RELATIONSHIP OF TRIBOLOGICAL PROPERTY OF DIFFERENT FLOORING TEXTURES ON HUMAN MOBILITY

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May 2019

This dissertation is submitted to
Universiti Sains Malaysia
As partial fulfilment of the requirement to graduate with honors degrees in
BACHELOR OF ENGINEERING
(MANUFACTURING ENGINEERING WITH MANAGEMENT)

School of Mechanical Engineering
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DECLARATION

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ACKNOWLEDGEMENT

My project would not have completed without the aid and support from various parties. First and foremost, I would like to extend my greatest gratitude to my supervisor, Dr Ramdziah Md Nasir for her continuous assistance and guidance given throughout the whole project process. I also would like to thank my supervisor for her unconditional support and valuable information which cleared my doubts and leaded me to the right direction.

Besides that, I would like to express my highest appreciation to Engineer Assistants of School of Mechanical Engineering who have gave good suggestions to me based on their experience in fabrication and parameters setting for machines. These helped me to avoid using wrong method and settings which eliminated repetitive experiments due to failure.

Similarly, I am grateful to Madam Rosni, Miss Azrina and technicians from School of Chemical Engineering who have arranged time and helped me in carrying out viscosity test. With their help, I am able to determine the viscosity of the surface contaminants which is an important data for my project.

In addition, I would like to thank my parents, course mates and friends who have gave comments, suggestions and encouragement to allow me generated more ideas and be more positive throughout this journey of completion of work.

Last but not least, I would like to appreciate all who have directly or indirectly supported me throughout this project.

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LIST OF ABBREVIATIONS

Abbreviations	Representation
COF	Coefficient of friction
DCOF	Dynamic coefficient of friction
SCOF	Static coefficient of friction
RCOF	Required coefficient of friction
POD	Pin on disc
SEM	Scanning electron microscope
XRD	X-ray diffraction
DOE	Design of experiment
EDX	Energy Dispersive X-Ray
ANOVA	Analysis of variance
HDF	High density fiberboard
MDF	Medium density fiberboard
Fe	Iron

ABSTRAK

Tekstur lantai merupakan salah satu faktor utama yang menyebabkan kegelinciran dan kejatuhan. Kemungkinan untuk tergelincir meningkat apabila terdapat cecair di permukaan lantai. Dalam kajian ini, sifat tribologi jubin seramik yang digilap kilat, jubin seramik yang licin, jubin seramik yang bercorak kasar, jubin kayu kamina dan jubin vinil, serta kesan wujudnya cecair terhadap jubin-jubin tersebut telah dikaji, untuk mendapatkan pemahaman yang lebih mendalam tentang sifat rintangan kegelinciran. Sifat-sifat tribologi tekstur lantai dikaji dengan menggunakan "pin-on-disc" tribometer, di mana jubin-jubin tersebut digosok dalam keadaan kering dan basah dengan air, larutan bahan pencuci dan minyak masak. Pekali geseran dinamik, pekali geseran statik dan kadar haus spesifik tekstur lantai telah ditentukan. Tekstur lantai dan kontaminan atas permukaan tekstur lantai adalah faktor utama yang menentukan pekali geseran dinamik serta menyumbang kepada pemulihan daripada tergelincir. Manakala kelajuan gosokan, tekstur lantai dan kontaminan atas permukaan tekstur lantai adalah faktor utama yang menentukan pekali geseran statik serta menyumbang kepada inisiasi kegelinciran. Permukaan yang lebih kasar tidak membawa kepada pekali geseran yang lebih tinggi. Pekali geseran dan kadar haus spesifik menurun apabila kepekatan kontamina lebih tinggi, disebabkan oleh kesan filamen terperosok. Semasa ujian "pin-on-disc" dijalankan, haus lekatan telah berlaku. Faktor utama yang menentukan kadar haus spesifik ialah tekstur lantai. Kadar haus spesifik lebih rendah bagi tekstur lantai yang lebih keras dan licin. Akhirnya, sifat tribologi tekstur lantai atas pergerakan manusia dari segi kegelinciran telah dinilai dengan melukis graf kadar haus spesifik terhadap pekali geseran. Tempat yang sesuai untuk pemasangan setiap tekstur lantai juga telah dicadang berdasarkan penilaian tersebut.

ABSTRACT

The flooring texture is one of the major factors that contributes to slip and fall incidents. The possibility of slips and falls increases when there are liquid or aqueous present on the flooring surface. In this research, tribological property of high-gloss polished ceramics tile, normal smooth ceramic tile, structural irregular pattern ceramic tile, laminate wooden tile and vinyl tile, and effect of the presence of different liquid/ aqueous on these flooring textures were investigated, aiming for a better understanding of slip resistance property. The tribological property of these materials were being measured using pin on disc tribometer, under dry sliding and wet sliding with water, detergent solution and oil. The dynamic coefficient of friction, static coefficient of friction and specific wear rate of those flooring textures had been determined. Types of flooring textures and surface contaminants are the significant factors affecting dynamic coefficient of friction and contribute to slip recovery. Whereas sliding speed, types of flooring textures and surface contaminants are the significant factors affecting static coefficient of friction and contribute to slip initiation. Higher surface roughness of flooring textures does not give higher coefficient of friction. The coefficient of friction and specific wear rate are lower when the viscosity of surface contaminant is higher, due to squeeze film effect. During pin on disc test, adhesive wear occurred. The significant factor affecting specific wear rate is the types of flooring textures. Specific wear rate decreases when the flooring texture is harder and smoother. Finally, the tribological property of the flooring textures on human mobility from the aspect of slipperiness was ranked by plotting graph of specific wear rate against coefficient of friction. The suitable areas of application for each flooring textures were also suggested based on the ranking.

CHAPTER 1.0 INTRODUCTION

1.1 Tribological Property of Flooring Textures and Slip and Fall Incidents

Home injuries are always an issue for concern in medical perspective. The prevalence for permanent disability due to home injuries was quite alarming, in which the prevalence was 2 % in children under 7 and 11.5 % in those above 60 years old. Permanent disability will negatively impact the quality of life and the social function of those affected by loss of productivity. The socio-economic impact, meanwhile will not only burden the family but the ministry of health and the nation as well, due to the life long suffering of those with permanent disability [1]. Injury among elderly people is usually associated with high morbidity and mortality, and is thus a public health concern. It requires longer hospitalization and more extensive medical attention, resulting in a greater health care burden [2].

Slip and fall from same level is one of the common causes of home injuries for children as well as elderly. Slip and fall from same level is the second highest cause of home injuries for children, with 29.5 % prevalence, while it is the highest cause for elderly, with 42.2 % prevalence [1]. It is predicted that the rate of home injuries for elderly will increase since the life expectancy of Malaysians is increasing. Most of the home injuries can be prevented. Improvement in home furnishings, especially in accident-prone areas such as the kitchen and bathroom/toilet is necessary [2]. Slippery floor is the third highest common contributing factors of injuries (15.6 %) after self-lack of attention (47.0 %) and health problem (18.6 %) [1].

To understand and reduce slip and fall accidents, tribological property of different flooring textures and biomechanics of slip and fall are two of the primary approaches used traditionally. Tribology is about the science and engineering of interacting surfaces in relative motion. It includes the study and application of principles of friction, lubrication and wear. When the available friction at the shoe-floor interface cannot meet the biomechanical requirements, a slip becomes imminent, possibly resulting in injury. Macroroughness or tread patterns are commonly designed into the shoe surfaces but become ineffective quickly after being worn. However, the surface roughness of the floor seems to provide better effects on slip resistance performance than the shoes because floor surface finishes may offer sharper, taller, and tougher texture in their surface features [3].

Furthermore, when the floor covered by water, detergent, oil, or other liquid, those liquid will increases the time to contact the tread with the floor. Before the liquid is discharged from the surface between tread and floor, the friction could not be produced. Therefore, the slip-resistance effect will decrease significantly and the falling and slipping will happen dramatically [4]. The slip resistance functions of floor and floor covering also deteriorate over time. With repeated walking, the surface finishes of floors seem to experience considerable changes owing to aging of flooring materials, wear and tear, soiling, and maintenance [3].

The older adults fell more often than the other age groups. Fall recovery threshold (FRT) measures indicated that younger adults were able to recover from a slip (thus preventing a fall) with higher sliding speeds and longer slip distances than older adults. Additionally, if elderly's adjusted friction utilization (AFU) on a slippery floor surface was not adjusted within the dynamic friction requirements, more falls will be resulted. Fall-related accidents among elderly seems more to be caused by factors influencing compensation of a slip rather than gait characteristics influencing slip initiation based on age-related differences observation [5].

1.2 Problem Statement

The flooring texture is one of the major factors that contributes to slip and fall incidents. The possibility of slips and falls increases when there are liquid or aqueous present on the flooring surface. Therefore, in this research, tribological property of different flooring textures and effect on flooring textures with the presence of different liquid/ aqueous will be investigated, aiming for a better understanding of slip resistance property of different flooring textures and able to recommend suitable types of flooring according to area of application.

1.3 Research Objective

1. To determine the frictional coefficient and specific wear rate of different flooring textures.

2. To investigate the effect on flooring textures with the presence of different liquid/ aqueous.

3. To rank the tribological property of different flooring textures on human mobility from the aspect of slipperiness.

CHAPTER 2.0 LITERATURE REVIEW

2.1 Tribological property of different flooring textures

Evaluation of floor slip resistance should be based on understanding of basic tribological characteristics [6]. Tribological property is related to the study on friction and wear. Previous studies confirm that measuring slipperiness is a complicated problem, not only because slip resistance is related to friction occurring at the surface/shoe interface, but surface roughness is also an important factor in determining the most appropriate finish for use in various environments and activities [7]. Kim suggests that the propositioned concept on operational ranges with lower and upper boundaries for the floor surface roughness may have applicable design implications for floors and floor coverings to provide optimal slip resistance implementation [3]. Terjék and Dudás uses arithmetical mean deviation (R_a) and the maximum height of the assessed profile (R_z) as parameters to measure the surface roughness while Kim choose peak height-related roughness parameters such as R_a, R_t, and R_{tm}. Some other researchers support that R_z is a useful indicator of the slip resistance of flooring materials [8, 9]. There were significant correlations between the floor surface roughness and dynamic coefficient of friction (DCOF) under polluted environments. When the floor surface roughness was raised, this improves slip resistance performance by raising the DCOF [3]. The research's results from J.D. et al. suggest that a linear relationship between roughness (Rz) and slip resistance, as measured by the pendulum test, may exist for stiff surfaces [9].

In the research carried out by Health and Safety Executive (HSE) [8], they classified some flooring materials according to slip potential in wet conditions using R_z data collected from ramp board and also the result collected from pendulum test respectively. The classification is shown in Table 2.1.

Table 2.1: Classification of flooring materials using R_z data and pendulum test data [8]

Slip Potential	**Classification using R_z data**	**Classification using pendulum test data**
High	• Polished marble • Agglomerate • Polished Granite • Terrazzo Natural Finish • Terrazzo Gloss Finish • Unfilled Travertime Gloss Finish • Honed Limestone	• Polished marble • Agglomerate • Polished Granite • Terrazzo Natural Finish • Honed Limestone
High/ moderate	-	• Terrazzo Gloss Finish
Moderate	• Polished Limestone • Unfilled Travertime Natural Finish	• Polished Limestone • Unfilled Travertime Natural Finish • Unfilled Travertime Gloss Finish • Artificial Slate Smooth Finish
Low	• Riven Slate Gloss Finish • Pebble Mosaic • Riven Slate Natural Finish • Natural Stone	• Riven Slate Gloss Finish • Pebble Mosaic • Riven Slate Natural Finish • Natural Stone

Studies have shown that the required COF for a person to walk without slipping is typically around 0.30 to 0.40 depending upon gait and other individual factors. The Underwriter's Laboratory established in the early 1940's that a COF of more than 0.5 was considered slip resistant. This value has been repeatedly cited and is acceptable in the flooring industry as the standard performance measure [8]. Furthermore, the Americans with Disabilities Act Accessibility Guidelines contain advisory recommendations for static COF of more than 0.60 for accessible routes (e.g. walkways and elevators) and static COF of more than 0.80 for ramps [10].

Kim [11] measured and compared the slip hazard using three kinds of slipmeter, which are British Pendulum Tester, BOT-3000 and English XL. Four common restaurant floor materials were tested under five contaminants. The results are shown in Figure 2.1.

Surface condition	Floor material	BPT	XL	BOT	
		4S-rubber	Neolite	Neolite	
		BPN	Slip index	SCOF	DCOF
Dry	Ceramic	83.6 (5.78)	0.78 (0.039)	0.999 (0.003)	0.786 (0.154)
	Vinyl	78.37 (2.56)	0.74 (0.041)	0.95 (0.050)	0.529 (0.048)
	Asphalt tile A	81.52 (4.66)	0.6125 (0.057)	0.945 (0.059)	0.547 (0.030)
	Asphalt tile B	93.9 (5.70)	0.633 (0.065)	0.876 (0.065)	0.902 (0.090)
Wet	Ceramic	18.93 (4.60)	0.545 (0.079)	0.573 (0.138)	0.435 (0.036)
	Vinyl	12.37 (1.83)	0.467 (0.107)	0.44 (0.048)	0.19 (0.036)
	Asphalt tile A	22.42 (3.86)	0.23 (0.024)	0.65 (0.094)	0.615 (0.031)
	Asphalt tile B	4.32 (0.70)	0.188 (0.042)	0.368 (0.029)	0.365 (0.006)
Detergent solution	Ceramic	15.52 (3.34)	0.24 (0.055)	0.332 (0.035)	0.306 (0.017)
	Vinyl	4.98 (1.95)	0.132 (0.020)	0.149 (0.014)	0.116 (0.013)
	Asphalt tile A	15.07 (6.18)	0.135 (0.041)	0.48 (0.059)	0.428 (0.062)
	Asphalt tile B	1.33 (1.18)	0.073 (0.013)	0.321 (0.012)	0.238 (0.029)
Soybean oil	Ceramic	4.55 (1.17)	0.065 (0.011)	0.22 (0.012)	0.123 (0.013)
	Vinyl	3.6 (0.85)	0.026 (0.019)	0.186 (0.009)	0.058 (0.010)
	Asphalt tile A	3.58 (0.72)	-	0.41 (0.018)	0.06 (0.014)
	Asphalt tile B	3.38 (0.89)	-	0.144 (0.014)	0.02 (0.007)
Engine oil	Ceramic	5.43 (0.87)	-	0.192 (0.020)	0.043 (0.009)
	Vinyl	6.62 (0.88)	-	0.172 (0.008)	0.038 (0.007)
	Asphalt tile A	8.167 (0.56)	-	0.397 (0.023)	0.019 (0.003)
	Asphalt tile B	9.5 (0.98)	-	0.156 (0.008)	0.01 (-)

BPT: British Pendulum Tester, XL: English XL, BOT: BOT-3000, BPN: British Pendulum Number, SCOF: static coefficient of friction, DCOF: dynamic coefficient of friction.
-: output value less than 0.001.

Figure 2.1: Means (standard deviations) of all tested devices and test conditions [11].

In all surface conditions, either dry, wet, covered with detergent solution, covered with soybean oil or covered with engine oil, ceramic shows a better slip resistance property compared to vinyl [11].

2.2 The effect on flooring textures with the presence of different liquid/aqueous

As reported by Chen et al., liquid viscosity is the most powerful factor affecting COF of flooring [4]. This influence can be described by squeeze-film effect. The equation of squeeze-film effect introduced by Moore is as follow.

$$t = \frac{K\mu A^2}{F_N}\left(\frac{1}{h^2} - \frac{1}{h_0}\right) \tag{2.1}$$

Where t is the time needed to reduce the liquid thickness from initial h_0 to h, F_N is the normal forces, K is the shape constant, μ is the viscosity of liquid, and A is the contact area between the surface. According to Moore’s equation, the thicker the liquid viscosity is, the longer time to contact the tread of shoes with the floor and thus the higher the risk of slipping will be. In other words, the higher the liquid viscosity, the lower the COF between shoes and the floor is, the lower the degree of anti-slippery will be. Thus, appropriate roughness of the floor surface could be effective to improve the squeeze film effect caused by liquid when the floor is contaminated by liquid.

Mohan et al. [12] reported two different types of lubrication mechanism in explaining the effect of presence of contaminant on shoe-floor slip resistance, which are boundary lubrication and hydrodynamic lubrication. The interface is in hydrodynamic lubrication region when the viscosity of contaminant is very high. The normal force is fully supported by the lubrication effect and the two contacting surfaces are fully separated by the contaminant at the interface. The shape and the relative motion of the soling surface cause the formation of a squeeze film that has sufficient pressure to separate the surfaces. The squeeze-film and wedge effects are dominant factors in friction in the hydrodynamic lubrication region. As the viscosity reduces, the contaminant thickness is reduced to a thinner film while the two contacting surfaces still maintain separation. The normal force remains fully supported by the lubrication effect and the asperities on both contacting surfaces deform without touching each other. With a further reduction in viscosity, the two contacting surfaces eventually establish solid to solid contact and the interface is in the boundary lubrication region in which the contaminant film does not completely separate both surfaces. The normal force is supported partially by the lubrication effect and partially by a direct solid to solid contact in the boundary lubrication region. COF is greater in boundary lubrication than in hydrodynamics lubrication. The surface contaminants investigated by Mohan et al. are water, water-detergent and engine-oil, with viscosity of 1.0 cPs, 1.5 cPs and 125.0 cPs respectively. The order of reduction in COF, or in other words, the increase in slipperiness for the contaminants can be set as water>detergent solution>oil. This trend is observed for all speeds of horizontal sliding.

2.3 Pin on disc (POD) tribometer

Xiu Qing et al. [13] use pin on disc tribometer to investigate the tribological property of hot-pressed B_4C-hBN ceramic composites. The density of specimens is first determined using Archimedes' method. Microhardness was tested using Vickers' indention with 1kg load and 15s loading time. Wear tests were carried out under dry sliding condition using pin on disc tribometer. The schematic diagram of rotary pin on disc tribometer is shown in Figure 2.2. The parameters of the experiment are 10 N normal load, 0.656 m/s sliding speed, 12.5 mm sliding radius and 800 m sliding distance. After that, the worn surfaces were observed and analyzed using scanning electron microscope (SEM) and X-ray diffraction (XRD).

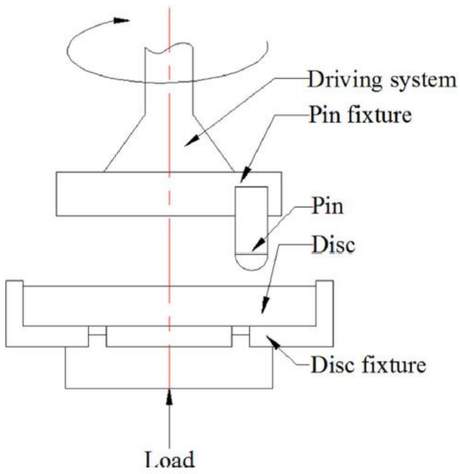


Figure 2.2: Schematic diagram of the rotary pin on disc tribometer [13].

Duanjie [14] reported the principle of Nanovea Tribometer and explained the measurement of static COF using the rotary tribometer. The sample is mounted on a rotating stage, while a known force is applied on a pin, or ball, in contact with the sample surface to create the wear. The pin-on-disk test is generally used as a comparative test to study the tribological properties of the materials. The COF is recorded in situ. The volume lost is used to calculate the wear rate of the material. Since the action performed on all samples is identical, the wear rate can be used as a quantitative comparative value for wear resistance. The evolution of COFs of one of the specimens, Glass sample is shown in Figure 2.3. Low speed starting at 0.0001 rpm allows us to observe a progressive friction force build up at the beginning of tests. The spike of the graph at the beginning of the COF test represents static COF. The relative motion at the interface of pin and disc takes place when the friction reaches the threshold (static COF), and the subsequent measured COF decreases. Thus, the static COF and average dynamic COF can be obtained.

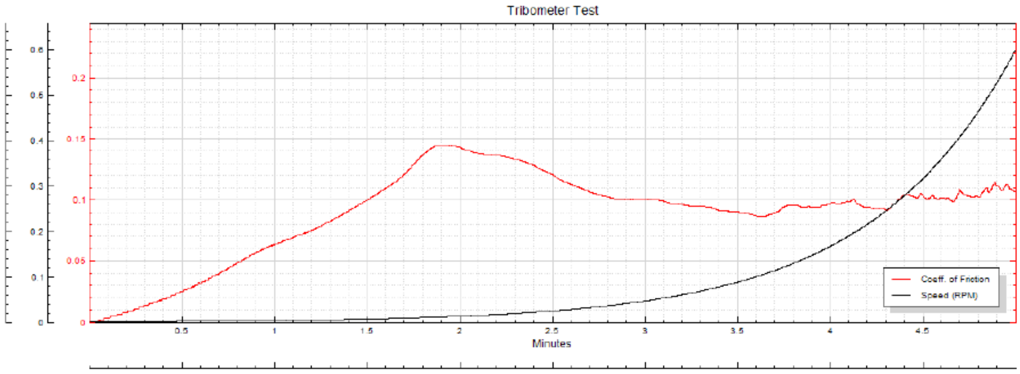


Figure 2.3: The evolution of COF of Glass sample- COF vs. Time [14].

Other than rotary tribotest discussed above, reciprocating tribotest is also one of the test can be performed to investigate the tribological properties of specimen. The pin is hold in stationary with a known load applied vertically and the disc is moving in reciprocal.

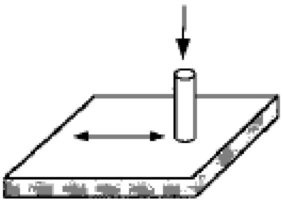
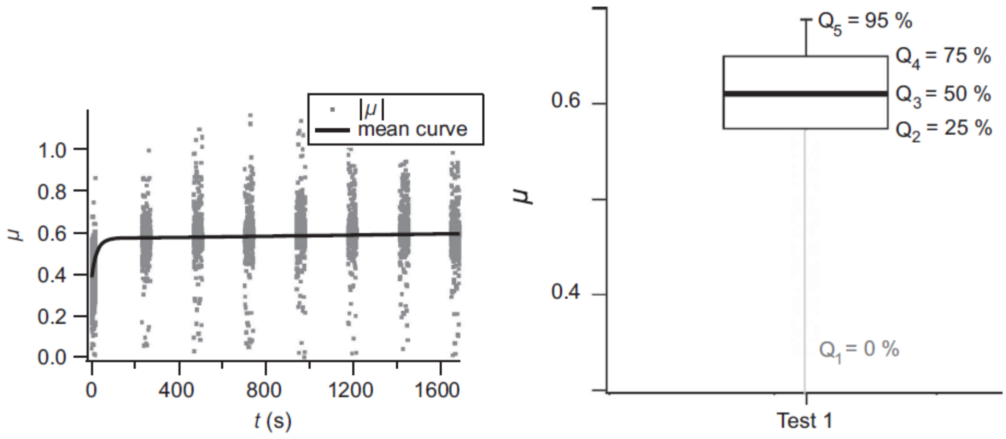


Figure 2.4: Illustration of reciprocating sliding wear test configuration. [15]

M. Yahiaoui et al. [16] used box and whiskers plot to distinguish the static and dynamic values of the friction coefficient from the signal generated from reciprocating sliding wear test. The Q3 third quartile represents an average of the dynamic friction coefficient. The Q2 and Q3 quartiles give the discrepancy of the dynamic friction coefficient. Because of the alternative crossing of the zero value by the friction coefficient, the Q1 quartile was set to 0%. Finally, the Q5 quartile gives an extreme value which is more like the static friction coefficient and the friction occurring at the end of the strokes upon reversals.



(a) (b)

Figure 2.5: Friction coefficient signal treatments: (a) mean curve; (b) box and whiskers plot.[16]

The wear rate can be calculated together with sliding speed of pin on disc tribometer using the equation below [17].

$$Wear\ rate = \frac{Volume\ loss\ (mm^3)}{Load\ (kg) \times Sliding\ distance\ (mm)} \tag{2.2}$$

Nuraliza et al. [17] reported few relationships between the parameters. COF value is inversely proportional to the sliding speed. The wear rate increases when the load is increased. High surface roughness will reduce the wear and COF will increase in long term period.

2.4 Slip and fall related to age

Required COF (RCOF) is one of the factors to investigate to understand the slip and fall incidents. RCOF is the minimum coefficient of friction that must be available at the shoe-floor interface to present slip initiation. RCOF was determined by the ratio of vertical ground reaction force over horizontal ground reaction force during heel contact phase of gait cycle [18]. Individual with higher RCOF indicates higher likelihood of slip initiation. However, previous researches [19] indicate that older adults did not exhibit a higher RCOF compared to younger adults since older adults walk with shorter step lengths and slower speeds. These have the net effect of decreasing the RCOF of older adults. Anderson et al. [19] suggested that the increased rate of falls among older adults is not due to a greater likelihood of slipping while walking.

The increased rate of fall among elderly may be due to the difficulty in recover from a slip. In humans, in order to recover balance from the loss of balance due to slipping or tripping depends on an effective and rapid protective step either behind or in front of the center of mass. People tend to increase the step length and generate a strong push off in the recovery foot order to recover balance after a trip and avoid falling [20], while fall avoidance after a slip is dependent upon arresting motion of the slipping foot and rapidly lowering the non-slipping limb to the ground behind the center of mass [21]. Recovery of balance after a slip or a trip becomes more limited as we grow older. Initially, people tend to be leaning forward due to the stooped posture and have a reduction in joint movement which further decreases their ability control to swing the recovery leg in order to take a large step [22].

It is normal to become less upright as one ages. Kyphosis is one of the factors that predispose us to have altered posture as we age. Age-related postural hyperkyphosis is an exaggerated anterior curvature on the thoracic spine. This condition effects mobility and increase the rate of falls [23]. From the research findings of Damasceno et al. [24], it is proven that older individuals show higher value in measurements for lumbar curvatures, and this lumbar curvature values are higher in females as compared to males. Thus, we can say that elderly may have higher risk of fall due to difficulty in recover from slips because of the age-related stooped posture.

CHAPTER 3.0 METHODOLOGY

3.1 Scope of Research

Few types of conventional flooring materials were used as specimens in this research, which are high-gloss polished ceramics tile, normal smooth ceramic tile, structural irregular pattern ceramic tile, vinyl tile, and laminate wooden tile. The tribological property of these materials were measured using pin on disc tribometer which is available in the laboratory of School of Mechanical Engineering, under dry sliding and wet sliding with water, detergent solution and oil. The surface roughness of the flooring tiles before and after tribology tests were also measured and discussed. Lastly, the obtained data regarding tribological property of the flooring tiles will be ranked with human mobility from the aspect of slipperiness.

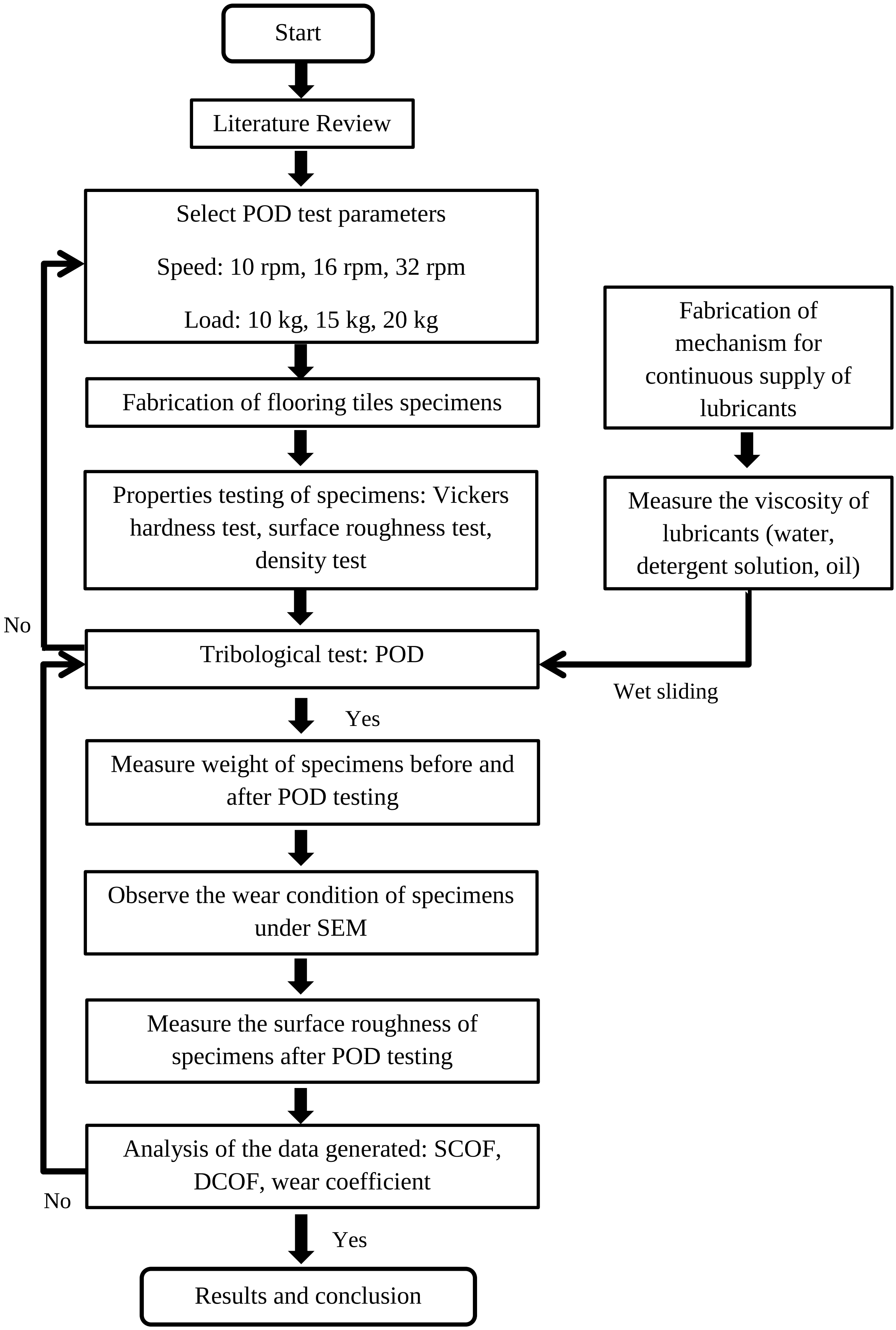


Figure 3.1: Overview of Scope of Work

3.2 Design of Experiment (DOE)

Pin on disc tribology test is carried out to investigate the tribological properties of different flooring textures. As shown in table 3.1, there are four factors with mixed levels to be investigated and it would not be realistic to run a full factorial design. Thus, Taguchi method is used to simplify the experiment by eliminating some combination of experiment which is not significant.

Table 3.1: Experiment Parameters

Factor	Level 1	Level 2	Level 3	Level 4	Level 5
Flooring texture	Ceramics A	Ceramics B	Ceramics C	Laminate D	Vinyl E
Lubricant	Dry	Water	Oil	Detergent	
Load (kg)	10	15	20		
Speed (m/s)	0.02	0.03	0.06		

L9 orthogonal (with four factors, three levels) is used in designing the experiment. The remaining level 4 and level 5 are manually assigned to cover their interaction with other factors. The final optimum combinations of experiment are shown in Table 3.2.

Table 3.2: Combinations of experiment

No.	Flooring texture	Load (kg)	Speed (m/s)	Surface contaminant
1	Ceramics A	10	0.02	Dry
2	Ceramics A	15	0.03	Water
3	Ceramics A	20	0.06	Oil
4	Ceramics A	10	0.02	Detergent
5	Ceramics B	10	0.03	oil
6	Ceramics B	15	0.06	dry
7	Ceramics B	20	0.02	water
8	Ceramics B	15	0.02	detergent
9	Ceramics C	10	0.06	water
10	Ceramics C	15	0.02	oil
11	Ceramics C	20	0.03	dry
12	Ceramics C	20	0.06	detergent
13	Laminate D	10	0.03	dry
14	Laminate D	15	0.06	water
15	Laminate D	20	0.02	oil
16	Laminate D	15	0.03	detergent
17	Vinyl E	10	0.06	dry

18	Vinyl E	15	0.03	water
19	Vinyl E	20	0.02	oil
20	Vinyl E	20	0.06	detergent

3.3 Preparation and Fabrication of Specimen

Five types of flooring textures; three ceramics tiles, one laminated wooden tile, and one vinyl tile are acquired. Ceramic tiles are cut into desired dimension using tile cutter and the edges are grinded using Makita grinder. Whereas laminated wooden tile are cut using electric saw. Vinyl tile are cut using paper cutter knife. The desired dimension is 22 mm × 98 mm, to suit the specification of pin-on-disc tester.

(a) (b) (c) (d) (e)

Figure 3.2: Five types of flooring textures used in the experiment. (a) High-gloss polished ceramics tile (Ceramics A). (b) Normal smooth ceramic tile (Ceramics B). (c) Structural irregular pattern ceramic tile (Ceramics C). (d) Laminate wooden tile (Laminate D). (e) Vinyl tile (Vinyl E).

(a) (b)

Figure 3.3: (a) Tile cutter. (b) Makita grinder.

3.4 Roughness Specification

Mitutoyo and Surfcom Surface Roughness Tester is used to measure the surface roughness of the specimen. The evaluation length is 4.0 mm. The R_a and R_z value are taken in three directions; 0^0, 45^0 and 90^0. The average values are calculated.

Figure 3.4: Mitutoyo and Surfcom Surface Roughness Tester

3.5 Vickers Hardness Specification

Vickers Hardness Tester-Mitutoyo HV-114 is used to measure the hardness value of the specimens. The load applied is 10 N, with 15 s loading time. The measurement is repeated 3 times for each specimen and the average values are obtained.

Figure 3.5: Vickers Hardness Tester-Mitutoyo HV-114

3.6 Density Specification

The densities of the specimens are determined using Archimedes' method. The mass of the dry specimen is first measured using Shimadzu AUW220D digital analytic balance with precision 0.0001 g, and is recorded as M. A volumetric cylinder is the partially filled with water and the water level is recorded as initial volume, V_0. After completely submerging the specimen into the volumetric cylinder, the water level is recorded as final volume, V_f. The density is then calculated using equation 3.1.

$$Density, mg/mm^3 = \frac{M}{(V_f - V_0)} \quad (3.1)$$

(a) (b)

Figure 3.6: (a) Shimadzu AUW220D digital analytic balance. (b) Specimen completely submerged in distilled water.

3.7 Viscosity Specification of Surface Contaminants

The viscosity of the surface contaminants (1) water is assumed as 0.0010 Ns/m^2 [12] while the viscosity of (2) detergent solution and (3) cooking oil is determined using Brookfield DV-111 Ultra Programmable Rheometer.

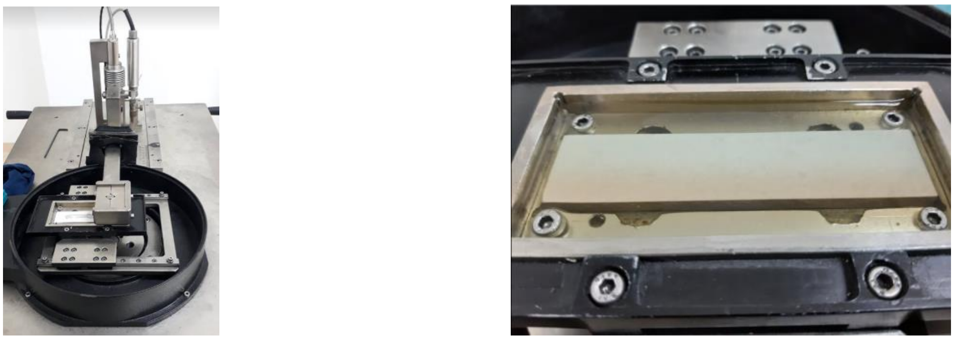
Figure 3.7: Brookfield DV-111 Ultra Programmable Rheometer in School of Chemical Engineering, USM

3.8 Tribology Characteristics

Friction and wear characteristics of flooring tiles are investigated using DUCOM Pin-On-Disc tester with model TR-20 according to ASTM G99 shown in Fig 3.8. Reciprocal POD test is chosen as the suitable method due to realistic conditioning. 10 mm diameter AISI 52100 alloy steel pin is used and the flooring tile is served as the sliding disc. The stroke length is 60 mm. Before POD test, the mass of the flooring tiles are measured and recorded as initial mass, M_1, using Shimadzu AUW220D digital analytic balance as shown in Figure 3.6 (a). The pin is loaded against the disc through a dead weight loading system.

Figure 3.8: DUCOM Pin On Disc tester model TR-20

20 sets of POD experiment are being carried out with the parameter combinations as shown in Table 3.2. The experimental setup is shown in Figure 3.9 (a) and (b). For wet sliding, the surface contaminant (water, detergent solution or oil) is poured into slot holding the flooring tile, until it completely covers flooring tiles at about 1 mm higher than the surface of the tile.



(a) (b)

Figure 3.9: (a) General POD experimental setup. (b) An example of flooring tile covered with oil for wet sliding

To set up WINDUCOM 2010 software in desktop, filename, sample id and remarks are entered and reciprocatory mode is selected before beginning the test. Sliding speed (RPM), load applied (in kg), and test time for 10 minutes on each sample testing were acquired. The “running continuously” button is clicked. The reference point is set zero and “RUN” button is then clicked to begin the test.

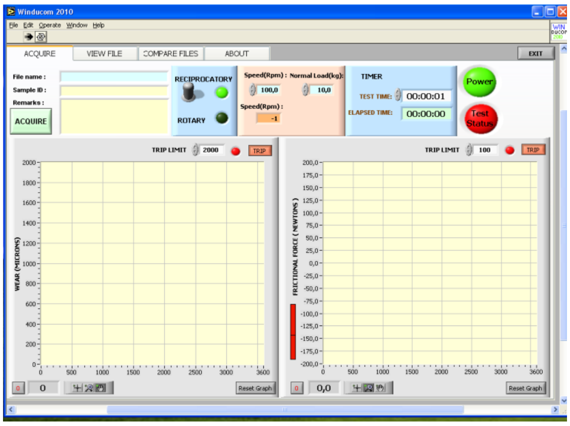


Figure 3.10: WINDUCOM 2010 software

After 10 minutes, the flooring tile is removed and the mass after POD test, M_2 is measured and recorded. The surface roughness after POD test is also measured. Wear volume loss is calculated by using Equation 3.2. Specific wear rate is calculated by using Equation 3.3 [17].

$$Wear\ volume\ loss,\ mm^3 = \frac{M_1 - M_2}{Density} \times 1000 \tag{3.2}$$

$$Specific\ Wear\ rate, mm^2/kg = \frac{Volume\ loss\ (mm^3)}{Load\ (kg) \times Sliding\ distance\ (mm)} \tag{3.3}$$

Whereas wear coefficient is calculated using Archard equation, Equation 3.4 [25],

$$Wear\ coefficient = \frac{Wear\ volume\ loss\ (mm^3) \times Hardness\ of\ specimen (kg/mm^2)}{Load\ (kg) \times Sliding\ distance\ (mm)} \tag{3.4}$$

The sliding distances for different sliding speed are tabulated in Table 3.3.

Table 3.3: Sliding distance of different sliding speed

Sliding speed (rpm)	Time taken to slide 1 stroke, 60mm (s)	Sliding speed (m/s)	Sliding distance (mm)
10	3	0.02	12000
16	2	0.03	18000
32	1	0.06	36000

3.9 Scanning Electron Microscope and Energy Dispersive X-Ray Analysis (EDX)

The worn surface of flooring tiles are observed using Hitachi S-3400 Scanning Electron Microscope (SEM). Elemental composition of the worn surface of the flooring tiles are analyzed Energy Dispersive X-Ray Analysis (EDX). Source of X-Ray has interacted with points of samples surface that selected and each element has a unique atomic structure with the presence of peak on its electromagnetic emission spectrum.

Figure 3.11: S-3400 Scanning Electron Microscope (SEM)

3.10 Signal Treatment

The raw data, which is the coefficient of friction (COF) over sliding time, is obtained from the pin on disc test. SCOF and DCOF are then determined from the box and whiskers plot of each set of data. Since the negative value for COF is indicating only the direction of sliding, absolute value of COF is taken to plot the box and whiskers plot. Q_2, which is median or 50 percentile, gives a good average of the DCOF. Q_1 and Q_3 give the discrepancy of the DCOF. Q_4 or 95 percentile gives an extreme value which is more like the SCOF and the friction occurring at the end of the strokes upon reversals [16].

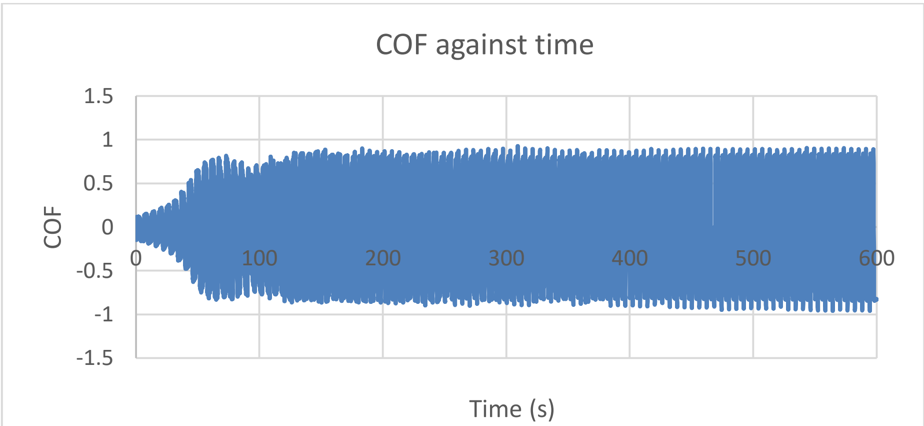


Figure 3.12: Signal generated when sliding on Ceramics A at sliding speed of 0.02 m/s and load applied 10kg at dry condition.

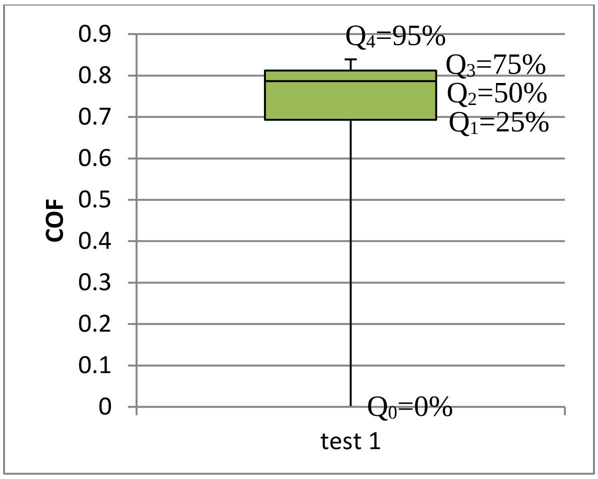


Figure 3.13: COF signal treatment; box and whiskers plot.

3.11 Analysis of Variance (ANOVA)

Analysis of Variance (ANOVA) is a statistical technique that identifies factors which significantly affecting the experimental results. In this research, MINITAB software are employed to analyze the experimental data based on statistical calculation to determine the levels of variability within a regression model and form a basis for tests of significance.

Normally, a p-value of 0.05 (5%) will be taken as the significance level in determining the significant factors. However, in this literature, p-value of 0.5 (50%) is used instead. This is because of the result from the experiment can only be served as a rough estimation on the relationship between tribological property of flooring and slipping incident. The experimental result is not related to human gait of walking. The physiology of human walking is not obtained due to resource limitation.

Main effect plot is also plotted using MINITAB to visualize how the response variables change with each factor. Interaction plot is generated using MINITAB as well to represent how any two factors interact with each other.

3.12 Verification

Two sets of experiment were carried out to further verify the reciprocal POD before proceed with the real experiments. Ceramics C and Vinyl E are used to obtain this initial reference value. Both Ceramics C and Vinyl E were tested with 10 kg load, 0.02 m/s sliding speed, under dry condition. Their COF was observed during 1 slide, 5 slides and 10 slides respectively. The specific wear rate and wear coefficient were calculated using Equation 3.2, 3.3 and 3.4.

3.13 Validation

A validation test is conducted in order to ensure that the experiment is representing the real world as much as possible. A piece of rubber shoe sole is stick to the pin and it is slid 10 times continuously on a randomly picked flooring texture, which is Ceramics C, in dry condition, with 10 kg normal load applied, and with 0.02 m/s sliding speed.

The initial and final weight of the shoe sole and flooring texture are measured using Shimadzu AUW220D digital analytic balance and the result is recorded. The initial surface roughness of both shoe sole and flooring tile is also measured using Mitutoyo and Surfcom Surface Roughness Tester and the result is recorded. The hardness of rubber shoe sole is measured using Teclock Hardness Tester Type GS-706G Shore A as shown in Figure 3.14. The hardness value is then converted to HV using online hardness conversion chart [26, 27]. The wear rate and wear coefficient of both pin and disc is then calculated using Equation 3.2, 3.3 and 3.4. The surface of the rubber shoe sole is then observed under SEM.

Figure 3.14: Measuring the hardness of rubber shoe sole using Teclock Hardness Tester Type GS-706G Shore A

CHAPTER 4.0 RESULT AND DISCUSSION

4.1 Surface Roughness Specification

Surface roughness (R_a and R_z) of all five different flooring textures is measured in three directions; 0^0, 45^0 and 90^0. The average value of each flooring textures is plotted in Figure 4.1.

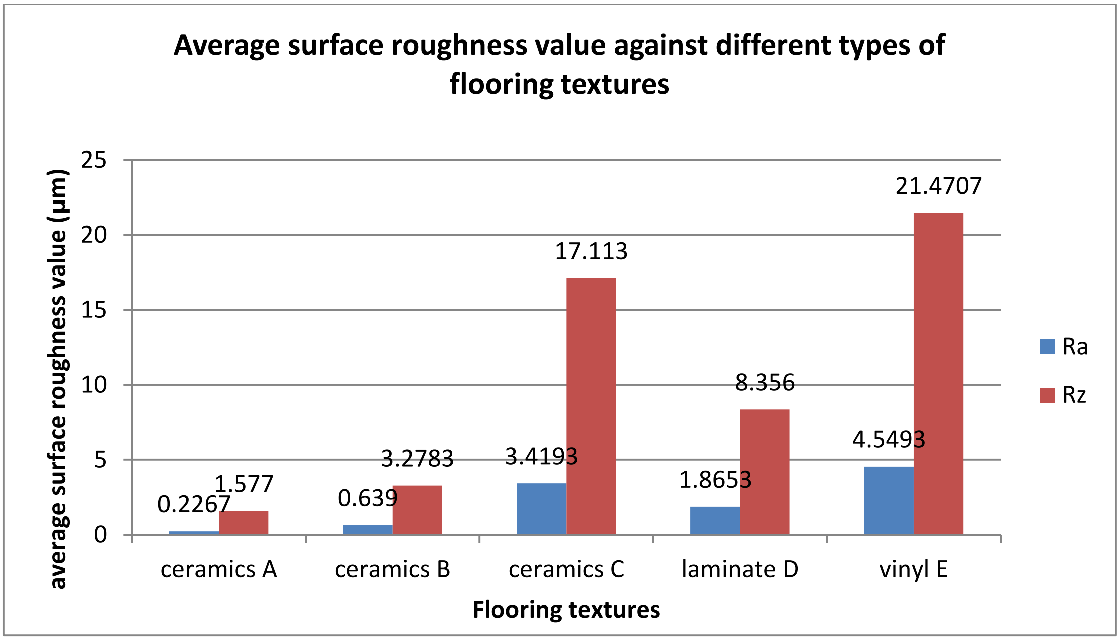


Figure 4.1: Average Surface Roughness Value for different types of flooring textures.

Both R_a and R_z show a same trend for all five flooring textures. Vinyl E has the roughest surface, followed by ceramics C, laminate D, ceramics B, and finally ceramics A. Vinyl E and Ceramics C show higher value in R_a and R_z because their surfaces are structural irregularly patterned. Ceramics A is the smoothest since its surface is high-glossed.

From the research done by Terjek et. al. [7], ceramics tile which is smooth and slightly polished has R_a of 0.61 µm and R_z of 7.67 µm, while ceramics tile which is high-gloss and polished has R_a of 0.04 µm and R_z of 0.28 µm. The R_a and R_z obtained for both ceramics A (R_a = 0.2267 µm and R_z = 1.577 µm) and B (R_a = 0.639 µm and R_z = 3.278 µm) is verified since they are also high-gloss ceramics and their surface roughness values compromise with the surface roughness values obtained in the mentioned research paper. While for ceramics tiles with structural and irregular pattern, like ceramics C in this paper, the R_a and R_z values range from 2.18 µm to 3.87

µm and from 12.85 µm to 20.53µm respectively [7]. The surface roughness result obtained for ceramic C (R_a = 3.4193 µm and R_z = 17.113 µm) shows no contradictory with the reference values. Smooth vinyl tile has R_a and R_z values of 1.55 µm and 13.61 µm respectively [3]. Thus, vinyl E which is structural and irregularly patterned definitely has a higher surface roughness value (R_a = 4.5493 µm and R_z = 21.4707 µm) than smooth vinyl tile.

4.2 Vickers Hardness Specification

Average Vickers Hardness value of different flooring textures is measured and the result is plotted as shown in Figure 4.2.

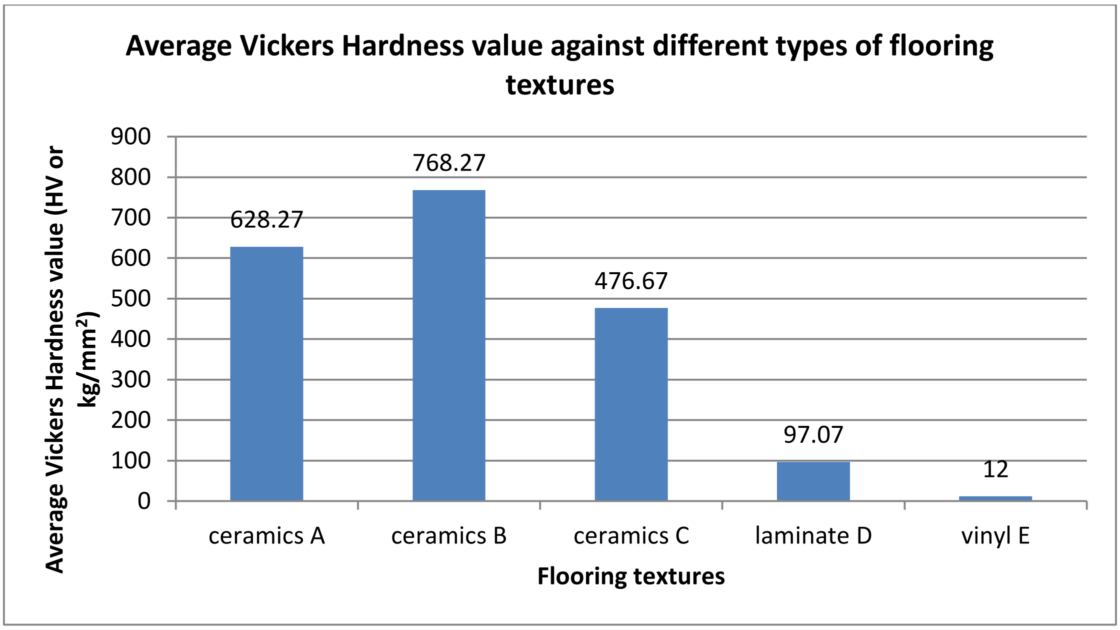


Figure 4.2: Average Vickers Hardness value for different types of flooring textures.

Ceramics tiles are much harder than wooden tiles; ceramics B is the hardest, followed by ceramics A, ceramics C, and laminate D. Vinyl E is the softest and it also shows some elastic surface property.

The Vickers Hardness value of ceramics tiles ranges from 225 HV to 1115 HV [28]. Thus, the result obtained for ceramics A (628.27 HV), ceramics B (768.27 HV) and ceramics C (476.67 HV) is verified since their Vickers Hardness values fall within the range. For laminate flooring tiles, they are normally made with high density fiberboard (HDF) core [29]. Studies have shown that the Vickers Hardness value for