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Full Length Research

Determination of Tribology Parameters for the Production of High Quality Personal Protective Boots Used In Industrial Environments

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Background: This study investigates the tribological parameters essential for producing high-quality personal protective boots used in industrial environments in Nigeria. The focus is on evaluating the slip resistance and performance of six commonly used local footwear soling materials: solid vulcanized rubber (SR), synthetic thermoplastic rubber (TPR), polyvinyl chloride (PVC), polyurethane (PU), ethylene vinyl acetate (EVA), and microcellular rubber (MCR).
Methods: Various physical properties, including density, hardness, tensile strength, elongation at break, and abrasion resistance, were measured for each material. The coefficient of friction (COF) was assessed under different contaminant conditions (dry, wet, detergent, vegetable oil, and engine oil) and on different floor types (marble, ceramic, quarry, and wood). Additionally, the impact of tread width (5 mm, 10 mm, and 15 mm) and orientation (vertical, horizontal, and diagonal) on slip resistance was analyzed.
Results: Polyurethane (PU) consistently exhibited the highest COF values, demonstrating superior slip resistance across all conditions and floor types. For example, PU showed a COF of 0.90 under dry conditions and 0.70 under wet conditions, and a COF of 0.87 with diagonal tread orientation. Solid vulcanized rubber (SR) and microcellular rubber (MCR) also showed strong performance, with SR exhibiting a COF of 0.85 with a 15 mm tread width and 0.82 with diagonal tread orientation. The study highlighted significant variability in the physical properties and slip resistance of the materials, such as SR with a tensile strength of 12.5 N/mm^2 and PVC with an abrasion resistance of 200 mm^3, emphasizing the importance of material selection and tread design.
Conclusions: The findings underscore the critical role of material selection and tread design in enhancing the safety performance of industrial footwear. The study provides valuable insights for manufacturers to optimize safety boot designs and contribute to the development of improved PPE standards and legislation in Nigeria. Emphasizing locally sourced materials, the research supports the potential for developing cost-effective, high-quality safety boots that enhance worker safety while supporting local economies.

Keywords: Slip resistance, Coefficient of friction, Safety boots, Industrial footwear, Tribology, Tread design, Local materials, Nigeria.

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INTRODUCTION

This research aimed to evaluate the quality of safety boots used in industrial environments for slip resistance, testing materials like solid vulcanized rubber (SR), synthetic thermoplastic rubber (TPR), polyvinyl chloride (PVC), polyurethane (PU), ethylene vinyl acetate (EVA), and microcellular rubber (MCR). The soles featured various tread widths and orientations, and were assessed under different contaminant conditions to determine the influence on the coefficients of friction (COF). This study simulated various industrial floor scenarios to provide empirical data for enhancing personal protective equipment (PPE) standards in Nigerian workplaces.

Safety boots, made from materials like leather or rubber, are essential for industrial workers, offering protection against various hazards such as heat, cold, water, slips, oil, and fire (Bartkowiak *et* ***al.***, 2012). Patel *et al*., 2017). They also provide electrical resistance and feature steel toe caps and metallic inserts for additional protection(Omale et al., 2013).The study underscores the universal need for high-quality safety boots in harsh industrial environments and their role in meeting industrial safety norms.

Statement of the Problem

Slips are a leading cause of workplace falls, particularly in environments like industrial halls, warehouses, and machine rooms. Properly designed personal protective equipment (PPE), such as safety boots, is crucial in preventing these accidents. However, defective PPE, including poorly designed sole patterns and grips, can increase the risk of slips and falls, potentially leading to severe injuries or fatalities from falls or head injuries.

In workplaces, the slip resistance of safety boots is influenced by factors such as tread width, depth, design, groove distance, and orientation. These geometric parameters significantly affect the coefficient of friction (COF) at the shoe-floor interface, thereby impacting safety. The study focused on evaluating commonly used local footwear soling materials in Nigeria across various conditions to determine their slip resistance. By systematically analyzing different tread designs and orientations, the research aimed to identify optimal configurations that enhance workplace safety and reduce the incidence of slips and falls. Emphasizing the use of locally sourced materials, the study supports economic sustainability while ensuring industrial workers in developing countries like Nigeria have access to affordable and effective protective footwear.

Goals and Objectives of the Research

The research aimed at determining the tribology parameters essential for producing high-quality personal protective boots used in industrial environments in Nigeria. The objectives of the research included:

1. Measuring and analyzing the coefficient of friction (COF) between shoe soles and floors using local and commonly used floor tiles.
2. Evaluating different soling materials under dry conditions and four liquid contaminant conditions (water, detergent, vegetable oil, and engine oil).
3. Investigating the effects of tread width, depth, design, groove distance, and tread orientation on the slip resistance of safety boots.
4. Identifying optimal sole material and tread design configurations that enhance safety and reduce the risk of slips and falls in industrial environments.
5. Providing empirical data to support the development of improved PPE standards and legislation for workplace safety in Nigeria.
6. Promoting the use of locally available materials to create cost-effective and high-quality safety boots, thereby supporting local economies and ensuring accessibility for industrial workers.

Significance of the Study

The study highlights the significant psychological and economic impact of workplace accidents in Nigeria and the importance of safety regulations and PPE compliance. It focuses on the quality of safety boots available to Nigerian industrial workers and the necessity for proper utilization and design specific to work environments. The study establishes tribology parameters for high-quality protective boots, providing essential data for setting standards in safety boot production using local materials. The findings aim to improve PPE standards and legislation, ensuring optimal protection and supporting local economies. The research stresses continuous innovation in safety boot design to meet industrial safety demands. Focusing on locally sourced materials, the research is particularly relevant for developing countries like Nigeria, offering affordable, high-quality PPE that meets international safety standards. This contributes to worker safety and the productivity of industrial sectors in the region

METHODOLOGY

Footwear sole samples made from six materials—solid vulcanized rubber (SR), thermoplastic rubber (TPR), polyvinyl chloride (PVC), polyurethane (PU), ethylene vinyl acetate (EVA), and microcellular rubber (MCR) were prepared by cleaning the bottom part with a 50% ethanol solution to ensure cleanliness and then stored under standard atmospheric conditions. Physical properties including density, Shore A hardness, tensile strength (N/mm²), elongation at break, and abrasion resistance (mm³) were evaluated following ASTM or ISO standards for accuracy and consistency. Slip resistance tests were conducted according to EN ISO 13287:2012 standards on four types of flooring (marble, ceramic, quarry, wood) under dry, wet, detergent, vegetable oil, and engine oil conditions. Each sole material and floor condition underwent ten measurements, with the last five averaged, resulting in 750 observations (6 materials x 5 floors x 5 conditions x 5 measurements).

Coefficient of friction (COF) testing, following the same standards as slip resistance tests, assessed the slip resistance of each sole material under various contaminant conditions. Contact area tests were performed on PVC, EVA, SR, MCR, and TPR sole materials to evaluate their contact area influence on slip resistance.

The study investigated the impact of tread width and orientation on COF to determine optimal tread design for maximizing slip resistance. Statistical analysis included descriptive measures (mean, standard deviation), Pearson's correlation coefficient to analyze vertical load dependence on COF, ANOVA to assess effects of floor type, sole material, and surface condition on COF, and Duncan's multiple range tests to identify significant differences ($p < 0.05$). Analysis was conducted using SPSS software.

RESULTS AND DISCUSSIONS

Table 1: Physical Properties of Sole Materials

Sole Material	Density (g/cm³)	Hardness (Shore A)	Tensile Strength (N/mm²)	Elongation at Break (%)	Abrasion Resistance (mm³)
SR	1.15	65	12.5	350	150
TPR	1.10	60	11.0	300	170
PVC	1.35	70	10.5	250	200
PU	1.20	55	13.0	400	130
EVA	0.95	50	8.0	500	110
MCR	1.00	58	9.5	330	140

Note: Solid Vulcanized Rubber (SR)' Thermoplastic Rubber (TPR); Polyurethane (PU); Polyvinyl Chloride (PVC); Ethylene Vinyl Acetate (EVA), Microcellular Rubber (MCR)

PVC exhibited the highest density (1.35 g/cm³) and hardness (70 Shore A), indicating its potential for durability and resistance to wear. However, its high density may also make it heavier, potentially affecting user comfort. EVA had the lowest density (0.95 g/cm³) and hardness (50 Shore A), suggesting a lighter and more flexible material, which could enhance comfort but may compromise on durability and slip resistance.

PU demonstrated the highest tensile strength (13.0 N/mm²) and elongation at break (400%), indicating its excellent ability to withstand stretching forces and deformation. This makes PU a robust material for safety boots, capable of enduring the stresses and strains typical in industrial environments. Conversely, EVA, with the lowest tensile strength (8.0 N/mm²), may not be as durable under high-stress conditions, despite its high elongation at break (500%), which provides good flexibility.

Abrasion resistance is crucial for determining the longevity of the sole material in harsh working conditions (Bhushan, 2012). PU showed the best abrasion resistance (130 mm³), followed closely by EVA (110 mm³), which, despite its lower tensile strength, offers substantial durability against wear and tear. PVC, on the other hand, had the highest abrasion loss (200 mm³), indicating it may wear down more quickly under abrasive conditions.

Solid Vulcanized Rubber (SR) and Thermoplastic Rubber (TPR) offer a balanced combination of good tensile strength, moderate hardness, and acceptable abrasion resistance, making them suitable for general industrial applications. Polyurethane (PU) stands out as the most versatile material with excellent tensile strength, elongation, and abrasion resistance, making it highly suitable for environments demanding both durability and flexibility.

Polyvinyl Chloride (PVC), despite its high hardness and density, may not perform as well in terms of flexibility and abrasion resistance, suggesting limited use in areas requiring high durability.

Ethylene Vinyl Acetate (EVA), with its low density and excellent elongation, provides comfort and flexibility but may need reinforcement for high-stress applications. Microcellular Rubber (MCR) presents a good balance of properties, making it a reliable choice for safety boots, particularly where moderate flexibility and durability are required (Afolabi *et al*., 2021).

Table 2: Coefficient of Friction (COF) under Different Contaminant Conditions

Sole Material	Dry	Wet	Detergent	Vegetable Oil	Engine Oil
SR	0.85	0.65	0.60	0.50	0.45
TPR	0.80	0.60	0.55	0.45	0.40
PVC	0.75	0.55	0.50	0.40	0.35
PU	0.90	0.70	0.65	0.55	0.50
EVA	0.70	0.50	0.45	0.35	0.30
MCR	0.80	0.60	0.55	0.45	0.40

Table 2 presents the COF values for various sole materials tested under dry, wet, detergent, vegetable oil, and engine oil conditions. Under dry conditions, PU exhibited the highest COF of 0.90, indicating strong frictional grip on dry surfaces. This suggests PU is effective in environments where moisture levels are low, offering stable footing and reducing the risk of slips. SR and TPR also performed well under dry conditions.

In wet conditions, where surfaces are more prone to slipping, PU again demonstrated superior performance with a COF of 0.70. This indicates PU maintains good traction even when surfaces are wet, making it suitable for environments where spills or wet floors are common. EVA, with a COF of 0.50, showed the lowest performance among the materials tested under wet conditions, suggesting reduced slip resistance.

The presence of detergents, vegetable oil, and engine oil further affects COF values. Generally, all materials showed decreased COF values under these contaminant conditions compared to dry and wet scenarios. PU consistently maintained higher COF values across all contaminants, emphasizing its robust slip resistance capabilities across diverse industrial settings.

Table 3: Coefficient of Friction (COF) on Different Floor Types

Sole Material	Marble	Ceramic	Quarry	Wood
SR	0.55	0.65	0.70	0.75
TPR	0.50	0.60	0.65	0.70
PVC	0.45	0.55	0.60	0.65
PU	0.60	0.70	0.75	0.80
EVA	0.40	0.50	0.55	0.60
MCR	0.50	0.60	0.65	0.70

On marble floors, which are typically smooth and slippery, PU displayed the highest COF (0.60), indicating better slip resistance compared to other materials. EVA had the lowest COF (0.40), suggesting it provides the least grip on marble surfaces, which could increase the risk of slips in such environments.

PU again outperformed other materials on ceramic floors with a COF of 0.70. This higher COF value highlights PU's capability to maintain traction on ceramic surfaces, which can be common in industrial settings. PVC, with a COF of 0.55, showed moderate performance, while EVA remained the lowest at 0.50.

Quarry floors are often rough and textured. PU achieved the highest COF (0.75), demonstrating excellent slip resistance on such surfaces. SR and MCR also performed well with COF values of 0.70 and 0.65, respectively. EVA, at 0.55, continued to show the lowest COF, indicating lesser effectiveness on rough surfaces.

On wood floors, PU reached the highest COF of 0.80, indicating superior grip and safety performance. SR followed with a COF of 0.75, and TPR and MCR both recorded 0.70. EVA, at 0.60, again had the lowest COF, suggesting less slip resistance compared to other materials on wooden surfaces.

Table 4: Contact Area Measurements

Sole Material	Contact Area (cm²)
SR	20
TPR	18
PVC	22
PU	19
EVA	17
MCR	18

Solid Vulcanized Rubber (SR) exhibited a contact area of 20 cm², indicating a substantial surface interaction that contributes to its good slip resistance properties observed in previous tests. This larger contact area helps in distributing weight and providing stability, making SR a reliable choice for safety boots in various industrial environments. Thermoplastic Rubber (TPR) with a contact area of 18 cm² provides a moderate level of surface interaction. This measurement supports its performance seen in the COF tests, where TPR showed reasonable slip resistance. The contact area is sufficient for general industrial use, balancing between flexibility and stability.

Polyvinyl Chloride (PVC) had the largest contact area of 22 cm² among the materials tested. This extensive surface interaction can enhance its slip resistance by providing more grip. However, despite its large contact area, PVC's COF values were lower than those of PU and SR, suggesting that other factors such as material hardness and elasticity also play critical roles in slip resistance.

Polyurethane (PU) displayed a contact area of 19 cm². This area is slightly larger than TPR and MCR but smaller than PVC. The combination of a moderately large contact area with high COF values in various conditions underscores PU's effectiveness in providing excellent slip resistance (Ammad *et al*., 2020). PU's balance of contact area and material properties makes it an optimal choice for safety footwear.

Ethylene Vinyl Acetate (EVA) had the smallest contact area at 17 cm². This limited surface interaction correlates with its lower COF values across different conditions, indicating less slip resistance. While EVA offers flexibility and comfort due to its material properties, its smaller contact area suggests it may not be ideal for environments where high slip resistance is crucial.

Microcellular Rubber (MCR) showed a contact area of 18 cm², similar to TPR. This measurement is adequate for providing reasonable slip resistance, as seen in its COF performance. MCR's contact area, combined with its material properties, makes it suitable for industrial settings requiring a balance of durability and slip resistance.

Table 5: Effect of Tread Width on Coefficient of Friction (COF)

Tread Width (mm)	SR	TPR	PVC	PU	EVA	MCR
5	0.75	0.70	0.65	0.80	0.60	0.70
10	0.80	0.75	0.70	0.85	0.65	0.75
15	0.85	0.80	0.75	0.90	0.70	0.80

SR shows a progressive increase in COF with increasing tread width, from 0.75 at 5 mm to 0.85 at 15 mm. This indicates that wider treads enhance the slip resistance of SR, making it more effective at preventing slips as the tread width increases.

Similar to SR, TPR also exhibits an increase in COF with wider treads. The COF values rise from 0.70 at 5 mm to 0.80 at 15 mm. This suggests that TPR benefits from wider treads, improving its traction and reducing the risk of slipping. PVC follows the same trend, with COF values increasing from 0.65 at 5 mm to 0.75 at 15 mm. Although PVC has the lowest COF values compared to other materials, the improvement with wider treads indicates that its slip resistance can be enhanced through tread design.

PU demonstrates the highest COF values across all tread widths, starting at 0.80 for 5 mm and reaching 0.90 for 15 mm. This consistent performance across varying tread widths highlights PU's superior slip resistance and its effectiveness in diverse conditions. EVA shows the lowest COF values among the materials tested, with an increase from 0.60 at 5 mm to 0.70 at 15 mm. While wider treads improve EVA's slip resistance, its overall performance remains lower compared to other materials, suggesting it may not be the best choice for high-slip-risk environments.

MCR exhibits a similar pattern to SR and TPR, with COF values increasing from 0.70 at 5 mm to 0.80 at 15 mm. This improvement with wider treads suggests that MCR can be an effective material for safety boots, particularly when designed with wider tread.

Table 6: Effect of Tread Orientation on Coefficient of Friction (COF)

Tread Orientation	SR	TPR	PVC	PU	EVA	MCR
Vertical	0.80	0.75	0.70	0.85	0.65	0.75
Horizontal	0.78	0.73	0.68	0.83	0.63	0.73
Diagonal	0.82	0.77	0.72	0.87	0.67	0.77

Solid Vulcanized Rubber (SR) demonstrates that diagonal treads provide the highest COF (0.82), indicating the best slip resistance among the tested orientations. Vertical treads follow closely with a COF of 0.80, while horizontal treads show a slightly lower COF of 0.78. This suggests that SR's slip resistance is enhanced with diagonal treads, likely due to improved multidirectional grip (Chatterjee *et al.,* 2022).

Thermoplastic Rubber (TPR) exhibits a similar trend, with diagonal treads yielding the highest COF (0.77). Vertical treads show a COF of 0.75, and horizontal treads have the lowest COF of 0.73. This pattern indicates that TPR benefits from diagonal treads, enhancing its overall slip resistance. Polyvinyl Chloride (PVC) shows the highest COF with diagonal treads (0.72), followed by vertical (0.70) and horizontal (0.68) orientations. While PVC's COF values are lower compared to other materials, the improvement with diagonal treads suggests that this orientation provides better traction.

Polyurethane (PU) consistently outperforms other materials across all tread orientations, with diagonal treads showing the highest COF (0.87). Vertical treads provide a COF of 0.85, and horizontal treads yield a COF of 0.83. PU's superior performance across all orientations highlights its excellent slip resistance and versatility. Ethylene Vinyl Acetate (EVA), although showing the lowest COF values overall, follows the same trend. Diagonal treads provide the highest COF (0.67), with vertical treads at 0.65 and horizontal treads at 0.63. EVA's performance improves with diagonal treads, but its overall slip resistance remains lower than other materials.

Microcellular Rubber (MCR) exhibits the highest COF with diagonal treads (0.77), followed by vertical (0.75) and horizontal (0.73) orientations. This pattern indicates that MCR's slip resistance is enhanced with diagonal treads, similar to SR and TPR. The findings also highlighted the impact of tread width and orientation on slip resistance. Wider treads generally improved COF values for all materials, with PU consistently performing best. Diagonal treads were particularly effective, enhancing contact with the floor surface and reducing slip risks compared to vertical or horizontal orientations. Manufacturers were advised to integrate diagonal treads into safety boot designs to enhance slip resistance and ensure worker safety in industrial settings (Li, *et al,* 2004).

RECOMMENDATIONS

This study recommends several actions to improve safety boot performance in Nigeria and ultimately protect workers. The focus is on prioritizing materials with high slip resistance, like polyurethane (PU), and using wider diagonal tread designs. Additionally, regularly testing boots and updating safety regulations are crucial to ensure consistent performance (Chang et al., 2001; Okafoagu *et al*., 2017)The study recommends the use of locally sourced materials to reduce costs and support Nigerian industries, with technical assistance offered to improve production quality. Finally, ongoing research should explore ways to enhance long-term durability and develop new materials and tread designs for even better safety boots. These steps can significantly reduce workplace accidents and create a safer industrial environment in Nigeria

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