Classification of parameters affecting slip safety of limestones

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Abstract: This study determines the appropriate surface processing techniques for limestone plates. Slip resistance, which is required for the slip safety of pedestrians wearing shoes, is one of the most important parameters for the surface processing of limestone plates used as floor covering. The slip resistances of five different limestone plates, each of which have undergone four different surface processes, were determined according to the TS EN 14231 Standard. To define the factors affecting slip resistance, the mineralogical and petrographic characteristics, chemical properties, physico-mechanical properties of five different types of limestone were identified. Statistical analyses were performed to define the relations among these parameters. Slip resistance values on limestone sample plates were found to change considerably depending on both the surface processing techniques applied and the dryness or wetness of the surface along with its physico-mechanical characteristics. Finally, the limestones used in this research were classified according to safety applications with consideration of their slip resistance values.

1. Introduction
Natural stones are commonly used in the residential sector and in domestic architecture as construction and flooring materials. Such stones are used as indoor flooring and tiling material. Meanwhile, in the bathroom and kitchen, as well as outdoors, these materials are used as flooring for stairs, pavement tiling, wall lining, flooring material, sculptures, and artistic construction (Sarıışık, 1998, 2007; Sarıışık & Sarıışık, 2010a).

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PUBLIC INTEREST STATEMENT
This study determines and assesses the anti-skid properties of floorings used in surfaces on which people move while wearing shoes. A series of tests were conducted on five commonly used limestone types. Slip resistance of limestone plates which were used in the tests were statistically analyzed. It was found that the parameters that affected slip resistance of limestone plates were surface processing techniques, dry/wet of surface. Classifying safety application of specimens based on slip resistance was achieved from results. In light of the results obtained with the pendulum method, we recommend that honed limestone samples be used for wet and dry environments.
Slip resistance has recently become a major issue in the design of natural stones as flooring material. Slip resistance results from the interaction between a barefoot and/or shoe insole and the surface of flooring material. Thus, the slip resistance of natural stones should be determined to ensure safe movement (Chang, 1999; Chang, Matz, & Chang, 2014; Derler, Huber, Kausch, & Meyer, 2015; Grönqvist, 1989, 1995; Kim, 2004; Manning, Jones, Rowland, & Roff, 1998; Rowland, Jones, & Manning, 1996). Slipping incidents result from one or more factors, including the person involved, the activity performed, environmental factors such as contaminants (water, oil, grease, ice, dust, detergent, soap, etc.), distractions, temperature and lighting, and the characteristic of the footwear and of the walking surface (Kim, 2015, 2016; Kim, Hsiao, & Simeonov, 2013; Li & Chen, 2004). Usage area, brightness, polishing, and anti-slip features are directly affected by surface treatment methods applied to natural surfaces (Sarıışık, 2009; Sarıışık, Akdaş, Sarıışık, & Çoşkun, 2011; Sarıışık & Sarıışık, 2010b; Sarıisik, Sarisik, & Akdaş, 2012). Therefore, the slip safety of the limestones used as floor coverings in wet and dry environments should be determined so that people can move safely while barefooted without the risk of slipping. To determine the slip safety of different types of limestones, the slip angles of the processed limestone with different-sized plates should be tested in a laboratory environment. Several different test devices have been identified in the literature (Burnfield & Powers, 2006; Chang & Matz, 2001; Chang et al., 2001a, 2001b; Grönqvist, Hirvonen, & Tohv, 1999; Leclercq, 1999; Leclercq & Saulnier, 2002; Powers, Kulig, Flynn, & Brault, 1999; Sarıışık, 2009; Sarıışık & Sarıışık, 2010b; Sarıisik et al., 2012; Sarıisik et al., 2011).

Several authors have studied the tribological phenomena that occur at the surface/shoe interface when a subject is walking normally (Cham & Redfern, 2002; Grönqvist, 1989; Hanson, Redfern, & Mazumdar, 1999; Kim, 2004; Kim & Nagata, 2008; Kim, Smith, & Nagata, 2001; Marpet, 2002; Sarıisik et al., 2012; Strandberg & Lanshammar, 1981).

In order to give an aesthetic appearance and make the surface safer for pedestrians walking barefoot on natural stones, a range of surface-processing techniques are used to reduce accidents stemming from this slipperiness. In recent years, mainly polished, honed and tumbled natural stones have been used in interior and exterior spaces in the construction sector. These surface-processing techniques affect the usability functions and some other technical characteristics of the limestones (resistance, environmental conditions or anti-slip) (Sarıisik et al., 2012). Many researchers have investigated usage areas and classification of natural stones. Most of these studies have considered the physical and mechanical properties of stones (e.g. density, porosity, water absorption capacity, knop hardness, compressive strength, compressive strength after freezing, bending strength, impact strength and abrasion resistance) as well as the impact of the environment on them (e.g. chemical corrosion, harmful pollutants, freezing and thawing phases, crystallization of salt solutions) (Benavente, García del Cura, García-Guinea, Sanchez-Moral, & Ordonez, 2004; Rodriguez-Navarro, Linares-Fernandez, Doehrne, & Sebastian, 2002; Sarıışık & Sarıışık, 2011; Sarıışık, Sarıışık, Koch, & Knoblauch, 2008; Sarıisik, Sarıisik, & Senturk, 2010; Sharma, Khandelwal, & Singh, 2007; Sharma & Singh, 2006; Singh, Singh, Mishra, Singh, & Singh, 1999; Vishal, Das, & Singh, 2012; Vishal, Pradhan, & Singh, 2011).

The aim of the present study was to determine the effects of the engineering characteristics of limestone on the anti-slip performance of such surfaces, and to apply this knowledge within the construction sector. To minimize the risk of slipping while walking barefoot or wearing shoes on wet floor coverings, a suitable surface processing method and the appropriate dimensions of natural stones should be determined (Li, Yu, & Zhang, 2011; Sarıışık, 2009; Sarıışık & Sarıışık, 2010b; Sarıışık et al., 2011; Sarıisik et al., 2012). The present study will therefore contribute to greater understanding of this issue within the design and construction sectors.
2. Experimental studies

2.1. Material
In recent years, limestones are used as floor covering materials in public areas with a high percentage of human circulation such as shopping centers, hospitals, bus stations, train stations, schools and swimming pools. To minimize the accidents caused by slipping in these areas, the properties of the limestones used as flooring materials should be known. Five sedimentary (five limestone) rock types were selected in this study. These limestone samples were obtained from or provided by firms that operate quarries in Afyonkarahisar/Iscehisar, Turkey. Limestone plates with dimensions of 300 × 300 × 10 mm³ were used for a slip resistance experiment. A total of 40 samples (one plate dimension, five rock types, four different surface processing, two different environments) were tested to determine the slip resistance of the limestones. Slip resistance measurements were conducted using (40 samples × 6 positions) randomised experimental design with ten replications (n = 10). A total of 2,400 measurements were recorded. At the termination of measurements the slip resistance values of each rock type were ranked and the samples were renumbered as B1 to B5 for limestone.

2.2. Characterization tests
Thin sections were prepared from 5 × 5 × 1 cm samples, and the mineralogical and petrographic characteristics of each rock type were examined with a polarized microscope. Mineral distributions and crystal dimensions were measured using a Clemex model display analysis system. Mineralogical analysis was conducted in the Mineralogical–Petrographic Analysis Laboratory of the General Directorate Mineral Research and Exploration in Ankara, Turkey. Chemical analyses were performed using the X-ray fluorescence method in ACME Analytical Laboratory, Canada. Physical and mechanical tests according to the TS EN (TS EN 14205, 2004; TS EN 1926, 2007; TS EN 1936, 2010; TS EN 12371, 2011; TS EN 1341-Ek C, 2013; TS EN 13755, 2014; TS EN 13161, 2014) standards (density, porosity, water absorption, knop hardness, compressive strength, frost resistance after compressive strength, bending strength, and abrasion resistance) of limestone samples were performed in Afyon Kocatepe University Mining Engineering Department Laboratories. The dimensions of the limestone samples were 70 × 70 × 70 and 30 × 50 × 180 mm³, and the averages were taken by conducting experiments with at least six samples.

2.3. Slip resistance tests
Several test devices can be used to measure slip resistance. However, no machine can provide an absolute reference for the measurement of a given slip resistance. Changing the surface floor materials also fails to provide such reference.

2.3.1. Pendulum tester
A WESSEX S885 pendulum device (Figure 1) was used to determine the friction forces of the tested stones (Wessex Catalog, 2010). This device was used to measure the friction between the conveyor and the testing surface, as well as to identify a standard value for slip resistance.

The pendulum test device was designed to measure the anti-slip properties of the surfaces in compliance with TS EN standards. The center of gravity should be on the bob axis (410 ± 5) mm from the string axis. In the conveyor system, when the pendulum bob reaches the top point while swinging and the sliding side of the conveyor comes in contact with the test sample, the conveyor plane should be mounted on the bob in such a way that a (26 ± 3)° angle is achieved against the horizontal plane. Under this mechanism, the conveyor can easily turn around its own axis as the pendulum swings, such that the surface roughness of the sample can be monitored. Pendulum friction test equipment should be designed as indicated in Figure 1.

The TS EN standard (TS EN 14231, 2004) was used as a reference to determine the anti-slip resistance of the surfaces of limestones used for the floors of standard buildings.
During the test, samples should include the whole product or a part that contains the top surface of the unit. Each sample should provide a test area of 136 × 86 mm. The area was tested by using a conveyor with 126 mm slip length and 76 mm wide. Identifications were made on the C scale. The friction test equipment, conveyor, and samples were kept at (20 ± 5)°C room temperature for laboratory measurements, for a minimum of 2 h before the test. The appropriate conveyor and test scale were selected on the basis of sample dimensions.

2.3.1.1. Test procedure in dry conditions: Prior to the test, the samples (30.5 × 30.5 × 1.0 cm plate size) are dried at (105 ± 5)°C for laboratory measurements. The indicator of the pendulum device is set to the starting point. The pendulum bob is made to move freely by pressing on the release button of the device. Before coming into contact with the test surface, the conveyor is retained at return movement. The value indicated on the scale is recorded. The bob and the indicator are set to the starting point to enable the conveyor and the surface to come in contact with the prepared mechanism. The procedure is repeated until five subsequent readings (on the C scale) exhibit a difference of no more than three units. If the F scale is used, a difference of no more than 0.03 should be observed among the five subsequent readings. For the laboratory measurements, the sample is turned 180° before being fixed, and all procedures are repeated after re-control.

2.3.1.2. Test procedure in wet conditions: Prior to the tests for laboratory measurements, the samples are kept in (20 ± 5)°C water for at least 2 h. Before each slip of the pendulum, the test surface and conveyor are continuously dampened with (20 ± 5)°C distilled and deionized water. The head piece of the test device that moves on the surface is lifted, and free slip is controlled to achieve zero error. For the laboratory measurements, the sample is turned 180° before being fixed, and all procedures are repeated after re-control.

For each sample or for each test area, average five-group reading values measured for dry and wet environments and in opposite directions are calculated. The calculated pendulum values are classified according to slip resistance (Table 1) and slip potential (Table 2).
2.4. Surface processing
The caliber and abrasive captions, amount of water, band speeds, pressure rates and the condition of the limestone surface used in polishing and honing processes, which are necessary for the procession of the surfaces of the limestone plates, are shown in Figure 2.

The beige-coloured limestones, which are widely used in wet places, were subjected to polishing, honing and tumbling, which are the preferred surface-processing techniques. These surface-processing techniques affect the area of usage and several technical characteristics (resistance, environmental conditions and anti-slip) of the limestones. Figure 3 shows the surface-processed limestones.

| Table 1. Classification of slip resistance according to Bowman (2004) |
|-----------------------------|---------------------------|
| Pendulum value | Slip resistance |
| 0–24 | Dangerous |
| 24–34 | Limited |
| 35–64 | Adequate |
| >65 | Very good |

| Table 2. Classification of slip potential according to Bowman (2010) and TS EN 14231 (2004) |
|-----------------------------|-----------------------------|
| Class | Pendulum value | Slip potential | Typical uses |
| V | >54 | Very low | Exterior areas, ramp area |
| W | 45–54 | Low | Exterior walking pathways, surroundings of swimming pools exterior areas, stairs |
| X | 35–44 | Medium | Shopping center food courts, hotel entrance saloons, public changing rooms, interior area stairs |
| Y | 24–34 | High | Bathroom, storage, laundry room |
| Z | <24 | Very high | Shopping centers |

Figure 2. Schematic representation of honing and polishing processes of the limestone plates used in tests (Kulaksız, 2007; Şentürk et al., 1996).
2.4.1. Polishing
The polishing process is basically a controlled abrasion process. Polishing uses abrasive grains (30–800 grits + varnish) with grain sizes that are gradually reducing. This process removes material and surface irregularities from the surface of limestones, gradually producing a uniform surface that can reflect light. Two machines called “slim line” and “varnish line” are used in the polishing process. In the slim line of limestones, the process is performed by scratching or scraping the particles with abrasives and then eliminating such particles from the surface of the limestone to achieve a smooth surface (Kulaksız, 2007; Şentürk, Gündüz, Tosun, & Sarıışık, 1996). The limestones used in the test were polished with DEMMAK brand plate line (3 + 12).

2.4.2. Honing
The honed surface finish is applied by tumbling the surfaces of plates with abrasives and then reducing the surface roughness without polishing. The honing process is performed by using fine abrasives (30–320 grits) on the surface. This process may be realized with 280 or 320 abrasives in accordance with the dullness required. The track left by the abrasives is then eliminated with the use of the head of a honing felt. As a result of the honing process, a surface that is rougher and duller than a polished surface is obtained. Given that the surface is not polished, any possibility of slipping and falling is reduced, and a safe floor is provided to walk on.

2.4.3. Tumbling
Tumbling is an abrasion process that uses small, prismatic-shaped abrasives for a pre-defined period of time. Limestone samples are placed into the tumbling tub with water and abrasives (60 grit). As a result of various mechanical movements of the machine, the limestone samples are mixed with the abrasive–water mixture and then abraded. In the tub that produces vibration, as well as beating and churning movements, the limestone samples are processed with different forms of abrasives (Kulaksız, 2007). The limestone samples used in this study were tumbled in Kromasbrand tanks, which have a capacity of 4,000 L and a maximum stone dimension capacity of 610 × 610 × 20 mm³.
2.4.4. Patinated
Brushes consisting of steel wires of different thickness are swept with rotational movements, similar to an automatic slim line. A certain amount of sawdust materials is removed from the soft parts of the surface. Finally, a rough and rugged finish is created on the surface and on the edge of the stone, which exhibits a rusty appearance. This method creates a soft and natural appearance. For this reason, brushing is a commonly employed method. Slight roughness, as well as irregular and visible brightness, can be noted depending on the surface. Visible surface details are evident, especially in large plates (Kulaksız, 2007).

3. Results and discussion
3.1. Characterization of the test results
The limestone rocks used in this study had various textures. All rock types were composed of at least 95% calcite minerals with 52.63–55.57% CaO as the main calcite crystals. The chemical analysis results, as well as the physical and mechanical characteristics of the samples used in this study, are presented in Tables 3 and 4, respectively.

| Table 3. Chemical characteristics of limestone samples |
|-----------------------------------------------------|
| Oxide compound | CaO (%) | SiO₂ (%) | Al₂O₃ (%) | Fe₂O₃ (%) | MgO (%) | K₂O (%) | TiO₂ (%) | P₂O₅ (%) | MnO (%) | LoI (%) |
|---------------|---------|----------|-----------|-----------|---------|---------|---------|---------|---------|--------|
| B1            | 55.57   | 0.1      | 0.02      | 0.37      | 0.16    | 0.01    | 0.04    | 0.01    | 43.71   |
| B2            | 54.92   | 0.1      | 0.01      | 0.41      | 0.13    | 0.01    | 0.04    | 0.01    | 44.36   |
| B3            | 55.53   | 0.1      | 0.02      | 0.34      | 0.14    | 0.01    | 0.02    | 0.01    | 43.82   |
| B4            | 53.06   | 1.4      | 0.45      | 0.29      | 0.29    | 0.03    | 0.04    | 0.01    | 44.13   |
| B5            | 52.63   | 0.1      | 0.01      | 2.99      | 0.24    | 0.01    | 0.13    | 0.01    | 43.87   |

LoI: Loss on ignition.

| Table 4. Physical and mechanical characteristics of limestones |
|---------------------------------------------------------------|
| Limestone samples                                            |
| Physical and mechanical properties                           |
| SI unit | B1 | B2 | B3 | B4 | B5 |
|---------|----|----|----|----|----|
| Mean ± SD³ |    |    |    |    |    |
| Density kg/m³ | 2650 ± 0.02 | 2700 ± 0.03 | 2750 ± 0.04 | 2750 ± 0.04 | 2800 ± 0.05 |
| Porosity %    | 0.89 ± 0.02  | 0.70 ± 0.02  | 0.53 ± 0.02  | 0.35 ± 0.01  | 0.21 ± 0.01  |
| Water absorption % | 0.34 ± 0.01  | 0.28 ± 0.01  | 0.26 ± 0.01  | 0.19 ± 0.01  | 0.16 ± 0.01  |
| Knoop hardness | 154.05 ± 0.51 | 168.15 ± 0.55 | 177.95 ± 0.59 | 178.50 ± 0.60 | 191.92 ± 0.64 |
| Compressive strength MPa | 75.08 ± 0.28 | 83.65 ± 0.31 | 89.43 ± 0.33 | 91.43 ± 0.34 | 97.30 ± 0.36 |
| Frost resistance after compressive stress MPa | 72.51 ± 0.27 | 82.25 ± 0.30 | 82.92 ± 0.31 | 84.15 ± 0.32 | 90.51 ± 0.34 |
| Bending strength MPa | 7.89 ± 0.10 | 8.23 ± 0.10 | 9.91 ± 0.10 | 10.58 ± 0.11 | 10.87 ± 0.11 |
| Abrasion resistance mm | 18.57 ± 0.16 | 18.24 ± 0.16 | 17.93 ± 0.16 | 17.67 ± 0.17 | 17.21 ± 0.17 |

³SD—Standard deviation.
3.2. Slip resistance analysis and classification of limestone plate samples

The slip resistance values of the limestone samples were statistically analyzed. These plates are the most preferred material for floor coverings. Two-factor variance analysis was conducted to determine the slip resistance of the limestone plate samples. In terms of slip resistance, a statistically significant difference was observed among wet and dry environments and surface processes ($p < 0.001$). When the limestone plates were used in floor coverings, it was found that wet and dry environments and surface processes have a statistically significant effect on the anti-slip performance of the finished plates (Table 5).

The paired comparison of the slip resistance of limestone samples on the basis of surface treatments in wet and dry environments is presented in Figure 4. The repeatability of these mean values is confirmed by the low standard deviation found for the different surface processes (mean standard deviation in the range 0.10–1.62).

Slip resistance values of polished, patinated, honed, and tumbled limestone samples in a dry environment are higher than those obtained in wet environments, as expected. The slip resistance values obtained from polished surfaces in a dry environment are lower than those obtained for other

| Dependent variable | Mean (I) | Mean (J) | Mean difference (I−J) | Std. error | Sig. | 95% confidence interval | Lower bound | Upper bound |
|--------------------|---------|---------|----------------------|-----------|-----|------------------------|------------|------------|
| Dry                | S1      | S2      | -12.4000*            | 0.51009   | <0.001 | -13.7119 -11.0881      |            |            |
|                    | S3      | S4      | -8.6000*             | 0.51009   | <0.001 | -9.9119 -7.2881        |            |            |
|                    | S1      | S3      | 8.0000*              | 0.51009   | <0.001 | 6.6881 9.3119          |            |            |
|                    | S1      | S4      | 3.8000*              | 0.51009   | <0.001 | 2.4881 5.1119          |            |            |
|                    | S2      | S1      | 12.4000*             | 0.51009   | <0.001 | 11.0881 13.7119        |            |            |
|                    | S2      | S3      | 8.0000*              | 0.51009   | <0.001 | 6.6881 9.3119          |            |            |
|                    | S2      | S4      | 3.8000*              | 0.51009   | <0.001 | 2.4881 5.1119          |            |            |
|                    | S3      | S1      | 4.4000*              | 0.51009   | <0.001 | 3.0881 5.7119          |            |            |
|                    | S3      | S2      | -8.0000*             | 0.51009   | <0.001 | -9.3119 -6.6881        |            |            |
|                    | S3      | S4      | -4.2000*             | 0.51009   | <0.001 | -5.5119 -2.8881        |            |            |
|                    | S4      | S1      | 8.6000*              | 0.51009   | <0.001 | 7.2881 9.9119          |            |            |
|                    | S4      | S2      | -3.8000*             | 0.51009   | <0.001 | -5.1119 -2.4881        |            |            |
|                    | S4      | S3      | 4.2000*              | 0.51009   | <0.001 | 2.8881 5.5119          |            |            |
| Wet                | S1      | S2      | -13.2000*            | 0.72611   | <0.001 | -15.0675 -11.3325      |            |            |
|                    | S3      | S4      | -12.8000*            | 0.72611   | <0.001 | -14.6675 -10.9325      |            |            |
|                    | S3      | S1      | -7.8000*             | 0.72611   | <0.001 | -9.6675 -5.9325        |            |            |
|                    | S2      | S1      | 13.2000*             | 0.72611   | <0.001 | 11.3325 15.0675        |            |            |
|                    | S2      | S3      | 5.4000*              | 0.72611   | <0.001 | 1.4675 2.2675          |            |            |
|                    | S2      | S4      | 5.4000*              | 0.72611   | <0.001 | 3.5325 7.2675          |            |            |
|                    | S3      | S1      | 12.8000*             | 0.72611   | <0.001 | 10.9325 14.6675        |            |            |
|                    | S3      | S2      | -5.4000*             | 0.72611   | <0.001 | -2.2675 1.4675         |            |            |
|                    | S3      | S4      | 5.0000*              | 0.72611   | <0.001 | 3.1325 6.8675          |            |            |
|                    | S4      | S1      | 7.8000*              | 0.72611   | <0.001 | 5.9325 9.6675          |            |            |
|                    | S4      | S2      | -5.4000*             | 0.72611   | <0.001 | -7.2675 -3.5325        |            |            |
|                    | S4      | S3      | -5.0000*             | 0.72611   | <0.001 | -6.8675 -3.1325        |            |            |

Notes: Based on observed means; S1: Polished, S2: Patinated, S3: Honed, S4: Tumbled.
*The mean difference is significant at the 0.05 level.
surfaces. For polished surfaces, sample B1 has the lowest slip resistance value with a 18 mean value, whereas sample B5 has the highest slip resistance value with a 24 mean value. For patinated surfaces, sample B1 has the lowest slip resistance value with a 19 mean value, whereas sample B5 has the highest slip resistance value with a 32 mean value. For honed surfaces, sample B1 sample has the lowest slip resistance value with a 21 mean value, whereas sample B5 has the highest slip resistance value with a 40 mean value. For tumbled surfaces, sample B1 sample has the lowest slip resistance value with a 30 mean value, whereas sample B5 has the highest slip resistance value with a 40 mean value.

The research shows that the slip resistance values of honed, tumbled, and patinated limestone samples in a dry environment are higher than those of polished surfaces. Furthermore, the slip resistance values obtained from polished surfaces in a wet environment are very low. For polished surfaces, samples B1, B2, and B3 have the lowest slip resistance value with a 1 mean value, whereas samples B3 and B5 have the highest slip resistance value with a 3 mean values. For patinated surfaces, sample B1 sample has the lowest slip resistance value with a 1 mean value, whereas sample B5 has the highest slip resistance value with a 19 mean value. For honed surfaces, sample B1 has the lowest slip resistance value with a 1 mean value, whereas sample B5 has the highest slip resistance value with a 24 mean value. For tumbled surfaces, sample B1 sample has the lowest slip resistance value with a 4 mean value, whereas sample B3 has the highest slip resistance value with a 29 mean value. Sample B5 has the highest slip resistance value both in dry and wet environments.

Limestone samples possess slip resistance values between 19 and 40 in a dry environment and between 1 and 29 in a wet environment depending on surface treatments. According to the test results, the use of tumbled limestone samples is safer for floorings in wet and dry environments. The
use of the tumbled B5 limestone sample will be the safest choice for wet floors. In addition, if tumbled limestones are preferred for their aesthetic appearance, samples B4 and B5 can be used in wet environments.

We determined the places in which limestones can be used in wet and dry environments according to the classification that indicates the slip resistance values of limestones on the basis of surface properties (Table 2). The limestone classes are presented in Table 6.

![Figure 5. Images of thin limestone sections (microscopic analysis with plane polarised light (×10 N).](image)

| Environments | Surface processing | B1 | B2 | B3 | B4 | B5 |
|--------------|-------------------|----|----|----|----|----|
| Dry          | Polished          | 18 | Z  | 21 | Z  | 23 | Z  | 23 | Z  |
|              | Patinated         | 19 | Z  | 23 | Z  | 25 | Y  | 28 | Y  |
|              | Honed             | 23 | Z  | 26 | Y  | 27 | Y  | 30 | Y  |
|              | Tumbled           | 30 | Y  | 34 | Y  | 37 | X  | 39 | X  |
| Wet          | Polished          | 1  | Z  | 1  | Z  | 1  | Z  |
|              | Patinated         | 1  | Z  | 3  | Z  | 5  | Z  |
|              | Honed             | 1  | Z  | 4  | Z  | 8  | Z  |
|              | Tumbled           | 4  | Z  | 5  | Z  | 9  | Y  | 24 | Y  |

Notes: SR: Slip resistance; V, W, X, Y and Z: see Table 2.
In a dry environment, polished samples B1, B2, B3, B4 and B5, honed sample B1, and the patinated samples B1 and B2, are categorized in the Z class because their slip resistance values are lower than 24. Honed samples B1, B2, B3 and B4, tumbled samples B1 and B2, as well as patinated samples B3, B4 and B5 are placed in the Y class because their slip resistance values are higher than 25. Tumbled samples B3, B4 and B5 are categorized in the X class because their slip resistance values are higher than 35.

In a wet environment, all polished and patinated samples, as well as honed samples B1, B2, B3, and B4 and tumbled samples B1, B2, and B3, are placed in the Z class because their slip resistance values are lower than 24. Honed sample B5 and tumbled B4 and B5 are placed in the Y class.
Limestones in the X classification are used for dressing rooms, indoor stairs, and hotel entrances. Limestones that are in the Y class can be used in bathrooms, storerooms, and laundry rooms, whereas those placed in the Z class are used in shopping centers.

3.3. Effects of mineralogical and petrographic characteristics on slip resistance
The main physical features affecting the alteration and corrosion of the limestone are fossil content, clay composition, micro-fissures and cracks. These parameters affect the water absorption and porosity features of the limestones. The mineralogical–petrographical properties of the tested limestones are given in Figure 5. Crypto-microcrystalline carbonates were observed in the limestone samples. Limestone consists of rock pieces with different dimensions, which are derived from carbonate, microfossils, and cryptocrystalline calcite pieces that include plant fossils and tiny opaque minerals. Crypto-crystalline and micro-crystalline were composed of carbonate minerals. Secondary formed microcrystalline carbonate minerals wrapped the boundaries of the pores. In addition, minerals, including iron as opaque minerals, were present.

Mineralogical–petrographical characteristics, rock texture, fossil content and porosity type (fracture porosity), microfissures and cracks on the limestones were found have an effect on the slip resistance value. Pore type, grain shape, grain size, and clamped grain level affect the physical and mechanical properties (density, water absorption, compressive strength) of natural stones (Sarıışık, 2007; Sarıışık & Sagular, 1998; Sarıışık & Sarıışık, 2010a; Sarıışık et al., 2008). When the values related to slip resistance are analyzed, it can be suggested that slip resistance increases in parallel with the decrease in porosity. For example, B1 and B2, which had a porosity of 0.89 and 0.70%, respectively, presented the lowest slip resistance compared with samples with lower porosity. Thus, B1 limestone has the lowest slip resistance (18) as its porosity rate is higher. The main component of the mineral content of any limestone is calcite. In addition, there are cracks, secondary calcite textures along dissolution cavities and iron stains. Since these cracks and dissolution cavities are filled with different minerals, areas develop on the rocks which have varying levels of hardness. During the ageing process, the surface characteristics are changed, since the micro-cracks and fillings in such areas erode. Therefore, slip resistance decrease, dependent on the level of ageing, when progressing from polished, to patinated, to honed, then to tumbled limestones. Moreover, B1, B2, B3, B4 and B5 limestones (all of which have a high fossil and stylolite content) produced low slip resistance values during the polishing process, which is one of the surface-processing techniques used. Accordingly, calcite-filled, horizontal and vertical micro-fissure veins intersecting each other include lime mud and calcite (along the cracks) and clay minerals. Therefore, B3 limestone had the largest slip resistance (23) on polished surfaces. B2 limestone produced the smallest slip resistance (21) on polished surfaces, since it includes high proportions of calcite crystals along the veins and is exposed to metamorphism.

3.4. Effects of physical and mechanical properties on slip resistance
The relation between slip resistance values, and the physical and mechanical properties of the limestone samples were evaluated through regression analysis. The results of the analysis are presented in Figure 6. According to the $R^2$ coefficients of the limestone samples, a linear relationship between slip resistance and the physical and mechanical characteristics is observed. As a result of the analysis, the following $R^2$ coefficient values have been obtained: $R^2$ coefficient for polished surfaces between 0.83 and 0.97, $R^2$ coefficient for patinated surfaces between 0.87 and 0.98, $R^2$ coefficient for honed surfaces between 0.82 and 0.96, and $R^2$ coefficient for tumbled surfaces between 0.87 and 0.98. Accordingly, as water absorption, porosity, and abrasion resistance decrease in the limestones, slip resistance increases. Moreover, as density, knoop hardness, compressive strength, frost resistance after compressive strength, and bending strength increase, slip resistance also increases. In terms of the slip resistance of limestones, a statistically significant determinant coefficient (<0.005) was found between physical and mechanical properties.
4. Conclusion

The conducted studies determined the slip resistance and friction coefficients of five different types of limestones with polished, patinated, honed, and tumbled surfaces determined in accordance with TS EN 14231 standards.

The results of the experimental study are summarized below.

- The analysis of slip resistance values of limestone samples obtained from tests conducted in wet and dry environments on the basis of surface processes reveals a statistically significant difference. Accordingly, the order in a dry and wet environment is as follows: polished < patinated < honed < tumbled.
- Limestone samples are classified by their slip resistance and are determined with experimental and statistical analyses. Safe usage areas for limestones are recommended. As expected, slip potential decreases in dry environments because slip resistance increases on all surfaces with the pendulum. In wet environments, slip potential and risk increase because slip resistance values decrease on all surfaces.
- The results show that in dry environments, five different limestone samples can be used more safely for floorings. However, in wet environments, slip resistance values significantly decrease. Hence, slip risk increases. In light of the results obtained with the pendulum method, we recommend that honed limestone samples be used for wet and dry environments.
- Mineralogical and petrographic characteristics have important roles to determine slip resistance. According to the test results, the porosity ratio, porosity type, fossil content, micro fissures, and cracks filled with clays all decrease the slip resistance.
- A linear relationship exists between slip resistance and the physical and mechanical characteristics of limestones. Accordingly, as water absorption, porosity, and abrasion resistance rate decrease, density, knoop hardness, compressive strength, frost resistance after compressive strength, and bending strength increase. The increase in slip resistance thereby reduces the slipping potential.

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References

Benavente, D., García del Cura, M. A., García-Guinea, J., Sanchez-Moral, S., & Ordonez, S. (2004). Role of pore structure in salt crystallisation in unsaturated porous stone. Journal of Crystal Growth, 260, 532–544. doi:10.1016/j.jcrysgro.2003.09.004.

Bowman, R. (2004). Practical aspects of slip resistance of stone. Retrieved 2011, May 29, from http://www.discoveringstone.com

Bowman, R. (2010). Slip resistance testing—zones of uncertainty. Boletín de la Sociedad Española de Cerámica y Vidrio, 49, 227–238.

Burnfield, J. M., & Powers, C. M. (2006). Prediction of slips: An evaluation of utilized coefficient of friction and available slip resistance. Ergonomics, 49, 982–995. doi:10.1080/00140130600665687

Cham, R., & Redfearn, M. (2002). Heel contact dynamics during slip events on level and inclined surfaces. Safety Science, 40, 559–576. doi:10.1016/S0925-7535(01)00095-5

Chang, W. R. (1999). The effect of surface roughness on the measurement of slip resistance. International Journal of Industrial Ergonomics, 24, 299–313. doi:10.1016/S0149-9190(98)00038-9

Chang, W. R., & Matz, S. (2001). The slip resistance of common footwear materials measured with two slipmeters. Applied Ergonomics, 32, 540–558. doi:10.1016/S0003-6870(01)00031-X
Çoşkun et al. (2016), 3: 1217821

Chang, W. R., Grönqvist, R., Leclercq, S., Brungarber, R. J., Mattke, U., Strandberg, L., ... Courtne Y, T. K. (2001). The role of friction in the measurement of slipperiness, Part 2: Friction mechanisms and definition of test conditions. Ergonomics, 44, 1217–1232. doi:10.1080/00140139508925100

Chang, W. R., Grönqvist, R., Leclercq, S., Myung, R., Makkonen, L., Strandberg, L., ... Thorpe, S. C. (2001). The role of friction in the measurement of slipperiness, Part 1: Friction mechanisms and definition of test conditions. Ergonomics, 44, 1217–1232. doi:10.1080/00140130110085574

Chang, W. R., Matz, S., & Chang, C. C. (2014). The prevention of slipping accidents: A review and discussion of work related to the methodology of measuring slip resistance. Safety Science, 31, 95–125. doi:10.1016/S0925-7535(98)00064-2

Leclercq, S., & Saunier, H. (2002). Floor slip resistance changes in food sector workshops: prevailing role played by "fouling." Safety Science, 40, 659–673. doi:10.1016/S0925-7535(01)00065-0

Li, K., W., Yu, R., & Zhang, W. (2011). Roughness and slipperiness of floor surface: Tactile sensation and perception. Safety Science, 49, 499–507. doi:10.1016/j.ssci.2004.06.010

Li, K. W., Yu, R., & Zhang, W. (2011). Roughness and slipperiness of floor surface: Tactile sensation and perception. Safety Science, 49, 499–507. doi:10.1016/j.ssci.2004.06.010

Manning, D. P., Jones, C., Rowland, F. J., & Roff, M. (1998). The surface roughness of a rubber soling material determines the coefficient of friction on water-lubricated surfaces. Journal of Safety Research, 29, 275–283. doi:10.1016/S0022-4375(88)00053-X

Marpet, M. (2003). Improved characterization of tribometric test conditions. Safety Science, 40, 705–714. doi:10.1016/S0925-7535(01)00065-6

Powres, C. M., Kulig, K., Flynn, J., & Brault, J. R. (1999). Repeatability and bias of two walkway safety tribometers. Journal of Testing and Evaluation, 27, 368–374. doi:10.1520/JTE12164 J

Rodriguez-Navarro, C., Linares-Fernandez, L., Doehne, E., & Sebastian, E. (2002). Effects of ferrocyanide ions on NaCl crystallization in porous stone. Journal of Crystal Growth, 243, 503–516. doi:10.1016/S0022-4067(02)01499-9

Rowland, F. J., Jones, C., & Manning, D. P. (1996). Surface roughness of footwear soling materials: Relevance to slip resistance. Journal of Testing and Evaluation, 24, 368–376. doi:10.1520/JTE11459 J

Sarışık, A. (2009). Safety analysis of slipping barefoot on marble covered wet areas. Safety Science, 47, 417–428. doi:10.1016/j.ssci.2009.03.006

Sarışık, A., & Sağular, E. K. (1998). Effects on geo-mechanical parameters of the petrographic-petrological characteristics of rocks used as construction and facing rock. In A. National Rock Mechanics Symposium, Proceedings Book (pp. 33–47). Zonguldak. (in Turkish).

Sarışık, A., & Sarışık, G. (2010a). Quality control of Turkish calcareous natural stone using the merkant system. Journal of Testing and Evaluation, 38(5), 1–13. doi:10.1520/JTE102774

Sarışık, A., & Sarışık, G. (2000a). Analysis of the parameters affecting the slip angle of surface-processed natural stones. Mining Journal, 49, 17–30. (in Turkish).

Sarışık, A., & Sarışık, G. (2011). Environmental interaction properties of marble used in the restoration of historical monuments (Dalyan-Kaunos). Ekojö, 19, 12–20. doi:10.5053/ekoloji.2011.792

Sarışık, A., Sariisik, G., Senturk, A. (2010a). Characterization of physical and mechanical properties of natural stones affected by ground water under different ambient conditions. Ekojö, 19, 88–96. doi:10.5053/ekoloji.2010.7713

Sarışık, A., Sariisik, G., & Akdağ, H. (2012). Slip analysis of surface processed limestones. Proceedings of the Institution of Civil Engineers - Construction Materials, 165, 279–296. doi:10.1680/coma.10.00062

Sarışık, A., Akdağ, H., Sarışık, G., & Çoşkun, G. (2011). Slip safety analysis of differently surface processed dimension marbles. Journal of Testing and Evaluation, 39(3), 1–10. doi:10.1520/JTE103702

Sarışık, G. (2007). Technical characteristics of some turkish natural stones with calcium carbonate root and their...
usage fields on structure and restoration (pp. 20–66) (Masters Thesis). A.K.U, Institute of Sciences, Department of Mine Engineering, Afyon.

Sarıışık, G., Sarıışık, A., Koch, R., & Knoblauch, U. (2008). The analysis of permeability feature of some limestones on utilization qualit. In Proceedings of Turkey VI. Marble and Natural Stone Symposium (p. 335). (in Turkish).

Sharma, P. K., Khandelwal, M., & Singh, T. N. (2007). Variation on physico-mechanical properties of Kota stone under different wetery environments. Building and Environment, 42, 417–423. doi:10.1016/j.buildenv.2006.11.032

Sharma, P. K., & Singh, T. N. (2006). Effect of saline water on strength and durability of granite rock-a case study. Mining Eng. Jl., 8, 20–26.

Singh, T. N., Singh, S. K., Mishra, A., Singh, P. K., & Singh, V. K. (1999). Effect of acidic water on physico mechanical behaviour of rock. Indian Journal of Engineering and Materials Sciences, 6, 66–72.

Strandberg, L., & Lanshammar, H. (1981). The dynamics of slipping accidents. Journal of Occupational Accidents, 3, 153–162. doi:10.1016/0376-6349(81)90009-2

Şentürk, A., Gündüz, L., Tosun, Y. I., & Sarıışık, A. (1996). Marble Technology (in Turkish) (p. 250). Isparta: Tugra Press.

TS EN 14205. (2004). Natural stone test methods—determination of knoop hardness (p. 11). Ankara: Turkish Standards Institute.

TS EN 14231. (2004). Natural stone test methods—determination of the slip resistance by means of the pendulum tester (p. 13). Ankara: Turkish Standards Institute.

TS EN 1926. (2007). Natural stone test methods—determination of compressive strength (p. 10). Ankara: Turkish Standards Institute.

TS EN 1936. (2010). Natural stone test methods: Determination of real density and apparent density, and of total and open porosity (p. 13). Ankara: Turkish Standards Institute.

TS EN 12371. (2011). Natural stone test methods—determination of frost resistance (p. 8). Ankara: Turkish Standards Institute.

TS EN 1341-Ek C. (2013). Natural stone test methods—determination of abrasion resistance (p. 34). Ankara: Turkish Standards Institute.

TS EN 13755. (2014). Natural stone test methods—determination of water absorption at atmospheric pressure (p. 3). Ankara: Turkish Standards Institute.

TS EN 13161. (2014). Natural stone test methods—determination of flexural strength under constant moment (p. 17). Ankara: Turkish Standards Institute.

Vishal, V., Das, R., & Singh, T. N. (2012). Investigating the frictional response of granite rock surface: An experimental approach. Journal of the Geological Society of India, 80, 493–498. http://dx.doi.org/10.1007/s12594-012-0168-y

Wessex Catalog. (2010). Pendulum test equipment. Retrieved from http://www.wessex-medical.com/wessexcataloguesumme2010final.pdf