Development of Tools to Evaluate Quiet Pavements in the Laboratory and Field

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ABSTRACT

Road traffic noise is becoming a major public concern. While there have been many claims of noise reduction from different agencies over the years, there was limited conclusive documentation and testing to support the claims. In late 2003, the University of Waterloo's Centre for Pavement and Transportation Technologies (CPATT) and the Regional Municipality of Waterloo embarked on a partnership to first design noise reducing pavement test sections and then secondly to conduct controlled noise testing on four different types of asphalt mixes. The four different surface courses were placed in lengths of 600m. The overall 2.4 km test area was closed to traffic and test vehicles were driven through the test area at different control speeds with sound level meters recording noise levels both at the tire/pavement interface as well as at monitoring stations off the roadway.

Noise level test results have indicated that the rubberized asphalt pavement mixes do achieve a reduction in measured noise. The paper will elaborate the use of testing protocol, measured noise results and the conclusions which will be of use by other municipalities in assessing the merits of using rubberized surface course asphalts to reduce noise in urban, noise-sensitive environments. CPATT has also started a laboratory program which involves the use of an impedance tube to test the sound absorption coefficient of the pavement in the laboratory. Preliminary results from the laboratory will be presented in addition to the field measurements. This study attempts to integrate laboratory and field test results to provide quiet pavement solutions.

INTRODUCTION

BACKGROUND

Road traffic noise is becoming a major public concern nowadays, especially for the people who live near highways or heavy traffic volume areas. Noise is defined as unwanted sound and no matter what time it is throughout the day; people exposed to excessive amount of noise will affect their lives at home, at work, and at play. This directly affects the comfort, health, and the quality of living of the people exposed to excessive noise. The World Health Organization (WHO) guidelines states that the standards for good sleep, sound levels should not exceed 30 dBA and 40 dBA for a continuous background noise and individual noises events exceeding 45 dBA and 55 dBA should be avoided during night-time and daytime, respectively.

The Ministry of the Environment in Canada has also implemented a guideline to control traffic noise impacts. The guideline recommends if the traffic noise level exceeding the acceptable limits, physical noise mitigation methods are required. The current certified type of physical mitigations includes constructing noise barriers and earthberms to control sound level at the outdoor living area, and upgrade building components and enforce to install central air conditioning unit at the building to control indoor sound level from the traffic noise [1]. These kinds of noise mitigation methods are neither economical nor practical because these current methods can only control the traffic noise propagation, but not actually reduce the traffic noise from the sources.

Road traffic noise is mainly generated by three sources: Power Engine, Aerodynamics, and Tire/Pavement Interaction. Noise generated by the interaction between tire and pavement becomes a dominant source when the vehicle speed is at 35 km/h [2]. Therefore, many transportation agencies are investigating noise reducing pavement to reduce road traffic noise. Experience reported from the United States, Europe, and Japan has shown that noise reducing pavement can reduce a significant amount of road traffic sound levels. These pavements include rubberized asphalt, open-graded asphalt, and stone mastic asphalt.

OBJECTIVES AND SCOPE OF STUDY

The Regional Municipality of Waterloo (RMOW), Ontario, Canada, in partnership with the University of Waterloo Centre for Pavement and Transportation Technology (CPATT), have decided to undertake an investigation in noise reducing asphalt pavement to determine whether traffic noise can be significantly reduced in the southern Ontario environment as compared to a conventional mix surface, Hot-Laid 3 (HL-3). In addition to rubberized open-graded friction course (rOGFC) asphalt pavement, this research will also investigate the noise reducing capability of stone mastic asphalt (SMA) mix.

Two types of field sound level measurements were conducted in this study: Close-Proximity Method and Controlled Pass-By Method. Laboratory testing, Impedance Tube Testing was utilized to determine the pavement sound absorption properties. Preliminary field and laboratory test results will be reported in this paper and recommendations of the potential use of the noise reducing pavement will be provided.

Although the test sections were constructed in 2004 and only a limited amount of data is available at this time, it is expected that the RMOW and CPATT will continue to monitor performance over time.

DESCRIPTION OF THE STUDIED PAVEMENTS

Two rubberized open graded friction courses (rOGFC) and stone mastic asphalt (SMA) were chosen to be the studied asphalt pavements. Rubberized asphalt is a process of incorporating crumb rubber with asphalt paving materials. Many agencies are using rubberized asphalt pavement in order to achieve the significant environmental benefit of reducing tire waste and recycling old tires instead of directing them to landfills. Some agencies claimed that rubberized asphalt pavement with open graded friction course (OGFC) can also reduce tire/pavement noise.

The mix designs and gradations for those two rOGFC are similar. The difference between these two rOGFC is that one uses premium aggregate and the other uses local aggregate. Premium aggregate meets much higher standards for the other aggregate tests when compared to the local aggregates. In order to distinguish the different between these two types of rOGFC, rOGFC with premium aggregate is named as rubberized open friction course (rOFC) and local aggregate is named as rubberized open graded course (rOGC) in this study.

In recent years, SMA is utilized for heavy traffic conditions and is gaining popularity in Canada and in the United States; it was also included in this study [3]. SMA mixes have a porous nature and may also have noise reduction capabilities as compared with dense-graded asphalt mix. The SMA is a gap-graded asphalt mix which combines strong, coarse aggregate with a high asphalt content, but lacks medium-sized aggregates [4]. The aggregates used in SMA are premium grade and meet much higher standards for the other aggregate tests.

These three asphalt pavements will be compared with a commonly used mix in municipalities in Ontario, Hot-Laid 3 (HL-3) which consists of 15% of recycled asphalt pavement (RAP) in this study. The design thickness of each pavement type is 40 mm. The asphalt binders for all studied pavements are PG 64-28. This means the binder is designed to comply with the performance criteria at an average 7-day maximum pavement design temperature of 64 ^{o}C and at a minimum pavement design temperature of -28 ^{o}C. The gradation, aggregate quality, and basic mix design properties have been summarized in Table 1.

TABLE 1 – Job Mix Formula and Basic Mix Design Properties

		Job Mix Formula			
		rOFC	rOGC	SMA	HL-3
Sieve Size	16.00 mm	100	100	100	100
	13.20 mm	98.1	97.8	98.1	98.8
	9.50 mm	64.5	71.7	63.2	84.9
	4.75 mm	27.1	27.9	22.4	58.7
	2.36 mm	20.6	16.5	19.3	50.2
	1.18 mm	14.1	12.1	16.4	37.7
	0.60 mm	11.1	8.8	14.7	22.7
	0.30 mm	6.8	6.5	12.1	13.7
	0.15 mm	3.6	5.1	9.9	7.7
	0.075 mm	2.5	4.1	8.1	4.9
Type of Aggregate		Premium	Local	Premium	Local
Asphalt Contents (%)		5.6	5.8	5.7	5.0
Air Voids (%)		6.9	8.6	3.9	3.7
VMA (%)		18.3	19.3	16.9	15.4
Stability (N)		7397	6234	N/A	14111
Flow (0.25 mm)		13.0	16.1	N/A	10.6
BRD		2.281	2.286	2.355	2.400
MRD		2.450	2.501	2.451	2.493

SITE DESCRIPTIONS

Four types of asphalt pavement surface courses were placed in August 2004 on William-Hasting Line (Road 11), between Manser Road and Chalmers Forrest Road in Waterloo, Ontario, Canada as shown in Figures 1 and 2.

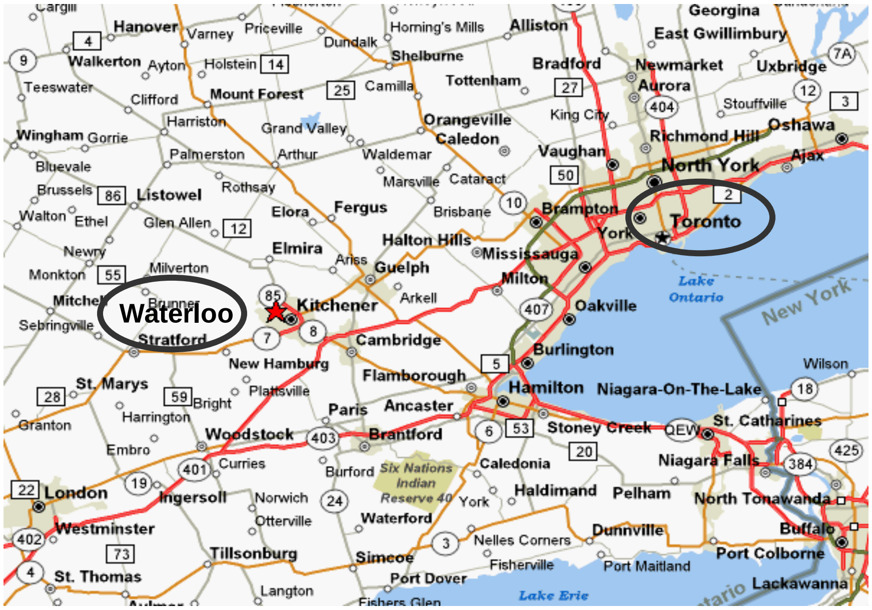

FIGURE 1 – Map of Waterloo, Ontario (Adopted from www.mapquest.ca)

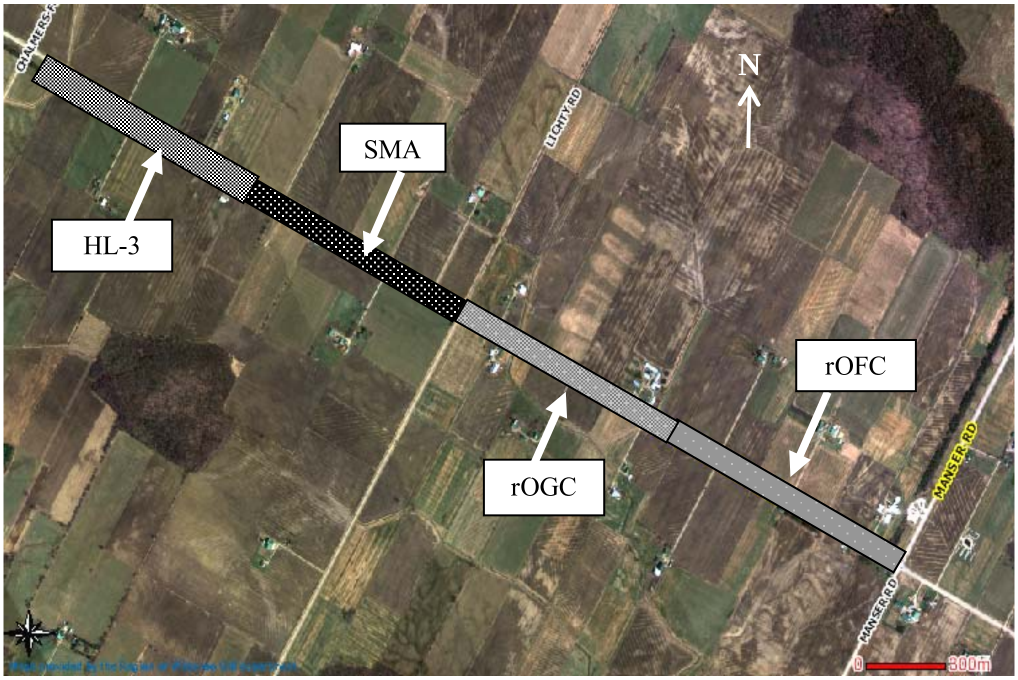

FIGURE 2 – Site Map

This test site is located in a rural area surrounded by farmlands. Pavement surface courses were placed in an order of rOFC, rOGC, SMA, and HL-3 from east to west. The length of each type of pavement section is approximately 600 m. A 40-mm thick cold-in-place recycled layer was placed throughout the test section areas as the binder or base course.

NOISE MEASUREMENT METHODS

Traffic noise measurements were taken in September 2004 which is about one month after pavement placement. There were 13 testing vehicles used for the noise testing and they were divided into three categories according to the Ontario Road Noise Analysis Method for Environment and Transportation (ORNAMENT): light (5 vehicles), medium (5 vehicles), and heavy (3 vehicles) vehicles, which are listed in Table 2 [5]. Each noise measurement consisted of a single test vehicle passing through the test site. The driver of the testing vehicle drove through the centerline of the test road at constant speeds of 60 km/h, 70 km/h, 80 km/h, and 90 km/h from east to west and then made a return trip. Thus two measurements for each speed were taken for each vehicle. However, since the two measurements are independent of each other, they can be considered as individual measurements.

TABLE 2 – Description of Testing Vehicles

Vehicle Size	Vehicles Type	Specifications
Car/Light Truck	2 cars, 1 mini van, 2 light trucks	2-axle, 4 wheels, ≤ 9 passengers, ≤ 4500 kg
Medium Truck	2 city buses, 3 city work trucks	2-axle, 6 wheels, 4500 to 12000 kg
Heavy Truck	3 snow plow trucks	≥ 3-axle, design for hauling cargo, ≥ 12000 kg

Two sound level measurement techniques were utilized in this analysis: the Close-Proximity Method (CPX) and the Controlled Pass-By Method (PBM). The purpose of these two methods is to compare the measured sound level on the studied pavements with the conventional pavement. PBM method is commonly used for measuring vehicle noise worldwide. The International Organization for Standardization (ISO) describes the measurement of Statistical PBM in ISO 11819-1:1997 [6]. In this study, controlled PBM was used instead of the statistical PBM. Essentially, controlled PBM is same as statistical PBM but with limited number of vehicles rather than with normal traffic stream. The standard of CPX method is still under development by the ISO. The purpose of the CPX method is to measure the noise generated by the interaction between tire and pavement with microphone(s) attached close to the tire and pavement interface.

The entire area was closed during noise testing and the total closure distance was 3.6 km on William Hasting Line from Manser Road to Chalmers Forrest Road. William Hasting Line is a straight road and surrounded by farmlands. Since the test section was closed during the testing and located in rural area, therefore the ambient noise should be minimized and constant, and would not affect the traffic noise measurement.

Close-Proximity Method

The Close-Proximity Method (CPX) can give a good acoustic quality estimation of the homogeneous road surface over a long distance and under a variety of conditions. In this project, a microphone was mounted with a windscreen on the test vehicle and was located approximately 45 cm (18 inches) to 50 cm (20 inches) away from the centre of the front or rear wheel as shown in Figure 3. The purpose of this set-up was to ensure that the CPX measurement would measure the direct noise generated from the interaction between vehicle tire and pavement and to avoid measuring the engine noise generated from the testing vehicle. The CPX method measured the sound level on each pavement section in terms of an equivalent sound pressure, L_{eq} (in dBA), which is the average sound level in a given period. Since each pavement section is approximately 600 m long, it is believed that the measured equivalent sound pressure will be a good representation of the sound level.

FIGURE 3 – Close-proximity Method Microphone Set-ups

Pass-By Method

The Pass-by Method (PBM) measures the sound as vehicles travel pass a stationary microphone. In this study, the controlled pass-by method with a steady speed was used. Four pass-by monitoring stations (PBM) were set-up at the midway point of each asphalt pavement section as shown in Figure 4.

FIGURE 4 – Pass-by Method Monitoring Station Set-ups

Each monitoring station was located 15 m away from the centreline of the road, a microphone with a windscreen was located 1.5 m above pavement, and was monitored by a technician. The maximum sound level (L_{max}) was measured by the PBM. The maximum sound level (L_{max}) identifies the maximum sound levels produced by an event. In this case, an event is defined as a test vehicle passing by.

PAVEMENT SOUND ABSORPTION MEASUREMENT METHOD

Traffic noise levels were measured on different types of asphalt pavements using the Pass-By Method and Close-Proximity Method. Traffic noise level depends on the pavement sound absorption property. Pavement sound absorption property is related to the pavement porosity that is influenced by the pavement thickness, air void content, airflow resistance, and tortuosity. These parameters are quantified by its sound absorption coefficient. The air flow resistance is defined as the resistance to air passing through open pores in the pavement. The tortuosity is an artificial parameter that describes the shape of pore in the pavement [7, 8]. Generally, the thickness of the pavement has a large effect on the sharpness of the peak; the thicker pavement will have a lower peak frequency, broader the peak, and lower the peak absorption. The airflow resistance and tortuosity also have an influence on these effects [8, 9]. The sound absorption coefficient of a pavement varies with the frequency of sound and it can have a value between 0 and 1, where 0 represents no absorption (total reflection) and 1 represents total absorption of all incident sound. For high speed roads (85 km/h and up), the most important frequency is at 1000 Hz and at 600 Hz on low speed roads (50 km/h) [7, 10]. There are two methods to measure the material absorption coefficient: Impedance Tube Method and Reverberation Time Method. The Impedance Tube Method is to determine the normal incident sound absorption coefficient in various frequencies. Reverberation Time Method is to determine the random incident sound absorption coefficient in various frequencies. In this study, only Impedance Tube Method was utilized to determine the pavement sound absorption properties.

Impedance Tube Method

The purpose of the impedance tube testing is to measure the sound absorption ability of the pavement in terms of frequency. The Impedance Tube Method is described in two standards: ISO 10534-2:1998 and ASTM E1050-98. This method uses an impedance tube with a sound source (i.e. loudspeaker) connected to one end and the testing sample mounted in the tube at the other end (Figure 5). In this study, testing sample refers to the asphalt pavement core.

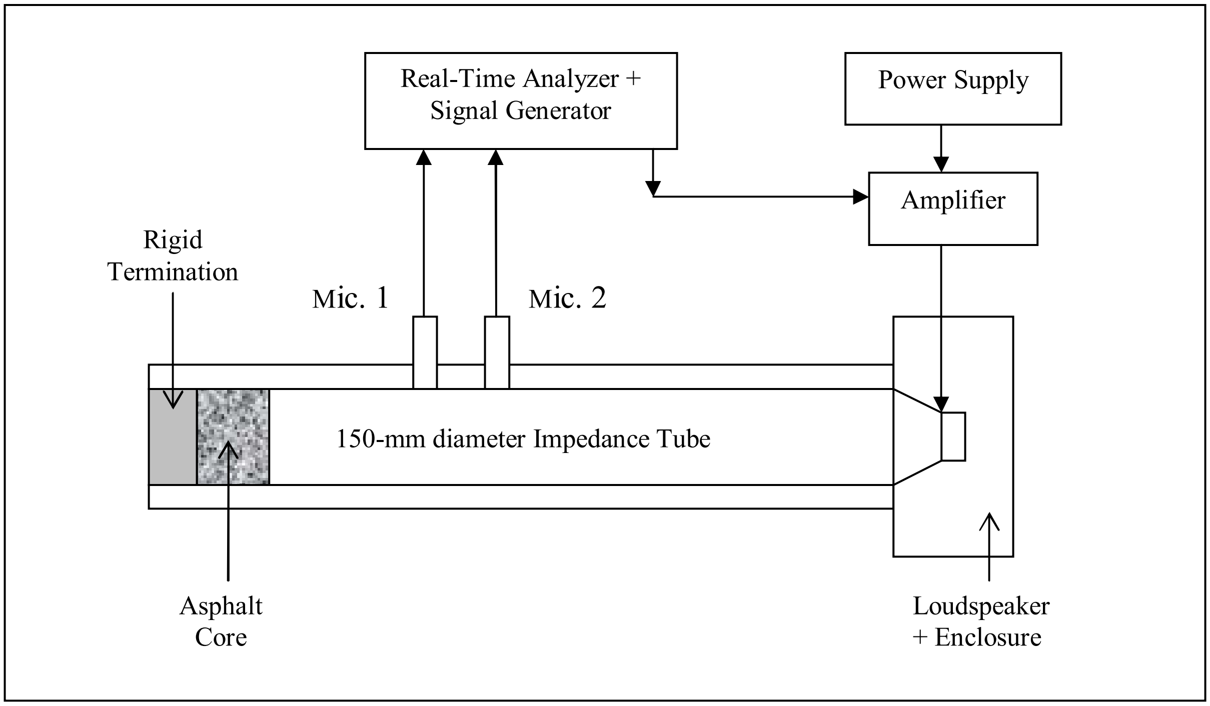

FIGURE 5 – Impedance Tube Setup Schematic

The diameter of the asphalt pavement cores is 150 mm (6 inches); however, a 150-mm diameter commercial impedance tube is not available on the market. For that reason, CPATT has purchased a 150-mm diameter (6-inch) impedance tube through the National Centre of Asphalt Technology (NCAT) in 2005. The design of the NCAT impedance tube is in accordance with ISO and ASTM standards. The frequency range is determined by the dimensions of the impedance tube setup. In terms of frequency, the lower limit is a function of microphone spacing and the upper limit is a function of tube diameter [8, 11, 12]. According to the tube design, the theoretical lower and upper frequency limits are 170 Hz and 1350 Hz, respectively [11]. The actual working frequency will be determined after the testing. Plane waves are generated in a tube through a loudspeaker using broadband white noise from the signal generation feature of Larson Davis Real Time Analyzer (Model 3000+). White noise is a type of noise that consists of all audible frequencies with equal intensity. The decomposition of the interference field is achieved by the measurement of acoustic pressures using two Larson Davis 1/2-inch free-field microphones. The real time analyzer is also used to calculate the complex acoustic transfer function for the use of determining the absorption coefficient from ACUPRO software. ACUPRO Version 2.1 "Measurement of Acoustical Properties of Materials and Systems" software is utilized to calculate the normal incidence absorption coefficient.

Asphalt core samples were made from the gyratory using the same mix from the testing site. Core samples are shown in Figure 6. Since the back of the cores surface were not smooth which would induce unwanted air gaps between the back of the core and rigid termination, all cores were saw-cut into 40 mm thick approximately in order to create a smooth back surface and increase the accuracy when averaging the result.

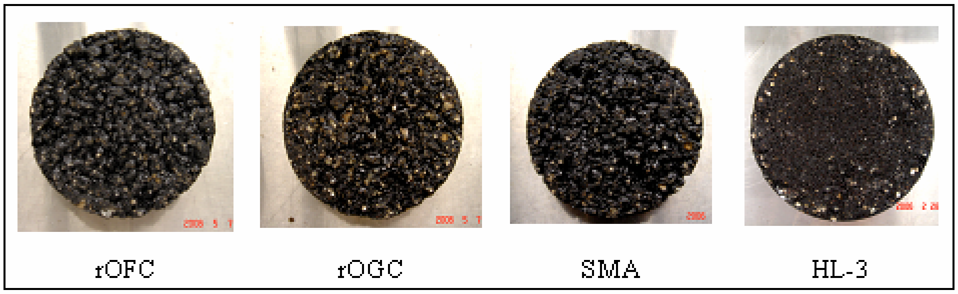

FIGURE 6 – Gyratory Asphalt Cores

The testing surfaces of the asphalt cores are not homogeneous; therefore, five samples of each type of asphalt pavement were tested and averaged in order to include representative regions of the surface. Eight random positions with same mounting condition were measured and averaged for each sample to provide measurement consistency and repeatability.

NOISE MEASUREMENT RESULTS

Close-Proximity Method (CPX Method) Results

The close-proximity method is used to measure the actual/direct noise generated between the tire and pavement. A graphical plot for the sound measurement versus vehicle speeds for each pavement type and vehicle size is shown in Figure 7. All four types of pavements show that when the vehicle speed or size increases, the sound level increases.

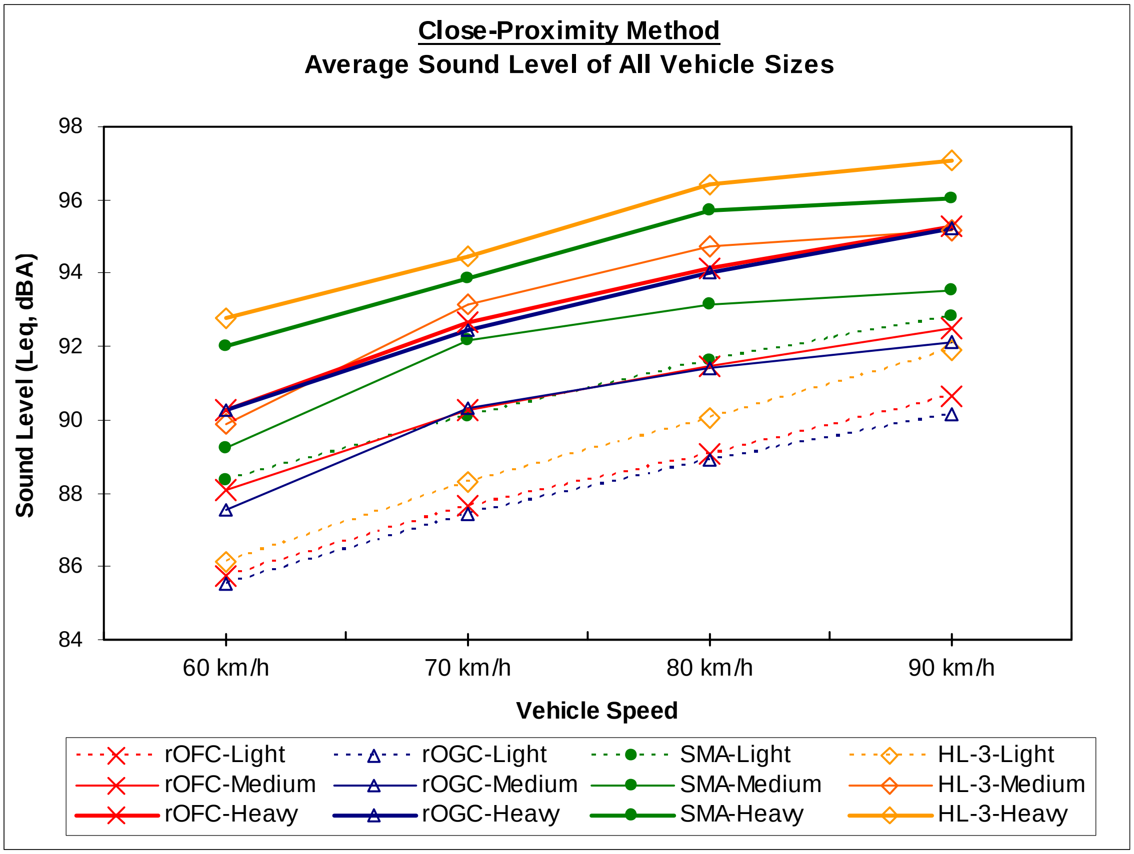

FIGURE 7 – CPX Method: Average Sound Levels (L_{eq}) versus Vehicle Speeds

The sound measurement results show that HL-3 has the highest sound level measurement at all speeds for the heavy and medium vehicle categories. It is noteworthy that the SMA has the highest sound level measurement for the light vehicle category for all speeds. Both the rOFC and rOGC have the lowest sound level measurement in all four vehicle speeds and three vehicle sizes. In addition, the sound levels of rOFC and rOGC are very similar and it is expected they would have a similar noise reduction result since the mix design in rOFC and rOGC are the very close except for the quality of the aggregate. The amount of noise reduction with respect to HL-3 (reference asphalt surface mix) is shown in Figure 8 that is presented by all vehicles, different vehicle speeds, and different vehicle sizes in a particular speed.

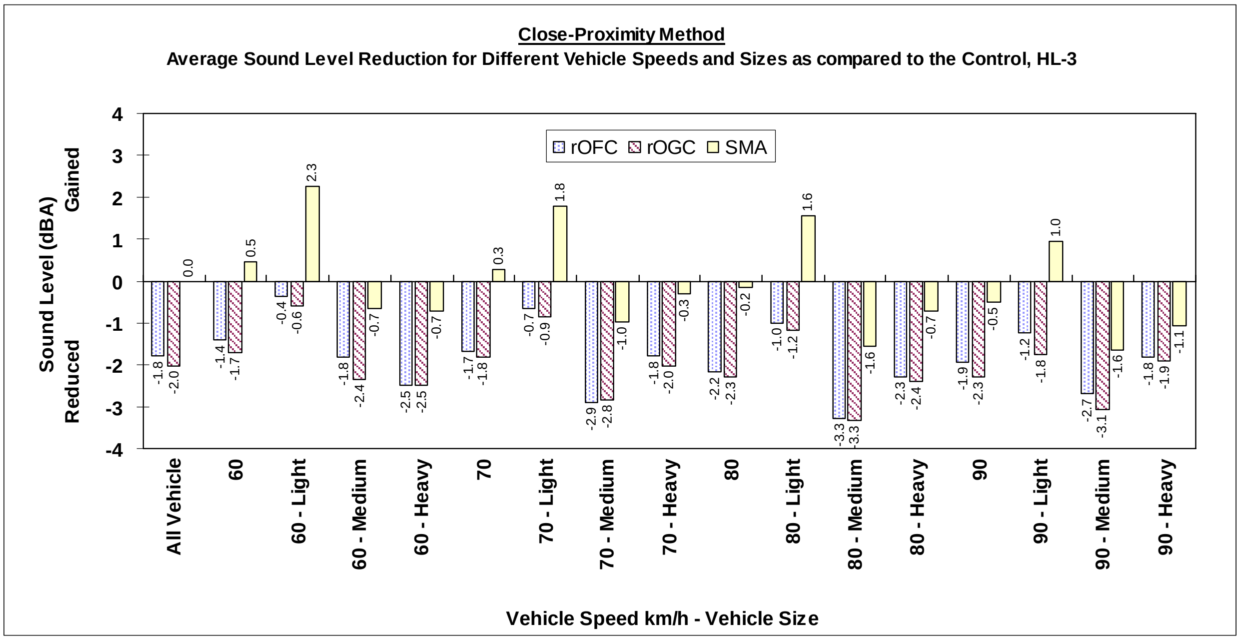

FIGURE 8 – CPX Method: Average Sound Level Reduction for Different Vehicle Sizes as compared to the Control, HL-3

In this initial study, the SMA shows the least amount of noise reduction among studied pavements. SMA does not reduce noise in the light vehicle category when compared to HL-3, but it shows noise reduction at the medium and heavy vehicle categories. Both the rOFC and rOGC pavements show the greatest amount of noise reduction. The highest noise reduction for rOFC and rOGC pavements is approximately 3.3 dBA in medium vehicle size at the speed of 80 km/h. In the overall performance (i.e. in terms of speed limit only), rOGC provides a slightly better noise reduction than rOFC and SMA. The highest noise reduction for rOFC is 2.2 dBA at the speed of 80 km/h and 2.3 dBA for rOGC at the vehicle speeds over 80 km/h. SMA only reduces noise by 0.5 dBA when the vehicle speeds are at 90 km/h, but it tends to reduce noise when the vehicle speed increases in all scenarios.

Pass-By Method (PBM) Results

The PBM tests measured the overall traffic noise at 15 m distance from a vehicle. The noise measurement results are presented in terms of Maximum Sound Level (L_{max}), which is shown in Figure 9.

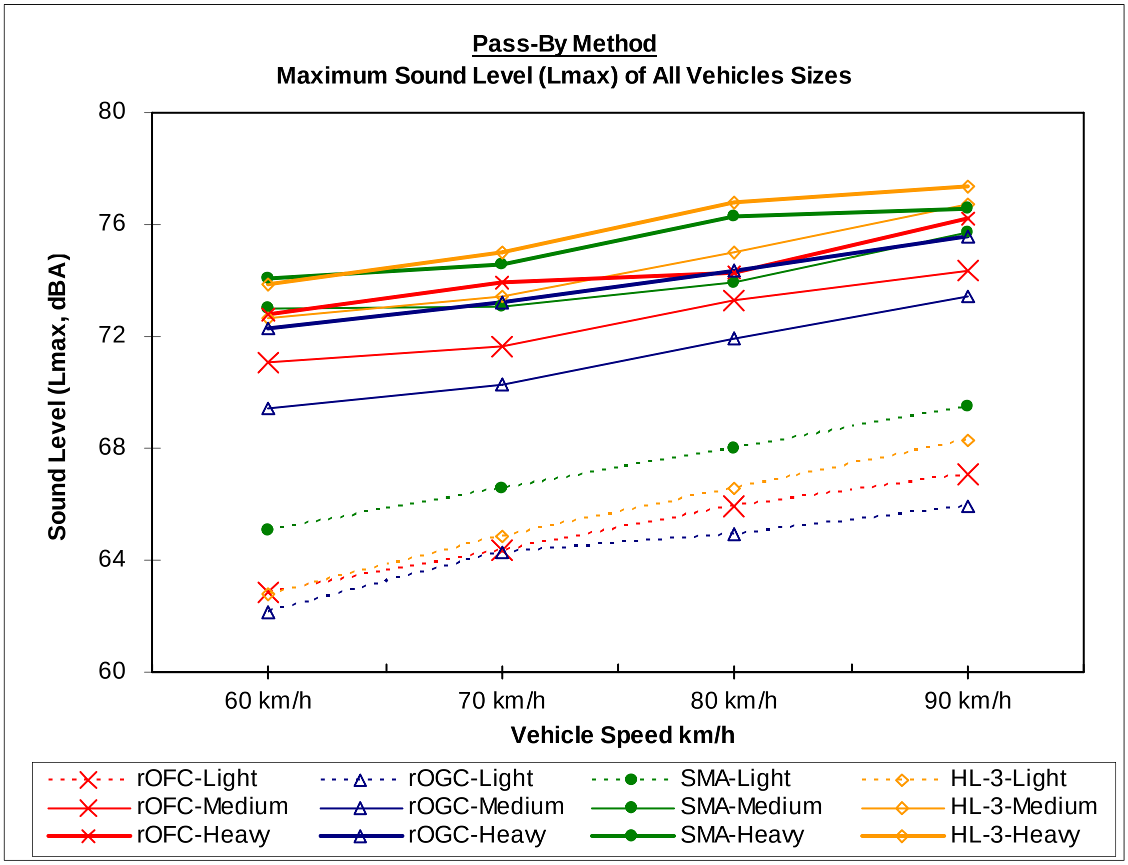

FIGURE 9 – PBM: Average Sound Levels (L_{max}) versus Vehicle Speeds

The PBM sound measurements of all four types of pavements are similar in terms of performance when compared to the CPX measurements. As the vehicle speed or size increases, the sound level increases. It also shows that SMA has the highest sound level measurement in light vehicle size for all testing speeds. HL-3 has the highest sound level measurement in medium and heavy vehicle sizes for testing speeds of above 70 km/h. However, at the speed of 60 km/h in the medium and heavy sized vehicles, the sound measurement level of SMA and HL-3 are similar and are the highest among all pavement mixes. Both the rOFC and rOGC have the lowest sound level measurement in all three vehicle sizes. The amount of noise reduction with respect to HL-3 is shown in Figure 10 which is presented by all vehicle, different vehicle speeds, and different vehicle sizes in a particular speed.

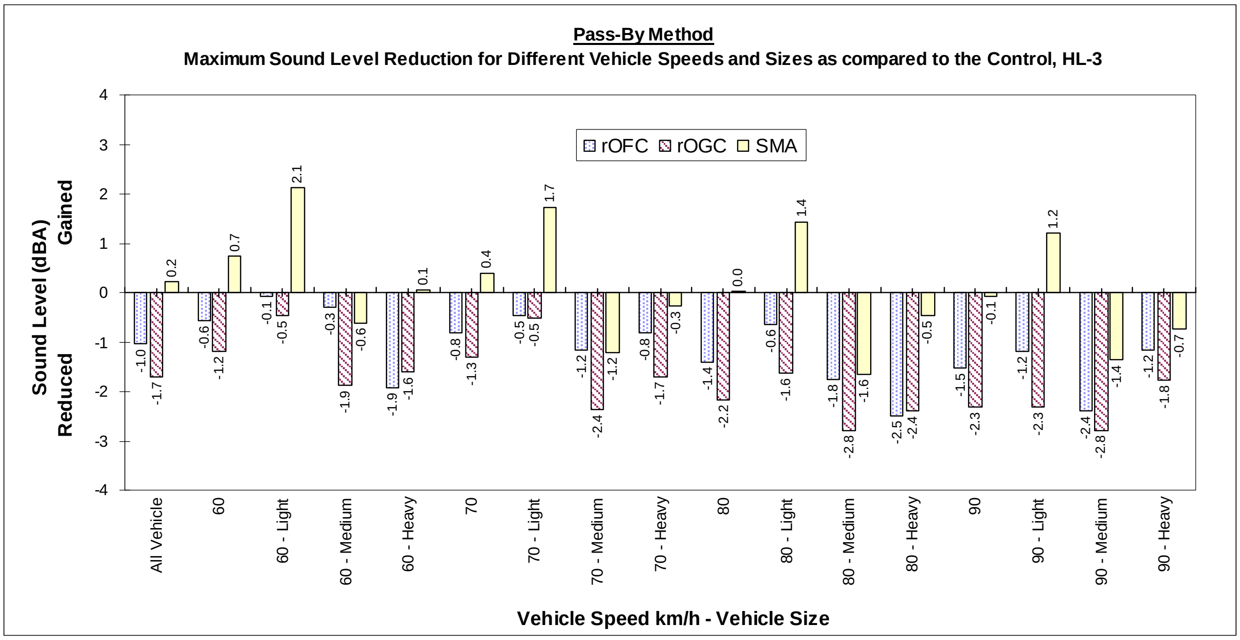

FIGURE 10 – PBM: Maximum Sound Level Reduction in Different Vehicle Sizes as compared to the Control, HL-3.

The pass-by noise reduction result illustrates a similar trend with the CPX results. SMA does not provide a noise reduction in the light vehicle category, but it can provide noise reduction in a medium category. The largest amount of noise reduction for SMA is 1.6 dBA at the medium sized vehicles at 80 km/h. rOFC and rOGC provide a significant amount of noise reduction in all situations. The highest amount of noise reduction in rOGC is 2.8 dBA for the medium sized vehicle at the speeds of 80 km/h and 90 km/h. The highest noise reduction value of rOFC is 2.5 dBA for the heavy sized vehicles at the speed of 80 km/h. Although both rOFC and rOGC can reduce noise when compared with HL-3, rOGC performs better than rOFC in terms of the speed limit. rOGC can provide 0.5 dBA to 0.8 dBA noise reduction more than rOFC.

Impedance Tube Testing Results

Five 6-in diameter core samples of each studied pavement were made from the gyratory using the same mix from the testing site. Eight random rotation positions with same mounting condition were measured and averaged for each sample to provide measurement consistency and repeatability. Figure 11 shows the average of five samples sound absorption-frequency curve in each pavement type from the impedance tube testing results. Figure 12 is the same graph as Figure 11, but with a finer absorption coefficient scale.

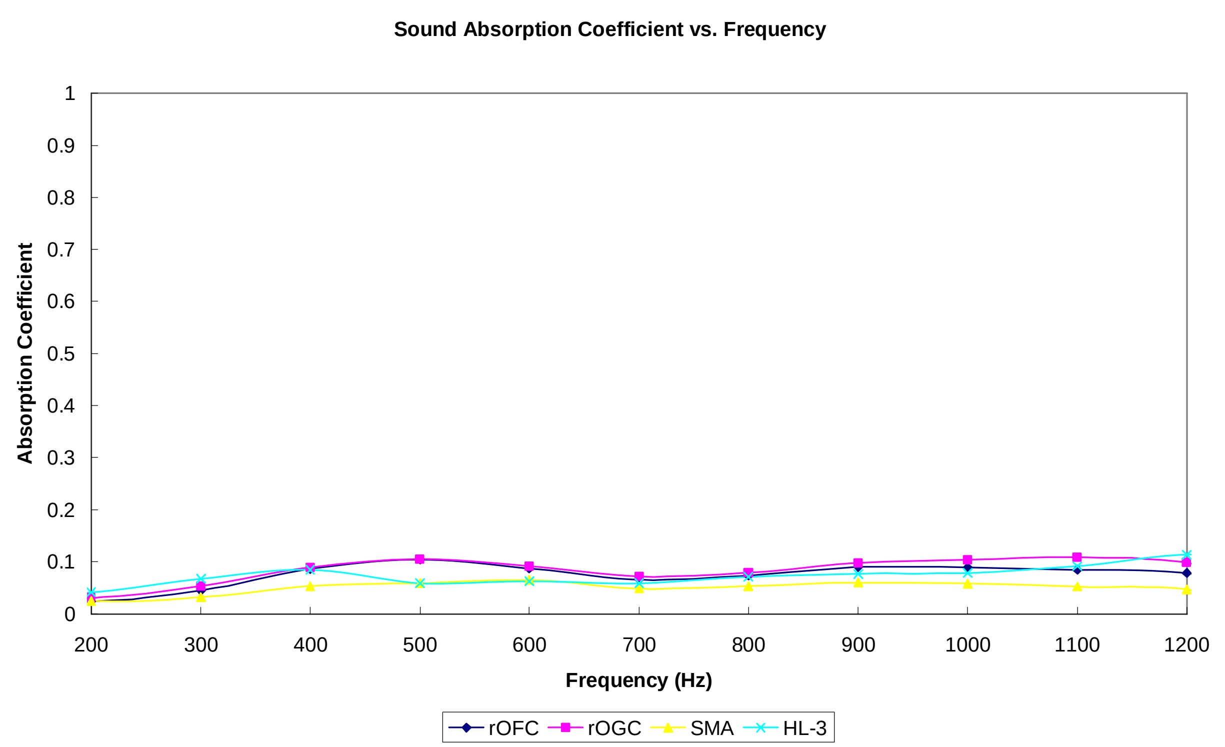

FIGURE 11 – Sound Absorption Coefficient vs. Frequency

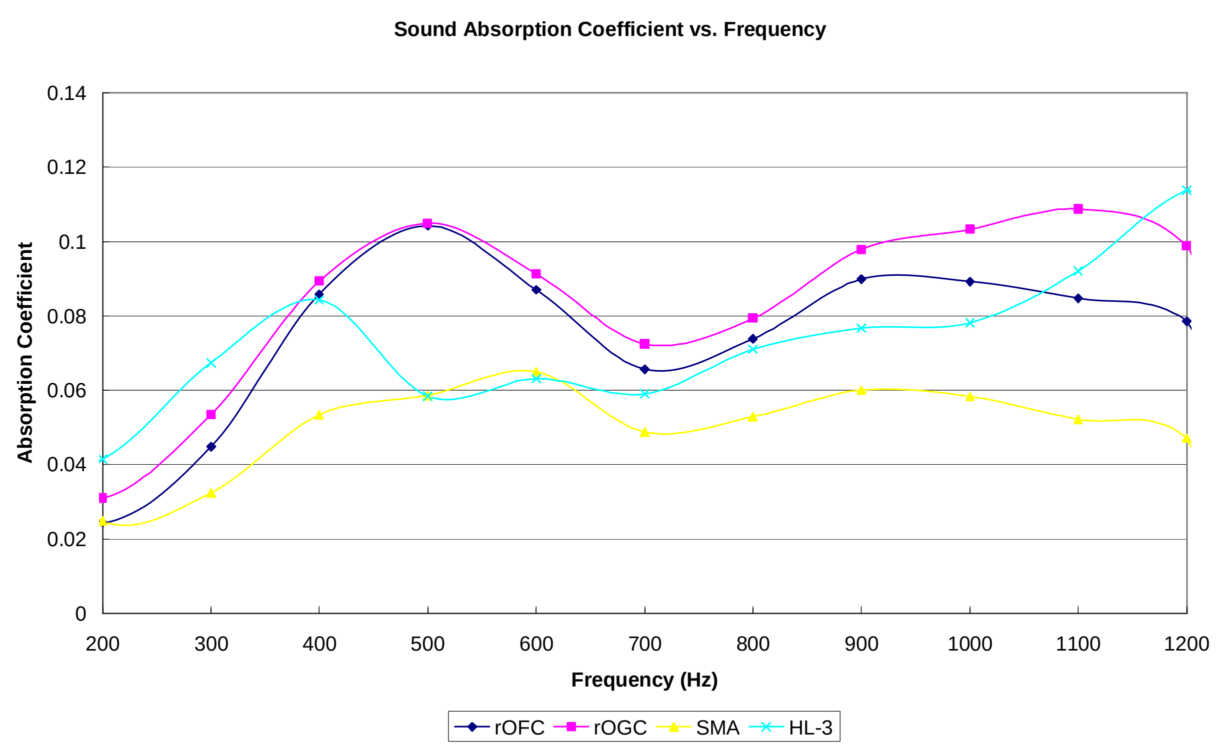

FIGURE 12 – Sound Absorption Coefficient vs. Frequency (Finer Scale)

Theoretically, the impedance tube can measure a frequency range from 170 Hz to 1350 Hz. However, it is observed that working frequency range is only valid from 200 Hz to 1200 Hz in this impedance tube. Impedance result shows that the first peaks of the rOFC and rOGC are occurred at 500 Hz with 0.1 absorption coefficient, the second peaks are occurred around 1000 Hz. The absorption coefficient refers to all the sound energy that is not reflected which includes the transmitted and absorbed component. Therefore, it means 10% of the sound energy is not reflected from rOFC and rOGC at 500 Hz. It is observed that rOFC and rOGC have similar sound absorption ability between the frequencies of 200 Hz to 900 Hz. SMA has a similar trend as rOFC and rOGC, but its sound absorption ability is lower. The peak of SMA occurred in 600 Hz with 6% of sound absorption ability. HL-3 has 8% sound absorption ability at 400 Hz and it performs the best among the studied pavement between 200 Hz to 400 Hz. rOGC provides the highest sound absorption ability between 400 Hz to 1100 Hz and then rOFC and HL-3. However, HL-3 tends to increase the sound absorption ability beyond 1100 Hz. Overall, SMA provides the lowest sound absorption ability among the studied pavement.

As mentioned previously, the most important frequency at low and high speed roads are at 600 Hz and 1000 Hz, respectively. Therefore, according to the impedance tube result, rOFC and rOGC provide the highest sound absorption among SMA and HL-3 for both low and high speed roads. rOFC and rOGC absorbs 9% of sound at 600 Hz and 9-10% at 1000 Hz. SMA and HL-3 provide the same amount of sound absorption (6%) at 600 Hz, but HL-3 provides 8% of sound absorption which is 2% higher than SMA at 1000 Hz.

CONCLUSIONS

The Regional Municipality of Waterloo, Ontario, Canada, in collaboration with the University of Waterloo, Centre for Pavement and Transportation Technology have measured road traffic noise levels on three types of noise reducing pavements, Rubberized Open Graded Friction Course Asphalt Pavements (rOFC and rOGC) and Stone Mastic Asphalt Pavement (SMA). The two types of open friction course asphalt pavements have a similar mix design, but different in the quality of the aggregate. One type contains premium aggregates (rOFC) and the other contains local aggregates (rOGC). SMA is a pavement for a heavy traffic area and also commonly used in the North America. The purpose of noise testing is to determine whether these three kinds of pavements provide significant noise reductions compared to a typical pavement with a Hot-Laid 3 (HL-3) surface. Two types of noise measurements were taken in this study: Close-Proximity Method (CPX) and controlled Pass-By Method (CPM). It is important to note that these findings are preliminary as only one set of measurement has been taken at this point. Impedance Tube Laboratory testing was also performed to determine the normal sound absorption properties of the pavement.

It was also found that vehicle noise increases when the vehicle speed or size increases for both test methods. The SMA pavement type does not provide any noise reductions for light sized vehicles and for vehicle speeds of 60 km/h and 70 km/h in both test methods. rOFC and rOGC provide the highest amount of noise reduction in both testing methods. The highest noise reduction amounts for rOFC and rOGC pavement are 3.3 dBA in the CPX results. For the PBM results, the highest noise reduction amounts are 2.5 dBA and 2.8 dBA for rOFC and rOGC pavement, respectively. Also, both rOFC and rOGC can reduce a larger amount of noise in a medium vehicle category. Although rOGC contains local aggregate, it performs slightly better than rOFC which contains premium aggregate at all testing vehicle speeds.

Impedance Tube testing is to measure the normal sound absorption ability of the pavement in various frequencies. The preliminary test result shows that, rOFC and rOGC provide the highest amount (7% to 10%) of sound absorption between 400 Hz to 1000 Hz. SMA provides the least amount of sound absorption ability among the other studied pavements. HL-3 provides the highest sound absorption below 400 Hz and it tends to increase the sound absorption ability beyond 1100 Hz.

Both sound level measurements and sound absorption property measurement show that rOFC and rOGC perform the best. However, the overall preliminary performance result shows that rOGC, which is using local aggregate, is slightly better than rOFC which is using premium aggregate.

RECOMMENDATIONS

This paper presents initial findings on the effectiveness of several noise reducing pavements based on field and laboratory measurements, it is recommended that additional sound level measurements be conducted in the future to monitor the pavement acoustical performance. Also, a comparison of the noise measurement results obtained from the two test methods should be performed. A life cycle cost for each pavement should also be performed for noise reducing pavement selection.

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