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Review Article

Texturing and evaluation of concrete pavement surface: A state-of-the-art review

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HIGHLIGHTS

- Current practices of concrete pavement surface texturization were discussed.
- Friction and noise emission properties of various surface textures were reviewed.
- Technical recommendations were proposed for diamond grinding & grooving applications.

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ABSTRACT

Concrete pavement is accompanied by two major functional properties, namely noise emission and friction, which are closely related to pavement surface texture. While several technologies have been developed to mitigate tire-pavement noise and improve driving friction by surface texturization, limited information is available to compare the advantages and disadvantages of different surface textures. In this study, a state-of-the-art and state-of-the-practice review is conducted to investigate the noise reduction and friction improvement technologies for concrete pavement surfaces. The commonly used tests for characterizing the surface texture, skid resistance, and noise emission of concrete pavement were first summarized. Then, the texturing methods for both fresh and hardened concrete pavement surfaces were discussed, and the friction, noise emission and durability performances of various surface textures were compared. It is found that the next generation concrete surface (NGCS) texture generally provides the best noise emission performance and excellent friction properties. The exposed aggregate concrete (EAC) and optimized diamond grinding textures are also promising alternatives. Lastly, the technical parameters for the application of both diamond grinding and diamond grinding & grooving textures were recommended based on the authors' research and practical experience in Germany and the US. This study offers a convenient reference to the pavement researchers and engineers who seek to quickly understand relevant knowledge and choose the most appropriate surface textures for concrete pavements.

1. Introduction

Concrete pavement is a widely used pavement type around the globe due to its various advantages. With high stiffness and loading bearing capacity, superior deformation resistance, good light-reflection properties, and low solar radiation adsorption, concrete pavement is an ideal choice for heavy traffic volume urban roads in tropical regions (Delatte, 2014). The application of concrete pavement in these areas can eliminate the risk of rutting in urban roads, while also mitigating the urban heat island effect. When designing concrete pavement, meeting structural requirements is the foremost priority, i.e., the pavement should be able to withstand traffic and environmental loadings without significant structural distresses. Nonetheless, it is also crucial to consider the pavement's functional properties, such as smooth riding, sufficient friction, and low

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noise. These factors are important because pavement maintenance and rehabilitation are often due to failure to meet the functional requirements rather than the structural deficiencies (Izevbekhai and Khazanovich, 2013).

Concrete pavement functionality highly depends on its surface texture, which affects skid resistance, driving safety, and tire-road noise. Micro texture and macro texture are two crucial components of pavement surface texture that affect pavement surface friction and tire-pavement noise (Hoerner et al., 2003). Micro texture refers to the texture with wavelengths of 1 μm to 0.5 mm, while macro texture refers to the texture with wavelengths of 0.5–50 mm (Cackler et al., 2006). The fine aggregate in the concrete mortar mainly contributes to micro texture. The hardened concrete pavement surfaces can generally be subdivided into three zones (Dames and Sulten, 1981). The uppermost zone mainly consists of cement paste, while the zone immediately below contains cement paste with fine aggregates. These two upper zones form the surface mortar. The third (bottom) zone consists of concrete (a mixture of cement paste, fine, and coarse aggregates). During service life, the cement paste in the surface mortar is removed by traffic and environmental conditions, resulting in an increased exposure of fine aggregates and an increase in roughness. Good micro texture is needed for a vehicle to stop on a dry concrete pavement surface or when the vehicle speed is less than 80 km/h on a wet pavement surface. Macro texture is mainly contributed by small surface channels, grooves, or artificial indentations. Concrete pavements with a design speed of above 80 km/h require good macro texture to prevent hydroplaning. The impact of macro texture on friction and noise depends on the selected surface texture type of the pavement and its detailed channel or groove pattern, including depth, spacing, and side angle.

According to the timing of implementation, the texturing methods can be divided into two categories: texturing of plastic concrete and texturing of hardened concrete. Surface textures of concrete pavement are traditionally constructed during the construction stage by dragging various materials or tools (like broom, artificial turf, and coarse burlap) across the fresh concrete. This produces a continuous series of undulations or grooves in the surface before the concrete hardens. For the low-volume concrete pavements where vehicle speeds are not very high, burlap-drag or broom textures are sufficient. The most common texture on high-speed road and highway pavements is transverse tining, and a shift is underway to longitudinal tining which has been shown to produce excellent long-term skid resistance and much lower tire/road noise qualities. Other innovative methods, such as exposed aggregate texturing and chip sprinkling, have also been proposed to enhance the surface functionality of concrete pavement (Hoerner et al., 2003). For hardened concrete pavements, diamond grinding & grooving are the most commonly used practices to improve surface functionality. Diamond grinding involves removing the hardened concrete using diamond saw blades gang-mounted on a cutting head, which creates uniformly distributed longitudinal surface textures. Diamond grooving also uses diamond grinding blades, but the longitudinally or transversely grooved textures are generally more than 10 mm in width (Skarabis and Stöckert, 2015). The next generation concrete surface (NGCS) was introduced in the US, which is achieved by a combination of diamond grinding & grooving methods. The NGCS is reported to be the quietest surface texture to date, providing an innovative solution to noise reduction (Komaragiri et al., 2020; Scofield, 2012b).

In addition to the diverse range of texturing methods available for concrete pavement surfaces, there has been significant research into the friction and noise emission properties of different surface types over the past few decades (Chu et al., 2022; Cong et al., 2020; Del Pizzo et al., 2020; Dzhambov and Lercher, 2019; He et al., 2023; Li et al., 2016; Licitra et al., 2019; Ling et al., 2021; Vaitkus et al., 2016). Despite well-established relationships between various factors and concrete pavement functionalities, there is a recognized general trade-off between the surface textures that exhibit better friction performance and those that produce higher levels of noise emission. Therefore, it is crucial for pavement engineers to comprehensively understand the effects of texture characteristics on both surface friction and noise emission when selecting surface-texturing technologies. The primary goal of this review is to provide a comprehensive overview of the latest technologies for reducing noise and enhancing friction of concrete pavement surfaces. This review presents a summary of the characterization methods of surface texture and the texturing methods for concrete pavement surfaces. In addition, this paper discusses the friction and noise emission properties of different surface textures and provides recommendations on grinding & grooving machinery and texture to optimize both friction and noise reduction of concrete pavement surfaces. The current review work is organized as shown in Fig. 1.

2. Texturing methods for concrete pavement surfaces

To optimize the skid resistance and reduce the noise of concrete pavements, multiple surface texturing methods have been developed, which can be broadly divided into two categories based on when they are implemented: texturing of plastic concrete and hardened concrete.

2.1. Practices for texturizing plastic concrete

Four types of texturing methods are commonly applied to plastic concrete, namely exposed aggregate concrete (EAC), drag textures, transverse tining, and longitudinal tining. In the US, the dragging and tining methods are commonly used, while in European countries, the exposed aggregate method is more prevalent.

2.1.1. EAC pavement

EAC pavements are created by intentionally removing the top layer of mortar before the concrete has fully cured, which exposes the coarse aggregate. Unlike most other concrete texturing methods, EAC creates an isotropic texture. The regular arrangement of coarse aggregate, along with a sufficiently deep macro texture, ensures high skid resistance and durable reduction of aerodynamic noise emissions from the tire-road contact patch. Construction of EAC requires high-quality aggregate.

The manufacturing process involves applying a retardant onto the fully compacted and smoothed concrete pavement before curing. Once the concrete has cured sufficiently to be driven on, the still-wet surface mortar is brushed off the surface. Since 2006, Germany has mandated the

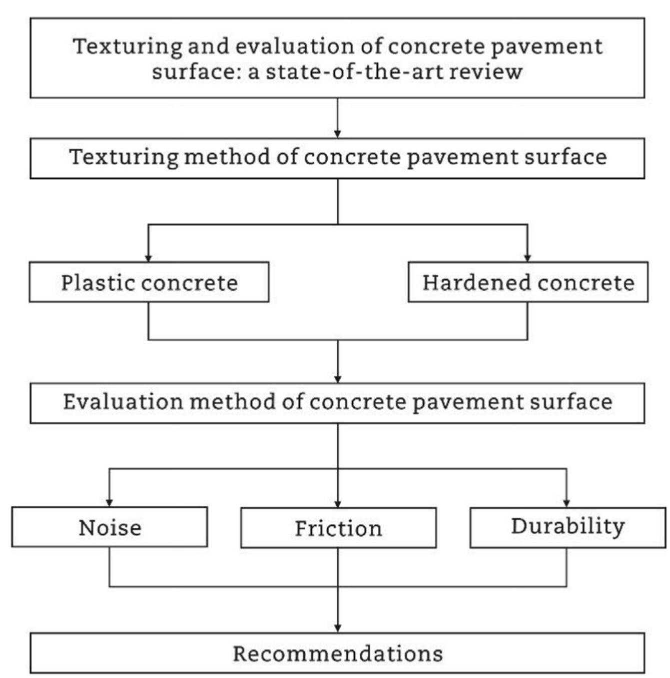

Fig. 1. The structure organization of the review work.

use of EAC with a two-lift construction process as the standard surfacing method for concrete motorways.

2.1.2. Drag textures

Drag textures include dragging a piece of burlap, a broom, or artificial turf over the wet concrete to create a uniform yet anisotropic texture, resulting in a very prominent macro texture and very high initial skid resistances. This texturing method is commonly applied to heavy-duty roads with high traffic loads, such as highways and runways. However, the macro texture tends to wear out over time, making it a less durable solution. Furthermore, the gritty textures significantly increase noise emissions due to mechanical noise excitation.

2.1.3. Transverse tining

Transverse tining has been widely used in the US for new high-speed (80 km/h or higher) concrete pavements. It involves a mechanical device equipped with a metal rake that moves laterally across the width of the paving surface. The optimal dimensions include random tine spacing between 10 and 40 mm, with no more than 25% exceeding 25 mm, a tine depth of 3–6 mm, and a tine width of 3 mm.

2.1.4. Longitudinal tining

Longitudinal tining is achieved in a similar manner as transverse tining, except that the tines are pulled in a line parallel to the pavement centerline. The optimal for longitudinal tining is a uniform tine spacing of 20 mm, a tine depth of 3–6 mm, and a tine width of 3 mm.

2.2. Practices for texturing hardened concrete

Diamond grinding & grooving of concrete pavements are two texturing methods commonly applied to hardened concrete. The original purposes of diamond grinding & grooving were to correct the surface irregularities, increase skid resistance, and improve the drainage capability of concrete pavements. Over the years, both techniques have been modified and improved for various purposes. Diamond grinding, in particular, has been found to produce various levels of traffic noise reduction benefits depending on the grinding configuration.

2.2.1. Diamond grinding

Grinding has been used to modify roads and airfields since the early 1960s, resulting in increased skid resistance and smoothness of the concrete pavement surface (Buddhavarapu et al., 2013). Diamond grinding wheels are fixed to a rotating shaft with a maximum distance of 3 mm from one another (Fig. 2) and moved over the pavement surface. The distance between the respective grinding wheels is precisely adjusted with smaller spacer wheels which are mounted in between grinding wheels (Fig. 3). Typically, the grinding depth is only a few millimeters.

Fig. 2. Grinding shaft of 1.2 m in width (Villaret et al, 2021).

Fig. 3. Diamond grinding wheel with spacer wheel (Izevbekhai and Khazanovich, 2013).

The diamond grinding wheel consists of a core that is about 2.7 mm thick and onto which diamond-studded grinding segments are welded. The grinding segments themselves have a thickness ranging from 2.5 to 3.2 mm (Fig. 4).

The grinding process is typically performed in a longitudinal direction. After the grinding process, the concrete surface has a series of fins and troughs as shown in Fig. 5. The width of the fin is determined by the width of the grinding segment and the spacer segments used during the grinding process. The respective fin geometry is determined by the grinding depth and the material strength of the coarse aggregate as well as the surrounding cement matrix. The area around coarse aggregate may exhibit very different fin-breakage behavior than in the surrounding concrete matrix. These eventually break off under traffic and become a more homogeneous surface. The geometry of troughs between the fins is defined by the width of the grinding segment. Therefore, the resulting texture is defined by the segment arrangement on the shaft (grinding segment width and spacer segments) as well as the properties of the concrete such as material strength and petrographic properties of coarse aggregate.

In addition to improving skid resistance and evenness, grinding is also applied to compensate for vertical slab offsets and create a smooth transition without bar reinforcement at joints. In such a case, concrete grinding may result in material removal of several centimeters. This

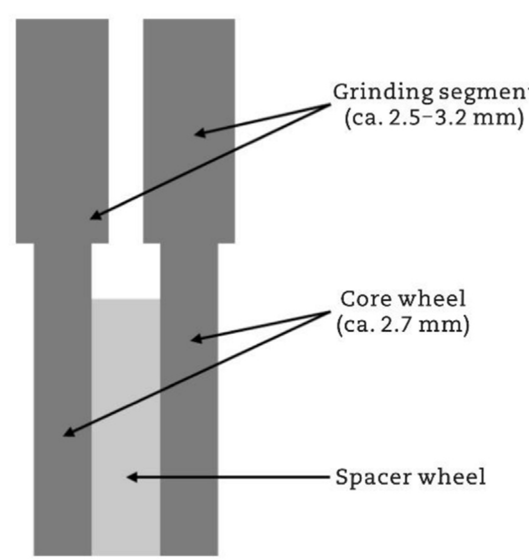

Fig. 4. Schematic sketch of spatial arrangement of grinding wheels and spacer wheels.

Fig. 5. Concrete surface immediately after grinding.

technique would remove several centimeters of material, which illustrates a pavement surface with transverse tining that has been textured using longitudinal grinding. Although transverse tining is a popular method to enhance texture and improve skid resistance, it also produces high-frequency tyre-road noise emissions that can be disruptive to those inside and outside the vehicle. In the areas where noise abatement is a priority, such textures are often improved using grinding techniques to reduce noise emissions.

2.2.2. Diamond grooving

Since the 1960s, grooving has been used on roads and airfields as a texturing method, similar to grinding. However, there is a key difference: grooving uses saw blades that are spaced over 10 mm apart, as shown in Fig. 6. The manufacturing process of this texturing method is analogous to grinding. Highways typically use grooving in the longitudinal direction to improve traction, while airfields use it in the transverse direction to enhance water drainage capacity.

2.2.3. Texture grinding

The main objective of texture grinding is to enhance skid resistance rather than surface smoothness. Unlike conventional grinding, texture grinding uses wheels that are spaced further apart, resulting in only partial abrasion of surface particles and grains. Nevertheless, it does not fully improve surface smoothness by removing vertical offsets of slabs and local irregularities. Instead, it follows the contour of the concrete pavement surface, increasing the macro texture to enhance skid resistance.

A special grinding texture was developed for urban roads with moderate traffic speeds. It features a high degree of flatness and a minimal number of fins with uncontrolled breakage, making it safer for activities such as cycling and skating. This type of grinding texture is produced using a specially designed grinding wheel. Unlike strongly pronounced textures, this surface is safe and durable, with a more subtle texture.

Investigations on pre-existing grinding surfaces with service lives of up to 12 years have concluded that this approach is generally effective in enhancing concrete pavement surfaces and producing durable textures with noise-reducing properties (Villaret et al., 2021). However, the textures of in-place pavements can change over time due to several parameters, including the concrete mixture, the thickness of mortar layer, spacers on the grinding shaft, and oscillation properties of selected sawing segments. In conventional grinding, defined and controlled surfaces are only created in the troughs, while the fin height and texture on the fins are mainly influenced by the boundary conditions mentioned before. Particularly on irregular surfaces, further fin breakage may occur under traffic loading, which can further alter the texture. Therefore, the resulting grinding texture is only partially controlled and subject to the influence of various factors that are not fully understood. This ultimately affects the appearance, skid resistance, and acoustic efficiency throughout the pavement's service life.

To achieve a texture that offers both high skid resistance and good noise-reducing properties, it is necessary to design and manufacture the entire surface with specific properties. Regardless of construction design, the acoustic functionality of pavements depends on three properties: texture, porosity, and flexibility (Beckenbauer, 2008). For rigid concrete pavements, the noise-reducing characteristics of porosity and flexibility are negligible, so the focus is on optimizing the texture. The texture influences mechanically induced noise generated by vibrating tread elements and the tire as a whole. Furthermore, the texture plays a role in air pumping noise caused by air pressure gradients inside and outside the tire-road contact patch.

Texture information can be represented by a continuous spectrum of wavelengths and amplitudes obtained by means of a Fourier transformation. In terms of acoustics, the wavelengths of the texture that matter are typically between 1 and 250 mm, which roughly corresponds to the size of tire tread elements and the entire tire-road contact patch. The texture of concrete pavements and the resulting mechanical vibration stimulation of the tyre tread depend on the selected material, concrete mixture, and manufacturing technique. Another important parameter is the specific airflow resistivity, which measures how easily air can escape from the tire-road contact patch. The specific air flow resistivity represents an important parameter to estimate aerodynamic noise emissions (Beckenbauer et al., 2002).

Advanced computational programs enable the prediction of generated noise, and they can be used to estimate and investigate the precise influence of pavement texture on noise generation. The significant difference between grinding pavement surfaces and other wearing courses is the isotropy of the texture. Most noise-reducing surfaces have isotropic textures, meaning the texture is the same in the transverse and longitudinal directions. In contrast, grinding textures have a distinctly anisotropic texture due to the one-directional processing of the surface.

Fig. 6. Pictures of the grooving shaft (Cable and Wiegand, 2010).

2.2.4. Next generation concrete surface

The next generation concrete surface (NGCS), also known as diamond grinding & grooving technology, was first introduced in 2007 by Purdue University, which represents the latest innovation in concrete texture (American Concrete Pavement Association, 2020). NGCS refers to a category of textures that have a desirable combination of smooth profile, good micro texture, and excellent macro texture. This texture can be applied to both newly constructed and existing pavements, and the properties of the manufactured texture are consistent and predictable, making it the quietest non-porous concrete texture developed to date.

The diamond grinding & grooving texture is developed based on a comprehensive laboratory study of varying blade and spacer widths and configurations. The test results indicate that the geometric configuration of the blades and spacers was not the controlling factor in noise generation. Instead, the variability in the fin profile height resulting from the grinding process was found to be the controlling variable. Thus, the diamond-ground surface must have uniform and consistent fin profiles. To avoid the surface texture in the upward or positive direction produced during the conventional grinding process, a manufactured surface texture with only negative texture was proposed. This surface is firstly diamond-ground smooth, followed by grooving to remove the additional texture. Close-up photographs of the surface textures of conventional diamond grinding and NGCS are shown in Fig. 7.

The NGCS concrete pavement can be achieved through either the single-pass method or the double-pass method with the latter being more practical in preventing excessive wear on grinding equipment. The first pass is to create the flush ground surface. The flush ground surface is created during the first pass using flush grind blades, which are mounted on a 4-foot grinding head with 0.125-inch wide blades separated by 0.035 ± 0.005-inch spacers. The second pass creates the longitudinal grooves, which are 1/8 inch wide and 1/8 inch to 3/16 inch deep, spaced on 1/2 inch to 5/8 inch centers (International Grooving and Grinding Association, 2014). Fig. 8 gives photos of the commonly used grinding heads for a typical NGCS head from single-pass construction and the first pass of the two-pass construction. To date, the NGCS technology has been successfully applied in 15 US states and four other countries, including Canada, South Korea, Australia, and Germany.

3. Functional characterization of concrete pavement surface

3.1. Testing of concrete pavement surface texture

The surface functionality of concrete pavement is directly determined by its pavement texture characteristics, specifically the geometrical irregularities of the pavement surface. Based on magnitude, shape, distribution, and effect, pavement surface texture can be divided into four categories of micro texture, macro texture, mega texture, and unevenness. Previous studies have demonstrated that the micro texture and macro texture have the most significant effect on the friction and noise emission performance of concrete pavement.

The micro texture of concrete pavement is closely related to the morphological property of fine aggregates. Its significance is reflected in two aspects: riding safety, which is determined by the skid resistance of concrete pavement, and riding cost, which is associated with tire wearing and oil costs. Coarse aggregate morphological properties have a significant influence on the macro texture of concrete pavement. The presence of macro texture on the pavement surface facilitates water drainage from beneath the vehicle's tires, thereby reducing the risk of hydroplaning. However, increased macro texture leads to higher fuel cost due to increased rolling resistance.

Given the significance of the concrete pavement surface textures in relation to skid resistance and tire-road noise, multiple methods have been developed to characterize concrete pavement surface textures. This section provides a general overview of the characterizing methods that are commonly employed in practice.

Mean profile depth (MPD) can be measured through volumetric techniques, such as the sand patch method, or optically with devices, such as ELAtextur, as shown in Fig. 9 (ISO, 2004).

Pavement textures comprise a range of texture wavelengths with varying amplitudes, which can be collectively represented in a textural spectrum. A textural spectrum exhibits profound maxima, which corresponds to the pair of values wave length λ_{max} and texture depth R_{max} which is used to characterize the texture spectrum of the pavement surface.

The Müller-BBM contactless laser profilometer, illustrated in Figs. 10 and 11, can non-invasively assess the macro texture of pavements on site. The measurement and characterization of surface texture comply with ISO 13473 (ISO, 2004). The pavement surface is scanned using a triangulation-laser measuring system in 2-m segments. Typically, the surface is scanned in six parallel tracks, each spaced 20 mm apart, to obtain a quasi-3D scan of the surface. A schematic representation of the device is presented in Figs. 10, and 11 depicts the device in operation.

3.2. Skid resistance of concrete pavement

3.2.1. British pendulum test (BPT)

The BPT is a widely accepted, portable instrument for measuring friction characteristics of pavement surfaces. While it is versatile and can be used for various test scenarios, it is mainly employed for evaluating the micro texture of pavement surfaces and measures low-speed friction at approximately 10 km/h. Despite its limitations, the BPT is a simple and effective device for friction assessment.

3.2.2. Wehner/Schulze (W/S) test

In the standard W/S test, three rubber measuring pads are arranged in a circular path with a diameter of 180 mm. Each pad is 14.5 mm wide, and 30 mm long and typically has a Shore scale hardness of 65, as shown in Fig. 12. During the measurement, they are accelerated to a velocity of 100 km/h and then dropped onto the test surface until they are

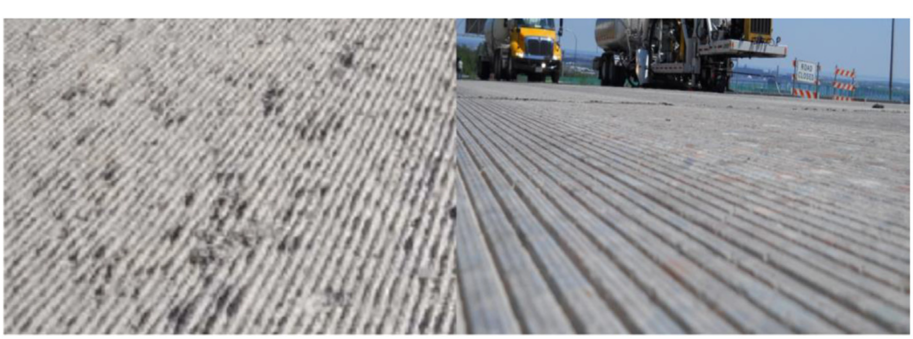

Fig. 7. Conventional diamond grinding surface (left) and NGCS (right) (Scofield, 2020).

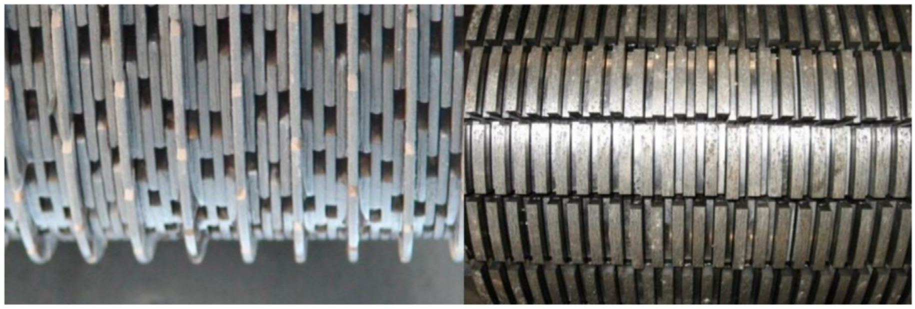

Fig. 8. Grinding head for the single-pass construction (left) and two-pass construction (right) (Scofield, 2012a).

Fig. 9. MPD measurement of the optical method using ELAtextur.

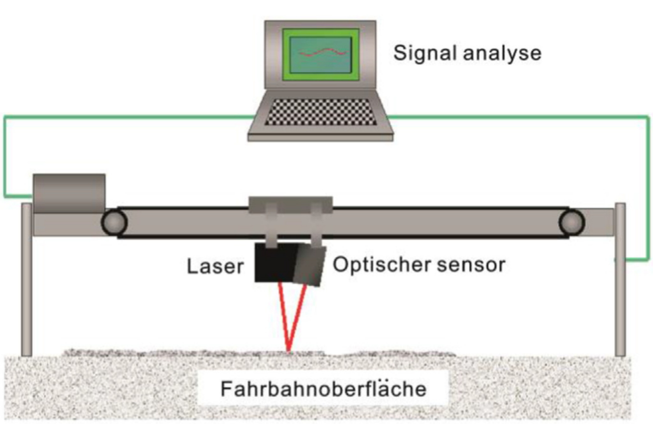

Fig. 10. Schematic depiction of laser profilometer (Villaret et al, 2021).

Fig. 11. Laser profilometer during field investigation (Villaret *et al*, 2021).

decelerated to a stationary state under wet conditions. The friction coefficient of W/S is normally measured at a velocity of 60 km/h and therefore depends on both the micro texture and the macro texture of the surfaces. The repeatability of the test procedure is approximately ±0.026 according to CEN-EN 12697-49 (CEN, 2022).

3.2.3. Harbin high-speed friction test (HSFT)

The Harbin Institute of Technology (HIT) has independently developed the HSFT, a sophisticated laboratory simulation tool capable of replicating the coupling effect of temperature, water film, tire pressure, load, and driving speed in the laboratory, as shown in Fig. 13. The experiment is conducted on a Giti-185/60R14 tire with a pressure of 2 bars and a maximum speed of 150 km/h. The maximum contact pressure is limited to 0.8 MPa, which is higher than the usual limit of 0.4 MPa for simulated car experiments. The water film thickness is controlled within the range of 0–15 mm using a pressure air watering can and waterproof silicone strip. Additionally, this test is equipped with a high-speed point contact Anti-Brake System (ABS) to measure the friction coefficient (He et al., 2023).

3.2.4. Sideway-force coefficient routine investigation machine (SCRIM)

The SCRIM is a widely used method for continuously measuring skid resistance while driving on a road. The SCRIM system consists of a measuring wheel that is mounted underneath a measuring vehicle and positioned at an angle that allows it to drag along as the vehicle moves. The slip of the tire can be adjusted to accurately determine the skid resistance of the road surface, providing valuable insights for road maintenance and safety (TP Griff-StB, 2007).

Among the above-mentioned tests, the BPT is the most used one, but it also provides the least information in evaluating the skid resistance of

Fig. 12. The Wehner/Schulze (W/S) test machine (Wang et al, 2018).

pavement surface. The W/S test is designed to simulate the dynamic friction behavior between tire and pavement surface, but it uses the rubber brick to represent the vehicle tire. To overcome this shortcoming, the HSFT introduced the real tire to conduct the dynamic friction coefficient measurement between tire and pavement surface in laboratory. The SCRIM can best evaluate the skid resistance of pavement surface under real driving conditions, and it is more suitable for engineering applications.

3.3. Noise emission of concrete pavement

3.3.1. Statistical pass-by (SPB) method

The SPB method serves to record and evaluate noise-related properties of traffic in general and particularly the pavement surface itself (Ascari et al., 2022; ISO, 1997). In this test, a microphone is placed 7.5 m away from the right lane at a height of 1.2 m above the upper edge of the pavement surface. When a single vehicle passes by, the maximum sound pressure level as well as the vehicle velocity are registered. As a vehicle passes by, the maximum sound pressure level and the velocity of the vehicle are recorded. The measurements are categorized according to vehicle type, and the ambient temperature and pavement temperature are also recorded. A temperature correction is applied using a reference temperature of 20 °C for passenger cars.

The area surrounding the measurement site should be chosen to be as even as possible, exhibit low reflections (no buildings) and be devoid of high vegetation–this applies to a radius of 25 m around the microphone. The measurement is conducted for dry pavements and air temperatures between 5 and 30 °C and pavement temperatures between 5 °C and 50 °C. The wind speed at a height of 4 m must be below 5 m/s. A measurement is only valid if the maximum sound pressure level is 6 dB above the background noise before and after the pass-by. For the evaluation of noise emissions of a road under given traffic loading, it is necessary to compare the measured values to a reference. In Germany, the D_{stro} represents this value. It is based on a passenger car at 120 km/h on a 11 mm maximum aggregate size stone mastic asphalt and is defined to be $L_{\text{ref, Statuspapier 2006}} = 85.2$ dBA.

3.3.2. Controlled pass-by method (CPB)

CPB measures the sound generated by passing vehicles, and the measurements are conducted identically to the SPB method. However, the CPB is evaluated for defined vehicles at predefined velocities. In general, the CPB test results are less representative comparing to SPB test, and its results depend on the condition of the test site. As a result, the applicability of CPB is compromised in urban contexts (Ji et al., 2020; Moreno et al., 2023).

Fig. 13. The Harbin high-speed friction testing equipment.

3.3.3. Close proXimity (CPX) measurement

The CPX method, as per ISO 11819-2 (ISO, 2009), measures noise emissions exclusively at the source, excluding factors such as sound propagation through the surrounding area, engine noise, or airflow noise. Nevertheless, it can effectively isolate noise emissions originating from the tire-road contact area. Moreover, its ability to continuously measure noise emissions across an entire road segment makes it ideal for determining the homogeneity of acoustical properties of pavements (Ganji et al., 2020; Knabben et al., 2019; Mikhailenko et al., 2022).

A measurement trailer, equipped with two tires spaced as per standard vehicles, is used to measure tire-road noise. The microphones are arranged according to predefined standards, as illustrated in Fig. 14. The two tires are situated in separate housings to attain acoustically decoupled measurements. Also, measurements are conducted under flowing traffic resulting in high requirements to acoustically insulate the microphones from the noise outside the housing. The interior of the housing is lined with acoustical absorbers to minimize sound reflection. An exemplary measurement setup by Müller-BBM is given in Fig. 15. The microphones are placed 100 mm above the pavement surface, and Fig. 16 illustrates their arrangement.

To ensure the reproducibility of results, the CPX specifies the acceptable tires for valid measurements. The selected tires must be pressurized to 2.0 bar. The measurements are conducted using two tire types, namely P and H, and the sound pressure level, velocity, and location are recorded. The energy-weighted average of sound pressure levels on intervals is computed. Finally, the sound pressure level is corrected to a reference velocity, based on the pavement surface and a reference temperature (ISO, 2009). The acoustical measurement uncertainty, represented by the standard deviation of repeatability, is typically ±0.5 dB.

Besides the above mentioned roadside SPB and CPB tests and on-board test, there also exists some other similar noise measurement methods. Every test is of its own advantages and disadvantages, and previous research has shown that the noise measurement tests that belong to the same category of mechanism generally show good correlation. The selection of test method should be based on a balanced consideration of the factors including site conditions, equipment accessibility, measurement objective and others (Li, 2018).

3.3.4. Simulation technologies–SPERoN®

Innovations in pavement design, particularly the development of new textures, can greatly benefit from accurate simulations. Software tool such as SPERoN® (Statistical Physical Explanation of Rolling Noise) enables virtual testing, providing a highly feasible approach. The tool was developed with the collaboration of Müller-BBM, the chair for applied acoustics at Chalmers University of Technology in Göteborg (Sweden), and integrated tire and road interaction (ITARI) as part of the Leiser Straßenverkehr-Reduzierte Reifen-Fahrbahn-Geräusche initiative by the Federal Ministry of Education and Research. The model consists of both deterministic and statistical components, making it a hybrid model. By inputting pavement textures and precise tire tread patterns (Figs. 17 and 18), the tool can predict SPB and CPX pressure levels.

The total sound pressure intensity level I_{total} is given to be the sum of mechanical noise excitation I_{vibr}, air pumping based excitation I_{air}, resonance in cavities I_{cavity} as well as a residual part I_{residual} (other air flow related sources) (Beckenbauer, 2006).

3.4. Friction and noise characteristics of various types of surface textures

3.4.1. Texturing methods for plastic concrete

Dragging methods like brooming, burlap dragging, and artificial turf dragging generally create shallower texture and lower noise levels compared to tining methods, which offer better friction resistance and longer texture life. Thus, many concrete highway systems in Germany are finished using a burlap drag texture (Larson et al., 1993; Sulten, 2004), while tining is not used because of the concern about pavement noise. Studies have shown that longitudinal dragged textures are sufficient for pavements with speed limits of less than 72 km/h (American Concrete Pavement Association, 2000). To ensure enough friction and service life of dragged textures, it is recommended that materials and mixes with improved wear resistance should be used. For example, the wear resistance of concrete with quartzite is better than that of concrete with granite, while the wear resistance of concrete with granite is better than that of concrete with limestone.

Transverse tining is the most common type of surface texture for high-speed concrete pavements in the US, favored for its good friction characteristics in wet weather conditions. The deep macro texture of transverse tining reduces water film thickness and the potential for hydroplaning. However, concerns have been raised about the noise generated by the interaction of pavement and vehicle tires. A study conducted in Wisconsin in the US has concluded that the wider and deeper transverse tines often produce larger noise (Kuemmel et al., 2000). It is generally believed that among various texturing methods for plastic concrete, transverse tining created the highest noise. However, it is also reported in the same study that the dBA level of a transversely tined surface is actually not necessarily higher than other texturing methods. It is the tonal nature of the whine caused by a uniform transverse spacing that makes this pavement texture objectionable to many. To alleviate the tonal effect, random tining spacing is recommended. A broad range of random spacing, between 10 and 76 mm, has been reported to be effective in reducing noise emissions. The US Federal Highway Administration (FHWA) recommends two random tining patterns with an average spacing of 13 mm and 26 mm, respectively, to reduce tonal noise.

Studies on the friction resistance and noise level of longitudinally tined pavements have produced conflicting results. Hoerner and Smith (2002) reported that longitudinal tining provided lower friction resistance when compared to transverse tining under the same conditions. However, other studies have suggested that longitudinally tined concrete pavements are quieter than transversely tined ones. In Wisconsin, longitudinally tined pavements were found to have friction characteristics and durability comparable to transversely tined concrete pavements

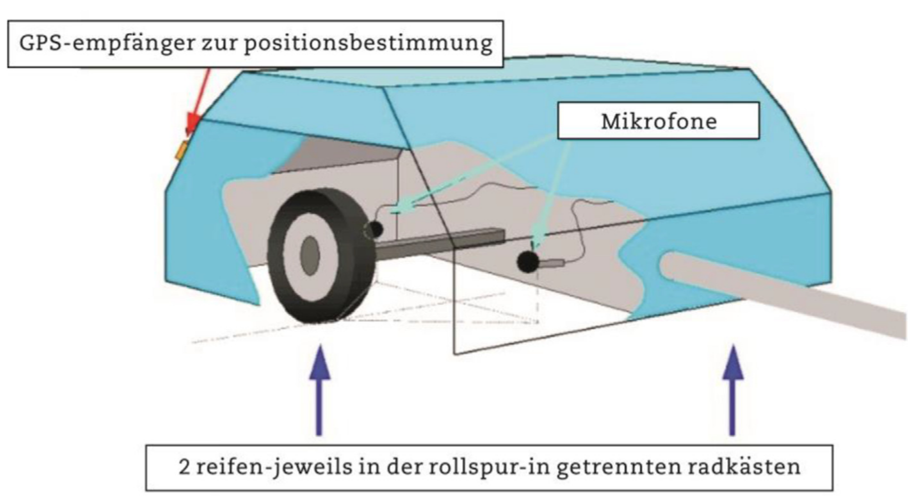

Fig. 14. Schematic depiction of CPX-trailer (Villaret et al, 2021).

Fig. 15. CPX-trailer supplied by Müller-BBM (left) and standardized tire with measurement microphones in the anterior position (right) (Villaret et al, 2021).

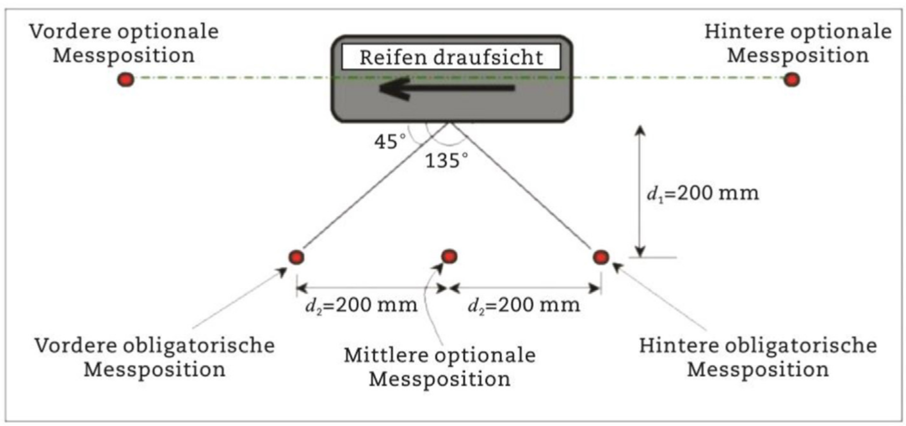

Fig. 16. Arrangement of microphones in accordance with ISO 11819-2 (Villaret et al, 2021).

Fig. 17. Measurement tyres (Villaret et al, 2021).

or dense-graded asphalt pavements (Kuemmel et al., 2000). However, in Colorado, some drivers reported experiencing uncomfortable lateral vehicle movement on longitudinally tined pavements. As a result, the Colorado Department of Transportation has stopped using tining on all concrete pavement projects (International Road Federation, 2013).

Exposed aggregate concrete pavements are often constructed using a two-lift "wet on wet" paving process. When designed and constructed appropriately, exposed aggregate concrete pavements have been reported to provide good friction resistance and low noise, and their durability is equivalent to that of conventional concrete pavements. The performance of the exposed aggregate concrete pavements is highly dependent on the quality of the aggregate in the concrete. To ensure adequate friction, exposed concrete with polish-resistant aggregates should be used. To achieve lower noise, aggregate with a smaller size is desired. In a study conducted by Swedish National Road Administration, concrete pavements with exposed aggregate surface texture and HMA pavements were tested for skid resistance and noise under heavy traffic. The results show that the exposed aggregate pavements with 16-mm and 8-mm stones provided noise levels that were 1.0 and 1.5 dBA lower, respectively. After one year, the noise level of the 16-mm exposed aggregate and asphalt pavement sections became identical while the 8-mm exposed aggregate section produced a quieter noise level. Since May 2006, Germany has specified the exposed aggregate technique combined with a two-lift construction process as the standard surfacing method for concrete roads on motorways. To remove the mortar and expose the aggregates at the pavement surface, the following two surface preparation techniques have been used: 1) applying a retarder and a curing compound after aggregates were exposed; 2) applying a retarder followed by covering the surface with a plastic sheet (Hall et al., 2007).

3.4.2. Texturing methods for hardened concrete

Diamond grinding has traditionally been used in the longitudinal direction to rehabilitate existing pavements by restoring smoothness, but it is also possible to use it as an initial texturing method for new pavements. In a study comparing the noise level of the longitudinal ground pavement and that of the transversely tined pavement, the former was found to be quieter than the latter by 2–5 dBA when the noise was measured on the side of the road (Burgé et al., 2002). However, it was believed that the skid resistances of the two texturing methods are comparable with each other. One study conducted in Guangdong Province in China shows that diamond grinding improved the average surface texture depth of an old concrete pavement from less than 0.2–1.1 mm, and increased its average British pendulum number from 27 to 52 (Villaret, 2021).

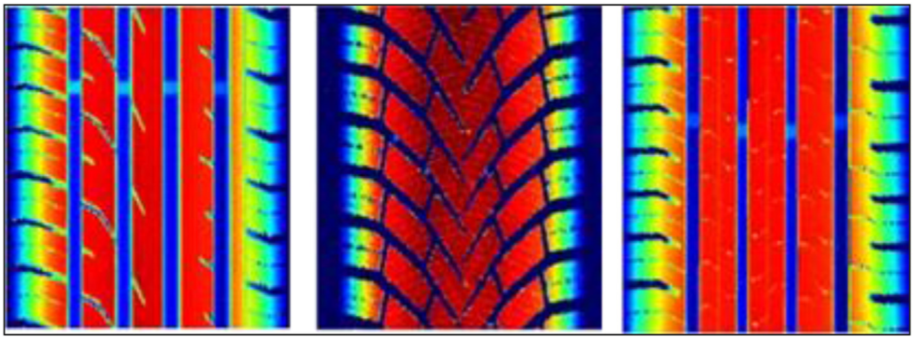

Fig. 18. Measured texture profiles for measurement tyres (Beckenbauer, 2006).

The research project aimed at generating grinding textures with well skid resistance properties and reproducible acoustic properties resulting in a correction D_{stro} of −4 dB was conducted at the Institute of Highway Engineering (ISAC) at RWTH Aachen University (Villaret et al., 2021). In this project, the optimal grinding texture geometry was identified by means of computer simulations, taking into account the 3D texture as well as the texture induced specific air resistivity. Devices to record the smoothness were also developed and integrated into the grinding machinery. Based on the simulation and test track results, the optimized surface texture that consists of a 2.4–2.8 mm grinding segment width, 1.0 mm spacer width, 0.6 mm fin in width, and grinding depth smaller than 4 mm was recommended.

Similar to diamond grinding, diamond grooving is mainly used along the longitudinal direction as a rehabilitation method to improve the drainage of water between the tires and pavement surface, thus improving friction resistance. Due to this reason, no study has been found in the literature documenting its noise performance. But it was pointed out by some researchers that noise is a concern when the grooving is in the transverse direction which is not common in practice. It is worth noting that both diamond grinding and diamond grooving should only be applied to pavements with sound structural and functional characteristics. In mainland China, diamond grooving has been used to improve the friction resistance of both newly constructed and old cement concrete pavements. It is specified that for newly constructed concrete pavements, diamond grooving should be implemented when concrete has gained at least 40% of its 28-d strength, while it is usually done after 21 d in practice (Villaret, 2021).

The NGCS, which is a non-porous concrete texture, is considered the quietest texture developed so far, with a typical noise level of 99 dBA that may range up to 103 dBA over time. In the test sections constructed to date, the NGCS begins approximately 1–4 dBA quieter than a conventional diamond ground surface and is approximately 0–1 dBA quieter after the first year. A three-year performance comparison of the diamond ground surfaces and the original transverse tining surface was conducted at the Minnesota Department of Transportation Road Research Project (MnROAD) test sections (Izevbekhai and Khazanovich, 2013). The results indicate that the NGCS exhibits better acoustic improvement than conventional diamond grinding and transverse-tined textures. Fig. 19 shows the OBSI values of several test sections at MnROAD measured in 2010, indicating that the combination of exposed aggregate (EA) and NGCS texture is the quietest, followed by the NGCS and the combination of exposed aggregate and conventional diamond grinding surface texture. The conventional diamond grinding (CDG) surface texture shows the worst noise emission performance.

The MnROAD test results also showed that conventional diamonding grinding can obviously improve the friction performance of the test cells, but no evidence was observed for the NGCS. However, it is believed that the grooves of NGCS provide additional benefits with regard to wet weather accidents. Another friction test study conducted by the International Grooving and Grinding Association (IGGA) using the California Test Method 342 evidenced the anisotropic friction behavior of NGCS (Donavan, 2009). This method measures the friction between the tire and pavement at various angles to the driving direction. The increased friction to nonzero orientation angles validates improved driving safety by avoiding the vehicles attempting to lose control. The field test project conducted in California performed a comprehensive functionality measurement on both the conventional diamond grinding surface and NGCS (Guada et al., 2012). Test results for the seven selected pilot projects again indicate that the NGCS is quieter than the conventional diamond grinding surface. The measured average OBSI value of the NGCS is 100.8 dBA, while the value for the conventional diamond grinding surface is 102.8 dBA. The skid resistance measured through the ASTM E 274 implies that both the NGCS and conventional diamond grinding surface textures meet the specification requirement.

4. Concrete pavement evaluation based on durability of surface functionality

4.1. Durability evaluation of surface functionality for concrete pavement

The durability of the surface functionalities, which is defined as the long-term evolution of the properties, is another critical concern for the use of concrete pavement. Despite extensive research efforts into surface functionality evaluation, there is limited information available on the long-term development of various concrete pavement surface textures. Previous studies have primarily relied on the impact polishing test, which is substantially different from the actual pavement polishing effect (Wang et al., 2013). To fill this research gap, the institute of highway engineering (ISAC) at RWTH Aachen University has developed an advanced real tire polishing simulator, the Aachen polishing machine (APM), as shown in Fig. 20. Based on previous test results (Wang et al., 2014), the APM can simulate the long-term polishing effect of actual conditions. The polishing effect of the APM is mainly achieved through two real vehicle tires (Continental, 165/75 R 14 C 8 PR 97/95 R TL, Hanover, Germany). In the polishing process, the tires move back and forth horizontally 9 times/min, and the tires self-rotate 41 times/min while the sled is moving. By spreading a standard polishing agent and water over the pavement surface evenly at a rate of 27 ± 7 g/min, the APM can simulate the most unfavorable shear state of the pavement surface (Lu et al., 2020). During each polishing process, both the macro and micro texture indexes are measured, and the development of surface functionalities such as skid resistance, noise, and drainage can be evaluated accurately.

The ISAC team has also investigated the polishing resistance of four different concrete pavement surfaces using the APM test (Lu et al., 2021). The selected test surfaces include two EAC surfaces, one diamond grinding surface, and one diamond grinding & grooving surface. The

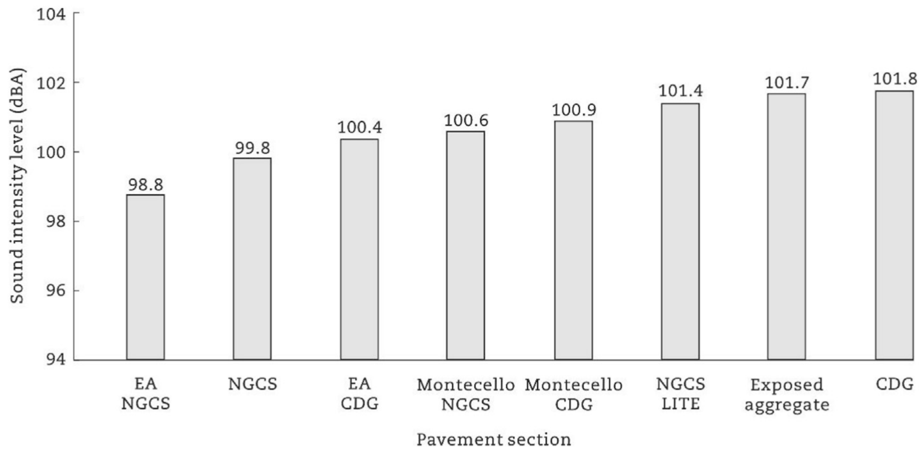

Fig. 19. Noise emission properties of several MnROAD test sections (Scofield, 2012b).

Fig. 20. The Aachen polishing machine (APM) (Wang et al, 2014).

diamond grinding and diamond grinding & grooving surfaces before and after APM polishing are shown in Figs. 21 and 22, respectively. Further measurements on the skid resistance and surface texture of the selected concrete pavement surfaces implied that the EAC surface with the aggregates of high polishing resistance shows excellent long-term surface functionality, and the diamond grinding & grooving surface exhibits better initial and long-term skid resistance than the diamond grinding surface.

4.2. Recommendations

Most of the research conducted so far has focused on the development of optimized grinding & grooving textures for concrete pavement surfaces. Machinery optimization has not been a primary area of interest as a grinding texture can be achieved using relatively simple methods. Much of the machinery has been applied merely as a means to achieve the desired texture. Nevertheless, the literature suggests that certain factors must be considered when selecting grinding machinery and auxiliary machinery. These factors include noise emissions during construction, construction speed, and the suspension of particulate matter, specifically in grinding slurry.

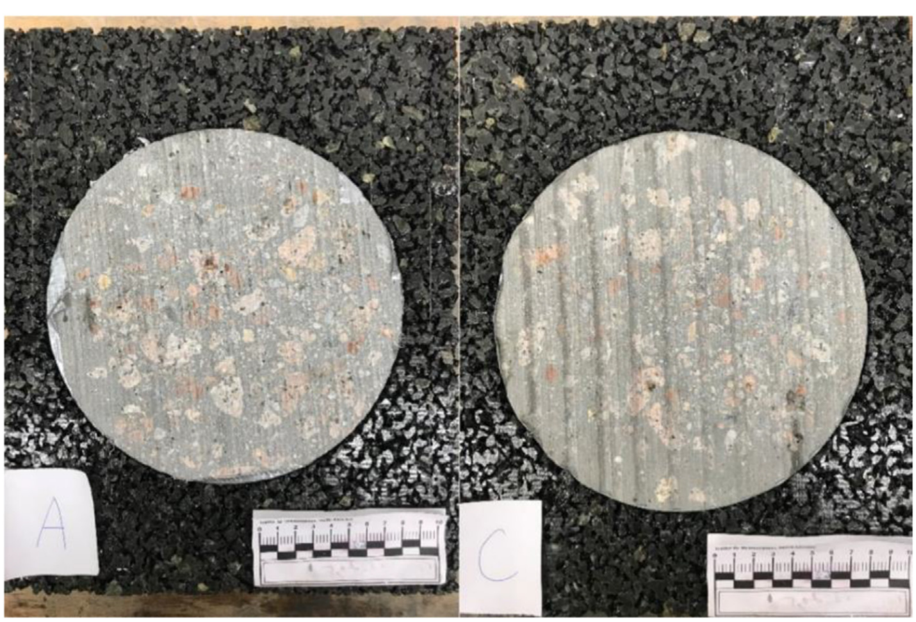

Fig. 21. The diamond grinding (left) and diamond grinding & grooving (right) surfaces before APM test (Lu et al, 2021).

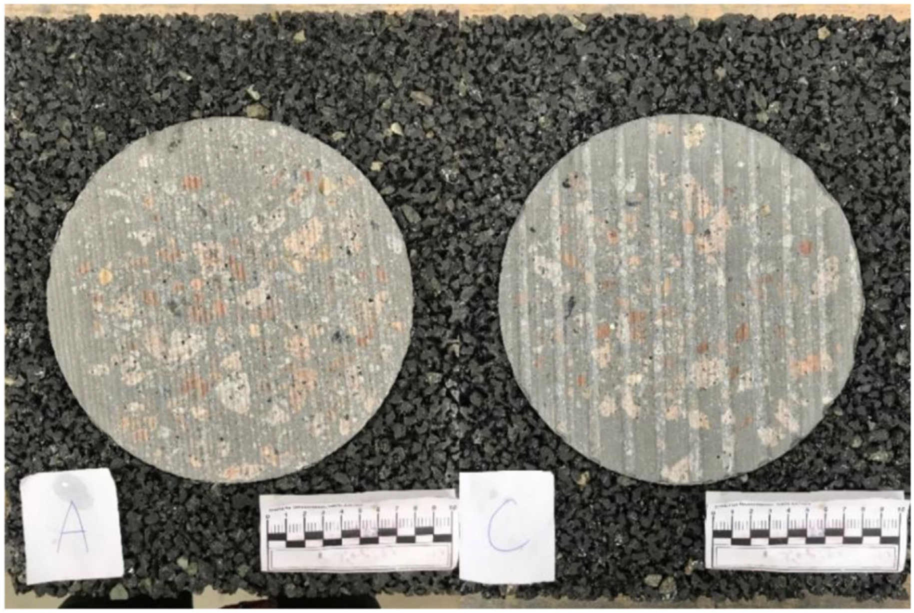

Fig. 22. The diamond grinding (left) and diamond grinding & grooving (right) surfaces after APM test (Lu et al, 2021).

The majority of grinding & grooving companies are based in the USA, but Germany also boasts numerous high-quality grinding & grooving companies. As a reference, here are some examples of USA-based companies: Diamond Grinding & Grooving, ABSL Construction, Atlantic Concrete Cutting Inc., Southeast Grinding and Grooving LLC., and Penhall Company. In Germany, there are companies like Otto Alte-Teigeler GmbH, SAT Straßensanierung GmbH, Heidelberg Cement Group, and Possehl Spezialbau GmbH that are also known for their expertise in grinding & grooving.

In addition to the machinery, several concrete pavement textures (mainly grinding and NGCS textures) are recommended based on this review for further discussion. According to the recommendations given by IGGA (International Grooving and Grinding Association, 2014) in 2014, diamond blade stacks should be arranged to provide a flush ground surface with longitudinal grooves. To achieve the flush grinding, 3.175 mm (1/8 inch) wide blades should be separated by 0.89 ± 0.13 mm (0.035 ± 0.005 inch) wide spacers. The blades used to produce the flush ground surface shall be flat across their contact surface and in the same plane as other flush grind blades (excluding grooving blades) when mounted. The longitudinal grooving blades will be spaced on 12.7–15.88 mm (1/2 inch to 5/8 inch) centers and shall produce grooves 3.175 mm (1/8 inch) in width and 1/8 inch to 3/16 inch (3.175–4.76 mm) in depth.

The A93 in Bavaria, Germany underwent rehabilitation in 2014 using only grinding, where the segment width was 2.8 mm with spacers of 1.8 mm and a depth of approximately 0.5 mm. This arrangement resulted in a noise reduction of 4 dBA. The German Federal Ministry of Transport and Digital Infrastructure (BMVI) conducted a research project in collaboration with the ISAC of RWTH Aachen University in 2021, which aimed to optimize the grinding texture and develop a new NGCS texture. The research findings, presented in Table 1, demonstrate the optimized textures and their impact on noise reduction (Villaret, 2021).

Table 1
Recommended grinding & grooving textures for noise reductions.

Texture	Grinding			Grooving		
	Segment (mm)	Spacer (mm)	Depth (mm)	Segment (mm)	Spacer (mm)	Depth (mm)
1	2.4	1.0	4.0	–	–	–
2	2.8	1.8	0.5	–	–	–
3	3.0	1.0	2.0	3.2	15.0	3.5
4	2.4	1.0	2.0	2.8	22.0	4.0

Note: 1 stands for the quietest grinding texture by ISAC (Villaret, 2021), 2 stands for the grinding texture used in Bavaria, Germany (Villaret, 2021), 3 stands for the NGCS according to IGGA guidelines (International Grooving and Grinding Association, 2014), 4 stands for the NGCS developed by ISAC (Villaret, 2021).

5. Conclusions

This review paper aims to provide an overview of the current practices in concrete pavement surface texturing and focuses on compiling current information related to the characterization of surface texture, texturing methods for fresh and hardened concrete pavement surfaces, and the friction and noise emission properties of various surface textures. The major conclusions of this study include.

(1) The NGCS texture was found to reduce the noise emission performance by 1–4 dBA, and it also provides excellent skid resistance and durability. However, it also requires high-quality construction machinery and is relatively expensive. Therefore, NGCS is well-suited for city and tunnel pavements.
(2) The optimized diamond grinding texture and exposed aggregate concrete surface were successful in reducing tire-pavement noise and improving friction performance. They can serve as promising alternatives to NGCS texture when balancing between cost and performance.
(3) Two grinding textures of ① segment/2.4 mm, spacer/1.0 mm, and depth/4.0 mm; ② segment/2.8 mm, spacer/1.8 mm, and depth/0.5 mm and two NGCS textures ① grinding: segment/3.0 mm, spacer/1.0 mm, depth/2.0 mm & grooving: segment/3.2 mm, spacer/15.0 mm, depth/3.5 mm; ② grinding: segment/2.4 mm, spacer/1.0 mm, depth/2.0 mm & grooving: segment/2.8 mm, spacer/22.0 mm, depth/4.0 mm were recommended based on extensive research work that has been subjected to sufficient experimental and field validations.

The technical parameters summarized in this paper provide convenient guidelines for the applications of diamond grinding and diamond grinding & grooving technologies. However, there still remain some other issues to be studied in the future. Investigations on the life cycle cost analysis of various texturing technologies should be carried out to support the selection of the technologies for different application scenarios. Developments of new grinding & grooving machines to improve the efficiency and reduce the cost of construction are also highly needed to promote the application of the new technologies.

Declaration of competing interest

Zhen Leng is an editorial board member of Journal of Road Engineering and Dawei Wang is a contributing editor of Journal of Road Engineering. They were not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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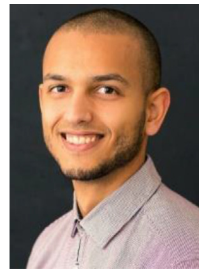

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Dr. Xi Jiang is currently working as an assistant professor (research) in the Department of Civil and Environmental Engineering at The Hong Kong Polytechnic University. He holds a PhD degree in civil engineering (pavement engineering) from the University of Tennessee, Knoxville, USA. Dr. Jiang's primary research interests lie in the field of geotechnical transportation engineering, with a particular emphasis on the development of resilient infrastructure, such as pavements and tunnels. His efforts and contributions to the field have been recognized through the publication of over 60 SCI papers. In addition to his research work, Dr. Jiang is also actively involved in professional organizations such as the ASCE (American Society of Civil Engineers) and TRB (Transportation Research Board) committees, where he actively collaborates with other professionals in his field.