NDOT Research Report

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The Tire Noise Performance of Nevada Highway Pavements: On-Board Sound Intensity (OBSI) Measurements

June 2008

Nevada Department of Transportation
1263 South Stewart Street
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Disclaimer

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On-Board Sound Intensity (OBSI) Measurements

Prepared for

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In Cooperation with

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TABLE OF CONTENTS

1. INTRODUCTION

On Board Sound Intensity measurements were conducted on freeway segments in the vicinity of Las Vegas and Reno, Nevada in an effort to document the tire-pavement noise levels of existing pavements. Tested pavements included Portland Cement Concrete (PCC), Open Graded Friction Course (OGFC), and Rubberized Open Graded Friction Course (ROGFC) sections on US 95, I-515, US 93, I-15, SR 160, and I-215 in the vicinity of Las Vegas and on I-80, and US 395 in the vicinity of Reno. In addition to the measurement and documentation of existing pavement sections, measurements were conducted prior to and after the placement of ROGFC on I-515 between the College Drive and West Horizon Drive Interchanges (Exits 57 and 59). This report summarizes the acoustical performance of the selected pavement sections, utilizing the results of on-board tire/pavement noise source measurements. A more detailed assessment of the I-515 overlay results were documented in a previous memo[i].

2. TERMINOLOGY

Below are brief definitions of acoustical terminology used in this report.

- **Decibel (dB).** A unitless measure of sound on a logarithmic scale. For sound pressure level, this applies to the squared ratio of sound pressure amplitude to a reference sound pressure amplitude of 20 micro-pascals. For sound intensity level, this applies to the ratio of the sound intensity amplitude to a reference intensity amplitude of 1 pico-watt per square meter.
- **A-Weighted Decibel (dBA).** An overall frequency-weighted sound level in decibels that approximates the frequency response of the human ear.
- **Sound Intensity.** The product of sound pressure and particle velocity in the direction of the intensity vector. The sound intensity in a specified direction is the amount of sound power flowing through a unit area normal to that direction.
- **Coherence:** A measure of how similar two signals are. It is computed as a correlation coefficient between the two microphone signals of any one sound intensity probe.
- **PI Index:** The difference between the sound pressure and sound intensity level.

3. DESCRIPTION OF FIELD PARAMETERS

A. Test Procedure

On-vehicle OBSI testing was conducted using a dual-probe sound-intensity fixture and associated microphones, attached to and supported by the test vehicle in free space as indicated in Figure 1, to allow for measurement positions that are very close to the leading or trailing edge of the tire contact patch. The dual-probe sound-intensity fixture allows the leading and trailing edge positions to be measured simultaneously. Each probe consisted of two ½" G.R.A.S phased matched condenser microphones, installed on ½" G.R.A.S 26AK microphone preamplifiers, attached to a plastic probe holder at a spacing of 0.63 inches (16mm) in a side-by-side configuration, and fitted with a spherical windscreen. The probe was positioned 3 inches (75mm) from the pavement surface and 4 inches (100mm) from the face of the tire, at locations opposite the leading and trailing contact patch of the tire, and oriented so that the sensitive axis was positioned toward the tire. Data from the leading and trailing edge positions are acquired separately for the same section of pavement and then averaged together during post-analysis. Use of the dual-probe sound-intensity fixture allows the leading and trailing edge positions to be measured simultaneously. Typically, two or more passes were made for each test section, which were averaged together during post analysis. Multiple sections on a site were selected and measured when the length of the test site allowed and, where sound levels and observations identified these sections as the same pavement type, the passes for all of the pavement sections were averaged together to result in an average OBSI level for that site. In situations where more than one pavement type was identified along a site, each pavement was measured and documented separately. For Sites 5 and 6, measurements were conducted at several sections along the length of the site over the course of a single pass, for efficiency of testing over these longer length sections with very long turnaround times.

Figure 1: OBSI Equipment Installed on the Malibu Test Vehicle

The November 2006 and October 2007 measurements were conducted on a Chevrolet Malibu test vehicle and the January 2008 measurements were conducted on a Pontiac G6, using the same Goodyear Aquatred 3 test tire under free flow traffic conditions with a load consisting of two people and the OBSI instrumentation. A photograph of the test tire is shown in Figure 2. For all of the test sites except Site 14, testing was conducted in the right through travel lane at a test speed of 60 mph (97 km/h) and a 'cold' tire inflation pressure of 30 psi. Due to lower speed limits and traffic flow speeds at Site 14, testing was conducted at a speed of 45 mph (72 km/h).

Figure 2: Photograph of Aquatred 3 Test Tire

The microphone signals were acquired with the Bruel & Kjaer PULSE System in FFT narrow band and ⅓ octave band levels using a 5-second averaging time. The microphones were calibrated using a Larson Davis Model CAL200 acoustic calibrator set for 94 dB at the beginning and end of each measurement period. OBSI quality metrics of coherence between the two microphones comprising each probe and the difference between sound pressure and sound intensity level were monitored during data acquisition. The actual time signals of the four microphones were also viewed.

B. Measurement Sites

Seventeen (17) test sites were identified by NVDOT along highway segments in the vicinity of Las Vegas and Reno. Site locations and surface types are indicated in Table 1.

Table 1: Identified OBSI Noise Monitoring Sites

Site	Direction	Location	Surface	Measurement Date
1-Pre	S	I-515, Exits 57 to 59	PCC	11/01/06
1-Post	S	I-515, Exits 57 to 59	ROGFC	1/21/08
2-Pre	N	I-515, Exits 59 to 57	PCC	11/01/06
2-Post	N	I-515, Exits 59 to 57	ROGFC	1/21/08
3	N	US 95, MP 57.0 to 58.0	OGFC	11/01/06
4	N	US 95, MP 91.0 to 92.0	OGFC	11/02/06
5	N	US 95, MP 108.0 to 109.0	OGFC	11/02/06
6	S	US 95, MP 125.0 to 126.0	Various	11/02/06
7	E	I-80 near Sparks Boulevard	PCC	10/24/07
8	S	US 395, Exits 60 to 61	PCC	10/24/07
9	S	US 395, Exits 44 to 42	OGFC	10/24/07
10	S	I-15, MP 11.0 to 12.0	OGFC	1/22/08
11	S	I-15, MP 28.0 to 29.1	OGFC	1/22/08
12	S	I-15, MP 32.0 to 33.2	OGFC	1/22/08
13	S	I-15, Exits 40 to 41	PCC	Not Measured
14	W	SR 160, MP 2.3 to 3.3	OGFC	1/22/08
15	E	I-215, Exit 4B to 5	PCC	1/21/08
16	E	I-215, Exit 9 to 10	PCC	1/22/08
17	S	I-215, Exit 68 to 69	PCC	1/21/08

During the noise measurement survey, multiple pavements were identified for Sites 6, 9, 12, 14, and 17. For Sites 9, 12, 14, and 17, each identified pavement was measured and documented separately, identified as ‘a’, ‘b’, ‘c’, etc. For Site 6, six or more pavements were identified along the length of the site. To avoid confusion and the misinterpreting of data, noise levels measured along Site 6 are not documented in this report. The remaining sites were observed to be comprised of a single pavement. For Sites 1, 2, 3, 4, 5, 7, 10, and 15, multiple measurement sections were selected along the length of the site, which were averaged together to result in an average OBSI level for that site. Site 13 was not measured due to stop and go traffic conditions, which persisted during three separate attempts to conduct measurements during the 2008 survey. Photographs of each pavement section are shown in Figure A-1.

C. Meteorological Conditions

Measurements were conducted between 1:00 and 3:00 pm on November 1st, 2006, between 9:30 am and 3:00 pm on November 2nd, 2006, between 2:00 and 6:00 pm on October 24th, 2007, between 2:30 and 5:00 pm on January 21st, 2008, and between 10:30 am and 4:00 pm on January 22nd, 2008. For the November 2006 measurements, air temperatures ranged from 72 to 75°F (22 to 24°C) on the 1st and from 59 to 64°F (15 to 18°C) on the 2nd. Air temperatures ranged from about 80 to 82°F (27 to 30°C) on October 24th, 2007 and from about 51 to 59°F (11 to 15°C) on January 21st and 22nd, 2008.

4. RESULTS OF FIELD MEASUREMENTS AND ANALYSIS

Tire/pavement noise measurements were conducted on twenty four (24) pavement sites, including nine (9) PCC pavements, thirteen (13) OGFC pavements, and two (2) ROGFC pavements. Photographs of each pavement section are shown in Figure A-1.

A. Overall A-Weighted OBSI Levels

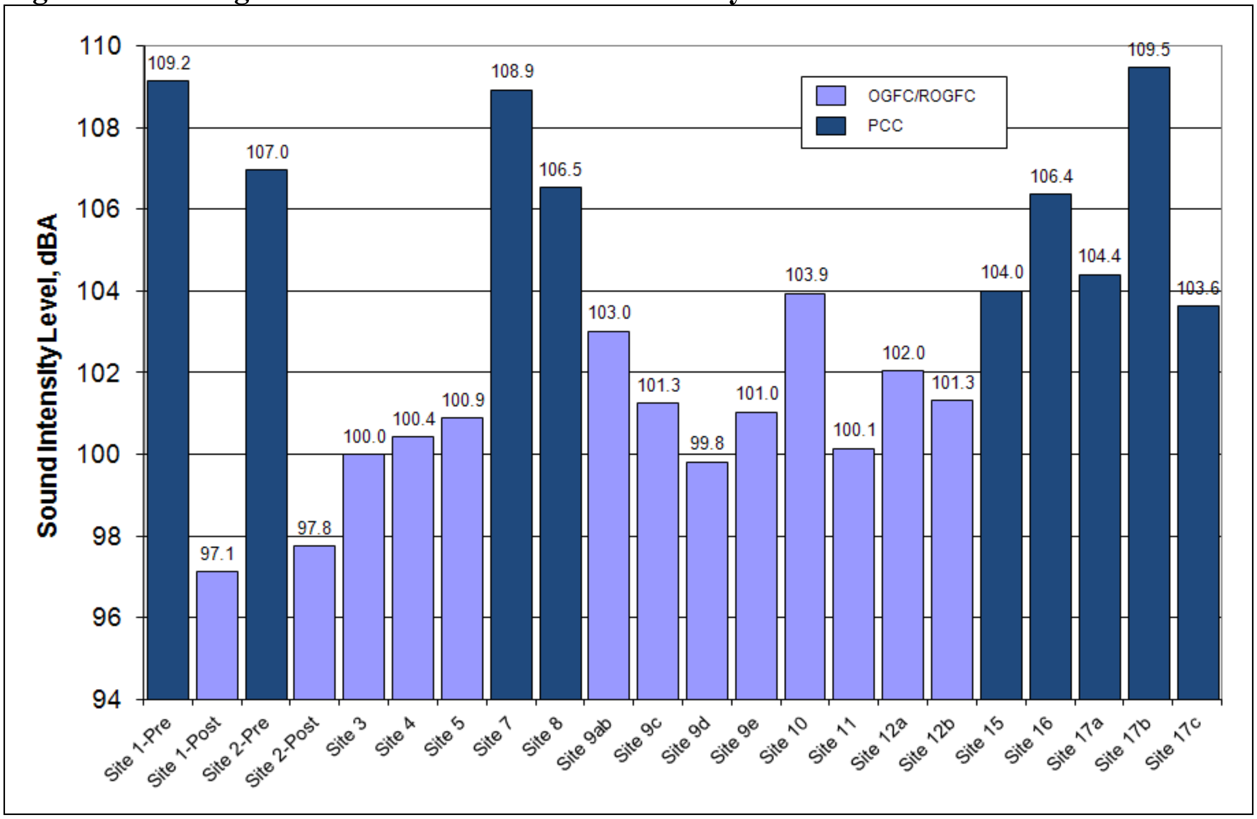
Table 1 shows a summary of the test sites and the resultant overall A-weighted sound intensity levels for each site. Averages, by pavement type, are also summarized in Table 1. A comparison of the overall A-weighted sound intensity levels for each test site is shown in Figure 3. Note that Sites 14a and 14b, which were conducted at a slower test speed of 45 mph, were not included in the calculated averages or in Figure 3.

Table 1: Summary of Test Sections and Overall A-Weighed Sound Intensity Levels

Site Number	Surface Type	OBSI Level, dBA
1-Pre	PCC - TT	109.2*
1-Post	ROGFC	97.1*
2-Pre	PCC - TT	107.0*
2-Post	ROGFC	97.8*
3	OGFC	100.0*
4	OGFC	100.4*
5	OGFC	100.9*
7	PCC - TT	108.9*
8	PCC - RT	106.5
9a,b	OGFC	103.0*
9c	OGFC	101.3
9d	OGFC	99.8
9e	OGFC	101.0
10	OGFC	103.9*
11	OGFC	100.1
12a	OGFC	102.0
12b	OGFC	101.3
14a	OGFC (45 mph)	98.8
14b	old OGAC (45 mph)	102.4
15	PCC - LT	104.0*
16	PCC - TT	106.4
17a	PCC - Ground	104.4
17b	PCC - RT	109.5
17c	PCC - Ground	103.6
Average PCC		*106.6*
Average OGFC (60 mph data only)		*101.4*
Average ROGFC		*97.4*
*Overall OBSI sound level is based on an average of measurements made for several sections of the same pavement.		

As indicated in Table 1 and Figure 3, the PCC sections were on average 5.2 dBA louder than the OGFC sections and 9.2 dBA louder than the ROGFC sections, with the transverse tined PCC (PCC – TT and PCC – RT) producing the highest levels. The loudest OGFC pavement was the measured at Site 10, which approached the sound intensity levels generated on the longitudinally tined (LT) and Ground PCC sections, but resulted in levels that were 2.6 to 5.6 dB below those generated on the transverse tined PCC sections.

Figure 3: A-Weighted Tire/Pavement Sound Intensity Levels



Figures 4 and 5 show comparisons of the resulting overall A-Weighted sound intensity noise levels of the Nevada sites compared with other ROGFC/OGFC and PCC pavements in California and Arizona measured at 60 mph using the Aquatred 3 test tire, respectfully. Again the 45 mph data is not included in these figures. Note that RAC, ARFC, and ROGFC are different acronyms used by State DOTs to specify the similar pavement types (Rubberized Asphalt Concrete). Similarly OGAC and OGFC are both used to specify Open Graded Asphalt Concrete. The Nevada test sites are indicated in dark blue.

Resulting noise levels for the Site 1 and 2 ROGFC sections were in the lower range of OGAC and RAC pavements, approximately 6 dBA lower than the aged I-80 OGAC pavement and about 1 dBA greater than the average of the new asphalt rubber friction course (ARFC) measured in the Arizona Quiet Pavement Pilot Program. The Nevada OGFC pavements (Sites 3, 4, 5, 9ab, 9c, 9d, 9e, 10, 11, 12a, and 12b) were in the mid to upper range of the pavements shown in Figure 4. Site 10 was louder than any of AC pavements shown in Figure 4, although the I-80 OGAC pavement is approaching the Site 10 levels as it ages. The Nevada sites were also in the mid to upper range of the PCC pavement measured in California and Arizona (Figure 5). The ground and longitudinal pavements (Sites 15, 17a, and 17c) are at the upper end of similarly textures surfaces in Figure 5 and are 3 to 4 dBA greater than the Ground PCC measured on SR 202 in Arizona. The transverse tined sections (Sites 1, 2, 7, 8, 16, and 17b) were within the range of levels measured along similar pavements on SR 202 in Arizona.

Figure 4: Overall A-weighted OBSI levels for OGAC and RAC pavements, 60 mph

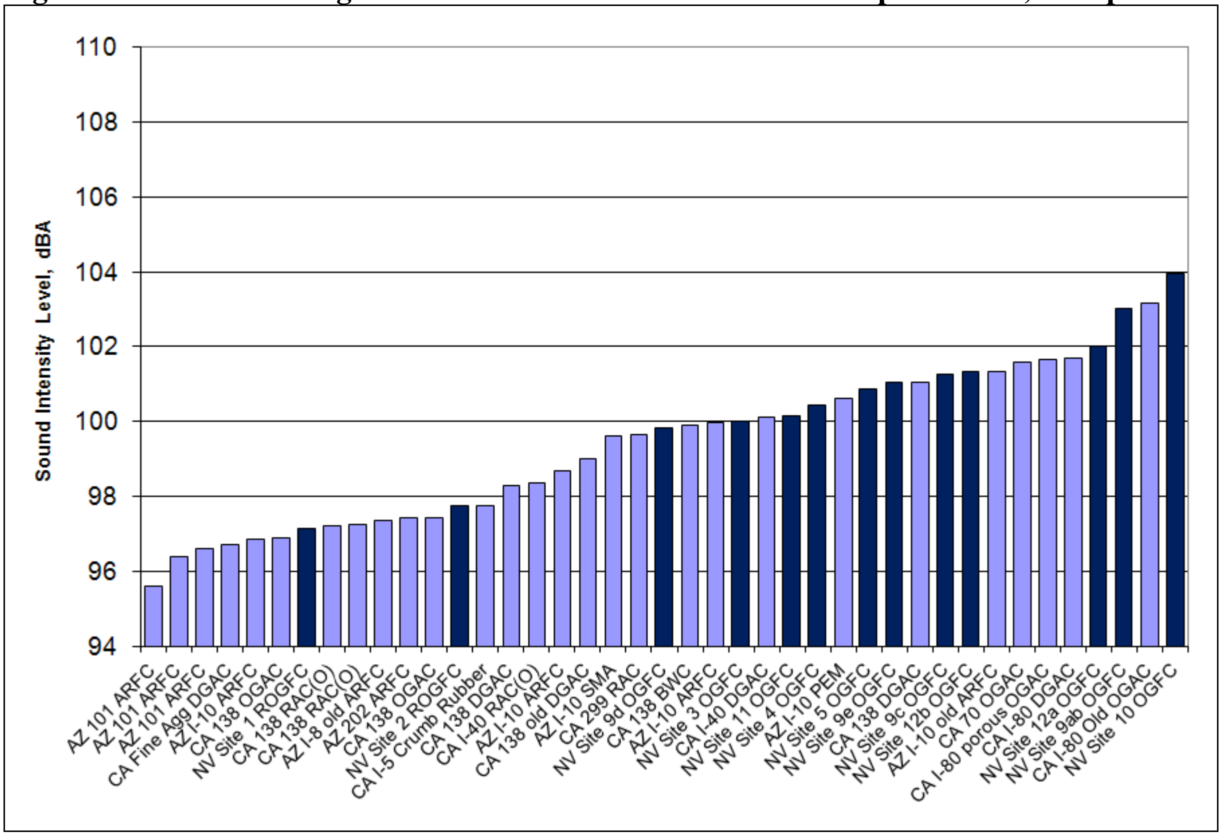
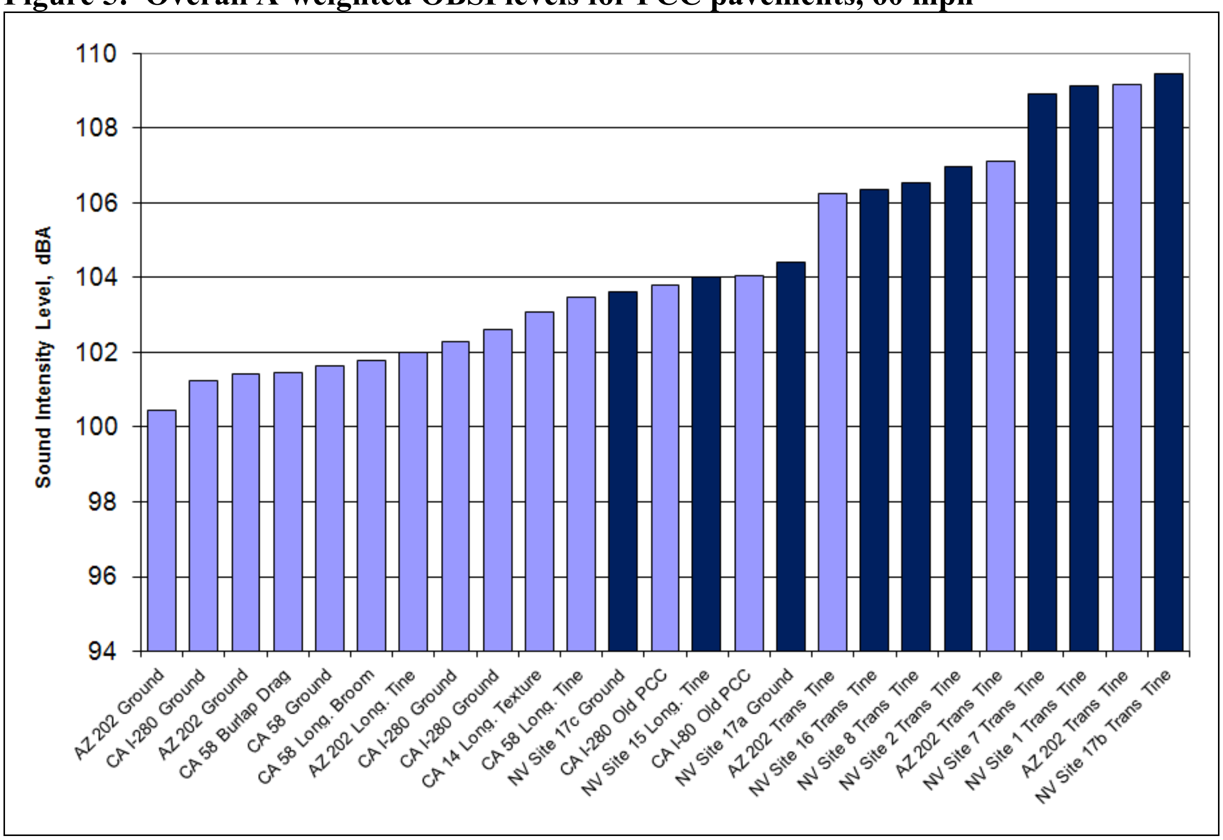


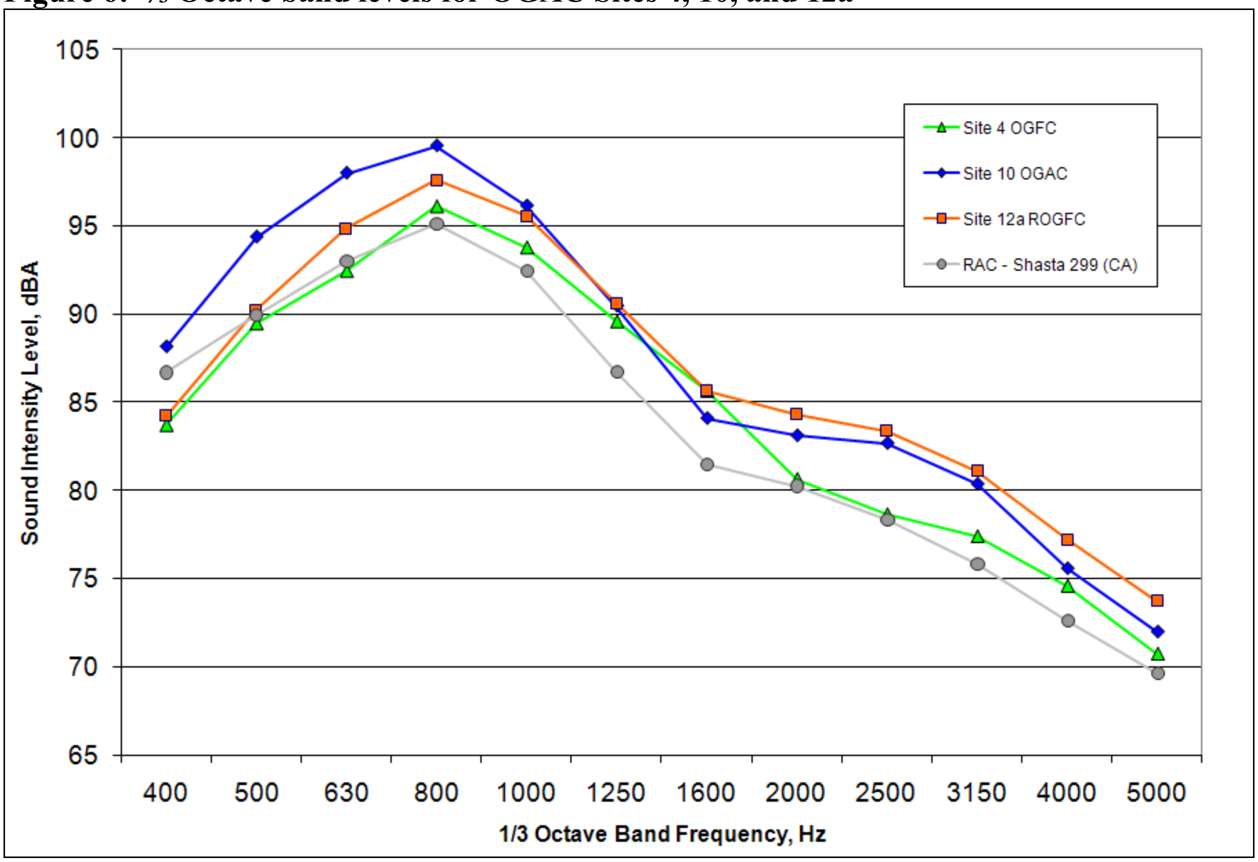
Figure 5: Overall A-weighted OBSI levels for PCC pavements, 60 mph



B. 1/3 Octave Band Levels

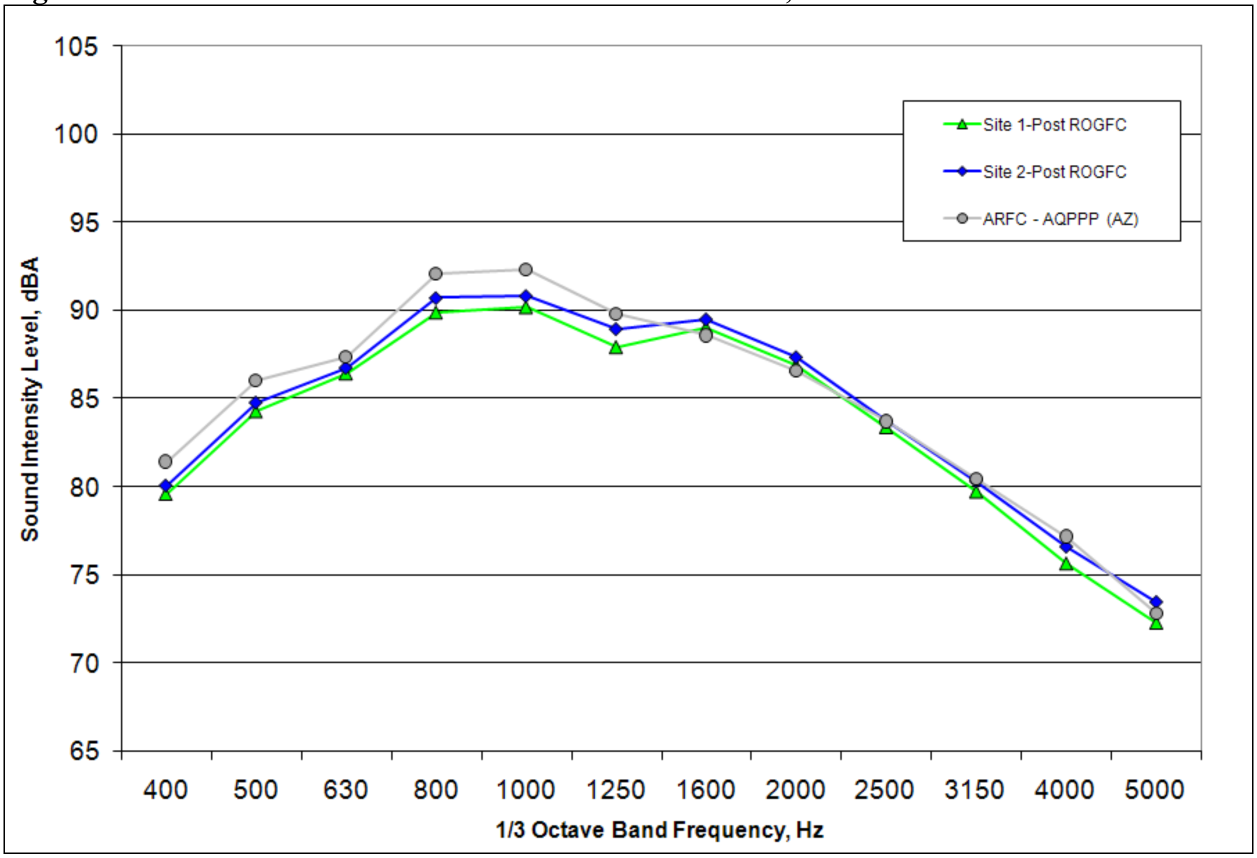
The ⅓ octave band spectra for Sites 4, 10, and 12a are typical of porous pavements, which generally have reduced levels in the 1600 to 2500 Hz bands. This is indicated in Figure 6, which plots these pavements against a Rubberized Asphalt Concrete pavement measured along Shasta 299 near Redding, California. Although decreased mid-frequency levels occurred for all three test sites, the overall A-weighted levels were not all in the lower range of OBSI levels, indicating that porosity alone does not necessarily result in a quiet pavement surface. Low frequencies, which are typically controlled by pavement roughness, varied or large aggregate size, and positive pavement texture, dominate the overall noise levels for these pavements. As mentioned earlier, Site 10 was the loudest of the OGFC pavements. Observation of the pavement at Site 10 (see Figure A-1) shows this to be a notably rough pavement with positive pavement texture.

Figure 6: ⅓ Octave band levels for OGAC Sites 4, 10, and 12a



The quietest pavements measured were the new ROGFC pavements constructed at Sites 1 and 2. These pavements performed very similarly to the asphalt rubber friction course (ARFC) measured in the Arizona Quiet Pavement Pilot Program, as shown in Figure 7. It is interesting to note the differences between the ROGFC pavements at Sites 1 and 2 and the porous pavements shown in Figure 6. The ROGFC pavements did not result in decreased mid-frequencies, indicating a lack of porosity in these pavements. This could be due to smaller aggregate filling some of the void area relative the pavements of Figure 6, added rubber content filling the void area, and/or rubberized binder filling these areas. This lack of porosity in the ARFC has also been noted in the Arizona pavement.

Figure 7: ⅓ Octave band levels for ROGFC Sites 1 and 2, Post Construction



Sites 3 and 5 are plotted in Figure 8 against an OGAC pavement section measured at LA-138 in California. Sites 3 and 5 resulted in similar spectral shapes, although Site 3 appears to have more porosity than Site 5, indicated by the slight decrease in the mid to high frequencies; this decrease is nowhere near that seen for the porous pavements shown in Figure 6. Both sites resulted in spectral characteristics similar to the LA 138 pavement.

Four different OGFC pavements were identified along Site 9, plotted in Figure 9 against the same OGAC pavement measured at LA-138 in California. Although these pavements diverge in the mid frequencies, between 1000 and 2500 Hz, levels were very similar for all four sections in the low and high frequencies. These may all be the same pavement constructed at different times or by different contractors, resulting in some variation in construction or age of pavement. The Site 9 pavements did not result in decreased mid-frequencies, indicating that these are not porous pavements. Reduced low frequencies as compared to the pavements shown in Figure 8 result from comparatively smaller aggregate size.

Figure 8: ⅓ Octave band levels for OGAC Sites 3 and 5

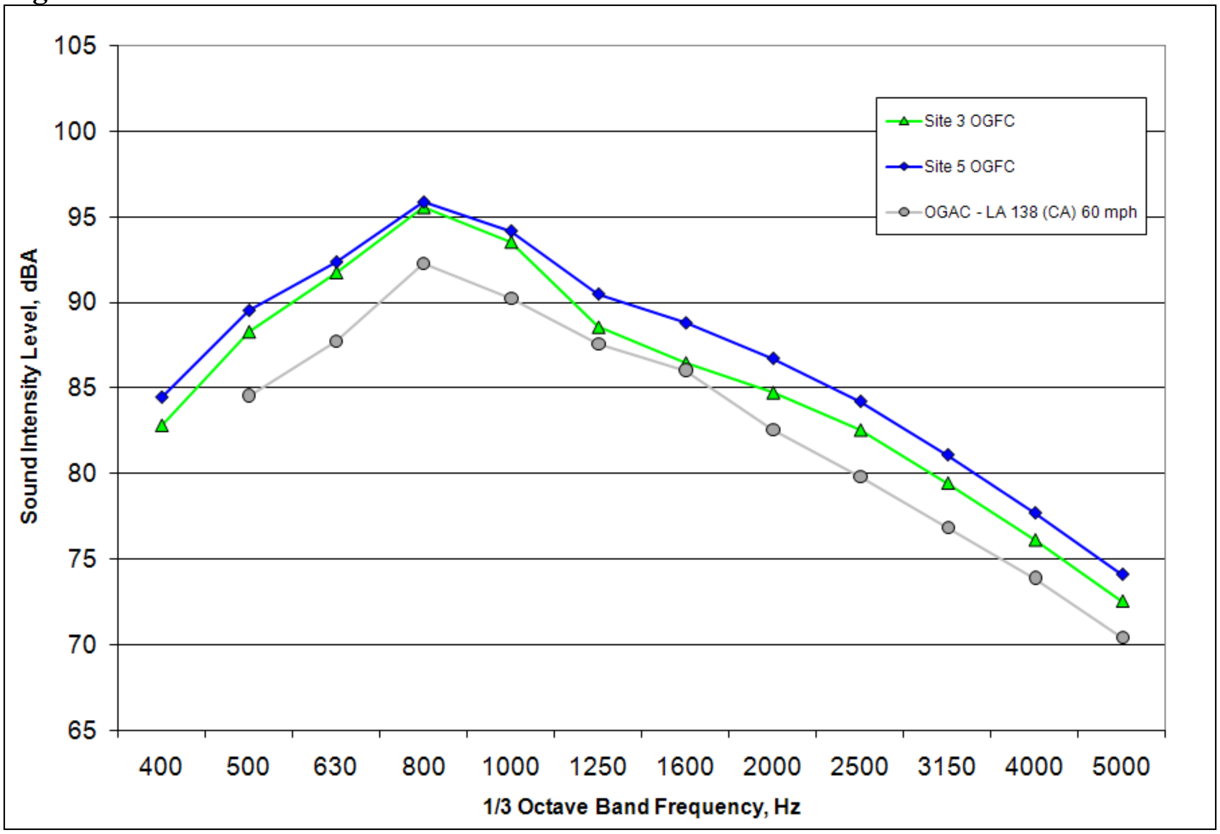


Figure 9: ⅓ Octave band levels for OGAC Sites 9ab, 9c, 9d, and 9e

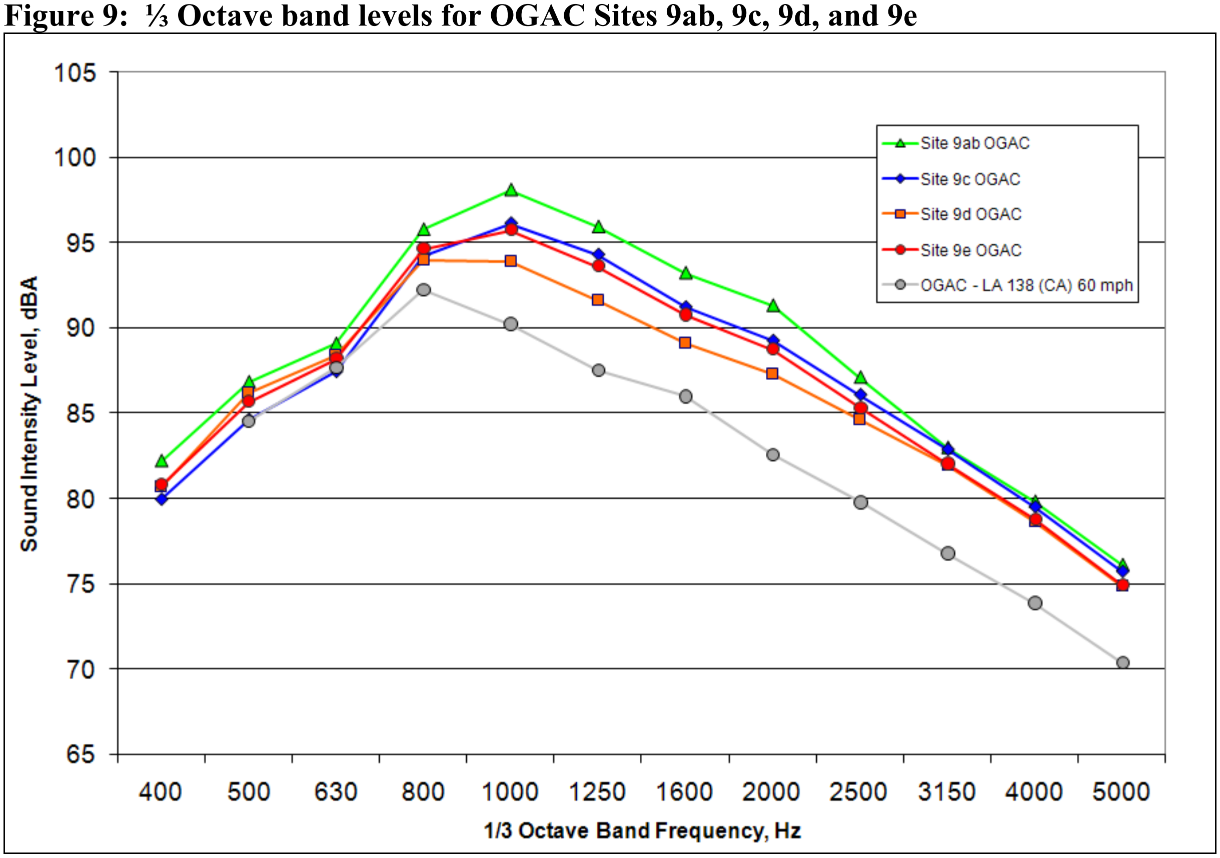
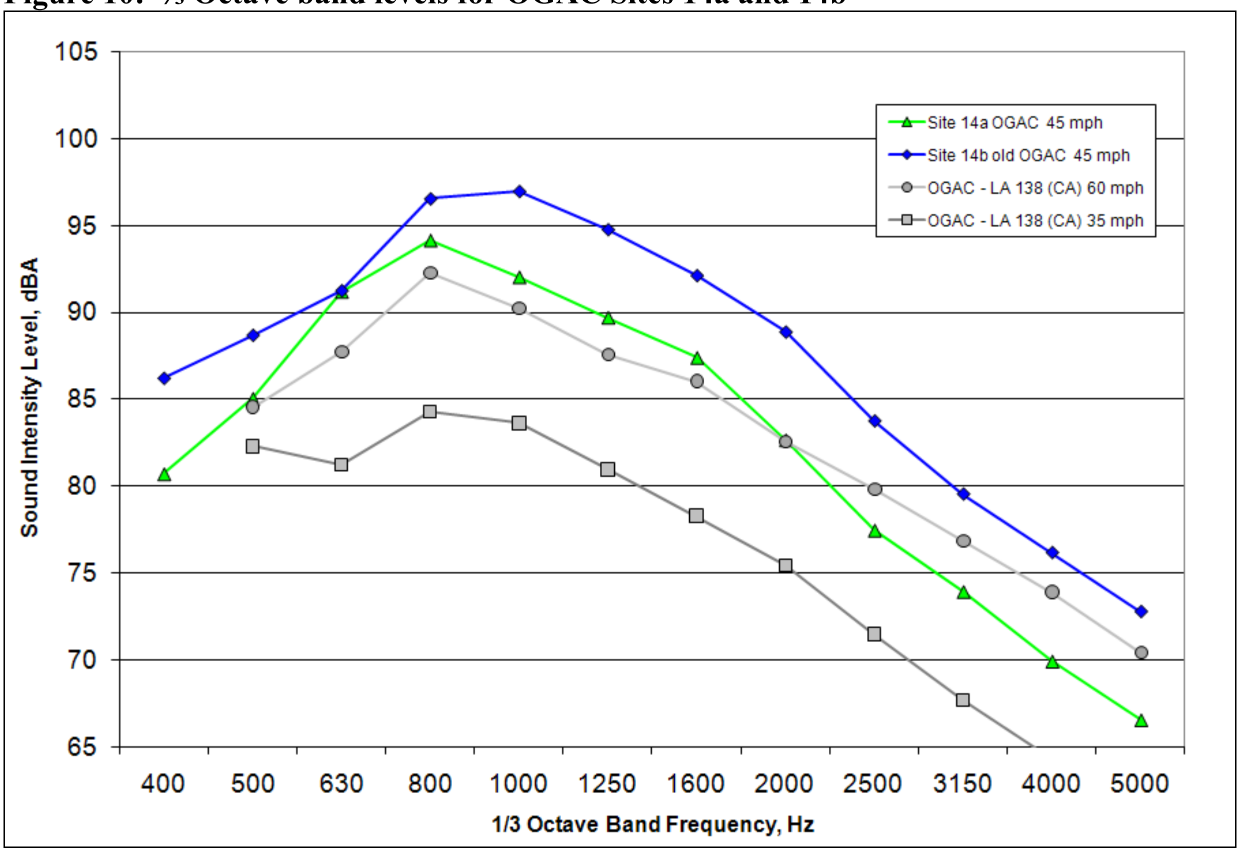


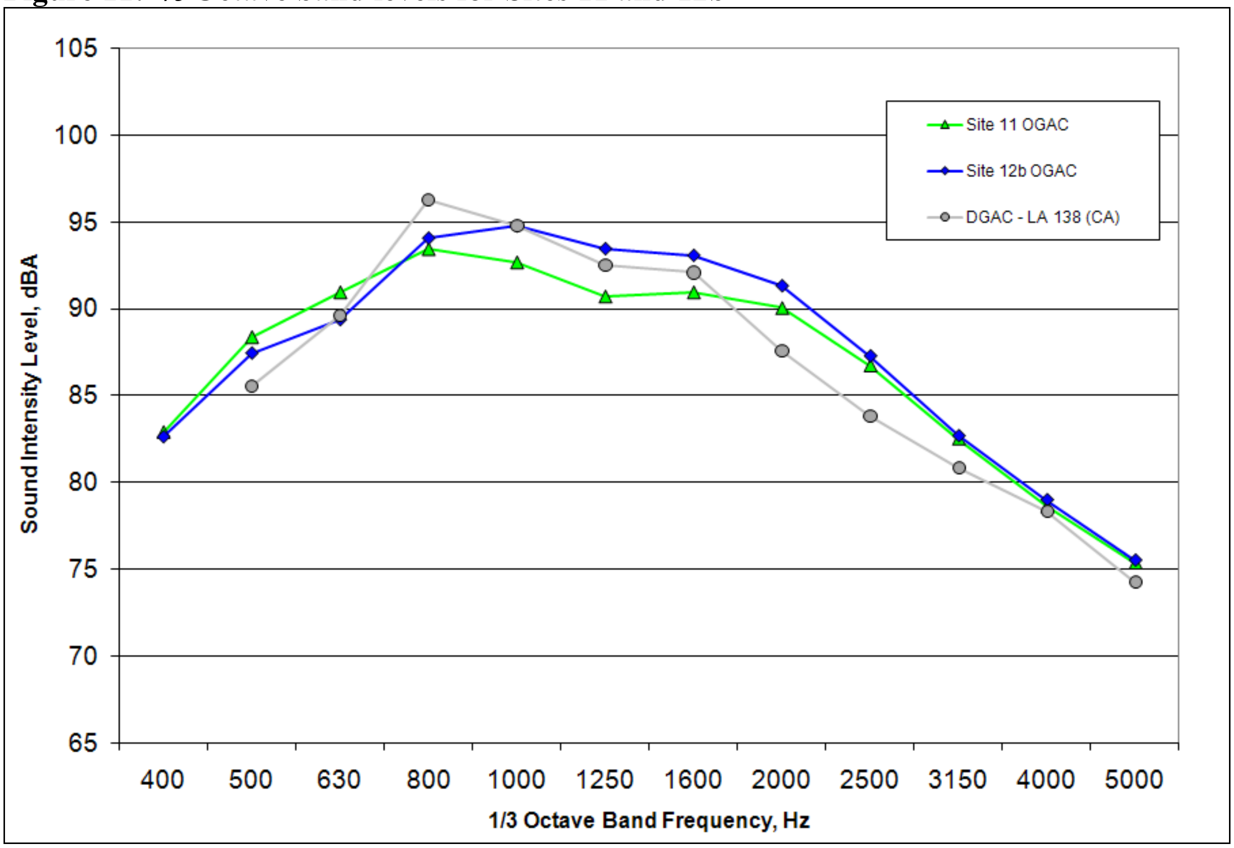
Figure 10 plots Sites 14a and 14b against the OGAC pavement section measured at LA-138 in California. Note that Sites 14a and 14b were conducted at a test speed of 45 mph, while the LA 138 pavement was measured at test speeds of 35 and 60 mph. Site 14a was visually identified as a newer OGAC pavement and Site 14b appeared to be an aged OGAC section (see Figure A-1). The spectral shape for these sites was similar to the LA 138 OGAC pavement, although the levels for the Site 14a and 14b pavements are notably higher, especially Site 14b. Decreases for both sites in the 2000 and 2500 Hz bands can be attributable to porosity and the increased low frequencies for Site 14b are likely due to varying and larger aggregate size and the condition of the pavement, which was aged and broken or heterogeneous in places. Not enough data is available for the Aquatred test tire at 45 mph to provide a dependable offset to adjust the data to be comparable to the 60 mph data. However, review of the 35 and 60 mph results for the LA 138 pavement give some indication of the type of increase in levels that would be anticipated. Comparison to the LA 138 pavement levels indicates that, at 60 mph, the Site 14a pavement would likely be in the upper range of levels shown for AC pavements in Figure 4. The Site 14b pavement was exceptionally loud, resulting in levels that were in the upper range of AC pavements measured in California and Arizona when tested at a speed that was 15 mph below the test speeds for the other pavements (see Figure 4). It is anticipated that the Site 14b pavement tested at 60 mph would likely be one of the loudest AC pavement measured to date, actually reaching the mid range of PCC levels shown in Figure 5.

Figure 10: ⅓ Octave band levels for OGAC Sites 14a and 14b



Although the pavements at Sites 11 and 12b were specified as OGFC pavements, the ⅓ octave band spectra appear more typical of Dense Grade Asphalt pavements (DGAC), which generally have higher levels in the 1250 to 2000 Hz bands due to a lack of porosity. Figure 11 plots these pavements against a DGAC pavement section measured at LA-138 in California. The rubberized pavements shown in Figure 7 indicate similar spectral characteristics. During field measurements, Sites 11 and 12b were both visually identified as OGFC; however, the pavements appeared to be compacted in the wheel path, which could explain the spectral shape similarities to DGAC pavement.

Figure 11: ⅓ Octave band levels for Sites 11 and 12b



As mentioned above, the loudest pavements measured were Sites 1 (pre-construction), 7, and 17b, which were all transverse tined PCC. Sites 1 and 7 had uniformly spaced tining and Site 17b had randomly spaced tining. The ⅓ octave band spectra for the uniformly transverse tined PCC pavements (Sites 1, 2, 7, and 16) and the randomly transverse tined PCC pavements (Sites 8 and 17b) are plotted in Figures 12 and 13 against similar pavements measured along SR 202 in Arizona. Both the random and uniformly tined sections resulted in raised levels in the frequencies from 630 to 1600 Hz. Typically, uniformly transverse tined sections generate a localized ‘peak’, resulting from the spacing between the tining. For the sites shown in Figure 12, the ‘peaks’ are more broad than in the Arizona section, which is likely due to shallow or worn tining (see Figure A-1). A localized peak does occur for the Site 1 pavement in the 800 Hz band. Sites 2 and 16 pavements have similar tine spacing and depth (Figure A-1), which explains the similarity in spectral shape between the two. The raised low frequencies that occurred for Site 7 are attributable to the condition of the pavement, which was observed to be broken up in parts resulting in a rougher and inconsistent pavement texture. Broad ‘peaks’ can also be seen for the randomly tined sections shown in Figure 13, which is expected since a distinct tine spacing does not occur for the randomly tined sections. Raised mid to high frequencies for both the uniform and random transverse tined pavements are again attributable to the shallow depth of the tining.

Figure 12: ⅓ Octave band levels for Uniformly Transverse Tined PCC Sites 1, 2, 7, and 16

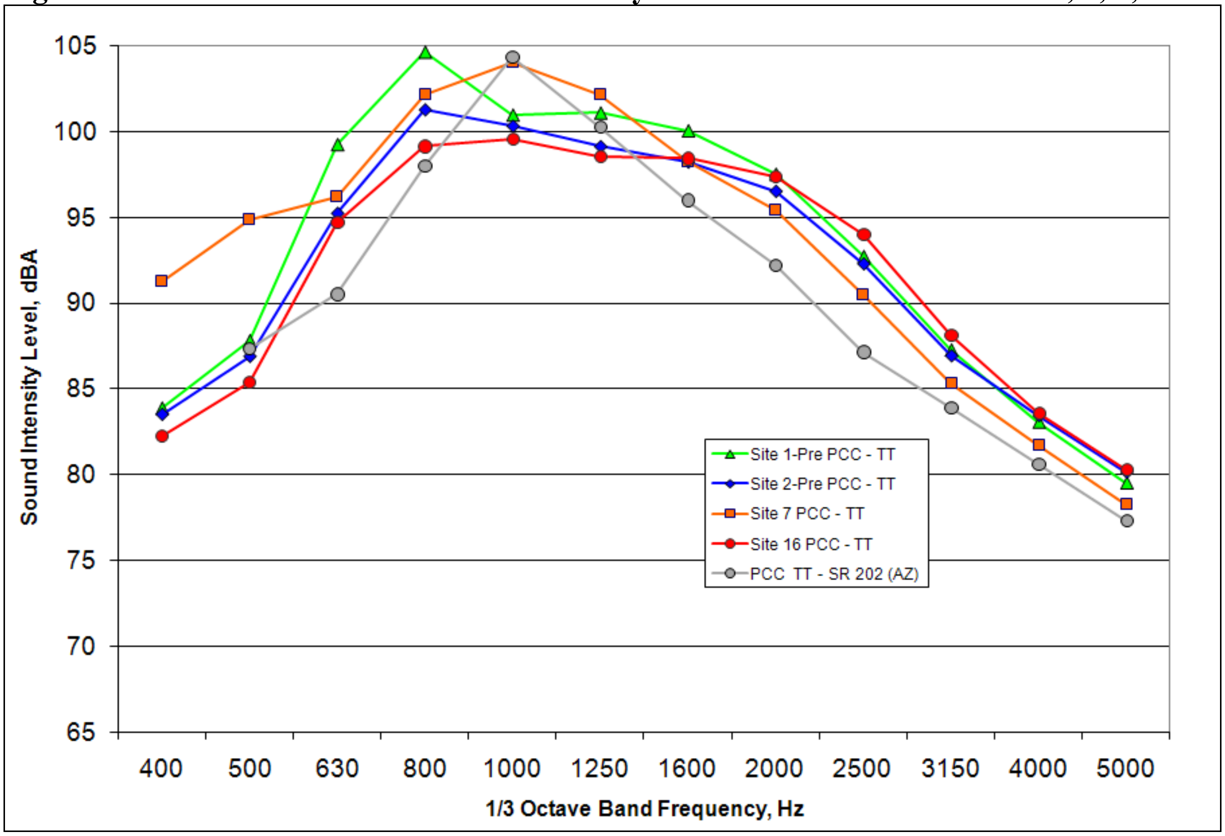
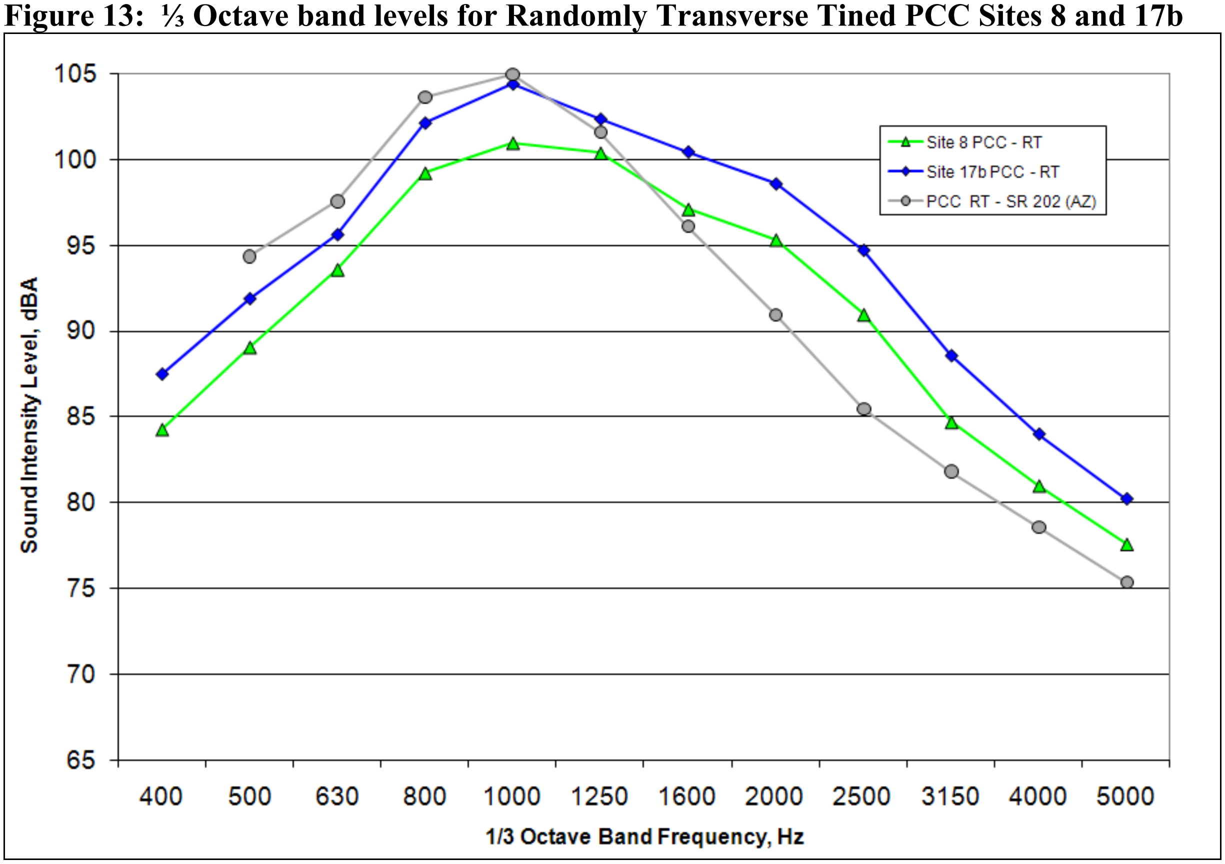
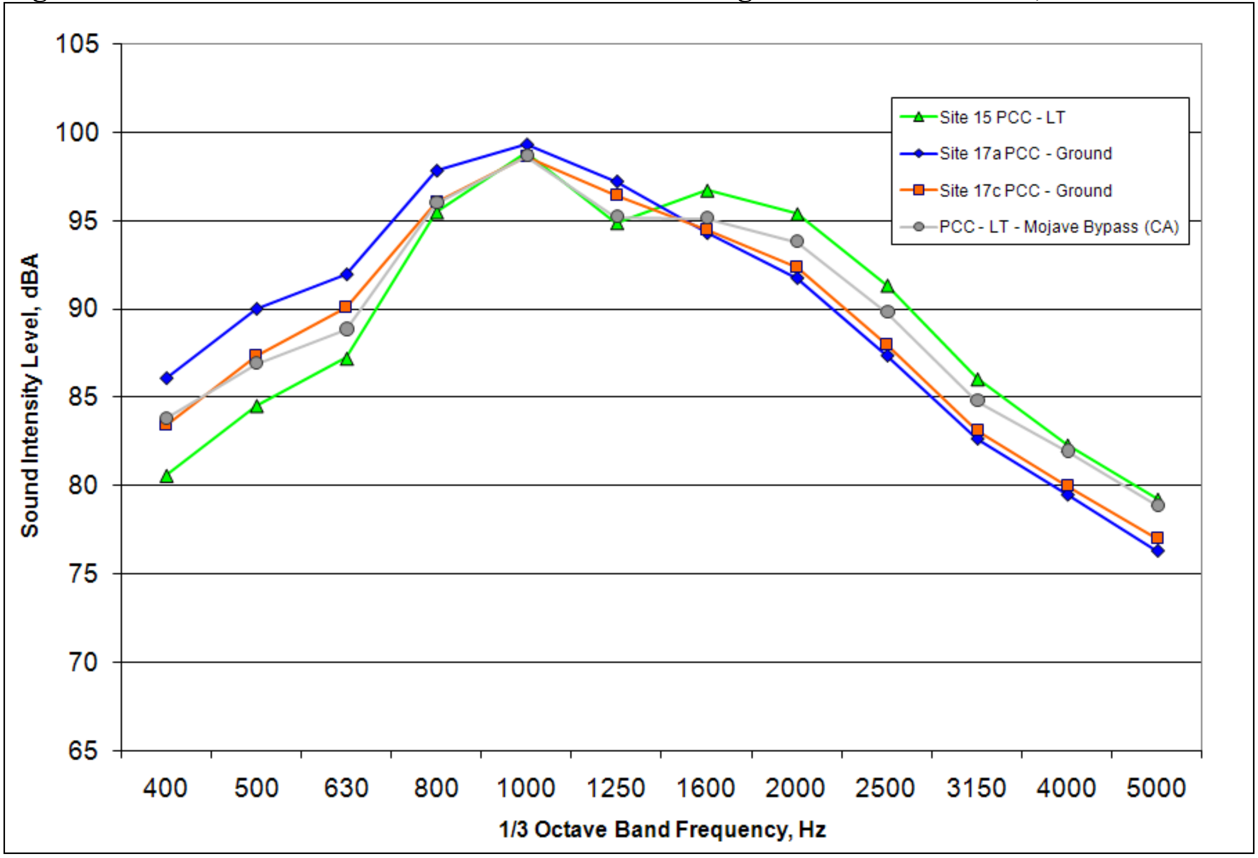


Figure 13: ⅓ Octave band levels for Randomly Transverse Tined PCC Sites 8 and 17b



The longitudinal and ground PCC pavements were, on average, 3.9 dB quieter than the transverse tined PCC sites. The overall OBSI levels are still, on average, 2.7 and 6.6 dB above those generated on the OGFC and ROGFC pavements, respectfully. The ⅓ octave band spectra for the longitudinally tined and ground PCC pavements (Sites 15, 17a, and 17c) are plotted in Figure 14 against a longitudinally tined PCC pavement measured on the Mojave Bypass near Mojave, California. The longitudinal pavement at Site 15 performed very similarly to the Mojave Bypass pavement, with raised levels occurring around 1000 Hz and again in the 1600 to 2000 Hz bands. The ground sections showed similarly raised levels around 1000 Hz; however, the OBSI levels for the ground sections dropped off above 1000 Hz, which would be expected given the smoothness of these surfaces. By comparing Figures 12, 13, and 14, it can be seen that the reduction in noise levels between the transversely tined and longitudinally tined or ground sections occurs mostly between 630 and 1600 Hz.

Figure 14: ⅓ Octave band levels for Ground and Long. Tined PCC Sites 15, 17a and 17c



5. CONCLUSION

Tire/pavement noise measurements were made on twenty four (24) pavement sites in Nevada, including nine (9) PCC pavements, thirteen (13) OGFC pavements, and two (2) ROGFC pavements. Principal findings developed from this data set are as follows:

1. Overall average sound intensity level for the ROGFC pavements (Sites 1 and 2, post-construction) were within the range of similar pavements measured in California and Arizona. Overall levels were, on average, about 9 dBA quieter than the Nevada PCC sections and about 4 dBA quieter than the Nevada OGFC sections.

2. Overall average sound intensity levels for the OGFC pavements (Sites 3, 4, 5, 9ab, 9c, 9d, 9e, 10 11, 12a, and 12b) were in the mid to upper range of AC pavements measured in California and Arizona, but were, on average, about 5 dBA below levels measured along the Nevada PCC pavement sections.

3. Overall average sound intensity levels for the ground and longitudinal PCC pavements (Sites 15, 17a, and 17c) were in the upper range of similarly textured PCC pavements measured in California and Arizona, but were, on average, 4 dBA below levels measured along the Nevada transversely tined sections.

4. The Nevada transversely tined PCC pavements (Sites 1, 2, 7, 8, 16, and 17b) were in the upper range of the pavements measured in Nevada, California, and Arizona, but were within the range of levels previously measured along transversely tined PCC sections in Arizona.

5. The ROGFC pavements show similar spectral characteristics as the ARFC pavement measured in the Arizona Quiet Pavement Pilot Program.

6. Sites 4, 10, and 12a show 1/3rd octave band signatures that are consistent with porous pavements. Site 10 resulted in the highest AC levels, resulting from the rough and positive pavement texture.

7. Compaction in the wheel path for Sites 11 and 12b resulted in spectral characteristics similar to DGAC pavements, which have very low porosity.

8. Site 14b, which was measured at a test speed of 45 mph, resulted in notably high levels throughout the frequency range, comparable to the higher range of AC levels measured in Arizona, California, and Nevada at the standard test speed of 60 mph. As a result, it is anticipated that Site 14b would be one of the loudest AC pavements measured to date at the standard test speed. This pavement was observed to be aged and broken up in places, resulting in a rougher and inconsistent pavement texture.

6. ACKNOWLEDGEMENTS

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Figure A-1: Photographs of Pavement Surfaces

 Site 2 Pre-Construction, Nov. 2006 Uniformly Transverse Tined PCC (PCC – TT)	 Site 1 Post-Construction, Jan. 2008 Rubberized Asphalt Concrete (ROGFC)
 Site 2 Post-Construction, Jan. 2008 Rubberized Asphalt Concrete (ROGFC)	 Site 3, Nov. 2006 Open Graded Friction Course (OGFC)
 Site 4, Nov. 2006 Open Graded Friction Course (OGFC)	 Site 5, Nov. 2006 Open Graded Friction Course (OGFC)
Site 7, Oct. 2007 – No Picture Available Uniformly Transverse Tined PCC (PCC – TT)	Sites 9a-e, Oct. 2007 – No Picture Available Open Graded Friction Course (OGFC)

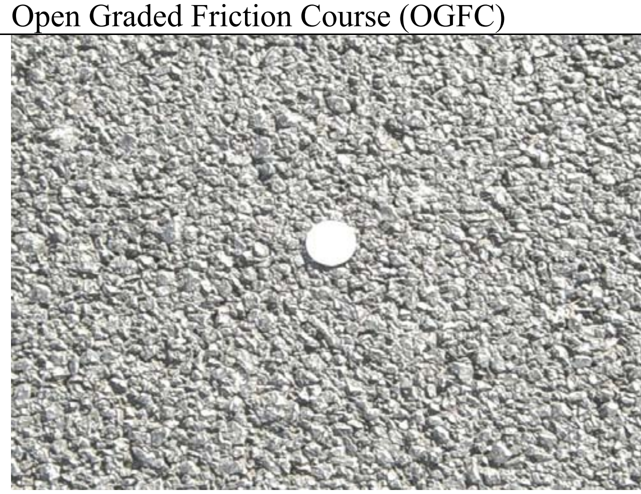
Site 8, Oct. 2007
Randomly Transverse Tined PCC (PCC – RT)

Site 10, Jan. 2008
Open Graded Friction Course (OGFC)

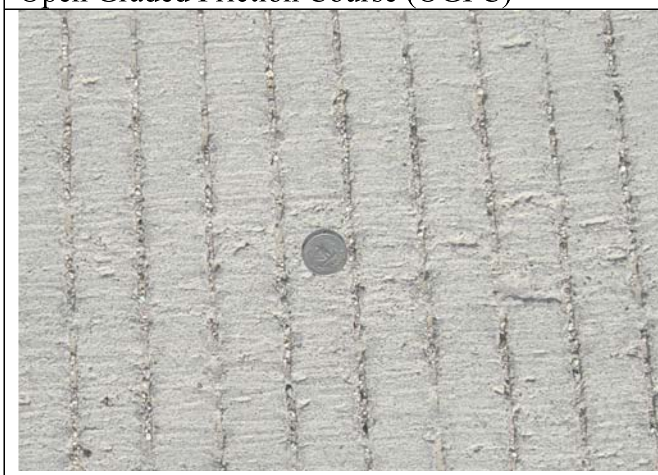
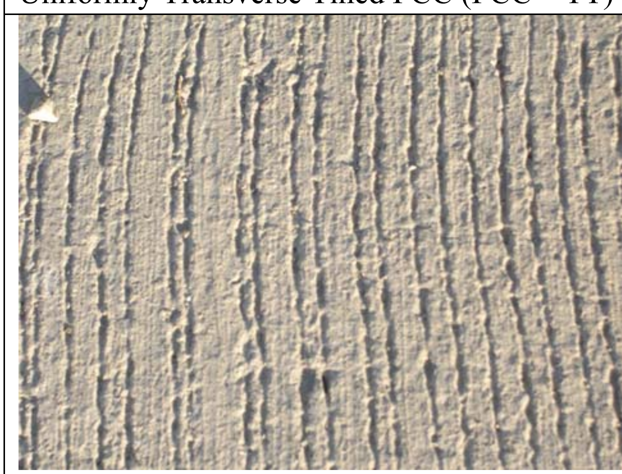
Site 11, Jan. 2008
Open Graded Friction Course (OGFC)

Site 12a, Jan. 2008
Open Graded Friction Course (OGFC)

Site 12b, Jan. 2008
Open Graded Friction Course (OGFC)



Site 14a, Jan. 2008
Open Graded Friction Course (OGFC)

 Site 14b, Jan. 2008 Open Graded Friction Course (OGFC)	 Site 15, Jan. 2008 Longitudinally Tined PCC (PCC – LT)
 Site 16, Jan. 2008 Uniformly Transverse Tined PCC (PCC – TT)	 Site 17a, Jan. 2008 Ground PCC (PCC – Ground)
 Site 17b Jan. 2008 Randomly Transverse Tined PCC (PCC – RT)	 Site 17c, Jan. 2008 Ground PCC (PCC – Ground)

[i] I-515 Pavement Overlay, OBSI Measurement, Memo from Dana M. Lodico to A. Reed Gibby, Illingworth & Rodkin, Inc, January 23, 2008.

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