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Article

An Investigation of the Polishing Behavior of Calcined Bauxite Aggregate

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Abstract: The application of top-grade calcined bauxite to improve the skid resistance of pavement surface coatings increases construction costs and causes excessive tire wear. Therefore, it is necessary to investigate the polishing behavior of different grades of calcined bauxite aggregate. The polished stone value of calcined bauxite was measured after the standard polishing time and the extended polishing time. The Los Angeles (L.A.) abrasion and the crushing value, profile roughness, hardness, X-ray diffraction, and micromorphology were also tested. The results showed that the calcined bauxite above 75# (the ratio of corundum to mullite by weight, C/M > 1) satisfied the requirement of the ultra-thin friction course. Compared with basalt, the calcined bauxite above 80# (C/M > 3) has better long-term skid resistance, even though the pavement surface is subject to heavier traffic. Due to the higher cohesion of lower porosity, more hard minerals to keep the surface roughness, and less soft minerals to smooth the surface roughness, calcined bauxite with a higher corundum content has the better skid resistance. There is a power law relationship between C/M and Polished Stone Value (PSV). Considering the diminishing returns of higher-grade calcined bauxite, it is necessary to accurately select the appropriate C/M of calcined bauxite before use in pavement surface coatings.

Keywords: pavement surface coatings; ultra-thin friction course; calcined bauxite; polished stone value; skid resistance

1. Introduction

Adequate skid resistance of pavement is necessary to ensure traffic safety [1]. Previously, a lot of studies have been carried out to study new functional surface layers with high skid resistance. Geng [2] utilized basalt in a dense graded ultra-thin wearing course mixture to improve the skid resistance of pavement. Feng [3] found that wearing course mixtures prepared with waste ceramic aggregates have better skid resistance than traditional wearing course mixtures. Ovidijus [4] evaluated the surface friction performance of the wearing course mixture with Dolomite aggregates. It is found that, as they account for more than 90% of the total pavement materials, aggregates directly affect the skid resistance of a road surface. Therefore, lots of natural and artificial aggregates with a high polishing stone value (PSV) were widely used in the wearing course for improving skid resistance.

Calcined bauxite was produced by sintering high-alumina bauxite in rotary, round, or shaft kilns at high temperatures [5]. At present, calcined bauxite is not widely used in pavement engineering. Only calcined bauxite with a very high alumina content can be used in polyester resin-based high-friction surface treatments (HSFT) to improve the friction of the pavement surface [6]. According to the specifications in AASHTO PP 79-14, the minimum alumina content in calcined bauxite used for HSFT is 87% [7]. Bauxite is abundantly mined in China, accounting for 77% of global storage and including various grades of calcined bauxite [8]. The calcined bauxite used in road engineering in the United States is mainly imported from China. The minimum requirement for alumina content in calcined bauxite in the AASHTO PP 79-14 specification is direct references the alumina content requirements of Class A calcined bauxite in the Chinese refractory specification, which is not based on the requirements of road performance [9,10]. Meanwhile, according to the estimation of world reserves of aluminum ores, high-grade bauxite accounts for a small proportion of the total [11]. Higher-grade bauxite is more expensive, and excessive skid resistance of pavement can also give rise to excessive tire wear. It is neither economical nor environmentally friendly to use only very-high-grade calcined bauxite in pavement engineering. Heitzman [12] evaluated the skid resistance of alternative aggregate sources (basalt, granite, flint, silica sand, steel slag, emery, and taconite) to determine if they had a similar performance to calcined bauxite. Li [10] found that the AASHTO specifications may be too stringent and thus may not adequately describe the real variability of the calcined bauxite. Therefore, to widen the scope of application in pavement engineering, lower the construction costs, and extend the lives of tires, it is necessary to understand the long-term polishing behavior of calcined bauxite for pavement surface coatings. However, few studies have reported on this.

In this paper, the polishing behavior of different grades of calcined bauxite aggregate for pavement surface coatings is investigated. The skid resistance of different grades of calcined bauxite is tested by PSV tests. The destruction mechanism of calcined bauxite under the polishing process is analyzed. The influence of mineral components of calcined bauxite on long-term skid resistance is also discussed.

2. Materials and Methods

2.1. Materials

In order to evaluate the effects of different grades of calcined bauxite on the polishing behavior, six types of calcined bauxite, including grades 90, 85, 80, 75, 70, and 65, were used in this study. The main chemical composition of calcined bauxite was tested with X-ray fluorescence analysis and is shown in Table 1. As coarse aggregates commonly used in pavement surface coatings, basalt and limestone were also chosen for a comparison of polishing performance with calcined bauxite. The physical properties of basalt and limestone aggregates meet the Chinese standard specifications (JTG F40-2017) for the construction of highway asphalt pavements, as shown in Table 2.

Table 1. Main chemical composition of calcined bauxite.

Grade	Al_2O_3	SiO_2	TiO_2	TFe_2O_3	MgO	CaO	K_2O	Na_2O
90#	90.14	3.32	4.47	1.55	0.15	0.17	0.17	<0.01
85#	84.36	9.35	3.87	1.78	0.17	0.35	0.11	<0.01
80#	81.29	12.84	3.51	1.01	0.13	0.08	0.06	<0.01
75#	75.51	19.59	3.29	1.12	0.16	0.3	0.18	<0.01
70#	70.53	25.31	2.32	1.45	0.22	0.17	0.14	0.03
65#	66.32	29.12	2.02	1.54	0.19	0.21	0.16	0.04

Table 2. Physical properties of basalt and limestone aggregates.

Type	Specific Gravity (g/cm^3)	Crushing Value (%)	L.A. Abrasion (%)
Basalt	2.87	11.52	12.92
Limestone	2.68	22.69	20.13
Standard specification	≥2.6	≤26	≤28

2.2. Test Methods

2.2.1. PSV Test

PSV test was used to evaluate the skid resistance coefficient of aggregates using in the pavement surface coatings [13]. The PSV test of aggregates was usually divided into the following three steps according to Chinese standard JTG E42-2005 [14].

(1) Sample preparation

Curved samples were prepared with the standard mold. The size of the specimen is 91 mm × 45 mm × 16 mm and it is curved to fit on a surface with a 203 mm radius of curvature. First, aggregates with sizes of 9.5–13.2 mm were closely arranged in the mold. Then, epoxy mortar was used to fill up the mold. The epoxy mortar was prepared by mixing epoxy resin and sand with a particle size of less than 0.3 mm. The specimens were cured at 40 °C for 3 h, cooled for 9 h at room temperature, and demolded. Four specimens were prepared for each aggregate.

(2) Accelerated polishing test

An accelerated polishing machine consisting of a road wheel and a loaded rubber tire was used to simulate the polishing action of vehicle tires on the aggregate. Fourteen specimens, including 12 test specimens and two standard specimens clamped around the wheel and a rubber tire, were placed on the wheel with 725 N force. The outer diameter of the road wheel was 406 mm and the rotation speed was 320 r/min. The polishing process of aggregates was divided into two stages. First, No. 30 brown corundum coarse sand was used to polish the specimens for 3 h. Then, No. 280 green silicon carbide fine sand was used to polish the specimens for 2 h. To simulate heavier traffic, the specimens continued to be polished with No. 280 green silicon carbide fine sand for 5 h.

(3) Determination of PSV value

After the standard polishing and extended polishing, the specimens were immersed in water at 20 °C for 2 h. The value of PSV was tested with the Pendulum Skid Resistance Tester (Wuxi JianYi Experiment Instrument Co., Ltd., Wuxi, China), which has been calibrated according to the Chinese standard specification of a JGG 053-2017 pendulum friction tester. Each specimen had this test repeated five times. The value of PSV is determined using Equation (1). PSV was rounded to the nearest integer.

$$PSV = PSV_{\mathrm{ra}} + 49 - PSV_{\mathrm{bra}}, \tag{1}$$

where PSV is the polished stone value of aggregate, British Pendulum Number (BPN); PSV_{ra} is the average polishing value of four test specimens, BPN; and PSV_{bra} is the average polishing value of four standard specimens, BPN.

2.2.2. Profile Roughness Measurement

Surface topography plays an important role in tribology. Profile roughness parameters are often used to describe surface topography characterization [15]. After the standard polishing and extended polishing, the profile roughness parameters of polished specimens were tested with 3D color laser microscope system. Five spots were selected on each surface. The measurement area at each spot is 700 um × 500 um. Figure 1 illustrates 3D profile of 90# calcined bauxite. The profile roughness parameters is measured and calculated by a VK-Analyzer (Keyence Corporation, Osaka, Japan), which is software used in a 3D color laser microscope system.

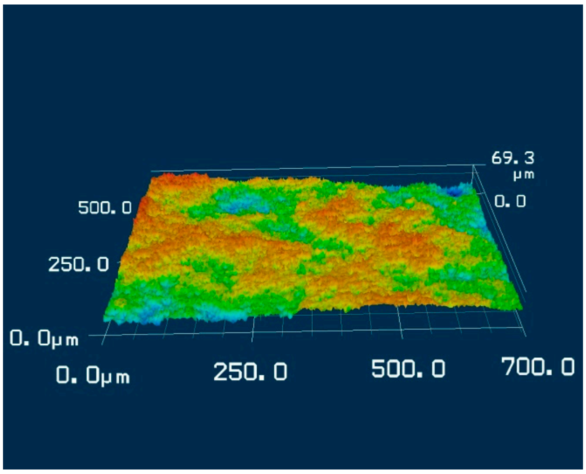


Figure 1. 3D profile of 90# calcined bauxite after the polishing process.

There are six typical profile roughness parameters in total, as follows: arithmetic mean roughness, maximum height, root mean square height, skewness, kurtosis, and load length ratio. According to the findings of Guan and Qian, root mean square height (R_q) was selected to evaluate the surface of aggregates after polishing [16,17]. Root mean square height (R_q) indicates the root mean square along the reference length, as illustrated in Figure 2. R_q is calculated using Equation (2):

$$R_q = \sqrt{\frac{1}{N}\sum_{n=1}^{N} Z_n{}^2} \tag{2}$$

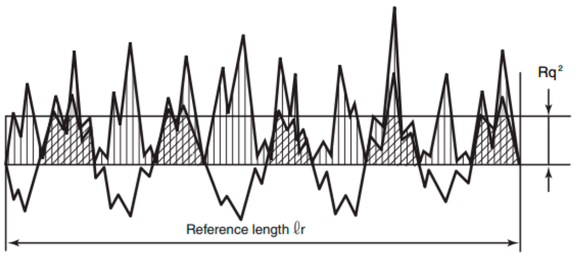


Figure 2. Illustration of R_q.

2.2.3. Vickers Hardness Test

The Vickers hardness was obtained by testing the polished surfaces. First, the aggregate substrates were cut to a thickness of about 1 cm from the rock using mechanical diamond saws, and the surfaces of the aggregate substrates were polished using 280 grade silicon carbide grits. The surface residue of the substrates was cleaned using an ultrasonic cleaner. Then, the aggregate substrates were dried at 150 °C for 1 h. An optical measurement system was used to measure the Vickers hardness. The aggregate substrates were placed on the testing platform. The diamond indenter was pressed into the aggregate surface at an angle of 136° and a full load with 10 kg was typically applied for 15 s. After removal of the load, the two diagonals of the indentation remaining on the surface were measured and their average values are calculated. For example, the average length of the diagonal left of 90# calcined bauxite was measured by a Nano Measurer, which is shown in Figure 3. It can be seen from Figure 3 that different colors were used to show changes in elevation. Because the surface is difficult to smooth completely by polishing, there is an elevation difference. The red area represents the higher elevation and the blue area represents the lower elevation.

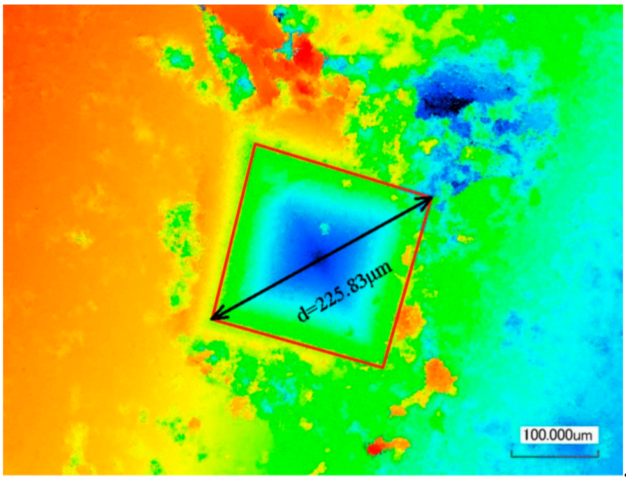


Figure 3. Vickers hardness test process of 90# calcined bauxite.

The area of the sloping surface of the indentation is determined using Equation (3). Five spots were tested on each surface.

$$H = \frac{2F \sin \frac{136^{\circ}}{2}}{d^2} = 1.854 \frac{F}{d^2}, \quad (3)$$

where H is the Vickers hardness (kg/mm^2), F is the force applied to the diamond (kg), and d is the average length of the diagonal left by the indenter (mm).

2.2.4. Water Absorption Test

Two kilograms of washed aggregate (9.5–13.2 mm in size) were placed in the wire basket and immersed in distilled water at room temperature for 24 h. Aggregates were completely surface-dried using absorbent cloths. The aggregate was placed in an oven at a temperature of 110 °C for 24 h. The water absorption was calculated using Equation (4):

$$Water\ absorption = \frac{W_1 - W_2}{W_2} \times 100\%, \quad (4)$$

where W_1 is the weight of the saturated surface dry aggregate in air, kg; and W_2 is the weight of oven dry aggregate, kg.

2.2.5. X-ray Diffraction Analyses

X-ray diffraction analyses (XRD) were carried out using an AXS D8 ADVANCE X-ray diffractometer (Bruker Corporation, New York, NY, USA). The powders of different aggregates of uniform size passing through a 90-micron sieve were scanned using Cu Kα X-ray (40 kV, 40 mA) from 10 to 50 2θ (degrees) with a step size of 0.03° (2θ) and a scan step time of 0.6 s.

2.2.6. Micromorphology

The micromorphology of the aggregate surface before and after polishing was characterized with scanning electron microscopy (SEM, S-4800; Hitachi, Tokyo, Japan), with a gold coating at room temperature.

2.2.7. Crushing Value Test

Three kilograms of aggregate (9.5–13.2 mm in size) were placed in a steel cylinder 15 cm in diameter with a plunger and base plate and subjected to a 400 kN load under standardized conditions according to Chinese standard JTG E42-2005. The crushing value is calculated using Equation (5):

$$Crushing\ value = \frac{M_1}{M_2} \times 100\%, \tag{5}$$

where M_1 is the weight of the fraction passing through the 2.36-mm sieve, kg; and M_2 is the weight of dry sample, kg.

2.2.8. L.A. Abrasion Test

The L.A. abrasion loss was tested using a Los Angeles Testing Machine. C gradation of aggregate was used in this test. According to the Chinese standard JTG E42-2005, the L.A. abrasion test parameters of C gradation of aggregate were as follows: (1) The size of the aggregate is 9.5–13.2 mm. (2) The weight of the aggregate is 5 kg. (3) The number of steel spheres is eight. (4) The weight of the steel spheres is 3.3 kg. (5) The number of rotations is 500 times. The test process is as follows: 5 kg of aggregate (9.5–13.2 mm in size) were placed in a rotating steel drum containing eight steel spheres weighing 3.3 kg each, and the steel drum was rotated at 30–33 rpm. After the aggregate was subjected to 500 rotations of the drum, the L.A. abrasion loss was calculated using Equation (6):

$$L.A.\ \text{abrasionloss} = \frac{W_1}{W_2} \times 100\%, \tag{6}$$

where W_1 is the weight of fraction passing through the 1.7-mm sieve, kg; and W_2 is the weight of the dry sample, kg.

3. Results and Discussion

3.1. Variation of PSV of Different Grades of Calcined Bauxite

The results of PSV testing are shown in Figure 4. PSV values after the standard time and the extended 5 h are shown in Table 3. By comparison, the PSV values of aggregate after polishing in the standard time are ranked as follows: 90# calcined bauxite > 85# calcined bauxite > 80# calcined bauxite > 75# calcined bauxite > Basalt > 70# calcined bauxite > limestone > 65# calcined bauxite. According to the PSV value results of different grades, a decrease in the alumina content will cause attenuation of the PSV. For example, compared with PSV of 90# calcined bauxite, PSV of 85# calcined bauxite is decreased by 6%. The PSV of aggregate in the ultra-thin friction course should be greater than 42BPN according to the Chinese standards [18,19]. The PSV values of 90# calcined bauxite, 85# calcined bauxite, 80# calcined bauxite, 75# calcined bauxite, and basalt meet this requirement. For calcined bauxite, the PSV increases as the alumina content increases. Calcined bauxite with a higher alumina content has a higher value of PSV. It can also be seen in Figure 4 that during the extended period of polishing, the PSV values of calcined bauxite first decreased and then stabilized. Six grades of calcined bauxite, basalt, and limestone exhibited approximately the same PSV development trend. The PSV values of aggregate after polishing for the extended 5 h are ranked as follows: 90# calcined bauxite > 85# calcined bauxite > 80# calcined bauxite > Basalt > 75# calcined bauxite > 70# calcined bauxite > 65# calcined bauxite > Limestone. It is noted that after the extended polishing time, basalt is lower than the minimum requirement of PSV for the ultra-thin friction course. Calcined bauxite above 80# has greater values of PSV in the stabilization stage than the Chinese requirement for aggregate using in the ultra-thin friction course. It indicates that compared with basalt, which is a good rock type for pavement surface coatings, calcined bauxite above 80# has better long-term skid resistance, even though the pavement surface is subject to heavier traffic. In China, limestone that meets the standard requirements is also used in the wear course for skid resistance. However, it can be seen from Table 3 that, compared to other aggregates, limestone had the largest reduction in PSV value, a drop of 20%. Therefore, limestone is not suitable for pavement requiring long-term skid resistance performance or pavement with heavier traffic.

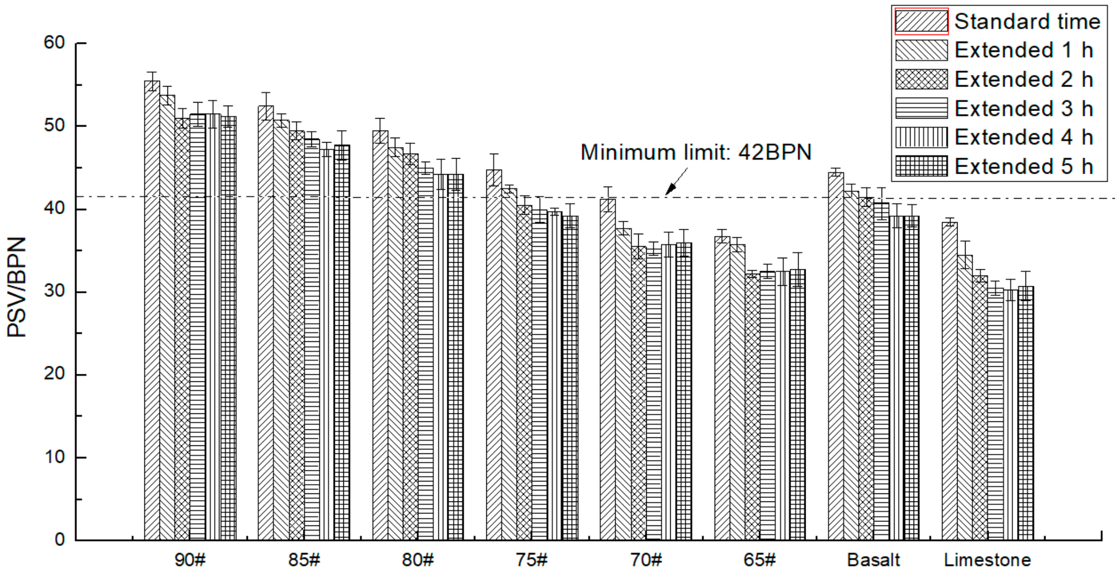


Figure 4. PSV values of aggregates after standard time and extended time.

Table 3. PSV values after standard time and extended 5 h.

Type	Standard Time		Extended 5 h	
	Average (BPN)	St. Dev.	Average (BPN)	St. Dev.
90#	55.5	1.11	51.3	1.29
85#	52.5	1.66	47.8	1.79
80#	49.5	1.50	44.3	1.92
75#	44.8	1.92	39.3	1.48
70#	41.3	1.48	36.0	1.58
65#	36.8	0.83	32.3	2.05
Basalt	44.5	0.50	39.5	1.50
Limestone	38.5	0.50	30.8	1.76

3.2. Polishing Mechanism of Calcined Bauxite Aggregate

It can be seen in Figure 4 that the PSV values of 90# calcined bauxite, 85# calcined bauxite, 80# calcined bauxite, 75# calcined bauxite, 70# calcined bauxite, 65# calcined bauxite, basalt, and limestone decreased by 7.6%, 8.9%, 10.5%, 12.3%, 12.8%, 14.2%, 11.2%, and 20.0%, respectively, after the extended 5 h polishing time. The reason for the deterioration in skid resistance of aggregate is that rough and angular aggregate particles are polished smooth by the rubber slider [20]. Vickers hardness is often used to evaluate the resistance of a sample to material deformation due to the load. It may be related to the attenuation of PSV caused by the change in the form, angularity, and texture of the aggregate. Data on the Vickers hardness of different aggregates are shown in Table 4. The correlations between the attenuation of PSV and Vickers hardness were studied by mathematical fitting, as illustrated in Figure 5. Figure 5 shows that there is a power law relationship between the attenuation of PSV and Vickers hardness. This shows that the greater the Vickers hardness, the smaller the attenuation of the skid resistance. Due to its larger Vickers hardness, the surface texture and angularity of the aggregate cannot be destroyed easily by the polishing action. This may be why the attenuation of PSV of higher grades calcined bauxite is smaller. The high Vickers hardness of aggregates can stabilize the angularity and texture of aggregates and retard the frictional attenuation during the long-term polishing process.

Table 4. Vickers hardness of different aggregates.

Type	Average (kg/mm^2)	St. Dev.
90#	1721	82
85#	1350	48
80#	1248	54
75#	817	69
70#	687	74
65#	458	44
Basalt	683	40
Limestone	397	26

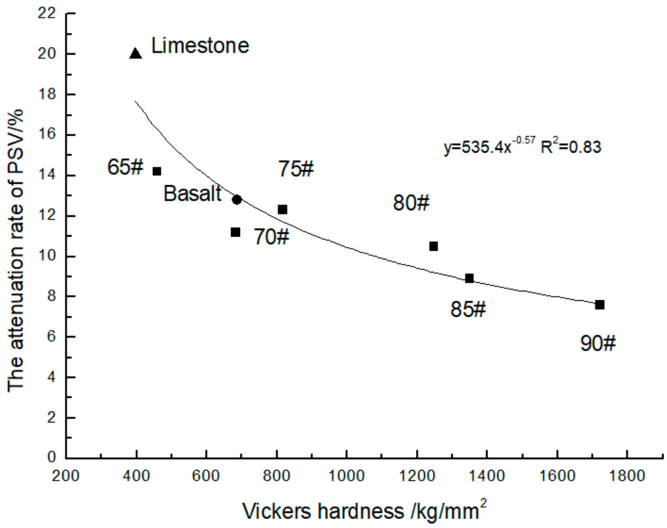


Figure 5. The relationship between Vickers hardness and the attenuation of PSV.

The mineral components of aggregates affect the hardness properties [21]. The main mineral components of aggregates and the Mohs hardness of the aggregates are shown in Table 5. Higher Vickers hardness mostly equates to higher Mohs hardness. For example, the main mineral components of limestone are calcite and dolomite, and their range of Mohs hardness is 3–4. The main mineral components of calcined bauxite are corundum and mullite, and their Mohs hardness is 8.5–9 and 6–7, respectively. Due to the higher Mohs hardness of the main mineral components, the Vickers hardness of calcined bauxite is much greater than the Vickers hardness of limestone. It is worth noting that, although the Mohs hardness of corundum and mullite in the 65# calcined bauxite is larger than that of plagioclase, augite, and olivine in the basalt, the Vickers hardness of the 65# calcined bauxite is smaller than that of the basalt. This indicates that the hardness of aggregates depends not only on the hardness of the mineral components, but also on the lower cohesion of higher porosity between the minerals [22]. The water absorption values of different aggregates are shown in Figure 6. The water absorption value of 65# calcined bauxite is 5.5 times that of basalt. This implies that, due to the larger porosity, the cohesion of 65# calcined bauxite is lower than that of basalt. The lower cohesion of the low-grade calcined bauxite may be the reason for the low Vickers hardness. To gain a better understanding of the influence of mineral components of calcined bauxite on the hardness, XRD analyses of aggregates were carried. The results are shown in Figure 7. The main mineral components of the aggregates were determined using Jade 5.0 software. The mineral content is calculated with X’Pert High Score Plus software (Version 2.0). The main mineral components of calcined bauxite are shown in Table 6. C/M is the ratio of corundum to mullite by weight. A higher value of C/M of calcined bauxite indicates a higher Vickers hardness, which is calculated from the mineral components of calcined bauxite in Table 6. The reason is that calcined bauxite with a higher C/M has a higher content of corundum than calcined bauxite with lower C/M. Meanwhile, calcined bauxite with higher C/M has a higher cohesion of lower porosity. Figure 8 shows that there is a power law relationship between C/M and Vickers hardness.

Table 5. Main mineral components and the Mohs hardness of aggregates.

Type of Aggregate	Mineral Components	Mohs Hardness
Calcined bauxite	Corundum	8.5–9
	Mullite	6–7
Basalt	Plagioclase	6–6.5
	Augite	5.5–6
	Olivine	6.5–7
Limestone	Calcite	3–4
	Dolomite	3–4

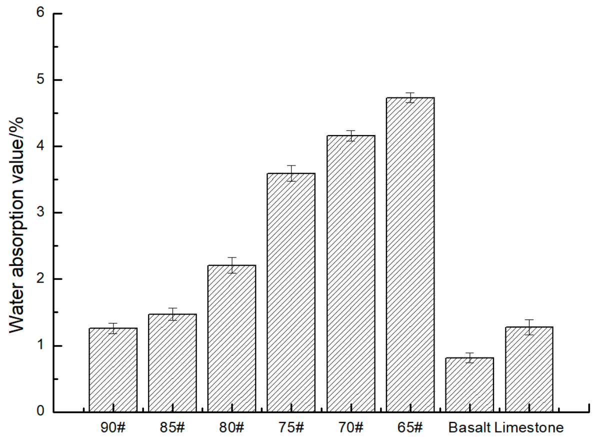


Figure 6. Water absorption values of different aggregates.

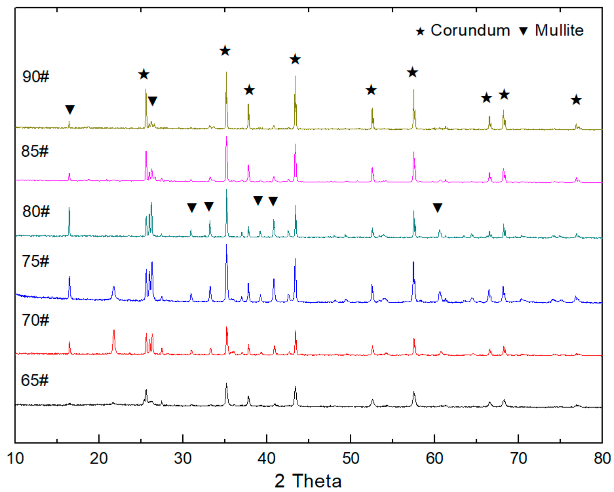


Figure 7. XRD patterns of calcined bauxite.

Table 6. Main mineral components of calcined bauxite.

Grade	Mineral Components (%)		C/M
	Corundum (C)	Mullite (M)	
90#	86	14	6.14
85#	78	22	3.55
80#	76	24	3.17
75#	50	50	1.00
70#	36	64	0.56
65#	27	73	0.37

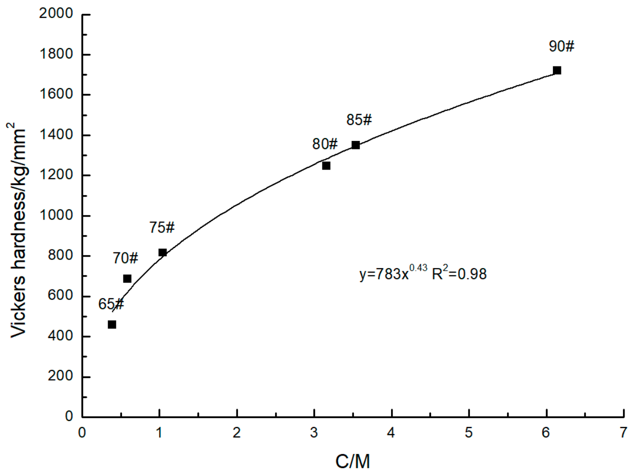
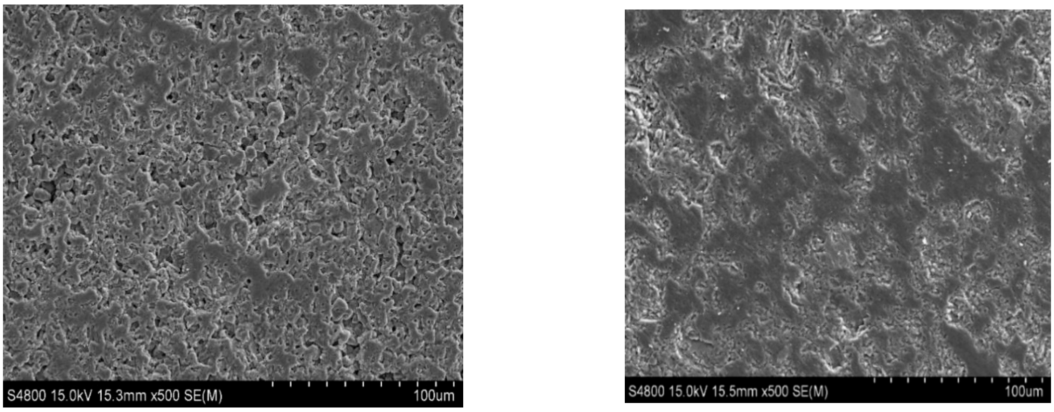


Figure 8. The relationship between C/M and Vickers hardness.

Figure 9 shows the change in the surface of 90# calcined bauxite aggregate before and after polishing. It can be seen that the pores on the surface of the calcined bauxite are filled and the surface becomes smoother. The surface of calcined bauxite consists of two parts: a polished area and a nonabrasive area. In order to analyze the composition of the polished and nonpolished areas, Figure 9b was magnified four times and Figure 10 was obtained. The SEM-EDS images of polished area and unpolished area are shown in Figure 11. The broken crystal powders are used to fill in the pores to form a smooth surface. Its main crystal composition is a large amount of mullite and a small amount of corundum. The hardness of mullite is lower than that of corundum. Therefore, mullite in the calcined bauxite is a "soft mineral" and corundum in the calcined bauxite is a "harder mineral". The soft mineral (mullite) with low hardness is easily destroyed by the polishing action. The destroyed mineral of calcined bauxite can be divided into two parts: one part is detached from the aggregate surface, and the other part becomes powders that are used to fill in the pores of the aggregate surface. Lots of soft minerals were destroyed and particles were embedded in the pores, which will form a new surface microtexture with the harder mineral. The microtexture of the new surface will provide skid resistance. Due to the sustained polishing action, the harder mineral (corundum) was also slowly destroyed. When harder minerals (corundum) were destroyed to a certain degree, the soft mineral (mullite) was subjected to polishing and destroyed. A new surface microtexture was formed again, similar to the previous surface microtexture. This process was repeated during the polishing process. The destruction and recovery of the surface microtexture are shown in Figure 12.



(**a**) (**b**)

Figure 9. Micromorphology of 90# calcined bauxite surface (×500): (**a**) before the polishing process; (**b**) after the polishing process.

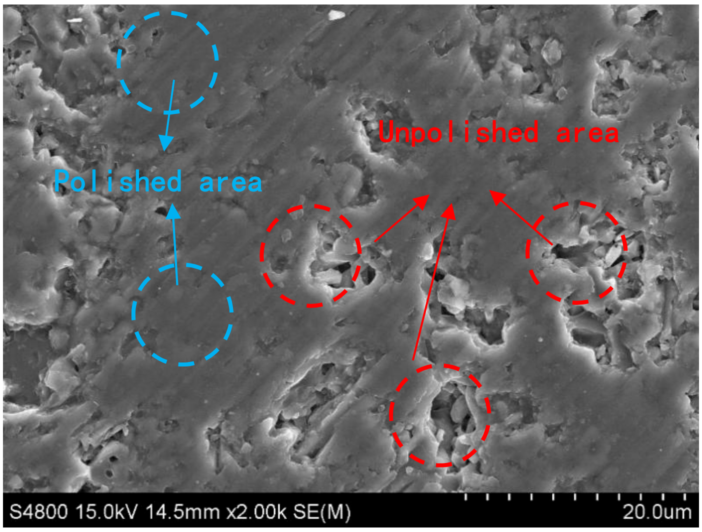
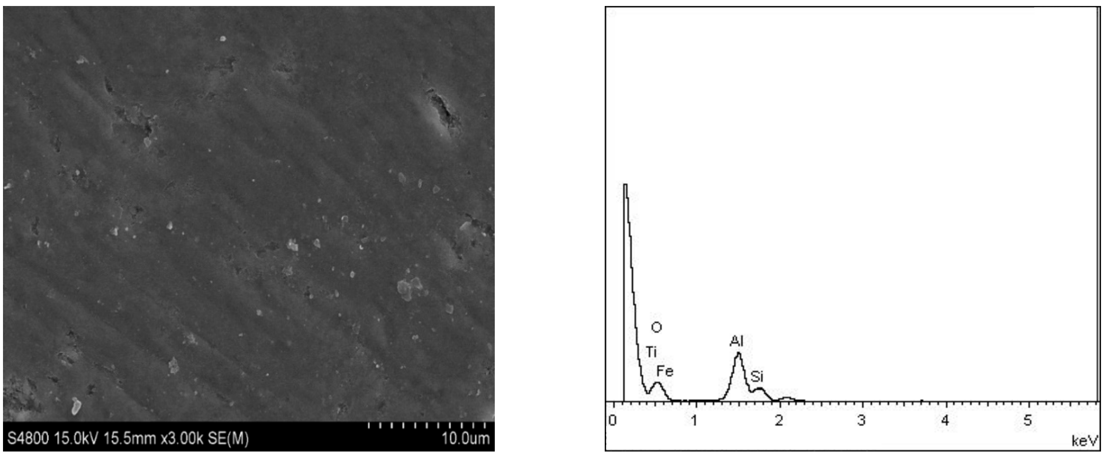


Figure 10. Micromorphology of 90# calcined bauxite surface after polishing (×2000).



(**a**) SEM image of polished area. (**b**) EDS analysis of polished area

Figure 11. SEM-EDS images of polished area.

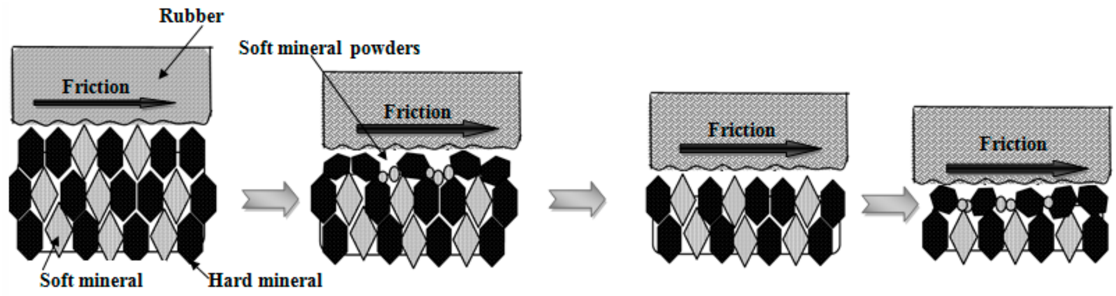


Figure 12. Destruction and recovery of surface microtexture.

According to the findings of Wang, the microtexture of the aggregate surface plays a major role in the skid resistance of aggregates [23]. R_q is a good indicator to evaluate the microtexture of a surface [15]. Figure 13 shows the mean value and standard deviation of R_q of aggregates after an extended 3 h, 4 h, or 5 h of polishing time. The small standard deviation of R_q indicates that the values of R_q of aggregate after the extended 3 h, 4 h, or 5 h of polishing time are similar, and also proves the recovery of the microtexture of the aggregate surface. It can also be seen in Figure 13 and Table 5 that, for the different aggregates (90# calcined bauxite, 85# calcined bauxite, 80# calcined bauxite,75# calcined bauxite, basalt, and limestone), the higher the hardness difference of minerals in the aggregate the rougher the surface texture, which is consistent with Wang's findings [23]. However, it is also noted that the R_q of 70# and 65# calcined bauxite is lower than that of basalt. This indicates that the surface texture is not only related to the hardness difference between soft minerals and hard minerals, but also to the cohesion. Due to the lower cohesion of higher porosity, more powders filled in the pores of the aggregate surface to make the surface smoother. In other words, the higher cohesion of lower porosity is beneficial for maintaining the skid resistance of the aggregate after polishing.

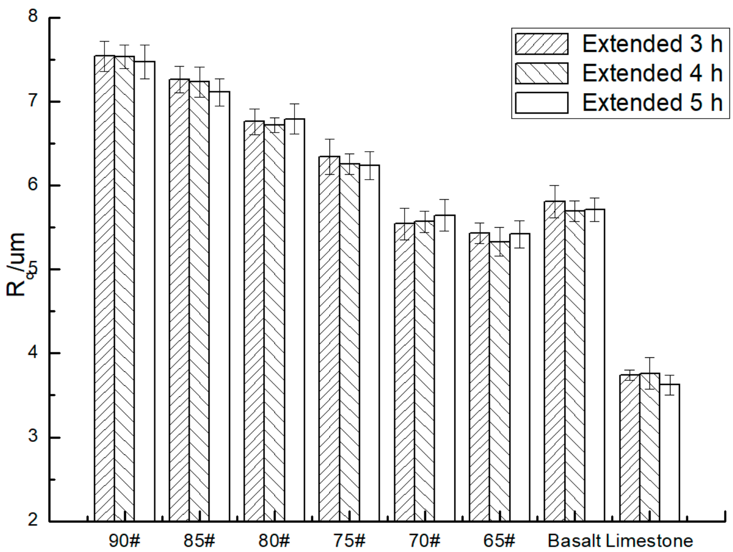


Figure 13. The value of R_q after the extended 3 h, 4 h, and 5 h polishing times.

3.3. *Effect of C/M on the Polishing Behavior of Calcined Bauxite*

Based on the above discussion, the attenuation of PSV is related to the microhardness, and PSV is related to the hardness difference and cohesion of minerals in the aggregate. In other words, the mineral components and cohesion of the aggregate determine the polishing behavior of the aggregate. Chinese standards YB/T 5179-2005 [10] and AASHTO PP 79-14 [7] specify the chemical composition of calcined bauxite. However, compared with the chemical composition, the mineral components of calcined bauxite are susceptible to many factors such as the type of kiln, type of fuel, flame temperature, feed amount, and feed speed, which will lead to changes in the physical properties. Meanwhile, minerals' atomic structure and physical properties directly affect the physical properties of aggregates [24]. Therefore, as the main mineral components of calcined bauxite, C/M is selected as an indicator for evaluating the calcined bauxite aggregate used in pavement surface coatings. Figure 14 shows that there is a power law relationship between C/M and PSV (Standard time). PSV is proportional to the value of C/M raised to the 0.14 power. The value of PSV increases rapidly and then increases slowly as the value of C/M increases. L.A. abrasion loss and the crushing value are also key indicators for evaluating the aggregates used in the pavement surface coatings. The results of L.A. abrasion testing and the crushing value tests are shown in Figures 15 and 16. From Figures 15 and 16, it can be seen that the L.A. abrasion loss and the crushing value increase as the grade of the calcined bauxite decreases. The relationships between C/M and L.A. abrasion loss, and the crushing value, are established as shown in Figures 17 and 18, respectively. Figures 17 and 18 show the power law relationship between C/M and L.A. abrasion loss, and the crushing value. L.A. abrasion loss and the crushing value are both inversely proportional to the value of C/M raised to the 0.27 and 0.4 power, respectively. The values of L.A. abrasion loss and crushing value decrease rapidly and then decrease slowly as the value of C/M increases. It can also be noted from the variation of physical properties (PSV, L.A. abrasion loss, and crushing value) with the increase in value of C/M that, after C/M reaches 1, the improvement of these physical properties gradually decreases. The L.A. abrasion loss and the crushing value of the aggregate used in the ultra-thin friction course should be smaller than 15% and 26% according to the Chinese standards. Considering the diminishing returns of higher-grade calcined bauxite, C/M = 1 (75# calcined bauxite) is the appropriate value of calcined bauxite used in the ultra-thin friction course according to the requirements of PSV, L.A. abrasion loss, and crushing value. If there is a requirement of long-term skid resistance or an expectation of heavier traffic for pavement surface coatings, the value of C/M should be larger than 3.

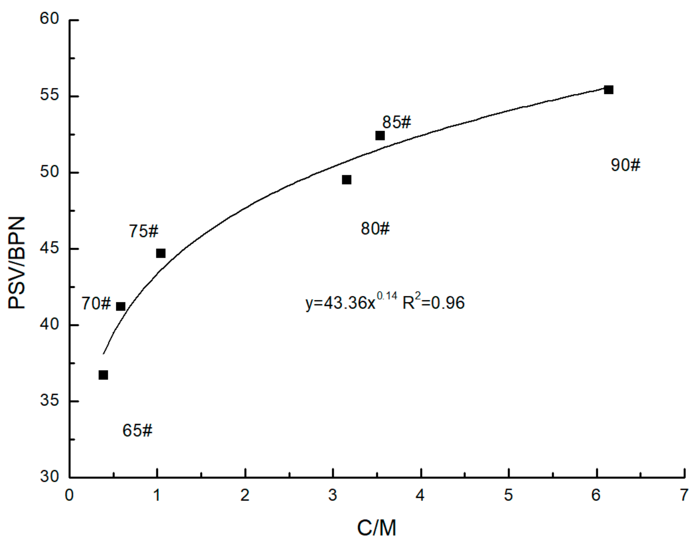


Figure 14. The relation between C/M and PSV.

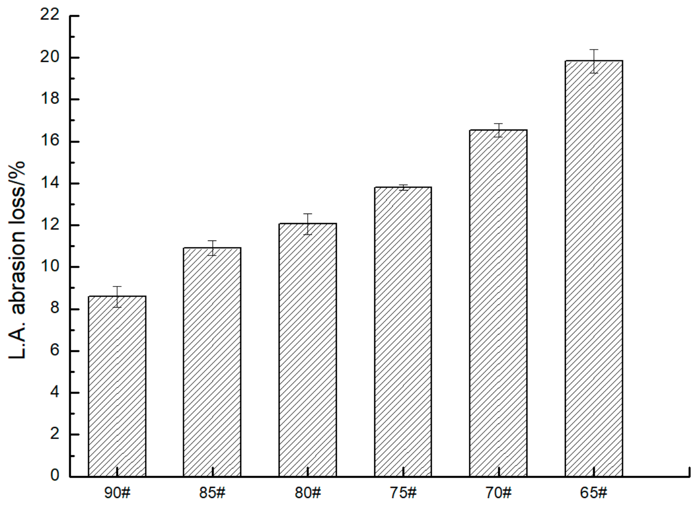


Figure 15. The results of the L.A. abrasion test.

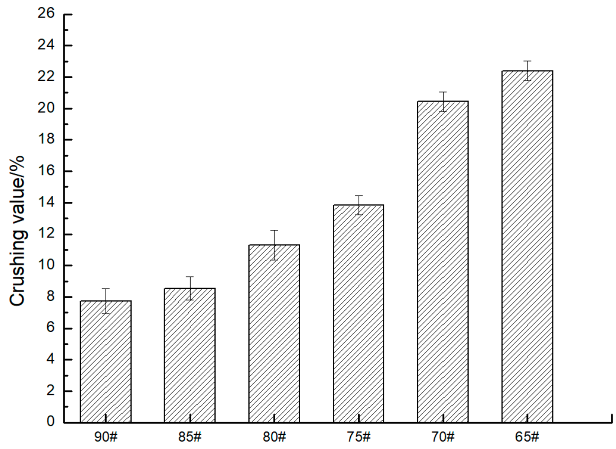


Figure 16. The results of the crushing value test.

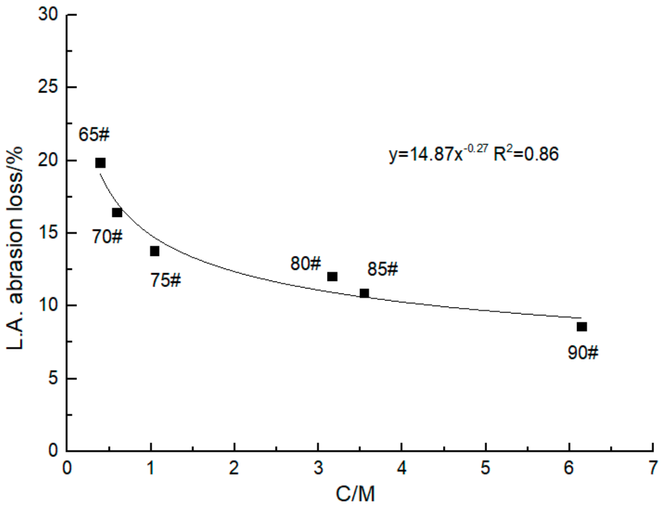


Figure 17. The relationship between C/M and L.A. abrasion loss.

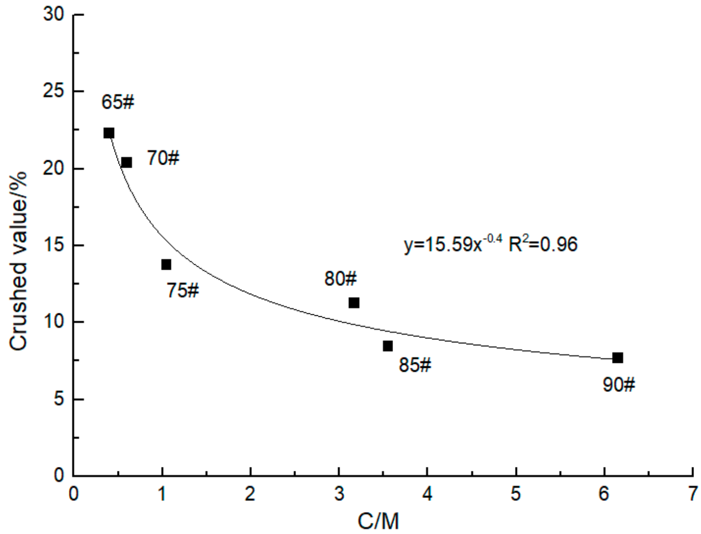


Figure 18. The relationship between C/M and the crushing value.

4. Conclusions

- Calcined bauxite above 75# (C/M ≥ 1) satisfies the requirements of polishing resistance, abrasion resistance, and crushing resistance, so could be used in the ultra-thin friction course. Compared with basalt, 80# calcined bauxite (C/M ≥ 3) has better long-term skid resistance, even though the pavement surface is subject to heavier traffic.
- The higher microhardness of the corundum and the larger hardness difference between the corundum and the mullite are the main reasons for the better long-term skid resistance of high-grade calcined bauxite.
- The microhardness of the aggregate is not only related to the hardness of minerals in the aggregate, but also to the cohesion in the aggregate. Higher cohesion of lower porosity is beneficial for the microhardness of aggregates.
- C/M is a good indicator for evaluating the calcined bauxite aggregate using in pavement surface coatings. There is a power law relationship between C/M and physical properties (PSV, L.A. abrasion loss, and crushing value). Considering the diminishing returns of higher-grade calcined bauxite, it is necessary to select the appropriate C/M of calcined bauxite before use in pavement surface coatings such as ultra-thin friction course, HSFT, or another skid resistance function layer.

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