International Journal of Sustainable Built Environment (2016) 5, 183–196

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International Journal of Sustainable Built Environment

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Original Article/Research

Effects of double layer porous asphalt pavement of urban streets on noise reduction

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Received 6 June 2014; accepted 12 February 2016

Abstract

Road traffic is the major noise source that impacts the largest numbers of city dwellers. Urban traffic noise control at the source typically involves providing quieter i.e. low noise pavement and regular maintenance. The aim of this paper is to propose a double-layer porous asphalt pavement for keeping the traffic noise at a low level with good durability. It contains the top layer of fine aggregates and bottom layer of course aggregates. The noise-absorption performance of this asphalt pavement is evaluated by adjusting the parameters of the pavement structure simulated in air–solid coupled numerical models. The reduction of noise by using the newly proposed asphalt pavement is compared with those of the traditional pavements such as the thin surfacing (TSF) with small aggregates and rubberized asphalt pavement (RAP). The results from the outdoor noise tests for the double-layer porous asphalt pavement verifies the virtual pavement models and noise reduction effects in practice. This asphalt pavement is designated to lower the noise level of urban road traffic and boost the living environments of the city dwellers.

Keywords: Low noise; Asphalt pavement; Double-layer; Porous

1. Introduction

As the city populations have grown in recent decades, so have the volumes of traffic on the streets and the noise levels the traffic generates. Noise is often defined as 'unwanted sound' and widely recognised as a form of environmental pollution (Federal Aviation Administration, 2004; Wakefield Acoustics, 2005). It could interfere with activities like speech and sleep and cause annoyance and fear. Therefore guidelines for acceptable levels of urban noise, especially traffic noise as its major source (Wang, 2007) have been established in many countries (Zhang and Wang, 1996; Berglund et al., 1999; Wakefield Acoustics, 2005; Environment Protection Authority (EPA), 2008). For example the widely referenced 24-h average noise level of 55 dB ($L_{Aeq,24h} = 55$ dB) was established for urban street traffic noise by the Canada Mortgage and Housing Corporation (CMHC, 1986). The maximal levels of acceptable noise for different activities were respectively regulated in World Health Organisation (WHO, 2009).

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Peer review under responsibility of The Gulf Organisation for Research and Development.

http://dx.doi.org/10.1016/j.ijsbe.2016.02.001

WHO argued that for a good night sleep the sound level should not exceed 30 dB for continuous background noise and individual noise events exceeding 45 dB should be avoided. In Environment Protection Authority (EPA, 2008) the noise levels for different types of activities in urban areas such as construction, road repair and maintenance, domestic refuse collections, aircrafts and helicopters were managed on varied periods of time on weekdays and weekends.

Methods to control traffic noise at low levels are generally from three aspects: at the source, along the sound path and at the receiver. Noise control at the source typically involves providing inherently quieter i.e. low noise pavements and vehicle tiers for less noise generation. Once the noise has been created and escaped from the source ways to prevent it from reaching the receivers may include noise barriers such as screens, solid fences, non-sensitive buildings and rows of trees. Noise control at the receiver may involve the upgrading of windows, doors and walls.

It is not surprising that low noise pavements have been receiving growing interests as the very effective way of noise reduction. Existing low noise pavements typically include (1) porous asphalt pavements such as the Open-Graded Friction Course (OGFC) developed in the USA (Leasure and Bender, 1975; Zhu, 2003; Putman, 2012) and used across European countries (Federal Highway Administration, 2005; Morgan, 2006). Porous asphalt pavements were initially designed to provide drainage and reduce surface water and spray during heavy rainfall. It was found out that these pavements also have acoustic benefits (Shen, 1994; Lin, 1992; Ministry of Transport, 2012). These asphalt mixture contains a small amount of aggregates entailing pavements with relatively large air voids. These connected air voids absorb a large amount of noise generated by the interaction between the vehicle tires and pavements. (2) Very thin small aggregates asphalt pavements: Most of the pavements are produced by hot-mix materials being laid to a thickness of between 20 and 40 mm. Products of asphalt mixture such as SMA10 (Stone Mastic Asphalt), SMA5 and Ultra-Thin Asphalt (APRG, 1999) have been developed to provide sustainable, quiet and durable pavements. The air voids of the asphalt mixture are large thus the traffic noise is absorbed during its downward transmission. The rough surface of thin layer pavements also repeatedly reflects the noise and at the same time absorbs the vibration energy due to its small aggregates and consequently deep texture depth. (3) rubberised asphalt pavements: Asphalt mixture used in these pavements contains reclaim crumb rubber (10–20%) to improve the elasticity of asphalt mastic. The toughness and durability of the pavement is enhanced in the way that the cracks and rutting are reduced markedly (Piggott and Woodhams, 1979). The deformation of pavements under the vehicle wheels dissipates the sound energy. The viscous–elasticity of rubber ensures conservation and absorption of the noise due to the complex deformation of its molecule chains. Traffic noise on the rubberised pavements can be significantly reduced (Cao and Ren, 2007). The used rubber tires as the material source of rubber are recycled (Piggott and Woodhams, 1979).

The effects of low noise pavements described earlier have been measured and compared in several studies (Shen, 1994; Lin, 1992; Morgan, 2006). In these studies the range of noise levels encountered from different types of vehicle traveling on different types of pavements with various ranges of speeds has been illustrated. It has been concluded that average noise levels at thin surfacing tend to be 3 dB lower for cars and 1 dB for heavy vehicles than at asphalt concrete. Porous pavements provide average noise reductions of 3–4 dB (Anderson et al., 2005). Analysis has shown that the use of rubberised asphalt pavements can reduce average noise level of 4 dB on the investigated road sections (1999). The performances of noise reduction would be deteriorated along with the ageing of the pavements especially the porous ones. Thin surfacing and rubberised asphalt pavements have a long durability however the effects of noise reduction are less significant than porous asphalt pavements.

In this paper a double layer porous asphalt pavement is proposed for sustainable noise reduction with a long service life. The top layer of the pavement contains fine aggregates while the below layer contains course ones with larger air void ratios. The top later is designed to avoid clogging and pavement material loosing and lost. The air voids in the two layers are connected to ensure the drainage of rain water for avoiding spray and splash. The air voids also acting as the mitigation tubes of air flow pressed by the rolling tires can reflect and absorb the noise energy. This pavement incorporates the benefits of single layer porous asphalt pavements and thin surfacing pavements as will be illustrated in the following sections.

In Section 2 the mechanism of noise reduction of porous asphalt pavement is illustrated. The numerical model of the double layer porous pavement is established in Section 3 with appropriate structure parameters. In Section 4 specimens of double layer porous pavements, thin layer pavements and rubberised asphalt pavements are produced for indoor noise measurement tests. Outdoor tests are also introduced in this section.

2. Mechanism of noise reduction of porous asphalt pavements

Porous asphalt pavement as one of the major low noise pavement has a relatively high air void ratio between 15% and 20%. These air voids are distributed within the asphalt mix being connected with each other and the outside air. When the sound wave reaches the pavement, part of it is reflected back from the surfaces and another part is transmitted through the interior structure of the pavement. During the transmission the air in the voids is vibrated. The generated sound energy is transmitted into heat energy due to the friction at the solid walls of voids. The reflected sound wave may be transmitted into the surface again when it reaches the surface the second time or for more times. The sound energy is transferred and dissipated, in other words absorbed by the pavement.

The pavement can be considered to be by structure porous sound absorption material with solid skeletons in acoustics. The pavement surfacing is considered to be composed of cavity resonance sound absorption structures as shown in Fig. 1 (Wei and Kong, 2004; Tao, 2006).

The Helmholtz resonance structure in Fig. 1(a) contains a cavity surrounded by a closed container and connected with the outside air through a hole with a small diameter and depth compared to the volume of the cavity. When the depth t and diameter d is much smaller than the sound wavelength, the elasticity of the air column within the hole is neglected and the air column is assumed to be a mass point without deformation. The air in the cavity is assumed to be an air spring under the elastic vibration of the sound wave. The structure can be depicted as a spring oscillator as shown in Fig. 1(b). When the incident sound frequency is in the same pace with the inherent frequency of the spring system, the air column is in violent vibration due to the resonance. The sound energy is dissipated during the friction between the air column and side walls of the hole.

The performance of the sound absorption of the porous pavement is dependent upon its dynamic response under the pressure of the sound wave and interaction between the air media transmitting the sound wave and solid material in the surfacing. Factors such as the air void ratio, texture pattern and thickness of the surfacing and the structures of the air voids may impose different impacts on the sound absorption performance (Xue, 2009). Generally the larger the air void ratio the larger absorption coefficient (defined in Section 3). The larger surfacing thickness the more amount of low frequency sound is absorbed. The texture pattern of the pavement surfacing contains roughness and texture depth. Appropriate parameters of the pavement surfacing are selected based on the numerical coupling model of air and pavement established in ABAQUS.

The coupling model of the sound and structure for the pavement surfacing is established to stimulate the interaction between the sound flow field and sound absorption structure. The cavities between the lumps of the tire patterns are filled with air. The vibrations of the tire and

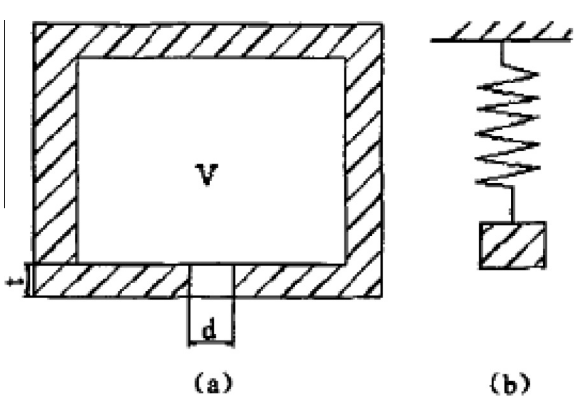


Figure 1. Cavity resonance sound absorption structure.

pavements lead to the vibration of the cavity air thus generating noise. The vibrations themselves also generate sound wave being radiated to the outside air filed. The deformation of the tire and pavement layer would also lead to the change of air volume thus more noise is created. Since the air does not possess mechanical behaviours the division of air elements is adjusted after each analysis step in the model. The purpose is to guarantee the acceptable gaps between the air and structure when the pavement is deformed greatly.

The finite element models in ABAQUS have limited sizes however the air is boundless so is the transmission of sound. Therefore the boundaries of air in the coupling model are defined as *Non reflecting radiation boundaries. Fig. 2 shows the coupling finite element models used for the analysis of the impact of vehicle speeds (a) and vibration intensities (b). In Fig. 2(a) the tier is simply modelled as a cuboid spread with surface patterns. The pavement structure is modelled as a much larger cuboid with texture depth and inside air voids. The air is simplified as a quarter of a sphere. In Fig. 2(b) the tier is modelled in its typical real shapes while the air is presented as a cuboid.

The surfacing structure is modelled as being linearly elastic. The structure is composed of solid elements of C3D8 while the outside sound field contains sound media elements of AC3D8 defined in ABAQUS. These two groups of elements are connected by the 'tie' command. The size of the elements is smaller than one over twelve of the sound wave. The incident and reflected sound wave are separated under the loaded harmonic sound waves. The distance between the loading positions of the wave and reflective surface is larger than six times of the sound wavelength, i.e. 50 cm from the pavement surface. The 'incident wave' command is used to load vertical sound waves. The difference between the sound pressure of the incident and reflective sound wave is measured to calculate the sound absorption coefficient of the structure material.

A cubic structure is created presenting a small portion of the pavement surfacing as shown in Fig. 3(a). Its size is 2 by 2 by 7 cm. Cubic columns running through the block are evenly distributed and the cross section of the structure is shown in Fig. 3(b). The side length of each cubic hole in the cross section is d and the hole distance is e. The correspondent values between the two parameters and air void ratio are shown in Table 1.

One of the sound cavities, i.e. vertical column in the cubic structure is extracted for analysis when the incident sound wave is vertically imposed. The boundaries of the extracted subject are the sides of its neighbouring holes. In the right diagram of Fig. 3, the analysis boundary of the objective cavity (shaded) is the dotted-line box.

The density and volume modulus of the air is 1.2 kg/m^3 and 142,000 Pa respectively. The sound speed in the air is 340 m/s. Density and Young's modulus of the asphalt mixture are 2300 kg/m^3 and $2E$+09 Pa.

The incident and reflective sound pressure are both recorded as shown in Fig. 4 under the incident sound wave

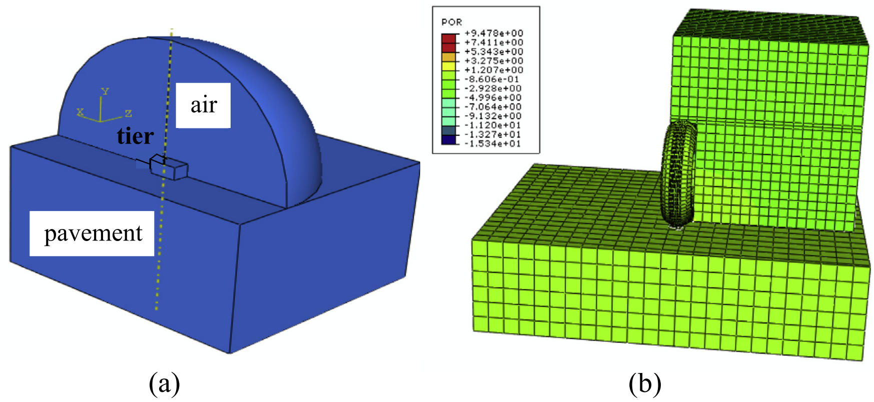


Figure 2. Finite elements coupling models of tire and pavement structure.

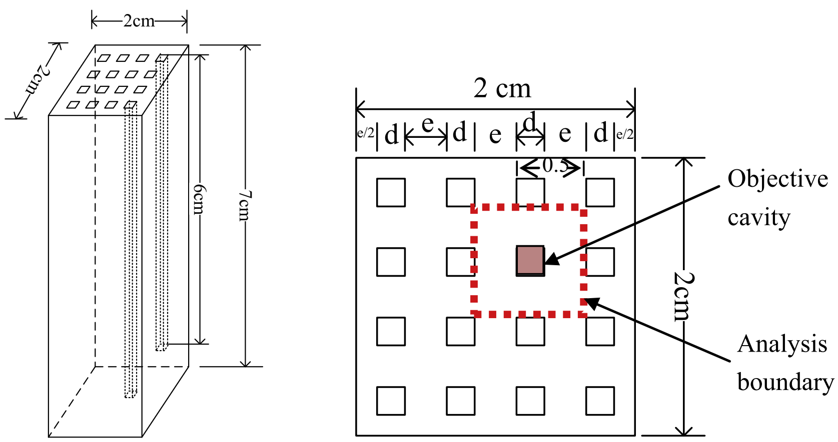


Figure 3. Cubic structure model of the porous pavement surfacing.

Table 1
Relationships between the air void ratio and cavity size in the model of pavement surfacing.

Air void ratio (%)	10	16	20	25	30
Hole diameter *d* (cm)	0.158	0.2	0.2236	0.25	0.274
Hole distance *e* (cm)	0.342	0.3	0.2764	0.25	0.226

of 800 Hz frequency, designed because the frequency of the traffic noise is usually in the range of 600–1200 Hz. In this figure it is apparent that the two sound pressures are separated with different amplitudes due to the absorption of the surfacing structures.

The curve of the changing of sound pressure indicates that it is feasible for the three-dimensional model of the pavement surfacing to simulate the procedure of the dissipation of sound energy. The features of the change of sound energy are acquired by adjusting the parameters for the coupling model of sound and structure.

3. Structures of double-layer porous asphalt pavements

The sound absorption coefficient α is often used to assess the performance of the sound absorption material. It is defined as the ratio of the absorbed sound energy to the received sound energy of the material surface (Owatecta, 2002). The coefficient is in the range between 0 and 1. The sound energy is totally absorbed when $\alpha = 1$ and it is totally reflected when $\alpha = 0$. The larger the coefficient the better the sound absorption performance of the material.

3.1. Parameters of the pavement surfacing

3.1.1. Air void ratio of single surfacing

The columns in the structure model are filled with air also being connected with the outside air field. The relationship between the coefficients and air void ratios is described in Figs. 5 and 6.

In Fig. 5 it is shown that the reduction of noise level is more significant at higher air void ratios. The noise reduction is 2, 3 and 4 dB when the air void ratios are 10%, 20% and 30% respectively. In Fig. 6 the increase in sound absorption coefficient at larger air void ratios also indicates that material with a large air void ratio presents better sound absorption performances.

3.1.2. Air void ratio of double surfacing

The model of double surfacing is shown in Fig. 7. The structure has the total height of 6 cm and its two layers are equally 3 cm. The air void ratios of the top layer have

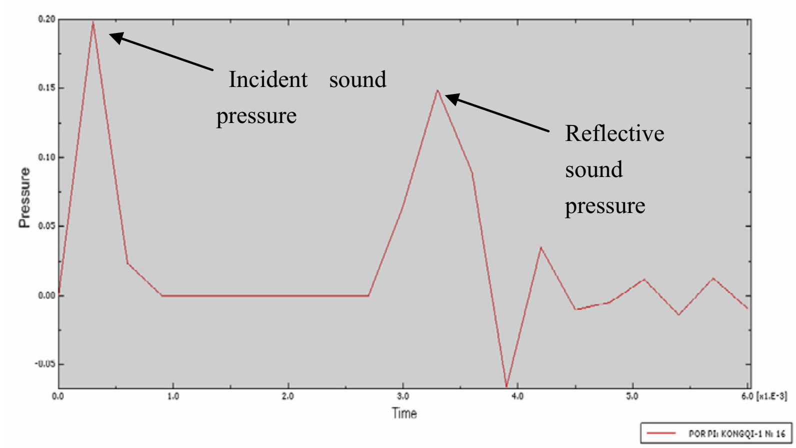


Figure 4. Change of sound pressures of the sound absorption asphalt mixture structure.

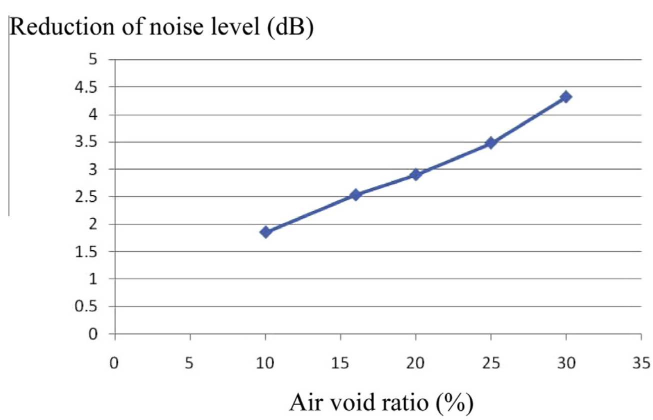


Figure 5. Relationship between the change of noise level and air void ratio of the pavement surfacing.

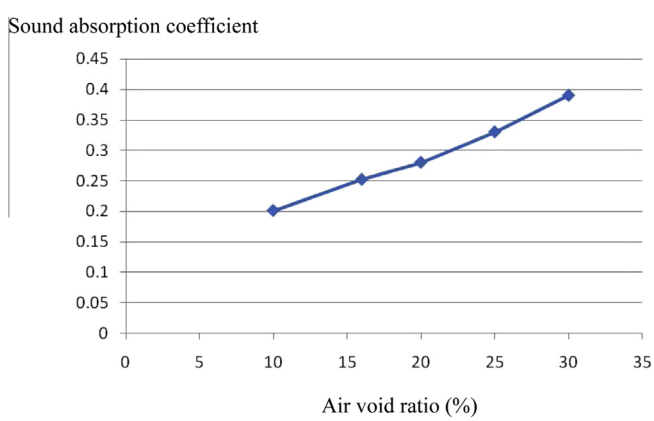


Figure 6. Relationship between the change of sound absorption coefficient and air void ratio of the pavement surfacing.

two candidate values of 10% and 16% and for the bottom layer four candidate values of 16%, 20%, 25% and 30%. Consequently seven combinations of the air void ratios of the two layers are presented in Table 2.

Fig. 8 shows the noise reduction efforts for different combinations of air void ratios of two porous layers of the pavement surfacing. It is concluded that the influence of the air void ratio of the top layer imposes little influence on the noise reduction performance. Noise reduction is greater at higher air void ratio in the bottom layer.

Though large air void ratio of the porous pavement surfacing possesses acoustic benefits the strength of pavement structure should not be impaired. Otherwise damaged surfacing due to the poorly structured pavement would result in the vehicles bumping and raise the traffic noise level. The air void ratio of the porous asphalt pavement is often controlled around 20% (Xue, 2009). In this work the air void ratios are 10% and 20% for the top and bottom layers respectively.

3.1.3. Thickness of the double layer surfacing

The thickness of the top layer increases from 0 to 6 cm with 1 cm increment while the thickness of the bottom layer

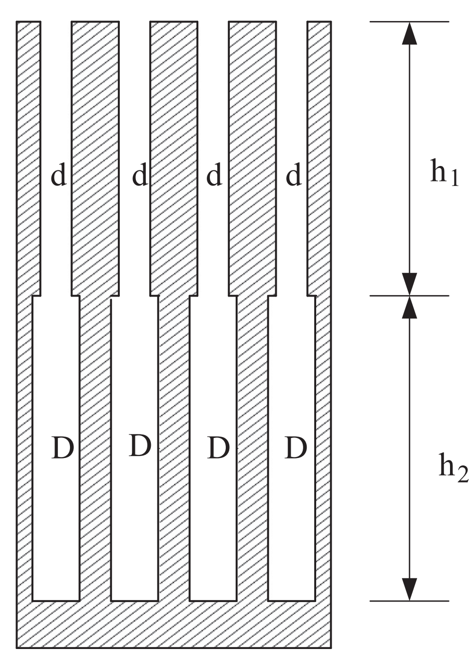


Figure 7. Longitudinal section of the cubic model of double surfacing of porous asphalt pavement.

Table 2
Combinations of air void ratios of the double layer pavement surfacing.

Combination	1	2	3	4	5	6	7
Air void ratio of the top layer (%)	10				16		
Air void ratio of the bottom layer (%)	16	20	25	30	20	25	30
Reduction of noise (dB)	2.748	3.153	3.682	4.032	3.143	3.715	4.043

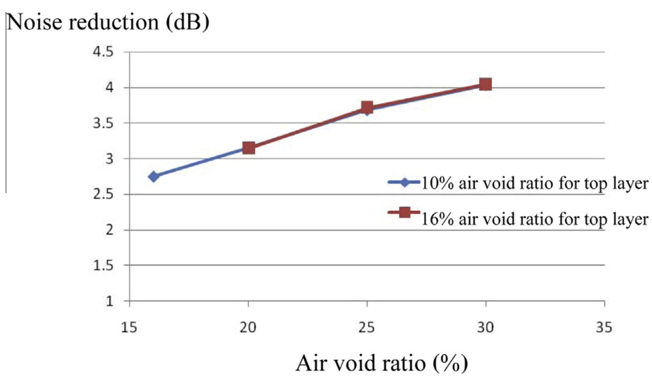


Figure 8. Noise reduction of different combinations of air void ratios of the two layers of the porous pavement surfacing.

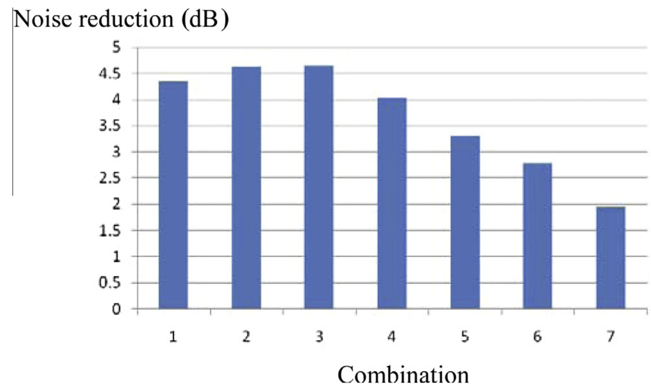


Figure 9. Noise absorption coefficients of different combinations of layer thicknesses of the two layers of the porous pavement surfacing.

decreases from 6 to 0 cm. The total thickness of the surfacing remains 6 cm thus seven combinations of layer thicknesses are proposed as shown in Table 3. The change of noise absorption coefficients with various combinations of layer thicknesses of the pavement surfacing is shown in Fig. 9.

In Fig. 9 the most significant noise reduction occurs at the combination No. 3, i.e. top layer 2 cm and bottom layer 4 cm. The results will be examined in the indoor noise tests in Section 4. Even under the boosting noise-reduce effect of the thickening top layer, the reduction effect weakens when the thickness of the bottom layer shrinks especially for very thin ones (the thickness is 3, 2, 1 and 0 cm).

3.1.4. Texture of the pavement surfacing

The structure of the pavement surface is locally enlarged as shown in Fig. 10. In this figure w is the width of the texture and is twice of the radius r. h is the texture depth which may be different from the texture radius. l is the texture wavelength, i.e. distance between two neighbouring bumps. The increase of texture depth would enhance the sound absorption performance as introduced in Section 1 for the very thin pavement surfacing with small aggregates. However the vibration distances of the tiers are extended thus more vibration noise may be generated. The increase of texture width elongates the contact time between the tire and pavement surface and may reduce traffic noise. The relationship between the texture pattern and noise reduction is determined jointly by the noise absorbed by the texture and that generated by the vibration.

The noise generated at the surface texture is compared with that at a smooth pavement surface as shown in Fig. 11. The surface texture is described by the ratio of texture depth and width. In this figure it is concluded that the effort of noise reduction decreases first with the ratio of texture depth and width and the values are negative when the ratio is in the range of 0–0.5. In other words the pavement surface with small and few texture patterns generates more noise than the smooth one. The reasons may be that the long distance between two neighbouring bumps turns their walls into the reflectors of traffic noise thus the spreading area of the noise is expanded.

When the texture ratio increases from 0.5 the noise reduction becomes more effective in a steady pace at a higher texture depth and width ratio.

3.1.5. Air void structure of the pavement surfacing

Air voids in the asphalt pavement surfacing include the main and side air voids (Tao, 2006) as shown in Fig. 12. When the air flows from the main air voids to the side ones, violent vibration occurs around the connection area of the two voids due to the speed of air flows and change of the

Table 3
Combinations of layer thickness of the double layer pavement surfacing.

Combination	1	2	3	4	5	6	7
Thickness of the top layer h_1 (cm)	0	1	2	3	4	5	6
Thickness of the bottom layer h_2 (cm)	6	5	4	3	2	1	0
Noise reduction (dB)	4.342	4.637	4.654	4.032	3.304	2.780	1.940

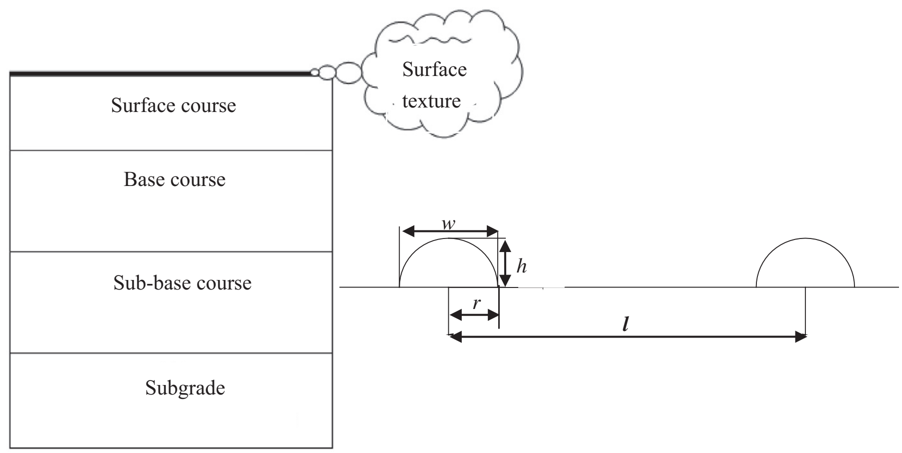


Figure 10. Structure of the pavement surface.

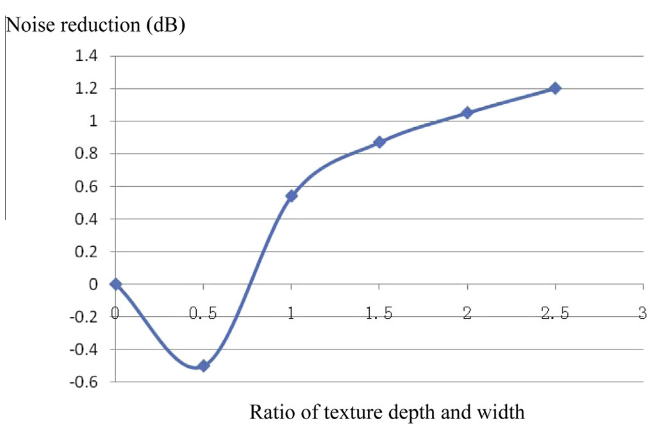


Figure 11. Relationship between noise reduction and texture pattern.

areas of two types of voids. The sound energy is dissipated during the friction between the air flow and air void walls. The air flow in the distant areas of the side air voids may be static.

The structure of the air voids is represented by the ratio of the volumes of the main and side voids. Here five volume ratios are presented and the sound above the testing voids is recorded in Table 4. The volume and radius of the side void remains unchanged since the influence of the side air void volume on noise generation is little (Xue, 2009). It is concluded that the generated sound is minimal when the volume ratio of the voids is around 50.

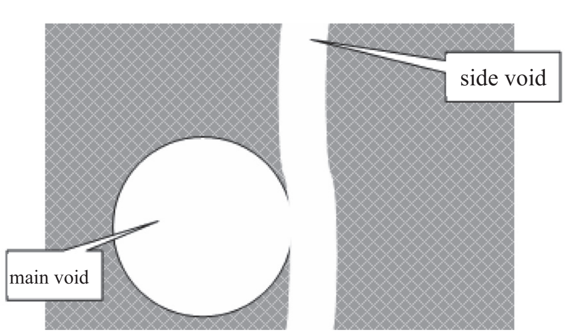


Figure 12. Structure of air voids in the asphalt pavement surfacing.

3.2. Structure of double layer porous asphalt pavement surfacing

The structure of the double layer pavement surfacing proposed in this work is shown in Fig. 13. The aggregates in the mixture have edges and corners aiming at providing the proposed volume ratio of main and side air voids in Section 3.1.5. Fine aggregates are paved in the top layer and course aggregates are paved in the next layer below. Then the fine aggregates are used in the next layer and then the course aggregates are paved again if required. The procedure ceases when the thickness of the surfacing is satisfied.

The fine aggregates in the top layer provide micro-pores absorbing rather than reflecting the noise. The course aggregates in the next layers create main air voids. Noise is reflected in these main voids through extended transmission paths. The sound energy is dissipated by the friction between the air flow and void walls. The remaining sound energy is transmitted to the next downward layer. Most of the noise can be absorbed by this pavement surfacing structure. The sound absorption performance is guaranteed by the appropriate ratio of the volume of the main and side voids. This volume ratio is determined by the aggregate particle sizes. Suppose that the edge length of the course and fine aggregates is b and a respectively. The ratio of b over a is calculated in Eqs. (1) and (2)

Table 4
Noise level for volume ratios of the main and side air voids.

Combination	Volume ratio (V_1/V_2)	Noise (dB)
1	12.5	76.77
2	21.5	76.55
3	52.5	52.55
4	80.0	60.00
5	100.0	76.08

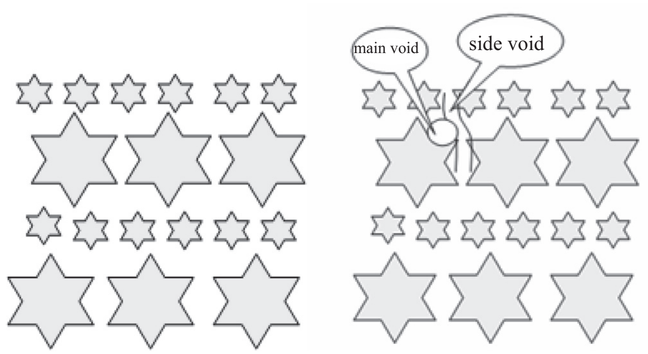


Figure 13. Structure of the double layer porous asphalt pavement surfacing.

$$\left(\frac{b}{4}\right)^3 = 50 * \left(\frac{b}{4} + a\right)\left(\frac{a}{4}\right)^2 \quad (1)$$

$$200 * \left(\frac{a}{b}\right)^3 + 50 * \left(\frac{a}{b}\right)^2 - 1 = 0 \quad (2)$$

The solution to these equations is $a/b = 0.55$.

3.2.1. Material parameters

3.2.1.1. Acoustic impedance. It is a complex and constant variable for a material reflecting its sound absorption ability. It contains the resistance and reactive parts represented respectively by the real and imaginary parts of this variable. The resistance part represents the transfer of sound energy while the reactive part stores or reflects the sound energy without transmission. The sound resistance is dependent upon the flow resistance and air permeability of the material. The absorption of high and low frequency sound is determined by the positive and negative imaginary parts of the sound reactive respectively.

The sound impedance of the asphalt pavement layers is assessed by modelling an air mass being vibrated with different resistance and measuring the output sound. The sound reactive parameter is set as −400 and the influence of the sound resistance on the noise level is shown in Fig. 14.

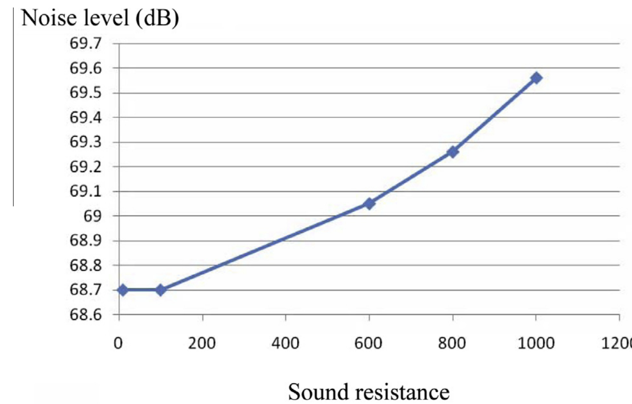


Figure 14. Relationship between the sound resistance and noise level.

It is shown that the noise level hardly changes when the sound resistance is lower than 200. The noise level rises rapidly with the increase in sound resistance from 200. The increment of the noise is small due to the small imposed action on the air mass.

The influence of the sound reactive parameter on the output noise level is shown in Fig. 15. The sound resistance is fixed as 200. In this figure the noise levels increases with a larger sound reactive parameter.

3.2.1.2. Sound flow resistance. It is the ratio of the air pressure over the flow speed passing the material. It reflects the resistance of the material for the passing flow. The sound absorption coefficients are measured for two different structures of the porous asphalt pavement layer therefore with different sound flow resistance. The two pavement layer structures are (1) the single layer porous pavement with 5% air void ratio and (2) double layer porous pavement with 10% and 25% air void ratio for the top and bottom layers. The measured coefficients are shown in Fig. 16.

In Fig. 16 the sound absorption effect of the double layer pavement structure is better than that of the single layer structure. For both structures the sound absorption coefficient increases slightly with higher sound flow resistance.

3.2.1.3. Vehicle speed. The influence of vehicle speeds on the noise reduction of the road pavements is shown in Fig. 17. In this figure it is seen that the efforts of noise reduction of the porous asphalt pavement are less significant under higher vehicle speeds. The pavement reduces 1.5% of noise when the vehicle is moving at 50–60 km/h. The noise is reduced to 0.8% when the vehicle speed is 100 km/h.

3.2.2. Impact factors for noise generation

Orthogonal array testing is applied here to examine the impacts of the factors on the index, i.e. the evaluated object and here the sound pressure. Various levels i.e. values of the impact factors are designed. An orthogonal table (see Table 5) is generated to present reasonable times of tests

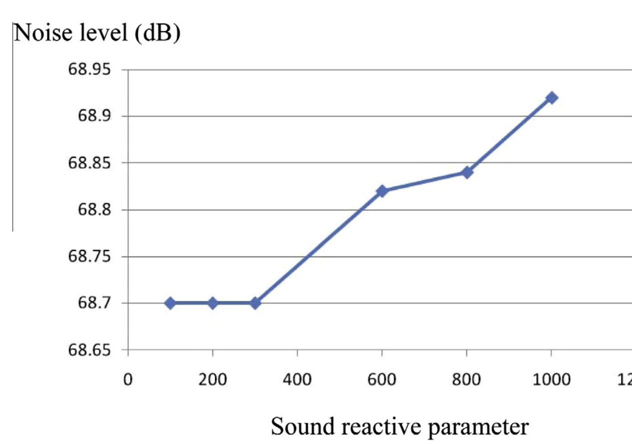


Figure 15. Relationship between the sound resistance and noise absorption coefficient.

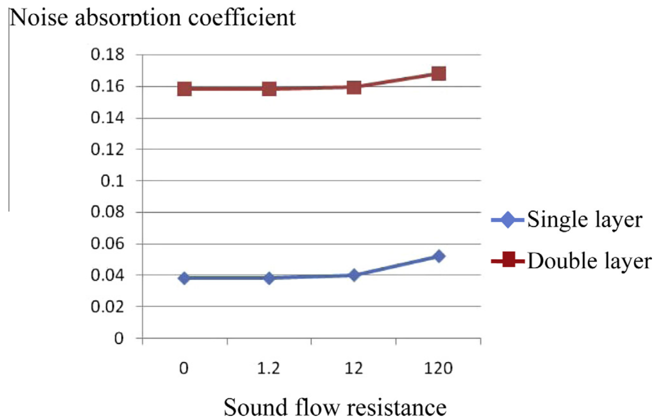


Figure 16. Relationship between the material sound flow resistance and noise absorption coefficient.

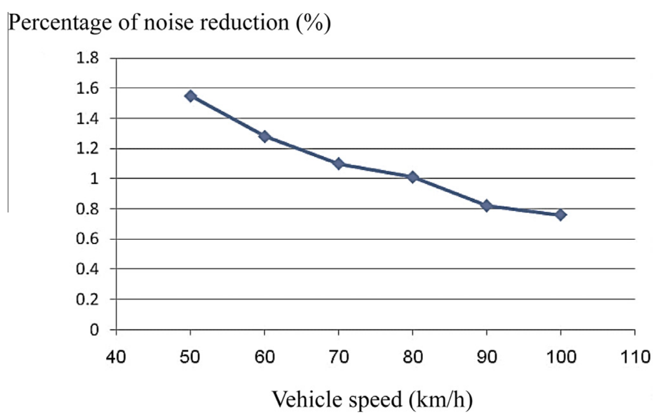


Figure 17. Relationship between vehicle speeds and noise reduction.

for good results (Gao, 1988). The extreme difference analysis is performed to identify the magnitude of the factor impact on the sound pressure (see Table 6). The extreme difference R is between the maximal and minimal values of the object index for each parameter at various levels (Gao, 1988). The larger the extreme difference is, the more significant the impact factor has on the magnitude of sound pressure.

Four parameters i.e. sound resistance and reactive parameters, tier pattern angle and vehicle speed, are chosen to assess their influences on the noise generated by the interaction between the vehicle tire, air and pavement surface structure. Each parameter has four levels of values.

From Table 6 it is concluded that the values of extreme differences for the four parameters from large to small are R(vehicle speed) > R(tier pattern angle) > R(sound resistance) > R(sound reactive). The rank of the extreme differences of the four factors represents the relative magnitudes of the impacts they impose on noise generation. Vehicle speed is the most significant impact factor for the traffic noise. The sound resistance and reactive parameters are to be controlled by providing excellent pavement structures.

4. Indoor and outdoor noise tests

The asphalt mixture widely used in low noise asphalt pavement structures i.e. porous asphalt, small aggregate asphalt and rubberised asphalt are produced for indoor noise tests.

4.1. Preparations of the asphalt mixture

4.1.1. Porous asphalt mixture

The asphalt mastic used is No. 70 asphalt added with Tafpack Super (TPS) modified asphalt of high viscosity. The aggregates are basalts. The gradation and asphalt–aggregate ratio are determined according to the standards and Marshall flow and stability test results. The nominal maximum size of aggregates is 13.2 mm and most ideal asphalt–aggregate ratio is 4.5%. The air void ratio is 19.6%.

4.1.2. Small radius aggregates asphalt mixture

The asphalt mixture is enhanced with SBS polymer modified asphalt. The nominal maximum size of aggregates is 4.75 mm. The most ideal asphalt–aggregate is 5.7% under the recommendations of the regulations (JTG E20-2011, 2011) and results from the Marshall drainage tests and Catanbro tests.

4.1.3. Rubberised asphalt mixture

The asphalt mastic used is No. 70 asphalt enhanced by ground rubber powder. The nominal maximum size of aggregates is 13.2 mm and the best asphalt–aggregate ratio is 8.0%.

Table 5
Sound pressures for the impact factors at various levels in the orthogonal array tests.

Parameter level combination	Sound resistance	Sound reactive	Tier pattern angle (°)	Vehicle speed (km/h)	Sound pressure (dB)
1	100	100	90	60	80.54
2	100	200	60	102	81.98
3	100	400	45	72	80.08
4	200	100	60	72	78.98
5	200	200	45	60	76.19
6	200	400	90	102	85.94
7	400	100	45	102	82.81
8	400	200	90	72	83.11
9	400	400	60	60	78.90

Table 6
Extreme differences of the sound pressures for the impact factors at various levels.

Extreme differences	Sound resistance	Sound reactive	Tier pattern angle	Vehicle speed
$I_j/3$	80.87	80.78	79.69	78.55
$II_j/3$	80.37	80.43	79.95	80.72
$III_j/3$	81.60	81.64	83.20	81.56
R	1.23	1.21	3.51	5.03

4.2. Basic performance tests

4.2.1. Stability under high temperature

The specimens of the previously described asphalt mixture are used in the rutting tests and the results are presented in Table 7. The stability of each mixture under high temperature environments meets the requirements of the regulations (JTG E20-2011).

4.2.2. Stability under low temperature

Low temperature bending tests are applied to assess the stability of various asphalt mixture in low temperature environments. The test results are shown in Table 8. From the table it is seen that the failure strain is smaller than the standard value in the regulations.

The water sensibility and stability of the asphalt mixture is assessed by the water immersion mechanical tests. The tensile strength ratios of the material before and after the freezing and thawing tests are calculated. The water stability of the three asphalt mixture meets the regulation standards.

4.3. Indoor sound absorption coefficient tests

4.3.1. Preparation of specimens

The specimens of asphalt mixture are produced by the Superwave Gyratory Compactor (SGC). The air void ratio for the small radius aggregates asphalt mixture specimen is 4%. For the single layer porous asphalt mixture specimens the air voids are 2.3%, 2.7%, 6.6%, 7.5%, 17.4% and 18.4%. The air voids for the top and bottom layers of the double layer porous asphalt mixture specimen are 10% and 25% respectively. For the rubberised asphalt mixture specimen the air void is 25%. The diameter and height of these specimens are 100 mm and 70 mm respectively. Fig. 18 shows the indoor specimens of a small radius aggregate and single layer porous asphalt mixture.

The specimens for the double layer porous asphalt have two combinations of layer heights, i.e. 2 cm and 4 cm for top and bottom layers and 3 cm and 3 cm for the two layers. The specimens are shown in Fig. 19.

4.3.2. Test procedures and results

The equipment used in the sound absorption tests is the Impedance Measurement Tube for ASTM Type 4206A from the German company of Brüel & Kjær. The equipment includes three parts in general, i.e. sound generation, sound amplification and sound collection. The sound absorption coefficient of a specimen is calculated by referring to the sound data collected with and without the input specimen applied in an open or closed terminal tube. The coefficients for the specimens shown in Figs. 18 and 19 are presented in Table 9 and shown in Fig. 20.

In Fig. 20 it is seen that the ranges of sound absorption coefficients of the porous (single and double layer) and rubberised asphalt mixture are similar. The peak values are usually in the range of 0.3–0.5. Coefficients of small radius aggregates asphalt mixture specimens are smaller and in the range of 0.1–0.2. The reason is that the coefficient is highly related to the air void ratio of the material (see in Fig. 6). The small radius aggregate asphalt mixture has a smaller air void ratio thus smaller sound absorption coefficients. However the performance of noise reduction of this material may not be challenged since sound energy is dissipated through multiple times of reflection between the raised wedges of surface texture. The sound energy is reduced by the friction between the air flow and cavity walls for the porous asphalt pavement surfaces.

The comparison of the sound absorption coefficients for the single and double layer porous asphalt pavement is shown in Fig. 21. The coefficients of the four types of specimens are close for the frequencies of 600 and 800 Hz. Peak values of the coefficients for the single layer specimens appear in the frequency range of 1000–1200 Hz. For the double layer specimens the coefficients increase slightly and steadily with higher sound frequencies.

4.4. Outdoor sound tests

4.4.1. Porous asphalt pavements

The sound tests were performed at the sites of the normal asphalt concrete pavements and porous asphalt pavements on the road sections of Shanghai and Nanjing

Table 7
Results from the rutting tests for the asphalt mixture.

Asphalt mixture	d_1 (mm)	d_2 (mm)	Dynamic stability (time/mm)	Standard regulations
Porous asphalt mixture	–	–	4300	>3000
Small radius aggregates asphalt mixture	1.661	1.798	4606	
Rubberised asphalt mixture	–	–	3862	

Table 8
Results from low temperature bending tests for various asphalt mixture.

Asphalt mixture	Bending tensile strength (MPa)	Failure strain (μ_{ε})	Bending stiffness modulus (MPa)
Porous asphalt mixture	7.84	1700	4696.6
Rubberised asphalt mixture	–	3723	–
Regulation standards	–	>2500	–

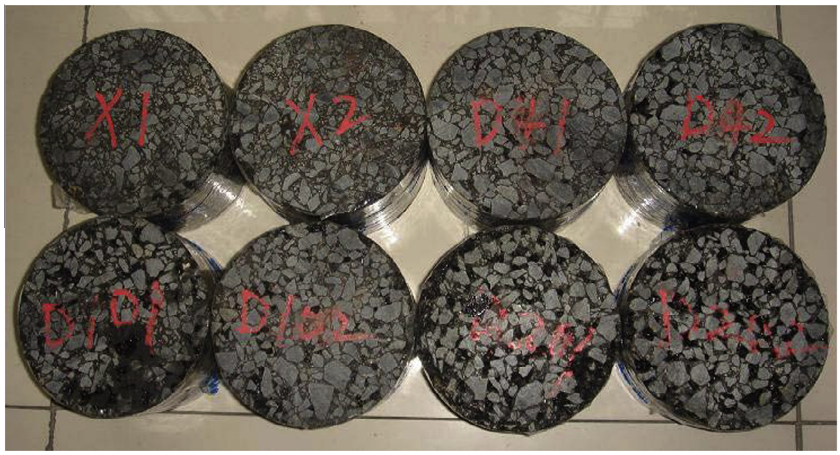
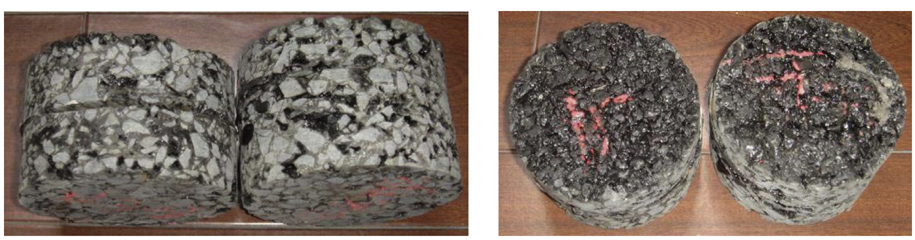


Figure 18. Indoor specimens for the small radius aggregates (X1 and X2) and single layer porous asphalt mixture (code starting with D).



(a) Side surface (b) top surface

Figure 19. Specimens for double layer porous asphalt mixture.

Table 9
Sound absorption coefficients of various asphalt mixtures.

Specimen	Asphalt mixture	Central frequency of one-third octave band (Hz)						Air void ratio (%)
		600	800	1000	1200	1400	1600	
D41	Porous (single layer)	0.08	0.14	0.18	0.16	0.21	0.23	2.3
D42		0.03	0.04	0.05	0.09	0.13	0.13	2.7
D101		0.09	0.17	0.19	0.30	0.27	0.25	6.6
D102		0.10	0.11	0.17	0.21	0.23	0.27	7.5
D201		0.08	0.15	0.40	0.26	0.24	0.30	17.4
D202		0.09	0.12	0.31	0.52	0.31	0.26	18.4
D2 + 4	Porous (double layer)	0.09	0.14	0.25	0.24	0.25	0.26	Top layer 11.6 Bottom layer 18.5
D3 + 3		0.11	0.13	0.20	0.23	0.24	0.26	Top layer 9.6 Bottom layer 19.0
X1	Small radius aggregates	0.06	0.08	0.12	0.15	0.16	0.17	2.3
X2		0.04	0.05	0.06	0.07	0.08	0.10	2.0
XJ	Rubberised asphalt	0.50	0.24	0.31	0.33	0.34	0.35	23.3

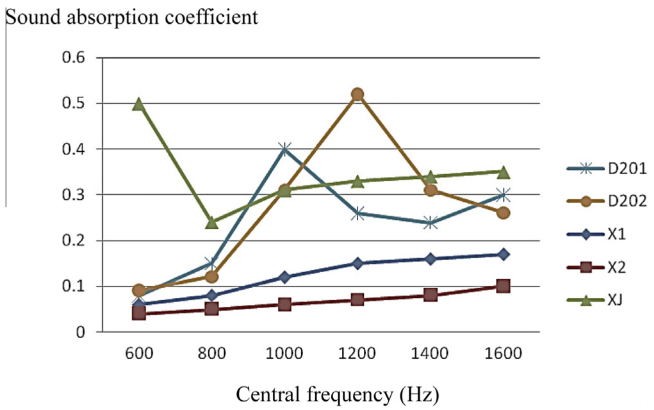


Figure 20. Sound absorption coefficients of various asphalt mixture specimens.

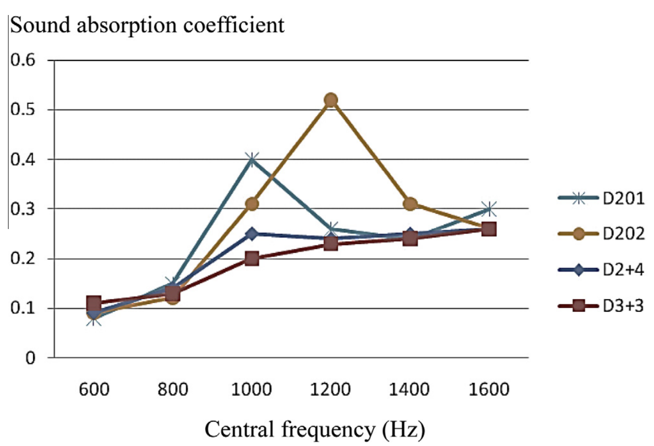


Figure 21. Sound absorption coefficients of single and double layer porous asphalt mixture specimens.

Highway in China. The test procedure was executed according to the standards (GB1496-2002, 2002). The locations of sound capturing points inside and outside the vehicles are shown in Figs. 22 and 23.

The sound measuring equipment outside the moving vehicles is placed at the height of 1.2 m. The maximal readings of sound pressure are recorded when the moving vehicles arrive at the header of the gauges at the speeds of 50 and 80 km/h. The vehicle speeds are 80 and 120 km/h for the sound pressure collected inside the vehicles. The average maximal readings of the sound pressure for two types of road pavements and under different vehicle speeds are shown in Table 10. From the table it is apparent that the traffic noise outside the vehicles is reduced about 3.5 dB on the porous asphalt pavements than on the normal asphalt concrete pavements. The difference of the noise level detected inside the vehicles when they are moving on the two pavements is about 0.3 dB.

4.4.2. Small radius aggregate asphalt pavements

The selected road section is from the Jiuhuashan tunnel in urban area of Nanjing. The pavement is constructed with SMA-13. The corresponsive road section is in the

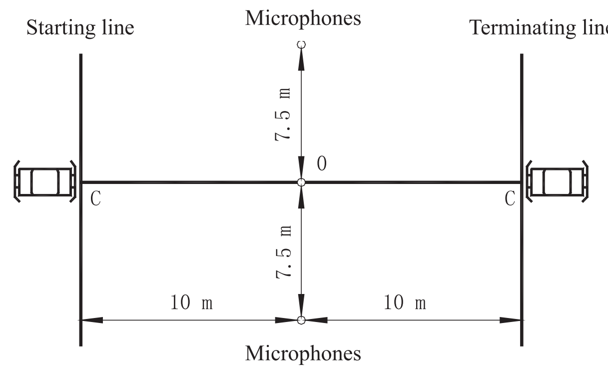


Figure 22. Measuring points of sound outside the vehicles.

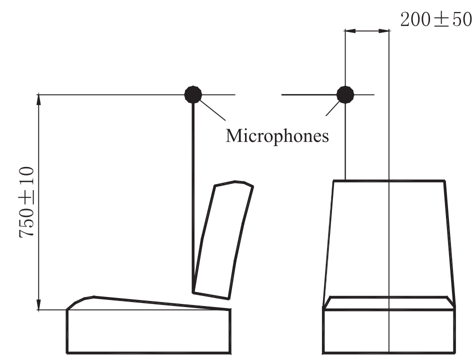


Figure 23. Measuring points of sound outside the vehicles (units: mm).

Xuanwuhu tunnel of Nanjing selected for comparison. The pavement is constructed with AC-13. The test vehicles travel respectively at the speeds of 40, 60, 80 and 100 km/h. Due to the curve of the Xuanwuhu tunnel the sound measurement for the speed of 100 km/h is not performed taking travelling safety into account. A major measuring point outside the vehicles in the tunnel is fixed with the clear view of at least 50 m of straight road alignments. Two assistant measuring points are established 50 m away at the two sides of the major point as shown in Fig. 24.

The test vehicles launch and accelerate at some distance away from Assistant point 1. The speed of the vehicle should reach 40 km/h, for example, when the vehicle passes point 1 and the speed is maintained until the vehicle passes point 2. The recording of the noise inside a vehicle starts and terminates when the vehicle passes points 1 and 2 respectively. The outside-vehicle traffic noise is recorded at the major point. The procedure is repeated for other testing vehicle speeds. The test results are shown in Fig. 25.

In Fig. 25 the noise levels both inside and outside the vehicles rise with higher vehicle speeds. The noise level for the SMA pavement is in general about 1–3 dB lower than that for the AC pavement.

4.4.3. Rubberised asphalt pavement

The selected road section with rubberised asphalt pavement surface is the one from the road section of the Belt

Table 10
Sound pressure measured on different types of asphalt pavements.

Sound measuring points		Speed (km/h)	Porous asphalt pavement (dB(A))	Asphalt concrete pavement (dB(A))	Reduced noise (dB(A))
Average value of sound pressure	Outside the vehicle	50	67.3	70.6	3.3
		80	72.3	75.9	3.6
	Inside the vehicle	80	62.7	63.3	0.4
		120	69.1	69.3	0.2

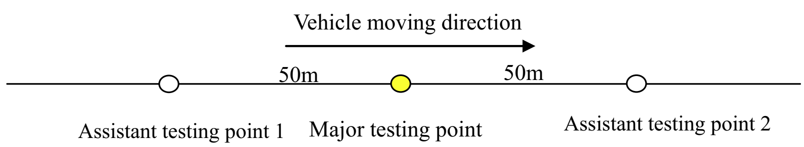


Figure 24. Layout of the testing points of sound level.

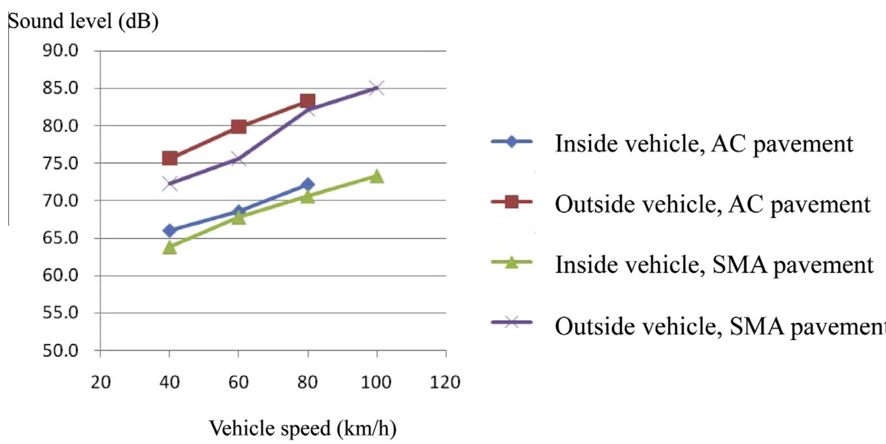


Figure 25. Noise level recorded for small radius aggregate and normal asphalt pavements.

Table 11
Sound test results for rubberised and normal asphalt pavements.

Roan pavements	First test results (dB)	Second test results (dB)
Rubberised asphalt	78.3	77.4
Normal asphalt	80.5	80.6
Noise reduction	2.2	3.2

Table 12
Noise reduction effects for low noise pavements.

Asphalt pavement	Theoretical effects (dB)	Measured effects (dB)
Porous	4–6	3.3–3.6
Rubberised	2–3	2.2–3.2
Small aggregate	1–2	1–4

Highway of Nanjing from the Second to the Third Yangtze River Bridge. The sound detectors are fixed near the anti-crash barriers and at the same heights. The test results for the rubberised asphalt pavement and its neighbouring normal asphalt pavements are presented in Table 11. From the table it is concluded that traffic noise is reduced from 2.2 to 3.2 dB for the rubberised asphalt pavements.

The effects of noise reduction for the three types of low noise pavements are generalised in Table 12.

5. Conclusions and discussions

Porous asphalt pavements access effective noise reduction ability because of its high air void ratios. The sound energy is dissipated during the transmission within the pavement surface structure by the friction between the vibrated air flow and solid cells of the voids. The ideal pavement structure developed in ABAQUS contains alternate layers of fine and course aggregates to generate an air void structure acting as Helmholtz resonance. The air void structure contains main and side voids and their volume ratio is determined by the ratio of the aggregate sizes of the two layers.

The theoretical model of the double layer porous asphalt pavement developed from the ideal pavement structure benefits from the durability of the small aggregate asphalt pavement and acoustical advantages of the single layer porous asphalt pavement. The structure of the double layer pavement surface is designed to achieve the best efforts of noise reduction. For the top layer the thickness is 2 cm and the nominal maximum size of aggregates is 9.5 mm. For the bottom layer the thickness is 4 cm and the nominal maximum size of aggregates is 16 mm. The air void ratios for the two layers are 10% and 20% respectively. The reduction of noise levels for the double layer pavement is slightly poorer than that for the single layer structure (1 dB).

The performance of noise reduction of four asphalt pavement structures, i.e. double layer, single layer, small aggregate and rubberised asphalt pavements is assessed in both indoor and outdoor experiments. Indoor test results show that the sound absorption coefficients of double and single layer pavements and rubberised pavements are similar (0.4–0.5) except for the sound of 1000 and 1200 Hz frequencies. Peak values of the coefficients for the single layer pavement occur at these two frequency bands. The coefficients of the small aggregate pavement are smaller (0.1–0.2) than those of the other three types of pavements.

The results of the outdoor noise detecting tests show that the efforts of noise reduction of the single layer porous pavement are the most significant as in 3.3–3.6 dB compared to normal asphalt pavements. Noise reduction for the rubberised and small aggregate asphalt pavements is 2.2–3.2 dB and 1–4 dB.

In modelling the double layer porous asphalt pavement structure column voids are used and distributed evenly within the material. The model can be improved its resemblance to the real material structure by the randomly distribution of aggregates and generation of air voids.

The indoor specimens of double layer asphalt pavement structure are produced by the cohesion of the two separately laid and compacted specimens with different air void ratios. The cohesive asphalt binder may clog the air voids of the surface of the bottom layer specimen therefore the connection between the voids of the top and bottom layers is impaired and also the sound transmission paths. This disadvantage in the specimen production procedure can be overcome by the 'hot-on-hot' method i.e. lay and compact the top layer on top of the already compacted below layer by the Superwave Gyratory Compactor (SGC).

Acknowledgement

This work was supported by the Nature Science Foundation of China under Grant [51178112].

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