Research Article

Study on the Influential Factors of Noise Characteristics in Dense-Graded Asphalt Mixtures and Field Asphalt Pavements

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Abstract

Determining the influential factors of noise characteristics in dense-graded asphalt mixtures and field asphalt pavement is important in constructing highways that are both low noise and environmentally friendly. In this study, the effects of nominal maximum aggregate size, asphalt binder type, air void percentage, and the service life of pavement on the noise absorption characteristics of asphalt mixtures were first investigated in laboratory. Hereafter, tire/pavement noise measurements were conducted on different types of dense-graded asphalt pavements. The effects of the service lives of the pavements, the types of the pavements, driving speeds, and test temperatures on the noise levels of the pavements were also studied. The Zwickerm method is used to calculate psychoacoustic parameters on the tire/pavement noise spectrum. The laboratory results indicate that reducing the nominal maximum aggregate size, using rubber asphalt, and increasing air void percentage as well as surface texture depth improve the sound absorption performance of asphalt mixtures. The field measurements show that laying down asphalt pavements with a shorter service life or larger texture depth, using rubber asphalt, reducing traffic speed, and increasing air temperature can reduce noise.

1. Introduction

Traffic noise is one of the primary contributors to sound pollution in a city [1, 2]. It has been widely recognized that traffic noise can introduce issues in long-term psychosocial health and well-being [3]. In general, traffic noise can come from four different sources: engine noise, exhaust noise, aerodynamic noise, and tire/pavement interaction noise. Among them, tire/pavement interaction is the dominant noise source for properly maintained vehicles at speeds above 50 km/h [4–7]. Therefore, knowing how to reduce tire/pavement noise plays an important role in controlling the problems associated with highway noise.

Many past studies have focused on optimizing the design and manufacture of quieter automobiles and tires [8, 9], effectively constructing sound barriers [10, 11], planting noise absorbent tree belts on both sides of a highway [12], and paving low-noise or porous pavement [13, 14]. Nevertheless, it must be noted that the reduction in the amplitude from tire/pavement noise caused by the improved design and manufacture of a car or its tire has begun exhibiting diminishing returns. On the other hand, sound barriers and noise absorbing tree belts are limited in their potential application due to the impact they have on the surrounding road space as well their engineering costs. As a result, low-noise pavement has been developed and applied in many sites to reduce tire/pavement noise [15].

Porous asphalt pavement was used mostly as the low-noise pavement of choice over the past twenty years [16]. It had been reported that the reduction on the sound pressure level of noise is 3∼5 dB for porous asphalt pavement [17]. However, porous asphalt pavement suffers from a shorter service life when compared with dense asphalt mixes, and this consideration has discouraged its widespread application [18]. In fact, most of the asphalt pavement used in worldwide highways is made of dense asphalt mixes. Therefore, how to control and reduce the tire/pavement noise from dense-graded asphalt pavement has become a central question with important strategic implications for developing quieter environment in the future. Regardless,
few studies have been conducted to investigate the noise reduction characteristics of dense-graded asphalt pavement. In this study, the influential factors of the noise reduction characteristics in laboratory compacted dense-graded asphalt mixtures are investigated first. An impedance tube experiment is conducted to analyze the sound characteristics of the mixtures. The effects of the nominal maximum aggregate size (NMAS), types of asphalt binders, and air void percentages on the noise reduction performance are studied. Here NMAS is measured specifically as one sieve size larger than the first sieve to retain more than 10 percent of the material. In addition, cored cylinder samples from three field pavements are also obtained to determine the effect of service life on noise reduction performance. Thereafter, the influential factors of noise reduction characteristics are investigated further in dense-graded field asphalt pavements. The effects of the types of asphalt binder, driving speeds, and test temperatures are studied. During field testing, the sound pressure level was used to characterize noise level. In addition, many researchers have focused on the quality of sound as well as the sound pressure level of noises with the aim of reducing the harm to human life from noise through improving sound quality. This novel aim provides a new research angle for evaluating tire-pavement noise. With this in mind, this study employs the Zwicker method to calculate and analyze tire-pavement sound quality parameters (e.g., loudness, sharpness, harshness, and fluctuation) in several field pavements [19, 20]. The findings of this study contribute to our understanding of the noise characteristics of dense-graded asphalt pavement, promoting the research on low-noise pavement and the improvement of tire/pavement noise control technology.

2. Mix Design and Sample Preparation in Laboratory

Before investigating the factors that affect noise characteristics in dense-graded asphalt concrete mixtures, the mix design for the different kinds of asphalt concrete mixtures to be used in this study was established. The detailed test results can be found in Tables 1–3. The number AH90♯ represents the virgin asphalt binder with a penetration of 80–100 (0.01 mm) following the ASTM D946/D946M-15 standard test methodology. Note that styrene-butadiene-styrene (SBS) and rubber are polymer materials used in the modification of asphalt binder.

In total, nine types of dense-graded asphalt concrete mixtures, with five gradations and five types of asphalt binders, were selected. In the line of gradations, the first number shows the NMAS, while the second number denotes the percent of aggregates that pass through the 4.75 mm sieve and settle in the 0.075 mm sieve. For example, AC16-30 translates to the asphalt concrete that has a 16 mm NMAS with 30% of its aggregates passing through the 4.75 mm sieve and settling in the 0.075 mm sieve. The detailed gradations for the experimental asphalt mixtures are presented in Table 2. After determining the gradations, a mix design was conducted. The results can be found in Table 3.

In addition, cylindrical asphalt concrete samples with a height of 4 cm, cored from three field pavement sections, were also prepared in order to investigate the effects of service lives on the noise characteristics of asphalt concrete. The varying lengths of service life for the pavements are presented in Table 4.

3. Sound Absorption Performance of Asphalt Mixtures in Laboratory

In order to reduce noise level, materials with greater sound absorption efficiency can be used. Specifically, better sound absorption performance indicates a state when most sound is absorbed by a given material and less sound is reflected back at the observer, thereby significantly reducing the noise level around the sound absorptive material [21]. There are two effective ways to characterize and measure the sound absorption performance of materials in a laboratory setting. The first is in using of a reverberation room, which has considerable costs and is typically only reserved for very particular studies. The second is by conducting an impedance tube experiment.

Past studies have shown that the impedance tube experiment is precise in its measures for the sound absorption properties of asphalt mixtures at lower frequencies [22]. The test picture and schematic plot of the impedance tube can be found in Figures 1 and 2. In this experiment, the test sample is mounted at one end of a straight, smooth, and closed impedance tube. During the measurement and calculation, the standing wave ratio method was selected to determine the sound absorption coefficients of materials. As indicated in Figure 2, the sample was put on one side of the impedance tube, while the loudspeaker on the other side produces an acoustic wave \( P_r \). The standing wave was formed due to the superposition of acoustic wave \( P_i \) and the sample’s reflected wave \( P_r \). Then the pressure maximum (antinode) \( P_{\text{max}} \) can be calculated when \( P_i \) and \( P_r \) are in phase, while the pressure minimum (node) \( P_{\text{min}} \) can be obtained when \( P_i \) and \( P_r \) are out of phase. The definitions of \( P_{\text{max}} \) and \( P_{\text{min}} \) can be expressed in (1) and (2). In the equations, \( r \) is the reflectance. The standing wave ratio \( G \) and the sound absorption coefficient \( \alpha \) can be then calculated as expressed in (3) and (4).

To reduce the relevant noise level, a material with a higher sound absorption coefficient will be sought [23].

\[
|P_{\text{max}}| = P_0 \cdot (1 + |r|),
\]

\[
|P_{\text{min}}| = P_0 \cdot (1 - |r|),
\]

\[
G = \left| \frac{P_{\text{max}}}{P_{\text{min}}} \right| = \frac{1 + |r|}{1 - |r|},
\]

\[
\alpha = 1 - |r|^2 = \frac{4 \times G}{(G + 1)^2},
\]

where \( P_0 \) is the amplitude of the acoustic wave produced by the loudspeaker and \( r \) is the reflectance which is defined to be \( P_i/P_r \).

For this study’s impedance tube experiment, details regarding testing methodology can be found in ASTM C384-04 [24]. The sound absorption coefficient for each kind of asphalt...
mixture is measured at different test frequencies. In addition, the noise reduction coefficient is calculated by finding the arithmetic mean of the sound absorption coefficients at 250, 500, 1000, and 2000 Hz [25]. A noise reduction coefficient of 0 indicates perfect reflection, while a noise reduction coefficient of 1 indicates perfect absorption. It needs to be carefully noticed that the noise reduction coefficient is just a general idea of the noise reduction effectiveness of a particular material. In order to clearly understand the sound absorption properties of materials, the sound absorption coefficients over the test frequencies have also been provided and analyzed in this study.

3.1. The Effects of Nominal Maximum Aggregate Sizes. Figure 3 presents the sound absorption coefficients of asphalt mixtures with different NMAS. As shown below, the noise reduction coefficients can be found in Table 5.

It can be seen in Table 5 that the noise reduction coefficients of the asphalt mixtures decrease with an increase in NMAS. However, the variations in sound absorption...
coefficients for the three types of asphalt mixtures shift in different frequency ranges. When the test frequency is lower than 500 Hz, the asphalt mixture with 10 mm NMAS has a higher sound absorption coefficient when compared with the AC13 and AC16 mixtures. When the test frequency is between 500 Hz and 800 Hz, the asphalt mixture with 16 mm NMAS exhibits a higher sound absorption coefficient. In addition, the asphalt mixture with 13 mm NMAS is found to have a relatively higher sound absorption coefficient at the high range of frequencies.

Therefore, it can be deduced that each asphalt mixture has its own dominant range of frequencies at which a higher sound absorption coefficient can be expected. Some past studies have indicated that the traffic noise for passenger vehicles and heavy trucks is primarily found in the frequencies around 1000 Hz and ranging from 500 to 1000 Hz, respectively [26]. As such, the type of pavement asphalt mixture to be used would best be individually recommended for specific highways with variable traffic conditions. For highways with more passenger vehicles, asphalt mixtures with a larger NMAS will have larger sound absorption coefficients and better noise reduction performance. As for highways with more heavy trucks, asphalt mixtures with a smaller NMAS are recommended.

3.2. The Effects of Asphalt Binder Types. The effect of the type of asphalt binder on the sound absorption performance of the asphalt mixture is analyzed next. The calculated sound absorption coefficients and noise reduction coefficients are presented in Figures 4 and 5.

It is interesting to note that, as seen in Figure 4, all the asphalt mixtures have a similar minimum sound absorption coefficient and similar sound absorption coefficients at the frequencies around 500 Hz. This indicates that the dense-graded asphalt mixtures exhibit poor noise reduction performance around the 500 Hz frequencies. In addition, the asphalt mixtures with different types of binders show different dominant frequency ranges from the viewpoint of noise reduction. For example, when the test frequencies are smaller than 500 Hz, the SBS modified asphalt exhibits comparably better noise reduction performance. However, the differences found among the asphalt mixtures with different binders are limited. When the test frequencies range from 500 to 1000 Hz, the virgin asphalt binder (AH90) has a relatively better noise reduction performance. The dominant frequencies for rubber asphalt mixtures are those above than 1000 Hz.

From this, we can specifically see that by adding more crumb rubber to the mixture, smaller sound absorption coefficients will be exhibited at frequencies lower than 1000 Hz while larger sound absorption coefficients will be exhibited at frequencies higher than 1000 Hz. The noise reduction coefficients can be also calculated and plotted thereafter, as seen in Figure 5. It is clear that SBS-modified asphalt and virgin asphalt binders have a similar noise reduction performance. Moreover, rubber-modified asphalt will have an even better noise reduction performance when compared with SBS-modified asphalt and virgin asphalt binders. This phenomenon had been reported by many researchers before [27–29]. A possible reason for this phenomenon is due to the better deformability of rubber asphalt, which can absorb the vibration energy of traffic vehicles and then reduce the tire/pavement noise level.

Therefore, we can see that the type of asphalt binder can be tailored in order to reduce the noise level of a given
highway. For highways with more passenger vehicles, rubber asphalt binder is to be recommended. As for highways with more heavy truck traffic, SBS-modified asphalt and virgin asphalt binders will present a relatively better noise absorption performance.

3.3. The Effects of Air Void Percentages. The effect of air void percentage on the sound absorption performance of the asphalt mixtures is investigated next. The measured results are presented in Figures 6 and 7.

It is clear that the sound absorption coefficients and noise reduction coefficients of the asphalt mixtures presented in Figures 6 and 7 increase consistently with an increase in air void percentage. Note that similar conclusions have been presented and calibrated in past studies on the topic [14–16]. A larger air void percentage means that the increased porosity in the material can be used predictably to absorb sound, resulting in a greater performance in noise reduction.

The variations of sound absorption coefficients seen in Figure 6 also tell us the respective peak frequencies for each of these asphalt mixtures. The SBS-AC10-10 and SBS-AC10-20 asphalt mixtures will exhibit greater noise reduction performance at a frequency around 800 Hz, while SBS-AC10-30 will exhibit a peak sound absorption coefficient at a frequency around 1000 Hz. However, the SBS-AC10-10 and SBS-AC10-20 asphalt mixtures (i.e., those with higher air void percentages) will have greater sound absorption performance on the entire range of tested frequencies when compared with the SBS-AC10-30 mixture. Therefore, higher levels of air void percentage can be recommended for dense-graded asphalt mixtures in order to reduce noise levels.
3.4. The Effects of Service Lives. As mentioned above, cylindrical asphalt concrete samples with a height of 4 cm were cored from three field pavement sections. The variations in their sound absorption coefficients along with their test frequencies can be found in Figure 8.

As the cored samples are characterized by relatively smoother sides when compared with the laboratory compacted asphalt mixtures, the variations in the sound absorption coefficients for cored asphalt mixture samples are different. It is clear that the cored asphalt mixture samples from the old pavement exhibit poorer sound absorption performance when compared with the pavements that have a shorter service life. A possible reason for this is that the surface texture of old pavement is simply worn out. Table 6 indicates the texture depths of the cored sample surfaces. A clear decrease in texture depth consistent with an increase in service life is observed.

In order to analyze the effects of texture depth on the sound absorption coefficients, the surface texture of the cored asphalt samples were cut with a saw. The sound absorption coefficient was measured again thereafter. The comparison of test results is presented in Figure 9. A small texture depth corresponds to a lower sound absorption coefficient. Therefore, it can be concluded that for dense-graded asphalt pavement with a long service life, some kind of construction technology (e.g., milling and grooving which can increase the texture depth of pavement) can be used to control and reduce tire/pavement noise levels. To summarize, reducing the NMAS, using rubber asphalt, and increasing the air void percentage as well as the surface texture depth can all work to improve the sound absorption performance of materials while reducing tire/pavement noise levels.

3.5. Statistical Analysis of the Test Results. In order to analyze the influential factors of noise characteristics for the laboratory compacted and cored asphalt concrete samples, statistical analyses are conducted. As to the different side surface characteristics, the laboratory compacted and cored asphalt concrete samples are analyzed, respectively. The stepwise regression analysis method is selected to analyze the significance of the influential factors. For this statistical analysis, the sound absorption coefficient was selected as the dependent variable. The test frequency, viscosity of asphalt binder at 175°C (which can differentiate the mechanical properties of asphalt binder and represent different types of asphalt), NMAS, and air void percentage were selected as the independent variables for the laboratory compacted asphalt sample, expressed as \( X_1, X_2, X_3, \) and \( X_4 \). The results presented in Table 7 show that the test frequency and air void percentage play the most important role in determining noise absorption performance.

A similar statistical analysis is conducted on the cored asphalt concrete samples. The test frequency, service life, and surface texture depth were selected as the independent variables, expressed as \( X_1, X_2, \) and \( X_3 \). The results presented in Table 8 show that all the three factors play an important role in determining the noise absorption performance of a mixture.

4. Noise Characteristics for the Dense-Graded Field Asphalt Pavement

4.1. Test Pavement Conditions and Test Description. Three pavements with the same AC13 asphalt concrete layers, but varying service lives, were selected first to analyze noise levels. Details can be found in Tables 4 and 6. In addition, in order to
Table 7: Results of the stepwise regression analysis on the laboratory compacted asphalt samples.

| $F$ statistic | $X_1$ | $X_2$ | $X_3$ | $X_4$ |
|--------------|-------|-------|-------|-------|
| Significance |       |       |       |       |

Table 8: Results of the stepwise regression analysis on the cored asphalt concrete samples.

| $F$ statistic | $X_1$ | $X_2$ | $X_3$ |
|--------------|-------|-------|-------|
| Significance |       |       |       |

analyze the influential factors of both tire/pavement sound quality and noise level, three types of dense-graded asphalt concrete pavement samples containing SBS-AC13, AR-AC13, and SBS-SMA13 located in Beijing were found. SMA here denotes stone mastic asphalt, one specific type of dense-graded asphalt concrete characterized by a larger surface texture depth. These sample pavements were exposed to a natural traffic environment and aged 3–6 years without any overhaul. The pavement conditions are presented in Table 9. Five driving speeds (40 km/h, 50 km/h, 60 km/h, 70 km/h, and 80 km/h) were measured to study the effect of vehicle speed on noise level and noise quality. Three test temperatures (30°C, 20°C, and 0°C) were also selected for the analysis. During field measurements, the tire/pavement noise spectrum was measured using a tire-pavement noise detection trailer according to the close proximity method [30]. The test tires and microphones were placed in a closed system installed in the test trailer. During testing, the trailer moves forward at a specified speed. Four microphones installed next to the test tire are then used to collect the continuous sound pressure level from the tire/pavement noise emitted at the given speed. Examples of the tested tires and their respective measuring devices can be found in Figure 10.

To avoid introducing external variables, only one specific type of tire was used: the Dunlop GRANDTREK AT20 265/65R17 112S. The numbers and letters denote that the tire has a 265 mm normal width cross section, a 65% height to width aspect ratio, and a 17 inch wheel diameter.

4.2. The Method to Calculate the Sound Pressure Level of Noise Spectrum and Sound Quality Parameters. Tire-pavement noise data were collected and sorted using the four channel data processing system developed by the Beijing Shengwang Commercial Company (BSWA). During data collection and treatment, an A-weighting curve was utilized to define the various international standards generally used for measuring sound levels. Note that this method is widely used for environmental noise measurement. Specifically, a 1/3 octave A-weighted sound pressure level was adopted for this study. As to the evaluation index for sound quality, loudness, sharpness, harshness, and fluctuation were selected, as explained above. Calculating the sound quality parameters was conducted using the Zwicker method, which is based primarily on the 1/3 octave spectrum. The audible noise frequency band is divided into 24 critical bands (on the Bark scale), as seen in Table 10.

Loudness ($N$) is a perceptual measure in which people judge the intensity of a sound, and it is dependent upon their hearing. It is a subjective feeling of both sound volume and intensity. Here, it is calculated by integrating the characteristic value of loudness at each critical band. The formula for calculating the specific value of loudness ($N$) and the excitation level of critical bandwidth is presented as follows:

$$N' (z) = 0.08 \frac{E_{TQ}}{E_0} 0.23 \left[ \left( \frac{0.5 + 0.5 \frac{E}{E_{TQ}}} {E_{TQ}} \right) - 1 \right].$$

where $E_{TQ}$ is the excitation of absolute audible threshold in quiet conditions, $E_0$ is the excitation under reference sound intensity, $E$ is the corresponding excitation of calculated sound, and $N' (z)$ is the loudness at the specified frequency band number $z$.

The variables $E_{TQ}$, $E_0$, and $E$ can be obtained in field data collection. The total loudness ($N$) can be calculated by integrating $N'$ on bands 0–24 using the following formula:

$$N = \int_0^{24} N' (z) \, dz.$$  \hspace{1cm} (6)

Sharpness ($S$) is a parameter that describes the proportion of high frequency components in the sound spectrum. The variable reflects the cacophony of sound signals. The calculation formula is shown as follows:

$$S = 0.11 \int_0^{24} \frac{N' (z) g(z) \, dz}{\int_0^{24} N' (z) \, dz}.$$ \hspace{1cm} (7)

The weighted item $g(z)$ is expressed by (8). The variable $z$ represents band number.

$$g(z) = \begin{cases} 1, & (z < 16), \\ 0.066 0.171, & (z \geq 16). \end{cases} \hspace{1cm} (8)$$

Harshness ($H$) denotes the psychoacoustic parameter, which describes the modulation amplitude and modulation frequency distribution of the sound signal. The calculation formula is presented as follows:

$$H = 0.3 f_{mod} \int_0^{24} \Delta L_E (z) \, dz,$$

$$\Delta L_E (z) = 10 \log_{10} \left( \frac{N'_{max} (z)}{N'_{min} (z)} \right).$$ \hspace{1cm} (9)

where $\Delta L_E$ is the variation of excitation level, $f_{mod}$ is the modulation frequency (kHz), $N'_{max}$ is the specified maximum loudness in a critical band, and $N'_{min}$ is the specified minimum loudness in a critical band.

Fluctuation ($F$) describes the level of sensitivity in the human ear to slowly modulated sound, reflecting the subjective feelings affected by fluctuation degree of sound loudness. The formula for calculating fluctuation is shown as follows:

$$F = 0.008 \int_0^{24} \frac{\Delta L_E (z) \, dz}{f_{mod} f_0 + (f_0 / f_{mod})},$$ \hspace{1cm} (10)

where $f_0$ is the modulated fundamental frequency of 4 Hz.
4.3. Influential Factors of Noise Characteristics in Dense-Graded Field Asphalt Pavement

4.3.1. The Effects of Service Lives and Driving Speeds.

Three dense-graded asphalt pavement samples with variable service lives (denoted Xingsheng Road-Section 1, Xingsheng Road-Section 2, and Fengxiang Street) were selected to study the effects of service lives on tire/pavement noise pressure levels. The results are plotted in Figure 11.

It is clear that noise pressure level increases correspond with an increase in the service life of the pavement and driving speed. This variation in field tire/pavement noise level is similar to that for the cored asphalt samples (presented in Figure 8). In considering the similar gradation of the asphalt mixtures but variable service lives and surface texture depths, best practices for noise reduction regarding dense-graded asphalt pavement can be recommended. As noted above, some kind of technology (e.g., milling and grooving) can be utilized to reduce the field tire/pavement noise pressure level for these ends.

4.3.2. The Effects of Asphalt Pavements Types and Driving Speeds.

The same noise measurements were conducted on the three pavements containing SBS-AC13, AR-AC13, and SBS-SMA13 asphalt concrete mixtures. As noted above, noise quality and noise pressure levels were measured and calculated for the three pavements. The results are presented in Figures 12–16. Note that AC, SMA, and AR denote the SBS-AC13, SBS-SMA13, and AR-AC13 mixtures, respectively, in Figures 12–16.

As seen in Figures 12–16, the significant effects of driving speeds on noise pressure levels and sound quality are evident. Therefore, something as simple as lowering or more rigorously enforcing speed limits presents a preliminary solution for reducing the tire/pavement noise level and loudness of traffic noise, particularly for urban areas. Similar with the findings from testing the laboratory compacted

| Pavement type | Age (year) | Thickness (cm) | Surface texture depth (mm) | Evenness (standard deviation, mm) | Air void percentage of cored sample (%) | Pavement deflection (0.1 mm) |
|---------------|------------|----------------|---------------------------|-----------------------------------|----------------------------------------|-----------------------------|
| SBS-AC13      | 3          | 4              | 0.85                      | 1.4                               | 5.7                                    | 13.8                        |
| SBS-SMA13     | 5          | 4              | 1.10                      | 1.1                               | 4.9                                    | 13.1                        |
| AR-AC13       | 6          | 4              | 1.00                      | 1.2                               | 4.5                                    | 14.3                        |

Table 9: Critical band and frequency.

| Critical band | Frequency (Hz) | Bandwidth |
|---------------|----------------|-----------|
| 1             | 0~100          | 100       |
| 2             | 100~200        | 100       |
| 3             | 200~300        | 100       |
| 4             | 300~400        | 100       |
| 5             | 400~510        | 110       |
| 6             | 510~630        | 120       |
| 7             | 630~770        | 140       |
| 8             | 770~920        | 150       |
| 9             | 920~1080       | 160       |
| 10            | 1080~1270      | 190       |
| 11            | 1270~1480      | 210       |
| 12            | 1480~1720      | 240       |
| 13            | 1720~2000      | 280       |
| 14            | 2000~2320      | 320       |
| 15            | 2320~2700      | 380       |
| 16            | 2700~3150      | 450       |
| 17            | 3150~3700      | 550       |
| 18            | 3700~4400      | 700       |
| 19            | 4400~5300      | 900       |
| 20            | 5300~6400      | 1100      |
| 21            | 6400~7700      | 1300      |
| 22            | 7700~9500      | 1800      |
| 23            | 9500~12000     | 2500      |
| 24            | 12000~15500    | 3500      |

Table 10: Technical parameters of sample asphalt pavement.
asphalt mixtures (presented in Figure 4), the use of more elastic rubber asphalts in dense-graded asphalt pavement can help to reduce the tire/pavement noise pressure level and loudness of traffic noise as well. Although the SBS-AC13 pavement has minimal service life, which in fact is helpful in the reduction of tire/pavement noise, the larger surface texture depth in the SBS-SMA13 pavement can help to absorb the noise differential. Therefore, it is recommended that SMA mixtures and rubber asphalt binders be used to replace standard asphalt concrete mixtures and unmodified asphalts when the noise control is a consideration.

With an increase in driving speed (ranging 50 km/h ∼ 80 km/h), the tire-pavement noise sharpness for the SBS-AC13 pavement exhibits small variation. However, the tire-pavement noise sharpness for the SBS-SMA13 and AR-AC13 pavements exhibits peak values at speeds of around 70 km/h. This observation may be attributed to the similar surface texture depths for the SBS-SMA13 and AR-AC13 pavements. With this consideration, a traffic speed limit can be proposed based on the variation in noise sharpness so as to avoid the excessive noise pollution. To sum up, the sharpness of the SBS-AC13 pavement is lower than that of the SBS-SMA13 and AR-AC13 pavements. This means that for the SBS-AC13 pavement, the high frequency component in the noise spectrum is relatively small and exhibits only slight variation when speed is changed. Therefore, it is likely that a larger surface texture depth has a negative influence on the variation of tire/pavement noise.

Harshness and fluctuation are used to describe the feelings conjured in humans when noise signals vary. The
4.3.3. The Effects of Test Temperatures. Tire/pavement noise was also measured at different air temperatures. One of the objectives behind this study is to investigate the variation in noise pressure levels at different seasons. During the field measurements included in this study, only two kinds of asphalt pavements (containing AR-AC13 pavement and SBS-SMA13 pavement) were selected. A speed of 50 km/h was decided upon as the test’s driving speed. Measurements were taken, and the noise spectrum was plotted (see Figures 17–19).

A peak noise level value at around 1000 Hz can be found for the AR-AC13 and SBS-SMA13 pavements at different test temperatures. Considering the dominant frequency of noise caused by passenger vehicles, the passenger vehicle can be regarded as the primary source of tire/pavement noise in light of this finding. In addition, the comparisons of noise levels between the AR-AC13 and SBS-SMA13 pavements are different at various frequency ranges. When the test frequency is smaller than 500 Hz, the AR-AC13 pavement exhibits greater noise when compared to the SBS-SMA13 pavement. When the frequency is greater than 500 Hz, it is the SBS-SMA13 pavement that produces the greater noise. Therefore, in considering the different dominant noise frequencies for passenger vehicles and heavy trucks [26], the AR-AC13 pavement is recommended for paving highways predicted to experience large volumes of passenger vehicle traffic. As for highways that will see more heavy trucks, the SBS-SMA13 pavement would be more suitable for controlling tire/pavement noise levels.

Specifically, the effects of the test temperatures on the noise emitted by the AR-AC13 and SBS-SMA13 pavements can be found in Figures 20 and 21.

It can be seen from Figures 20 and 21 that although lower test temperatures can induce higher levels of tire/pavement noise, the differences in the noise levels at different temperatures are not significant. Specifically, the difference is only about 2–3 dB for temperatures between 0 °C and 20 °C. Therefore, the noise issues in colder regions or seasons are more urgent than for warmer climates. This phenomenon can be attributed to the brittle property of asphalt mixtures in cold temperature, which works to reduce their sound absorption performance.

4.4. Statistical Analysis of Field Test Results. A similar stepwise regression statistical analysis is conducted to investigate the influential factors of noise levels for dense-graded field asphalt pavement [31]. The noise pressure level functions as the regression’s dependent variable, while driving speed, service life, air void percentage, texture depth, the viscosity of the asphalt binder at 175°C, and measurement temperature function as independent variables (expressed as $X_1, X_2, X_3, X_4, X_5,$ and $X_6,$ resp.). Table 11 presents the analysis results.

Driving speed, service life, asphalt type, and measurement temperature noticeably affect the noise level of dense-graded field asphalt pavement. The statistical insignificance exhibited for air void percentage, texture depth, and type of asphalt binder can be attributed to the small quantity of selected representative samples.
5. Conclusions and Recommendations

This study has investigated the influential factors of noise characteristics in dense-graded asphalt mixtures and field asphalt pavements. The paper’s findings can be used to guide noise control design and policy for the most widely used dense-graded asphalt mixtures and pavements. Specifically, the following conclusions and recommendations are offered in light of the findings:
(1) For highways with greater passenger vehicle traffic, asphalt mixtures with a larger NMAS that use rubber asphalt binders will have superior noise reduction performance. As for highways with greater heavy truck traffic, asphalt mixtures with a smaller NMAS, SBS modifications, and virgin asphalt binders are recommended for reducing tire/pavement noise. The comparisons of noise reduction coefficients conducted in this study indicate that asphalt mixtures with a smaller NMAS and rubber asphalt exhibit superior noise reduction performance.

(2) Larger air void percentages in dense-graded asphalt mixtures exhibit superior sound absorption and noise reduction performance. Therefore, in order to reduce the noise level, increasing air void percentage is recommended for dense-graded asphalt mixtures so long as the durability of the mixtures can be retained.

(3) Pavements with a longer service life exhibit inferior noise absorption performance and large noise levels, which has been shown by laboratory test results of the cored asphalt concrete as well as by field noise measurements. The surface texture depth of pavement was found to play a key role in determining the noise reduction characteristics. Improvements in milling and grooving technology can be utilized to reduce the field tire/pavement noise level for dense-graded asphalt pavement therein.

(4) Field measurement results indicate that the reasonable control of traffic speed limits and the use of rubber asphalt can help to reduce tire/pavement noise and noise loudness for dense-graded asphalt pavement.

(5) Field measurement results also indicate that AR-AC13 pavement can emit smaller levels of noise for highways with a large volume of passenger vehicles, while SBS-SMA13 pavement is more suitable for controlling the tire/pavement noise levels for highways with more heavy truck traffic. This recommendation derives from both field testing as well as laboratory testing.

(6) The tire/pavement noise level in dense-graded asphalt pavement increases when the air temperature gets cooler. Therefore, stricter noise control policies should be considered for locales that experience lower temperatures in general.

In this study, it has been found that the effects of asphalt pavement types and driving speeds on the specific sound quality parameters of sharpness, harshness, and fluctuation are still not clear. Future research is needed to analyze these subjective parameters further.

Data Availability

The test data in lab and in field used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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References

[1] E. Freitas, C. Mendonca, J. A. Santos, C. Murteira, and J. P. Ferreira, “Traffic noise, abatement: how different pavements, vehicle speeds and traffic densities affect annoyance levels,” Transportation Research Part D: Transport and Environment, vol. 17, no. 4, pp. 321–326, 2012.
[2] G. Bluum, E. Nordling, and N. Berglind, “Road traffic noise and annoyance—an increasing environmental health problem,” Noise Health, vol. 6, no. 24, pp. 43–49, 2004.
[3] E. Öhrström, A. Agge, and M. Björkman, “Sleep disturbances before and after reduction in road traffic noise,” in Proceedings of the 7th International Congress on Noise as a Public Health Problem: Noise Effects 98, Sydney, NSW, Australia, 1998.
[4] R. Bernhard, R. Wayson, J. E. Haddock et al., An Introduction to Tire/Pavement Noise of Asphalt Pavement, Asphalt Pavement Alliance, Lanham, MD, USA, 2004.
[5] R. M. Larson and B. O. Hibbs, “Tire pavement noise and safety performance,” in Proceedings of International Symposium on Pavement Surface Characteristics, Christchurch, New Zealand, September 1996.
[6] U. Sandberg and J. A. Ejsmont, Tyre/Road Noise Reference Book, Informex, Kisa, Sweden, 2002.
[7] O. Sirin, “State-of-the-art review on sustainable design and construction of quieter pavements-part 2: factors affecting tire-pavement noise and prediction models.” Sustainability, vol. 8, no. 7, p. 692, 2016.
[8] M. D. Rao, “Recent applications of viscoelastic damping for noise control in automobiles and commercial airplanes,” Journal of Sound and Vibration, vol. 262, no. 3, pp. 457–474, 2003.
[9] J. Winroth, W. Kropp, C. Hoever, T. Beckenbauer, and M. Mannel, “Investigating generation mechanisms of tyre/road noise by speed exponent analysis,” Applied Acoustics, vol. 115, pp. 101–108, 2017.
[10] P. Reiter, R. Wehr, and H. Ziegelwanger, “Simulation and measurement of noise barrier sound-reflection properties,” Applied Acoustics, vol. 123, pp. 133–142, 2017.
[11] J. Bull, G. Watts, and J. Pearse, “The use of in-situ test method EN 1793-6 for measuring the airborne sound insulation of noise barriers.” Applied Acoustics, vol. 116, pp. 82–86, 2017.
[12] T. Van Renterghem, “Guidelines for optimizing road traffic noise shielding by non-deep tree belts,” Ecological Engineering, vol. 69, pp. 276–286, 2014.
[13] K. Kowalski, R. McDaniel, A. Shah, and J. Olek, “Long-term monitoring of noise and frictional properties of three pavements: dense-graded asphalt, stone matrix asphalt, and porous friction course,” Transportation Research Record: Journal of the Transportation Research Board, vol. 2127, no. 1, pp. 12–19, 2009.
[14] L. Chu, T. F. Fwa, and K. H. Tan, “Evaluation of wearing course mix designs on sound absorption improvement of
porous asphalt pavement,” Construction and Building Materials, vol. 141, pp. 402–409, 2017.

[15] A. Smit, M. Trevino, N. Z. Garcia, P. Buddhavarapu, and J. Prozzi, “Selection and design of quiet pavement surfaces,” FHWA/TX-16/0-6819-1, Texas Department of Transportation and the Federal Highway Administration, Austin, TX, USA, 2016.

[16] Y. Ding and H. Wang, “FEM-BEM analysis of tyre-pavement noise on porous asphalt surfaces with different textures,” International Journal of Pavement Engineering, pp. 1–8, 2017.

[17] P. Herrington, S. Reilly, and S. Cook, “Porous asphalt durability test. Transfund New Zealand research,” Report No. 265, Transfund, New Zealand, 2005.

[18] J. P. Wu, P. R. Herrington, and D. Alabaster, “Long-term durability of epoxy-modified open-graded porous asphalt wearing course,” International Journal of Pavement Engineering, pp. 1–8, 2017.

[19] E. Zwicker and H. Fastl, Psychoacoustics-Facts and Models, Springer Verlag, Heidelberg, Germany, 1990.

[20] E. Zwicker, “A proposal for defining and calculating the unbiased annoyance,” in Contributions to Psychological Acoustics, pp. 187–202, Oldenburg University Library, Oldenburg, Germany, 1991.

[21] S. Amares, E. Sujatmika, T. W. Hong, R. Durairaj, and H. S. H. B. Hamid, “A review: characteristics of noise absorption material,” Journal of Physics: Conference Series, vol. 908, article 012005, 2017.

[22] K. Vissamraju, Measurement of Absorption Coefficient of Road Surfaces Using Impedance Tube Method, Auburn University, Auburn, AL, USA, 2005.

[23] X. Tang, X. Zhang, H. Zhang, Z. Zhuang, and X. Yan, “Corn husk for noise reduction: robust acoustic absorption and reduced thickness,” Applied Acoustics, vol. 134, pp. 60–68, 2018.

[24] ASTM C384–04 (2016), Standard Test Method for Impedance and Absorption of Acoustical Materials by Impedance Tube Method, ASTM International, West Conshohocken, PA, USA, 2016.

[25] M. J. Crocker, Handbook of Acoustics, Vol. 77, John Wiley & Sons, Hoboken, NJ, USA, 1998.

[26] J. L. Rochat and D. Reiter, “Highway traffic noise,” Acoustics Today, vol. 12, pp. 38–47, 2016.

[27] M. Fickes, ”The asphalt rubber,” Hot Mix Asphalt Technology, pp. 20–23, 2003, http://asphaltrubber.org/art/Noise/The_Asphalt_Rubber_Phenomenon.pdf.

[28] H. Barry Takallou, C. Ashcroft, and D. D. Carlson, “Tire recycling contributions to safety, noise reduction, and long term performance in high ways using asphalt-rubber,” in Rubber Pavements Association Seminar Specification Handbook, Rubber Pavements Association Inc., Tempe, AZ, USA, 2012.

[29] D. D. Carlson, “Noise reduction and asphalt rubber,” in Proceedings of the Asphalt Rubber Greenbook Workshop, UCSB, Santa Barbara, CA, USA, August 2002.

[30] International Organization of Standardization. ISO/CD 11819–2, Acoustics—Method for Measuring the Influence of Road Surfaces on Traffic Noise—Part 2: the Close-Proximity Method, ISO, Geneva, Switzerland, 2000.

[31] A. Calixto, F. B. Diniz, and P. H. T. Zannin, “The statistical modeling of road traffic noise in an urban setting,” Cities, vol. 20, no. 1, pp. 23–29, 2003.
