Tire-Pavement Interaction Noise: Recent Research on Concrete Pavement Surface Type and Texture

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Abstract

Several solutions have been proposed for quieter riding surfaces, including porous pavements, tining, and grinding. This paper deals with certain aspects of a recent large-scale research that has been carried out to examine the influence of cement concrete pavement surface type and texture on noise generation. One pavement surface type (Enhanced Porosity Concrete – EPC), and one surface texturing method (transverse tining) is dealt with in detail in this paper. Experimental studies to ascertain the physical (porosity and pore size), mechanical (strength), and acoustical (acoustic absorption using impedance tube) properties of EPC are discussed. It is shown in this paper that, with careful selection of aggregate gradation and cementing materials content, it is possible to generate a system of optimally-sized pores in the material to maximize acoustic absorption. Mathematical modeling of noise to evaluate the influence of transverse tine geometry (depth, width, and shape) on noise reduction characteristics is explained in the second part of this paper. A mathematical model has been used to determine the stress distribution between the concrete pavement and the tire. The stress distribution model is used to describe the stress and ultimately noise generated by various geometries of tining patterns. Experiments on Tire-Pavement test apparatus are also discussed.

Introduction

An increase in the volume of road traffic has resulted in an increase in road-generated disturbance to nearby residents as well as vehicle occupants (Sandberg and Ejsmont, 2002). Noise is frequently reported as one of the most common road-generated disturbance by vehicle users and the population living near highways (Christory et al., 1993). This effect has been reported to be more significant in Portland Cement Concrete (PCC) pavements (Onstenk et al., 1993, Descornet, 2000). Currently, the most commonly adopted solution to reduce the noise generated by traffic is the installation of sound barriers. While the construction of sound barriers impedes the sound transmission path between vehicles and the neighboring development alongside the highways resulting in noise abatement, they tend to be extremely costly, unsightly, and not practical for bridges and/or urban highways. The fact that the road surface has a significant effect on pavement noise generation mechanisms is widely

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known (Nelson, 1994, Francois and Michel, 1993, Descornet, 2000). The pavement surface plays a very important role in the propagation of noise from the tire/pavement contact area to the sideline receiver (Wayson, 1998). The acoustic and mechanical impedance effects of the pavement surface are suggested as noise reducing mechanisms. The acoustic impedance depends on the connected voids and the surface texture of the pavement whereas the mechanical impedance depends on the relative stiffness of the tire and the pavement.

Surface texture and pavement surface type (porous or non-porous, for instance) both play important roles in the noise reduction properties of the pavement through acoustic impedance effects. The absorption capacity of the pavement surface depends on accessible porosity, specific flow resistance, a shape factor, and the layer thickness (BRITE EURAM 3415, 1994). An absorptive surface will reduce both the horn effect and the sound at the roadside because the sound energy is not as efficiently reflected (Wayson, 1998). Several surface texturing methods like tining, grinding, chip sealing, and exposed aggregates are also used in practice to reduce tire-pavement interaction noise (Descornet, 2000, BRITE EURAM 3415, 1994).

This paper deals with certain aspects of a recent large-scale research that has been carried out to examine the influence of concrete pavement surface type and texture on noise generation. One pavement surface type (Enhanced Porosity Concrete - EPC), and one surface texturing method (transverse tining) is dealt with in detail in this paper.

Enhanced porosity concrete (EPC) is proportioned by gap grading the coarse aggregates and either eliminating or limiting the sand volume in the matrix so as to develop a network of interconnected pores in the material. In EPC, noise-reduction is a result of a combination of reduced noise generation and sound absorption (BRITE EURAM, 1994, BRRC, 2000). The propagation of noise is altered by the porous surface since this will affect the surface impedance and phase interactions that occur between the direct and reflected sound waves (Nelson, 1994). Experimental sections of porous concrete pavements in Europe have shown that altering the pavement surface can reduce the noise level by as much as 10dB (A) (Descornet, 2000, BRITE EURAM 3415, 1994).

Surface texturing for concrete pavements has been done for many years with the primary purpose of improving the skid resistance of pavements. Modification of surface texture of concrete pavements by grinding or tining is commonly followed as a means of noise reduction. Transverse tining is defined as a texture created by a single pass of an artificial turf or burlap drag followed by a mechanically operated transverse (in a direction perpendicular to traffic movement) texturing device (ACI 325, 1988).

Research Significance

While several research studies have reported the influence of pavement surface type and texture on the noise reducing properties of concrete pavements, there has not been any systematic attempt to address the mechanisms by which these noise reductions are achieved. It is imperative to know the characteristic features of these techniques that have a bearing on their performance with respect to noise reduction. This paper attempts to (i) develop an understanding of how concrete mixture proportions influence the pore structure of EPC, which is crucial in achieving noise reduction, and (ii) understand the influence of the geometrical features of the transverse tine on its noise reduction capacity.

Enhanced Porosity Concrete (EPC) as a Quiet Pavement Surface

The structural requirements (strength, durability) of the EPC pavement as well as the functional requirements (noise, skid resistance) have to be addressed to develop design procedures for EPC. In order to develop a noise mitigating material, a "designed" porosity and pore structure is necessary. EPC mixtures can be useful for sound attenuation; however the mixture compositions and the pore properties need to be carefully optimized so that the methods used to maximize noise-reduction do not have a negative impact on mechanical performance and durability of the pavement.

Materials and Mixture Proportions. The three sizes of aggregates used to produce gap graded EPC mixtures in this study were # 8 (passing 4.75 mm and retained on 2.36 mm sieve), # 4 (passing 9.5 mm and retained on 4.75 mm sieve), and 3/8" (passing 12.5 mm and retained on 9.75 mm sieve). The aggregate sizes shown refer to the sieve in which they were retained (for instance, # 4 indicates that the aggregates passed through a 3/8" (9.5 mm) sieve and were retained on the # 4 (4.75 mm) sieve). Moreover, binary blends of these aggregate sizes were also used. Blends were prepared by replacing 25, 50, and 75% by weight of the larger sized aggregates successively by smaller sized aggregates. The water-to-cement ratio (w/c) for all mixtures was maintained constant at 0.33. Figure 1 shows a cross section of a hardened EPC.

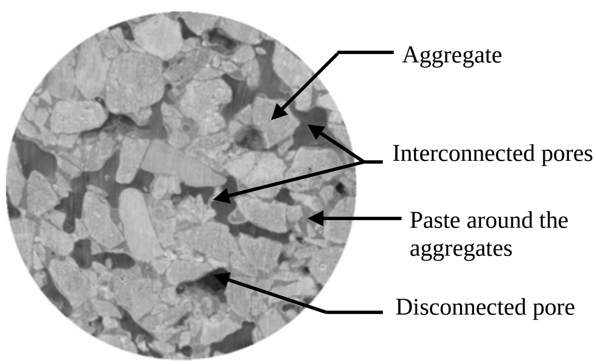


Figure 1. Cross section of hardened EPC (the connected and disconnected pores were separated by an epoxy impregnation procedure)

Porosity and its dependence on aggregate sizes and proportions. Porosity is one of the most important characteristics of EPC. A connected network of pores is necessary for the sound waves to pass through and dissipate inside the system, thereby reducing the reflected noise.

Cylindrical specimens (95 mm in diameter and 150 mm long) were immersed in water for 24 hours to saturate the pores in the matrix. After this period, the sample was removed from water and allowed to achieve a SSD condition. The sample was then enclosed in a latex membrane and the bottom of the cylinder was sealed to a stainless steel plate using silicone sealant. The combined mass of the sample, latex membrane, and the steel plate (M_1) was measured. Water was added to the top of the sample until it was filled, which indicated that all the interconnected pores were saturated. The mass of the system filled with water was then taken (M_2). The difference between the masses ($\Delta M = (M_2 - M_1)$) gives the mass of the water in the pores. This mass was converted into a volume, and expressed as a percentage of the total volume of the specimen to provide an indication of the total porosity (Neithalath et al., 2004).

Figure 2 illustrates the variation in porosity with percentage of # 8 aggregates, the remaining percentage being made up of either # 4 or 3/8" aggregates, i.e., 50% # 8 aggregates indicate that the remaining 50% is made up of either # 4 or 3/8" aggregates. There is no significant difference in the total pore volume between mixtures consisting of single sized (# 4, # 8, or 3/8") aggregates; with an accessible porosity between 21% and 24% for all of these mixtures. For mixtures made using blends of # 4 and # 8 aggregates, the porosity is found to be higher than that for mixtures with single sized aggregates, attributed to the increased volume of voids in the skeleton of coarse and fine particles. When 3/8" aggregates are blended with # 8 aggregates, the accessible porosity is higher than or at least roughly similar to that of single sized aggregate mixtures. The only exception was for the case of 50% of 3/8" aggregates replacing # 8. This may be due to the fact that the # 8 aggregates (2.36 mm) appear to fill the pore spaces that develop between the 3/8" aggregates because they are smaller than the characteristic pore sizes in a system with 3/8" aggregates alone.

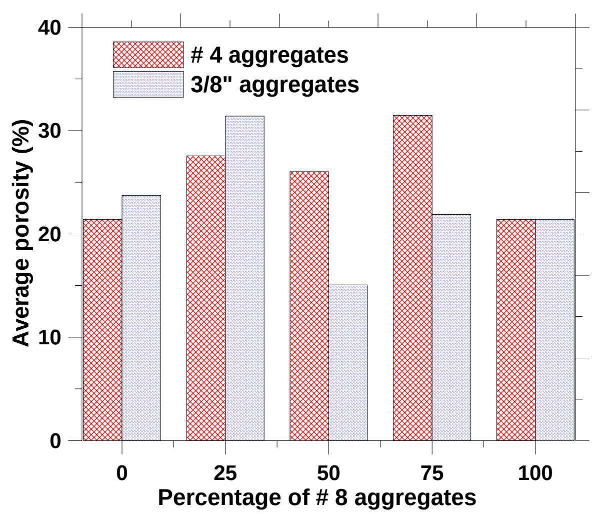


Figure 2. Variation in porosity with aggregate blends (# 8 and either # 4 or

Pore sizes and its dependence on aggregate sizes and proportions. The acoustic characteristics of porous materials are heavily dependent on the size of the pores in the system. The pore size was estimated using an image analysis procedure (Marolf et al., 2004) conducted on cut slices of the EPC specimen. The maximum and minimum diameters of the each of the selected pores were recorded. The median of all the pore sizes greater than 1 mm was chosen as an approximation of the representative pore size of the sample, and is termed as the "characteristic" pore size. The pore sizes determined by this method are only estimates to provide an indicator of the sizes of the pores in the system and provide a useful method of comparison of different systems with varying aggregate sizes and blends.

The characteristic pore size is plotted against the percentage of larger aggregates replacing smaller ones in Figure 3. Replacing smaller sized aggregates with an increasing percentage of larger sizes result in an increased median pore size. This happens because the introduced coarser particle may not be able to fit in the void left behind by the removed finer particle. Also, according to particle packing theory, when fewer coarser particles are introduced in a mixture of finer particles, there is a further amount of voids introduced in the packing of finer particles at the interface (de Larrard, 1999). The trends indicate that an increase in aggregate size increases the characteristic pore size of the system.

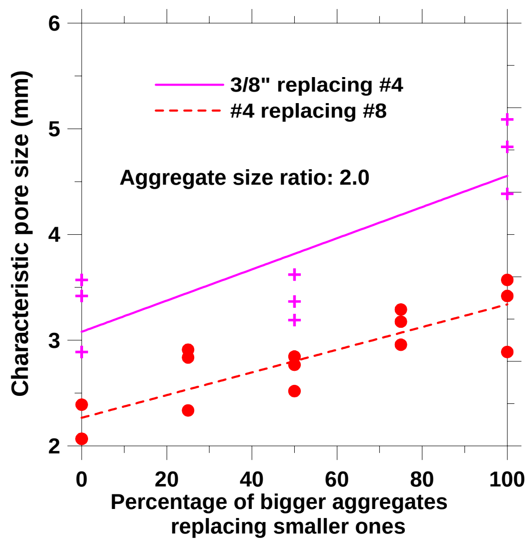
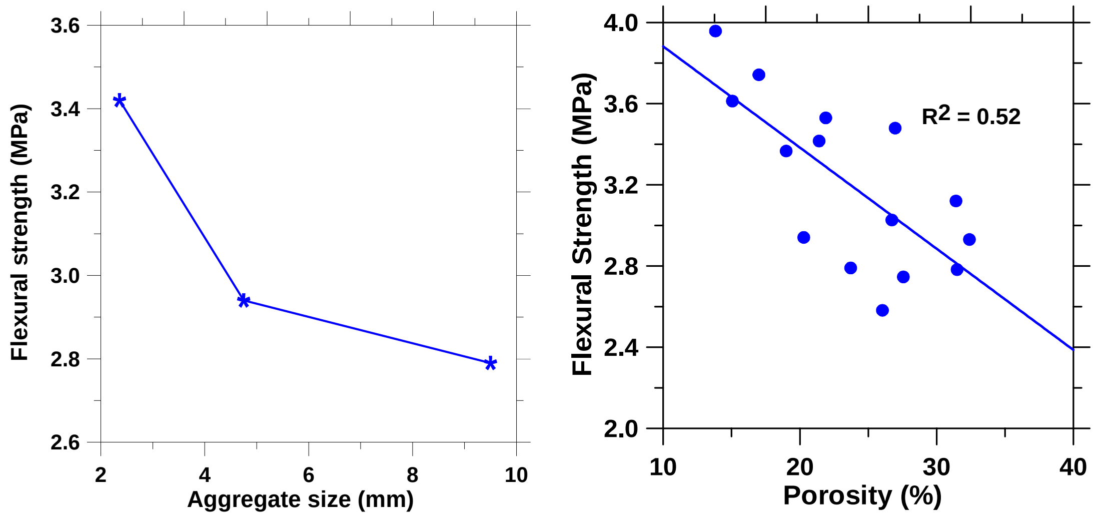


Figure 3. Variation of characteristic pore size with aggregate size for binary blends

Influence of Mixture Proportioning on Flexural Strength. Flexural strength was determined in accordance with ASTM C 78-02 on 150 x 150 x 700 mm beams.

For single sized aggregates, Figure 4a depicts the influence of aggregate size on the flexural strength. It can be seen that the flexural strength is reduced as the aggregate size is increased. This trend has been found true for the blended systems also. Substituting the smaller size aggregate fraction with larger size results in a reduced strength. This occurs since an increase in aggregate size results in an increase in pore size and overall porosity of the mixture. The relationship between flexural strength and porosity of EPC mixtures is shown in Figure 4(b).

Acoustic Absorption Coefficient – Determination, and the Influence of Mixture Proportions. The absorption coefficient (α) is commonly reported (Marlof et al., 2004) as a measure of a material's ability to absorb sound. A material with an absorption coefficient of 1.0 indicates a purely absorbing material whereas a material with an absorption coefficient of 0 indicates that the material is purely reflective. Normal concrete, for example, typically has an absorption coefficient of 0.03-0.05 (Marlof et al., 2004).



(a)

Figure 4. Variation of flexural strength with (a) aggregate sıze, and (b) porosity

The acoustic absorption coefficient of EPC was measured using a Brüel & Kjær™ impedance tube shown in Figure 5 as per ASTM E 1050-98.

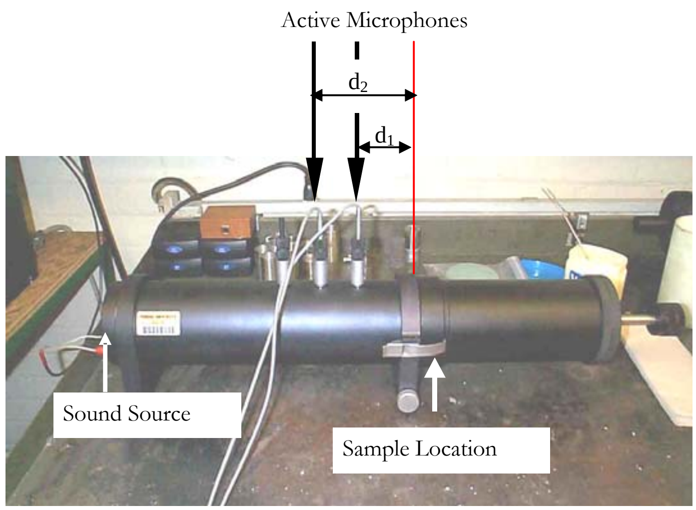


Figure 5. Impedance tube set up to determine the acoustic absorption coefficient

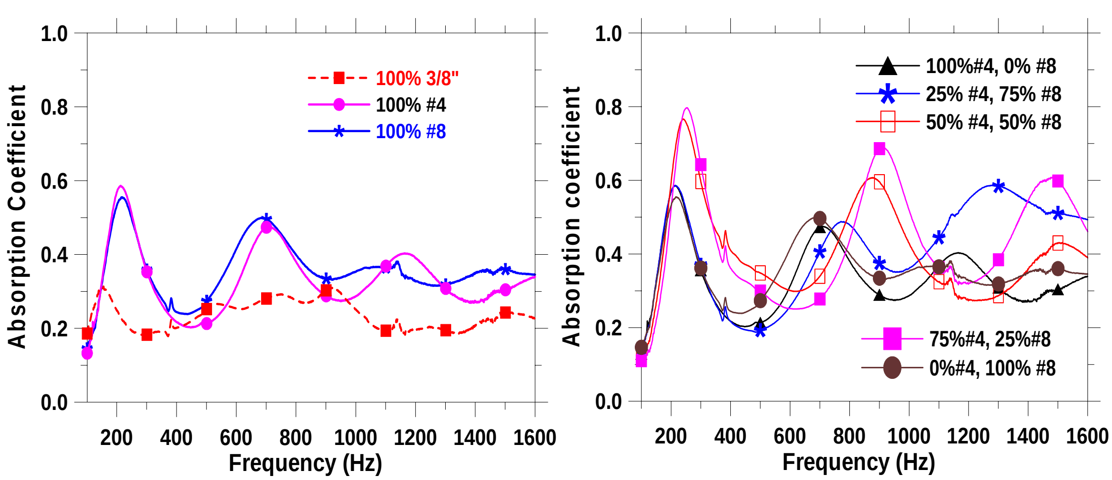
The sample was placed in a thin cylindrical Teflon™ sleeve and the assembly was placed against a rigid backing at one end of the impedance tube. Microphones placed along the length of the tube were used to detect the sound pressure levels (P), which were then translated into the reflection (R) and absorption (α) coefficients, as shown in Equations 1 and 2.

$$R = \frac{e^{jkd_1} - e^{jkd_2} P}{e^{-jkd_2} P - e^{-jkd_1}} \quad (1)$$

$$\alpha = 1 - |R|^2 \quad (2)$$

d_1 and d_2 are the distances from the microphones as shown in Figure 5, and k is the wave number. Further details about measurement and data analysis of these specimens can be found elsewhere (Marolf et al., 2004, Neithalath et al., 2005).

Figure 6(a) depicts the acoustic absorption spectra of EPC with single sized aggregates. The mixture with only 3/8" aggregates has a markedly lower absorption coefficient (~0.30) than the other two single sized aggregate mixtures. This can be explained by the fact that as the aggregate size increases, the pores tend to be larger. The acoustic absorption is a function of total porosity as well as pore constrictions in the system, which increases the frictional losses. EPC with 3/8" aggregates has a higher porosity but low frictional losses due to smaller number of pore constrictions, thus leading to a markedly lower sound absorption. This implies that, finer, but well connected pores may be more efficient in dissipating sound than larger pores. There is no discernible variation observed between mixtures with 100% # 4 and 100% # 8 aggregates (maximum α around 0.60), which is likely due to the existence of similar pore volumes and similar pore geometries in these mixtures. The influence of blending of aggregates on acoustic absorption of EPC is shown in Figure 6(b).



(a) (b)

Figure 6. Acoustic absorption spectra for (a) single sized aggregate mixtures, (b) blended aggregate mixtures

The blends with 75% # 4 (25% # 8) and 50% # 4 (50% # 8) are found to be extremely effective in absorbing sound, with maximum absorption coefficients of approximately 0.80. Replacing larger aggregates (# 4) with smaller size ones (# 8) changes the characteristics of the pore structure. It can be noticed from Figure 3 that the characteristic pore sizes of those blends, which are effective in absorption, are in the same range (approximately 2.5 to 3.5 mm) and are all lower than that for the mixture with the larger size aggregate. For a given porosity, a smaller pore size therefore appears to be more effective in increasing absorption. With further increase in the # 8 fraction (75%), the maximum absorption coefficient tends to approach that of EPC with single sized aggregates.

Influence of Specimen Thickness on Acoustic Absorption. The magnitude of the peak absorption coefficient is dependent on the mixture characteristics, whereas the frequency at which the absorption peaks occur is primarily dependent on the thickness of the specimen. Figure 7 shows the absorption spectra for an EPC mixture with a blend of 75% # 4 and 25% # 8 aggregates. It can be seen that for three specimens, as the thickness changes from 150 mm to 37.5 mm, the absorption spectra shifts as a function of the frequency. It can be shown that this characteristic can be effectively used to arrive at the thickness of specimens (alternatively, the thickness of EPC pavements) so that attenuation of sound in the desired frequency range is obtained.

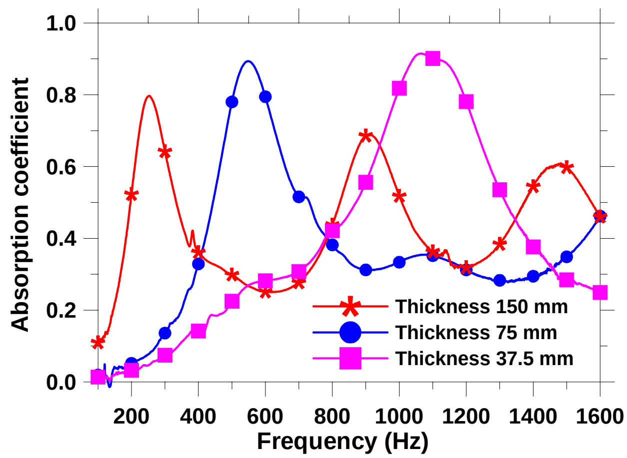


Figure 7. Influence of specimen thickness on frequency at peak absorption

The peaks of acoustic absorption occur at frequencies that can be calculated according to the relationship (Zwikker and Kosten, 1949)

$$f_{peak} = \frac{nc}{4l} \tag{3}$$

where f_{peak} is the frequency at peak absorption, n is an odd integer number corresponding to the peak (1 for 1st peak, 3 for 2nd peak and so on), c is the effective speed of wave in the medium (343 m/s for air at 20^{o}C), and l is the thickness of the sample. For example, 800-1200 Hz is frequency range in which more of the objectionable highway noise falls. Hence, using a frequency of 1000 Hz and speed of sound in air as 343 m/s, the thickness of overlay required (1st absorption peak, hence n=1) can be calculated from Equation 3 as 8.6 cm (3.4 inches).

Transverse Tining as a Surface Texturing Method to Reduce Noise

Transverse tining is the most common texture on high-speed road and highway pavements in North America (ACPA). It is produced by a mechanical device equipped with a tining head (metal rake) that moves laterally across the width of the paved surface. For smaller areas, a hand rake is often used. Optimal dimensions vary from 10 to 40-mm spacing for random tines with no more than 50% above 25 mm, 3-6 mm tine depth, and 3 mm tine width. Skewing of tines has been found to reduce tire-pavement interaction noise.

This section of the paper describes the development and the use of a mathematical model to simulate the influence of tine geometry on noise generation caused by tire-road interaction. The noise was modeled by obtaining a contact stress distribution between the pavement and the tire. The tine shapes considered in this study included square tine, and round-edged tine. Different depths and widths of tines were also modeled to evaluate their influence on pavement noise. Tests on tire-pavement test apparatus are also discussed.

Stress Distribution Modeling. Clapp (1988) developed a model to approximate tire-pavement interaction using a two dimensional contact theory. In this model (Figure 8), a rigid material is used to represent the pavement while a semi-infinite elastic half plane is used to represent the tire.

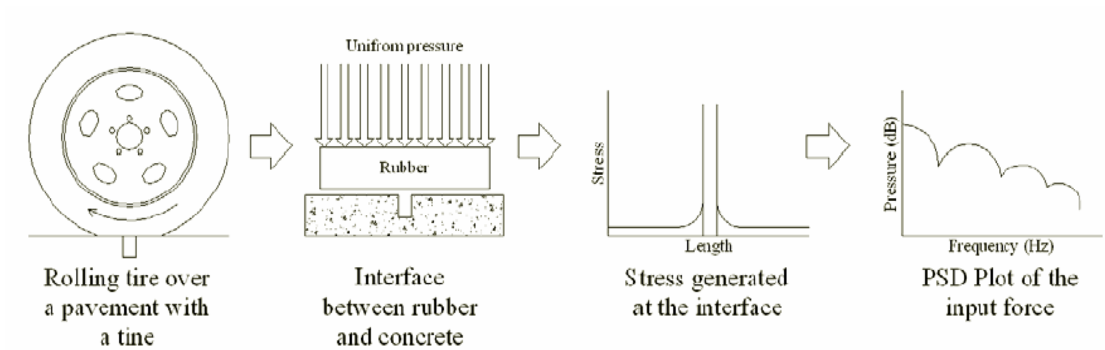


Figure 8. Relating interfacial stress and noise

A uniformly distributed load is applied to the rubber to force contact with the pavement. The pressure distributions associated with the individual contact areas produce forces that excite the tire structure. The mathematical model can predict the contact stress distribution between a hard pavement surface and the tire. The contact pressure fields can be transformed into a time-varying pressure by dividing the contact patch length by the vehicle speed to obtain a sampling frequency. At each point in the contact patch, there is pressure acting on the tire; a Fourier transformation can be applied using a previously determined sampling frequency to generate a power density spectrum to identify the frequency content of the stress distribution. The greater the pressures at the tire-pavement interface, the louder the noise generated. The factors affecting the tire-pavement noise generation mechanisms, and the transformations required to be carried out in order to obtain the power spectrum density (PSD) from contact stresses are explained elsewhere (Garcia, 2003).

The stress distribution model is used to describe the stress and ultimately noise, generated by various geometries of tining patterns. Modeling of these surfaces will help understand the implications of varying size, shape, and depth of tines on stress generated. A stress distribution was obtained for each parameter and was related to the noise that the tire will emit while running over the surfaces.

Influence of Tine Width. The tine width was varied to assess its influence on stress generation. Tine width varied between 0.2 mm and 6 mm in 0.2 mm increments, for a uniform depth of 10 mm. The observed variation in the peak stress levels shown in Figure 9 is due to the precision of the iterative process in load computation that was set to 5%; had the precision been set to a smaller value, the data points would have converged to the trend line. Due to the considerable amount of computational time needed to obtain the exact values the peak stress, the values of stress corresponding to the trend line were used in the simulation to obtain the noise levels. In general, it can be observed that, the peak stresses tend to decrease as the tine width increases.

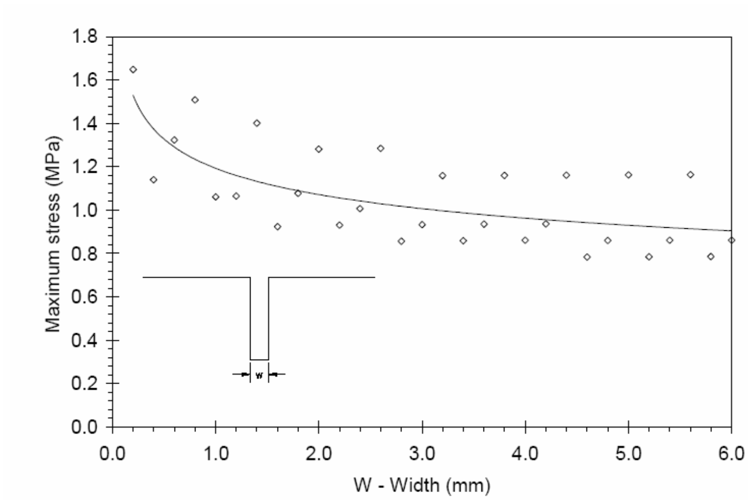
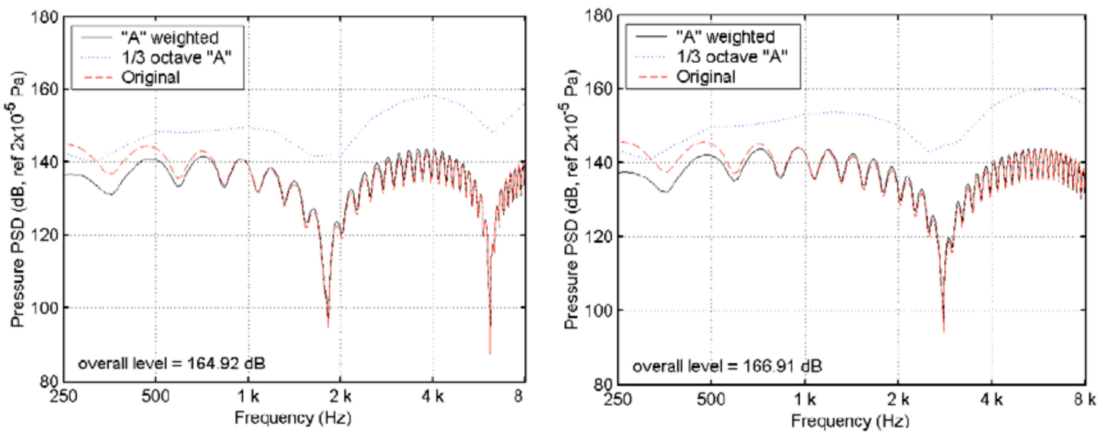


Figure 9. Influence of tine width on stress generated (10 mm deep tine)

The power density spectrum for a 3 mm wide, 10 mm deep tine is shown in Figure 10(a); the solid line is the power spectrum after "A" weighting, the dashed line is the power spectrum before "A" weighting, and the dotted line (topmost) is the power spectrum after applying a 1/3 octave filter. As indicated by the power spectrum, the intensity of the pressure has a tendency to fluctuate at a value of 150 dB for frequencies below 2 kHz. After this, frequency modulation waves are more predominant giving a higher pressure of 160 dB. The overall band level for this tine is 164.91 dB. As the width of the tine changes, the PSD shifts the frequency at which the main pressure is located. Figure 10(b) shows the PSD of a tine with a 2 mm width and 10 mm depth. Comparing Figure 10(a) and Figure 10(b), it can be seen that there is an increment of 2 to 3 dB at pressure levels below 2 kHz for the 2 mm wide tine. There is also some shifting in the modulation of the main events due to the width of the tine.



(a) (b)

Figure 10. Variation of PSD with frequency at 13.41 m/s for a 10 mm deep tine (a) tine width 3 mm, (b) tine width 2 mm

Influence of tine depth. The tine depth was varied to assess its influence on the surface stress generation. The penetration of the rubber into the tine was also computed. The variation of tine depth was investigated for a 3 mm width. The depth was varied from 0 mm to 1 mm in increments of 0.1 mm. The influence of depth on stress generation is shown in Figure 11. The peak stress reaches a maximum level of 1 MPa at a certain depth.

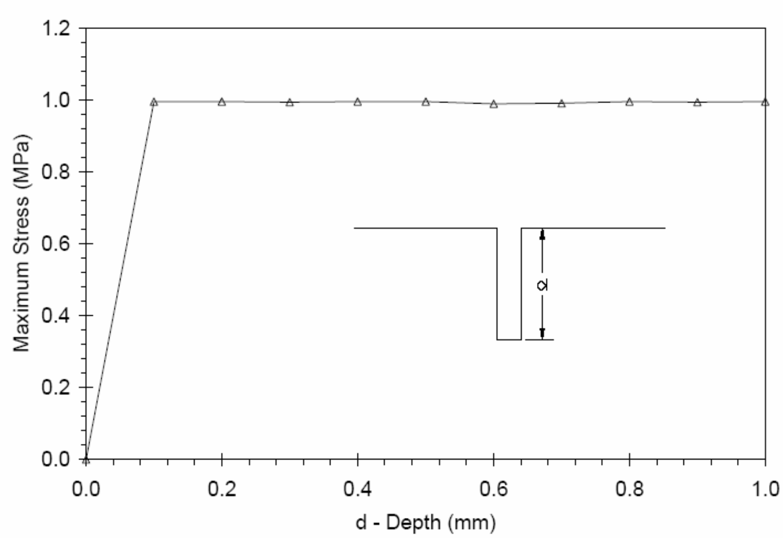


Figure 11. Influence of tine depth on stress generated

The power density spectrum for a 3 mm wide and 0.5 mm deep square tine is shown in Figure 12; the black solid line represents the power spectrum after "A" weighting, the dashed red line represents the power spectrum before "A" weighting, and the solid blue line represents the power spectrum after applying a 1/3 octave filter. This power density spectrum is similar to the one obtained for a 10 mm deep tine, because of the similar magnitude of the main contact stresses. The intensity of the pressure has a tendency to fluctuate at about 152 dB for frequencies below 2 kHz. After that, the frequency modulation waves are more predominant giving a higher pressure of 159 dB. The overall band level for this tine is 166.47 dB; this value is almost the same as the one obtained for 10 mm deep tine. The difference in the overall band level and in the levels on the spectrum is due to the change in the peak stress level from 0.93 MPa for the 10 mm deep tine to 0.99 MPa for the 0.5 mm deep tine. The difference in stress level may also be related to the precision of the iterative process that was set to 5%.

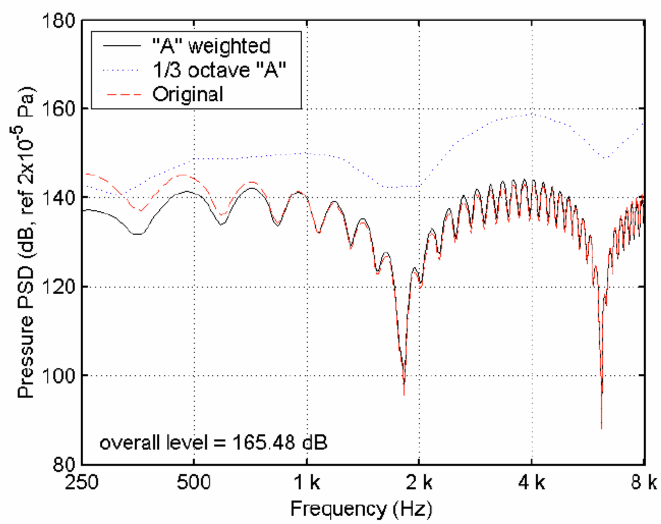
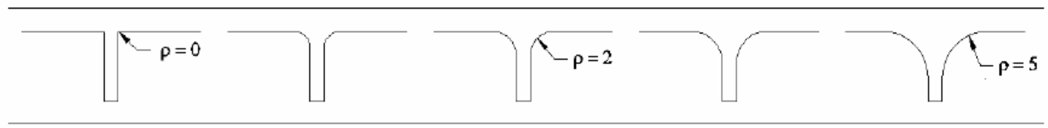


Figure 12. Variation of PSD with frequency at 13.41 m/s for a 0.5 mm deep, 3 mm wide tine

Influence of Rounding the Edges of the Tine. The edges of the tines were rounded to investigate how removing the sharp edge affects the stress concentration. The implementation of the rounded edges was done gradually to analyze at which point curvature is optimal. The modeling started with a standard rectangular tine and then quarter circles were introduced in the edges. The variation of the circle geometry was done by changing the radius, starting from 0.0 mm radius (square edge), and incrementing 0.1 mm each time to the maximum value equal to the depth of the tine (10.0 mm). Figure 13 shows how the geometry variation was implemented.

The simulations for rounded tines were performed at tine widths of 2, 3, 4, and 5 mm. The results of the analysis are displayed in Figure 14. The peak stress at the



tine does not appear to be influenced significantly by the width of the tine after a radius of 1.7 mm. The peak stress reaches a constant value of approximately 0.15 MPa after the radius reached 6 mm.

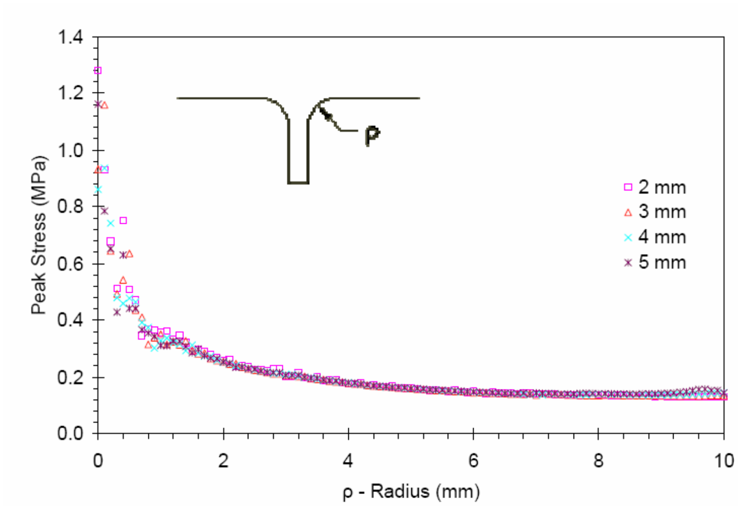
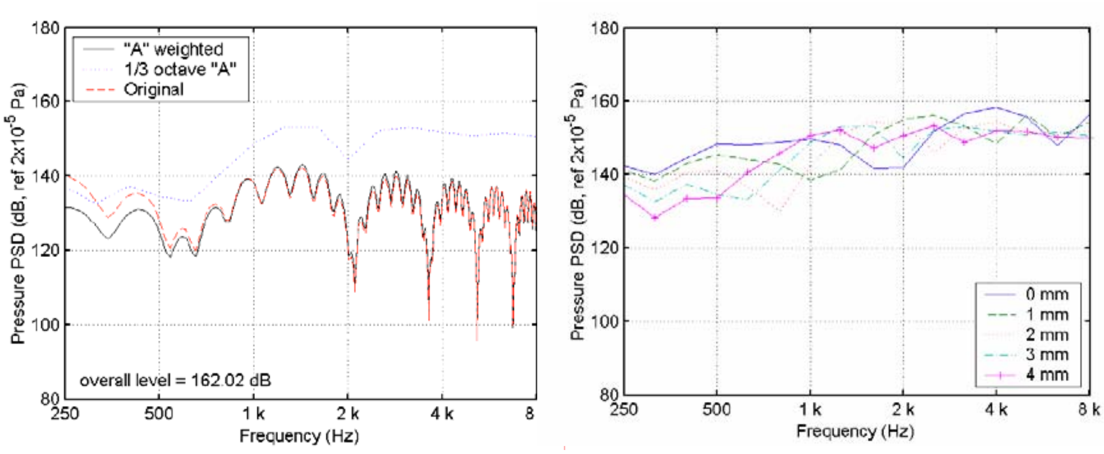


Figure 14. Variation of peak stress with radius of the rounded edge for different tine widths

The PSD plot of the rounded edge tines is shown in Figure 15(a). Comparing this spectrum to the one obtained for the square tine (Figure 10(a)), it can be seen that there is a considerable reduction in the pressure on the tire rubber at frequencies between 250 Hz and 1 kHz (drop from 150 to 135 dBA). It can be concluded that this decrease is due to the rounding of the edges of the tine. In addition, a decrease in the size of the wave modulation (from 4000 to 1800 Hz) was observed, due to the increment in the distance between the centers of the two primary stress concentrations that were shifted by the rounding of the edges. The overall noise level was reduced from 164.91 dB for the square tine to 162.02 dB for the rounded edge tine.

Figure 15(b) shows a comparison between the PSD spectra for tines with rounded edges for radius of 0, 1, 2, 3, and 4 mm. The tine with 0 mm radius can be interpreted as a square tine. As it is shown, a variation on the edge radius changes the location of the main stress concentrations resulting in a change on the modulation frequency.



(a) (b)

Figure 15. (a)Variation of PSD with frequency at 13.41 m/s for a time 3 mm wide, 10 mm deep, with 3 mm radius of rounded edges, (b) Comparison between PSD spectra for tines with different radii of edges

Using the Tire-Pavement Test Apparatus to Investigate the Influence of Time Geometry. Experimental studies were conducted on the Tire-Pavement Test Apparatus at Purdue University (Figure 16) to assess the influence of the modeled parameters on the actual pavement surface.

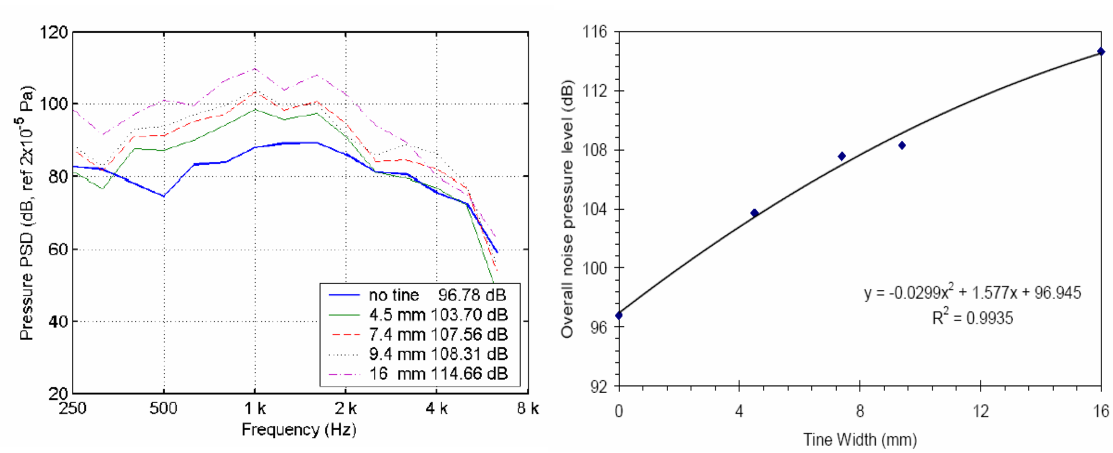
Figure 16. TPTA with the test specimens and tire mounted

The TPTA consists of a stationary drum 3.7 m in diameter. The pavement sections are placed on the circumference of the TPTA. The construction and operational details of this apparatus could be found elsewhere (Garcia, 2003, Bernhard et al., 2003). The TPTA has the ability to run at constant speed ranging from 0 to 50 km/h measured at the interface between the tire and the pavement.

The TPTA is equipped with a Bruel & Kjaer PULSE Noise and Vibration Analysis Type 7700 system that uses wireless technology. The five microphone array used in TPTA was set up in such a way that three of the microphones satisfy the requirements of the Close Proximity Method (CPX) draft standard (ISO/CD 11819-2). Two other microphones were placed 5 cm above the pavement surface and away from the tire surface. Only one of these five microphones (lead microphone located 5 cm above the pavement surface) was used to collect data in this study. The other four microphones were not used in this study.

Only the testing concerning the influence of tine width is presented in this section. It was found that the tine shape (radius of the rounded edge) does not have an influence on the noise generation characteristics, corroborating the observations from Figure 14, where the model predicted no changes in peak stress levels with changing radius of the rounded edge.

The tines were spaced 25 mm apart in the pavement section. The PSD was obtained for such a small section of the sample by performing a FFT to the time-pressure history. Figure 17(a) shows the PSD plot for ground tines with different widths. It can be seen that higher pressure level is associated with wider tines. The overall pressure levels for the different width are presented in the textbox. The tine width was progressively increased without modifying any of the data acquisition settings. Figure 17(b) shows a relationship between the overall pressure level and the width of the tine. This observation is in contrast with the stress modeling results, shown in Figure 9.



(a) (b)

Figure 17. (a) Variation of PSD with frequency for different tine widths, (b) Relationship between the overall noise level and width of the tine

The possible reasons for this discrepancy could be (i) inherent variations in the contact force input to the model and the actual force on the TPTA, (ii) variations in transformations from contact stresses to pressure spectrum, or (iii) differences in time-averaging (does not consider background noises) and frequency averaging (considers background effects like wind noise – more realistic) to arrive at the PSD.

Conclusions

The major conclusions arrived at from this study are summarized as follows:

Enhanced Porosity Concrete:

- Pore size, along with porosity, is instrumental in determining the acoustic characteristic of EPC. Blending aggregates of different sizes typically results in a higher porosity as compared to the mixtures made using single sized aggregates.
- The blended aggregate system resulted in an increased acoustic absorption in most cases. Blending of aggregates, especially # 4 and # 8, is found to more effective than single sized aggregates.
- An increase in aggregate size results in a reduction in the flexural strength of EPC, due to the increased total porosity and pore size.
- The frequency at the peak absorption is related to the thickness of the specimen. A procedure is provided to calculate the optimal specimen thickness once the optimal frequency range is known.

Transverse tining:

- The peak stresses predicted by the contact stress distribution model decreases with increasing width of the transverse tine. However, testing of tined concrete sections in TPTA showed the opposite. The sound pressure level increases with increasing tine width in the TPTA tested specimens.
- Tine depth has no influence on the contact stresses generated. From the model prediction, it could therefore be inferred that the transverse tine depth should be dictated by friction and drainage requirements. But the experimental studies showed that noise generation is dependent on tine depth. More studies are needed in this regard.
- The radius of the rounded edge also has no influence on the noise generated, as predicted by the model.

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