Influencing factors of measurement results of polished stone values of coarse aggregates

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Abstract. The polished stone value (PSV) of a coarse aggregate indicates its ability to resist the polishing action of tires. In the measurement tests of PSV of coarse aggregates, due to the complicated process, artificial factors or instrumental performances may cause measurement deviations. In order to explore the influences of instrumental factors, based on the features and working principle of a pendulum friction coefficient tester, the main influencing factors were firstly analyzed and then experimentally verified through measuring PSV of andesite and basalt. With the one-variable linear regression method, the testing data were fitted in order to determine the variations of the PSV of coarse aggregates with the hardness of rubber strip used in the slider block and the axial deformation distance of the slider block corresponding to the maximum positive static pressure on the tested surface. With the increase in the hardness of rubber strip, the measured PSV increased. With the increase in the axial deformation distance of slider block corresponding to the maximum positive static pressure on the tested surface, the measured PSV decreased. The quantitative analysis of the factors affecting PSV can improve its determination accuracy.

1. Introduction
Highway safety has always been concerned worldwide. The skid resistance of pavement is an important factor affecting highway safety. When the pavement is pressed, a coarse aggregate is usually used as the surface material. The indicators for evaluating the skid resistance and abrasion resistance of coarse aggregates mainly include polished stone value (PSV), aggregate abrasion value (AAV), impact value (LSV), and loss on ignition (LOI). PSV of a coarse aggregate indicates the ability of the pavement surface layer to resist the polishing action of tires and is a key indicator to measure the skid resistance of pavements. Typical measurement methods of skid resistance include pendulum friction coefficient tester method, sand patch method, and PSV test method [1]. Among these measurement methods, the pendulum friction coefficient tester method is the most common method. Based on the PSV attenuation curves of different coarse aggregates, the skid resistance of various coarse aggregates is determined so as to provide the basis for the selection of coarse aggregates.

In the testing procedure of the PSV of coarse aggregates in JTG E42-2005 Test methods of aggregates for highway engineering, many factors causing testing errors have been found [2]. Sample preparation steps (discharging materials, blowing sand, prefabricating parts, and curing), polishing steps with the sander (control of residual sand) and testing steps with the pendulum instrument (the sliding length of slider block on the specimen) affected measurement results [3]. In addition, the factors related to the
pendulum friction coefficient tester also directly affected measurement results, such as the hardness of
the rubber strip of slider block, axial deformation distance of slider block corresponding to the maximum
positive static pressure on the surface to be tested, maximum positive static pressure and ambient
temperature [4]. Previous studies focused on the external factors in the preparation process of coarse
aggregate specimens, but the instrumental performance factors have not been fully considered [5-6]. In
this study, the PSV of the coarse aggregate specimen was firstly tested under different performances of
the tester and then the variations of PSV were analyzed with the linear regression method. The testing
results proved that the performance of the pendulum friction coefficient tester largely affected the
measurement results. The study provides the basis for improving the measurement accuracy of PSV.

2. Influences of various factors on aggregate PSV

After an aggregate is polished with a sander, its PSV is measured as aggregate PSV with a pendulum
friction coefficient tester. The tester can be used to measure the friction coefficient of pavements and
the PSV of aggregates. The two indicators have the same measurement principle and different evaluation
methods. The units of friction coefficient and polished stone value are respectively BPN and PSV. In
the study, PSV was mainly measured with the pendulum friction coefficient tester. The core component
of the tester is a pendulum equipped with a slider block and placed in the center of a circular panel. In
the test, it is released from a certain height and the slider block moves in a circular direction relative to
the center of the instrument panel and drops to the lowest point, so that the slider block rubs against the
aggregate specimen. According to the law of conservation of energy, the PSV of the aggregate specimen
can be estimated. The measurement principle is shown in Fig. 1. The slider block is in contact with the
surface to be tested. If the influences of air resistance or mechanical friction is not considered, when the
pendulum swings downward freely from a certain height, the rubber strip contacts the tested surface and
slides for a certain distance. In the process, the energy lost caused by friction is equal to the gravitational
potential energy loss of the pendulum. According to the law of conservation of energy, a mathematical
model is established as follows:

$$\int_{S}^{N} \mu(x) dx = Mg (h_1 - h_2),$$  \hspace{1cm} (1)

where $\mu$ is the friction coefficient between the sliding block and the tested surface; $N$ is the positive static
pressure; $S$ is the friction distance; $M$ is the mass of the pendulum; $g$ is the local acceleration of gravity;
($h_1$-$h_2$) is the height difference of the hammer from the horizontal release position to the highest position
where the hammer reaches after passing through the friction surface, as shown in Figure. 1.

Since it is difficult to measure the height $h_2$ of the pendulum, the angle on the dial is used to indicate the
height of the pendulum:

$$h_1 = MgR(1 - \cos \alpha),$$  \hspace{1cm} (2)

$$h_2 = MgR(1 - \cos \theta).$$  \hspace{1cm} (3)

Figure. 1 Principle diagram of the pendulum friction coefficient tester.

The friction process between the pendulum and the aggregate specimen can be approximately
considered as a transient process, so the frictional work can be approximated as:
\[ \mu \int N(x) \, dx \approx \mu NS. \quad (4) \]

Therefore, the friction coefficient of the pendulum under ideal conditions is obtained as:

\[ \mu = \frac{Mg (\cos \theta - \cos \alpha)}{NS}. \quad (5) \]

According to Eq. (5), the working principle of the pendulum friction coefficient tester is simple, but the actual calculation process is more complicated. The positive static pressure \( N \) is usually replaced by the maximum forward static pressure and depends on multiple indicators of the slider block. The pressure between the rubber strip and the tested surface is undoubtedly the key factor. Taking into account the performance indicators of the slider block, the hardness of the rubber strip and the axial deformation distance of the slider block corresponding to the maximum positive static pressure directly affect the pressure between the rubber strip and the tested surface. According to the principle of the tester, the changes in the pressure result in different energy losses, thus affecting the measurement results of friction coefficient.

According to the measurement principle of Shore hardness [7], the larger the hardness value is, the harder the rubber strip is, and vice versa. Shore hardness is measured with a Shore hardness tester. In the measurement process, when a steel pin with a certain shape is pressed vertically into the specimen surface under the action of the testing force. When the surface of the pressing foot is completely attached onto the surface of the specimen, the protruding length of the tip of the pressing needle relative to the surface of the pressing foot is certain \( L \). Shore hardness is calculated as:

\[ HA = 100 - \frac{L}{0.025}. \quad (6) \]

The hardness value is only a measure of relative hardness, and cannot accurately describe the deformation of an object under the action of an external force. When the end of the pendulum rubs against a specimen, too large or too small hardness will affect the measurement result. If the hardness is too large, when the pendulum strikes the ground, the rubber strip is not fully deformed and the pressure between the pendulum and the ground increases. If the hardness is too small, the deformation of the rubber strip increases and the pressure between the rubber block and the specimen surface decreases.

According to JJG 053-2017 Verification regulation of pendulum friction coefficient testers, the maximum positive static pressure between the rubber strip and the tested surface is \((22.2 \pm 0.5)\) N and the corresponding axial deformation distance of slider block is \((4.0 \pm 0.1)\) mm. From Hooke's law, we know that within the linear elastic range of a material, the relationship between the stress and the strain in the material is a linear relationship:

\[ F = K \cdot \Delta Y. \quad (7) \]

In the normal working range, the elastic coefficient is a fixed value and a deformation corresponds to an external force. If the spring adjustment device of the pendulum friction coefficient tester is aged or the operation error is generated, the corresponding relationship between the axial deformation distance of sliding block and the maximum positive static pressure is changed. When the slider block rubs against the specimen, the actual pressure between them is changed, thus leading to a deviation in the measured friction coefficient.

In summary, the maximum positive static pressure between the rubber strip and the surface to be tested and the hardness of the rubber strip of slider block directly affect the pressure between the rubber strip and the tested surface as well as the measurement results of friction coefficient. Therefore, the experiment of measuring the PSV of coarse aggregates aims to explore the influences of the hardness of the rubber strip and the axial deformation distance of the slider block corresponding to the maximum positive static pressure on the PSV of coarse aggregates.

3. Experimental design and data analysis

In the experiment, two materials (andesite and basalt) were tested and 10 specimens were arranged. Among them, Specimens 1, 3, 4, 6, 7, 8, and 10 are andesite and Specimens 2, 5, and 9 are basalt, as shown in Figure. 2. According to JTG E42-2005 Test Methods of Aggregates for Highway Engineering),
test preparation, specimen preparation, specimen polishing and other procedures were carried out. Each specimen was measured 5 times and the difference between the maximum and minimum readings shall be no more than 3. The average value of 5 readings shall be taken as the PSV of corresponding specimen.

Figure. 2 Specimens of coarse aggregates.

3.1. Influences of hardness on measurement results of PSV

In order to explore the influences of the hardness of rubber strip on measurement results, several rubber strips with different hardness values were used to determine the PSV of each specimen for several times. The environmental temperature was 26 °C and the axial deformation distance of the sliding block corresponding to the maximum positive static pressure was 4 mm. Rubber strips with different Shore hardness (52 HA, 55 HA, 58 HA, and 62 HA) were used in the test. In order to reduce the influences of impact resistance, all the rubber blocks had been fully polished. The rubber strip with Shore hardness of 55 was set as the standard group.

The testing results are summarized in Table 1. The variations of PSVs of andesite and basalt with the Shore hardness of rubber strips are shown in Figure. 3.

Table 1 PSV of each specimen measured with various rubber strips with different hardness.

| Hardness (HA) | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 | Specimen 6 | Specimen 7 | Specimen 8 | Specimen 9 | Specimen 10 | Mean hardness of andesite | Mean hardness of basalt |
|--------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|-------------|--------------------------|------------------------|
| 52           | 23.1       | 20.2       | 24.9       | 27.0       | 22.5       | 25.9       | 26.9       | 26.9       | 22.6       | 26.0        | 25.81                   | 21.8                   |
| 55           | 23.4       | 20.2       | 25.0       | 27.2       | 23.0       | 26.5       | 27.4       | 27.3       | 23.3       | 27.0        | 26.26                   | 22.17                  |
| 58           | 24.8       | 20.9       | 25.7       | 28.0       | 23.8       | 27.0       | 27.9       | 28.2       | 24.6       | 27.6        | 27.03                   | 23.10                  |
| 62           | 26.8       | 22.7       | 26.9       | 30.5       | 25.9       | 28.5       | 29.9       | 30.1       | 26.0       | 28.6        | 28.76                   | 24.87                  |

Notes: Specimens 1, 3, 4, 6, 7, 8, and 10 are andesite; Specimens 2, 5, and 9 are basalt.

Figure. 3 Fitted curves of PSV in respect to hardness of rubber strips.
The PSVs of coarse aggregates (andesite and basalt) significantly increased with the hardness of the rubber strip (Table 1). The increasing trend was consistent with the estimated influence of the hardness of rubber strip on the measured PSV. In order to explore this trend quantitatively, the linear regression analysis was performed with the PSVs of the specimens and hardness values. Good linear regression curves could be obtained with the data of the specimens of andesite and basalt (Fig. 3). With the linear regression curves, the influences of hardness on PSV measurements could be quantified. According to the goodness-of-fit, the R² values of the two groups of data were about 0.95, indicating that the goodness-of-fit was extremely high. The analysis results also indicated that the PSVs of aggregates had a linear relationship with the hardness of rubber strip. With the increase in the hardness of rubber strip, the PSV of aggregates increased.

The error between the slopes of the fitting equations of two materials was about 5%, which was acceptable. Therefore, we believed that the slopes of the two materials were basically the same. In other words, the variations of PSV of coarse aggregates with the hardness of rubber strip had nothing to do with the material itself. Under the same circumstances, andesite had the larger PSV than basalt. In order to design highways with stronger skid resistance, andesite is recommended.

### 3.2. Influences of pressure on measurement results of PSV

In order to explore the influences of the axial deformation distance of slider block corresponding to maximum positive static pressure on the measurement results of PSV, the deformation distance was adjusted several times to determine the PSV of specimens. The environmental temperature was 26 °C and the Shore hardness of rubber strip was 55 HA. When the hanging weight method was used for instrument calibration, the axial deformation distance of slider block corresponding to the maximum static pressure was respectively set as 2 mm, 3 mm, 4 mm, 5 mm, and 6 mm for measuring PSV. The deformation distance of 4 mm was as the standard group.

The test results are provided in Table 2. Figure 4 shows the variations of the PSVs of andesite and basalt with maximum positive static pressure.

| Deformation (mm) | Specimen 1 | Specimen 2 | Specimen 3 | Specimen 4 | Specimen 5 | Specimen 6 | Specimen 7 | Specimen 8 | Specimen 9 | Specimen 10 | Mean hardness of andesite | Mean hardness of basalt |
|------------------|-----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|--------------------------|------------------------|
| 2                | 40.1      | 33.6       | 39.8       | 43.6       | 38.4       | 42.7       | 41.9       | 36.0       | 41.6       | 35.9       | 41.16                    | 38.93                  |
| 3                | 24.9      | 20.2       | 21.0       | 23.1       | 21.8       | 23.4       | 21.9       | 21.4       | 23.9       | 21.1       | 21.09                    | 22.22                  |
| 4                | 23.4      | 20.1       | 22.6       | 26.0       | 25.0       | 24.6       | 24.9       | 22.2       | 26.3       | 23.2       | 22.01                    | 22.17                  |
| 5                | 22.0      | 17.7       | 22.6       | 23.9       | 23.0       | 25.7       | 23.1       | 24.5       | 22.2       | 22.3       | 22.11                    | 19.37                  |
| 6                | 21.3      | 17.6       | 21.6       | 22.0       | 20.9       | 22.4       | 22.7       | 19.8       | 22.4       | 20.0       | 22.04                    | 19.00                  |

Notes: Specimens 1, 3, 4, 6, 7, 8, and 10 are andesite; Specimens 2, 5, and 9 are basalt.

Figure 4 Fitted curves of PSV in respect to axial deformation distance of slider block corresponding to the maximum static pressure.
The PSVs of coarse aggregates (andesite and basalt) significantly decreased with the axial deformation distance of slider block corresponding to the maximum static pressure (Table 1), but the decreasing magnitude was not regular. Linear regression analysis was performed with the PSVs of the specimens and the axial deformation distance of slider block corresponding to the maximum static pressure. The linear regression curves could be obtained with the data of the specimens of andesite and basalt (Fig. 4). According to the goodness-of-fit, the $R^2$ values of the two groups of data were about 0.60, indicating that the goodness-of-fit was moderate. The error between the slopes of the fitting equations of two materials was about 10%. When the deformation distance increased from 2 mm to 3 mm, the PSV was decreased by 43.9%. When the deformation distance increased from 3 mm to 6 mm, the PSV was decreased by 10%.

When the maximum positive static pressure was constant, the corresponding axial deformation distance of slider block directly affected the pressure between the rubber strip and the tested surface, thus resulting in the deviations in measurement results of PSV. The above variations of PSV with the axial deformation distance of slider block might be interpreted as follows. In the test of the anti-friction ability of coarse aggregates, it is necessary to consider both the macroscopic and microscopic properties of aggregates and the surface texture of an aggregate is determined by various factors such as the type of aggregate rock, diagenesis mechanism and crushing mechanism [8]. The surface of an aggregate was uneven and the rubber strip was softer than the aggregate. As mentioned above, when the rubber strip contacted the aggregate, it deformed, wrapped or filled the protrusions or depressions on the surfaces of aggregates [9]. Therefore, when the pressure was small (deformation distance = 2 mm), the deformation of the rubber strip was not enough to fully contact the surface of an aggregate, so the adhesive friction force did not peak. When the deformation distance increased from 2 mm to 3 mm, the adhesive friction gradually increased and the PSV also decreased. When the deformation distance was 3 mm, the rubber strip and the aggregate were in full contact and the adhesive friction peaked. When the deformation distance corresponding to the maximum positive static pressure further increased, only the sliding friction increased, so the slope decreased.

4. Conclusion and prospect
In the study, we mainly explore the influences of the hardness of the rubber strip of slider block and the maximum positive static pressure on the measurement results of the PSV of coarse aggregates. Firstly, the influencing factors were analyzed based on the principle of the pendulum friction coefficient tester. Then, rubber slider blocks with different hardness and different maximum static pressures were selected to carry out the PSV measurement experiment on andesite and basalt pavements. According to the experimental results, the linear regression analysis was performed. The analysis results are summarized as follows. Firstly, the hardness of rubber strip had a significant effect on the measurement result of PSV. PSV increased with the increase in the hardness of rubber strip. Secondly, PSVs of andesite and basalt showed the consistent variation with the hardness of rubber strip and maximum positive static pressure. Under the same conditions, andesite had the stronger resistance to tire polishing. The study results can be used to decrease measurement errors of PSV.

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