Technical Paper

ISSN 1997-1400 Int. J. Pavement Res. Technol. 4(1):41-47

Acoustic Absorption of Conventional Pavements

M. Alauddin Ahammed[1+] and Susan L. Tighe[2]

Abstract: Traffic noise is a growing problem throughout the world. Pavement with a high acoustic absorption capability can significantly reduce the roadway traffic noise. The durability of such acoustically absorptive pavements is however major concern for the highway application. The sound absorption capabilities of typical portland cement concrete (PCC) that were surface textured in different configurations and typical asphalt concrete (AC) were measured in the Centre for Pavement and Transportation Technology (CPATT) laboratory at the University of Waterloo, Ontario (Canada) using a impedance tube and a custom designed portable reverberation chamber. On average, the regular 12.5 mm Superpave^{TM} (SP12.5), 12.5 mm stone mastic asphalt (SMA12.5) and the fine graded 12.5 mm Superpave^{TM} (SP12.5Fine) mixes were shown to absorb 6.3%, 7.5% and 8.5% of the sound energy, respectively. Textured PCC surfaces were shown to absorb 5% to 6% of the sound energy. The varying thickness has shown no significant effect on the variation of sound absorption of conventional dense AC and PCC pavements. The variation of bulk relative density (BRD) was shown to affect significantly the sound absorption capabilities of the AC pavements. However, the effect of the air voids content in the dense AC mixes was shown to be insignificant or minimal for the variation of sound energy absorption.

Key words: *Concrete surface texture; Conventional dense mix; Fine graded Superpave^{TM}; Regular Superpave^{TM}; Stone mastic asphalt ; Sound absorption.*

Introduction

Traffic noise is a growing concern for both public health and economy of each country, especially in urban areas. Study indicated that 30% of European Union (EU) citizens are exposed to traffic noise exceeding the World Health Organization (WHO) recommended acceptable level. In addition, a 1dB increase in noise results in a 1% decrease in house prices near the busy roads in Denmark [1]. In fact, the traffic noise impacts on communities are escalating worldwide due to increasing traffic volume and development near the highway facilities [2].

The three main sources of roadway traffic noise are vehicle engine (power train), aerodynamics and tire-pavement interaction. With the current vehicle/tire technologies, the tire-pavement interaction was found to be the major contributor to traffic noise for passenger vehicles traveling at a constant speed of 35 km/h or greater [3]. This provides a window for noise reduction by the pavement itself.

The noise reduction mechanisms by the pavement itself include mechanical and acoustic impedance. The mechanical impedance is related to the relative stiffness of the tire and the pavement. Alternatively, the acoustic impedance largely depends on the system of interconnected voids on the surface i.e., pavement surface type (porous or non-porous) and the pavement surface texture [4]. An absorptive surface prevents effective reflection of the sound energy produced due to the interaction of pavement and vehicle tire and helps to reduce the roadside noise [5].

A study indicated that sound absorption depends on voids content, thickness, resistance to airflow (measure of sound dissipation through the pavement) and shape factor (ratio of the square of sound speed through air to the square of sound speed within the pavement mixture). Higher void ratio, greater thickness, lower resistance to airflow and lower shape factor mean increased sound energy absorption [6]. The mechanism of sound propagation (dissipation of acoustic energy) through the pavement layer(s) is schematically shown in the manuscript prepared by Bernhard and McDaniel [7]. All these study depicted that for identical surface textures (textures with identical shapes, orientations and magnitudes) and for a given tire, the sound propagation to the nearby receptor will decrease as the sound absorption increases. In addition, the reduced air compression due to air escaping through the pavement voids may be helpful in reducing noise generation with an ultimate reduction in the perceived noise level.

Porous pavements with air voids content of 15% to 20% can absorb 10% to 20% of the sound energy [8]. However, clogging of voids that result in a noise increase within a short period after the construction and the durability are major concerns for such pavements. In fact, durability is a prime consideration in the selection of pavement surface type, especially for the roadways carrying a high volume of traffic. The selected surface course should minimize the noise without compromising the structural performance and durability for best utilization of the public investments.

Other examples of noise-reducing pavements include rubberized asphalt, open-graded asphalt, SMA, PCC with longitudinal tine, diamond ground and exposed aggregate textures, and two-layer porous AC or PCC pavements [9]. Normal weight (conventional dense) PCC pavements provide high stability and durability. The SMA was introduced in the US during 1990s after an American Association of State Highway and Transportation Officials (AASHTO) team's European Asphalt Study Tour [10]. It is a

---

[1] Pavement Research Engineer, Materials Engineering Branch, Manitoba Infrastructure and Transportation (MIT), MB R3C 3P3, Canada.

[2] Professor and Associate Director of CPATT, and Canada Research Chair in Pavement & Infrastructure Management, Department of Civil and Environmental Engineering, University of Waterloo, ON N2L 3G1, Canada.

[+] Corresponding Author: E-mail alauddinalam@hotmail.com

Note: Submitted March 29, 2010; Revised June 15, 2010; Accepted June 24, 2010.

gap-graded asphalt mixture with the intermediate size aggregate missing i.e., the mixture contains larger stones and mastic, a blend of asphaltic binder and fine aggregates/fillers. The stone rich blend of the SMA provides close contact with each other and prevents segregation during the placement and compaction. The durability of SMA has been found to be good [11].

The concept of blending aggregates for open-graded asphalt (OGA) is similar to the porous pavement (PA) but OGA contains lower air voids than the PA, which is achieved using a greater amount of fine aggregates. OGA also provides for noise reduction potential because a part of the sound energy is absorbed through the voids. It has greater durability than the traditional PA does but potential durability problems are higher when compared to the SMA and dense hot mix asphalt (HMA). The Superpave™, known as the superior performing pavement, is a dense AC mix that has been evolved as a part of the US strategic highway research program (SHRP). It is known for high durability in all climatic conditions.

The study presented in this paper measured and compared the sound energy absorption capabilities of normal (conventional) asphalt and concrete pavements that are known for good durability and are typically used in Ontario highway pavement construction.

Relevant Past Studies

In Wisconsin and Minnesota, the Superpave AC was shown to produce the lowest noise among the AC and tined PCC surfaces [12]. In Europe, the exposed aggregate PCC surface was shown to be five dBA quieter than the transversely tined PCC surface [5]. In Ohio, a 1-year old OGA surface was shown to be the quietest pavement [13]. However, a global survey has indicted that OGA pavements can reduce the pass-by noise by 1 to 9 dBA when compared to the dense HMA, but their noise reduction benefit diminishes in just 5 to 7 years [5].

In Europe, a double layer (25 mm 0/10 over 40 mm 0/18) PA pavement was shown to be 3.3 dBA quieter, with sound absorption coefficient of 0.39, than the single layer (40 mm 0/18) PA. A 4-year old (0/18) PA was shown to be 1.7 dBA louder than a similar new one indicating a noise increase for the PA over time [14]. In the UK, the SMA, 10 mm Superpave and 14 mm Superpave were shown to be 4.9, 1.3 and 0.9 dBA, respectively, quieter for light vehicles, and 3.7, 2.5 and 1.4 dBA, respectively, quieter for heavy vehicles as compared to the conventional dense hot rolled asphalt. The SMA was shown to be the quietest pavement and was expected to remain quieter for a long period [15].

A study found that pavement surface macrotexture positively influence the sound energy absorption i.e., sound absorption increases with an increase in surface texture. The sound absorption of 0/10 SMA was shown to vary from 6% to 10%. For the 0/15 SMA, the absorption ranged from 6% to 12%. The paper based on this study, however, concluded that further research is needed to find the actual correlation between the pavement surface macrotexture and the sound energy absorption [16]. In another study, the SMA was shown to absorb 12% while the Superpave mixes were shown to absorb 6% to 7% of the sound energy. Alternatively, a 50.8 mm and a 25.4 mm thick OGA were shown to absorb 80% and 92% of the sound energy, respectively [17]. The results for the OGA seem to be unreasonable because in a CPATT-Waterloo Region joint study the rubber modified OGA mixes were shown to absorb only 9% to 10% of the sound energy. The Waterloo regional standard dense surface mix (HL3) and the SMA were shown to absorb 8% and 6% of the sound energy, respectively [18].

A research study examined several enhanced porosity concrete mixes for the sound absorption properties. These mixes were produced using gap-graded coarse aggregates and eliminating or reducing the sand volume in the fresh mixes for a porosity of 15% to 33%. The blends of 75% #4 size aggregate with 25% #8 size aggregate and 50% #4 size aggregate with 50% #8 aggregate were shown to be the most effective in absorbing the sound energy. These mixes were shown to absorb approximately 80% of the sound energy as compared to 3% to 5% sound energy absorption by the normal concrete mixes. For the same porosity, mixes with smaller pores were shown to be more effective in sound absorption than that with large pores i.e., mix with large size aggregates [4].

An Alberta (Canada) study found the gap graded asphalt rubber concrete surface to be an unfavorable choice because of the concerns over durability, higher cost and uncertainty in the noise reduction benefit over time [19]. A study observed a decline in sound intensities (tire-pavement interaction noise) at all frequencies for the dense and gap graded asphalts with an increase in sound energy absorption. Alternatively, the higher sound absorption capability of the OGA was not shown to be beneficial for the reduction of low frequency roadway noise [20].

Many other studies have measured the tire-pavement interaction or traffic noise of different AC and PCC pavements with a wide variation in results [21]. Some examples are presented above. However, as discussed above, limited studies have been carried out to determine the sound absorption capabilities of conventional (normal) PCC and AC pavements.

Objectives

The objectives of this study, which is part of a comprehensive research on pavement surface characteristics by the CPATT at the University of Waterloo (Ontario, Canada), are: i) quantifying the sound absorption capabilities of the normal weight (conventional) PCC specimens that were surface textured in different configurations, ii) determining the effect of surface macrotexture and thickness variation on the variation of PCC pavements sound absorption capability, iii) quantifying the sound absorption capability of specimens obtained from as-built conventional/durable AC pavements on Ontario highways, and iv) examining the effect of AC mix density, thickness, air voids content and the surface macrotexture on the variation of sound absorption capability.

Sample Collection and Specimen Preparation

Preparation of PCC Specimens

A standard 30 MPa ready mix concrete with 20 mm nominal maximum size aggregate, which is used for various structural applications including the PCC pavements in Ontario, was used for preparing the PCC specimens for sound absorption testing. The slump and air voids content of the fresh concrete at the delivery point were 100 mm and 5.4%, respectively. The compressive

a) Screed Finish b) Astroturf Dragged Surface

c) Burlap Dragged Surface d) Broom Dragged Surface

Fig. 1. Sample Pictures of the Textured PCC Surfaces.

strength at 28 days was 37.3 MPa. All the PCC specimens for sound absorption testing were prepared at the same time and location (CPATT laboratory) from a single load of this concrete mix.

For preparing the PCC specimens that are to be tested for the sound energy absorption using the CPATT impedance tube, the standard 152 mm (6 in.) diameter plastic cylindrical molds (used for concrete compressive strength) were used. However, the standard molds were cut to reduce the height to 76 mm (3 in.) so that the hardened PCC specimens will fit into the impedance tube. The fresh concrete in cylindrical molds was consolidated using the standard tamping rods. All the fresh PCC specimens were initially surface finished with wooden screeds.

The fresh PCC cylindrical specimens were then surface textured in different configurations with three replicate specimens in each configuration. The surface textures included screed finish, burlap, corn broom and plastic turf drag, exposed aggregate, and 3.2 mm wide and 4 mm deep various tining using steel tines. Two exposed aggregate surface textures were produced by spraying different rates of surface retarder on the fresh concrete surface and washing out the surface mortar after curing for 24 hours. The tines were spaced uniformly at 16 mm c/c (Ontario Provincial Standard) or randomly at 10 to 22 mm c/c. Specimen preparation in such a manner has enabled to evaluate the true effect of various surface textures on sound reflection or absorption properties, by controlling the effect of varying materials, mixes, temperature, aggregate gradation, age and the uses. Fig. 1 shows sample pictures of the textured PCC surfaces. Table 1 shows the list of PCC surface texture configurations that were tested for the sound absorption using the CPATT impedance tube.

To determine the effect of normal PCC thickness on sound absorption capability, three large slabs (1.20 m side square) were prepared from the same mix/batch of the concrete for cylindrical specimens. These slabs were large enough to fit the CPATT portable reverberation chamber for sound absorption testing. The thicknesses of the PCC slabs were 76 mm, 200 mm and 260 mm, respectively. The 76 mm thickness was chosen to compare the sound absorptions measured using two different methods/equipment (impedance tube and reverberation chamber). Other two thicknesses (200 mm and 260 mm) represent the typical concrete pavement thicknesses used on Ontario highways. The fresh concrete for these panels were consolidated using a concrete vibrator. The slabs were surface finished using a wooden screed (similar surface finishing for all). These allowed for the determination of the difference in sound energy absorption purely due to the variation in thickness of the conventional concrete pavement.

Preparation/Acquisition of AC Specimens

For the sound absorption testing of AC pavements, cores were obtained from the as-built (new) surfaces on Ontario highways before they were opened for the traffic. The asphalt mixes of available cores include six regular 12.5 mm Superpave (SP12.5), six fine graded 12.5 mm Superpave (SP12.5Fine) and a 12.5 mm SMA. Five to ten cores were available from each site, except the SMA for which only two cores were available. All the cores were approximately 150 mm in diameter. Fig. 2 shows the aggregate skeletons of typical regular SP12.5, fine graded SP12.5 and SMA mixes.

Three cores of approximately equal thickness were selected from each Superpave site, except a regular 12.5 mm Superpave for which five cores of varying thickness were selected to examine the effect of varying asphalt layer thickness on the variation of sound absorption capability. For the SMA, both of the available cores were selected. The bottom surface of each core was ground or saw cut to

Table 1. PCC Surface Textures for Sound Absorption Testing and Peak Sound Absorptions.

Group	Tools	Texture configuration	MTD	Peak sound absorption
Reference	Screed finish	Smooth surface	0.57 mm	4.9% (1200 Hz)
Drag	Coarse burlap	Burlap drag	0.87 mm	5.3% (400 and 1200 Hz)
	Broom (corn)	Broom drag	1.84 mm	5.0% (1000 Hz)
	Plastic turf	Turf drag	1.21 mm	4.8% (1000 and 1200 Hz)
Exposed aggregate	Retarder: 250 sq-ft/gallon	Low exposed aggregate (1)	1.86 mm	6.1% (1000 Hz)
	Retarder: 150 sq-ft/gallon	High exposed aggregate (2)	2.17 mm	5.4% (400, 900, 1000 and 1200 Hz)
Tining	Steel tine	10-22 mm random	1.70 mm	4.7% (1200 Hz)
	Coarse burlap/ steel tine	Burlap drag and 10-22 mm random	1.57 mm	4.6% (1200 Hz)
		Burlap drag and 16 mm uniform	1.65 mm	5.4% (1200 Hz)

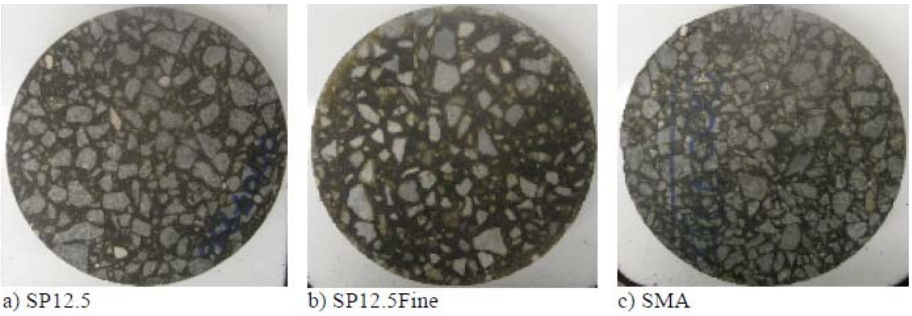
a) SP12.5 b) SP12.5Fine c) SMA

Fig. 2. Aggregate Skeletons of Three Types of AC Pavements.

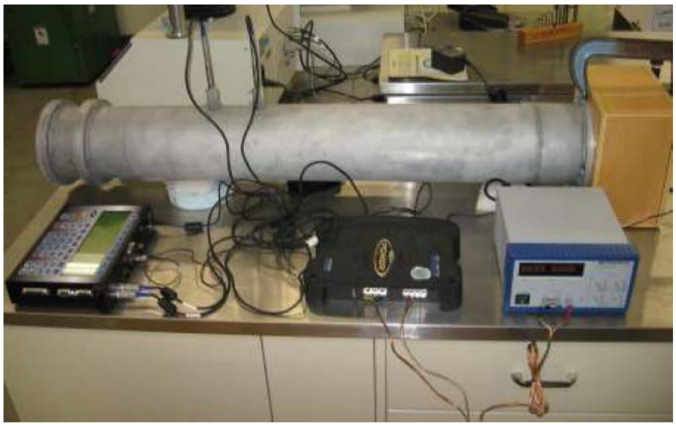

Fig. 3. Impedance Tube for Sound Absorption Testing at CPATT Laboratory.

Fig. 4. Sound Absorption Testing using Portable Reverberation Chamber.

provide a similar smooth bottom surface to be consistent in specimen preparation. The thickness of each core was then measured. The average thicknesses of regular Superpave, fine graded Superpave and SMA specimens were 41 mm, 45 mm and 49 mm, respectively.

Measurement of Sound Absorption, Surface Texture and Density

The normal incident sound absorption of cylindrical PCC and AC specimens were measured using the CPATT impedance tube (Fig. 3). The impedance tube method is described in European standard ISO 10534-2 [22] and US standard ASTM E-1050 [23]. In this method, the cylindrical specimen is mounted at one end and a speaker is mounted on the other end (rectangular box in Fig. 3) of the impedance tube. A sound pulse is generated by an analyzer and is amplified by an amplifier that sends a sound wave at 20 Hz-10 kHz into the impedance tube through the speaker. The generated normal incidence sound is propagated to the specimen that absorbs a part of the sound energy and the remaining energy is reflected back. Two microphones capture the incident and reflected sound wave amplitudes, respectively, which are then used to calculate the sound absorption coefficient or percentage absorption of sound energy of the material under test. The CPATT tube was designed and manufactured by the National Centre for Asphalt Technology (NCAT) at Auburn University in the US. The sound absorption measurement with this impedance tube is valid for 170 Hz to 1,350 Hz frequency range (working frequency).

Five to ten repeated measurements (transfer functions of the incident and reflected sound wave amplitudes) were taken for each cylindrical AC and PCC specimen. The average sound absorption of each specimen was then calculated using the ACUPRO software developed at the Kentucky University in the US. The mean texture depth (MTD) of each AC and PCC surface was measured using the sand patch method [24]. The specific gravity (bulk relative density) of each asphalt core was then measured using the surface dry method.

The sound absorption of the PCC panels was measured using the portable reverberation chamber (Fig. 4). The portable reverberation chamber is an innovative method for measuring the sound absorption of actual in-situ pavement and the pavement slabs prepared in the laboratory or obtained from the field. The CPATT at the University of Waterloo has developed this method with the help of an acoustic consultant following the concept of ASTM C423 [25]. The small (1m×1m) chamber is placed on the pavement surface, a random incident sound power (at 20 Hz to 10 kHz) is generated in the chamber using the noise signal generator, amplifier and speaker as in the case of the impedance tube. The decay time of a 60 dB sound is measured using the microphone mounted on the top of the reverberation chamber. The decay time is then used to calculate the sound absorption coefficient of the test pavement using the Sabine formula.

To determine the accuracy of the reverberation chamber sound absorption test results, the cylindrical PCC specimens that were tested with the impedance tube were also tested using the reverberation chamber. The peak sound absorptions were shown to be identical using these two methods. Five to ten measurements were taken for each PCC slab and the average sound absorption was

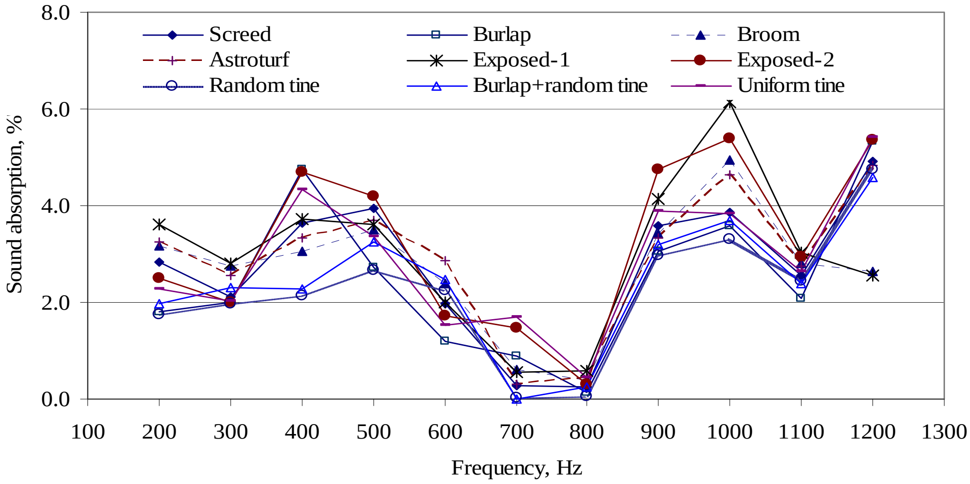

Fig. 5. Sound Absorption of Different PCC Surfaces at Different Frequencies.

determined for each.

Analysis and Results

Sound Absorption of Various PCC Pavement Surfaces

PCC slabs were shown to absorb 3% to 4% of the sound energy (peak sound absorption coefficients of 0.03 to 0.04). The variation in thickness (260 mm, 200 mm, and 76 mm) of conventional dense PCC has shown no noticeable effect in sound energy absorption. This shows that higher thickness of the conventional PCC is not beneficial in terms of reducing the roadway noise. Fig. 5 shows the variation of sound absorption at different sound frequencies for PCC specimens that were prepared in the laboratory with different surface texturization. The summary of the peak sound absorptions and corresponding frequencies for various surface textures are presented in Table 1. As shown in Fig. 5 and Table 1, the textured PCC surfaces were able to absorb a maximum 5% to 6% of the sound energy (peak sound absorption coefficients of 0.05 to 0.06). The frequencies at the peak sound absorption varied from 400 Hz to 1,200 Hz. Table 1 shows that the smooth (screed) finished surface absorbed similar percentage of the sound energy as absorbed by other specimens that were surface textured in different configurations and are varies in texture depth. Alternatively, the exposed aggregate-2 surface with a slightly higher texture depth was shown to absorb slightly lower than the sound energy absorbed by the exposed aggregate-1 surface. These show that surface texture type and texture depths are insignificant for the variation of sound energy absorption of the conventional PCC tested in this study. The slightly higher sound energy absorption of the cylindrical specimens as compared to that of the PCC slabs prepared from the same concrete mix is probably associated with the variation in consolidation (density) of two specimen types. It should be noted that a concrete vibrator was used for consolidation of the PCC slabs where as tamping rods were used for the preparation of cylindrical PCC specimens.

The observation/analysis presented above indicates that sound generation and sound absorption are two different measures. Sound is generated due to the complex interaction of the tire and pavement surface. It mainly depends on tire tread patterns, stiffness of tires as well as pavements and the shape (type and orientation) and magnitude (width and depth) of the pavement surface texture. Alternatively, the absorption of the generated sound energy depends mainly on the interconnected voids in the pavement surface layer. However, for the same texture shape and magnitude, a porous surface will absorb a higher percentage of sound than a non-porous surface. In such cases, the porous surface is expected to produce lower tire-pavement interaction noise that is transmitted to a roadside or on-road receiver.

Sound Absorption of Various AC Pavement Mixes

The regular 12.5 mm Superpave mixes were shown to absorb maximum 4.8% to 7.9% of the sound energy (peak sound absorption coefficient of 0.048 to 0.079) with an average sound absorption of 6.3%. The 12.5 mm SMA was shown to absorb maximum 7.5% of the sound energy. Alternatively, the fine graded 12.5 mm Superpave mixes were shown to absorb maximum 6.8% to 9.2% of the sound energy with an average absorption of 8.5%. On average, the fine graded 12.5 mm Superpave mixes were shown to absorb 2.2% higher sound energy as compared to the similar regular Superpave mixes. The frequencies at peak sound absorption ranged from 400 Hz to 1,100 Hz. These results closely agree with other similar studies [16, 17].

Fig. 6 shows the variation of sound energy absorption with the variation in bulk relative density (BRD) of the Superpave mixes (excluding the SMA). The SMA was shown to be deviant from the trend of Superpave possibly because of the variation in mix constituents (cellulose and/or rich binder in the SMA). As shown in Fig. 6, the sound absorption of AC mixes decreases with an increase in the density of the tested AC mixes. With this trend, the sound absorption was shown to decrease by 1.4% for each 0.1 increase in the BRD. The correlation (correlation coefficient, r = 0.54) was shown to be statistically significant at the 5% level of significance.

Fig. 7 shows the variation of sound energy absorption of the Superpave AC mixes with the variation of layer thickness. A negligible increase in sound energy absorption has been observed

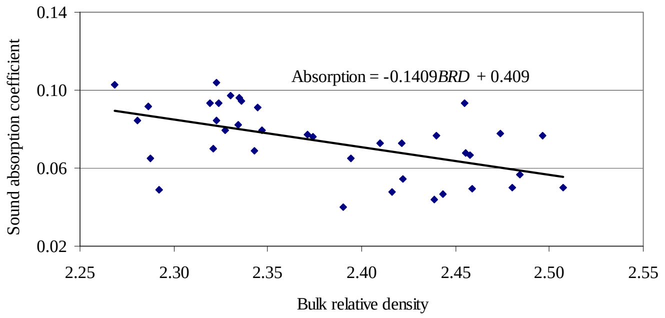

Fig. 6. Variation of Sound Absorption with Variation in BRD of AC Mixes.

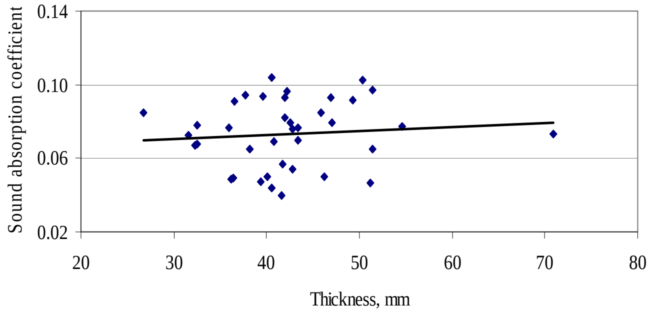

Fig. 7. Variation of Sound Absorption with AC Layer Thickness.

with an increase in the AC layer thickness. The correlation (*r* = 0.09) between the sound energy absorption and AC pavement layer thickness was not shown to be statistically significant at the 5% level of significance. This indicates that the variation of sound energy absorption with the variation in layer thickness of dense AC mixes is of minimal importance i.e., there is no justification of increased thickness with respect to the sound energy absorption capability of conventional dense AC mixes.

The sound energy absorption of the Superpave AC pavements tested in this study was shown to increase slightly with an increase in air voids content in the mix (Fig. 8). However, the correlation (*r* = 0.28) was also not shown to be statistically significant at 5% significance level. This is probably due to the narrow range of the air voids content for the tested specimens. The variation of sound energy absorption with the variation of the Superpave AC pavements surface texture is shown in Fig. 9. As shown in the figure, the sound absorption increases very slightly with an increase in pavement surface texture. However, the correlation (*r* = 0.12) was shown to be very poor and statistically insignificant at 5% significance level. This further indicates that the shape, level or orientation of pavement surface texture has no significant effect on the sound energy absorption, although they have effect on the generation and propagation of sound (noise).

Conclusions and Recommendations

This paper has examined the noise reduction potential of the conventional PCC and AC surfaces including the true effect of surface texture, thickness, density and air voids content on sound energy absorption. On average, the regular 12.5 mm SP, 12.5 mm SMA, and 12.5 mm SPFine mixes were shown to absorb 6.3%, 7.5%, and 8.5% of the sound energy, respectively. Textured PCC surfaces were shown to absorb 5% to 6% of the sound energy. The sound absorption of the conventional (dense and durable) AC surfaces was shown to decrease at 1.4% for each 0.1 increase in the density. The effect of normal/conventional PCC and AC layer thickness and surface texture as well as AC mixes air voids content were shown to be insignificant for the variation of sound energy absorption. However, further research is encouraged to examine the effect of PCC as well as AC surface textures, air voids content and pavement layer thickness on sound energy absorption.

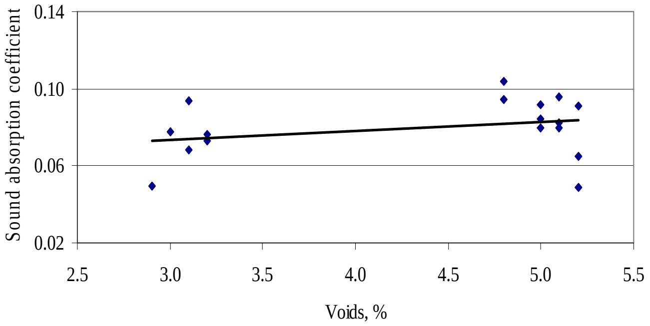

Fig. 8. Variation of Sound Absorption with AC Air Voids Content.

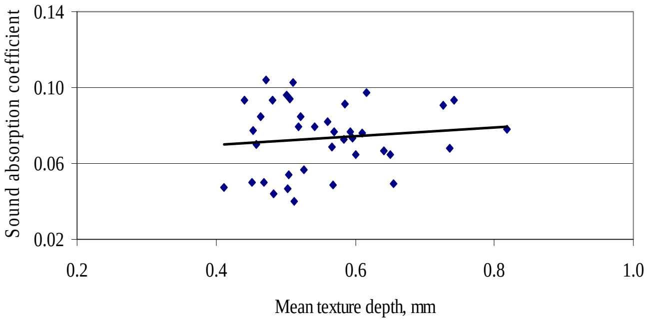

Fig. 9. Variation of Sound Absorption with AC Surface Texture Depth.

Acknowledgements

The authors would like to thank the Ministry of Transportation of Ontario (MTO) Pavement/Materials Engineering team, the Cement Association of Canada (CAC), Natural Science and Engineering Research Council (NSERC) of Canada and Dufferin Ready Mix for their assistance in this research.

References

1. FEHRL, (2006). Sustainable Road Surfaces for Traffic Noise Control: Guidance Manual for the Implementation of Low-noise Road Surfaces, *Report no. 2006/2,* Forum of European National Highway Research Laboratories (FEHRL), Brussels, Belgium.
2. Herman, L.A., (1998). Analysis of Strategies to Control Traffic Noise at the Source: Implications for Policy Makers, *Transportation Research Record,* No. 1616, pp. 41-48.
3. McDaniel, R.S. and Thornton, W.D., (2005). Field Evaluation

of a Porous Friction Course for Noise Control, *Proceedings of the 84th Annual Meeting of Transportation Research Board*, Washington, D.C., USA, CD-ROM.

4. Neithalath, N., Garcia, R., Weiss, J., and Olek, J., (2005). Tire-pavement Interaction Noise: Recent Research on Concrete Pavement Surface Type and Texture, *Proceedings of the 8th International Conference on Concrete Pavements*, Colorado Springs, Colorado, USA, CD-ROM.
5. Wayson, R.L., (1998). Relationship between Pavement Surface Texture and Highway Traffic Noise, *NCHRP Synthesis of Highway Practice, No. 268*, Transportation Research Board, Washington, D.C., USA.
6. García, A. and Mérida, A., (2005). Urban Traffic Noise Reduction by Quiet Pavements: Experimental Results, *Proceedings of the 84th Annual Meeting of Transportation Research Board*, Washington, D.C., USA, CD-ROM.
7. Bernhard, R.J. and McDaniel, R.S., (2005). Basics of Noise Generation for Pavement Engineers, *Transportation Research Record*, No. 1941, pp. 161-166.
8. Sandberg, U. and Ejsmont, J.A., (2002). *Tyre/road Noise Reference Book*, INFORMEX Ejsmont & Sandberg Handelsbolag, Harg, Kisa, Sweden.
9. Snyder, M.B., (2006). Pavement Surface Characteristics: A Synthesis and Guide, *Report No. EB235P*, American Concrete Pavement Association (ACPA), Skokie, Illinois, USA.
10. Prowell, B.D., (2005). Design of Finer SMA Mixes, *Quiet Asphalt 2005: A Tire/Pavement Noise Symposium*, Lafayette, Indiana, USA.
11. Bastow, R., Webb, M., Roy, M., and Mitchell, J., (2008). *An Investigation of the Skid Resistance of Stone Mastic Asphalt Laid on a Rural English County Road Network*, Dorset County, Dorchester, UK. Online http://www.transit.govt.nz/technical/surfacefriction/pdf/Investigation-Skid-Resistance-Stone-Mastic-Asphalt-laid-Rural-English-County-Road-Network.pdf, Last Accessed August, 2008.
12. Kuemmel, D.A., Jaeckel, J.R., Satanovsky, A., Shober, S.F., and Schmiedlin, R.B., (1997). Impacts Related to Pavement Texture Selection, *Report No. WI/SPR-06-96*, Wisconsin Department of Transportation, Madison, Wisconsin, USA.
13. Herman, L.A., Ambroziak, M.J., and Pinckney, E., (2000). Investigation of Tire-road Noise Levels for Ohio Pavement Types, *Transportation Research Record*, No. 1702, pp. 57-62.
14. Lancieri, F., Licitra, G., Losa, M., Cerchiai, M., and Berengier, M., (2000). Field and Laboratory Testing on Different Porous Asphalt Pavements, *Proceedings of the Fourth International Symposium on Pavement Surface Characteristics of Roads and Airfields: SURF 2000*, pp. 339-346, Nantes, France.
15. Chandler, J.W.E., Phillips, S.M., Roe, P.G., and Viner, H.E., (2003). Quieter Concrete Roads: Construction, Texture, Skid Resistance and Noise, *TRL Report No. 576*, Transportation Research Laboratory, UK.
16. Boscaino, G., Pratico, F.G., and Vaiana, R., (2004). Texture Indicators and Surface Performance in Flexible Pavements, *Proceedings of the Fifth International Symposium on Pavement Surface Characteristics (SURF 2004)*, Toronto, Ontario, CD-ROM.
17. Crocker, M.J., Hanson, D., Li, Z., Karjatkar, R., and Vissamraju, K.S., (2004). Measurement of Acoustical and Mechanical Properties of Porous Road Surfaces and Tire and Road Noise, *Transportation Research Record*, No. 1891, pp. 16-22.
18. Leung, Y.T.F., Tighe, S.L., MacDonald, G., and Penton, S., (2006). Development of Tools to Evaluate Quiet Pavements in the Laboratory and Field, *Proceedings of the 2006 Annual Conference of Transportation Association of Canada (TAC)*, Charlottetown, Prince Edward Island, Canada, CD-ROM.
19. Treleaven, L., Pulles, B., Bilawchuk, S., and Donovan, H., (2006). Asphalt Rubber - the Quiet Pavement, *Proceedings of the 2006 Annual Conference of Transportation Association of Canada (TAC)*, Charlottetown, Prince Edward Island, Canada, CD-ROM.
20. Nelson, J., Kohler, E., Rymer, B., and Ongel, A., (2008). Acoustical Absorption of Porous Pavement, *Proceedings of the 87th Annual Meeting of Transportation Research Board*, Washington, D.C., USA, CD-ROM.
21. Ahammed, M.A., (2009). Safe, Quiet and Durable Pavement Surfaces, *Ph.D. Dissertation*, Department of Civil and Environmental Engineering, University of Waterloo, Ontario, Canada.
22. ISO 10534-2, (1998). *Acoustics: Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes, Part 2: Transfer Function Method*, International Organization for Standardization, Geneva, Switzerland.
23. ASTM E1050, (2008). *Standard Test Method for Impedance and Absorption of Acoustical Materials using a Tube, Two Microphones and a Digital Frequency Analysis System*, ASTM International, West Conshohocken, Pennsylvania, USA.
24. ASTM E965, (2006). *Standard Test Method for Measuring Pavement Macrotexture Depth Using a Volumetric Technique*, ASTM International, West Conshohocken, Pennsylvania, USA.
25. ASTM C423, (2008). *Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method*, ASTM International, West Conshohocken, Pennsylvania, USA.