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Design and Construct of Coefficient of Friction (COF) Machine utilizing ISO 13287: 2006 And Analyzing to Find Better COF of Shoes' Sole Material

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Abstract

The objectives of this research were to design and construct of coefficient of friction (COF) measuring machine according to ISO 13287: 2006 standard and to analyze and increase the values of COF of safety shoe heels that available in the market. The machine designed was utilizing metal weight to generate the vertical force. The heel angle could be set between 3 and 20 degrees. A pneumatic cylinder of 50 mm in diameter was used to move the tested floor with the speed of 30 – 500 mm /s. Two force transducers were used to detect vertical and horizontal forces. Each one had the capacity of 1,000 N. After assembling, the machine was tested. The results of the tests were comply with the standard. After that, 29 heel materials classified into 4 material groups were measured. According to the tested results, acrylonitrile - butadiene synthetic rubber (NBR) was selected to be further developed to gain better values of COF. Additives phenolic resin (P) and silicon dioxide (E) were added between 7-15 percents by weight into the original ingredient of NBR. The totals of 99 heels were made to find the best ingredient giving the maximum value of COF among them. The testing results indicated that the P14 ingredient gave the highest value of COF. This ingredient was the original NBR added 14 percents of phenolic resin. To compare the values of COF between the original NBR and the P 14, 4 testing combinations were carried out. One way ANOVA was used to find the difference between the 2 heel materials. The ANOVA results indicated that the differences of COFs from the 2 heels were significant ($p<0.0001$). It could be concluded that the ingredient P14 gave higher values of COFs than the original NBR.
Keywords: Acrylonitrile-butadiene synthetic rubber, Coefficient of friction(COF), Shoes' sole material, Phenolic resin

1. Introduction

Accidents in workplaces cause both direct and indirect losses to manufacturers and countries. In Thailand, the number of accidents caused by slips trips, and falls (STF) was 15,465 workers. In these accidents, 86 deaths, 5 disabilities, 88 loss of body parts, and 5,574 more than 3 days absent from work were found (Workmen's Compensation Fund, 2008 [1]). In the USA, the number of deaths of 700 persons per year from STF was found which was the second cause of deaths from overall accidents (Bureau of Labor Statistics, 2008 [2]). In Germany, Workers Safety Institute reported that there were 300,000 STF accidents per year. The average cost of these accidents was around € 28,000 (Gunter Klob Institute for Occupational Safety, 2008 [3]). In the UK, in 2008, there were 27,594 accidents and one-third of these were from STF (Health and Safety Executive, 2008 [4]). When the STF occurred, the average time to be hospitalized was 28 days (Workers Compensation Board, 1998 [5]). In Australia, there were STF accidents of 28,000 workers per year (The Australian Building Codes Board, 2008 [6]). These accidents were on floor level (Gallagher and Scott, 1997 [7]; Workers Compensation Board, 2002 [8]). The numbers of injured workers from falls at the same floor level were 14.3 percents for men and 20.7 percents for women. Usually, fall accidents were from slips and trips more than 60 percents. In comparing slips and trips accidents, 86 percents were from slips (Health and Safety Executive, 1996 [9]). Therefore, slipping accident was a big problem causing losses to our societies.

Perkin (1978) [10] studied reaction forces inserted on the floor during walking and created an equation to find coefficient of friction (COF or μ) by using horizontal over vertical forces or $\mu = F_H/F_V$ (where F_H = horizontal force and F_V = vertical force). He suggested that if the value of COF occurred during walking (or friction use) approaches COF available between floor surfaces and shoe heel materials, slipping is likely to occur. So, high COF between floor surfaces and shoe heel materials is very important to prevent slipping. There are many factors affecting the value of COF between floor surfaces and shoe heel materials such as ingredient of heel materials, tread of heel surface, heel size, heel hardness, vertical force, and angle of heel (Derler, Kausch, and Huber, 2008 [11]; Fong et al., 2008 [12]; Li, Wu, and Lin, 2006 [13]; Tsai, and Christopher, 2006 [14]; Beschorner et al., 2007 [15]; and Bunterngchit, 1990 [16]). From the factors mentioned above, the heel material is important because it affects the level of COF directly. If the ingredient of heel materials has been developed correctly, the value of COF could be good enough to reduce slipperiness.

In the past, measuring of COF had been researched for quite long. Starting from James' Machine and Portable Slipperiness Tester of the Pendulum Impact Type (Sigler, Geib, and Boone, 1948 [17]). Then some other machines e.g. Universal Friction Testing Machine, Big Foot, Slipometer, British Portable Skid Tester, Tortus, FIDO, SATRA, Hydraulic-power System and Programmable Slip Resistance Tester were found (Andres, and Chaffin, 1985 [18]; Wilson, and George, 1988 [19]; Gronqvist et al., 1989 [20]; Redfern, and Bidanda, 1994 [21]). These machines were different in measuring methods and working principal. Therefore, the value of COF from various machines could not be compared and accepted among them.

International Organization for Standardization (ISO, 2006) [22] set up a technical committee to identify the COF measuring procedure to be a accepted worldwide. The latest version of measuring procedure set up by this organization and seems to be accepted worldwide was ISO 13287:2006. So this procedure or standard was selected to be used in this work. In using this standard, an appropriate machine must be designed and built according to the identified procedure. The objectives of this research were (1) design and make a machine that can be used to measure the value of COF between floor surfaces and shoe heel materials following the ISO 13287:2006 standard and (2) finding the ingredient of shoe heel material that giving better value of COF.

2. Methodology

This research method comprised 8 steps as presented in Fig. 1.

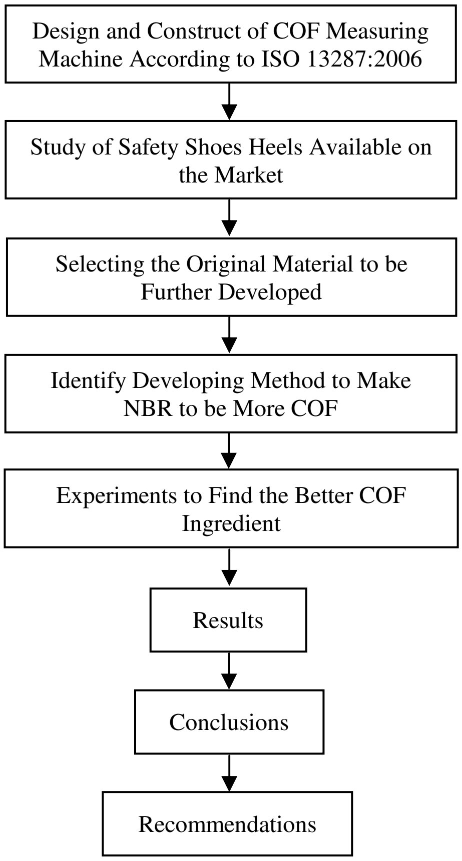

Fig. 1 The eight research steps.

2.1 Design and Construct of COF Measuring Machine According to ISO 13287: 2006

2.1.1 Detailed study of ISO 13287: 2006 Before designing the machine, the detailed information of ISO 13287:2006 was studied. The information in this standard could be concluded as follows (ISO, 2006).

2.1.1.1 The test was forward heel slip at the contact angle of 7.0 ± 0.05 degrees with the sliding velocity of 0.3 ± 0.03 m/s.

2.1.1.2 Normal force of 500 ± 25 N was used with footwear Paris points size 40.

2.1.1.3 Two type of tested floors were used: stainless steel plate with the roughness (R_z) of between 1.6 and 2.5 µm and pressed ceramic tile floor of the roughness between 14 and 18 µm.

2.1.1.4 The normal force of 50 N to 500 N must be inserted within not more than 1 second and after getting the maximum normal force, the sliding must be begun within not more than 0.5 second.

2.1.1.5 The average COF should be calculated from 0.3 - 0.6 second after the movement.

2.1.1.6 The thickness of contaminated fluid was at least 1 mm.

2.1.2 Design of the machine

2.1.2.1 The steel weight of 500 N was used to make normal force which could be put up and down utilizing linear electrical actuator. The pneumatic cylinder of diameter 50 mm was used to make the sliding with the adjustability of between 30 and 500 mm/s and sliding stroke of 200 mm. The working pressure of the cylinder was between 0.4 and 7 bars. The force transducers were used to measure the normal and horizontal forces.

2.1.2.2 Profile aluminum alloy of size 40 x 80 mm was used as frame of the machine. For the whole machine sizes,

they were 1,160 mm x 500 mm x 980 mm for the length, width, and height, respectively.
2.1.2.3 The tested heel angle was adjustable between 3 and 20 degrees. The adjusting screw was used to adjust the tested angles required.
2.1.2.4 The force transducers model S2 of Hottinger Baldwin Messtechnik Company Limited (HBM, 2009 [23]) were used in the machine. These transducers had capacity of 1,000 N and the error not more than 0.05 percent. An amplifier model Spider 8 of also HBM Company (HBM, 2010 [24]) was used to magnify the signal from the transducers. The sampling rate of this amplifier was 9,600 Hz with the accuracy of 1.0 percent.
2.1.2.5 The linear guideway model of HGH15CA of HIWIN Company Limited (HIWIN Company Limited, 2010) was used to carry the tested floor. This guideway had the capacity of 11.38 kN.
2.1.2.6 A computer notebook and CATMAN program (HBM, 2010) were used to display the information of normal and horizontal forces. Later, these forces could be used to calculate COF between the tested floors and heel materials.
2.1.2.7 The stainless steel and ceramic floors, both of size 216 mm x 553 mm were used in the machine. The calibration center of King Mongkut's University of technology certified that the floors had the roughness of between 1.69 and 17.02 µm, respectively. These measuring results were in the acceptable range of the standard.
After assembling the machine according to the design criteria mentioned above, Fig. 2 illustrated the machine with some other facilities e.g. an air pump, an amplifier, a control box, a computer, etc.

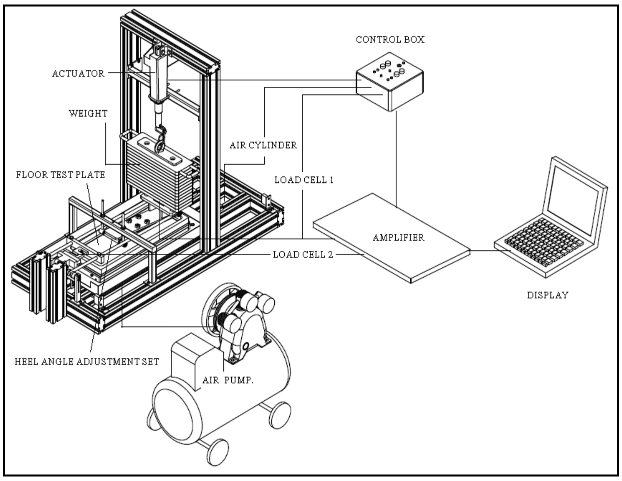

Fig. 2. The machine and accessories.

2.1.3 Test of the machine
If the machine was designed and constructed correctly, it must be able to measure the value of COF following the ISO 13287:2006. The tests for this machine were carried out several times. The sample of the obtained data was illustrated in Fig. 3. These graphs of normal (Fz) and horizontal (Fy) forces were from stainless floor, glycerol contaminant, and acrylonitrile butadiene rubber (NBR) heel material. After that, the COF available between floor surface and the NBR heel material was calculated as presented in Fig. 4.

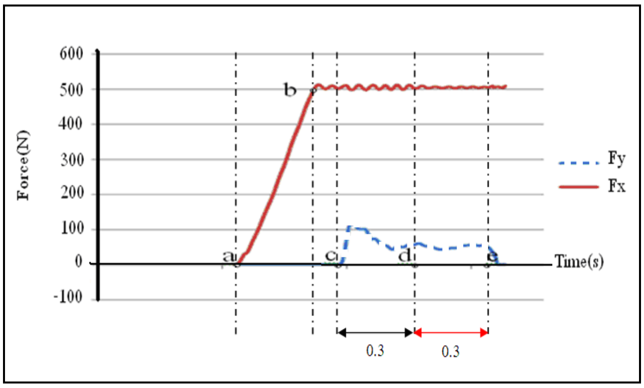

Fig. 3. Vertical (Fz) and horizontal (Fy) force taken from the measurement.

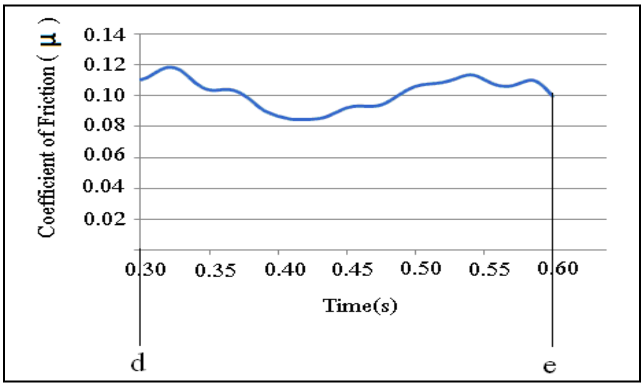

Fig. 4. The COF graph calculated from the points d and e in Fig. 3.

As could be seen in Fig. 3, point a on the vertical force graph (Fz) was the starting point of the weight exerted on the tested floor. At the point b, the vertical force reached the maximum value of 500 N in this case. The time from a to b must be less than 1 second. In the test, a to b was about 0.285 second, complied to the standard. After reaching the maximum value of the vertical force, the floor movement must be started within not more than 0.5 second. In the graph, the point c was the starting to move of the floor. The time between b and c was 0.095 second, complied to the standard also. As defined in the standard, the average COF measured must be started from 0.3 second from the point c, which was exactly the point d.

The time length to collect the data must be 0.3 second, which up to the point e. The graph illustrated the value of COF was in Fig. 4, which was the information taken from the point d to e in Fig.3. The equation used in the calculation of COF was the Perkin's equation as mentioned earlier.

2.2 Study of Safety Shoes Heels Available on the Market

Before finding the better COF of the heel material, 4 types of materials or 29 shoe heels with tread on the surface were measured using the machine made. The 4 types of the materials were polyvinyl chloride (PVC) of 6 heels, polyurethane (PU) of 7 heels, acrylonitrile butadiene rubber (NBR) of 14 heels, and natural rubber (NR) of 2 heels, for the total of 29 heels. Each piece of heel tested, the tests were done with both stainless steel and ceramic floors. Each floor was tested with glycerol and sodium lauryl sulphate contaminants. Therefore, each heels tested had 4 combinations. Five replicates were carried out for each combination. The total of 20 tests was done on one heel. For the 29 heels mentioned earlier, the 580 tests were carried out. The brief tested results were illustrated in Table 1. The values in the table were from the averages of all heels tested for each type.

2.3 Selecting the Original Material to be Further Developed

According to the information in Table 1, PU and NBR had the average COF of higher than the others for all tests. Therefore, these materials had been selected to be further developed to get even more COF. Considering the PU, the maker of this material ordered the solution from suppliers to make PU heel material without any change. So, this material was not easy to be further developed to gain more COF. There were advantages for NBR e.g. longer working life, oil resistant, and ease to be developed to get more COF. In conclusion, only NBR was selected to find new ingredient to obtain more COF.

Table 1. The average values of COF from 4 types of heel materials (29 heels)

Shoe Heel Material	Average COF			
	Ceramic Floor		Stainless Floor	
	Glycerol	Sodium Lauryl Sulphate	glycerol	Sodium Lauryl Sulphate
PVC	0.04(±0.004)	0.04(±0.002)	0.05(±0.005)	0.22(±0.006)
PU	0.07(±0.004)	0.11(±0.003)	0.11(±0.004)	0.30(±0.006)
NBR	0.07(±0.003)	0.10(±0.002)	0.09(±0.004)	0.34(±0.005)
RUBBER	0.04(±0.002)	0.06(±0.004)	0.06(±0.005)	0.18(±0.007)

2.4 Identify Developing Method to Make NBR to be More COF

According to the maker of this material, the NBR heel had original ingredients as presented in Table 2.

Table 2. The original ingredient of NBR heel material

Ingredient	Quantity(Kg)	Ingredient	Quantity(Kg)
NBR 35L	37.00	TQM	0.36
NBR 40CD	5.60	Petro resin	1.40
Silica	16.50	DARFX	2.00
DOP oil	5.50	ZnO_2	1.30
PPD	0.36	Stearic acid	0.56

After considering many methods to increase the value of COF of shoe heel material, it was found that phenolic resin was the one to be added into the original ingredient because it improved mechanical properties of high friction thermoplastic rubber e.g. increase hardness, toughness, friction, and wear resistant. Also, it affected the value of COF (Gopal, Dharani, and Frank, 1994 [25]; Yesnik, 1996 [26]; and Masoomi, Ali, and Nazockdast, 2006 [27]). Also this resin did not change the original mechanical properties of NBR. Therefore the phenolic resin would increase the value of COF of NBR if appropriate amount was used. In this study, the phenolic resin named SIRFEN BL-302 of Hexian Specialty Company Limited (Hexian Specialty Company Limited, 2010 [28]) was used.
Silicon dioxide was also considered to be used in this study because it was the additive to gain better properties in adhesion and toughness of plastics (Wood and Stacy, 1983 [29]; and Wolff, 1985 [30]). This silicon dioxide also tolerate to friction and scratch both dry and wet conditions, better adhesion without softness, and increase the value of COF (Kestner, 1974 [31]). So, silicon dioxide was also selected to be the other additive in this study. The synthetic silicon dioxide of Asahi Chemical Company Limited type E-10HD (Asahi Chemical Company Limited, 2010 [32]) was used in this study.
According to the information presented above, the phenolic resins and silicon dioxide were used as the additives of the original ingredient of the NBR. The amount of these two materials could be varied to obtain the new ingredient with the better value of COF.

2.5 Experiments to Find the Better COF Ingredient

To do the experiments to find the better COF, the additives as mentioned before could be 10-15 percents (Wood and Stacy, 1983 [29]; Gopal, Dharani, and Frank, 1994 [25]; Yesnik, 1996 [26]; Bijwe, 2007 [33]; and Chauhan, 2011 [34]). So, in this study, the maximum amount of additives used was 15 percents of the total weight for each additive. The minimum value of each additive was half of the maximum value, 7 percents. For each additive, the values of it were 7, 8, 9, 10, 11, 12, 13, 14, and 15 percents. The ingredients started from adding only phenolic resins (P) from 7-15 percents as mentioned above and the same adding for only silicon dioxide (E). After that, both adding were used. Starting from E7P7, the original ingredient was added by 7 percents of the E and 7 percents of the P. These both

additives were E7P7, E7P8,…, E15P15. The total members of combinations were 99 ingredients. The total members of combinations were presented in Table 3. For each ingredient, two shoe heels were prepared. One was used in the mechanical property tests and the other one to be measured the value of COF.
The heel material tested size was 100x100x10 mm. without any tread on the surface. The tested heel was prepared utilizing compression molding process at 130 degrees Celsius, 15 bars pressure and 3 minutes curing time.

Table 3. The total numbers of combinations of the NBR tested started from the original ingredient

E7	E8	E9	E10	E11	E12	E13	E14	E15
P7	P8	P9	P10	P11	P12	P13	P14	P15
E7P7	E7P8	E7P9	E7P10	E7P11	E7P12	E7P13	E7P14	E7P15
E8P7	E8P8	E8P9	E8P10	E8P11	E8P12	E8P13	E8P14	E8P15
E9P7	E9P8	E9P9	E9P10	E9P11	E9P12	E9P13	E9P14	E9P15
E10P7	E10P8	E10P9	E10P10	E10P11	E10P12	E10P13	E10P14	E10P15
E11P7	E11P8	E11P9	E11P10	E11P11	E11P12	E11P13	E11P14	E11P15
E1P7	E12P8	E12P9	E12P10	E12P11	E12P12	E12P13	E12P14	E12P15
E13P7	E13P8	E13P9	E13P10	E13P11	E13P12	E13P13	E13P14	E13P15
E14P7	E14P8	E14P9	E14P10	E14P11	E14P12	E14P13	E14P14	E14P15
E15P7	E15P8	E13P9	E15P10	E15P11	E15P12	E15P13	E15P14	E15P15

Remarks: 1. P = phenolic resin; E = silicon dioxide
2. The figures after the preceding alphabet are percents of that additive.

Before measuring the values of COF, all 99 ingredients were tested on the nine mechanical properties as illustrated in Table 4.

Table 4. The nine mechanical properties that all shoe heels must comply

Properties	Standard Used	Unit	Pass Criteria
Durometer	ASTM D224	Shor A	≥ 55
Specific Gravity	ASTM D792	g/cm^3	1.05-1.20
Die-c Tear	ASTM D624	Kg/cm	≥27
Trouser Tear	ASTM 1938	Kg/cm	≥13.4
Tensile	ASTM D412	Kg/cm^2	≥79
Elongation	ASTM D412	%	≥500
300% Modulus	ASTM D412	Kg/cm^3	≥30
DIN. Abrasion	Intl. 53516	mm^{3}loss	≤160
Ross Flex	ASTM D1052	23c	≥100

After all of the 99 heels had been tested, 53 heels were not good enough to pass the tested criteria. The detailed information was illustrated in Table 5. The first row in the Table 5 could be interpreted that the heel of ingredients E7, E10, E11, and E12 did not pass the tests.
As shown in Table 5, only 46 heels passed the tests. These 46 heels were tested to find COF according to ISO 13287:2006. Each heel was tested 5 times. The value of COF for each heel was the average values of the 5 tests. So, the 920 + 20 = 940 tests were carried out. Each heel was tested 4 conditions, each condition was repeated 5 times, therefore, 920 was from 46 x 4x 5. Also, the number of 20 was from the original ingredient which was tested 4 conditions and 5 replicate for each condition or 1 x 4 x 5 = 20. These extra 20 tests were from the original NBR without tread. As already shown in table 1, the values of COF of NBR were the heel with the tread. Therefore, the original NBR heel without tread was made to be measured the COF values.

Table 5. The ingredient that failed the tests

Properties Tested	Failed Ingredient
Durometer	E7, E10, E11, E12
Specific Gravity	-
Die-c Tear	-
Trouser Tear	-
Tensile	E7,E15P7
Elongation	-
300% Modulus	E7, E8, E9, E10, E11, E12,E13,E14,E7P7, E7P8, E7P9, E9P7, E9P8, E10,P7, E10P15, E11P7, E13P9, E13P11, E13P14,
DIN. Abrasion	E9, E10, E11, E12, E13, E14, E15, E9P13, E9P14, E9P15, E10P15, E11P11, E11P12, E11P13, E11P14, E11P15, E12P9, E12P10, E12P11, E12P12, E12P13, E12P14, E12P15, E13P12, E13P13, E13P14, E13P15, E14P10, E14P11, E14P12, E14P13, E14P14, E14P15 ,E15P7, E15P8, E15P9, E15P10, E150P110, E15P12, E15P13, E15P14, E15P15
Ross Flex	-

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After the 940 tests were carried out, the average values of the COF for the ingredients were calculated. The

ingredient given the maximum values of COF was P14. The COF value of P14 including the original NBR without tread were present in Table 6. The percentages of COF increased were also presented in this Table. For example, the percentages increase for the ceramic floor with glycerol contaminant was [(0.07 - 0.030)/0.03] x 100 = 133.3 percents

Table 6. The ingredient giving maximum values of COF and the Original NBR compared

Ingredients	COF			
	Ceramic Floor		Stainless Floor	
	Glycerol	Sodium Lauryl Sulphate	Glycerol	Sodium Lauryl Sulphate
Original NBR	0.03(±0.001)	0.05(±0.001)	0.03(±0.001)	0.13(±0.006)
P14	0.07(±0.003)	0.09(±0.001)	0.08(±0.002)	0.30(±0.007)
COF Increased (%)	133.3	80.0	166.7	130.8

3. Results

3.1 This work created the machine used in measuring the value of COF according to the ISO 13287:2006.
3.2 The ingredient given better values of COF was the original NBR added with 14 percents of phenolic resins or P14.
The one-way ANOVA was used to compare the COF values of original NBR and P14. The tested results were indicated in Table 7.

Table 7. ANOVA results comparing the COF values of the original NBR and P14

Contaminant	Floor	COFs of original VS P14	F	P
Glycerol	Ceramic	0.03 VS 0.07	832.92	< 0.0001
	Stainless	0.03 VS 0.08	2733.15	< 0.0001
Sodium Lauryl Sulphate	Ceramic	0.05 VS 0.09	2524.10	< 0.0001
	Stainless	0.13 VS 0.30	1675.77	< 0.0001

According to the information in Table 7, all combinations tested between the COF values of the original NBR and P14 were highly significant ($p < 0.0001$).

4. Conclusions

As already presented above, the conclusion could be made as follows.
4.1 The designed and made machine used to measure the value of COF between floor surfaces and shoe heel materials following ISO 13287:2006 was able to be used in this work and future measurement.
4.2 The ingredient obtained from this work was the original NBR adding 14 percents by weight of phenolic resin (P). This ingredient gave 133.3, 80.0, 166.7, and 130.8 percents more than the original NBR for the floors and contaminants of ceramic and glycerol, ceramic and sodium lauryl sulphate, stainless and glycerol, and stainless and sodium lauryl sulphate, respectively.

5. Recommendations

5.1 The ingredient obtained from this study should be used to make safety shoe sole material to reduce slipping accidents.
5.2 All footwear sole materials should be specified the values of COF for the safety reason of the users. The Office of Thailand Industrial Standards should be responsible for this matter.
5.3 Some other shoe heel materials should be studied and developed to be better values of COF. The more the value of COF, the more the safety of the users.

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