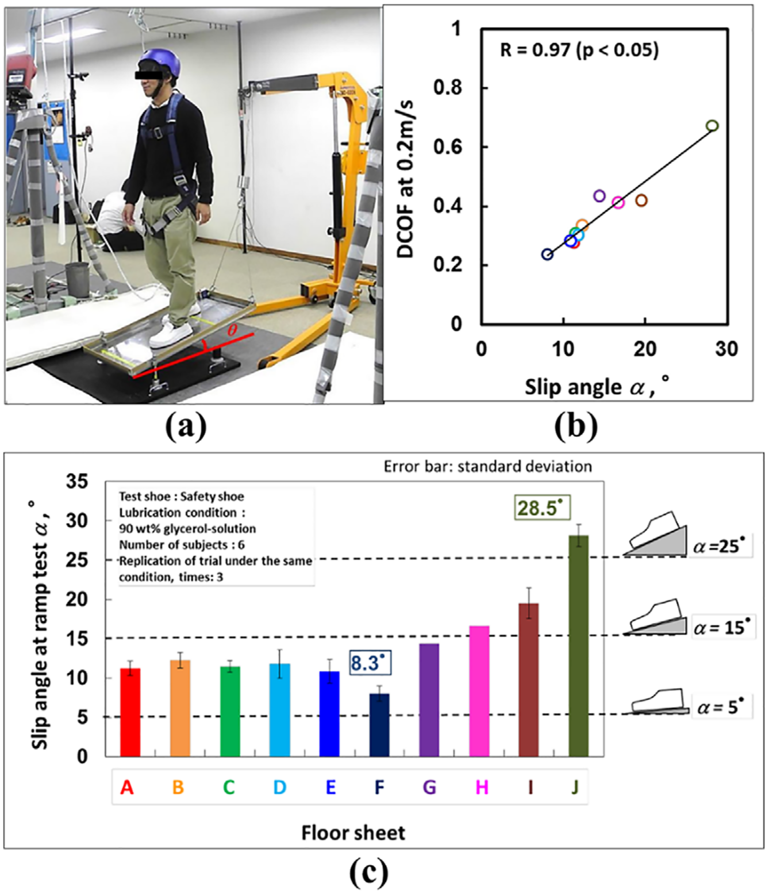


FIGURE 14 | (a) Overview of ramp test (b) Correlation between average slip angle values in the ramp test and average DCOF values (c) Average slip angle value of different floor sheets. Reproduced under the terms of the CC BY 4.0 license [130]. Copyright 2018, The Japan Society of Mechanical Engineers.

a single setup. The polishing process utilizes a rotating head equipped with three rubber-covered conical rollers (Figure 15a), which operate at a speed of 500 rpm, enabling up to 90 000 polishing passes per hour. To enhance the polishing effect, a water-quartz powder slurry is continuously applied to the surface. After completing a user-defined number of polishing passes, the process is halted, and the specimen is thoroughly washed to remove any residual quartz powder. Following the polishing phase, the skid resistance is assessed using a measurement head equipped with three testing rubbers (Figure 15b) [137]. As a practical example, Wang et al. [138], investigated how different aggregate sizes affect the skid resistance of asphalt surfaces. Using the Wehner–Schulze test, the research separately evaluates fine and coarse aggregates embedded in epoxy to simulate pavement surfaces. Results revealed that both aggregate types significantly influence polishing resistance, with fine aggregates playing a more critical role than previously assumed. This study concludes that the Wehner–Schulze test is an effective method for assessing the frictional performance of pavement materials under realistic wear conditions.

4.5 | Tire-Pavement Dynamic Friction Test

The tire-pavement dynamic friction analyzer (TDFA) testing system is created to evaluate the frictional characteristics of pavement by considering the interaction between tires and pavement [139]. It can measure the COF of pavement under various conditions, like tire speeds, slip ratios, and loads in real-time. As the engine turns the pavement specimen, the test wheel will also rotate. Constrained by the rear tension sensor, each testing tire can rotate around the wheel centre. This allows for the real-time recording of data on upper load and tire-pavement friction by controlling the system based on specified working conditions like upper loads, slip ratios, and tire rotating speeds. Subsequently, the COF can be determined [121, 139, 140]. Figure 16, illustrates the devices explained in this section. In Figure 16a, the testing system is shown where the upper load is applied to the wheels via vertical displacement and pressure control. This control is achieved through a hydraulic pump in combination with electromagnetic valves, as further detailed in Figure 16d. Real-time monitoring of tire pressure is performed using a pressure sensor mounted vertically above each tire, as shown in Figure 16a. To account for the circular-motion tendency of the tires resulting from the rotation of the slab specimen, a tension sensor is placed at the rear of each tire (Figure 16b,c), which constrains the movement. This configuration allows the system to detect the friction force between the tire and the specimen, as it is equivalent to the tension force. Figure 16e,g, further illustrate the overall setup and component placements, ensuring precise control and measurement throughout the testing process.

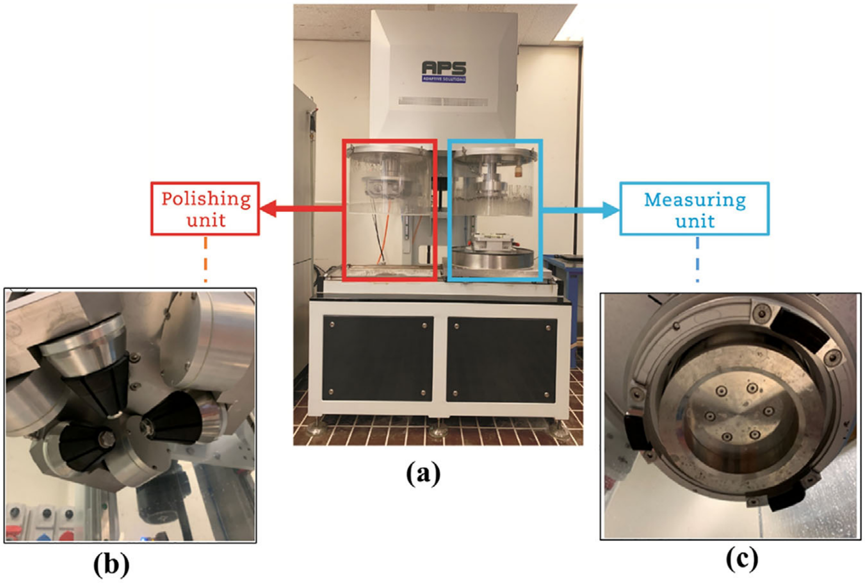


FIGURE 15 | (a) Wehner Schulze (W/S) device; (b) polishing head with rubber rollers (c) Measuring head equipped with three testing rubbers. Reproduced under the terms of the CC BY-NC-ND 4.0 license [137]. Copyright 2024, Periodical Offices of Chang'an University. Publishing services provided by Elsevier B.V. on behalf of KeAi Communications Co. Ltd.

Table 2 presents an overview of various testing methods used to evaluate slip resistance and anti-slip performance, summarizing both traditional and modern techniques. It outlines the specific procedures and conditions under which each method is applied, such as surface type and test environment, and also highlights the key parameters measured, including the COF, PTV, and critical slipping angle. To summarize, methods like the friction Test, BPT, and slip resistance test are commonly used for evaluating flooring materials, coatings, and pavements, while more advanced tools, such as the portable slip tester and dynamic friction tester, enable on-site or high-precision analysis under wet or dry conditions. Moreover, simulated walking and ramp tests provide realistic assessments of footwear and anti-slip materials, and long-term performance is captured through techniques like the Wehner/Schulze test. Together, these methods offer a comprehensive comparison of available tools for assessing slip resistance in both laboratory and real-world scenarios.

For a more efficient use of the mentioned testing methods, a better comparison is crucial to understand their distinct advantages, limitations, and appropriate application contexts. This is particularly important because slip behavior is highly sensitive to environmental conditions, material properties, surface contamination, and even human gait. For instance, the BPT remains widely used due to its portability and standardized PTV classification, but it is less suitable for highly textured or soft materials where slider deformation affects accuracy. In contrast, ramp-based tests incorporate human subjects, offering superior real-world relevance for assessing wet, oily, or contaminated surfaces. Although they are more labor-intensive and costly. Friction testing by Tribometer measurements provides controlled, reproducible conditions for research into textures, coatings, and filler-modified materials, mostly used in research studies in laboratories. However, finding the best protocol for different materials on various conditions would be challenging, particularly when it comes to simulating the real-world conditions. On the other hand, portable slip testers such as the BOT-3000E bridge laboratory precision with field practicality by enabling dynamic COF assessments on-site.

Inclined walking tests simulate actual heel-strike mechanics and are therefore highly valuable for footwear and sloped surfaces, but they require specialized equipment and strict safety protocols. To clearly differentiate these approaches, Table 3 presents a comparative analysis summarizing their strengths and limitations, offering a structured basis for selecting appropriate slip-testing methods depending on the intended environment and material system.

5 | Applications of Anti-Slip Materials

Anti-slip materials play a vital role in ensuring safety across a wide range of applications. These materials mitigate the risk of accidents caused by slipping and falling in transportation infrastructure, indoor environments, and personal protective equipment. This section explores the practical applications of the material strategies discussed above, highlighting unique functional requirements and recent advancements. Figure 17 illustrates the deployment of anti-slip materials across a wide array of environments and use cases.

In transportation, anti-slip coatings are commonly applied to pavements, roads, and highways to enhance skid resistance, particularly under adverse weather conditions such as rain, snow, or ice. Studies have demonstrated the effectiveness of anti-slip and wear-resistant coatings in reducing accidents while improving the longevity of roads [12]. Maintaining surface grip is critical for road safety in transportation infrastructure. To ensure long-term skid resistance, engineers often use hard, rough aggregates, such as calcined bauxite [141] or igneous rocks [142] in the top layer

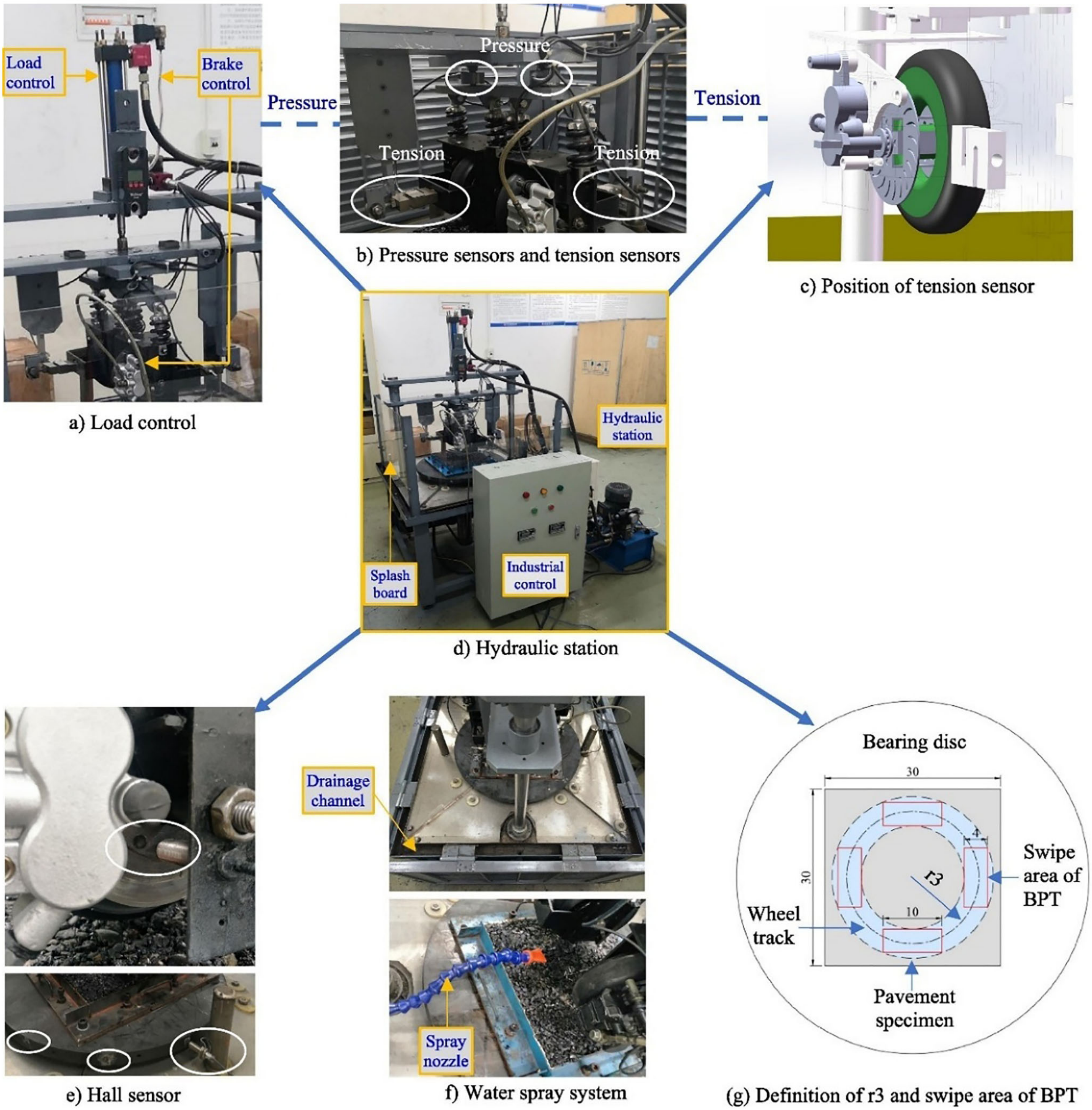


FIGURE 16 | Major Components of Tire-pavement Dynamic Friction Test. Reproduced with permission [140]. Copyright 2020, Elsevier Ltd.

of asphalt. While polymer-modified asphalt binders [143] can slightly enhance traction by increasing surface elasticity, the type and quality of the aggregate have a more substantial and lasting impact. Over time, traffic wears down road surfaces, making them smoother and reducing their skid resistance. Additionally, the buildup of dust, oil, and rubber can further decrease friction. To address these issues, transportation authorities regularly assess skid resistance using tools like the British Pendulum Tester and apply maintenance measures such as resurfacing or surface treatments when needed [144]. The friction mechanism itself is complex, involving adhesion, hysteresis, and plowing effects. A deep understanding of these components is essential for designing pavements with enhanced and durable skid resistance [145, 146].

Recent research highlights advancements in materials and surface treatments to enhance the skid resistance of the pavements. For example, Meng et al. [106] found that incorporating basalt aggregates into asphalt mixtures significantly improved both skid resistance and durability. Additionally, surface treatment technologies have been developed to effectively improve the skid resistance and durability of concrete pavements. Lei et al. [147] demonstrated that applying surface treatments to tunnel concrete pavements effectively improved their skid resistance, creating safer driving conditions. These innovations underscore the importance of material engineering in transportation safety. On the vehicle side, slip resistance corresponds to traction, the grip between the tire and the road surface. Both tread pattern and rubber composition are critical factors in tire

TABLE 2 | Overview of testing methods for evaluating slip resistance and anti-slip performance.

Test	Device/Tool	Procedure	Measured parameters	Applications in slip resistance testing
Friction test	Tribometer	A sample is slid across a surface under controlled conditions to measure friction force.	Coefficient of Friction (COF) values indicating the frictional properties of the material.	Evaluating slip resistance of various materials, coatings, and surfaces,
British Pendulum Tester (BPT)	Tester	A pendulum with a rubber slider strikes the surface, and the energy loss is recorded.	Pendulum Test Value (PTV); a PTV of 36 or higher is generally considered slip resistant.	Assessing slip resistance of wet/dry pavements, tiles, and road surfaces.
Slip resistance test	Slip resistance tester	Simulates slip by applying a standard test foot to the surface, assessing friction during simulated movement.	Coefficient of friction (COF) values; higher values indicate better slip resistance.	Flooring surfaces, industrial applications, and coatings.
Ramp test	Inclined plane or ramp system/ SATRA whole shoe test	A surface is inclined gradually until the material begins to slip, and the angle is recorded.	Critical angle at which slipping occurs; used to classify slip resistance.	Testing footwear, tiles, and flooring materials for slip resistance.
Portable slip tester	BOT-3000E portable tester	The device moves across the surface, applying a known force and measuring static and dynamic COF.	Dynamic coefficient of friction (DCOF) values; a DCOF of 0.42 or higher is often considered acceptable.	On-site testing for walkways, ramps, and industrial floors.
Simulated walking test on an inclined surface	Inclined surface ramp, motion capture system	Test subjects walk on an inclined ramp, which is raised until slipping occurs, and the angle is noted.	Angle at which slipping occurs; provides practical assessment of slip potential in real-world scenarios.	Evaluating anti-slip materials and footwear under realistic conditions.
Wehner/Schulze friction test	Wehner/Schulze device	The device polishes a sample using rotating rubber rollers to simulate traffic wear, followed by measuring the friction coefficient.	Friction after polishing (FAP) values; indicates how road surfaces maintain friction over time.	Long-term evaluation of pavement and road surface friction.
Tire-pavement dynamic friction test	DFT	A rotating disk with attached rubber sliders is brought into contact with a wetted pavement surface, and the friction force is measured as the disk decelerates	Coefficient of friction as a function of speed; used to assess pavement skid resistance under various conditions.	Evaluating road coatings, tires, and pavements under wet or dry conditions.

TABLE 3 | Comparison between testing methods for evaluating slip resistance.

Method/Tool	Strengths	Limitations
British Pendulum Tester (BPT)	Portable and easy to use Standardized PTV scale Effective on pavements and hard flooring	Less accurate on soft or highly textured surfaces Slider deformation reduces reliability Limited realism for contaminated surfaces
Tribometer (laboratory friction testing)	Highly controlled testing conditions • High reproducibility Suitable for studying materials, coatings, and textures	Limited real-world relevance Difficult to simulate human gait or contaminants Protocol selection varies with material type
Ramp-based Test / SATRA Whole Shoe Test	Incorporates human walking dynamics High realism for wet, oily, or contaminated surfaces Widely accepted for footwear and flooring	Labor-intensive and costly Requires trained subjects and safety protocols Limited portability
Portable Slip Tester	On-site dynamic COF measurement Combines lab precision with field practicality Standardizable and portable	Sensitive to calibration and operator influence Not ideal for highly irregular surfaces
Inclined Walking /Human Gait Simulation	Realistic heel-strike mechanics High relevance for sloped and outdoor surfaces Useful for ice and winter-footwear studies	Requires specialized equipment Safety concerns and strict protocols Variability between subjects
Wehner/Schulze Test	Measures long-term friction after wear Good for durability evaluation Standard for pavement friction over time	Large and complex equipment Only suitable for hard materials Not applicable to flexible polymers

design. In recent years, manufacturers have increasingly used high-silica rubber compounds to enhance wet traction without compromising durability. This approach builds on the “green tire” technology introduced in the 1990s and has since been refined. Silica particles in the rubber matrix help reduce hysteresis losses at low frequencies (improving rolling resistance) while maintaining or even increasing hysteresis at higher frequencies, which are more relevant to microscale slip. As a result, these compounds improve wet friction and overall grip performance [148].

Slip resistance is equally crucial for indoor floor coverings and winter footwear to prevent accidents caused by slipping. The choice of materials and surface treatments plays a vital role in these applications. In winter footwear, the design of outsoles and the materials used are critical for providing adequate traction on icy and snowy surface [7, 133, 149]. In casual and outdoor footwear, anti-slip features are often promoted under terms like “traction” or “grip” technology. Brands have developed proprietary rubber formulations specifically designed to improve performance on challenging surfaces such as wet ice.

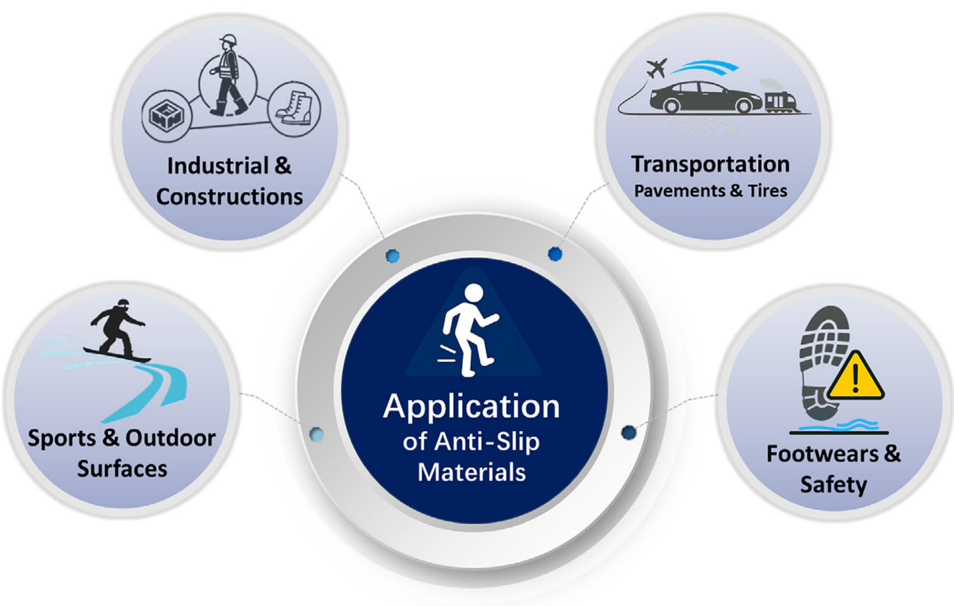


FIGURE 17 | Application of anti-slip materials in industrial environments and everyday use.

For example, incorporating glass fibers into shoe soles enhances traction by physically scratching into the ice surface. A study by Nishi et al. demonstrated the potential of carbon/salt-filled rubber compounds to improve grip on icy surfaces. This innovation could be integrated into the next generation of winter footwear [48]. Repeated incidents of slipping and falling are also frequently observed in workplaces and are often attributed to reduced friction between the floor and shoes due to wear and tear [150]. However, the choice of outsole material greatly influences slip resistance. In a study conducted by Bagheri et al. [101], the anti-slip performance of shoes using composite soles was degraded after 75 000 steps. They examined the effect of wear on the slip resistance of winter footwear with composite outsoles, highlighting the importance of material durability in maintaining slip resistance over time. Previously, they had found that shoes with composite materials in their outsoles significantly reduced the risk of slipping. They employed the most achievable angle (MAA) protocol, which measures the steepest ice-covered slope that individuals can walk on without skidding [151]. Furthermore, they investigated the use of a poly(p-phenylene-2,6-benzobisoxazole) composite as a soft fiber and carbon fiber as a hard fiber in a thermoplastic polyurethane matrix to enhance the COF. The best result was achieved with a composite containing 8% fiber content by volume, molded at 120°C, yielding a COF of 0.61 ± 0.053. The inclusion of PBO improved abrasion resistance and addressed the disadvantages of CF, such as low elongation and poor fracture toughness [97]. Similarly, Colonna et al. [152] investigated the effect of glass fiber/rubber composites on ice grip. Their study showed that incorporating glass fibers enhanced the COF due to the stiffness of the fibers, which increased the mechanical grip on icy surfaces.

Since slip resistance is a critical requirement in work and safety footwear, many countries regulate it through standards such as ASTM F2913 and ISO 13287 [133]. Footwear that performs well in these tests typically features soft rubber compounds designed to maximize hysteresis (viscoelastic) friction. Soft rubbers easily conform to microscopic surface irregularities, increasing contact and grip [153]. These compounds are often designed with additives to enhance performance under specific conditions. For example, nitrile butadiene rubber is commonly used in food-service and kitchen footwear due to its resistance to oil saturation by maintaining effective grip [154]. Outsole designs also play a key role: tread designs with numerous micro-lugs or channels improve fluid drainage and provide multiple biting edges for traction on uneven surfaces [155]. In recent years, there has been a growing focus on slip-resistant footwear for healthcare and hospitality workers, sectors that report high rates of slip-related injuries. Notably, a large randomized controlled trial in the healthcare sector showed nearly a 50% reduction in slip-induced falls among workers wearing high-rated slip-resistant shoes [156].

Beyond footwear, ensuring safe walking surfaces in public buildings, particularly for the elderly and disabled, is a top safety priority [157]. Slipping and falling remain significant causes of injury. Kim [32] emphasized that slip resistance and floor surface finishes are closely related, especially in environments with high slipperiness. Derler et al. [158] investigated the effects of various anti-slip treatments on resilient floor coverings. These treatments include protective two-layer coating, anti-slip quartz coating, and polymer coating with granules. The protective coating consists of a two-layer system; Spirit Sealer followed by a Topcoat (Henkel), applied sequentially over resilient floor coverings. This treatment creates a micro-roughened surface that increases the initial coefficient of friction while providing wear resistance. Their findings revealed minimal changes in the annual average COF for untreated and reference floors (approximately +0.08). These results underline that not all anti-slip treatments are equally effective over time. Selecting the right surface treatment is critical to maintaining long-term slip resistance, especially in areas with vulnerable populations.

In summary, the application of effective anti-slip materials, whether through surface finishes or specialized treatments, directly impacts safety in many settings. Whether it is ensuring the stability of the transportation systems, providing a secure footing in homes and workplaces, or enhancing the safety of personal protective gear, these materials are indispensable for modern safety. As we continue to advance in technology and prioritize safety, the ongoing innovation and integration of these solutions will undoubtedly keep improving well-being in all aspects of our lives.

6 | Challenges and Future Outlooks

Material strategies for enhancing slip resistance have advanced significantly in recent years, driven by a deeper understanding of friction mechanisms and the adoption of cross-disciplinary design approaches. Modern anti-slip solutions now operate across multiple scales, from macro-scale rough textures and embedded grits to micro- and nano-scale engineered structures and coatings, each designed for specific application contexts. These innovations have found practical use in industries such as construction, healthcare, and sports, where they have contributed to safer flooring, equipment, and personal protective gear. Despite these advancements, important challenges remain, which can be grouped into two main areas: designing materials with targeted properties for durability and performance, and developing representative testing methods that simulate real-world conditions.

One key issue in material development is maintaining slip resistance over time, especially under mechanical and environmental stress, an issue related to durability. Future materials may address this by incorporating self-renewing or self-cleaning features. For example, surfaces that restore their roughness as they wear, or soles that shed debris automatically. Another major challenge is narrowing the gap between laboratory results and real-world performance. While standard tests like the friction testing provide useful benchmarks, more advanced and biomimetic testing methods are needed to better predict how materials perform in actual slip scenarios and to ensure they truly help prevent falls. Looking ahead, the emergence of bioinspired and smart materials presents exciting new possibilities. Innovations such as gecko-inspired hydrophilic adhesives and kirigami-patterned spiked surfaces demonstrate that effective slip resistance can be achieved through mechanisms beyond conventional roughness or tackiness [158]. As advanced manufacturing technologies evolve, these novel designs could become increasingly viable in everyday products. Furthermore, incorporating sensing capabilities into anti-slip materials such as magnetized flakes that provide both traction and feedback could enable predictive safety features, including footwear that warns users of low-traction conditions.

In summary, the challenges endure in the development of anti-slip materials. Durability under mechanical and environmental stress, cost-effectiveness for large-scale applications, and environmental sustainability are key concerns. Materials used in road coatings, winter footwear, and indoor surfaces often lose effectiveness due to wear and extreme conditions. Furthermore, variations in performance across different environments, such as icy vs. wet surfaces, emphasize the need for adaptable solutions. The reliance on synthetic polymers, while effective, raises ecological concerns, making the development of sustainable alternatives crucial.

To address the challenges mentioned above, future developments in anti-slip materials are expected to focus on multi-functional solutions that integrate slip resistance with additional performance attributes, such as mechanical strength, user comfort, ease of maintenance, and even energy harvesting, particularly in applications like smart footwear. At the same time, sustainability is emerging as a central priority, with increasing efforts to incorporate recycled materials (e.g., crumb rubber, recycled glass) and to minimize the use of volatile organic compounds (VOCs) in surface treatments. In the past decade, advances in science and material engineering have built a solid foundation for improving slip resistance.

Through careful testing, smart design, and a better understanding of user needs, today's surfaces and footwear are much safer. Looking forward, the next generation of anti-slip materials is expected to be even more effective, durable, and adaptable, helping to further reduce slip-and-fall accidents on roads, in workplaces, and in everyday life. Moreover, nanostructured surfaces, inspired by nature's textures, and the integration of nanoparticles like silica particles can significantly improve the durability, friction, and multifunctionality of anti-slip materials. The incorporation of adaptive materials that respond dynamically to environmental changes will help overcome the limitations posed by varying surface conditions. Additionally, establishing standardized testing protocols will be critical to accelerating the adoption of these innovations.

By combining these advanced design strategies with sustainable innovations, future anti-slip materials can deliver optimized performance, durability, and environmental compatibility. As research progresses, tailored solutions for specific applications ranging from pavements to footwear will ensure safer, more resilient materials, contributing to enhanced safety and sustainability across diverse sectors.

Looking forward, anti-slip material development will increasingly focus on application-specific designs for safety-critical environments. This includes vehicle types, where anti-slip performance remains underexplored, and durable footwear, where maintaining friction under real-world conditions is challenging. Hybrid surface patterning at micro- and nano- scales, inspired by biomimetic designs, can improve traction without compromising comfort or wear resistance, while hierarchical structures help maintain friction across a variety of slippery conditions. To bridge the gap between laboratory and practical performance, simulation and modeling, along with realistic durability testing protocols that account for dynamic loads, environmental variations, and friction behavior, are essential.

Beyond material composition and surface patterning, the integration of smart sensing and adaptive features presents promising opportunities. For example, magnetized or piezoelectric fillers could enable surfaces to respond dynamically to moisture, ice, or wear, or provide user feedback for predictive safety. Sustainability is also a critical consideration: future anti-slip solutions should incorporate recyclable elastomers, bio-based polymers, and low-VOC or water-based formulations, particularly for high-volume products such as footwear. Ultimately, multi-functional approaches that combine slip resistance, mechanical strength, user comfort, and environmental adaptability will be essential. By integrating these strategies, next-generation anti-slip materials can achieve durable, high-performance, and environmentally compatible solutions across diverse applications, from pavements to types and winter footwear, significantly enhancing safety under real-world conditions.

7 | Conclusion

This review has explored the key material strategies and recent advancements in the development of anti-slip surfaces, emphasizing the roles of surface texturing, chemical treatments, and filler incorporation. Emerging techniques such as laser texturing, biomimetic designs, and hierarchical structuring have demonstrated promising improvements in grip and frictional performance. Additionally, the incorporation of functional fillers and surface grooving methods has further enhanced performance, particularly under harsh or variable conditions. Standardized evaluation methods, including the Friction Test, British Pendulum Test, Ramp Test remain critical for assessing slip resistance and ensuring materials meet regulatory and safety standards. Despite these advancements, several challenges persist. Ensuring long-term durability under mechanical and environmental exposure, reducing environmental impact, and translating laboratory performance into real-world effectiveness remain key concerns. Addressing these issues will require the development of adaptive materials, improved sustainability practices, and the implementation of more application-specific testing protocols. Moving forward, interdisciplinary efforts combining materials science, surface engineering, and biomechanics will be essential to design the next generation of anti-slip materials that are not only more effective and durable, but also sustainable and tailored to the demands of diverse real-world environments.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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