Vol. 45, No. 3 (2023) 416-430, DOI: 10.24874/ti.1434.01.23.05

Tribology in Industry

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RESEARCH

Frictional Characteristics of Progressively Worn Footwear Outsoles on Slippery Surfaces

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Keywords:

Slips
Falls
Friction
Wear
Tread

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Received: 10 January 2023
Revised: 21 February 2023
Accepted: 24 May 2023

A B S T R A C T

Slip and fall related injuries are common in workplaces and sufficient shoe-floor friction is required to prevent such incidents. Besides the presence of slippery contaminants, shoe wearing over time is one of the key factors which may lead to significant reduction in shoe-floor friction. While footwear-based slip testing has been conducted widely across floorings and contaminants, limited studies have focused on the effect of worn shoes on slipping. In this work, twelve formal shoes from common brands were tested through modelling of their outsoles in normal and different degrees of progressively worn conditions. Mechanical slip testing was conducted to quantify the available coefficient of friction (ACOF) of the outsole models across dry and two common contaminant conditions (i.e., floor or surface cleaner, and canola oil), and on three commonly available floorings. The effect of flooring, contaminant, and worn area, on the ACOF were characterized extensively. Progressively worn outsoles were found to lead to reduction in ACOF in the range of 28-97%. Outsoles having tread channels oriented at different angles with respect to the direction of footwear motion, were found to generate higher ACOF, than ones with horizontal tread patterns. Outsoles which had larger treads but with lesser intervals (i.e., large tread surface area) showed lower ACOF values. These outsoles experienced less reduction in the ACOF in the following cycles of wear. For safety against slips, outcomes from this work are expected to provide essential information for buying or replacing the formal shoes in its new or worn condition.

1. INTRODUCTION

Slips and falls lead to over 16% occupational injuries [1] including 50% falls on the same level, which recently accounted for over $10 billion in worker's compensation [2]. These accidents cause workers to draw hospitalization leaves accounting for more than 20 days, which further results in delay of official work with increase in compensation. Slip related accidents are the major reasons for both fatal and non-fatal workplace injuries in the U.S. (Fatal occupational injuries, U.S, 2019) [3]. Furthermore, slips lead to approx. 50% of the injuries reported due to fall

[4]. Common injuries to the lower extremities such as, dislocations, tears, and sprains are known to be the outcomes of slips, trips, and falls [5,6]. Reduction in the available coefficient of friction (ACOF) between the shoe and floor is the principal factor which result in slips [7–9]. Hence, to minimize the risk of slipping, understanding the role of footwear and its features is essential to guide the public, and shoe manufacturing companies in the selection of various parameters for maintaining sufficient shoe-floor friction.

Adequate traction between the shoe and floor is required to perform regular tasks such as, walking or running where, low traction at the interface directly relates to higher slip risks. ACOF measurements are able to indicate the slip risk at the shoe-floor interface [10–12]. The ACOF is dependent on the surfaces or the bodies which are in contact i.e., shoe treads and the floor [13–15]. Shoe outsole tread features are vital in determining the influence on slipping risk [16,17]. Various outsole design features include orientation, depth, width, and hardness of the treads which can significantly alter the ACOF [17–21]. Recently, Yamaguchi et al. [22] concluded that tread features impact the ACOF between the shoe and floor and sufficient ACOF can be obtained by disseminating the excess fluid through tread channels to reduce the risk of slipping. Shibata et al. [23] tested a urethane coating on a vinyl flooring sheet and discovered that the type of footwear worn affects the level of slip resistance provided by any surface coating. The sheet samples without the coating had a noticeably higher static coefficient of friction than those of the other sheet samples. Also, as the slipping velocity increased (i.e., upto 0.5 m/s), the dynamic friction coefficient (DCOF) significantly reduced. In comparison to the other samples, those with wider widths and no coating had larger DCOFs. The sample with the coating and narrow width had the lowest DCOF. Therefore, further research is required to understand the tribology of the shoe-floor interface in commercially available footwear by studying the tread features.

The performance of shoes in retaining the friction due to its tread features decreases with wear, significantly affecting the ACOF at the interface [24,25]. In a recent study, Cook et al. [24] evaluated the frictional differences between new and worn shoes. It was reported that the worn shoes experienced a significant drop in friction, which was directly associated with the increased slipping risks. In another study, Hemler et al. [10], studied the effects of natural shoe wear on frictional performance of slip-resistant shoes and assessed the correlation between the wear metrics and friction performance. Several parameters were found to affect the reduction of ACOF in worn shoes. There have been a few studies on performance testing of slip-resistant (SR) shoes in new and worn conditions [8,9,26–28]. Recently, Iraqi et al. [8] reported variations in the ACOF values across SR shoes which ranged from 0.127 to 0.710 depending on different floorings (i.e., ceramic and laminate). Also, worn footwear experienced approximately 30% reduction in the ACOF values as compared to the new footwear [9]. Hemler et al. [26] estimated the performance of artificially worn SR shoes in fluid contaminant conditions, where the ACOF ranged from approx. 0.06 to 0.41. Only a few footwear were able to cross the ACOF of 0.3 which is reported as the threshold to reduce the slips drastically [14]. These studies included several types of American footwear styles such as, athletic, casual, and SR-labelled dress footwear. However, the traction performance of common formal footwear in India and the effect of progressive wear, have not been characterized to date to the best of our knowledge. Studying the effects of wear to evaluate the traction performance in formal shoes will be helpful to understand the increasing slip risk which could further help determine replacement thresholds of these shoes.

In the current work, 12 formal Indian shoes, irrespective of the brand heterogeneity and which had higher sales in terms of quantity, were selected and their tread features were captured. A novel method to replicate the treads for traction performance analysis was implemented. The developed outsoles were then worn at regular intervals to simulate progressive wear. The ACOF values were estimated in dry and different contaminant conditions (i.e., floor cleaner, and canola oil), on three common floorings (i.e., glossy, matt, and anti-skid) using mechanical slip testing. The results are anticipated to provide a better understanding of the effect of different tread patterns and wear cycles on footwear skip risk across floorings and contaminants.

2. MATERIALS AND METHODS

2.1 Replication and fabrication of footwear outsoles

Twelve shoes with a substantial sales volume in India were considered for this research. The selected shoes branded with BATA (Lausanne, Switzerland) were identified with "B", Lee Cooper (London, United Kingdom) with "LC", and EGOSS (India) with "E". All the shoes had visually varying tread patterns with a similar outsole material (i.e., polyurethane). Polyurethane (PU) is a widely used material to develop shoe outsoles for formal shoes due to its durability and ease in distribution of plantar pressure [29–31]. Cuticles are a distinctive feature of PU. It is a thin layer of material that is harder than the material inside and has entirely distinct tribological properties. Faster heat dissipation by the material in contact with the mould during injection is connected with the creation of the skin layer. Together with flooring materials, it has a higher hardness and a lower coefficient of friction. Shoe metrics such as, shore hardness, and outsole tread features were reported to be instrumental in ACOF characterization studies [8,17]. All the shoes had a shore hardness ranging from 71.5 to 72 at the baseline and treads had depth ranging from 2.85 mm to 3.00 mm. The Shore hardness was measured using a Durometer (Precision Instruments, India) and the tread depth was measured by a surface depth gauge (Precision Instruments, India). The tread geometries of all the shoes were modeled using a 3D design software SolidWorks 2019 (Dassault Systèmes, France). The generated CAD models were then 3D printed using an Ender-3 3D printer (Creality, China) as moulds. All the moulds were filled with pourable liquid silicone (LSR 110, Chemzest Techno Products, India). The silicone mixture was left to dry for 24 hours and were removed from their respective moulds. The material aspect of the footwear was fixed by using a single material (i.e., polyurethane) for all the outsole patterns. A two-part mixture (i.e., part A and part B) of PU (Aditya Polymers, India), of shore A hardness 72, in a ratio of 100:80 was prepared and placed inside the silicone moulds. The mixture was left to cure for 24 hours in a dry environment. Silicone was used as a mould material to ensure easy removal of the polyurethane. After the removal of polyurethane, extra edges of the developed outsoles were trimmed. To ensure the exact replication of the outsoles, the tread features and the shore hardness were again measured and confirmed to be in range of the original shoe treads. This method was adopted so that the outsoles are compatible and can be fixed with the mechanical slip tester used in our study.

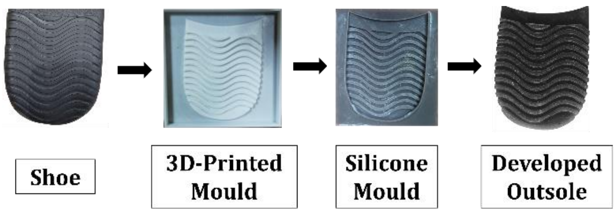


Fig. 1. Procedure implemented to develop the outsoles.

Figure 1 shows the procedure implemented to manufacture the outsoles.

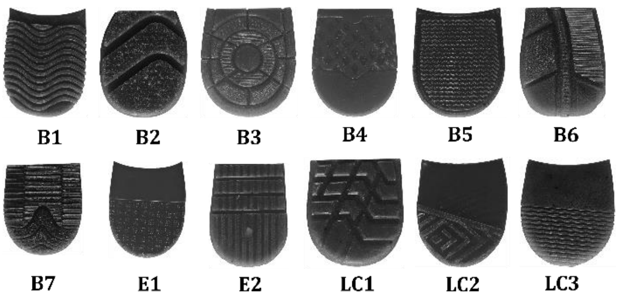


Fig. 2. The manufactured footwear outsoles.

Figure 2 represents all the outsoles with their respective designations. In this study, the heel region measuring up to 50 mm from the posterior end was considered based on the observations by Singh and Beschorner [32]. It was found that the 50 mm measure was crucial to determine the fluid pressures which affects the slip resistance of the treads.

2.2 Experimental setup for slip testing

To assess the friction performance of the footwear outsoles across different contaminant condition and flooring tiles, a slip risk measurement device, namely British pendulum slip tester was employed. The device's portability, user-friendliness, and accuracy [33,34], has made it to be utilised in numerous studies to assess the footwear slip risk of tiles in a variety of contexts, including kitchens and offices [28,29]. The outsole was attached to the heel region of a footwear and the assembly was affixed with the tester using a customized connector mimicking the human heel (Figure 3).

Fig. 3. Process of fabricating the 3D printed heel connector.

The biofidelic heel connector was designed to simulate natural foot loading condition over the outsoles. 3D printed parts have previously been reported as a rigid support for instantaneous or varying loads [35,36]. This heel connector was manufactured by 3D scanning the heel portion of a human subject and converting the scanned data points into a 3D printable format (STL format), and subsequently 3D printing it to attach the assembly to the slip tester (Figure 4).

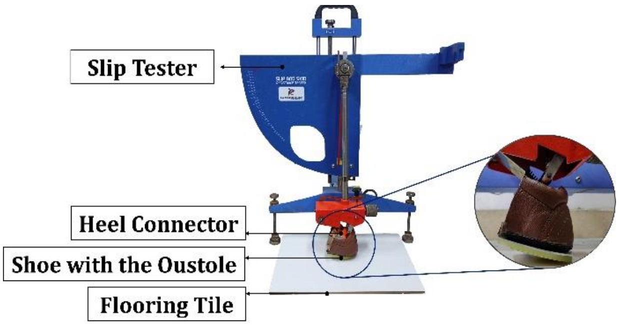


Fig. 4. British pendulum skid tester along with the shoe modification for the outsole attachment.

The shoe-floor angle was maintained at 17 ± 1º which is reported to be the angle of slip observed during unintentional slips and falls [8,14,17,26,32]. Other parameters such as sliding distance, normal load, and the sliding speed were also looked upon. In the case of slips initiated by heel-strikes, the slip distances observed in the previous studies by Didomenico et al. [37] and Cham et al. [38] varied from 30 mm to 100 mm primarily depending on the flooring. Based on the product manual, the slip tester included in our study had a slip distance of 76 mm for the laboratory test setting. The slip distance of our device was found to be comparable with the majority of human slip lengths. The device was calibrated to produce an average speed of 0.5 m/s, which mimics the human slipping velocity [8,14,17,26,32,39]. The normal force of 250N was adjustable using the load spring and was tuned to be comparable to human slipping [40,41].

The device was calibrated after each outsole was changed and the available coefficient of friction (ACOF) was quantified. The surface roughness of the floorings was Ra=6.4 µm for glossy tile, Ra=21.5 µm for matt tile, and Ra=36.2 µm for anti-skid tile which were quantified using a surface profilometer. Specifically, Ra was focused in this work instead of the other parameters such as, Rq, Rz, skewness, etc. This work considered averaged peak to valley measurements as, internationally, it is the most used parameter for the manufacturing of flooring tiles. Also, this was included based on a previous study by Chanda et al. [14], range of floorings were measured for their Ra and evaluated for its friction performance across the contaminants. In another study by Jones et al. [17] the authors measured the Ra and found to be effective in determining slip risk potentials of the considered simulated situations. In addition to this, the measured roughness values (i.e., Ra) of the floorings are comparable to a recent study by Chatterjee et al. [41] which measured the roughness of 15 different flooring tiles and reported Ra values ranging from 2.8 µm to 32.5 µm. The two contaminants included 10 ml of floor cleaner (i.e., Lizol), and oil (i.e., canola oil) which were dropped separately on the flooring tiles for realistic slip assessment tests. Each shoe-floor-contaminant condition was repeated thrice, and the average ACOF results were reported.

2.3 Wearing protocol

The developed outsoles were gradually worn using an artificial wear protocol which helped to reduce the overall observation period to evaluate the treads throughout their life as suggested by Chang et al. [42]. Based on the study by Grönqvist (1995) [43], the wear procedure was only carried at the concerned heel regions (up to 50 mm). To perform the accelerated wear, the outsoles were attached beneath the shoe and abrased using a sandpaper abraser (100 Grit, 3M Industries). The shoe-floor slipping angle consisting of 17 ± 1º was implemented for the wear operation. This angle was considered to be an important metric to assess slips and falls in shoes in the previous studies [8,14,17,26,32]. It has previously been studied that the shoes lose their performance and tread life after continuous usage of 6 months which results in the increased slip risk by 54% [44]. Therefore, our work included the wear simulation of the treads corresponding to 3 as well as 6 months, and finally wear up to the outsole base (fully worn) based on the abrased lengths on the sander as studied by Hemler et al. [10]. In summary, the outsoles were worn, cleaned and the slip testing experiments were performed across different contaminants and floorings. Similarly, to simulate the progressive wearing, same procedure was followed for the 2nd and 3rd wear cycles. Figure 5 summarizes the schematic of wear procedures and slip testing.

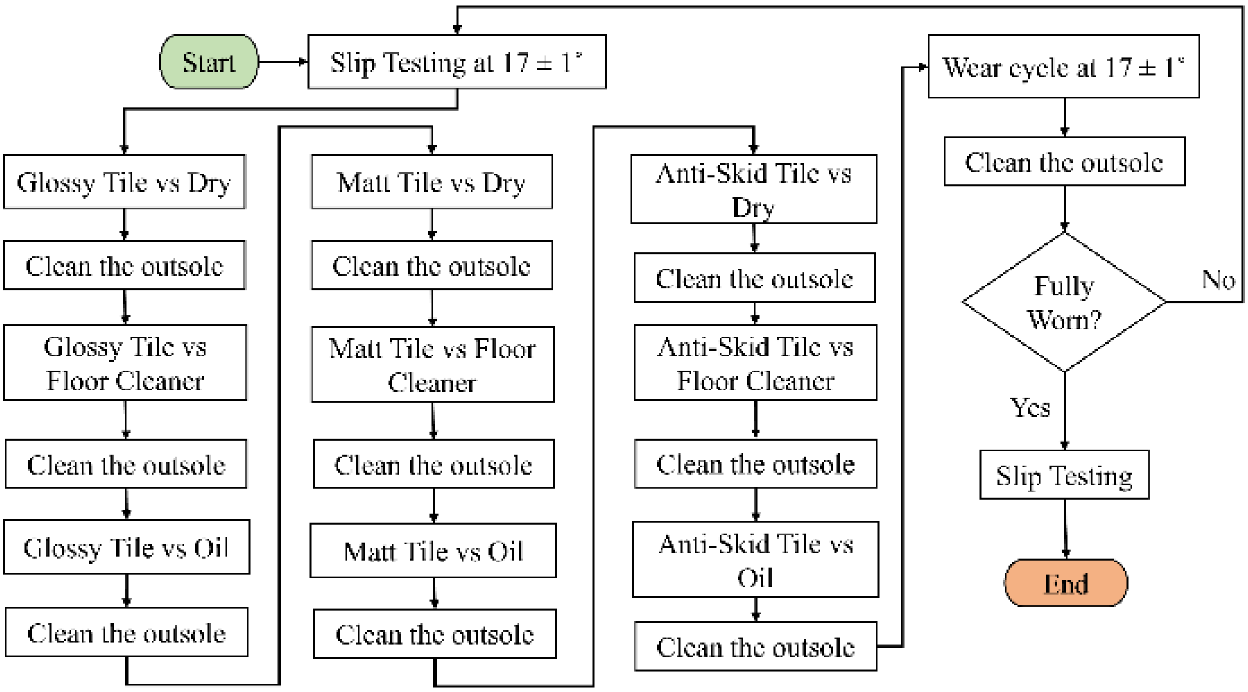


Fig. 5. Mechanical slip testing and protocol for progressive wear cycles.

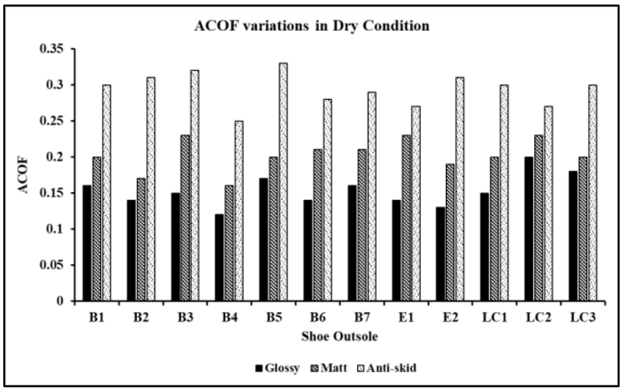
2.4 Data analysis

The ACOF values of the twelve outsole patterns were estimated on different flooring tiles and contaminant conditions. The ACOF data of the outsoles in progressively worn conditions were also evaluated. The worn region area of the outsoles was characterized using scaling and boundary tracing in SolidWorks. The outsole's image was first appropriately scaled, the worn regions were marked using a tracer, and the concerned area was estimated using the planar section properties. The quality of correlations of the worn region size in the tread patterns and ACOF were described using the correlation coefficient (R^2) where, $0.5>R^2$ was considered insignificant, $R^2>0.7$ as significant correlations whereas, $0.5<R^2<0.7$ was considered as moderate correlation.

3. RESULTS

3.1 Traction performance of new outsoles

The ACOF of the new outsoles varied from 0.05 to 0.33 across all the considered slippery conditions (Figure 6). In case of dry anti-skid tile, the ACOF of the outsoles ranged from 0.27 to 0.33. Compared to anti-skid flooring, the ACOF values for the glossy tiles ranged from 0.13 to 0.20, and matt tile ranged from of 0.16 to 0.23, which corresponds to reduction in the ACOF values by 40 % and 30% respectively (Figure 6a). Out of all the outsoles, seven of them (B1, B2, B3, B5, E2, LC1, and LC3) crossed the ACOF threshold of 0.30, indicating decreased risk of slipping [14].



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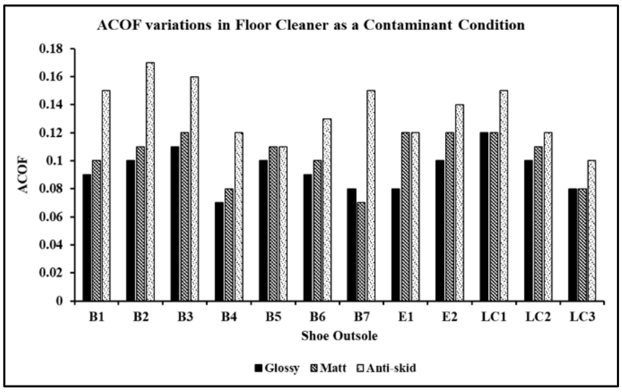

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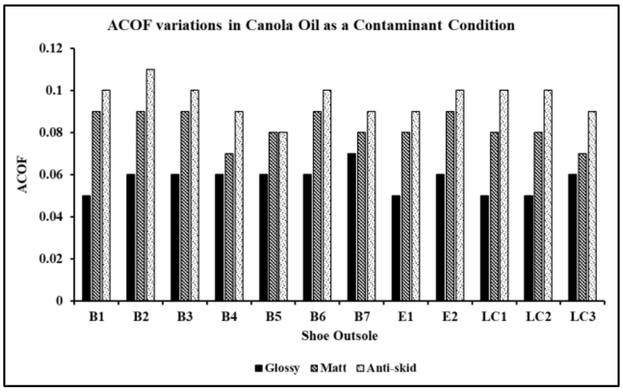

(c)

Fig. 6. Variations in ACOF of new outsoles across different floorings in (a) No contaminant or dry condition, and with contaminants, (b) Floor cleaner, and (c) Canola oil.

Across all the floorings in the presence of floor cleaner as a contaminant condition, the ACOF of new outsoles varied from 0.07 to 0.17 (Figure 6b). The traction performance of the outsoles was found to reduce from the dry condition, and the slip risk was observed to increase by 46-48%. The friction values varied between 0.05 to 0.11 across each floorings in the presence of canola oil based contaminated condition (Figure 6c). Canola oil posed the highest slip risk amongst all the tread patterns by further reducing the overall traction performance by 75%.

3.2 Traction performance of outsoles after wear

As the measured tread depths across the selected footwear ranged from 2.85 mm to 3 mm, three wear cycles were simulated to account for 3 months of usage (max. 1 mm wear), 6 months of usage (max. 2 mm wear), and more than 6 months of usage (max. 3 mm wear or fully worn condition) for all the outsole models.

Post the initial accelerated wear, the wearing behaviour and locations are represented in the Figure 7. Due to the considered biofidelic wear protocol, the outsoles showed bevelled wear at the rear areas of the outsole heel. Majority of the outsoles, namely B1, B3, B4, E2, LC1, and LC2 retained the tread features (i.e., tread geometries) whereas B2, B5, E1, and LC3 observed wearing of treads at the heel area. E1 had small but numerous tread patterns which showed breakage of the treads in the first wear cycle.

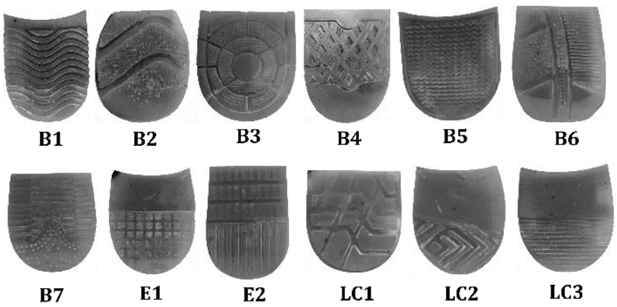

Fig. 7. Outsoles post the initial accelerated wear.

Figure 8a represents the ACOF outcomes of the outsoles post the initial wear cycle in no contaminant or dry condition across all the floorings. For glossy flooring, the ACOF of the outsoles ranged from 0.09 to 0.16 for glossy floorings where, E2 showed the lowest and B5 showed the highest ACOF values. Further, the ACOF values varied from 0.15 to 0.23 for the matt flooring where, E1, E2, LC3 showed the lowest and B3 showed the highest ACOF. For anti-skid flooring, the lowest ACOF was observed in LC3 (i.e., 0.19) and the highest ACOF in B5 (i.e., 0.30). All the outsoles experienced reduction in the traction performance by 7 % to 28%.

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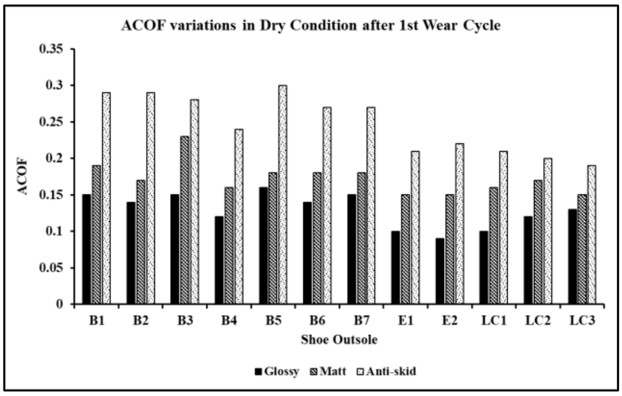

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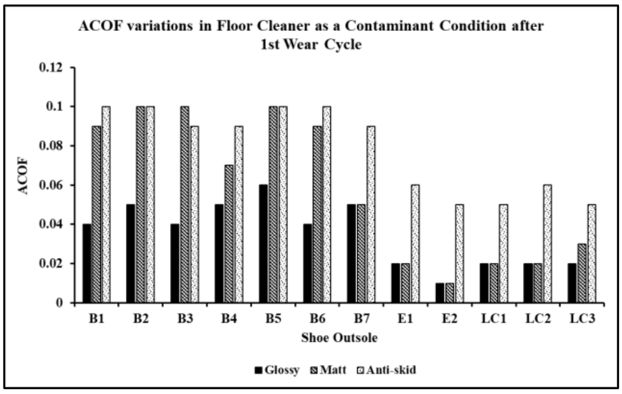

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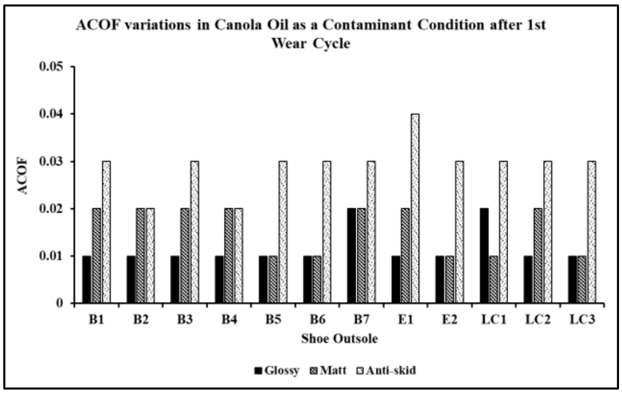


(c)

Fig. 8. Variations in ACOF values of outsoles post the initial wear: (a) in no contaminant or dry condition, (b) in the presence of floor cleaner, and c) in the presence of canola oil.

Figure 8b represents the traction performance of the initially worn outsoles on floor cleaner contaminated floorings. The ACOF values varied from 0.01 to 0.06 for glossy floorings where, E2 showed the lowest and B5 showed the highest ACOF values. Further, for the matt flooring, the ACOF values varied from 0.01 to 0.09 where, B2, B3, B5, and E2 showed the lowest, and B1 and B6 showed the highest ACOF. For anti-skid flooring, the ACOF of the worn outsoles varied from 0.05 to 0.09 where, B3, B4, and B7 performed better than other outsoles. Overall, the traction performance was further decreased by 20% to 40%.

The ACOF values of the outsoles after the first wear cycle on the canola oil as a contaminant condition is presented in Figure 8c. The ACOF across each slippery condition varied from 0.03 to 0.09. In glossy flooring, the lowest ACOF value (i.e., 0.03) was observed for the LC1 outsole followed by B1, E1, LC2 (ACOF=0.04), and B2, B5, B3, B4, E2, B6, B7, and LC2 (ACOF=0.05). Matt flooring also showed a lower range of 0.06 to 0.08 whereas, anti-skid flooring showed ACOF values ranging from 0.06 to 0.09. When compared to the performance of new outsoles in the oil contaminant condition, a reduction in the ACOF value by 0.04 to 0.09 was observed, which shows high risk of slips and falls. Overall, similar ACOF trends were observed in the case of oil, which exhibited high generalizability across the outsoles.

Wear behaviour and locations of the outsoles following the second accelerated wear are represented in the figure 9. All the outsoles observed a further increase in the bevelled wear at the heel region. As compared to first wear cycle, only B3, E2, LC1, and LC2 retained the superficial tread features whereas B2, B5, B7, E1, and LC3 observed wearing of few treads at the heel region.

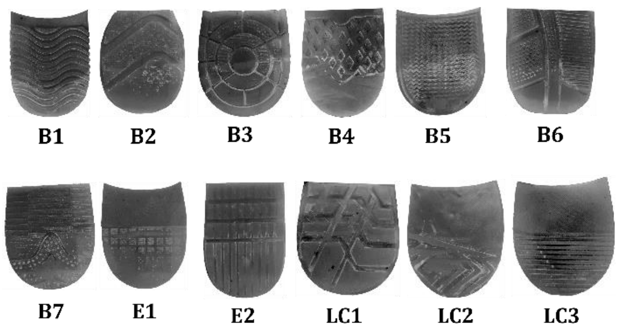
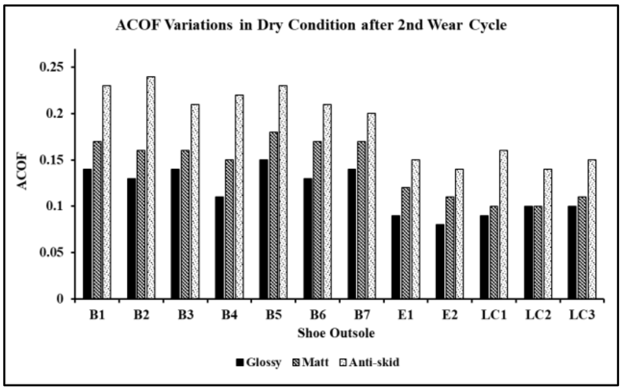


Fig. 9. Outsoles post second accelerated wear.

Figure 10 represents the reduction in the ACOF values post second accelerated wear. The friction outcomes varied between 0.08 to 0.24 including each in no contaminated or dry condition (Figure 10a). For the glossy flooring, E2 showed the lowest ACOF value (i.e., 0.08) whereas, B1 and B5 showed the highest (0.15). For matt flooring, ACOF values ranging from 0.10 to 0.18 was observed with the same trends as observed over the glossy flooring.

In floor cleaner contaminated floorings, ACOF values varied from 0.01 to 0.09 (Figure 10b). For the glossy floorings, ACOF ranged from 0.01 to 0.03 whereas, for the matt flooring it ranged from 0.01 to 0.05. In case of oily floorings, the friction values ranged between 0.01 to 0.03 (Figure 10c). This condition experienced further decrease in the traction performance by maximum 90% as compared to the previous wear cycle. Overall, in oily condition, generalizable ACOF outcomes amongst all the shoe outsoles were observed. Also, the outsoles were not able to provide adequate friction to prevent unintentional slips and falls.



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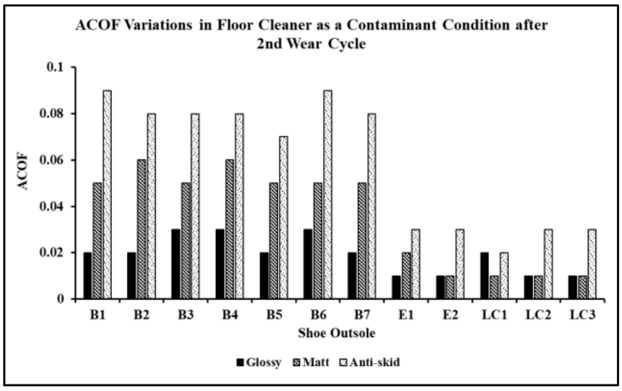

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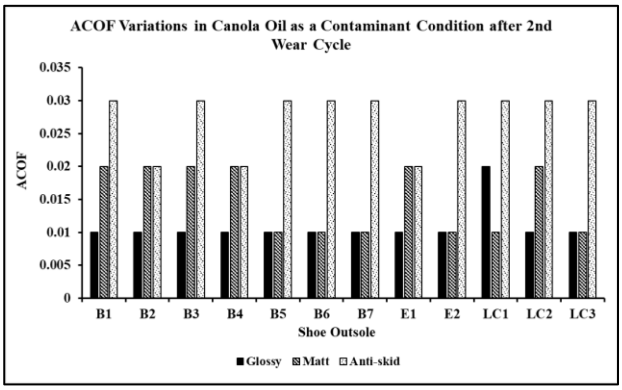


(c)

Fig. 10. Variations in ACOF values of outsoles post second wear: (a) in no contaminant or dry condition, (b) in the presence of floor cleaner and (c) in the presence of canola oil.

Wear behaviour and locations of the outsoles following the third accelerated wear are represented in the Figure 11.

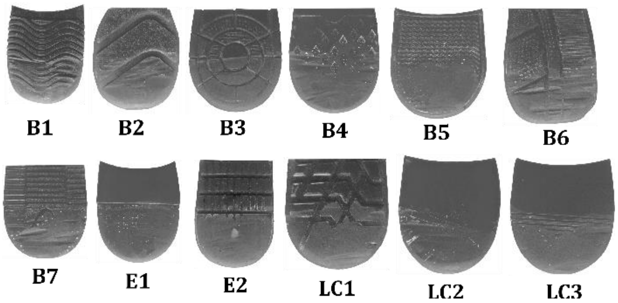
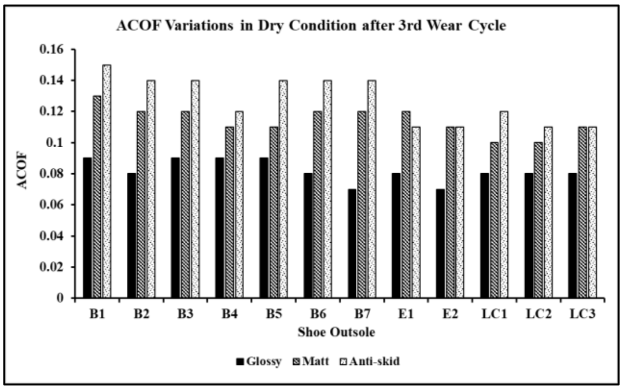


Fig. 11. Outsoles post third accelerated wear.

Each sample observed bevelled shape at the rear areas of the outsole's heel. It can be observed that the third wear cycle resulted in fully worn outsoles which completely removed the treads. All the shoe outsoles observed worn treads except B1. Minor tread features were retained by B1 which could be due to the difference in pressure loading of the shoe by the heel. Other tread patterns such as, B4, B5, B6, B7, E1, E2, LC1, LC2, LC3 showed fully removed treads whereas, B2 and B3 were retained the tread outlines to some extent.



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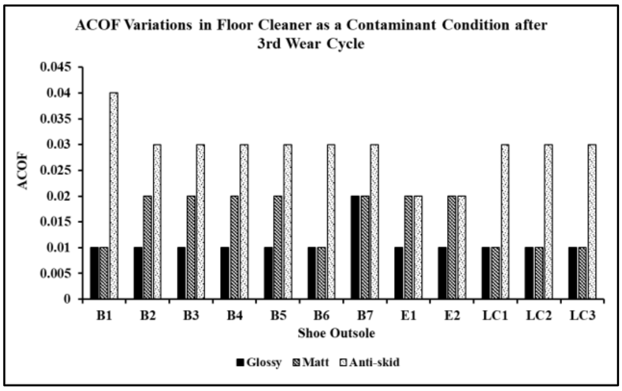

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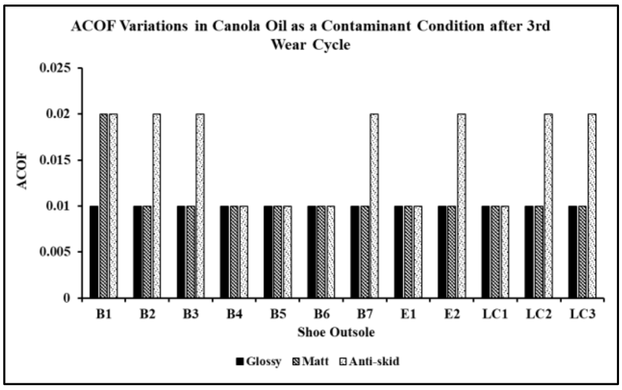

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Fig. 12. Variations in ACOF values of outsoles post third wear: a) in no contaminant or dry condition, b) in the presence of floor cleaner, and c) in the presence of canola oil.

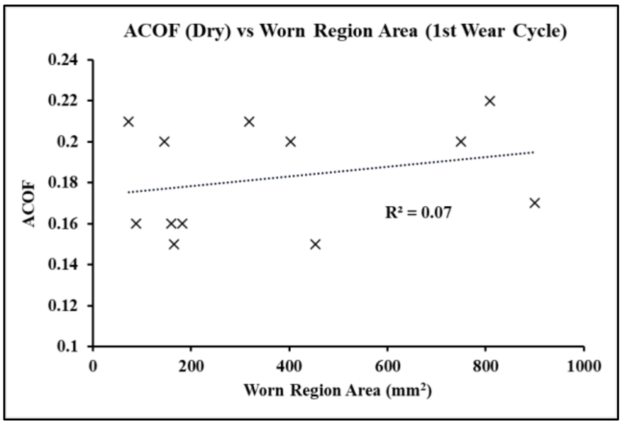
Figure 12 represents the ACOF values of the outsoles after the third wear cycle was performed. In dry slip testing across all the floorings, ACOF values varied from 0.07 to 0.15 (Figure 12a). Traction performance further decreased by 50% as the ACOF values were generally low for all the outsoles. The friction values were found between 0.01 to 0.04 on floor cleaner contaminated floorings (Figure 12b). B1 exhibited the highest traction value amongst all the shoe outsoles. The ACOF outcomes were found to be minimally dependent on the type of flooring. For the canola oil as a contaminant on all the floorings, the range of values was further confined to 0.01 to 0.02 (Figure 12c). Slip testing of the fully worn outsoles in oil as a contaminant posed the highest risk of slips and fall amongst each wear cycle and slippery conditions.

3.3 Correlation between outsole worn region area and acof outcomes

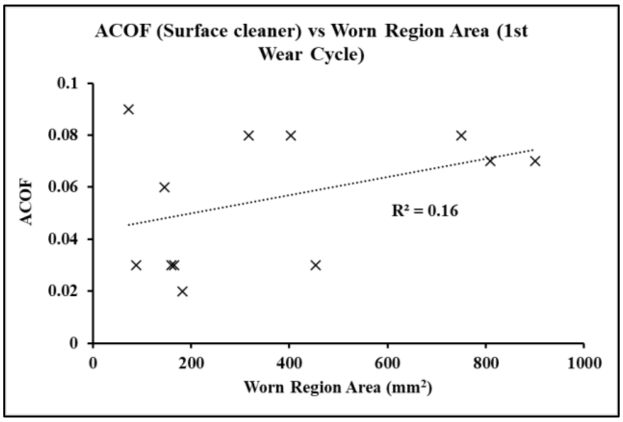
To understand the dependence of ACOF values on worn region size, correlations of averaged ACOF with worn region area, across all the contaminants and floorings, were estimated for each wear cycle (Figure 13). For the first wear cycle, the ACOF in dry condition was weakly and positively correlated (R^2 = 0.07) with the worn region area (Figure 13a). In this case, seven outsoles (i.e., B1, B3, B5, B7, E1, LC1, LC2) exhibited high ACOF values at low worn region. In case of surface cleaner and canola oil as a contaminant, weak correlations were observed with R^2 = 0.16 (Figure 13b) and R^2 = 0.05 (Figure 13c) respectively. These observations show that the worn region areas does not have significant impact on the ACOF after 1st wear cycle.

For the second wear cycle, the ACOF in dry condition was weakly and positively correlated (R^2 = 0.36) with the worn region area (Figure 13d). Similarly, in case of surface cleaner and canola oil as a contaminant, weak correlations were observed with R^2 = 0.36 (Figure 13e) and R^2 = 0.04 (Figure 13f) respectively. These observations show that the worn region areas does not have significant impact on the ACOF across each slippery condition even after the 2nd wear cycle.

On the contrary, for the third wear cycle, the ACOF in dry condition was strongly and positively correlated (R^2 = 0.89) with the worn region area (Figure 13g). The ACOF increased with the increase in the worn region area. However, in case of surface cleaner and canola oil as a contaminant, weak correlations were observed with R^2 = 0.01 (Figure 13h) and R^2 = 0.02 (Figure 13i) respectively. These results show that the worn region areas have significant impact only on dry ACOF after the third wear cycle.



(a)



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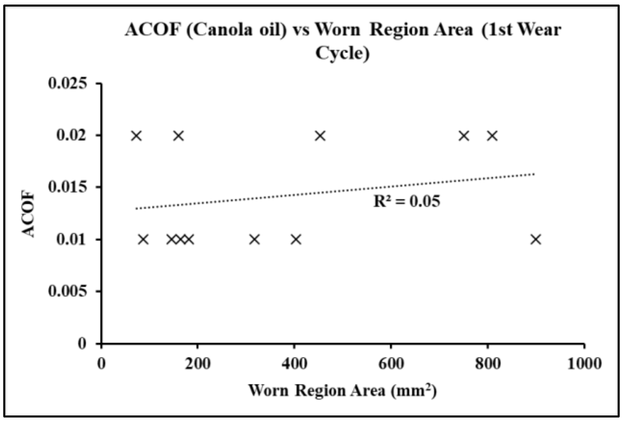
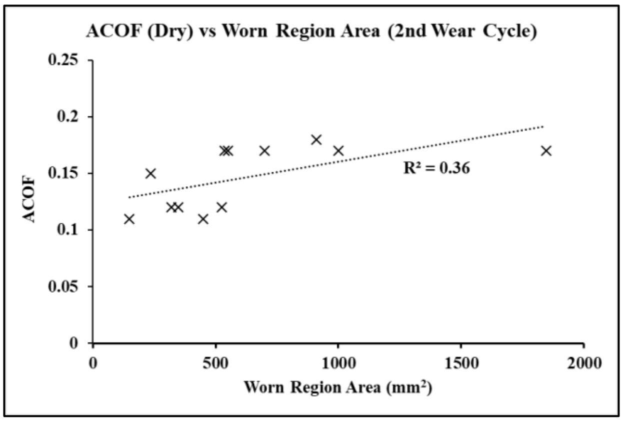
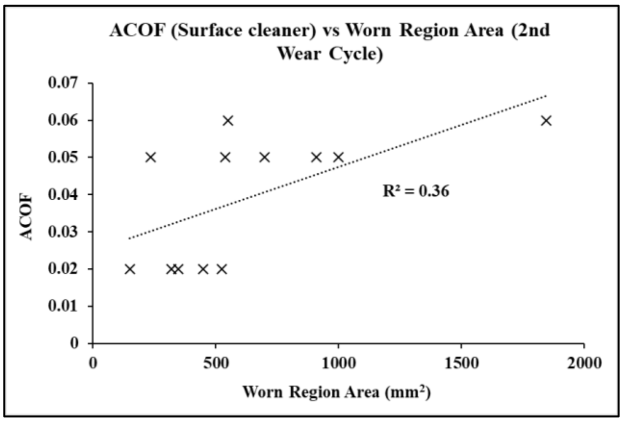


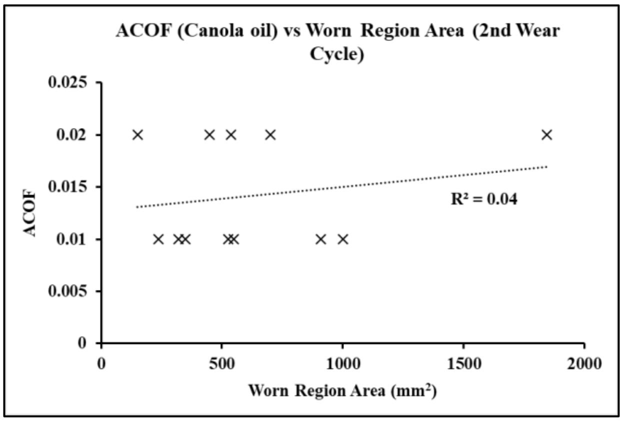
(c)



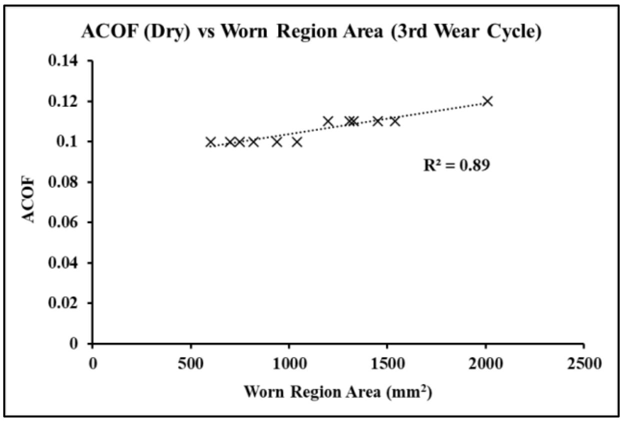
(d)



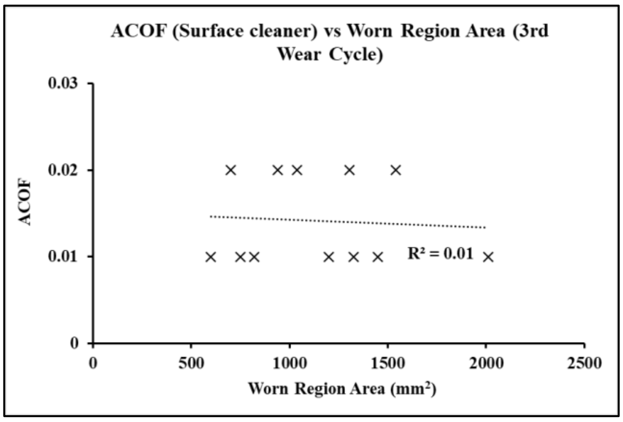
(e)



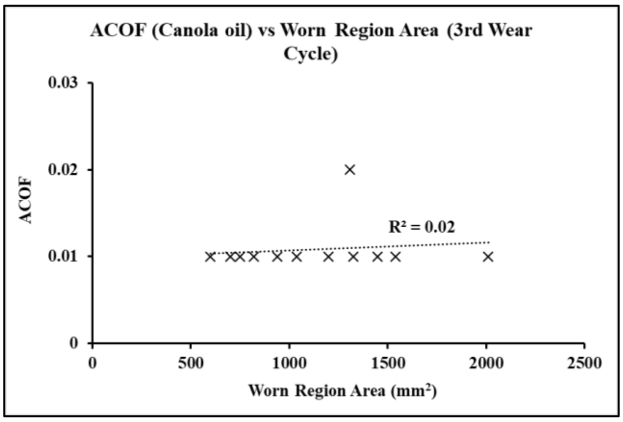
(f)



(g)



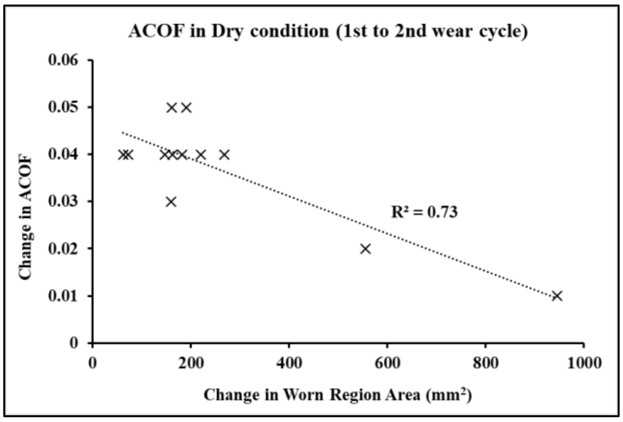
(h)



(i)

Fig. 13. Correlation of worn region area and ACOF for: a) Dry condition after 1st wear cycle, b) Surface cleaner condition after 1st wear cycle, c) Canola oil condition after 1st wear cycle, d) Dry condition after 2nd wear cycle, e) Surface cleaner condition after 2nd wear cycle, f) Canola oil condition after 2nd wear cycle, g) Dry condition after 3rd wear cycle, h) Surface cleaner condition after 3rd wear cycle, and i) Canola oil condition after 3rd wear cycle.

Furthermore, Figure 14 represents the effect of change in worn region area on the change in averaged ACOF of the selected patterns across each slippery condition.



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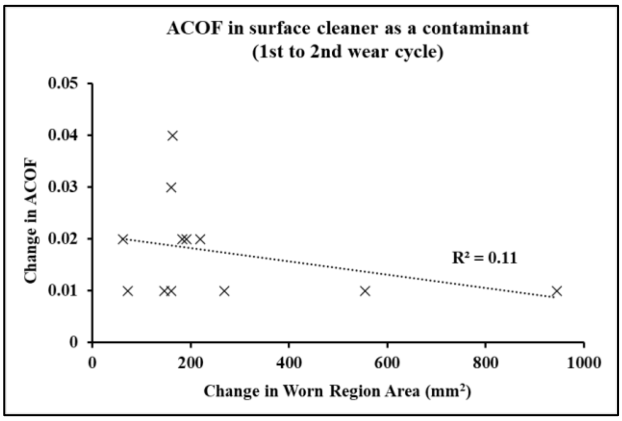

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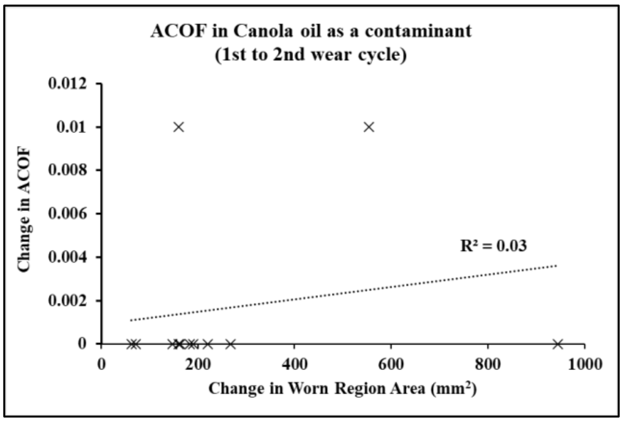
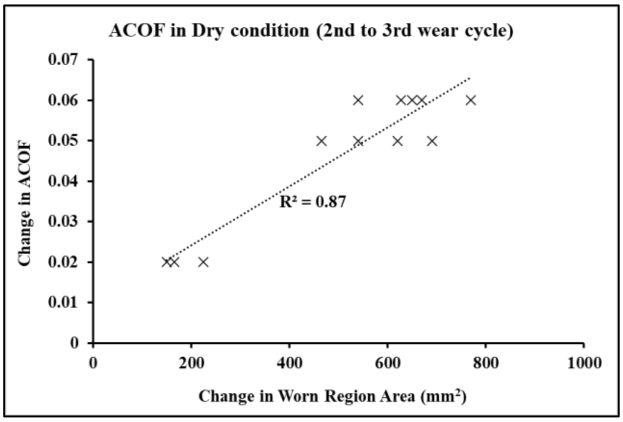


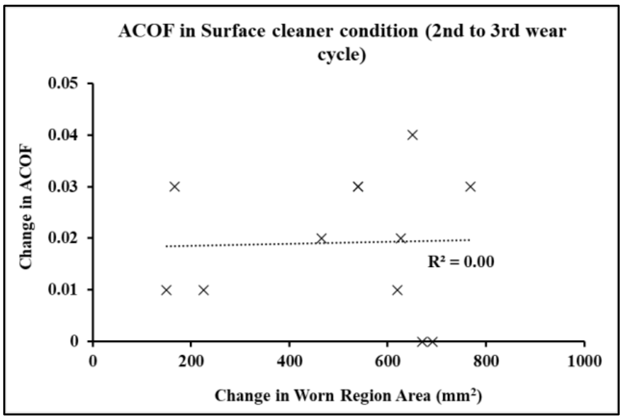
(c)

Fig. 14. Correlation of change in worn region area and change in ACOF for progression from 1st to 2nd wear cycle: A) Dry condition, B) Surface cleaner condition, and C) Canola oil condition.

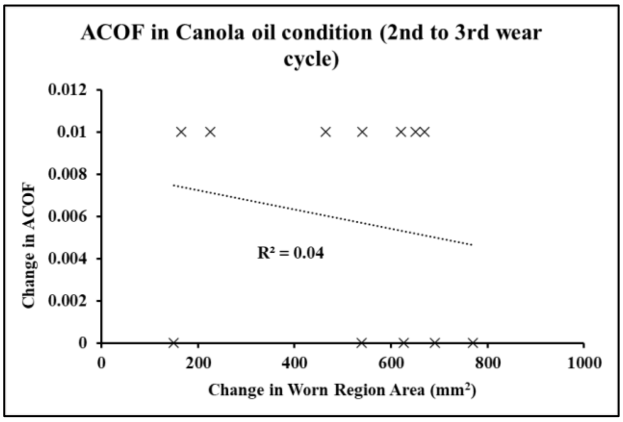
Figure 14a shows the effect of worn region area on the ACOF progressing from the first wear cycle to second wear cycle. The difference in worn region area correlated strongly (R^2 = 0.73) with the change in ACOF in dry conditions across all the floorings. The majority of the outsoles experienced a progression in wear areas ranging from 72 mm^2 to 268 mm^2. Also, a negative trend was observed which suggests that the change from the first wear cycle to the second led to a reduction in ACOF with an increase in the overall worn region areas. On the contrary, the effect of changing worn areas on the changing ACOF were weakly correlated with R^2 = 0.11 (Figure 14b) across the surface cleaner as a contaminant condition. Similar results were observed (R^2 = 0.03) in the case of canola oil as a contaminant (Figure 14c).



(a)



(b)



(c)

Fig. 15. Correlation of change in worn region area and change in ACOF for progression from 2nd to 3rd wear cycle: A) Dry condition, B) Surface cleaner condition, and C) Canola oil condition.

While studying the effect of change in worn region areas on the change in ACOF of second and third wear cycles in dry condition, most of the outsoles experienced a progression in wear areas ranging from 465 mm^2 to 770 mm^2. In dry condition (R^2 = 0.87), a strong correlation and a positive trend was observed which shows that the progression from the second to the third wear cycle led to a slight increase in ACOF with an increase in the overall worn region areas (Figure 15a). On the contrary, the effect of changing worn areas on the changing ACOF were not found to be correlated with R^2 = 0 (Figure 15b) across the surface cleaner as a contaminant condition. Similar results were observed (R^2 = 0.04) in the case of canola oil as a contaminant (Figure 15c).

4. DISCUSSIONS

The current work presents the traction performance of a variety of common Indian formal shoes in its new, partially worn and fully worn states. A modified version of a pendulum based mechanical slip risk measurement device was implemented to assess the outsole friction across different floorings and contaminants. Testing across different conditions and wear cycles indicated that the footwear tread patterns have a significant effect on the traction performance in both new and worn conditions. ACOF widely varied across the shoe outsoles in the ranges 0.07 to 0.33, 0.02 to 0.17, and 0.01 to 0.11 for dry condition, on floor cleaner contaminated, and oily floorings respectively. Initially worn outsoles showed reduced traction performance by a maximum 28%, whereas for the second accelerated wear cycle, the performance decreased further by 55%. The fully worn outsoles experienced the lowest ACOF with up to 45% reduction in the traction from the second wear cycle.

In the dry condition, majority of the outsole patterns showed near slip-resistant performance in the anti-skid flooring, moderate traction performance in matt, and lowest traction in glossy floorings. In case of floor cleaner, outsole treads inclined to several axes performed better those in the horizontal direction (i.e., orthogonal to the shoe movement direction). However, in case of canola oil, no specific traction performance trends were observed. After the first wear cycle, the outsoles which had larger treads, did not exhibit much change in the ACOF across all floorings and contaminants. After the second wear cycle, only a few outsoles, which retained the original large tread patterns, exhibited high ACOF. After the third wear cycle, treads were absent in majority of the outsoles, leading to low and generalizable ACOFs.

On studying the correlation of worn areas and ACOF, the outsoles with low tread surface area and high tread intervals, showed higher ACOF. Additionally, these kinds of outsoles have an easy, faster wear cycle with a notable reduction in ACOF. Conversely, larger outsoles with fewer intervals and larger treads (i.e., high surface area) displayed lower ACOF values. These outsoles experienced less reduction in the ACOF in the subsequent wear cycles. The ACOF was found to exhibit highly generalizable trends for fully worn outsoles, especially in presence of canola oil as the contaminant. This finding could be related to the hysteresis component of the friction due to an overall increase in the wear areas [19]. In a previous study by Bhave et al. [45], significant deformations of the tread blocks during slipping on a flooring caused the polymeric material to dissipate the energy and hence, led to enhanced friction. The reduction in depth of tread blocks due to wear restricted the overall bendability of the treads. Another contributing factor could be related to the fluid's chemical constituents, which seemed to have an impact on the boundary friction coefficient by causing longer-chain molecules to have a lower coefficient of friction. The rate of coefficient of friction decay increased with rising fluid entrainment velocity as fluid viscosity increased, indicating less material contact and increased film thickness. This concept was previously mentioned in a work by Moore et al. [46].

In recent work, Gupta et al. [47] a few footwear designs were tested under normal and worn conditions across some floorings and contaminants. The tests were conducted in a lab environment and not on realistic flooring conditions. In the current study, a portable slip testing device was used to test low-cost footwear designs in realistic contaminated floorings enduring environmental fidelity. Also, the test conditions were adjusted to simulate the human slipping experiments. In addition to this, the footwear outsole hardness was uniform for all the shoe designs allowing us to effectively focus on understanding the effect of tread patterns on wearing and the shoe-floor friction. In earlier research, Hemler et al. [26] examined the performance of used slip-resistant footwear in fluid-contaminated settings and found that traction reduced as fluid pressure over the untreaded or worn region increased. Only a few footwears were able to surpass the ACOF criterion of 0.3. The current work also reported some novel findings. Treads which could drain excess contaminant fluids were found to generate high ACOF. Specifically, the outsoles with horizontally aligned tread patterns produced low ACOF, as they were not able to drain excess fluids. Whereas, outsoles with either inclined or small extruded tread patterns exhibited higher wet friction as compared to other designs. In several cases, wearing led to reduction in the tread channel dimensions as well as the number of tread channels, leading to drastic reduction in ACOF. A few outsole designs, which allowed the drainage of excess contaminant in all possible directions, were found to produce high ACOF and slip resistance. Such findings were consistent with literature [14,48,49].

A few studies in the past have considered different types of tread designs, footwear materials, varying sole hardness, types of flooring material and contaminants. In a previous study by Walter et al. [50], three different types of tread designs have three independent material with different hardness were considered. The shoes were artificially worn and slip tested on a vinyl composite tile. Small lug designs were found to produce high ACOF and comparatively more resistance to wear. In a previous study by Jones et al. [17], five slip-resistant shoes with different types of tread patterns were selected to understand the tread-floor tribology. Only by varying the outsole design, it was found that a certain type of tread produced high friction as compared to others. Based on these studies, we have also compared the friction performance of several tread designs in new and worn conditions. In addition to this, further research considering several materials of shoes i.e., thermoplastic rubber (TR), shoe rubber, natural leather, and ethylene vinyl acetate (EVA) could help in understanding the science behind the footwear tribology.

5. CONCLUSION

In conclusion, the shoe tread pattern retention was found to be the key to maintain adequate shoe-floor traction and to avoid slips and falls. Also, the combination of viscous contaminants and shoe tread wear was reported to be detrimental to the slip safety of footwear outsoles. Due to the viscous contaminants having longer-chain molecules, it generally led to lower coefficient of friction across the selected footwear. It may also be suggested that, footwear worn for a simulated six months period may require replacement. The analyses and study outcomes are expected to enhance the knowledge of footwear designs and to guide for selection and replacement of formal shoes for safety against slips.

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