WARSAW UNIVERSITY OF TECHNOLOGY Index 351733
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
POLISH ACADEMY OF SCIENCES ISSN 1230-2945

DOI: 10.24425/ace.2026.1388

ARCHIVES OF CIVIL ENGINEERING

Vol. LXXII ISSUE 3 2026

 pp. 269 – 283

Research paper

Road surface friction coefficient measured at different slip ratios – comparison of results from the ViaFriction and SRT-3 devices

Jan Czmiel[1], Zbigniew Perkowski[2], Daniel Frączek[3], Robert Jurczak[4]

Abstract: The anti-skid properties of road surfaces play a key role in ensuring the safety of road users. The paper emphasizes the need to use friction coefficient measurement with a variable slip of the test wheel, which allows for more detailed control of the surface technical condition, e.g., using the ViaFriction device. In Poland, the minimum required friction coefficient values have so far been clearly defined only for the SRT-3 device with the locked wheel. This motivated the authors to compare the friction coefficient measurements obtained with the SRT-3 and ViaFriction devices. The tests were conducted on selected road sections in the Opole Voivodeship (Poland), considering two road surface technologies: stone mastic asphalt (SMA) and cement concrete. In the case of SMA, the operating time and the temperature surface were also taken into account. As a result, a strongly correlated linear relation between the friction coefficients from the SRT-3 and ViaFriction devices was observed for the SMA surface.

Keywords: friction coefficient, road surface, skid resistance, SRT-3, stone mastic asphalt, ViaFriction

[1]MSc., Eng., Opole University of Technology, Doctoral School, Prószkowska 76, 45-758 Opole, Poland, e-mail: jan.czmiel@student.po.edu.pl, ORCID: 0009-0009-5843-3347
[2]DSc., PhD., Eng., Opole University of Technology, Faculty of Civil Engineering and Architecture, Katowicka 48, 45-061 Opole, Poland, e-mail: z.perkowski@po.edu.pl, ORCID: 0000-0003-4509-6467
[3]PhD., Opole University of Technology, Faculty of Civil Engineering and Architecture, Katowicka 48, 45-061 Opole, Poland, e-mail: d.fraczek@po.edu.pl, ORCID: 0000-0001-6233-9163
[4]PhD., Eng., West Pomeranian University of Technology, Faculty of Civil and Environmental Engineering, Al. Piastów 50a, 70-311 Szczecin, Poland, e-mail: robert.jurczak@zut.edu.pl, ORCID: 0000-0003-3149-7497

1. Introduction

In order to ensure traffic safety and driving comfort, road surface diagnostics primarily focus on longitudinal evenness, transverse evenness (ruts), and anti-skid properties. If the first two parameters meet the required criteria, the anti-skid properties will be the most important for braking safety and ensuring the adhesion of vehicle wheels to the surface. For this reason, these properties are determined in individual countries using standardized measurement techniques. For example, a comparative description of the requirements and testing methods for anti-skid features of road surfaces across the European Union member countries can be found in the report [1], which was developed within the ROSANNE project.

Many statistical studies show information on the importance of ensuring roads' anti-skid properties. For example, based on annual measurements of the friction index using the Sideway-force Coefficient Routine Investigation Machine (SCRIM) in the years 1997–2002, conducted by the New Zealand road administration, a significant reduction in the risk of a road accident was demonstrated with an increase in this index [2]. Another example in this respect is the research conducted by the Federal Highway Administration of the U.S. Department of Transportation on the relationship between accidents and the anti-skid properties of road surfaces, which also showed a significant impact of insufficient friction. In 2009, two locations near Louisville (KY) with a high accident rate were selected for research (65 accidents on wet surfaces in 3 years). It was decided to use the high friction surface treatments (HFTS) to improve the anti-skid properties, which consists in the surface consolidation using a two-component technology: epoxy topped with a hard, fractured aggregate. After implementing this technology, accidents dropped to 15 within 4 years [3]. In Poland, no detailed studies have been conducted so far on the relationship between accidents and anti-skid properties, but related information can be found in the Police reports. For example, the 2023 annual report shows that the cause of 51 accidents in Poland was the improper condition of the roadway, resulting in 1 death and 58 injuries [4]. Unfortunately, friction coefficient measurements are not covered by an international standardized method, as is the case, for example, with roughness measurement using profilographs and the international roughness index (IRI). There are many research methods worldwide for determining the friction coefficient, and each country defines its own requirements. European research projects within the World Road Association (PIARC), such as TYROSAFE [5] or ROSANNE [1], aimed to harmonize devices for measuring anti-skid properties, and the latest ROSANNE project from 2016 [1] assumed the development of a single standard that would specify requirements for all groups of measuring devices and replace the current national regulations. However, there is still no common definition of these standards in Europe, even for similar road design technologies. In Poland, the requirements for these surface features are specified in the Regulation of the Minister of Infrastructure of June 24, 2022, on technical and construction regulations regarding public roads [6]. The standard test method for determining anti-skid properties is measurement using the SRT-3 device with the locked test wheel, which was developed in the 1960s by the Road and Bridge Research Institute (Poland) in cooperation with the Warsaw University of Technology. Currently, the General Directorate for National Roads and Motorways (GDNRM) in Poland has 11 such ones. In contrast, in other European countries, devices that measure the friction coefficient continuously with a fixed or variable slip of the test wheel are more common and meet appropriate technical specifications (e.g., ViaFriction (VF) according to the standard [7]). In Poland, methods for determining anti-skid properties using a wheel lock and variable wheel slip are presented in the document of the Minister of Infrastructure [8]; however, in the latter case, the minimum required friction coefficient values have not been clearly defined. Considering that the minimum friction coefficient values from the SRT-3 device (for acceptance of contract road works and diagnostic) result from many years of experience of Polish road engineers, providing statistical data that relates them to the measurements performed using a more modern method with a slipping wheel is necessary for its scientifically justified implementation. This was the reason the authors undertook research, the main goal of which was to determine whether there is a basis for establishing a statistically justified relationship between measurements obtained with the SRT-3 and VF devices. The detailed goal of the research was, in turn, whether it is possible to determine the minimum required friction coefficient values for the VF device that correspond to their well-established counterparts for the SRT-3. The tests were carried out on specially selected road sections with surfaces made of stone mastic asphalt (SMA) and cement concrete (CC).

2. Anti-skid properties of road surfaces

2.1. Friction coefficient

Friction plays a key role in keeping vehicles on the road, enabling drivers to safely control and maneuver them in both the longitudinal and lateral directions. Furthermore, when designing road geometry, friction is a key 1 factor in determining minimum stopping distances, minimum curve radii, and super-elevation. For the obvious reasons, the greater the friction between the tire and the road surface, the greater the driver's ability to control the vehicle. Road friction is defined as the net force that opposes the relative motion between a vehicle tire and the road surface (Fig. 1). Friction forces occur both during rolling and sliding on the road surface [9].

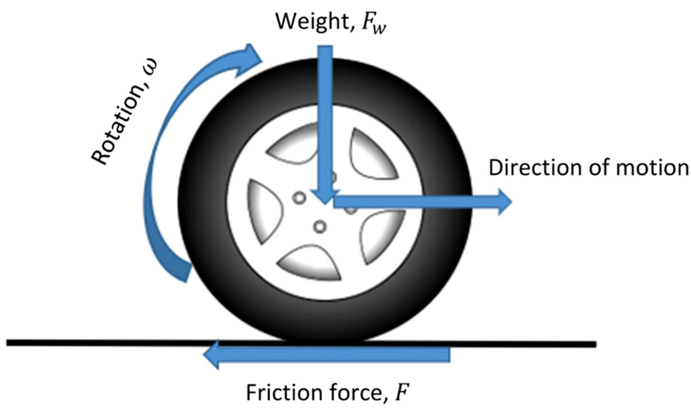


Fig. 1. Simplified diagram of the forces acting on a rotating vehicle wheel [9]

The measure for assessing the anti-skid properties is the dimensionless coefficient of friction calculated using the formula [9, 10]:

$$\mu = \frac{F}{F_w} = \frac{F_a + F_c + F_h + F_d}{F_w} \tag{2.1}$$

where: μ – friction coefficient; F – tangential friction force between the tire and road surface; F_w – vertical wheel load; F_a F_c, F_h, F_d – components of the friction force respectively from: the adhesion between the tire rubber and the road surface, the cohesion between the tire rubber and the surface rubber contaminants, the hysteresis in stress-strain relation during deformation of tire rubber in contact with the road surface, and the air and fluid drag.

F is mainly the result of two phenomena – adhesion (F_a) and hysteresis (F_h) of the rubber. Adhesion results from the bonding/interlocking of the tire rubber and the surface at the micro- scale and depends on the contact shear strength and area. In turn, the hysteresis in the tire rubber's stress-strain relationship depends on the intensity of the strain energy dissipation. When the rubber is compressed in contact with the surface, the strain energy is stored in it. When the rubber is unloaded, some of the stored energy is recovered, while the rest is irreversibly lost as heat. Since F_a is generated at the interface of the road surface and tire, it depends primarily on the surface micro- unevenness. It is described by the so-called micro-texture, which depends primarily on the micro-roughness of the aggregate with which the tire is in contact. On the other hand, hysteresis in the stress-strain relationship appears primarily in those parts of the tire that are deformed in contact with macro-irregularities of the surface. They are referenced as macro- texture, which depends primarily on the manufacturing technology and the composition of the mixture for a wearing course. Adhesion is primarily responsible for friction on smooth, dry surfaces and hysteresis on wet, rough surfaces.

The friction forces, which are longitudinal to the direction of travel, occur during both free-rolling and constant braking. In free-rolling, the relative speed between the tire and the traveled surface at the center of the contact area (called slip speed) is zero. In the constant braking mode, the slip speed increases from zero and can be equal to the vehicle's speed at most. For example, it can be defined by the relationship [9]:

$$S = V - V_P = V - \omega r \tag{2.2}$$

where: S – slip speed, V – speed of the vehicle, V_P – average peripheral speed of the tire, ω – angular speed of the tire, r – mean dynamic radius of the tire.

When the wheel is rolling freely, V_P is equal to V, and when the wheel is locked, V_P is zero. Knowing V and V_P, the slip ratio is determined in percentage terms according to the formula [9]:

$$SR = \frac{V - V_P}{V} 100\% = \frac{S}{V} 100\% \tag{2.3}$$

where: SR – slip ratio.

The friction coefficient increases rapidly with increasing slip to a peak value, which usually occurs for SR in the range of 10–20% (critical slip). Then the coefficient decreases to a value known as the sliding friction coefficient at $SR = 100\%$. The difference between the peak and sliding friction coefficients can be up to 50% and is significantly greater on wet surfaces than on dry ones. The relationship shown in Fig. 2 is the basis of the anti-lock braking system (ABS) operating principle, which is to use the peak friction and minimize the friction loss due to sliding action [9].

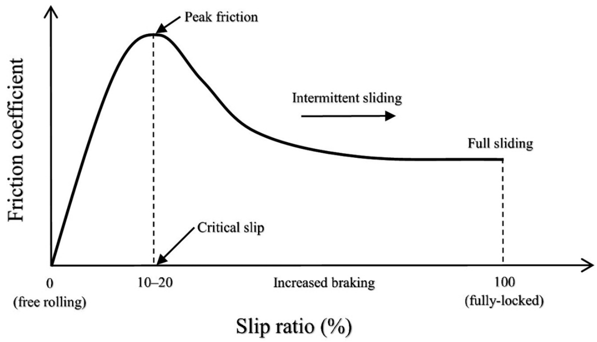


Fig. 2. The friction coefficient in the contact of the tire and the road surface vs. slip ratio [9]

2.2. Measurement methods

Each country implements preferred methods of measuring the friction coefficient of road surfaces based on its own experience. The dominant group of devices uses a wheel with $SR < 100\%$ (Table 1). In Poland, the SRT-3 device is a current standard one with a locked test wheel ($SR = 100\%$).

The SRT-3 set shown in Fig. 3 consists of a towing vehicle (with a water tank) and a measuring trailer. Currently, it is the third generation of the device, developed in the 1960s and used only in Poland. The measurement consists in bringing the test wheel to a lock every 50 m or 100 m. During the measurement, the surface is wetted with water in the amount of 0.5 L/m^2. The ribbed tire PIARC 165 R15 is used, compliant with the standard [13] (Fig. 4). As a standard, the measurement is performed at a speed of 60 km/h [8, 14].

Fig. 3. The SRT-3 device

Table 1. Types of devices used to measure the anti-skid properties in Europe (measuring speed is not given if the information was not available to the authors) [11, 12]

Country	**Device type**	***SR* [%]**	**Device name**	**Tire type**	**Measurement speed [km/h]**
Belgium	slip	26	Stradograhe	smooth	–
Denmark	side-force slip	21 18	Stradograf ROAR	smooth smooth	– 60, 80
Finland	locked wheel slip	100 13	RRL-Trailer BV-11	ribbed ribbed	– 70
France	locked wheel side-force	100 34	ADHERA SCRIM	smooth smooth	40, 60, 90, 120 50
Germany	locked wheel side-force	100 34	Struttgarter Gerat SCRIM	ribbed smooth	– 50
Great Britain	side-force	34	SCRIM	smooth	50
Italy	locked wheel slip	100 13	Model Ariano Skiddo-meter BV8	smooth smooth	– 40, 60, 80
Norway	slip	16	ROAR II	smooth	–
Poland	locked wheel	100	SRT-3	ribbed	60
Spain	slip	13	Skiddometer BV8	smooth	40, 60, 80
Sweden	slip	13	Sarsys Friction Tester	ribbed	–
Switzerland	slip	13	Skiddo-meter	smooth	–

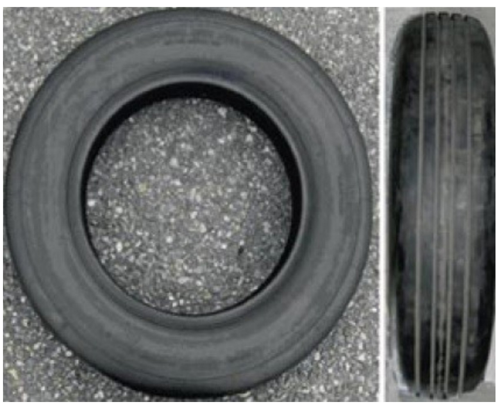


Fig. 4. The test tire PIARC 165 R15 for the SRT-3 [13]

The VF is a device standardized, among others, in accordance with [7]. It is used worldwide for scientific, acceptance, and diagnostic purposes. In the latter two cases, the VF is used by road administrators in Norway, Denmark, Estonia, Lithuania, Mexico, and India, and friction measurement is performed continuously with the skid of the test wheel for SR from 1% to 75%. Usually, this is the range of 15–20%, which corresponds to braking conditions with the ABS system. As one of the few devices, the VF can also measure the maximum friction coefficient with variable slip. In the VF, SR is regulated by an electric brake. There are currently two VF devices in Poland, owned by the Opole and Kraków branches of the GDNRM. The device in Opole (Fig. 5), which the authors of the paper had at their disposal, is mounted on a truck with a 2000 L water tank, enabling an uninterrupted 50 km measurement. It is performed using a tire compliant with the standard [15] on a wetted surface with a 0.5 mm water film. The tire wears out on average after 500–600 km of measurements (Fig. 6).

Fig. 5. The VF device

Fig. 6. The test tire for the VF. For comparison, a new tire is shown (bottom) and after 600 km of measurements (top)

3. Friction coefficient measurements using the SRT-3 and VF devices

3.1. Research program

Road surface sections in the Opole Voivodeship (Poland), where the GDNRM branch has a VF device, were selected for the study. The first criterion for selecting individual surfaces was their location from a logistical point of view, i.e., ensuring convenient refilling of water necessary for wetting the surface and the travel time to a given section. The second selection criterion was based on the analysis of archived diagnostic data from the GDNRM and on the identification of sections with possibly different values of the friction coefficient and SMA or CC technology (SMA is currently the standard for asphalt surfaces of national roads in the Opole Voivodeship). Basic data for the selected five measurement sections are presented in Table 2, and their locations are shown in Fig. 7.

Table 2. Data of the selected road surface sections

<table>
<tr><th rowspan="2">Symbol</th><th rowspan="2">Road No./
Description
of section</th><th colspan="2">Location
in road (km+m)</th><th rowspan="2">Distance
[m]</th><th rowspan="2">Technology</th><th rowspan="2">Operation
time</th></tr>
<tr><th>Beginning</th><th>End</th></tr>
<tr><td>RS1</td><td>46 / Lane 1 of Nysa-bound carriageway</td><td>57+700</td><td>56+600</td><td>1,100</td><td rowspan="2">SMA
Aggregate: gabbro,
max. diameter
11 mm</td><td rowspan="2">new</td></tr>
<tr><td>RS2</td><td>46 / Lane 2 of Nysa-bound carriageway</td><td>57+700</td><td>56+600</td><td>1,100</td></tr>
<tr><td>RS3</td><td>94 / Single-carriageway, Opole-bound lane</td><td>141+520</td><td>150+900</td><td>9,380</td><td>SMA
Aggregate: gabbro
with
graywacke/basalt
max. diameter
11 mm</td><td>since 2009</td></tr>
<tr><td>RS4</td><td>46 / Single-carriageway, Kłodzko-bound lane</td><td>21+750</td><td>26+000</td><td>4,250</td><td rowspan="2">CC (C35/45, CEM I)
Aggregate:
amphibolite,
max. diameter 8 mm
texturing method:
exposed aggregate
concrete</td><td rowspan="2">since 2023</td></tr>
<tr><td>RS5</td><td>46 / Single-carriageway, Nysa-bound lane</td><td>26+000</td><td>21+750</td><td>4,250</td></tr>
</table>

Three road surfaces (RS1-RS3) were made of SMA, and the other two (RS4-RS5) of CC. RS1 and RS2 were new and unused surfaces of the dual-carriageway national road no. 46 between Pakosławice and Nysa. It was being rebuilt in the form of widening. RS1 is on lane 1, and RS2 is on lane 2 of the Nysa-bound carriageway. RS3 is on the surface of the single-carriageway national road no. 94 between Opole and Brzeg, which is heavily trafficked as an alternative route to the A4 motorway running through the Opole Voivodeship. The measurement on RS3 was taken on the Opole-bound lane. RS4 and RS5 are surfaces of the single-carriageway national road no. 46 between Nysa and Kłodzko. This is the only section of the national roads in the Opole Voivodeship constructed using CC surface technology, which was opened to traffic in 2023; therefore, selecting a road with a new, unused CC surface for comparison was impossible during the measurement campaign. RS4 is on the Kłodzko-bound lane, and RS5 is on the Nysa-bound lane.

In each section, measurements were taken with two devices: the SRT-3 and VF with a water film thickness of 0.5 mm, assuming the speed (V) and slip ratio (SR) given in Table 3. The SR values for the VF were selected in the range corresponding to the average maximum friction coefficient values according to Fig. 2. The measurements were taken at the turn of summer and autumn 2024 over seven consecutive days. Due to the weather conditions, the surface temperature ranged from 13°C to 30°C. About 200 and 12,300 results were obtained from the SRT-3 and VF, respectively.

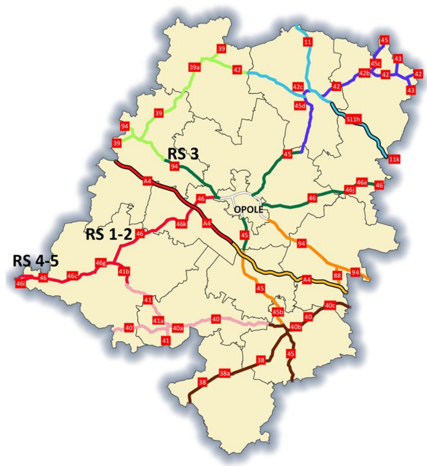


Fig. 7. Location of the tested RS1-RS5 surfaces shown on the road network map of the Opole Voivodeship

Table 3. Measurement parameters

<table>
<tr><th>SRT-3</th><th>VF</th></tr>
<tr><td>Distance between measurements: 100 m</td><td>Distance between measurements: 10 m</td></tr>
<tr><td>Measurement trace: center of lane</td><td>Measurement trace: center of lane</td></tr>
<tr><td rowspan="5">V = 60 km/h
SR = 100%
(locked wheel)</td><td>V = 60 km/h SR = 18%</td></tr>
<tr><td>V = 30 km/h
SR = 18%</td></tr>
<tr><td>V = 40 km/h
SR = 18%</td></tr>
<tr><td>V = 60 km/h
SR = 15%</td></tr>
<tr><td>V = 60 km/h
SR = 21%</td></tr>
</table>

3.2. Measurement results and analysis

In Figs. 8 and 9, the friction coefficient measurements are presented as points, the coordinates of which correspond to the values of the VF on the horizontal axis and the SRT-3 on the vertical axis from the same 100 m measurement sections. The linear approximation of the measurements is plotted against the points as a red solid line (determined by the linear regression method), which is given by the function:

$$\mu_{\mathrm{SRT}} = a \cdot \mu_{\mathrm{VF}} + b \tag{3.1}$$

where: μ_{SRT}, μ_{VF} – friction coefficients from the SRT-3 and VF, respectively; a, b – slope and intercept of the straight line, respectively.

The standard deviation with respect to approximation (3.1), i.e. $\mu_{\mathrm{SRT}} \pm \sigma(\mu_{\mathrm{SRT}})$, is marked with two red dashed lines, calculated according to the relation:

$$\sigma(\mu_{\mathrm{SRT}}) = \sqrt{\frac{\sum\limits_{i=1}^{n} \left(a \cdot \mu_{\mathrm{VF},i} + b - \mu_{\mathrm{SRT},i}\right)^2}{n-1}} \tag{3.2}$$

where: n – number of measurements; $\mu_{\mathrm{SRT},i}$, $\mu_{\mathrm{VF},i}$ – the i-th measurement of the friction coefficient from the SRT-3 and VF on the same road subsection, respectively.

In turn, two violet solid lines indicate the limit values $\mu_{\mathrm{SRT}(0.05)}$ and $\mu_{\mathrm{SRT}(0.95)}$, which meet the conditions:

$$P\left(M_{\mathrm{SRT}} < \mu_{\mathrm{SRT}(0.05)}\right) = 0.05 \text{ and } P\left(M_{\mathrm{SRT}} < \mu_{\mathrm{SRT}(0.95)}\right) = 0.95 \tag{3.3}$$

where: $P(\ldots)$ – probability of event occurrence, M_{SRT} – a random variable with a normal distribution $\mathcal{N}(\mu_{\mathrm{SRT}}, \sigma(\mu_{\mathrm{SRT}}))$.

The legend of the graphs also provides numerical values for μ_{SRT}, $\sigma(\mu_{\mathrm{SRT}})$, and the Pearson correlation coefficient R of approximation (3.1). It was arbitrarily assumed that $|R| \le 0.3$, $0.3 < |R| \le 0.5$, $0.5 < |R| \le 0.7$, and $|R| > 0.7$ indicate no correlation, a weak, moderately strong, and strong correlation between the variables, respectively.

The results presented in Fig. 8 illustrate the wide range of friction coefficients for the SMA surface based on measurements on the road just after reconstruction and after 15 years of operation. On the total length of the RS1-RS3 surface sections of about 12 km, μ_{SRT} was obtained in the range of about 0.35 to 0.75 and μ_{VF} from about 0.5 to 1.5. In particular, in Fig. 8a–8c, there is a clear distinction between the two groups of measurements depending on the surface wear. Lower friction coefficient values (black points) were obtained on the used SMA, while higher ones (blue points) were obtained on the newly made one. Moreover, based on the value of the coefficient R (equal to about 0.75), it can be stated that the linear relationship between the friction coefficients on the SMA with the SRT-3 and VF is characterized by a strong correlation regardless of the measurement speed V (30 km/h, 40 km/h, or 60 km/h) and the slip ratio SR (15%, 18%, or 21%), which were used in the VF device. Moreover, the VF parameters for the measurement did not affect significant changes in the parameters a and b of the μ_{SRT} function.

The obtained value σ (μ_{SRT}) = 0.063 allows for a reasonably safe estimation of μ_{SRT} based on measurements from the VF with a specified level of probability. For example, assuming a normal distribution of measurement deviations, for a given value of μ_{VF}, the corresponding point on the lower violet solid line in Fig. 8 will give such a value of μ_{SRT}, that only 5% of the surface may have a lower friction coefficient when it is measured by the SRT-3. This provides a rational basis for the road administration to conduct acceptance tests based on data from the VF device after referring them to the minimum values required for the SRT-3, as specified in [8]. However, it may be compared only within the same surface temperature range as that, accompanying the described tests, using the measurement parameters for the VF device listed in Table 3, and the material characteristics for the SMA listed in Table 2.

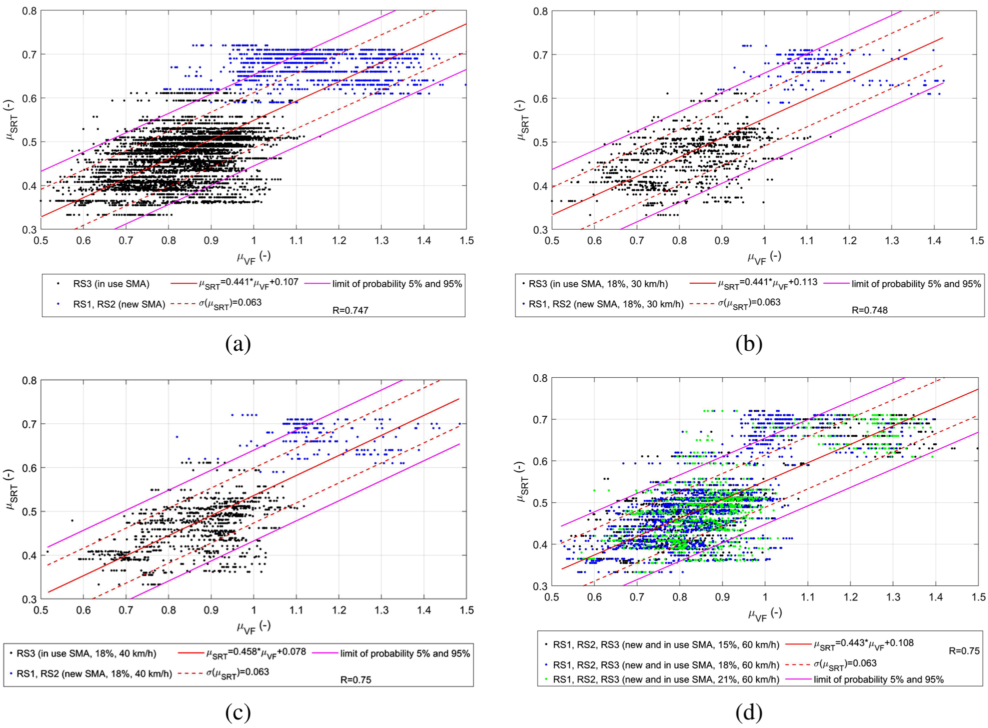


Fig. 8. Dependence between μ_{SRT} and μ_{VF} on the SMA surface: (a) RS1-RS3; all measurements, (b) RS1–RS3; the VF measurement: V = 30 km/h, SR = 18%, (c) RS1–RS3; the VF measurement: V = 40 km/h, SR = 18%, (d) RS1–RS3; the VF measurement: V = 60 km/h, SR = 15%, 18%, or 21%

The results for the CC road surface, which are presented in Fig. 9, illustrate a smaller range of friction coefficient variability compared to the SMA. According to the authors, this results from the lack of differentiation in the degree of wear of the CC surface that they had at their disposal (one type of road surface put into service in 2023). On the total length of the RS4-RS5 sections of 8.5 km, μ_{SRT} was obtained in the range of about 0.46 to 0.58 and μ_{VF} about 0.67 to 1.1. Moreover, based on the obtained values of the R coefficients (from about 0.02 to 0.22), it can be stated that the correlation between μ_{SRT} and μ_{VF} is not indicated; it is not possible to rationally conclude based on the presented measurements about μ_{SRT}, having measured μ_{VF}. The lack of a satisfactory level of correlation applies to all types of measurements due to the selection of the vehicle speed V and the slip ratio SR in the VF.

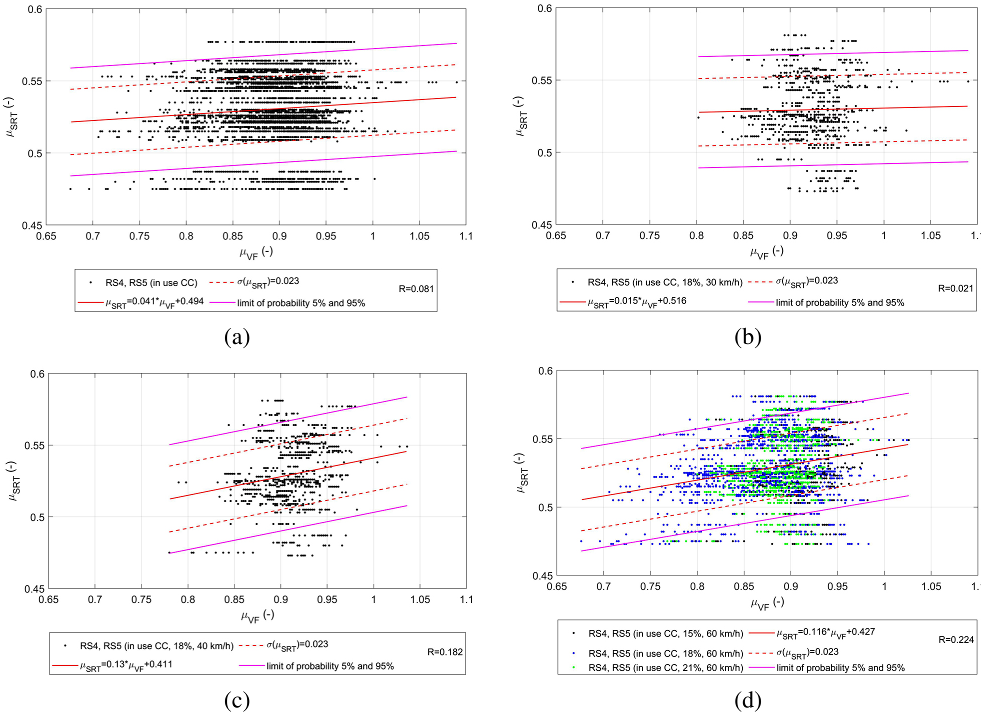
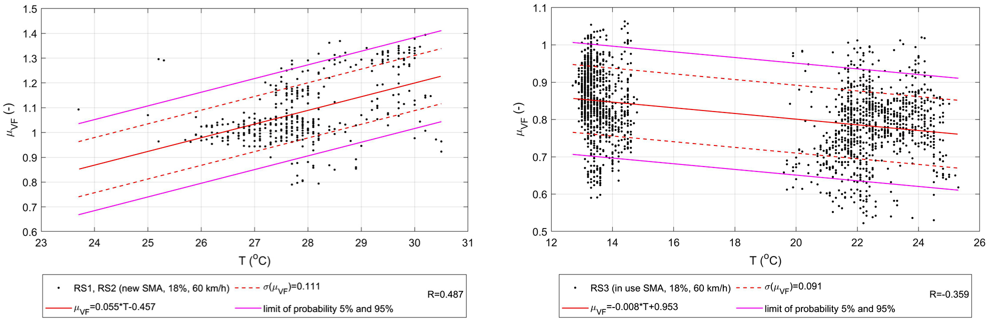


Fig. 9. Dependence between μ_{SRT} and μ_{VF} on the CC surface: (a) RS4-RS5; all measurements, (b) RS4-RS5; the VF measurement: V = 30 km/h, SR = 18%, (c) RS4-RS5; the VF measurement: V = 40 km/h, SR = 18%, (d) RS4-RS5; the VF measurement: V = 60 km/h, SR = 15%, 18%, or 21%

Measurements on the SMA with the VF device were also carried out at the same settings V = 60 km/h and SR = 18%, but with different road surface temperatures T, which occurred as a result of different levels of insolation on one day (from 24°C to 30°C for RS1 and RS2 with the new SMA) or the average temperature change between different days (from 13°C to 25°C for RS3 with the SMA in use). The results are shown in Fig. 10, where, using analogous relations to (3.1)–(3.3), the linear approximation of μ_{VF} as a function of T is shown in a red solid line; $\mu_{\mathrm{VF}} \pm \sigma\ (\mu_{\mathrm{VF}})$, where $\sigma\ (\mu_{\mathrm{VF}})$ is the standard deviation of μ_{VF}, are shown in two red dashed lines; the limit values $\mu_{VF(0.05)}$ and $\mu_{VF(0.95)}$ for the probability of occurrence marked with the subscripts in the parentheses are shown in two violet solid lines. The figure legend also gives numerical values of μ_{VF}, $\sigma\ (\mu_{\mathrm{VF}})$, and the Pearson correlation coefficient R. The latter ranges from about 0.35 to 0.5, which allows the authors to conclude that the correlation between the measured μ_{VF} and T is detectable, but it can be described as weak on the SMA.



(a) (b)

Fig. 10. Dependence between μ_{VF} and T on the SMA surface: (a) RS1-RS2; the VF measurement: V = 60 km/h, SR = 18%, (b) RS3; the VF measurement: V = 60 km/h, SR = 18%

μ_{VF} shows a slightly decreasing trend for the used SMA in the surface temperature range of 13–25°C ($a = -0.008$ in Fig. 10b), which can be explained by the decrease in rubber hysteresis with increasing temperature [16, 17]. However, for the new and unused SMA surface, an increasing trend of μ_{VF} was found in the temperature range of 24–30°C ($a = 0.055$ in Fig. 10a). According to the authors, this suggests the need for further research to specify the nature of the temperature effect on the friction on the SMA surface immediately after construction. In particular, the following factors should be considered in this context. The new SMA surface has a significantly greater macrotexture depth (after just 90 days of use, it can be reduced by 20–35% [18]), which increases the hysteresis phenomenon [17]. In addition, protruding coarse aggregate fragments are surrounded by a thin bitumen layer, which is worn away after the road is opened for traffic [18], changing the adhesion conditions.

4. Conclusions

It was found that there is a strong correlation for the SMA surface in the linear relationship between the friction coefficient measured with the SRT-3 and VF devices. It was found in the temperature range of 13–30°C regardless of the VF device's applied speed (from 30 km/h to 60 km/h) and the slip ratio (from 15% to 21%). This provides justified premises for using this device in Poland in acceptance and diagnostic tests of the SMA anti-skid properties based on the previous requirements specified for the SRT-3 device [8]. A weak correlation of the linear relationship between the VF friction coefficient on the SMA surface and the surface temperature was demonstrated in the range of 13–30°C, and in particular, there is a need for further research to specify the untypical effect of surface temperature on the friction for new and unused SMA surfaces.

In the case of the CC surfaces tested, the presented studies did not allow for a conclusion on a reliable relationship between the friction coefficients from the SRT-3 and VF devices due to the very small absolute value of the Pearson coefficient. Therefore, further measurement campaigns are required for the CC surfaces to determine whether the low correlation level results from the specificity of the applied measurement method, an insufficient sample size, or insufficient differentiation of the measurement conditions.

References

[1] M. Greene, et al., "Deliverable D1.1. Definition of boundaries and requirements for the common scale for harmonisation of skid resistance measurements", ROSANNE Project. [Online]. Available: https://www.rosanne-project.eu/documents?id=7299#. [Accessed: 11 Mar. 2025].

[2] R.B. Davies, P.D. Cenek, and R.J. Henderson, "The effect of skid resistance and texture on crash risk", presented at International Surface Friction Conference: roads and runways: improving safety through assessment and design, 1–4 May 2005, Christchurch, New Zealand, 2005.

[3] H. von Quintus and A. Mergenmeier, "Case Study: Kentucky Transportation Cabinet's High Friction Surface Treatment and Field Installation Program", Federal Highway Administration. [Online]. Available: https://highways.dot.gov/sites/fhwa.dot.gov/files/2022-06/ky_hfst_15_038.pdf. [Accessed: 11 Mar. 2025].

[4] „Road accidents in Poland in 2023", Police Statistics. [Online]. Available: https://statystyka.policja.pl/st/ruch-drogowy/76562,wypadki-drogowe-raporty-roczne.html. [Accessed: 11 Mar. 2025] (in Polish).

[5] "Tyre and Road Surface Optimisation for Skid Resistance and Further Effects (TYROSAFE). Final Summary Report". [Online]. Available: https://cordis.europa.eu/docs/results/217/217920/tyrosafe-final-summary-report.pdf. [Accessed: 11 Mar. 2025].

[6] "Regulation of the Minister of Infrastructure of June 24, 2022 on technical and construction regulations regarding public roads", ISAP. [Online]. Available: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20220001518. [Accessed: 11 Mar. 2025] (in Polish).

[7] CEN/TS 15901-14:2016 Road and airfield surface characteristics – Part 14: Procedure for determining the skid resistance of a pavement surface using a device with longitudinal controlled slip (LFCN): ViaFriction (Road Analyser and Recorder of ViaTech AS). CEN, 2016.

[8] A. Szydło and P. Mackiewicz, „WR-D-64: Guidelines for determining the surface features of road surfaces and other road parts. Version 01", Ministry of Infrastructure. [Online]. Available: https://www.gov.pl/web/infrastruktura/wr-d. [Accessed: 9 September 2025] (in Polish).

[9] Z. Rado, "Evaluating Performance of Limestone Prone to Polishing: Final Report", ROSAP. [Online]. Available: https://rosap.ntl.bts.gov/view/dot/17621. [Accessed: 11 March 2025].

[10] T.F. Fwa, "Determination and prediction of pavement skid resistance-connecting research and practice", *Journal of Road Engineering*, vol. 1, pp. 43–62, 2021, doi: 10.1016/j.jreng.2021.12.001.

[11] M. Wasilewska, W. Gardziejczyk, P. Gierasimiuk, and M. Motylewicz, „Review of devices for assessing the anti-skid properties of road pavements", in *LVIII Techniczne Dni Drogowe*. Radom, Poland: Wydawnictwo Naukowe Instytutu Technologii Eksploatacji, 2015, pp. 49–63 (in Polish).

[12] R.B. Kogbara, E.A. Masad, E. Kassem, A. Scarpas, and K. Anupam, „A state-of-the-art review of parameters influencing measurement and modeling of skid resistance of asphalt pavements", *Construction and Building Materials*, vol. 114, pp. 602–617, 2016, doi: 10.1016/j.conbuildmat.2016.04.002.

[13] PIARC Committee 1 on surfaces characteristics 2009R03, *Specification for a standard test tire for friction coefficient measurement of a pavement surface: Ribbed test tire.* World Road Association (PIARC), 2004.

[14] L. Bukowski, „Issues related to friction coefficient of pavement", *Drogownictwo*, no. 10, pp. 337–344, 2017 (in Polish).

[15] ASTM E1551-16(2020) Standard Specification for a Size 4.00-8 Smooth Tread Friction Test Tire. ASTM, 2020.

[16] Y. Luo, "Effect of Pavement Temperature on Frictional Properties of Hot-Mix-Asphalt Pavement Surfaces at the Virginia Smart Road", M.A. thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, 2003 [Online]. Available: https://vtechworks.lib.vt.edu/items/098bf208-ad54-4566-b931-e5ac815cec08. [Accessed: 21 March 2025].

[17] K. Anupam, S.K. Srirangam, A. Scarpas, and C. Kasbergen, "Influence of Temperature on Tire-Pavement Friction: Analysis", *Transportation Research Record: Journal of the Transportation Research Board*, vol. 2369, no. 1, pp. 114–124, 2013, doi: 10.3141/2369-13.

[18] M. Wasilewska, "Analysis of skid resistance of road pavements in the initial period of its life", *Budownictwo i Architektura*, vol. 13, no. 4, pp. 285–292, 2014 (in Polish).

Współczynnik tarcia nawierzchni drogowej mierzony przy różnych wartościach poślizgu – porównanie wyników z urządzeń ViaFriction i SRT-3

Słowa kluczowe: mastyks grysowy, nawierzchnia drogowa, SRT-3, ViaFriction, właściwości przeciwpoślizgowe, współczynnik tarcia

Streszczenie:

Streszczenie: Właściwości przeciwpoślizgowe nawierzchni drogowych odgrywają kluczową rolę w zapewnieniu bezpieczeństwa użytkowników dróg. W pracy podkreśla się w tym zakresie potrzebę stosowania pomiaru współczynnika tarcia przy zmiennym poślizgu koła testowego, który pozwala na bardziej szczegółową kontrolę stanu technicznego nawierzchni – np. za pomocą urządzenia ViaFriction. W Polsce minimalnie wymagane wartości współczynnika tarcia określono dotychczas jednoznacznie tylko w przypadku urządzenia SRT-3 z pełną blokadą koła. Było to dla autorów motywacją do porównania wyników pomiarów współczynnika tarcia z urządzeń SRT-3 i ViaFriction. Badania prowadzono na wybranych odcinkach dróg w województwie opolskim, uwzględniając dwie technologie nawierzchni z mastyksu grysowego (ang. stone mastic asphalt (SMA)) i betonu cementowego. W przypadku SMA brano pod uwagę także czas eksploatacji i temperaturę nawierzchni. W rezultacie wykazano silnie skorelowaną liniową zależność pomiędzy współczynnikami tarcia z urządzeń SRT-3 i ViaFriction na nawierzchni SMA.

Received: 2025-09-03, Revised: 2026-02-19