Pavement sound absorption measurements in the U.S.

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In the U.S., the topic of pavement sound absorption in regard to tire-pavement noise has shown increased interest and research over the last several years. Four types of pavement sound absorption measurements with various applications are discussed: 1) In-situ measurement of effective flow resistivity (EFR), applying a modified version of ANSI S1.18-1999 – obtaining EFR values for pavements allows for direct input to the FHWA Traffic Noise Model to more precisely represent pavement sound absorption in the propagation algorithms. 2) Laboratory measurement of near-grazing incidence sound propagation properties over porous pavement, as compared to a perfectly reflecting surface – the results provide a descriptor of sound propagation at shallow angles of incidence, which cannot be predicted from absorption data alone. 3) Developing method to

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simulate the propagation of tire noise over pavement surfaces – the average sound intensity for a compact loudspeaker is measured along with resultant sound pressure levels at two distances, and the difference in levels is reported. 4) In-situ measurement of pavement sound absorption using an impedance tube mounted on pavement, part of ISO 13472-2 – method is used in the qualification of pass-by test tracks mandated by ISO 10844 and can be used in other applications where sound absorption is less than ~15%.

1 INTRODUCTION

In the U.S., the topic of pavement sound absorption in regard to tire-pavement noise has shown increased interest and research over the last several years. Ongoing research is being conducted on how pavement affects tire-pavement noise, vehicle noise, and highway traffic noise, and pavement sound absorption research helps to understand the relationship among those. In addition, sound absorption measurements help in the design and conformity of pavements. Several types of pavement sound absorption measurements are being conducted, where the type of measurement is dependent on the application. In this paper, a brief overview of four measurement methodologies is provided, along with associated applications. Section 2 reviews an in-situ measurement of effective flow resistivity with application to more precise representation of pavement sound absorption in a traffic noise model. Section 3 reviews a laboratory measurement of near-grazing incidence sound propagation properties over porous pavements. Section 4 reviews a developing method using average sound intensity of a loudspeaker along with sound pressure levels measured at two distances to simulate the propagation of tire noise over pavement surfaces. Section 5 reviews an in-situ measurement of sound absorption using an impedance tube mounted on pavement, used in the qualification of pass-by test tracks.

2 IN-SITU EFFECTIVE FLOW RESISTIVITY MEASUREMENTS

2.1 Measurement Methodology

The methodology described here was adapted/developed as part of the U.S. DOT / Federal Highway Administration (FHWA) Traffic Noise Model® (TNM®)[1,2] Pavement Effect Implementation (PEI) Study.[3] An in-situ measurement of effective flow resistivity (EFR) was used, applying a modified version of ANSI S1.18-1999, Template Method for Ground Impedance,[4] using "Geometry A." (It should be noted that there is a new version of this standard, ANSI S1.18-2010, Method for Determining the Acoustic Impedance of Ground Surfaces, which post-dated the bulk of this work and was not applied to the study.)

EFR is a measure of sound absorption, where EFR = flow resistivity + other parameters based on ground material (e.g., tortuosity, porosity, shape of ground surface, etc.). The ANSI S1.18 method measures sound levels at two microphones placed in a precisely controlled geometry at two heights above the ground and a set distance from a point source. A series of one-third octave band center frequency tones is generated from 250 to 4000 Hz, and the series of delta sound levels between the two microphones is noted. Analysis provides for the extraction of an EFR value based on curve fitting (sound pressure level deltas as a function of frequency, comparing measured values and those calculated with sound propagation theory). Please refer to Figure 1 for a photo of the instrumentation set-up.

It was determined that the analysis process in ANSI S1.18 was insufficient for determining EFR values for specific pavement types; the ANSI S1.18 process seems to be appropriate for identifying very broad general ground types (e.g., lawn, pavement, etc.), but is inadequate for identifying sensitivities within a general ground type. As such, a modified analysis process was developed for the TNM PEI Study. The modifications include the following: 1) expanding the range of theoretical EFR curves and refining the steps in that range; and 2) using a two-step curve matching process, which first restricts the range of potential EFR values based on the frequencies of the first dip and first peak of the measured curve, and second, extracts the EFR value based on the amplitude of the peak. This process is described in more detail in Rochat, et al. 2012.[3]

2.2 Application of Measurement Methodology

The FHWA TNM uses EFR values in ground reflection equations as part of sound propagation modeling. In the current version of TNM (v2.5), the EFR value applied to roadways is 20000 cgs rayls, representing a national average pavement; it is known from literature[5] that for general pavement categories based on type and age, EFR values can range from 5000 to 30000 cgs rayls (note: values up to 10^6 cgs rayls have been reported for extreme cases). When sound level predictions are being calculated for a highway with a specific pavement, obtaining EFR values for the specific pavement would allow for direct input to TNM to more precisely represent pavement sound absorption in the propagation algorithms.

In order to demonstrate the use of pavement-specific sound absorption values in TNM, the measurement method described in Section 2.1 was applied to obtain EFR values for 30+ specific pavement types. EFR values for these measurements ranged from 7200 to 30000 cgs rayls. It should be noted that actual values for three porous pavements with air void > 16%, were likely well below 7200, however the exact EFR values were indeterminable due to insufficiently thick asphalt layers, where reflections from the underlying structures affected sound levels above the porous asphalt surfaces. Please refer to Figure 2, which shows a typical EFR curve with a dip-peak-dip shape and an atypical curve with a dip-peak-peak-dip shape, where the extra peak is evidence of an underlying structure affecting the measurements. (An additional application for the subject methodology could be in identifying reflections from an underlying structure, which could help with the design of porous pavements.)

Using a special research version of TNM v2.5, EFR values for the specific pavements being evaluated were used to replace the default EFR value for roadways. For an open-graded rubberized asphalt, with an EFR value of ~7000 cgs rayls for 6- and 8-lane highways, use of the specific EFR value improved wayside sound level predictions by about 0.5 dB (primarily in the 1250 to 2500 Hz range), when comparing predictions for sound measured at a distance of 15.2 m (50 ft). The effect would be greater for a pavement with lower EFR values; a brief study using TNM showed that when using an EFR value of 2000 cgs rayls and comparing predicted sound levels to results obtained when using an EFR value of 20000 cgs rayls (the default), predicted wayside sound levels for an 8-lane highway could be 2.0 dB lower with the EFR value of 2000 cgs rayls.

It should be mentioned that the methodology described in Section 2.1 is also being applied to the Arizona Quiet Pavement Pilot Program (QPPP),[6] where the EFR value is one of the pavement properties being monitored over time to see how this property affects tire-pavement noise and traffic noise as the pavement ages.

3 LABORATORY MEASUREMENT OF NEAR-GRAZING INCIDENCE SOUND PROPAGATION PROPERTIES OVER POROUS PAVEMENTS

3.1 Measurement Methodology

An experimental procedure was designed for the measurement of near-grazing incidence noise reduction on pavement surfaces.[7] This laboratory test was designed so that an experimenter can directly measure sound propagation properties at a shallow angle of incidence and compare these properties to other pavement designs. This experiment can be used in conjunction with other laboratory tests of physical and acoustic properties to identify potential quiet pavement designs.

A diagram of the setup for the near-grazing incidence noise reduction test is shown in Figure 3. The test requires a pavement specimen with approximate dimensions 1 m × 0.5 m. The test is conducted in an anechoic chamber. A microphone and an omnidirectional sound source are each placed 10 cm above the specimen, and each are placed 40 cm from the center of the specimen so that they are 80 cm apart and centered between the two long sides of the specimen. The placement of the source and receiver yields an angle of incidence of approximately 76° from normal incidence.

A white noise signal is generated and used to drive the sound source. The narrow-band sound pressure spectrum at the microphone is then measured. After the measurement is made, the pavement specimen is removed from the test chamber, and another measurement is made without a reflecting surface in place. This result, known as the anechoic condition, is used in the data analysis to determine the direct sound reaching the microphone.

The results of the near-grazing incidence noise reduction test are reported with respect to an ideal reflecting pavement. The sound spectrum measured in the anechoic condition is used to calculate the theoretical spectrum that would be measured if the surface were perfectly reflecting according to Equation 1:

$$P_R = P_A\left(1 + \frac{r_1}{r_2} e^{jk(r_1 - r_2)}\right) \qquad (1)$$

where P_R is the sound pressure spectrum expected for an infinite, perfectly reflecting surface, P_A is the complex sound pressure spectrum measured in the anechoic condition, r_1 = 80.0 cm is the length of the direct path from the sound source to the microphone, r_2 = 82.5 cm is the length of the reflected path, k is the acoustic wavenumber, and j is the imaginary unit. The decibel difference between the spectrum measured with the pavement specimen and that of a perfectly reflecting surface is then calculated according to Equation 2:

$$L_S = 20\log_{10}\frac{|P_S|}{|P_R|} \qquad (2)$$

where L_s represents the excess near-grazing incidence noise of a given surface compared to an ideal reflecting surface. A negative value of L_s at a given frequency is an indication that the test surface reflects less sound than a perfectly reflecting surface at this frequency. Values of L_s are generally between -6 and 0 dB, except at frequencies where the direct and reflected sound are significantly out-of-phase.

The valid frequency range of the near-grazing incidence noise reduction test is determined by physical properties of the pavement specimen. The low-frequency limit is the frequency with wavelength equal to the smallest dimension of the test sample. For the dimensions described above, the low-frequency limit is approximately 680 Hz. The high-frequency limit is the frequency with wavelength equal to ten times the length of the largest pavement feature. For asphalt pavements, this can be calculated using the largest top-layer aggregate size. For example, for a pavement with a maximum aggregate size of 9.5 mm, the high-frequency limit is approximately 3600 Hz.

Typical results of the near-grazing incidence noise reduction test are shown in Figure 4. The specimen used for this test was a single-layer porous hot-mix asphalt sample. The sharp dip near 1350 Hz is due to interference between the direct and reflected sound waves, and does not indicate that the pavement is absorbing significantly more sound at this frequency. The sharp dip is an indication that the pavement is not locally-reacting, meaning that incident sound is not necessarily reflected at the same angle. For extended-reaction surfaces, normal incidence data cannot be used to accurately predict sound properties at other angles of incidence.

3.2 Application of Measurement Methodology

Many types of pavement surfaces have been shown to be extended-reacting, including porous concrete, porous asphalt, and thin gap-graded asphalt. For these surfaces, normal incidence absorption data is not sufficient. The results of other methods, such as the grazing-incidence noise reduction test, must be used in addition to standard normal incidence data to quantify the effect of the pavement on tire-pavement noise.

4 DEVELOPING METHOD TO SIMULATE THE PROPAGATION OF TIRE NOISE OVER PAVEMENT SURFACES

4.1 Measurement Methodology

The intent of this procedure is to replicate the rather unique sound propagation circumstance of noise radiated by a tire to the wayside. For the dominate tire noise frequencies from about 400 to 5000 Hz, source regions are very close to the pavement, typically within 10 cm or less.[8] With such close proximity of the source to the ground, there are no interference effects between the direct and reflected sound as there is essentially no path length difference in this frequency range. In an attempt to replicate this propagation case, an experimental method is under development to examine the effect of porous pavements in this situation. In this procedure, a compact loudspeaker is placed on the ground to substitute for the tire/pavement noise source. The speaker currently used has a 10 by 10 cm face and is otherwise enclosed on its other surfaces. This speaker is not ideally compact, however at distances of 7.5 m and receiver heights of 1.5 m, it does provide a nominal path length difference of less than 1/10 of an acoustic wavelength for frequencies up to 5000 Hz.

To replicate typical vehicle pass-by noise measurement conditions, microphones are placed at distances of 7.5 and 15 m from the face of the loudspeaker in a direction along the test surface at a height of 1.5m (Figure 5). Sound pressure levels at each of these positions are measured while the loudspeaker broadcasts pink noise. To quantify the source level, the average sound intensity of the loudspeaker is measured using the scanning method developed for sound power level determination.[9] This is accomplished by moving a sound intensity probe over and very close to the face of the loudspeaker for duration of 20 seconds. This method of source level determination is preferred over a sound pressure level measurement as sound intensity measures only the propagating energy in the acoustic nearfield of the loudspeaker. This determines the average of the intensity of the sound propagating toward the microphones analogous to an on-board sound intensity measurement.[10] After the measurements are complete, the differences between the source and the receiver positions are determined by subtracting the distant sound pressure levels from the sound intensity level on a one-third octave band basis.

4.2 Application of Measurement Methodology

The most extensive application of the methodology to quantify the effects of tire noise propagation over pavements was completed at the National Center for Asphalt Technology (NCAT) Test Track located near Auburn, AL. This facility contains 48 sections of different asphalt pavements five of which are designed and documented to be porous. Testing was performed on 12 pavements at NCAT, 7 non-porous and the 5 porous sections. Results of sound level difference between the sound intensity level at the loudspeaker and the sound pressure levels measured at 25ft and 50 ft are shown in Figure 6 for the non-porous pavements having air void percentages in the range from 2% to 5.5%. The lack of sound absorption for these pavements is further supported by the observation that up to about 2500 Hz, the offset between the two distances is about 6 dB for the doubling of distance between the two microphone locations. This fall-off rate is expected for a point source in the absence of any additional attenuation from the pavement. The constant offset also indicates the absence of any interference effects between a direct and reflected path.

Testing was repeated on the five porous pavements that ranged from 16% to 22% air voids. Pavement sound absorption is generally expected to occur above about 15% air voids.[8] To more clearly display the effects of the porous pavement, it is convenient to compare them to a non-porous baseline. For this purpose the sound level differences averaged for the non-porous pavements was subtracted from the sound level difference for each porous pavement at the respective distances of 25ft and 50ft. These values then represent the additional attenuation produced by the porous pavement relative to the non-porous pavement. These additional attenuation levels are shown in Figure 7 for four single layer porous pavements and one double layer porous pavement. For the single layer porous pavements (S3, S4, S8, and N2), additional attenuation is produced in the mid to high frequencies starting at 800 to 1000 Hz. Below these frequencies, the attenuations are nearly zero implying no additional attenuation occurs relative to the non-porous pavements. Above 800 to 1000 Hz, the additional attenuation levels vary with frequency and each pavement is unique. Peaks in the additional attenuation for these single layer porous pavements range from 1000 to 2000 Hz. Some of these differences in peak frequency may be related to the thickness of the porous layer, however other possible factors include details of specific pavement designs and pavement age.[11] The attenuation provided by the double layer porous section in Figure 7 (N13) is substantially different from the single layer pavements. For this pavement, there is no real "peak" in the attenuation values versus frequency. Also, the additional attenuation extends lower in frequency than it does for any of the single layer porous pavements.

Figure 7 also shows the effect of the distance on propagation over porous versus non-porous pavements. For the single layer porous pavements in particular, the magnitudes of the attenuations at 50ft are considerably higher than at 25ft data. Instead of maximum one-third octave band attenuations of 3.8 to 9.3 dB at 25ft, the range at 50ft is from 7.5 to 14.8. Although the attenuation increases, the shapes of the attenuation curves are similar for increased distance of propagation over the porous pavements. This indicates that there is no path length difference between the direct and reflected sound as the interference pattern would shift as the receiver moves away from the source. This implies that the term "reflected sound" for propagation of tire noise sources at ground level does not apply in the conventional sense. Instead, as sound propagates outward from the tire, energy in the sound wave is dissipated by the sound absorptive properties of the porous pavement reducing the strength of the sound wave.[12]

5 IN-SITU MEASUREMENT USING AN IMPEDANCE TUBE

5.1 Measurement Methodology

ISO 13472-2[13] describes a new method for the measurement of sound absorption of pavement surfaces as well as the specification of the hardware for making the measurement. The measurement is made *in situ* using a version of the familiar impedance tube (Kundt's tube) and the "two microphone technique" familiar to many and described in ISO 10534-2. The new method is non-destructive, i.e., it replaces the need for extracting core samples, is fast, and is generally accurate for pavements with sound absorption coefficient less than approximately 0.15. The new method is already in use in the qualification of pass-by facilities for the measurement of tire and vehicle noise; this qualification procedure is implemented in ISO 10844:2011.[14] A recent paper[15] describes the use of pavement absorption measurement in the context of ISO 10844. Figure 8 shows a fully-portable system conforming to ISO 13472-2 from Spectronics, Inc. (www.spectronics.net). The system includes a portable data acquisition system and uses ordinary one-half inch microphones.

An important part of the measurement is the pavement attachment fixture. This fixture must seal well with the impedance tube and with the pavement surface so that sound does not leak out (and that ambient sound does not leak in). Typically, sealing between the fixture and the pavement is made by using a flexible sealant such as modeling clay or putty. Fig. 9 shows the pavement attachment fixture.

5.2 Application of Measurement Methodology

A key element in ISO 13472-2 is the adjustment of the measured pavement absorption by subtracting the latent sound absorption of the impedance tube, called the "reference" sound absorption to make the measurement more accurate. This is necessary because the sound absorption coefficient of pavements is typically less than 0.15. The reference sound absorption coefficient is measured by placing the impedance tube on a rigid plate, at least 10 mm thick, and making a measurement of the sound absorption, as seen in Fig. 10. Because the plate has sound absorption of approximately zero, the measurement yields the latent sound absorption of the impedance tube. To qualify, the impedance tube must have a reference sound absorption coefficient of no more than 0.03 in all one-third octave bands from 315 Hz to 1600 Hz. Figure 11 shows the pavement sound absorption measurement in progress. Once the raw sound absorption of the pavement is determined the reference sound absorption is subtracted and the result converted to one-third octave bands from 315 to 1600 Hz. An example of the adjusted sound absorption coefficient for an actual pavement measurement is shown in Fig. 12.

6 CONCLUSIONS

In this paper, four methodologies are described for measuring various pavement sound absorption parameters. Example applications for each method are provided. This paper was written to help promote a better understanding of the various sound absorption measurement methods and potential applications, which will serve to help guide future testing and research regarding pavement design and tire-pavement interaction noise and its propagation into communities.

7 ACKNOWLEDGEMENTS

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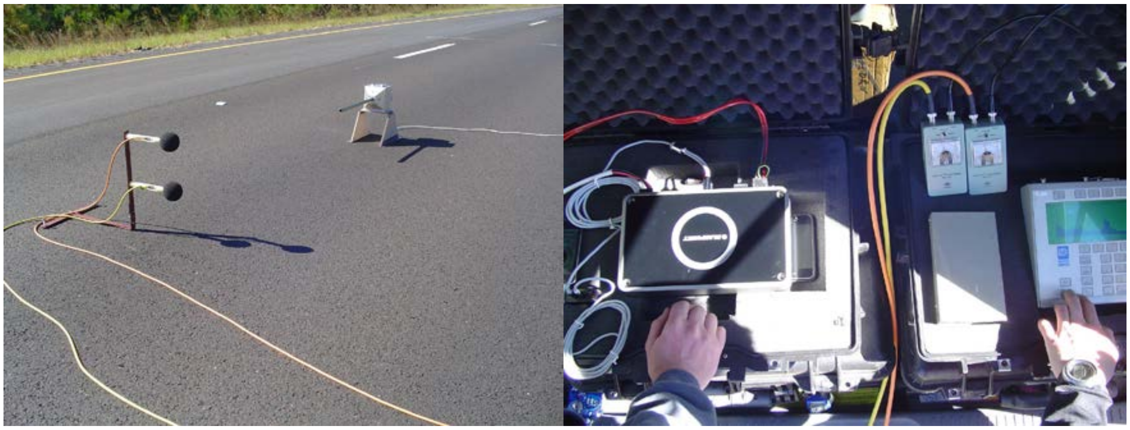

Fig. 1 - Photos of EFR data collection system.

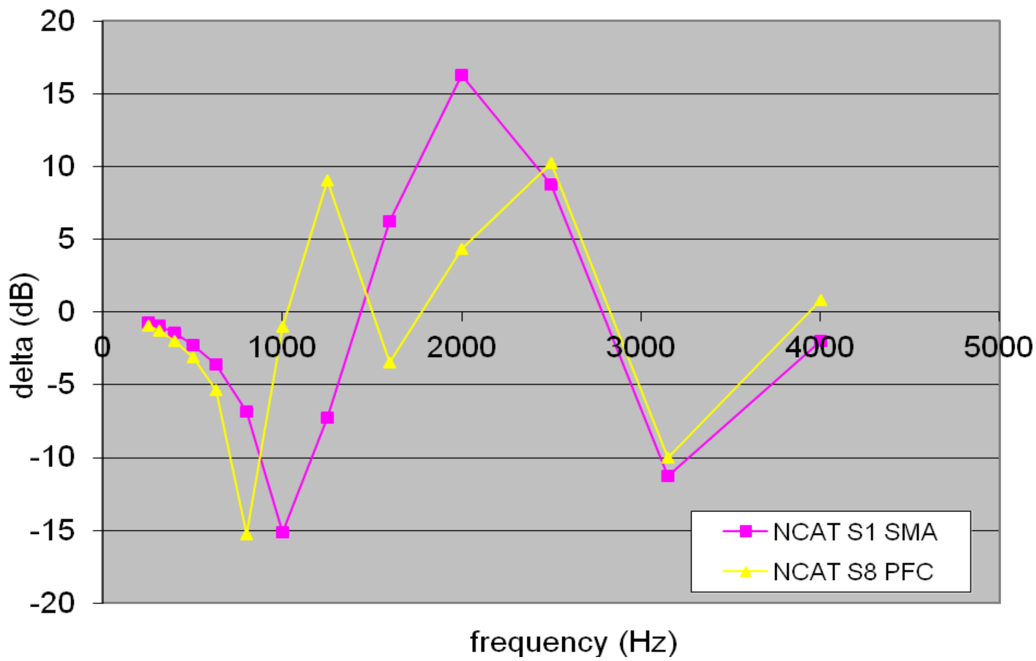

Fig. 2 - Example of measured EFR curves, typical and atypical, where the atypical curve has two peaks, showing evidence of an underlying structure.

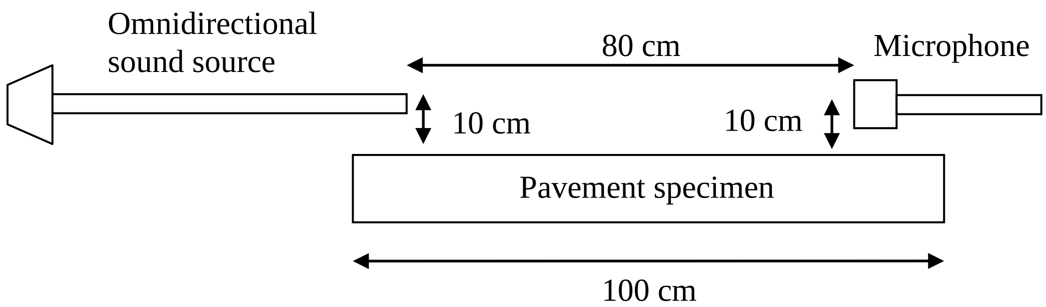

Fig. 3 –Diagram of near-grazing incidence noise reduction test setup.

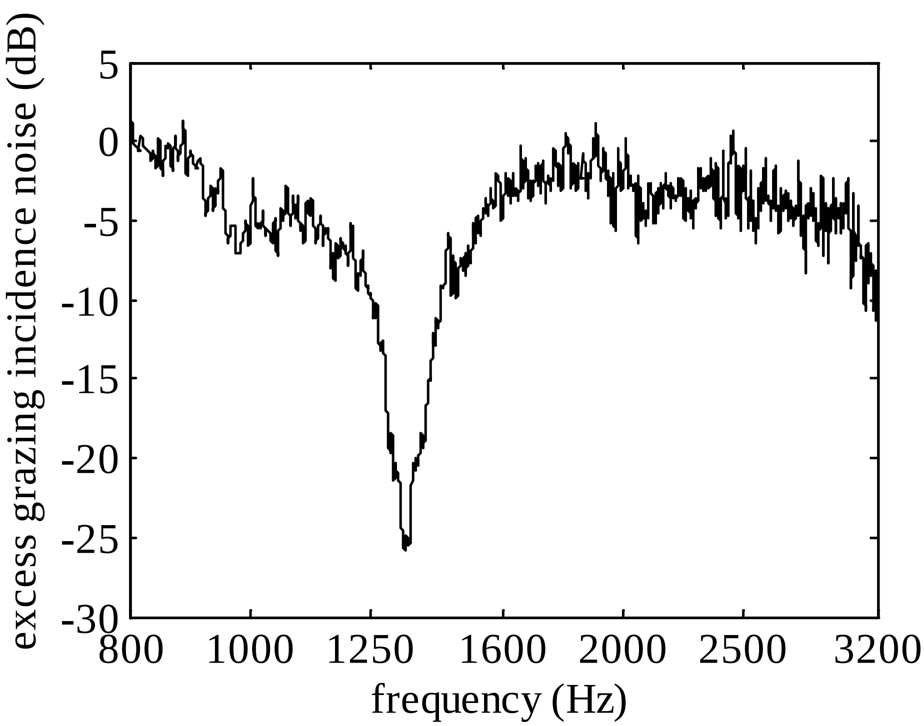

Fig. 4 –Typical results of near-grazing incidence noise reduction test.

Fig. 5 - Instrumentation set-up for tire noise sound propagation measurements.

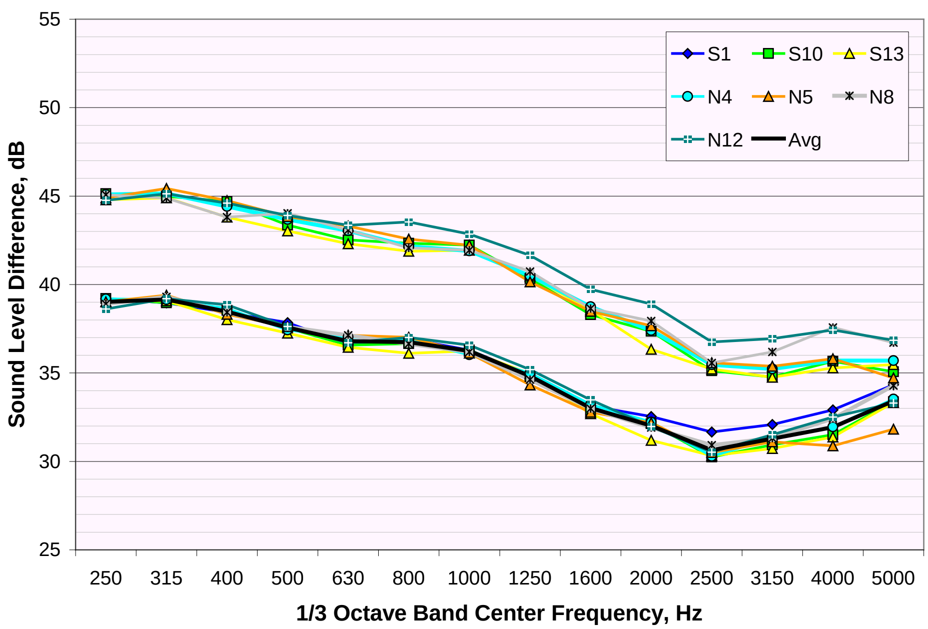

Fig. 6 - One-third octave band OBSI level differences between loudspeaker sound intensity levels and sound pressure levels measured at 25 ft and 50 ft for non-porous pavements.

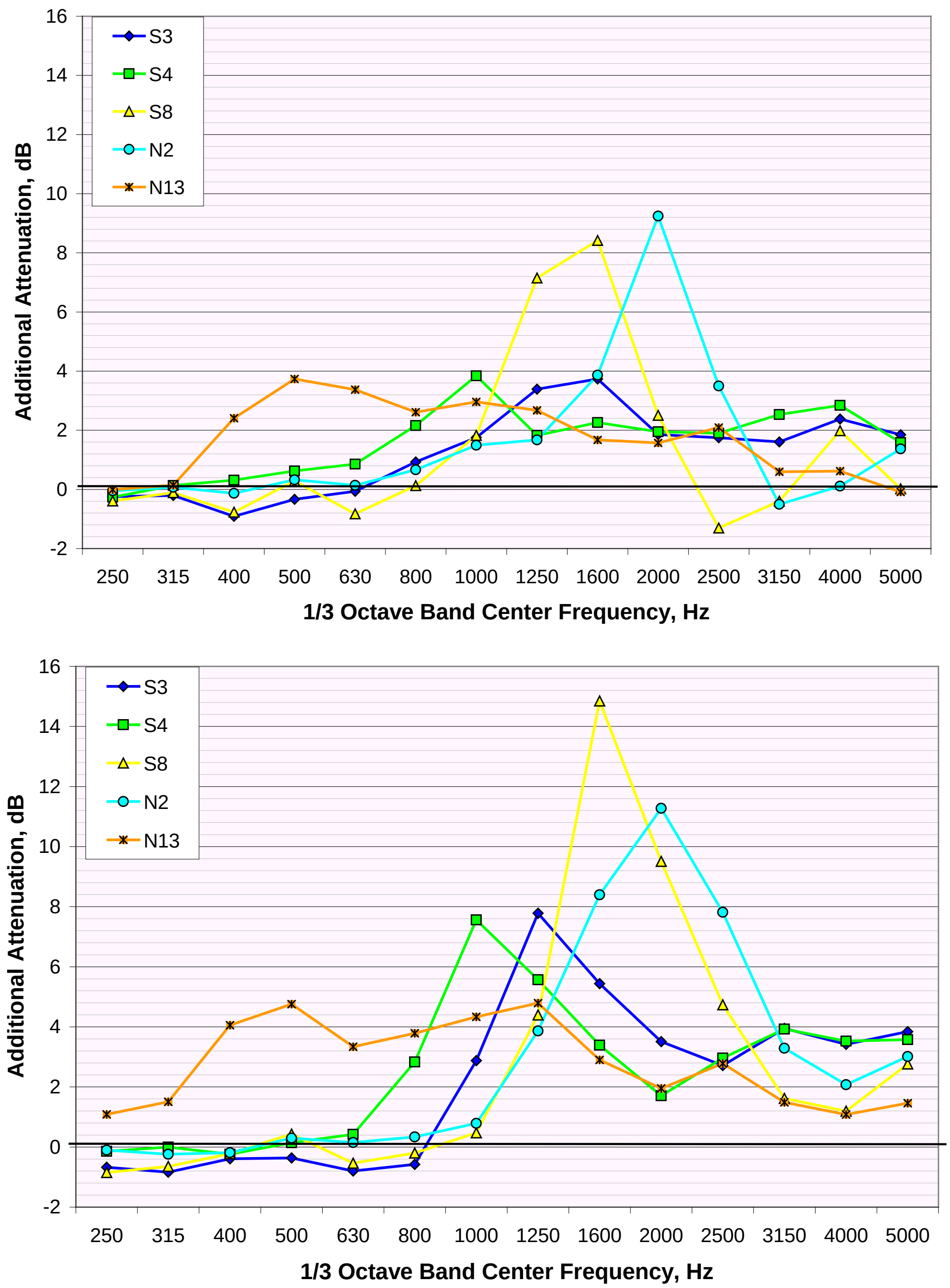

Fig. 7 - Additional one-third octave band attenuation for sound propagating over porous pavements relative to the average non-porous pavements as measured at 25 ft and 50 ft.

Fig. 8 – Sound absorption measurement system.

Fig. 9 – Pavement attachment fixture.

Fig. 10 – Measuring the reference absorption using a 10 mm thick plate.

Fig. 11 – Pavement measurement.

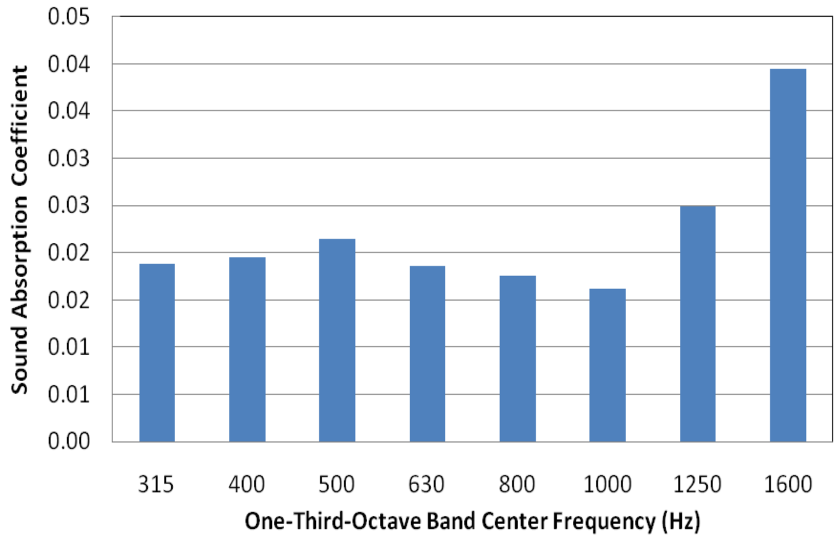

Fig. 12 – An example of pavement sound absorption.