JOURNAL OF TRAFFIC AND TRANSPORTATION ENGINEERING (ENGLISH EDITION) 2022; 9 (5): 880–891

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Original Research Paper

Characterization of road surfacing aggregates based on their mineralogical fingerprint

Dawei Wang [a,b], Yulin He [a], Chonghui Wang [b], Zeyu Zhang [b], Guoyang Lu [c], Pengfei Liu [b,*], Markus Oeser [b,a]

[a] School of Transportation Science and Engineering, Harbin Institute of Technology, Harbin 150090, China
[b] Institute of Highway Engineering, RWTH Aachen University, Aachen 52074, Germany
[c] Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hong Kong, China

HIGHLIGHTS

- Long-term influence of polishing and wearing on the surface aggregate is simulated.
- Characterizations of the mineralogical fingerprint and morphological parameters of aggregates are determined.
- Correlation between skid resistance, morphological properties and mineralogy of aggregates is derived.

ARTICLE INFO

Article history:
Received 12 September 2020
Received in revised form
3 February 2021
Accepted 25 February 2021
Available online 29 September 2022

Keywords:
Skid resistance
Morphological properties
Mineralogical fingerprint identification
Road surface
Accelerating polish

ABSTRACT

To ensure the safety of infrastructure users, the long-term skid resistance is a crucial factor and is determined in large by the mineralogical and morphological characteristics of surfacing aggregate. Most studies have investigated these aggregate properties separately without considering the interrelation between one another. The objective of this study is to consider the morphological characteristics as well as the mineralogical fingerprint of aggregate to develop an innovative approach to optimize the aggregate selection process. The investigations are based on 11 different aggregate types with a broad range of mineralogy, commonly used in Germany. The long-term influence of polishing and wearing on the surface aggregate was simulated by means of the Aachen Polishing Machine and the Micro-Deval test respectively. To evaluate the impact of these tests, the aggregate shape was characterized by means of an imaging system called Aggregate Image Measurement System while the skid resistance of aggregates was evaluated with the British Pendulum Test. The test results show that the quartz and calcite are the key crystals to determine the anti-wear resistance of aggregates. A correlation between the skid resistance, morphological properties and mineralogy is derived, which proves the mineralogical fingerprint technology is practical for characterization of aggregates used in pavement surface layers.

* *Corresponding author*. Tel.: +49 241 80 20389; fax: +49 241 80 22141.
E-mail addresses: wang@isac.rwth-aachen.de, dawei.wang@hit.edu.cn (D. Wang), yulinhe@hit.edu.cn (Y. He), c.wang@isac.rwth-aachen.de (C. Wang), zeyu.zhang@isac.rwth-aachen.de (Z. Zhang), guoyang.lu@polyu.edu.hk (G. Lu), liu@isac.rwth-aachen.de (P. Liu), oeser@isac.rwth-aachen.de (M. Oeser).

Peer review under responsibility of Periodical Offices of Chang'an University.
https://doi.org/10.1016/j.jtte.2021.02.007

1. Introduction

The vehicle behavior during cornering and braking is primarily determined by the skid resistance of the aggregate and plays a critical role in ensuring the safety in traffic (Ergun et al., 2005; Wang et al., 2015a). Studies have correlated the skid resistance of pavements in wet conditions with the occurrence of high speed accidents (Ergun et al., 2005; Henry, 2000; Kogbara et al., 2016; Mala et al., 2010; Plati et al., 2020; Wang et al., 2015b). The high speed limit throughout the German highway network necessitates the continuous evaluation and monitoring of the friction characteristics throughout the service life.

The decline of skid resistance of asphalt pavement is the result of many factors. In the early stage of pavement service, the asphalt film attached to the aggregate surface is wore by tire, i.e., the aggregate is exposed, so the skid resistance is slightly increased (Kane et al., 2013; Zhang et al., 2014). However, with the increase of time, the corner angle and surface textures of the aggregates become more and more smooth, which leads to continuous decline of pavement texture, and then it causes the decline of skid resistance (Lopez et al., 2012; Wang et al., 2011). Polishing resistance of the aggregate is important to the long-term skid resistance of the pavement, which is in urgent need of in-depth research (Cheng, 2010; Flintsch et al., 2003).

Usually the Polished Stone Value (PSV) test (AASHTO, 2014; ASTM, 2017; BSI, 2009; Ma et al., 2018) and Wehner/Schulze (W/S) tests (BSI, 2014; Kane et al., 2012) are used to research the impact of aggregate quality on the skid resistance performance of pavement. The polishing action in the PSV test is applied on coarse aggregates through a solid rubber wheel under the addition of water and emery. The British Pendulum Test (BPT) (BSI, 2002) is then used to evaluate the polishing resistance of the aggregate. The polishing in the W/S test is applied on the aggregate through a rotating unit with three rubber cones which is lowered onto the coarse aggregate under the addition of water and quartz powder. The friction measurement is conducted in a similar manner to the polishing procedure. A rotating unit with three rubber pads is accelerated and then rapidly lowered onto the polished aggregate plate. As it decelerates, the friction coefficient is measured continuously and evaluated at 60 km/h (BSI, 2014; Gonçalves et al., 2007; Perry et al., 2001). However, the complex loading conditions induced through vehicle cornering, accelerating and braking are not reproduced accurately by the PSV and the W/S test. Furthermore, traffic loading results in changes of texture, angularity and sphericity of aggregates, which are not accurately simulated with conventional testing methods.

Mineral characteristics (such as stability, hardness, brittle value, crystal size, etc.) and morphological characteristics (such as texture, corner angles and sphericity, etc.) determine the anti-polishing performance of the aggregates (BSI, 2014; CEN, 2002; Wang et al., 2015a, 2015b, 2016, 2018a, 2018b; Xie et al., 2016). Any aggregate can be fundamentally defined by its mineralogical fingerprint. Previous research supports that the mineral composition, crystal structure and the corresponding proportion of a specific aggregate affect the general mechanical be behavior (Gonçalves et al., 2007; Perry et al., 2001; Zhang et al., 2019). An in depth analysis of the mineralogy may give improve our understanding of the mechanical and chemical properties and the underlying effects (Huschek, 2002). The mineralogical fingerprint offers much more different information about the aggregate composition in comparison to the common types of aggregate from different quarries. The aggregates also exhibit distinctly different mineralogy which may be the key point to understanding the underlying effects responsible for the respective aggregates behavior (Huschek, 2002; Kokkalis et al., 2002). However, studies found in literature do not thoroughly investigate the correlation between the long-term skid resistance and mineralogical as well as morphological properties of aggregates due to the lack of suitable comprehensive testing methods.

2. Research objectives

To facilitate an adequate pavement design process and to optimize the material selection, this study proposes a methodology to characterize road surfacing aggregates based on their mineralogical fingerprint. First, the traffic load was simulated by the Aachen Polishing Machine (APM) to wear the aggregate, in which 11 kinds of aggregates were used. Then, the X-ray Fluorescence (XRF) and high resolution of Aggregate Image System II (AIMS II) were used to measure the mineralogical and morphological parameters of aggregates before and after the Micro-Deval test (MD). Finally, a relationship between the aggregate mineralogical and morphological characteristic and the long-term skid resistance of the pavement was established.

3. Experimental program

3.1. *Mineralogical analysis and morphology characterization*

The mineralogical analysis of 11 selected types of aggregates was conducted through XRF analysis. XRF is an elemental analysis technique to efficiently identify the major constituents as well as trace materials without destroying the sample, which has been broad applied in science and industry. XRF is based on the principle that individual atoms, when excited by an external energy source, emit X-ray photons of a characteristic energy or wavelength. By counting the number of photons of each energy level emitted from a sample, the elements present may be identified and quantitated. Another investigation method is the petrography, whereby the mineral structure and composition determined. The samples are cut and ground into 30 μm thick wafers with a diamond saw and then ground and polished until they are optically flat and smooth. The mineral structure is then determined by means of a polarized petrographic microscope. More details about this section can refer to the authors' previous publication (Wang et al., 2015c).

Fig. 1 – AIMS II (Wang et al., 2015c).

Individual aggregate exhibits distinct morphological properties. The imaging system Aggregate Image Measuring System II (AIMS II, Fig. 1) is an optically-based system capable of characterizing surfaces texture on both the macro- and the micro-scale and can accurately describe the shape of grains based on several representative parameters. The MD test was performed on batches consisting of 500 g of aggregates per type. The aggregate morphological properties before (BMD) and after (AMD) MD tests are characterized by AIMS II: two dimensional sphericity (2DS), gradient angularity (GA) and texture index (TI) (Gunaratne et al., 2000; Rezaei et al., 2009). The detailed calculation process about these three indicators can be found from the authors' previous publication (Wang et al., 2015c).

3.2. *Investigation of the polishing behavior and skid resistance*

The MD test is a reliable, precise and quick test, which requires simple equipment. To replicate aggregate polishing and wearing processes, the MD method polishes aggregates by making use of the interaction between aggregates and steel balls as well as amongst aggregates with the addition of water. Two test specimens are used in the standard testing procedure, and each specimen consists of aggregate with a total mass of 500 g and the range of 10–14 mm. It is washed and soaked in water for a period of at least 1 h before the test. The prepared aggregate sample is then placed in a steel drum and loaded with 5000 g of steel balls and 2000 ml of tap water. The contents are then subjected to 12,000 revolutions with a rotational speed of 100 min^{-1}. After polishing, the percentage of test specimens that pass a 1.60 mm sieve is determined and the sample's weight loss is calculated (Wang et al., 2015c).

To investigate the polishing behavior and skid resistance, aggregates (BMD and AMD) are manually laid out on a test slab with an area of 32 cm × 26 cm × 4 cm according to standard EN 12697-49 (BSI, 2014), as depicted in Fig. 2. The spaces between the single grains are filled with quartz sand to a minimum height of 3 mm, after which the spaces as well as the aggregate tips are covered with a cementitious binder. The sand can then be brushed out of the crevasses once the sample has been turned around. The grains protrude out of the cementitious base sufficiently that the polishing unit cannot come into contact with the cement layer.

To tackle the limitations of conventional methods as discussed in the introduction, the Institute of Highway Engineering (ISAC) at RWTH Aachen University developed a state-of-the-art polishing device named the Aachen Polishing Machine (APM) which is depicted in Fig. 3. The device is equipped with real vehicle tires with an internal pressure of 0.2 MPa and vertical loading of 200 kg (Wang et al., 2016; 2018a; 2018b).

The specimens after a 300-min polishing process in the APM unit consisting of aggregates both BMD and AMD were tested by British pendulum tester. The British pendulum tester is a common laboratory test for measurement low-

Fig. 2 – Test sample made with the Mosaic assembly method (Wang et al., 2018b).

Fig. 3 – Aachen Polishing Machine (Wang et al., 2016; 2018a; 2018b).

speed friction of pavement surface which is related to surface microtexture of road surface. The British pendulum number (BPN) is used to describe the changes of skid resistance and micro-texture according to the EN 13036-4 (Xie et al., 2018).

4. Results and discussion

4.1. *Mineralogical fingerprint*

The mineral compositions of the selected aggregate groups are shown in Table 1 (Wang et al., 2015c). This visualizes that the compositions vary between aggregate types, but also between the same aggregate types from different sources with regard to their composition. The primary component found in greywacke is carbonate minerals followed by silicate minerals. A large amount of silicate minerals can also be found in basalt, granite, gabbro and rhyolite. In limestone the main component is calcium oxide mineral. Although the proportion of each mineral varies for different aggregate sources, oxide minerals account for a large proportion for all types of diabase and greywacke.

The various mineral compositions of grains reflect the different forms of minerals and crystal types. The mechanical and chemical properties of these aggregate are determined by their representative features in terms of both crystallography and mineralogy.

The data presented in Table 1 demonstrates the distinctions between mineral compositions of the selected aggregates. The mineral components and the respective proportions vary between selected aggregates as well as their sources. As a consequence, the variation of the micro-structure and the micro-texture of aggregate can be observed, resulting in different material behavior. Table 2 presents the properties of the mineral components including the chemical formulae, the Mohs hardness and the density. Quartz exhibits the highest Mohs hardness, while that of chlorite is the lowest.

4.2. *MD test results*

It can be seen the differences of the selected aggregate (BMD and AMD) in Fig. 4. A visual evaluation finds that BMD aggregates exhibit sharp edges, indicating a higher angularity, while the AMD aggregates seem to have much more rounded surfaces. Differences in ellipticity can be observed between aggregate types as well as between aggregate sources of the same aggregate type. These differences are attributed to the mineralogical compositions of the aggregates which result in various degrees of wearing resistance. The angularity was most significantly reduced in basalt, greywacke and limestone after MD testing while rhyolite and granite were least affected. These discrepancies support the presented approach which is focusing on the mineral composition instead of merely on the type of aggregate.

4.3. *Morphological analysis results*

The morphological indicators of the aggregates (BMD and AMD) were collected with AIMS II including 2DS, GA and TI.

The cumulative distribution function (CDF) is used to differentiate between aggregate types when analyzing the change in morphological properties of aggregates due to wearing. The cumulative distributions of the same aggregate with different grain shape parameters (i.e., BMD and AMD) can be found in Fig. 5. It is worth noting that the CDF of morphological characteristics with different aggregates follow the log-normal distribution well. Thus, the expected value of each aggregate can be selected as a representative parameter for a correlation analysis considering the skid resistance and mineralogical properties of the aggregate. Based on these results, significant developments in all morphological parameters are observed as a result of the MD process.

As shown in Fig. 5(a), compared to other morphological parameters, the distributions of 2DS do not show obvious variation among different aggregates. Based on the data represented in these figures, it can be easily found that the wearing process due to the MD does not significantly affect the overall shape of aggregate grains.

As shown in Fig. 5(b), from the angularity distribution it is obvious that this index is significantly reduced by the MD test for all types of aggregates. The GA of most aggregates is located at a moderate level before MD testing; granite 2 has the highest value. However, this index decreases after MD test for all samples; limestone exhibits the most significant reduction of GA. After the MD test rhyolite exhibits the highest level of GA followed by Diabase 2. High value in the AMD state indicates excellent wearing resistance properties. Limestone on the other hand performs the worst among these grains.

As shown in Fig. 5(c), as for the texture index, large changes were observed when comparing the BMD and AMD states. Basalt has the highest texture index before MD testing. As expected, the TI of limestone is the lowest value after MD. The results show that the TI of both types of granite exhibit suitable values before and after MD test, these four cumulative curves are all locate at moderate level. With regard to the influence of MD testing, it should be

Table 1 – Aggregate mineral identification.

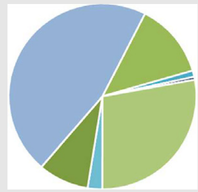
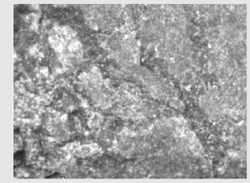
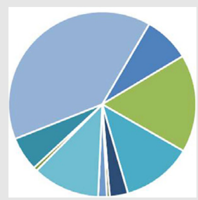
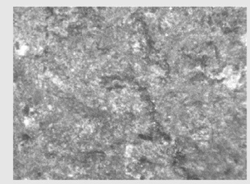
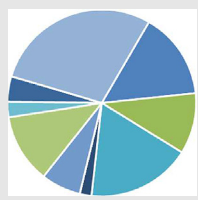
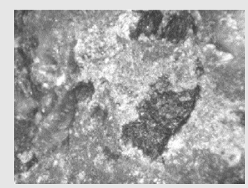
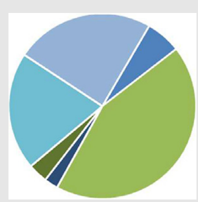
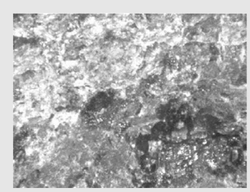
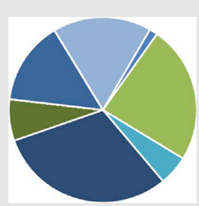
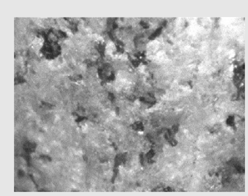
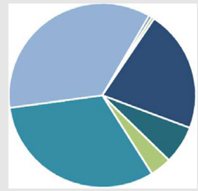
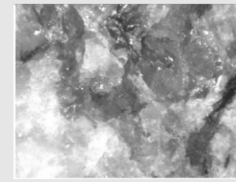
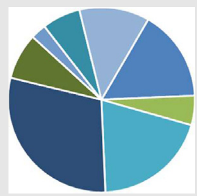
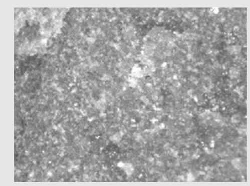
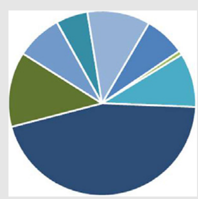
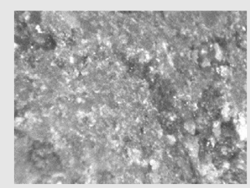
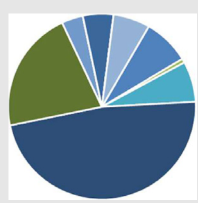
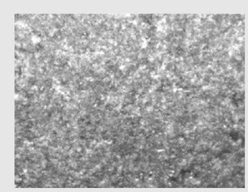
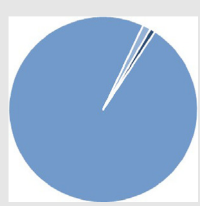
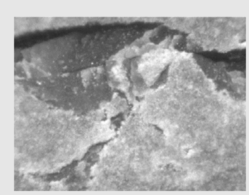
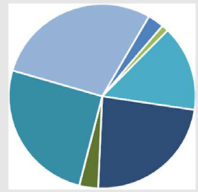
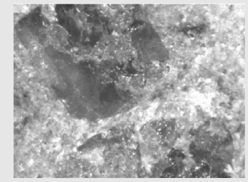
Aggregate type	Mineral composition proportion	Mirco-texture
Basalt Crystal size: 100 μm Average Mohs hardness: 5.35		
Diabase 1 Crystal size: 224 μm Mohs hardness: 5.30		
Diabase 2 Crystal size: 165 μm Mohs hardness: 4.41		
Gabbro Crystal size: 792 μm Mohs hardness: 5.25		
Granite 1 Crystal size: 366 μm Mohs hardness: 5.93		

Table 1 – (*continued*)

Aggregate type	Mineral composition proportion	Mirco-texture
Granite 2 Crystal size: 1550 μm Mohs hardness: 5.88		
Greywacke 1 Crystal size: 142 μm Mohs hardness: 5.26		
Greywacke 2 Crystal size: 57 μm Mohs hardness: 5.34		
Greywacke 3 Crystal size: 45 μm Mohs hardness: 5.26		
Limestone Crystal size: 256 μm Mohs hardness: 3.04		

(*continued on next page*)

Table 1 – (continued)

Aggregate type	Mineral composition proportion	Mirco-texture
Rhyolite Crystal size: 234 μm Mohs hardness: 6.02		

Note: Chlorite, Plagioclase, Albite, Quartz, Muscovite, Mica, Calcite, Others.

emphasized that one type of aggregate exhibited an inverted trend of the TI; the texture of rhyolite aggregate increased significantly after the MD testing.

4.4. *Skid resistance results*

The skid resistance of the samples was studied with the APM test and British pendulum test. Fig. 6 shows the skid resistance results (BPN) after a 300-min polishing process in the APM unit for aggregate both BMD and AMD. The 11 groups of aggregates show different levels of skid resistances. The effect of MD and APM on the skid resistance performance of the aggregate plate is significant. For all aggregate types, the friction coefficients of BMD samples are higher than those of AMD samples. Specially, the BMD and AMD values of basalt, greywacke and limestone are significantly different, i.e., the skid resistances of the various aggregate types exhibit significant differences; this is due to variation in both mineral structure as well as composition. Furthermore, the BMD and AMD values of greywacke 1, greywacke 2 and greywacke 3 are much different. It shows that the aggregate types are same but the sources are different, which leads their skid resistances are different. In a word, it should place great emphasis in the future engineering application to choose the most suitable aggregate for the long-term skid resistant of the pavement.

4.5. *Multiple regression analysis*

As abovementioned, mineralogical and morphological parameters were determined in the scope of this study. Before analyzing the correlation between the skid resistance and mineralogical and morphological properties, it is fundamental to exclude the parameters which do not significantly affect the skid resistance.

The correlation between morphological and mineralogical parameters and their influence on frictional behavior was investigated. With the aid of a correlation analysis, the relationship between the skid resistance and morphological indexes, such as 2DS, TI, GA etc., are verified. The results show that the TI does not have a significant correlation with polishing resistance properties or the lifetime of skid resistance, because the composition of mineral affects the polishing process of aggregate, and TI is an external characteristic that can only determine the initial performance.

Based on the results, it can be concluded that analyzing the mineralogical properties of aggregates and linking them to the skid resistance of surface aggregates is a necessary step to fully understanding the underlying mechanisms. The correlation between the mineralogical fingerprints and the parameters for polishing tests is derived by means of correlation and regression analysis of multiple variables.

The correlations between the skid resistance, morphological properties and mineralogy are verified through the correlation analysis which shows that only the mass proportion of quartz and calcite have a significant correlation with the skid resistance. It is observed that the quartz content is positively correlated, while the calcite content is negatively correlated with the final skid resistance. Therefore, in this study only the mass fraction of calcite and quartz is considered in the multivariate regression analysis. The correlation between the mineralogical and morphological indexes of aggregate and the skid resistance performance is established by SPSS statistical analysis method, as shown in Eq. (1).

Table 2 – Description of mineral components.

Mineral	Chemical components	Crystal system	Mohs hardness	Density (g/cm^3)
Chlorite	$(Mg, Fe, Mn, Ni, Zn, Al)_{4\text{-}6;}$ $(Si, Al)_4O_{10}(OH, O)_2$	Monoclinic	2–3	2.6–3.4
Plagioclase	$NaAlSi_3O_8$-$CaAl_2Si_2O_8$	Monoclinic or triclini	5.5–6.5	2.5–2.8
Albite	$NaAlSi_3O_8$	Monoclinic or triclini	5.5–6.5	2.5–2.8
Quartz	SiO_2	Trigonal	7	2.65
Muscovite	$KAl_2(AlSi_3O_{10})$ $(F,OH)_2$	Monoclinic	2–3	2.7–3.2
Mica	$I_{0.5\text{-}1}M_{2\text{-}3}$ $[T_4O_{10}A_2]$	Monoclinic	2–3	2.7–3.2
Calcite	$CaCO_3$	Trigonal	3	2.6–2.8

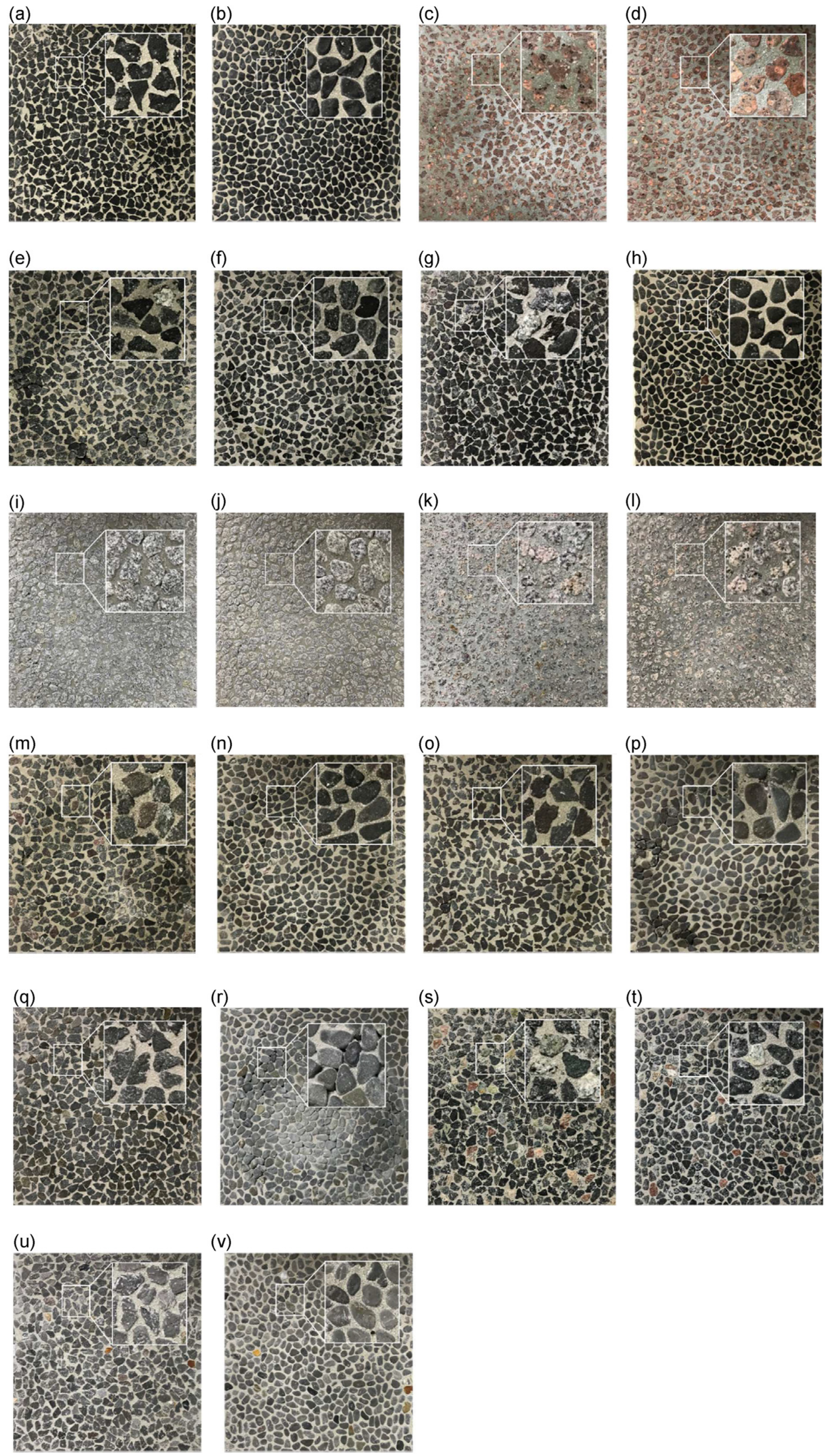


Fig. 4 – Aggregate test plates BMD and AMD. (a) Basalt BMD. (b) Basalt AMD. (c) Rhyolite BMD. (d) Rhyolite AMD. (e) Diabase 1 BMD. (f) Diabase 1 AMD. (g) Diabase 2 BMD. (h) Diabase 2 AMD. (i) Granite 1 BMD. (j) Granite 1 AMD. (k) Granite 2 BMD. (l) Granite 2 AMD. (m) Greywacke 1 BMD. (n) Greywacke 1 AMD. (o) Greywacke 2 BMD. (p) Greywacke 2 AMD. (q) Greywacke 3 BMD. (r) Greywacke 3 AMD. (s) Gabbro BMD. (t) Gabbro AMD. (u) Limestone BMD. (v) Limestone AMD.

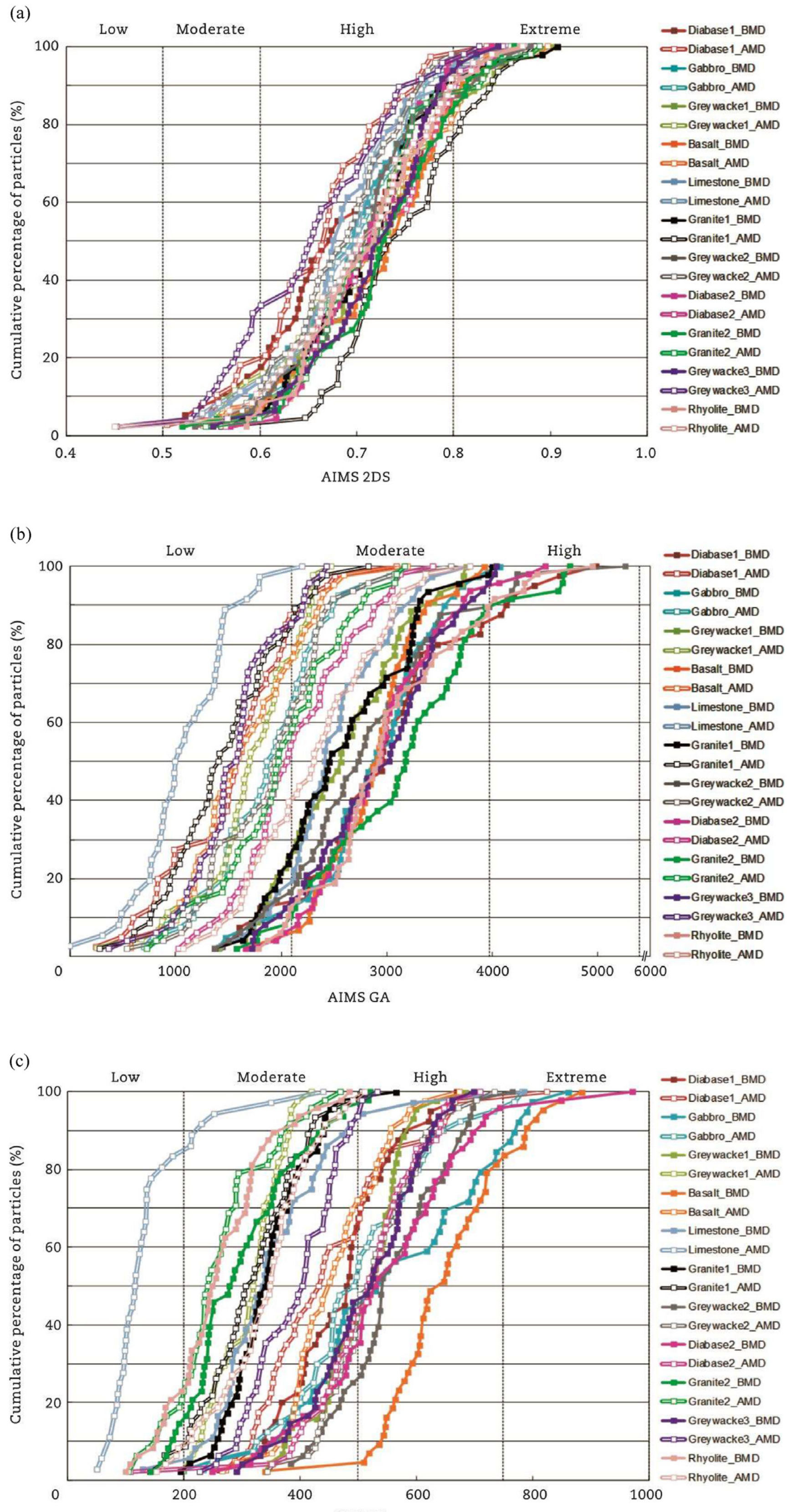


Fig. 5 – Morphological indicators from different aggregates. (a) Cumulative distribution of the 2DS. (b) Cumulative distribution of the GA. (c) Cumulative distribution of the TI.

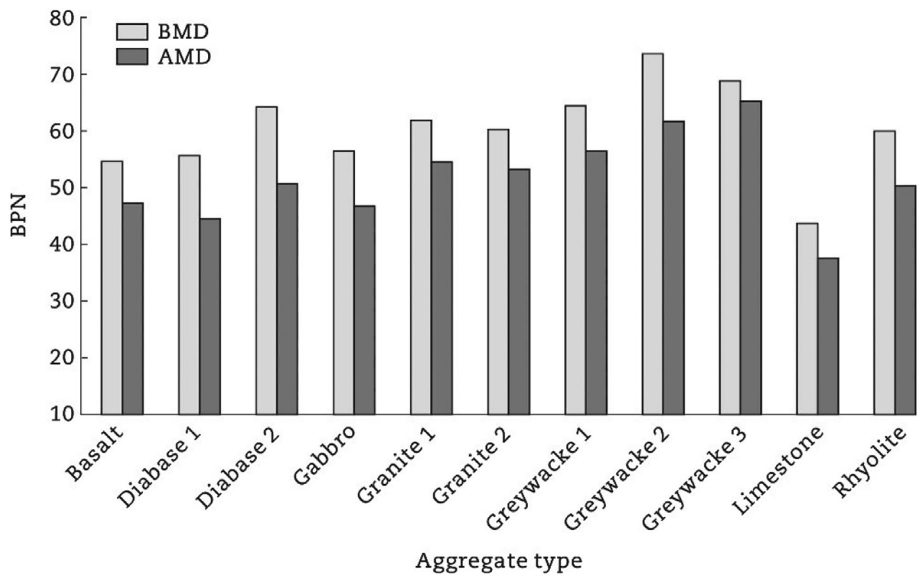


Fig. 6 – BPN of the AMD and BMD samples after APM test.

$$\mathrm{BPN} = 69.83 - 49.07 \cdot 2\mathrm{DS} + 0.007 \cdot \mathrm{GA} + 135 \cdot \mathrm{Quartz}^3 - 9.28 \cdot \mathrm{Calcite}^3 \quad (1)$$

where the adjusted complex correlation coefficient $R^2 = 0.86$, the significance of $F = 0 \ll 0.05$, and the significance of the comprehensive standardization coefficient is 87%. This indicates that the regression analysis is accurate. A higher GA and higher quartz content both lead to higher friction value. While a higher 2DS and higher calcite content leads to a decreased skid resistance performance.

The measured and calculated friction coefficients are compared in Fig. 7. It proves the reliability of Eq. (1). This correlation is of critical importance to the pavement engineering as it could be an effective approach to predict the skid resistance of aggregate based on mineralogical and morphological parameters. In addition, the effectiveness of selecting appropriate aggregate using the proposed correlation equation has been demonstrated. This correlation equation also provides the possibility to optimize the aggregate used in pavement surface layers. However, it should be noted that due to the limitation of aggregate types and sample size, the feasibility of the proposed correlation equation still needs to be further investigated.

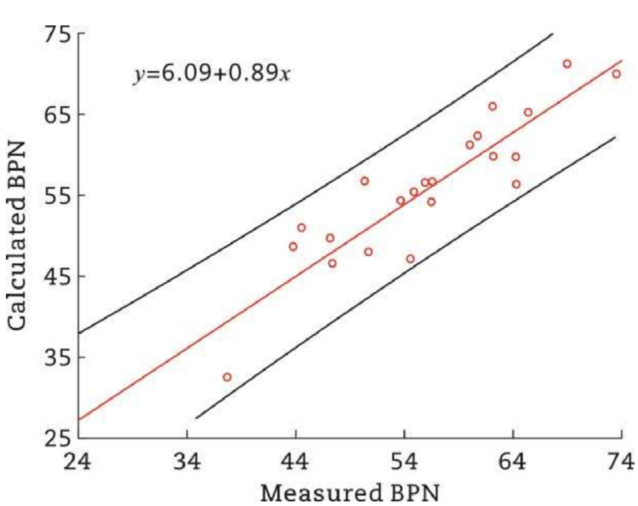


Fig. 7 – Comparison of measured and calculated friction coefficients.

5. Conclusions and recommendations

To investigate the potential of selecting surfacing aggregate for pavements based on the long-term skid resistance, an innovative approach to characterize surface aggregate based on their mineralogical fingerprint and morphological properties was developed in this study. Eleven different types of aggregates that are widely used in the German asphalt pavement industry were selected and exhibited diverse mineralogical and morphological properties. The MD test and the APM procedure were used to simulate the wearing and polishing processes due to traffic loading. The polishing behaviour and the skid resistance of the aggregates were then evaluated by the BPN. Based on the experiments, the main conclusions of this study can be summarized as follows.

- The skid resistances of the aggregate types exhibit significant differences; this is due to variation in both mineral structures and compositions. In addition, the source of aggregates also affects the coefficient of friction as differences can be observed between aggregates of the same type, yet from different sources.
- With a multiple non-linear regression analysis, the correlation between the skid resistance, morphological properties and mineralogy can be derived. This correlation is practical for the characterization of aggregate used in pavement surface layers. Furthermore, the results show that the quartz content and the calcite content exhibit a significant correlation with the skid resistance.

As a continuation of this research, the following recommendations can be given.

- The complex behavior of the frictional behavior based on the numerous properties of aggregate requires more extensive research. For instance, more types of aggregate with individual mineralogical fingerprints should be included in further tests; the environmental effects should be taken into account in further studies.
- More advanced imaging technologies (e.g., X-ray CT) could be applied for the aggregate image acquisition.
- More efforts are to be expended on the building of a database for the mineralogical fingerprint of aggregate for the purpose of effectively selecting aggregate based on scientific research.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

Acknowledgments

This work was supported by the National Key Research and Development Program of China (2019YFE0116300), National Natural Science Foundation of China (52250610218), Natural Science Foundation of Heilongjiang Province of China (JJ2020ZD0015), Opening Project Fund of Materials Service Safety Assessment Facilities (MSAF-2021-005), National Key Research and Development Program of China (2018YFB1600100), and the German Research Foundation (OE 514/15-1 (Project ID 459436571)). The authors are solely responsible for the content.

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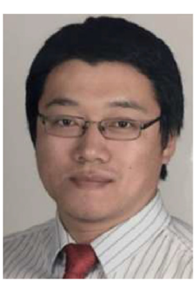

Prof. Dr.-Ing. Dawei Wang is the professor and doctoral supervisor in the School of Transportation Science and Engineering at Harbin Institute of Technology. His research interests and expertise focus primarily on asphalt pavement skid resistance, multi-scale characterization of the asphalt pavement mechanical behavior and functional pavement theory and technology. His work has been published in more than 100 peer reviewed SCI journal papers.

Mr. Yulin He is a PhD student in the School of Transportation Science and Engineering at Harbin Institute of Technology, China. His main research areas could be summarized as pavement engineering, skid resistance performance of pavements, numerical methods applied in asphalt pavement, microstructural modeling and characterization of pavements, morphology and mineralogy of aggregates, reuse of engineering materials. His work has been published in about 8 peer reviewed SCI/EI/Scopus indexed journal papers.

Mr. Chonghui Wang is a PhD candidate at Institute of Highway Engineering, RWTH Aachen University, under the supervision of Prof. Markus Oeser. He received his master degree from Chang'an University in 2017. His master thesis was finished at School of Highway, under the supervision of Prof. Dr. Hainian Wang. His main research area is the simulation and advanced measurement of pavement compaction.

Mr. Zeyu Zhang, M.Sc. is a research engineer at Institute of Highway Engineering, RWTH Aachen University. His research interests mainly include sustainable pavement materials and technologies, nondestructive evaluation of transportation infrastructure, and fatigue damage evolution of asphalt materials. His research works have been published in several prestigious peer-reviewed journals. He has served as an invited reviewer for more than 10 SCI journals.

Dr. Guoyang Lu is a research assistant professor at Hong Kong Polytechnic University. His research and teaching mainly focus on the innovative and recycled construction materials, the hydraulic and mechanical behaviour of permeable pavement, multi-scale and multiphysics simulations, and intelligent and nondestructive road technologies for smart cities. His research work has been published in about 30 peer-reviewed SCI indexed journal papers.

Jun-Prof. Dr.-Ing. Pengfei Liu is a junior professor at Institute of Highway Engineering, RWTH Aachen University, Germany. His main research areas could be summarized as pavement engineering, numerical methods applied in asphalt pavement, microstructural modeling and characterization of asphalt mixtures. His work has been published in about 100 peer reviewed SCI indexed journal papers.

Prof. Dr.-Ing. habil. Markus Oeser is the chair-professor of pavement engineering, the director of the Institute for Pavement Engineering and the dean of Faculty of Civil Engineering at RWTH Aachen University, Germany. His research and teaching mainly focus on numerical methods (FEM, FSAFEM, BEM), constitutive models (elsto-visco-plastic models, hypo-elastic models, critical state concept) and so on. He is an active member at the International Conference on Asphalt Pavements. His work has been published in more than 100 peer reviewed journal papers.