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Impact of multiple coating layers on finished floor slip resistance

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Abstract
Slip, trip and fall (ST&F) events are a cause of significant mortality, hospitalisations and financial expense. Floor conditions are a factor in some portion of ST&F events and thus important to monitor. In commercial buildings, flooring surfaces are often coated with a removable floor finish to protect the floor and provide a consistent walking surface. The relationship between the number of coating layers of a floor finish and the slip resistance, i.e. coefficient of friction, is poorly reported in the literature. In this study, vinyl composite floor tiles were coated with four different floor finishes, varying from 2 to 10 coating layers. The static coefficient of friction (SCOF) was tested using the James Machine and ASTM D2047 to determine whether there was a change in the SCOF/slip resistance and thus the ST&F risk, associated with different numbers of coating layers of finish. The number of coating layers of floor finish did not negatively impact the SCOF/slip resistance of the tiles. This study suggests that maintaining an appropriate layer of floor finish, typically recommended by manufacturers to be four coating layers, provides a slip-resistant walking surface that is not negatively affected by additional coating layers of finish.

1. Introduction

The general public expects that commercial buildings open to the public are safe to use in various ways including being safe for ambulation, i.e. walking on floors, ramps and steps. Businesses have to comply with a wide range of regulatory requirements to ensure their facilities are safe for the general public, including regulations related to floor safety [1]. Slip, trip and fall (ST&F) events are a serious public safety issue. In the USA there were an estimated 44,686 deaths from falls in 2021 and 6.8 million injuries in 2020 [2]. In addition to direct medical costs associated with ST&F accidents, there are costs related to accident investigation, lost time from work and compensation for injuries [3]. Liberty Mutual Insurance (LMI) publishes a workplace safety index for the US market and reports that in 2020 "falls on the same level", which includes ST&F events resulting in a fall, is the number two cause of workplace injuries and has direct costs of $10.84 billion per year associated with falls [4]. Additionally, LMI reports that slips or trips without a fall are the seventh cause of workplace injuries, costing $2.06 billion per year [4]. The mean time away from work as a result of an ST&F event has been reported as 8 days, with 26.7 % of ST&F injuries requiring 31 days or more from work [3].

The ST&F events are typically complex, involving phenomena from the fields of biomechanics, tribology, neurophysiology, human cognition, psychology, ergonomics and others [5-7]. Consequently, trying to understand an ST&F event through the lens of a single field likely ignores important information relevant to the ST&F event [5]. Thus, understanding ST&F events typically involves disaggregating the event so that particular aspects or factors can be studied and understood in the context of their overall impact on the factors contributing to the ST&F event.

Because the condition of the floor is implicated in some portion of ST&F events, appropriate floor maintenance and floor safety practices are important. A significant portion of ST&F events can be prevented by following standard floor safety risk management practices [2,3,8]. Still, not all ST&F events are preventable because of the wide range of factors involved. Studying ST&F events is also complicated by the lack of a straightforward method to measure the slipperiness of a floor in use and the safety criteria for slip risk or safety thresholds to estimate a slip hazard, which are key elements to understanding ST&F risk [5]. Regulations governing floor safety are often ambiguous, generally requiring slip-resistant surfaces without providing clear definitions or measurement methods to determine appropriate slip resistance. A range of ASTM standards on floor safety, including ASTM F1637, ASTM F695 and ASTM F2966, discuss the need for a slip-resistant walkway under various conditions without defining what slip resistance means or how to measure it [9]. Understanding how ST&F events occur and the risk factors likely to increase the chances of an ST&F event are essential parts of accident prevention.

Decorative removable floor coatings (floor finishes) are commonly applied to a wide range of flooring substrates in commercial buildings visited by the public to improve floor safety by providing a uniform slip resistance on the floor which is easier to clean and maintain, provides a sacrificial layer to protect the floor substrate, improves facility appearance by increasing the reflected light, makes floors easier to clean after inevitable contamination and provides a lower overall cost to maintain the floor by extending the cycle of floor replacement. The standard instrument used to measure the slip resistance of a floor finish is the James Machine using the methodology described in ASTM standard D2047 [10]. Historically, testing of a floor finish involves hand coating of sample tiles in a laboratory and testing using the James Machine. It is generally not possible to test the slip resistance of floor tiles with floor finish from a commercial floor in the lab after installation of the floor because any procedure to remove installed floor tiles could compromise the testing process. Often portable tribometers are used to assess the slip resistance of an installed floor in the field despite their significant limitations discussed elsewhere [5,11-14]. The James Machine is not a portable tribometer, but rather an instrument used in a laboratory under a controlled set of conditions to measure the static coefficient of friction (SCOF) by using a weighted leather pad pressed down on a floor tile coated with a floor finish. As the angle of the weight changes from an initial 90° with the tile, the normal force on the tile is reduced, the parallel force increases and eventually, a slip of the leather pad occurs. The interaction between the leather pad and the floor finish determines when the slip occurs, with a SCOF of 0.5 being the passing criteria for the test [10]. The ASTM D2047 is performed using four layers of floor finish hand-coated onto control and test tiles [10].

Floor finishes are formulated with ingredients that provide specific properties to the coating when applied to a floor. In a floor finish, no single ingredient determines the slip resistance of the finish, but the long-chain polymers, wax, short-chain polymers or resin, plasticiser and surfactant can impact the slip resistance. Floor finish formulators balance the concentration of the various materials to achieve the desired slip resistance for the finished product.

The Occupational Safety and Health Administration (OSHA) is the regulatory body responsible for workplace safety in the USA. OSHA regulations include a requirement that commercial facilities provide walking surfaces free of hazards and maintained in a safe condition [15]. OSHA has further provided clarifications on their standard in Appendix A to Subpart D that walking and working surfaces are to be free of hazards that could cause employees to slip, trip or fall and that a reasonable definition of slip-resistance for a floor is a static coefficient of friction of 0.5 [15]. OSHA further clarifies that a SCOF of 0.5 is not an absolute value as certain situations may require a higher SCOF, but floors with a SCOF > 0.5 have been shown in studies to provide a low-risk walking surface [9,15]. Thus, a walking surface that provides a SCOF > 0.5 is generally considered slip-resistant and safe for ambulation. Other measurements of the coefficient of friction (COF), including the dynamic COF and the transitional COF have been proposed by various groups, but measurements of these properties have failed to achieve the same level of acceptance by OSHA in the USA.

When using floor finish in their facilities, managers of commercial buildings determine the number of layers of floor finish to apply to their floors to provide an acceptable balance between desired wear properties and gloss level. This may be different than the floor finish manufacturer's recommendations, which are provided on the product label. It is not clear what impact additional coating layers of finish have on the slip resistance of the finish and whether higher numbers of coating layers of finish have a positive or negative impact on the slip resistance of the floor. When walking on a floor coated with a finish, the public only walks on the topmost layer of the finish, but the impact of the number of additional coating layers of finish is not well studied in the literature.

The aim of this study was to investigate the relationship between the number of coating layers of floor finish applied to a vinyl composite tile floor and the slip resistance of the tiles as measured by the SCOF when tested using a modified version of the ASTM D2047 method. It is important to understand to what degree the number of coating layers of floor finish impacts the slip resistance of the floor and whether additional layers of finish beyond what is recommended by the manufacturer increase, decrease or have no impact on the slip resistance of the finish. We believe this study confirms the recommendations of floor finish manufacturers.

2. Materials and methods

2.1 Floor installation

To facilitate testing of tiles from an installed floor, a magnetic floor of approximately 27.9 m^2 (approx. 3.7 × 7.6 m), i.e. 300 ft^2 (12 × 25 ft) was installed in a training centre (Fig. 1) using Armstrong Premium Excelon M601C black vinyl composite tiles. Steel strips were permanently attached to the floor using adhesive and approx. 0.09 m^2 (1 ft^2) backings were attached to the bottom of the tiles using adhesive, allowing for individual tiles to be removed for testing in the laboratory.

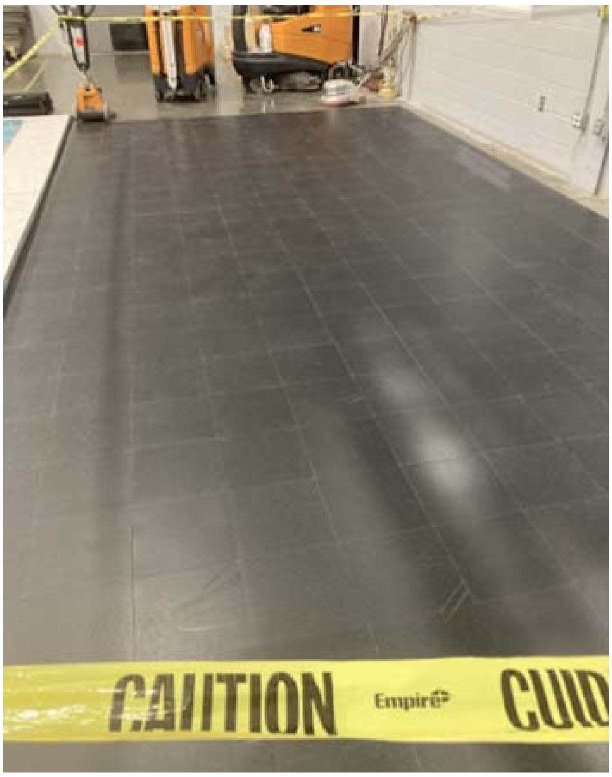

Figure 1. Photo of the installed magnetic floor in the training centre prior to the application of the coatings

2.2 Floor finishes used in the study

Four commercial floor finishes were selected for the study as shown in Table 1. The finishes were selected from the leading floor finish manufacturer in the USA and were chosen to represent a range of floor finishes in use in the commercial market.

Table 1. Commercially available floor finishes used in the study

Product	Finish description from the company website
Finish A	Ultra-high-speed floor finish with maximum wet-look gloss for resilient floors; this finish is commonly used in retail stores in the USA receiving heavy foot traffic
Finish B	High-durability high-gloss finish with soil resistance for resilient floors; this finish is used in a wide range of facilities and is suitable for a wide range of resilient floors
Finish C	Multi-maintenance floor finish for resilient and non-resilient floors; this finish is used heavily on stone and terrazzo floors, but can be used on resilient floors
Finish D	High solids, low odour finish with high gloss and high durability; this finish is used primarily on resilient floors

2.3 Floor layout

After installation of the magnetic floor, the tiles were stripped using standard floor care practices to remove any mill finish from the tile manufacturer. A diagram of the floor was prepared (Fig. 2) to indicate which tiles were to be removed for testing. Tiles in rows 2 to 6 were coated with finish A. Tiles in rows 8 to 12 were coated with finish B. Tiles in rows 14 to 18 were coated with finish C. Tiles in rows 20 to 24 were coated with finish D.

The manufacturer of the floor finishes indicates on their product label to apply floor finish at a rate of 139 to 232 m^2 (1500 to 2500 ft^2) per 3.78 l (1 US gallon) of finish. While we did not attempt to measure or control the amount of finish applied, one of the investigators is a floor care application expert and applied all coating layers to ensure consistency of application and that the method of application was consistent with standard floor finish application practices.

	1	2	3	4	5	6	7	8	9	10	11	12	
1													
2													
3		2	2	2		6	6	6		10	10		
4											10		Finish A
5		4	4	4		8	8	8					
6													
7	Adhesive tape to separate the product areas												
8													
9		2	2	2		6	6	6		10	10		
10											10		Finish B
11		4	4	4		8	8	8					
12													
13	Adhesive tape to separate the product areas												
14													
15		2	2	2		6	6	6		10	10		
16											10		Finish C
17		4	4	4		8	8	8					
18													
19	Adhesive tape to separate the product areas												
20													
21		2	2	2		6	6	6		10	10		
22											10		Finish D
23		4	4	4		8	8	8					
24													
25													

Figure 2. Floor layout of the tiles removed during testing; coloured tiles were removed for testing; the numbers on the coloured tiles indicate the number of coating layers of finish on the tiles when they were removed for testing

For each section of the floor, a similar procedure was used to prepare the tiles. On day 1 of the study, all of the tiles in a section (e.g. rows 2 to 6 for finish A) had two layers of finish applied using a finish applicator and the appropriate finish, allowing 30 min to dry between coating layers. Tiles indicated with a "2" in Figure 2 were removed, marked on the bottom using tape and marker with the appropriate finish code and number of coating layers and set aside for testing. The empty tile locations were filled with extra tiles to keep the floor stable.

Two additional coating layers of finish (layers 3 and 4) were applied to each section on day 1 allowing 30 min to dry between coating layers. Tiles indicated with a "4" in Figure 2 were removed, marked on the bottom using tape and marker with the appropriate finish code and number of coating layers and set aside for testing. The empty tile locations were again filled with extra tiles. Per manufacturer recommendations, only 4 coating layers of finish were to be applied in 24 hours. The following day (day 2) the same procedure was used to apply coating layers 5 and 6 and 7 and 8, with appropriately identified tiles removed, marked and labelled and set aside for testing. On day 3, coating layers 9 and 10 were applied and the indicated tiles were removed for testing.

2.4 ASTM D2047 testing

Per ASTM D2047 [10] control tiles for the James Machine testing were prepared and tested to validate the James Machine was performing within specifications. All removed tiles were tested between days 3 and 4 of the study. The temperature in the lab during testing was 20 °C (68 °F) on day 3 and 21.1 °C (70 °F) on day 4. The relative humidity in the lab was 50 % on day 3 and 51 % on day 4. Modifications to the method were used to allow tiles finished in the training centre using standard floor applicator tools to be tested in the lab. ASTM D2047 requires the tiles to be coated by hand in the laboratory area and for four coating layers of finish to be applied to the tiles [10]. The method also uses a pass/fail criteria of a minimum of 0.5 SCOF to pass the test. In this study, we compared the individual SCOF measurements to provide the ability to perform a statistical analysis of the results.

The ASTM D2047 test was selected for several reasons. It is the preferred test for measuring the slip resistance of an uncontaminated, i.e. dry floor coated with floor finish and is commonly used and accepted in slip-fall litigation in the USA. The test meets the OSHA criteria, which recommends measurement of the SCOF of a floor and that the floor have a SCOF of 0.5 or higher to be slip resistant. The performance criteria for ASTM D2047 is that a passing floor tile coated with a finish will have an SCOF greater than 0.5, consistent with the OSHA recommendations. Wet conditions were not evaluated as there is no similar OSHA standard and test for slip resistance of contaminated floors with floor finish.

Statistical analysis was done using Minitab version 21.4.2.0. Mean values and standard deviations were calculated by a combination of product and number of coating layers for each set of 12 readings from ASTM D2047. Tukey analysis [16] was performed by product analysing the impact of varying numbers of layers of finish.

3. Results and discussion

ASTM D2047 [10] requires four measurements of the SCOF per tile and testing of three tiles, giving 12 measurements per set (per combination of product and number of coating layers). Measurements were averaged and the resulting mean values are provided in Figure 3 and Table 2.

Statistical tests were performed by finish (product) on the mean values from Table 2 using the Tukey honest standard difference test at the 95 % confidence level as shown in Table 2, which identified 4 distinct groups, A, B, C and D. Any group assigned to a specific letter with no other groups sharing that letter should be interpreted as having a statistically significant difference from all other results (for that finish). When a group is assigned two letters (or more) it means that in a pairwise comparison, it is not statistically significantly different from either group, but is statistically different from other groups not sharing a group letter.

Studying the risks contributing to ST&F events is complicated [5]. The ASTM D2047 standard has been used for decades as an appropriate way of measuring the slip resistance of a finished floor tile [10] but is a lab-based test that relies on hand coating floor tiles and then measuring the SCOF to assess the slip resistance of the floor. For tiles on in-use floors, this approach is limited by the ability to remove the tile and measure the SCOF without damaging or modifying the SCOF. Accurately measuring the slip resistance of the floor may not be enough to predict the risk of an ST&F event as floor slipperiness has been estimated to be a factor in only 40 – 50 % of fall injuries [17]. Even so, accurate measurement of the slip resistance of the floor is an important part of estimating the risk of an ST&F event.

By design, foot traffic wears away part of the floor finish over time, so different parts of a commercial floor may have different numbers of coating layers of finish remaining on the floor. Understanding how the SCOF of a finished floor varies when different numbers of layers of floor finish are present may help predict the impact of the slip resistance of the floor.

Table 2. Tukey grouping by finish with SCOF mean value for varying coating layers of finish

Product	No. of layers	Mean SCOF value and *SD*	Tukey group
Finish A	2	0.54 (0.053)	A
	4	0.56 (0.040)	A
	6	0.55 (0.035)	A
	8	0.59 (0.054)	A
	10	0.55 (0.031)	A
Finish B	2	0.52 (0.031)	B
	4	0.57 (0.045)	A
	6	0.61 (0.045)	A
	8	0.58 (0.035)	A
	10	0.58 (0.032)	A
Finish C	2	0.54 (0.031)	C D
	4	0.52 (0.045)	D
	6	0.56 (0.025)	B C
	8	0.59 (0.033)	B
	10	0.64 (0.040)	A
Finish D	2	0.58 (0.044)	B
	4	0.57 (0.055)	B
	6	0.66 (0.046)	A
	8	0.70 (0.038)	A
	10	0.66 (0.075)	A

SD – standard deviation (in parenthesis)

No evidence was found that increasing the number of coating layers of finish negatively impacts the slip resistance of the floor tiles. For Finish A there was no statistically significant change in SCOF from 2 to 10 layers of finish. For Finish B, there was a statistically significant change

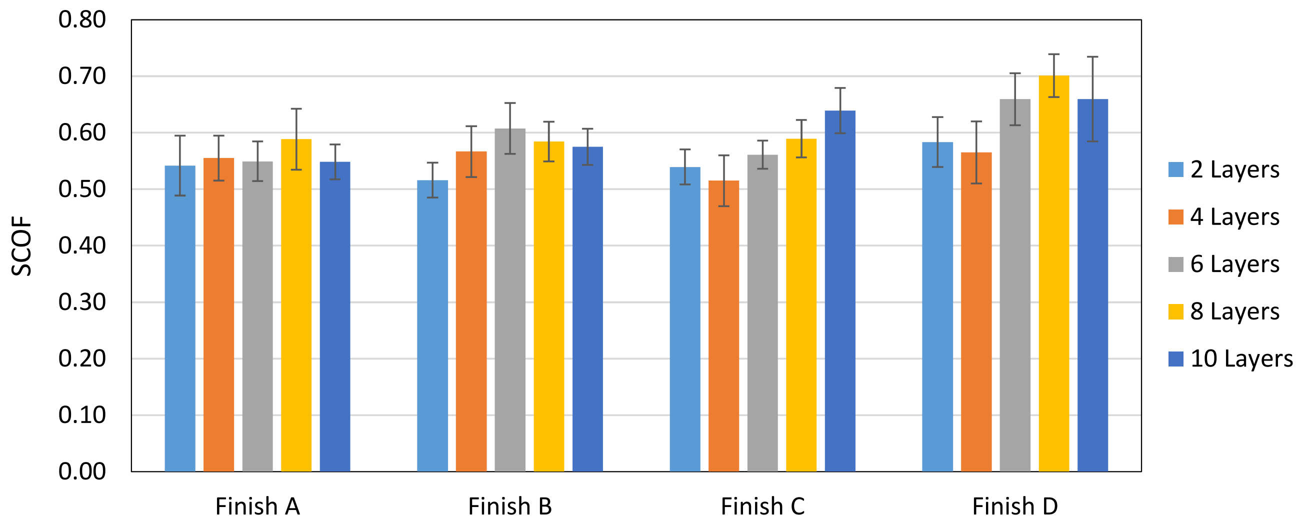

Figure 3. Mean SCOF measurements and standard deviation from the James Machine using ASTM D2047

in SCOF between 2 and 4 layers of finish, but once 4 layers of finish were applied, which is the manufacturer's recommendation on the product label, there was no significant change in SCOF between 4 and 10 layers of finish. For Finish C, there were statistically significant differences in the SCOF for different numbers of layers of finish, but the trend was to increase the SCOF and thus the slip resistance, by applying more layers of finish. For Finish D, there was a statistically significant change in SCOF between 2 and 4 layers of finish versus 6, 8 and 10 layers of finish, but once 6 layers of finish were applied, there were no significant differences in SCOF between 6 and 10 layers of finish.

In interpreting the results, it was concluded that when floor finish is first applied to a floor there is an initial build of SCOF as the topography of the floor plays a role. The first several coating layers tend to fill in the valleys of the floor, eventually providing a consistent and more even/smooth surface, presumably reducing the surface roughness at the same time. For some coatings, this occurred after the application of two coating layers, while for others it took four to six coating layers. After this initial build of slip resistance and the likely reduction in surface roughness, additional coating layers tended to either further increase the SCOF or have no impact on the SCOF. This is thought to be due to a relationship between the coating hardness, the surface roughness of the coating layer and the way the James Machine tests for SCOF. In classical tribology, the roughness of the floor would be a major factor in determining the SCOF as peaks would tend to create compression points that increase the slip resistance [18,19]. However as the number of coating layers increases, the presumed reduction in surface roughness of the coated floor could be offset by the increased compressibility of the coating layers. The James Machine uses a 76.2 × 76.2 × 6.35 mm (3 × 3 × 0.25 in) leather pad [10] which is abraded prior to testing to ensure a fresh surface. As this pad is pressed into the coating layers during testing, the thicker the overall coating, the more likely that there is the potential for compression of the coating, providing an increase in SCOF. Additionally, floor finishes are often characterised as being harder or softer, depending on the ability to resist scratches, prevent black heel marks and respond to certain maintenance procedures. It is possible that for a harder coating, the additional layers are more important in creating the potential for compression, while for a softer coating, this is less relevant. Although this was not tested in this study, it would have been helpful and would have further demonstrated the role of floor roughness and coating hardness on SCOF and thus is a limitation of this work. To the best of our knowledge, this is the first study to investigate the relationship between the slip resistance, assessed through the SCOF of the finished tiles and the number of coating layers of floor finish applied to a vinyl composite tiles floor.

This study demonstrated some limited evidence that for some floor finishes, increasing the number of layers of floor finish may increase the SCOF of the tiles, but this was limited to 1 of 4 (25 %) of the products tested and would likely represent an improvement in slip resistance, rather than an increase in risk associated with walking on this finish. For 2 of 4 (50 %) of the products tested, the SCOF did not change once the manufacturer's recommended number of coating layers of floor finish was applied to the floor tiles and for the remaining product, the SCOF levelled off once six coating layers of finish were applied.

Since the amount of finish applied to a tile is not controlled, some amount of variability in the slip resistance would be expected as a minimum layer of floor finish may be needed to achieve a consistent SCOF, regardless of the number of layers of finish applied. This is a limitation of this study but is consistent with the real-world application of floor finish, where the thickness of a finish layer may vary from person to person when applying finish to the floor. Because we had an application expert in floor care applying the finish, presumably the application was more consistent than might be found in commercial facilities but still confounds this work. There was also no attempt to measure the film thickness of the floor finish once applied to the floor, which would have added to our understanding of how the overall thickness of the floor finish correlated with the SCOF. This would have been difficult to achieve but will be considered in future experiments. Additional limitations of the study include the number of products tested, testing products from only one manufacturer, not controlling or measuring the amount of floor finish applied with each coating layer, not testing at different temperatures and humidities, and using a single floor care application expert to apply the finish.

4. Conclusion

In summary, this study found that increasing the number of coating layers of finish on a vinyl composite tiles floor above the minimum number of layers recommended by the manufacturer did not negatively impact the slip resistance of the floor and where the SCOF changed, increasing the number of layers of finish increased the SCOF and thus the slip resistance of the floor. This work demonstrates the importance of applying the manufacturer's recommended minimum number of coating layers of floor finish to maintain an appropriate layer of floor finish on the floor. Since ASTM D2047 operates on pass/fail criteria, the use of the individual measurements of SCOF for purposes of statistical analysis in this study should not be confused with whether the finishes tested passed the ASTM D2047 method's pass/fail test criteria. All measurements in this study passed the ASTM D2047 criteria and thus provided a slip-resistant walkway surface as required by OSHA. The variability detected in this study all tended to increase the slip resistance by applying additional layers of finish, which may or may not have any practical safety benefit. The results of this study suggest that rather than increasing the risk of an ST&F event, applying additional coating layers to a floor actually improves the safety profile of a finished floor.

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