DOI: 10.5604/01.3001.0015.8367

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TRIBOLOGICAL ASPECTS OF FOOTWEAR SAFETY

TRIBOLOGICZNE ASPEKTY BEZPIECZEŃSTWA UŻYTKOWANIA OBUWIA

Key words: safety, footwear use, friction coefficient, soles, ground.

Summary: The key factor, from the consumer's point of view, during the use of footwear is the safety of use, characterized, among others, by the friction coefficient. A low coefficient of friction can cause skidding, which is very dangerous for the elderly, people with motor apparatus injuries, those with impaired motor skills, and those with a high body BMI index. Fall injuries result in hospitalization, generating high costs of treatment and compensation.

The article presents the results of tribological tests of typical footwear sole materials in combination with selected base materials depending on the load on the friction junction, the initial temperature, and the presence of water. The combination of the friction coefficient with the safety of footwear use for typical operating conditions is a new approach to the requirements of ergonomics and increasing comfort while walking.

Słowa kluczowe: bezpieczeństwo, użytkowanie obuwie, współczynnik tarcia, podeszwy, podłoże.

Streszczenie: Kluczowym czynnikiem, z punktu widzenia konsumenta, podczas eksploatacji obuwia jest bezpieczeństwo użytkowania, charakteryzowane między innymi współczynnikiem tarcia. Mały współczynnik tarcia może powodować poślizg, który jest bardzo niebezpieczny dla osób starszych, osoby z urazami aparatu ruch, z upośledzoną motoryką oraz z wysokim indeksem BMI ciała. Urazy powstałe podczas upadku są powodem hospitalizacji generującej wysokie koszty leczenia oraz odszkodowania.

W artykule przedstawiono wyniki badań tribologicznych typowych obuwniczych materiałów spodowych w skojarzeniu z wybranymi materiałami podłożowymi w zależności od obciążenia węzła tarcia, temperatury początkowej oraz obecności wody. Powiązanie współczynnika tarcia z bezpieczeństwem użytkowania obuwia dla typowych warunków eksploatacji stanowi nowe podejście do wymogów ergonomii i zwiększenia komfortu podczas chodzenia.

INTRODUCTION

The friction process is a key phenomenon that determines the safety of footwear use and determines its durability. It occurs during the contact of the sole with the ground and depends on many factors, such as the following: the type of ground and the bottom of the footwear, the speed of movement, walking technique, the type of contamination between the sole and the ground, ground moisture, human body weight, ambient temperature, and many others. The size of the friction coefficient between the footwear and the ground ensures proper walking, but it also affects the occurrence of a slip that makes it difficult to maintain the stability of the body and correct posture while walking. The phenomenon of shoe slip is one of the significant causes of injuries to the body of people moving on foot **[L. 1–5]**.

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Such incidents intensify in winter, when the ground is icy or snow-covered **[L. 6]**. Economic losses due to hospitalization and compensation payments are significant **[L. 7]**.

One of the methods of increasing the safety of wearing footwear is the appropriate selection of the sole material to the surface of the ground. Due to the large number of factors influencing tribological processes during walking and the lack of standardized modern methods of testing material systems, the selection of the bottom of the footwear to the operating conditions is most often performed without safety requirements.

Determining the tribological characteristics of the footwear soles in association with the substrate is a complex issue, and it is these material properties that play a decisive role in assessing their suitability for footwear soles. The determination of the tribological properties is carried out experimentally, because too many factors influence the obtained results to be able to determine them theoretically. Tribological tests of footwear materials are standardized to a small extent; hence, the obtained results largely depend on the method of their conduct.

In order to be able to talk about the correct selection of the sole material, it should be possible to precisely define requirements for them. Therefore, it is very important to develop such a method of testing their tribological properties that would allow for accurate selection of the most advantageous sole material **[L. 8]**.

The commonly used classification of materials for the soles of footwear assumes that the footwear material with high skid resistance is one whose static friction coefficient on a dry glass substrate is greater than 0.55. In the case of materials with medium skid resistance, the friction coefficient ranges from 0.40 to 0.55. However, if the friction coefficient is lower than 0.38, the material is classified as less resistant to skidding **[L. 9]**.

The coefficients of friction between the skin and natural moisture are sufficient to prevent the sole from slipping **[L. 10]**, because moist natural leather has a greater friction coefficient than dry leather **[L. 10, 11]**. This phenomenon is caused by the hydrophilicity of the skin, contributing to the swelling of collagen fibres, and thus their better adhesion to the substrate **[L. 11]**.

The lack of systematized data on the impact of footwear use conditions, in particular the impact of the friction junction load in the presence of water and water contaminated with anti-skid additives at elevated temperature on the friction coefficient in combination with various surfaces, was the inspiration for writing this article.

SUBJECT AND METHODOLOGY OF RESEARCH

The research covered typical plastics and natural leather used for the soles of shoes in frictional combination with a ceramic (floor tiles) and a wooden substrate. Plastic samples were cut from commercial raw material (shoe soles) of similar hardness, from the metatarsal part with a constant thickness of approx. 10 mm. Wooden counter-samples were cut from commercial parquet planks. Commercial polyurethane varnish was used for varnishing the wood. Ceramic samples were cut from a smooth, glazed surface, commercial floor tile of the 4th abrasion class. The tests were carried out on the T-15 test stand (**Fig. 1**) of the ring-disc type, produced by the Institute of Sustainable Technology – National Research Institute **[L. 12]**, enabling the use of test elements made in a simple way and conducting tests in a distributed contact at various surface pressures and sliding velocities. The diagram of the friction pair is shown in **Fig. 2**. Three test runs were performed for each combination.

The main tribological tests were carried out at room temperature (22ºC) and humidity, which did not change by more than 5%. Additional tribological tests of natural leather in combination with ceramics and wood were carried out under wet friction conditions in the presence of water and 10% aqueous NaCl solution, at room temperature and at temperatures of 40ºC and 60ºC.

The conducted research took into account the influence of surface pressures on the value of the friction coefficient for typical friction pairs: the bottom of the footwear material in combination with the surfaces typical for shopping centres. The choice of the friction junction load corresponded to the surface pressures exerted by persons with a BMI index from about 18 to 32. It was assumed that the increase in the BMI index was not accompanied by a proportional increase in the number of shoes. The research was carried out at sliding speeds corresponding to a slow walk, typical for overweight and underweight people.

Samples of the materials described above, mechanically cut from commercially available

Fig. 1. View of the test stand [L. 13]
Rys. 1. Widok stanowiska badawczego **[L. 13]**

materials, were used for the test. For each combination, three runs were carried out, with a constant sliding speed of 0.13 m/s, and a variable load of the friction junction from 0.03 MPa to 0.18 MPa, with a friction path of 200 m.

In order to check the effect of typical conditions in shopping centres in winter, additional tribological tests were carried out for ceramic and wooden substrates, during which the influence of the presence of water and water with table salt on the friction coefficient of natural leather and selected substrates with simulated under-floor heating was determined.

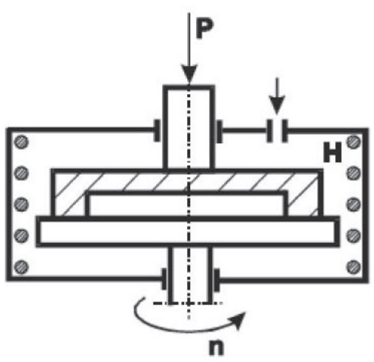

Fig. 2. Diagram of the friction pair
Rys. 2. Schemat węzła tarcia

The test result was the average of at least three test runs, the size of which did not contain the results requiring exclusion using the Dixon test.

The parameters of the main tests were selected on the basis of preliminary tests so that they correspond to the actual conditions of use of the footwear and that the obtained tribological characteristics had a stable course.

RESULTS AND DISCUSSION

The results of measurements of the friction coefficient of the tested material systems, depending on the load, are presented in the diagrams (**Fig. 3** and **Fig. 4**), while the results of the measurements of the friction coefficient of individual sole materials with the base materials in the diagrams of water and a water solution of table salt in the friction zone are shown in **Fig. 9** and **Fig. 11**, while changes in the friction coefficient of natural leather in combination with wood and ceramics, depending on the initial temperature of the friction junction, are shown in **Fig. 8** and **Fig. 10**.

The presented relationships clearly indicate a decrease in the friction coefficient of all tested material combinations with an increase in the load of the friction junction. The highest friction coefficient recorded for the combination of shoe rubber with wooden, **Fig. 4**, and ceramic substrates. On the other hand, natural leather and thermoplastic rubber are characterized by similar values of the friction coefficient, depending on the surface pressures in **Fig. 4** and **Fig. 5**. The obtained results are consistent with the data available in the literature, while the determined relationships clearly indicate a decrease in the safety of footwear use with an increase in the index BMI.

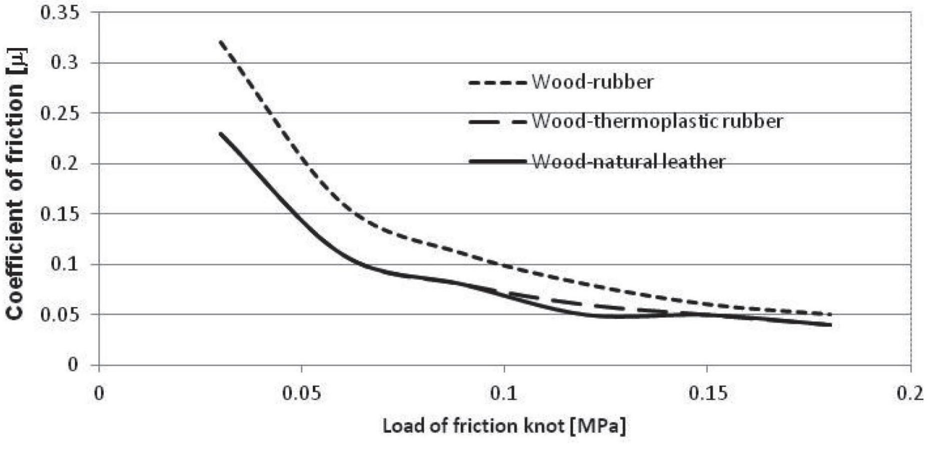

Fig. 3. Dependencies of the friction coefficient on the load of the friction pair at a constant slip speed of 0.13 m/s for combinations of wood with rubber, thermoplastic rubber, and natural leather

Rys. 3. Zależności współczynnika tarcia od obciążenia przy stałej prędkości poślizgu 0,13 m/s dla skojarzeń: drewna z gumą, kauczukiem termoplastycznym i skórą naturalną

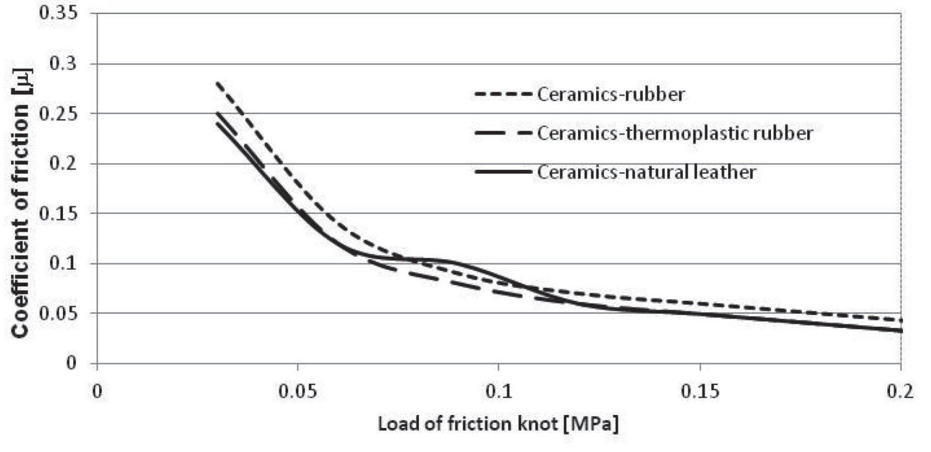

Fig. 4. Dependencies of the friction coefficient on the load of the friction pair at a constant slip speed of 0.13 m/s for combinations: ceramics with rubber, thermoplastic rubber, and natural leather

Rys. 4. Zależności współczynnika tarcia od obciążenia przy stałej prędkości poślizgu 0,13 m/s dla skojarzeń: ceramika z gumą, kauczukiem termoplastycznym i skórą naturalną

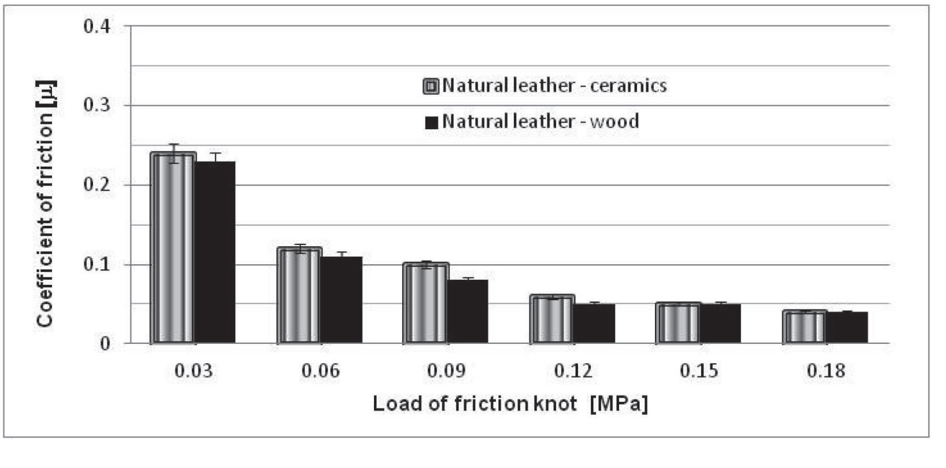

Fig. 5. The size of the friction coefficient depending on the load for combinations: natural leather with ceramics and wood

Rys. 5. Wielkość współczynnika tarcia w zależności od obciążenia dla skojarzeń: skóra naturalna z ceramiką oraz drewnem

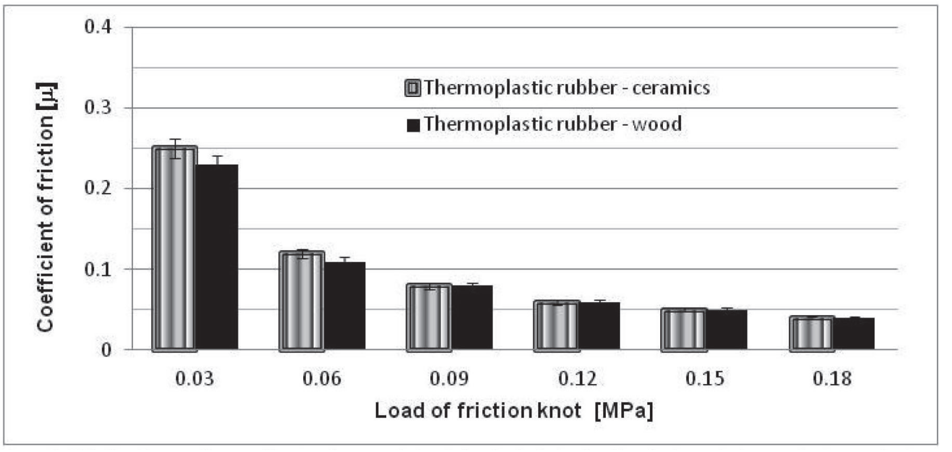

Fig. 6. The size of the friction coefficient depending on the load for combinations: thermoplastic rubber with ceramics and wood

Rys. 6. Wielkość współczynnika tarcia w zależności od obciążenia dla skojarzeń: kauczuk termoplastyczny z ceramiką oraz drewnem

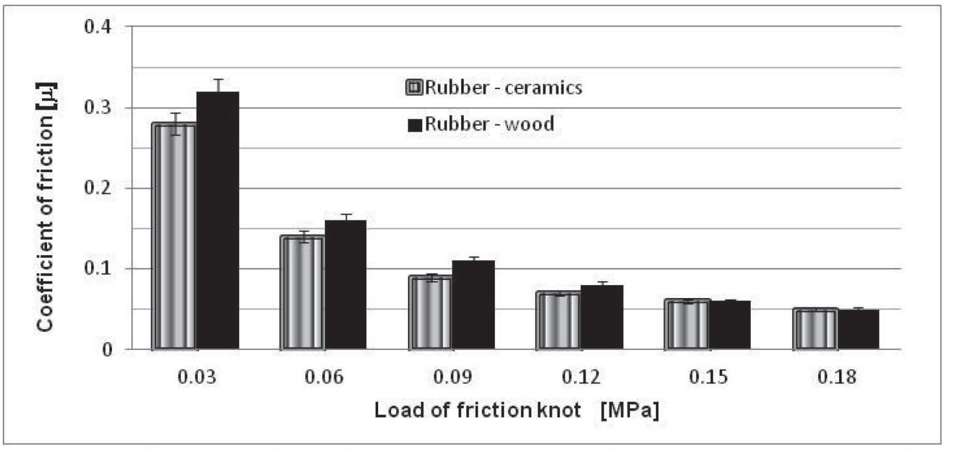

Fig. 7. The size of the friction coefficient depending on the load for combinations: rubber with ceramics and wood

Rys. 7. Wielkość współczynnika tarcia w zależności od obciążenia dla skojarzeń: guma z ceramiką oraz drewnem

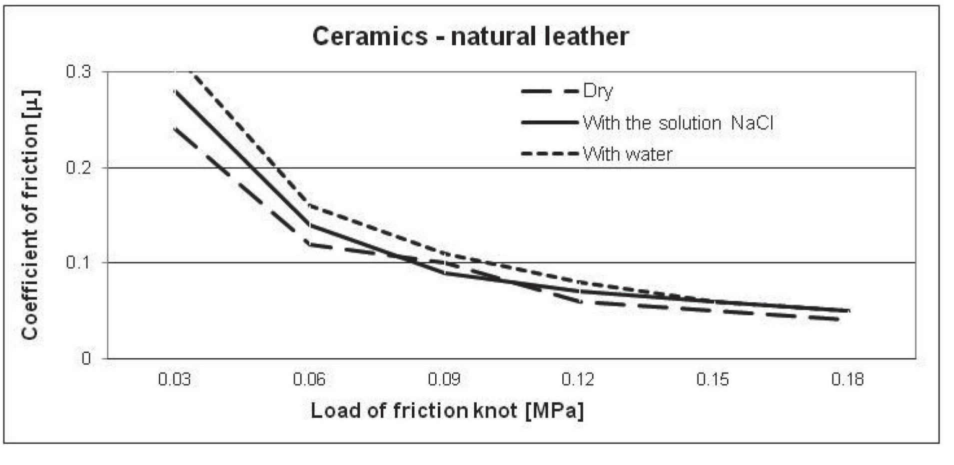

Fig. 8. Dependencies of the friction coefficient on the contamination of the friction pair and the load on the friction pair at a constant sliding speed of 0.13 m/s for the combination of ceramics with natural leather

Rys. 8. Zależności współczynnika tarcia od zanieczyszczenia węzła tarcia i obciążenia pary trącej przy stałej prędkości poślizgu 0,13 m/s dla skojarzenia ceramika ze skórą naturalną

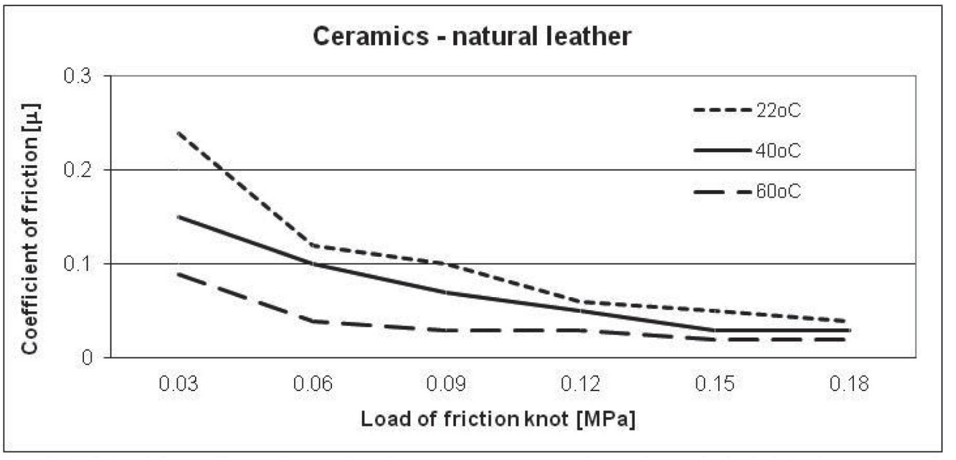

Fig. 9. Dependencies of the friction coefficient on the ambient temperature of the friction pair and the load on the friction pair at a constant sliding speed of 0.13 m/s for the combination of ceramics and natural leather

Rys. 9. Zależności współczynnika tarcia od temperatury otoczenia węzła tarcia i obciążenia pary trącej przy stałej prędkości poślizgu 0,13 m/s dla skojarzenia ceramika ze skórą naturalną

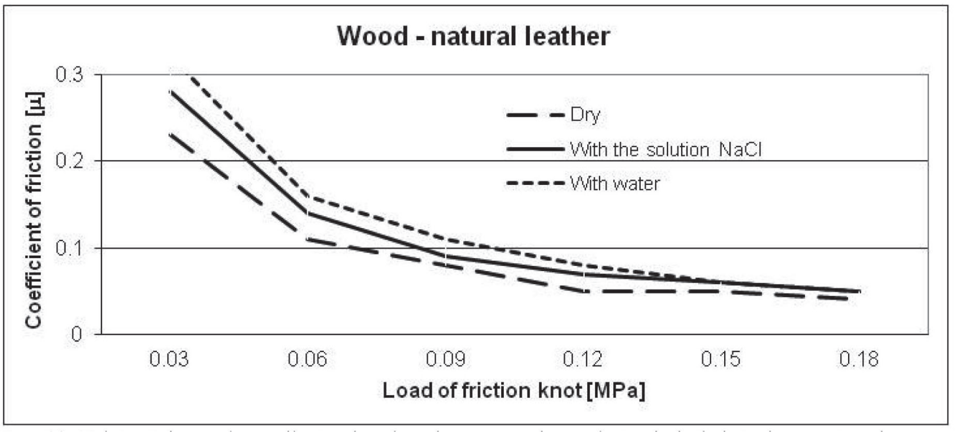

Fig. 10. Dependencies of the friction coefficient on the contamination of the friction pair and the load on the friction pair at a constant sliding speed of 0.13 m/s for the combination of wood with natural leather

Rys. 10. Zależności współczynnika tarcia od zanieczyszczenia węzła tarcia i obciążenia pary trącej przy stałej prędkości poślizgu 0,13 m/s dla skojarzenia drewna ze skórą naturalną

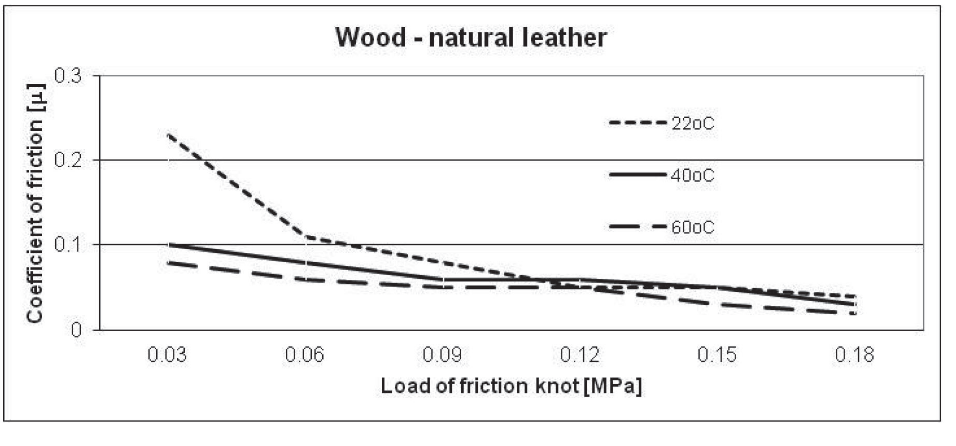

Fig. 11. Dependencies of the friction coefficient on the ambient temperature of the friction pair and the load on the friction pair at a constant sliding speed of 0.13 m/s for the combination of wood with natural leather

Rys. 11. Zależności współczynnika tarcia od temperatury otoczenia węzła tarcia i obciążenia pary trącej przy stałej prędkości poślizgu 0,13 m/s dla skojarzenia drewna ze skórą naturalną

The results presented in **Figs. 5–7** clearly indicate a significant, over 50%, decrease in the friction coefficient with a double increase in the friction junction load. A further increase in surface pressures results in a reduction of the coefficient of friction of the mating surfaces, but it has a milder course. This means that the greatest risk of slippage when walking corresponds to an increase in BMI from underweight to normal weight. A further increase in human body weight increases the likelihood of skidding, but this change is slower. Both natural leather and thermoplastic rubber are characterized by a greater coefficient of friction in combination with the ceramic substrate, in the entire range of tested surface pressures, than in combination with the wooden substrate (**Fig. 5** and **Fig. 6**). The inverse relationship was observed for the system of substrate materials with rubber (**Fig. 7**). In this case, a greater coefficient of friction was noted for the association of rubber with a wooden substrate.

The characteristic relationships shown in **Fig. 8** and **Fig. 10** were noted for the tested material combinations of natural leather in combination with wood and ceramics under friction conditions in the presence of water and aqueous NaCl solution. For these cases, a greater coefficient of friction was noted when sliding in the presence of water and an aqueous salt solution than in the case of dry friction. It is the only footwear material that is characterized by an increase in the coefficient of friction when sliding in the presence of water **[L. 14]**. Footwear with natural leather soles should be used by people with locomotor injuries, with impaired motor skills and with a high BMI index, especially if there is a possibility of walking on wet ceramic and wooden surfaces.

The increase in the initial temperature of the friction junction for the material system natural leather – ceramic and wooden substrate contributes to the reduction of the friction coefficient (**Fig. 9** and **Fig. 11**). It is caused by the desorption of moisture from the working surface of the skin and the stiffening of collagen fibres resulting in a reduction of the actual contact surface.

SUMMARY

The conducted research allows concluding that, on the basis of the obtained friction characteristics, it is possible to assess the safety of use of the tested combinations in terms of the possibility of shoe slip, which is currently one of the main conditions for the development of shoe soles.

Among the tested material combinations, the highest coefficient of friction was recorded for the rubber-wood substrate for the smallest applied surface pressures, under technically dry friction conditions. In the first stage, an increase in the friction junction load results in a sharp drop in the friction coefficient. Increasing the load causes a uniform reduction of the friction coefficient, which, however, results in a further deterioration of the safety of using the footwear.

Covering the wooden and ceramic substrate with water or a water solution of table salt, typical for shopping mall surfaces in winter, contributes to increasing the safety of using footwear on natural leather soles. It is the only known footwear material with such properties.

However, footwear with natural leather soles in combination with a ceramic and wooden substrate shows a decrease in the friction coefficient also with increasing temperature. It proves the deterioration of the safety of footwear use on surfaces with installed under-floor heating and during high temperatures in summer.

The method and results of tribological tests presented by the authors of various materials used for the soles of footwear in combination with various floor materials, under various friction conditions, i.e. pressures, temperature and the type of medium surrounding the tested materials, enable the selection of materials for the soles of footwear, reducing the possibility of slippage, and hence – increasing the level of security.

REFERENCES

1. Iraqi A., Natasa S., Vidic N.S., Redfern M.S., Kurt E., Beschorner K.E.: Prediction of coefficient of friction based on footwear outsole features. Applied Ergonomics, vol 82, 2020.
2. Kurt E. Beschorner K.E., Iraqi A., Redfern M.S., Cham R., Li Y.: Predicting slips based on the STM 603 whole-footwear tribometer under different coefficient of friction testing conditions. Ergonomics, vol. 62 (5) 2019.
3. Dhanapal D., Melese B., Shawel L., Mesfin G.: Analysis of Footwear Slip Resistance Property in Floor Tiles. Research Journal of Textile and Leather, vol 2 2020.
4. Tsai, Y.J., Powers, C.M.: The Influence of Footwear Sole Hardness on Slip Initiation in Young Adults. Journal of forensic sciences vol 53, 2008.
5. Hanson, JP, Redfern, MS, Mazumdar, M.: Predicting slips and falls considering required and available friction. Ergonomics vol 42, 1999.
6. Stanisławska Z., Ślusarski L.: Zjawisko poślizgu obuwia. Przegląd Skórzany 1979.
7. Stanisławska Z, Ślusarski L.: Wpływ rodzaju materiału spodowego i rodzaju urzeźbienia na wielkość kinetycznego współczynnika tarcia. Część I. Spody olejoodporne. Przegląd Skórzany 1987.
8. Tuszyński W, Matra E., Wulczyński J.,Piekoszewski W., Szczerek M., Woźniak B., Wlazło M., Michał Nowicki M., Przepiórka J.: A test machine and methods for testing friction and wear of an anti-slip coating deposited on the soles of shoes. Tribologia 4/2017.
9. Rybska M., Wiśnios E., Bieńkowski S.: Wpływ rodzaju materiału spodowego na poślizg obuwia. Przegląd Skórzany 1989.
10. Kaszuba Z.: Uwagi do badań nad ślizganiem podeszew obuwia w czasie chodzenia. Przegląd Skórzany 1981.
11. Zając H., Bieńkowski S.: Wpływ rodzaju mieszanki gumowej na wartość współczynnika tarcia. Przegląd Skórzany 1986
12. http://katalog.itee.radom.pl/index.php/karty-katalogowe/urzdzenia-tribologiczne.html.
13. http://www.tribologia.org/ptt-old/inst/rad/T-15.jpg.
14. Przepiórka J., Piekoszewski W., Szczerek M., Wlazło M.: Wpływ wody na właściwości tarciowe podeszew obuwia. Tribologia 6/2015.