Analysis of the impact of pavement surface mixture on traffic noise and related public health

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16. Abstract

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1 Introduction

Noise is a harmful environmental pollutant and has negative impacts on public health such as annoyance, sleep disturbance, and learning impairment (*1*, *2*). Road traffic noise is one of major sources of environmental noise, particularly in areas with high population density near or along highways or streets (*3*, *4*).

Road traffic noise mainly arises from three sources: vehicle engine and exhaust noises, aerodynamic noise, and noise generated at the interface of tire and pavement surface ("tire-pavement noise"). The tire-pavement noise becomes more dominant when vehicle speed increases (*5*). With the rapid market penetration of electric vehicles, which have an electric motor instead of an internal combustion engine and therefore produce little motor and no exhaust noise, the share of tire-pavement noise in the road traffic noise is expected to further increase. Reducing the tire-pavement noise, therefore, may have significant bearing on health promotion for the public. In recent years, there has been a body of research in the pavement community that investigated the impact of pavement type and surface conditions on the tire-pavement noise (*6*–*8*). There are also recommendations on the design of pavement surface mixtures to improve the acoustic performance of pavements. For example, it is generally agreed upon that placing a thin layer of porous asphalt mixture at the pavement surface may result in so-called "quiet pavement" (*5*). Research efforts have been continued to evaluate the relationship between various design parameters and acoustic performance of asphalt mixtures and to suggest modifications to their designs for an optimal balance among acoustic performance, permeability, durability, and other desirable pavement surface properties (*9*–*13*). Meanwhile, pavement construction consumes large quantities of nonrenewable resources such as good-quality natural aggregates, whose excavation and processing have not only consumed large amount of energy but also generated negative environmental impact. Replacing virgin aggregates with renewable or waste materials, such as recycled concrete aggregate, slag, reclaimed asphalt pavement, seashell, and other alternatives, has become a major interest and practice in the pavement community (*14–17*).

In the documented research efforts, on one hand, the impact of pavement surface mixture on road traffic noise was mainly evaluated by (1) direct measurement of the noise in the field either near the tire-pavement interface or at the roadside, (2) indirect characterization through the measurement of mixture acoustic properties (e.g., sound absorption coefficient) in the laboratory. The impact of pavement surface design on the road traffic noise perceived by the public and their health, however, has not been commonly considered in the evaluation and design of pavement surface mixtures. On the other hand, during the development of noise-reducing asphalt mixtures, other goals, such as sustainable or green development, also deserve imperative considerations.

The main objective of this study is to analyze the impact of pavement surface mixture design on the noise originated at the tire-pavement interface and perceived by the public and their health, and to develop and evaluate porous asphalt mixtures that incorporate renewable materials (i.e., seashell) to partially replace non-renewable natural aggregates. The specific tasks include: (1) performing a literature review on pavement surface mixture designs for noise reduction, road traffic noise models and tools, and relationship between road traffic noise and public health; (2) analyzing the relationship between pavement surface mixture designs and traffic noise perceived by the public and their health outcome; (3) developing and evaluating porous asphalt mixtures containing renewable seashell materials; (4) providing recommendations on pavement surface mixture designs for mitigating noise impact on public health.

The remainder of the report is structured as follows. A review of the literature on asphalt mixture designs for noise reduction and modeling of mixture acoustic performance, traffic noise models, relationship between traffic noise exposure and public health, and the use of seashell in pavement is summarized in Section 2. The methods for correlating asphalt mixture design to public health and evaluating the performance of porous asphalt mixtures containing seashell are described in Section 3. Section 4 presents analysis results and discussions. Finally, the conclusions and recommendations are provided in Section 5.

2 Literature review

To explore the relationship between pavement surface mixture design and noise perceived by the public and their health, the noise discussed in this study is limited to the tire-pavement noise, while other source noises (e.g., aerodynamic, engine and exhaust noises) are out of scope. Three aspects of literature were reviewed in relating mixture design to perceived noise and public health: pavement surface mixture designs for lower tire-pavement noise and measurement/prediction of tire-pavement noise, road traffic noise models, relationship between traffic noise and its impact on the public health. The use of seashell in pavement and other engineering applications is also reviewed in this section.

2.1 Design and acoustic performance characterization of pavement surface mixtures

It has been recognized that pavements associated with lower tire-pavement noise generally have the following features in the surface material: small and negative surface texture, high air-void content (or porosity), and low stiffness (*5*). Since asphalt concrete surface is generally quieter than portland cement concrete surface and the majority of paved roads in the U.S. have asphalt concrete surface, this review focuses on asphalt mixtures used for the pavement surface, and in particular, porous asphalt mixtures.

The most commonly used mixture type for asphalt pavement surface is dense-graded asphalt concrete (DGAC), which features a low air-void content (about 4-8%) and an aggregate gradation that optimizes the mixture density. This type of mixture, however, does not have significant acoustic benefit in contrast to open- or gap-graded asphalt mixtures (*5*). There have been some efforts to modify DGAC designs for better acoustic performance while still maintaining its mechanical durability. One product from such efforts is semi-dense asphalt concrete, which has an air-void content of 12-16% and has been used in some European countries such as Switzerland (*18*).

Asphalt mixtures of gap aggregate gradation are often quieter than DGAC due to their favorable surface texture, and the use of smaller maximum aggregate sizes often leads to a further lower tire-pavement noise (*19*). Examples of this type of mixture include ultra-thin wearing course (UTWC) mixture (*20*), stone mastic asphalt (SMA)(*19*, *21*), and thin overlay mixture (TOM) (*13*). Gap-graded asphalt concrete, however, often has a low air-void content that is comparable to that of DGAC. Its noise reduction capability, therefore, is generally lower than that of open-graded asphalt concrete (OGAC) (or porous asphalt concrete [PAC]) of a similar maximum aggregate size (*10*).

Both field observations and laboratory tests have shown that pavement surfaces constructed with OGAC generally have a lower tire-pavement noise than pavements of dense- or gap-graded surfaces (*22*, *23*). OGAC or PAC features a high air-void content, typically in the range of 18-26% (*24*). The high porosity has limited the service life of OGAC to a short duration (7-10 years) (*23*), but research has shown that a combination of strategies such as reducing the maximum aggregate size and using modified asphalt binder (e.g., asphalt rubber, epoxy asphalt) may significantly improve it (*22*, *25*).

To characterize the acoustic performance of a mixture, the most common approach is noise measurement, either directly in the field on or near a pavement surface, or indirectly in the laboratory on compacted mixture specimens.

Field measurement methods include wayside measurements and source measurements (*26*). Wayside measurements are done at the side of a road with microphones set at a fixed distance from the road or at the location of receivers to record the traffic noise. Depending on the volume of traffic and knowledge of vehicle type, speed, and tire type, wayside measurements can be classified into three types: statistical pass-by (SPB), controlled pass-by (CPB), and continuous flow traffic time-integrated model (CTIM). The maximum sound levels (L_{max}) of individual vehicles are measured in SPB and CPB while an average equivalent sound level (L_{eq}) is calculated in CTIM. The source measurements in the field are performed near the tire-pavement interface to record the tire-pavement noise. There are two techniques for source measurements: on-board sound intensity (OBSI) and close-proximity (CPX). The OBSI uses two microphones positioned near the interface of a standard reference test tire (SRTT) and a pavement surface to measure sound intensity while the CPX uses one microphone near the tire-pavement interface to measure sound pressure (*26*). Typically, the CPX test is done in an enclosed trailer while the OBSI test is not.

Laboratory measurements characterize the mixture properties that affect tire-pavement noise, mainly including acoustic absorption, macrotexture, and air-void content (i.e., porosity) of compacted mixture specimens. Acoustic absorption is commonly measured on a cylindrical specimen placed in an impedance tube according to ASTM E 1050 (*27*). Macrotexture can be measured using a sand patch method (ASTM E 965) (*28*) or laser-based height sensors. Air-void content is calculated from the bulk specific gravity and the theoretical maximum specific gravity of a compacted specimen.

Empirical (statistical) models have been developed in various studies to correlate measured noise to mixture parameters (e.g., mixture type, modulus, binder type, aggregate gradation, macrotexture) using field measurements of noise on in-service pavements or test sections of pavements (*23*). The applicability of the models, however, is limited to various extents to the conditions under which the data used for training the models were collected. There have also been some efforts to correlate noise measurements to mixture acoustic absorption (*29*) and to develop semi-empirical models to predict acoustic absorption from mixture design parameters (*9*, *10*).

Based on the literature review, it is determined that this study will focus on the design and evaluation of open-graded or porous asphalt mixtures.

2.2 Road traffic noise models

The work related to the estimation of traffic noise level got momentum since the time when authorities started recognizing the impact of environmental noise on the public and emphasized to develop regulations to control the impact. The European Union released a series of directives in these regards, which recommended preparation of noise maps around major sources of transportation noises (*30*). The process of developing tools to predict traffic noise started long before that. In 1975, Japan published its ASJ Model 1975 that could predict sound pressure level coming from traffic noise sources. The Federal Highway Administration (FHWA) in the U.S. published a report in 1978 that proposed a method for predicting noise generated by road traffic moving at a constant speed (*31*). Since then, several road traffic noise models and tools have been developed by the governmental agencies around the world. Some commonly used models are summarized as follows.

In the U.S., the FHWA Traffic Noise Model (TNM®) is required to be used on all highway projects that receive federal funding (*32*). The TNM applies several adjustments to a reference noise level, which is the maximum A-weighted sound level emitted by a vehicle pass-by and recorded at a distance of 15 m from the vehicle and a height of 1.5 m over flat, generally absorptive terrain. This reference noise level, called a vehicle's noise-emission level (EL), is a function of the vehicle type and speed, engine throttle status, roadway slope, and pavement type. The adjusted noise level is defined as in Equation (1).

$$L_{Aeq,1h} = EL_i + A_{traff(i)} + A_d + A_s \tag{1}$$

where, $L_{Aeq,1h}$ is hourly equivalent A-weighted sound pressure level (dBA); EL_i is the vehicle noise emission level for the ith vehicle type; $A_{traff(i)}$ denotes the adjustment for the volume and speed for the ith vehicle type; A_d is the adjustment for distance between the roadway and receiver and for the roadway segment length; and A_s represents the adjustment for ground and shielding effects between the source and the receiver (*32*).

In the United Kingdom, the CoRTN model was developed to predict road traffic noise (*33*). This model first predicts a reference noise level L_0 using Equation (2), which is basic hourly noise level L_{10} at a reference distance of 10 m from the nearest roadway, in terms of hourly flow of traffic. A reference traffic speed of 75 km/h is assumed while estimating L_0. Then the model also applies a series of adjustments to predict the hourly A-weighted sound pressure level ($L_{A10,1h}$) by Equation (3).

$$L_0 = 42.2 + 10Log_{10}q \quad dB(A) \tag{2}$$

$$L_{A10,1h} = L_0 + \Delta_f + \Delta_g + \Delta_p + \Delta_d + \Delta_s + \Delta_a + \Delta_r \tag{3}$$

where, q is the hourly traffic flow, and $\Delta_{f,}$ $\Delta_g, \Delta_{p,}\Delta_d, \Delta_s, \Delta_a, \Delta_r$ are adjustments for traffic flow, gradient, pavement type, distance, shielding, angle of view, and reflection, respectively.

In Germany, the RLS90 model is used (*34*). It uses a reference distance of 25 m from the center of the lane. It first predicts the A-weighted mean noise level, L_{mE}, as a function of hourly vehicle flow Q and the percentage of heavy vehicle in the traffic stream p, as shown in Equation (4), for a reference condition (i.e., traffic speed is 100 km/h; road gradient is below 5%; and the road surface follows a special specification).

$$L_{mE} = 37.3 + 10\ Log\{Q(1 + 0.082p)\} \tag{4}$$

The model then applies a series of corrections to the reference noise level by Equation (5).

$$L_m = L_{mE} + R_{SL} + R_{RS} + R_{RF} + R_E + R_{DA} + R_{GA} + R_{TB} \tag{5}$$

where, R_{SL}, R_{RS}, R_{RF}, R_E, R_{GA}, R_{TB}, R_{DA} are adjustments for speed limit, road surface types, unevenness of the road surface, absorption by the building surfaces, ground and atmospheric conditions, topography and building dimensions, and distance from the receiver and air absorption, respectively (*35*).

The ASJ RTN-Model used in Japan divides the vehicles in traffic stream in two or four different categories (*36*). The model estimates the A-weighted noise level of a vehicle by Equation (6).

$$L_{WA} = a + b\log(V) + C \tag{6}$$

where, L_{WA} is the sound power level (dB), *V* is the vehicle speed (km/h), a and b are regression coefficients that depend on the vehicle type and flow condition. The term C accounts for a series of correction factors for any deviation from reference conditions, including road gradient, pavement surface type, sound radiation directivity, and all other factors. The model takes a wide range of conditions into account and provides methodology to predict noise level propagation if those conditions arise (*37*).

The SonRoad model developed in Switzerland has separate formulae for passenger cars and trucks to predict the A-weighted maximum noise level for a pass-by vehicle (*38*)(*39*).

As a result of EU directive on assessment and management of environmental noise, the Harmonoise model was developed for use by member states (*40*). This model categorizes the vehicles in three classes (light, medium, and heavy vehicle) and considers two point sources of noise (0.01 m and 0.3 m above the ground). Each point has specific sound level consisting of noise produced by powertrain or tire-road friction (*41*). The rolling noise is estimated by Equation (7).

$$L_{WR}(f) = a_R(f) + b_R(f)\log\left(\frac{v}{v_{ref}}\right) \tag{7}$$

where, v_{ref} is reference speed of 70 km/h; a_R, b_R are coefficients in 1/3rd octave bands; f is frequency in Hz; v is vehicle speed in km/h.

The Nord2000 model developed for Scandinavian also predicts the noise level by applying a number of adjustments to a reference noise level, as shown in Equation (8).

$$L_R = L_w + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r \quad (8)$$

where, L_w is sound power level within the considered frequency band and in an assumed reference roadway and terrain condition; ΔL_d, ΔL_a, ΔL_t, ΔL_s, ΔL_r are corrections for propagation effect for sound divergence, air absorption effect, terrain type, propagation effect of the scattering zones, and obstacle effect, respectively (*42*). More details can be found in references (*43*), (*44*), and (*45*).

The NPMB model was the first noise prediction method introduced in France in 1996. Later this model was chosen by 11 other European countries. This model estimates the A-weighted sound pressure level at a distance from the source and in a particular propagation condition, $L_{A,C}$, using Equation (9):

$$L_{A,C} = L_w - \left(A_{dlv} + A_{atm} + A_{bnd,C}\right) \quad (9)$$

where, L_w is sound power level of the source; A_{dlv} is geometrical spreading; A_{atm} is atmospheric absorption; $A_{bnd,C}$ is the attenuation factor accounting for boundary condition and speed profile. The specialty of NPMB model is that it was designed to take meteorological conditions into account. Similar to standard engineering models like ISO 9613-2, it breaks down the noise source into elementary ones and considers a set of propagation paths between the source and the receiver at a certain meteorological condition. The long-term noise level at the receiver is obtained by the energetic summation of noise level for all probable meteorological conditions. References (*43*), (*46*), (*47*) provide detailed description of this model.

Apart from the models listed above, a few other models are also widely used in different regions. For example, the Common Noise Assessment Methods for the EU Member States (CNOSSOS) used in Europe, the Traffic Noise Exposure (TRANEX) used in the UK, and the Burgess model used in Australia are a few to mention.

It can be seen that most models follow a similar approach to predict the vehicle noise level perceived by the public: first estimating the noise level under a reference condition, then applying a series of correction factors to account for various deviations from the reference condition. There is also a trend in later or newer versions of the models: they are moving from empirical equations to equations integrating more scientific principles along with application of numerical techniques (*43*). It is, however, difficult to delineate the pros and cons of different models since they were calibrated and validated in different regions (*42*). Variations in the conditions of different regions would lead to site bias in model predictions (*42*, *48*, *49*). This makes the model suitable for only the region it was developed and validated.

2.3 Relationship between traffic noise and public health

Exposure to traffic noise or overall environmental noise and its impact on public health has been widely studied in the field of public health. A literature review shows that a wide range of physiological and psychological health issues have been found to be related to noise exposure.

Among them, sleep disturbance and annoyance are the most negative outcomes of transportation noises. Studies relating these health issues to traffic noise were mainly carried out by statistical analysis approaches, using survey data on health issues collected from the public and noise data measured from the field, calculated using noise models, or estimated from surrogate variables (e.g., traffic volume). The survey data often included other relevant information of the survey respondents such as socioeconomic factors, and there are discussions in the literature pointing out that the studies in this field still should look deeply into the non-acoustical factors that may affect the public health while conducting the analyses (*50*, *51*). Sometimes factors other than noise exposure may play a significant role in affecting the health of the survey respondents. For the interest of this study, the quantitative relationships between road traffic noise and public health measures, as estimated in various studies in the literature, are reviewed and summarized as follows.

In a study conducted in the Republic of Korea (*2*), the impact of road traffic noise on sleep disturbance and annoyance was evaluated in terms of the percentages of highly-annoyed people (%HA) and highly sleep-disturbed people (%HSD) based on two empirical equations (10) and (11).

$$\%HA = 9.994 \times 10^{-4}(L_{DN} - 42)^3 - 1.523 \times 10^{-2}(L_{DN} - 42)^2 + 0.538(L_{DN} - 42) \quad (10)$$

$$\%HSD = 20.8 - 1.05L_N + 0.01486L_N^2 \quad (11)$$

where L_{DN} is day-night road traffic noise level and L_N is nighttime level of road traffic noise. The day-night noise level may be estimated from daytime and nighttime noise levels by Equation (12) (*2*).

$$L_{DN} = 10\log\left(\frac{15}{24} \times 10^{\frac{L_D}{10}} + \frac{9}{24} \times 10^{\frac{L_N+10}{10}}\right) \quad (12)$$

where L_D is daytime noise level.

In a study conducted in Norway (*52*), structural equation models were applied to explore the relationship between road traffic noise and sleep and health problems, and it was found that there is a significant relationship between nighttime noise and nighttime sleep disturbance. The standardized regression weight for the relationship between the nighttime equivalent noise level and nighttime sleep disturbance was estimated to be 0.24.

The correlation between road traffic noise and sleep disturbance was also found to be statistically significant explored among children of 7-14 years old in a study performed in Poland (*53*). The study used traffic density as a surrogate index of traffic noise level and estimated an odds ratio of 1.44 (95% confidence interval [CI] of 1.05 to 1.97) when the traffic density within 100 m radius of the place of residence is greater than 90th percentile of traffic densities.

In a study conducted in Sweden (*51*), the impact of road traffic noise on hypertension was analyzed with a logistic regression model on survey data of self-reported hypertension and noise exposure estimated from a Nordic noise propagation model. It was found that for every 5 dBA increase in the road traffic noise in terms of annual mean 24-h equivalent noise level (L_{Aeq24h}), the odds ratio of hypertension was 1.38 (95% CI of 1.06 to 1.80).

In a hospital-based case-control study in the city of Berlin (*54*), it was found that long-term (over 10 years) exposure to high levels of traffic noise would increase the risk of cardiovascular diseases such as myocardial infarction. In particular, the odds ratio of having myocardial infarction in men is 1.13 (95% CI of 0.86 to 1.49) when the traffic noise level, in terms of 12-month average A-weighted sound pressure level, is between 66 and 70 dBA and 1.27 (95% CI of 0.88 to 1.84) when the traffic noise level is greater than 70 dBA. Among women, there was no apparent risk (*54*).

In a large European research project on the relationship between environmental noise and hypertension (high blood pressure) and annoyance, 4861 people of ages between 45 and 70 years living near six European airports were surveyed (*55*). The road traffic noise was estimated from national noise calculation models. Multiple logistic and linear regression models were applied to explore the relationship between road traffic noise and hypertension and annoyance, respectively, and the effects of exposure modifying factors on this relationship. For hypertension, it was found that for every 10 dBA increase in the road traffic noise in terms of L_{Aeq24h}, the odds ratio of hypertension was 1.10 (95% CI of 1.01 to 1.21). For noise annoyance, which was assessed on an 11-point scale from 0 (lowest) to 10 (highest), multiple regression models showed that for every 10 dBA increase in the road traffic noise in terms of L_{Aeq24h}, the increase in noise annoyance is 1.58 (95% CI of 1.46 to 1.69).

A Switzerland study assessed the relationship between traffic noise and blood pressure based on a study sample of 6450 people of ages between 28 and 72 years (*56*). It was found that traffic noise was associated with higher blood pressure only in vulnerable populations (diabetics), possible due to low exposure levels. Among people with diabetes, for every 10 dBA increase in the traffic noise, the increase in the systolic blood pressure (SBP) is 5.2 (95 CI of -0.08 to 10.50 for nighttime and 1.35 to 10.25 for daytime).

A Germany study examined the association between environmental noise annoyance and mental health in adults using national survey data with 19,294 respondents (*57*). Noise annoyance was subjectively assessed at several discrete levels including “not at all”, “slightly”, “moderately”, and “highly”. The results demonstrated an association between high noise annoyance and impaired mental health. When the road traffic noise annoyance increased from “not at all” to “highly annoyed”, the odds ratio of impaired mental health was 1.49 (95% CI of 1.07 to 2.07) in women and 2.10 (95% CI of 1.47 to 3.01) in men.

A systematic review and analysis of data collected from the literature on the relationship between traffic noise and the risk of stroke found that the effect of road traffic noise on the stroke risk is nonlinear (*58*). For every 10 dB increase in the traffic noise, the relative risk of stroke was 1.01 (95% CI of 0.96 to 1.06) when the noise level was less than 55 dB, but increased to 1.29 (95% CI of 0.74 to 2.24) when the road traffic noise was in the range of 70 – 75 dB.

In a Switzerland study with 3796 participants, it was found that long-term exposure to road traffic noise may increase the risk of obesity (*59*). For every 10 dB increase in the 5-year mean traffic noise, the relative risk of obesity was 1.25 (95% CI of 1.04 to 1.51). In a Sweden study with 5075 participants (*60*), it was also found that road traffic noise exposure can increase the risk of obesity. For every 5 dBA increase in the day-evening-night noise level (L_{den}) from road traffic, the change in waist circumference was 0.21 cm (95% CI of 0.01 to 0.41). The odds ratio for central obesity was 1.18 (95% CI of 1.03 to 1.34) among people exposed to road traffic noise greater than 45 dBA in comparison to those exposed below this level.

As the above literature review shows, most studies used some measures of the overall noise level and related them to health issues, and in their results the impacts of noise are often expressed in terms of every 5 or 10 dBA increment of the noise level. There is a lack of studies and results in the literature regarding the correlation between health issues and traffic noise at various frequencies. This study, therefore, will only estimate the overall noise level from asphalt mixture designs and correlate it to health measures.

2.4 Use of seashell in pavement

Aggregate and asphalt binder are two major constituents of asphalt mixture and generally aggregate accounts for about 90% of the mixture mass. Therefore, aggregate properties and size distribution play an important role in the performance of asphalt pavements. To ensure a high porosity in OGAC or PAC, these mixtures have a higher percent of coarse aggregates (aggregates retained on 4.75 or 2.36 mm sieve) than DGAC.

Natural aggregate is the largest source of materials in building and pavement construction. For example, the U.S. produces two billion tons of aggregates annually (*61*). In recent decades, due to the depletion of many good aggregate sources and increased negative environmental impact from the processing of natural aggregates, many studies have considered the replacement of virgin aggregates in pavements by alternative materials that are industrial byproducts, waste, or renewable (*14–16*, *62*, *63*). Cost reduction is another major benefit from replacement of natural aggregates in asphalt mixtures (*17*). In regions where the source of natural aggregate is limited, using locally available alternative materials may significantly reduce the transportation cost (*63*). For coastal regions, such as Florida, one commonly available material is seashell. The consumption of shellfish by humans worldwide also generates thousands of tons of seashells. For example, oyster waste is considered a problem in Asian countries where 370–700 kg of waste is produced from every 1000 kg of oyster shell (*64*). Landfill is the most common method of managing these seashells, but it has negative environmental impact (*62*, *63*).

Most previous studies have focused on reusing seashell in certain areas, such as biochemical technology, water-quality refining, and soil enhancement (*65*). Recently, however, a limited number of studies have investigated the use of seashell material in asphalt mixtures as coarse aggregate or filler (*15*, *66*). It was found that, when seashell material was used as a filler in asphalt concrete, it increased the stability and stripping resistance of the asphalt mixture (*66*). There is, however, little research on the properties and design of porous asphalt mixtures containing seashells as aggregate. Due to the high angularity of broken seashell, it is postulated that the inclusion of seashell material in OGAC or PAC would contribute to an aggregate-interlocking skeleton structure for good mixture stability and desirable interconnected air void system that may improve the acoustic performance of the mixtures. Currently, there is no guidance on the use, particularly at high percentages, of seashell as coarse aggregates in OGAC or PAC.

3 Methods for correlating asphalt mixture design to public health and evaluating the performance of open-graded asphalt mixtures containing seashell

To estimate the relationship between mixture design, noise exposure, and public health, a series of empirical models either developed in previous studies or developed in this study are combined for analysis. To evaluate the impact of seashell on the performance of OGAC, a laboratory experiment was designed and performed.

3.1 Methods to estimate noise exposure and health impact from mixture design

To estimate the noise exposure, part of the FHWA TNM noise model is applied in this study. In particular, Equation (1) is used to calculate the A-weighted sound pressure level perceived by a receiver. The TNM uses a set of regression equations to predict the reference noise emission level from a particular vehicle type at a certain speed. These equations are specific to three general pavement types (i.e., PCC, DGAC, and OGAC) and so cannot differentiate between various designs of OGAC. This study uses the following approach to estimate the reference noise emission level of a passenger car traveling at the speed of 96.6 km/h (60 mph), which is the speed used in the OBSI measurement. Other vehicle types (e.g., truck) and speeds are not included in this study.

- Step 1. For a known OGAC mixture design, estimate its acoustic absorption coefficient and macrotexture from mixture design parameters.
- Step 2. Estimate OBSI from acoustic absorption, macrotexture, and other inputs.
- Step 3. Estimate the sound level emitted by a vehicle pass-by from OBSI.

In Step 1, a semi-empirical microstructural model developed in a prior study (*9*) for acoustic absorption of OGAC is used to estimate the acoustic absorption coefficient from mixture design parameters. In this model, an OGAC layer is treated as a porous medium with equally spaced cylindrical pores of identical radii (R) and identical lengths (d). Its acoustic absorption coefficient for a normal incident sound wave, α, is theoretically calculated by Equation (13).

$$\alpha = 1 - \left|\frac{-jZ_c \cot(kd) - \phi Z_0}{-jZ_c \cot(kd) + \phi Z_0}\right|^2 \tag{13}$$

where, k is angular wave number of the porous medium; d is the length of the pore; Z_c is the characteristic specific acoustic impedance of the porous medium; $j^2 = -1$; ϕ is porosity of the porous medium; Z_0 is the characteristic impedance of air (416.9 Pa·s/m at 15°C).

The characteristic specific acoustic impedance, Z_c, is defined by

$$Z_c = \frac{p}{u} = \sqrt{K(\omega) \cdot \rho(\omega)} \tag{14}$$

where, p is sound pressure; u is particle velocity; $K(\omega)$ is bulk modulus of the medium in which sound wave travels; $\rho(\omega)$ is effective density of the medium; ω is the angular frequency of the sound wave, $\omega = 2\pi f$, and f is the frequency of the sound wave.

The angular wave number, k, can be expressed as

$$k = \omega\sqrt{\rho(\omega)/K(\omega)} \tag{15}$$

The bulk modulus, $K(\omega)$, and the effective density, $\rho(\omega)$, of the medium are given by

$$\rho(\omega) = \rho_0 \left[1 + \frac{1}{\sqrt{3^2 + \frac{(aR)^2}{2}}} - j\frac{8}{(aR)^2}\sqrt{1 + \frac{(aR)^2}{32}} \right] \quad (16)$$

$$K(\omega) = \frac{\gamma P_0}{\gamma - (\gamma - 1)(1 - \frac{Nu}{j(aR)^2 Pr + Nu})} \quad (17)$$

where, R is pore radius; ρ_0 is air density (1.213 kg/m^3); $a = \sqrt{\frac{\omega\rho_0}{\eta}}$; η is shear viscosity of air (1.83×10^{-5} Pa·s or kg/(m·s)); P_0 is air pressure (1.013×10^{5} Pa); γ is the ratio of specific heats (1.4); Nu is Nusselt number (3.10); Pr is Prandtl number (0.71). More details of the model can be found in the reference (*9*).

The three model geometric parameters (ϕ, R, d) are correlated to mixture design parameters through linear regression models as shown in Equations (18) through (20) (*9*).

$$\phi = -0.945 + 0.035(P2.36) + 0.055(BC) + 0.112(FM) \quad (18)$$

$$R = -5.657 \times 10^{-4} + (1.309 \times 10^{-5})(P4.75) + (5.869 \times 10^{-5})(BC) + (6.35 \times 10^{-5})(NMAS) \quad (19)$$

$$d = 0.02375 + (5.091 \times 10^{-4})(P4.75) - (2.237 \times 10^{-3})(P0.075) + 1.95(T) \quad (20)$$

where, P4.75, P2.36, and P0.075 are percentages passing No. 4 (4.75 mm), No. 8 (2.36 mm), and No. 200 (0.075 mm) sieve sizes, respectively; BC is asphalt binder content (%); NMAS is nominal maximum aggregate size (mm); T is layer thickness (m); FM is fineness modulus, which is obtained by adding the total percentage of aggregates retained on each of a series of sieves and dividing the sum by 100. A higher value of fineness modulus indicates a coarser aggregate gradation.

The pavement surface macrotexture, characterized by mean profile depth (MPD) (mm), is estimated from the NMAS using Equation (21), which was also developed in the prior study (*9*).

$$MPD = 0.7237 + 0.0554(NMAS) \quad (21)$$

In Step 2, a linear regression model that correlates OBSI with acoustic absorption and MPD for OGAC is used to predict the OBSI. This regression model was developed in this study using the field survey and laboratory test data collected in a previous study conducted in California between 2006 and 2009 (*23*). The data presented in the reference (*23*) were extracted and re-analyzed by a multiple regression model with the OBSI as the dependent variables and acoustic absorption coefficient (measured from core specimens taken at the lane center) and MPD as the independent variables. In the reference (*23*), it was shown that for OGAC, OBSI has poor correlation with the arithmetic average of acoustic absorption coefficients in one third octave band frequencies from 200 Hz to 1700 Hz, but it has good negative correlation with the acoustic absorption coefficient at high frequencies (1250 and 1600 Hz). At low frequencies (500 and 630 Hz), OBSI has a positive correlation with the acoustic absorption coefficient, suggesting the confounding effect of pavement macrotexture. In the multiple regression model, therefore, we selected the acoustic absorption coefficient at the high frequency of 1250 Hz and MPD as the independent variables to account for high-frequency and low-frequency tire-pavement noises, respectively. Pavement age was also included as an independent variable to account for the acoustic aging effect of pavements in the field. Nonlinear terms of the independent variables were considered to maximize the goodness of fit of the model. The least squares estimations of the coefficients of the final model are summarized in Table 1, with an adjusted R^2 value of 0.52 and residual standard error of 1.02 dBA. Residual plots showed that the assumptions of the linear regression model were not violated. The estimated model for OBSI is then shown in Equation (22).

$$OBSI = 107.370 - 22.203(\alpha_{1250}) + 38.176(\alpha_{1250})^2 - 8.027(MPD) + 4.545(MPD)^2 + 0.126(Age) \quad (22)$$

where α_{1250} is the acoustic absorption coefficient at 1250 Hz and MPD is mean profile depth (mm).

Table 1. Estimated multiple linear regression model for OBSI (dBA)

Predictor	Estimate	Standard Error	t value	P-value
(Intercept)	107.3695	0.9408	114.13	< 0.001
Absorption at 1250 Hz	-22.2028	4.6118	-4.81	< 0.001
(Absorption at 1250 Hz)^2	38.1757	10.8758	3.51	< 0.001
MPD (mm)	-8.0273	2.1846	-3.67	< 0.001
(MPD (mm))^2	4.5452	1.0227	4.44	< 0.001
Pavement Age (Year)	0.1255	0.0559	2.25	0.0285

The P-values in Table 1 show that absorption coefficient at 1250 Hz and MPD are statistically significant in affecting OBSI at a significance level of 0.05. The signs of the coefficient estimates indicate that the OBSI increases with pavement age. Within the feasible ranges of acoustic absorption coefficient at 1250 Hz (< 0.5) and MPD for OGAC (0.9 – 2.0 mm), OBSI decreases with the increase of acoustic absorption and increases with the increase of MPD.

In Step 3, the sound level emitted by a vehicle pass-by is estimated from OBSI using Equation (23), which was developed from a study conducted at and around the National Center for Asphalt Technology (NCAT) test track facility in 2006 (*67*).

$$L_{Ap} = 0.87(OBSI) - 12\ dBA \quad (23)$$

where, L_{Ap} is the A-weighted sound level emitted by a vehicle pass-by (dBA) measured at a distance of 7.5 m from the vehicle; OBSI is the on-board sound intensity (dBA).

Once the reference noise level from a single vehicle is estimated, it is adjusted for vehicle volume and speed to calculate the reference traffic sound energy for a reference location 15 m from an infinitely long straight roadway. The adjustment for the volume and speed for the i^{th} vehicle type, $A_{traff(i)}$, may be determined by using Equation (24) from TNM:

$$A_{traff(i)} = 10 \cdot \log_{10}\left(\frac{v_i}{s_i}\right) - 13.2\ dB \quad (24)$$

where, s_i is the speed of vehicle type i (km/h); v_i is the equivalent volume of vehicle type i (vehicles per hour).

When the perpendicular distance from a receiver to a roadway segment is greater than 0.3 m, the adjustment for roadway length and distance, A_d, is given by Equation (25) from TNM.

$$A_d = \log_{10}\left[\left(\frac{15}{d}\right)\left(\frac{\alpha}{180}\right)\right]\ dB \tag{25}$$

where, d is the perpendicular distance from the receiver to the roadway segment (m); α is the angle subtended at the receiver by the roadway segment (degree).

The application of the adjustment for roadway length and distance is very involved along with the adjustment for ground and shielding effects between the source and the receiver. Since generally a larger distance between the receiver and the source leads to a lower noise level due to attenuation of sound energy along the propagation path, this study will put the receiver at the reference distance of 15 m from the roadway. Therefore, the adjustments for roadway length, distance, and ground and shielding effects are all set to zero.

Once the noise exposure level is estimated, its impact on public health (e.g., annoyance and sleep disturbance) is assessed based on the relationships between road traffic noise and public health summarized from the literature, as described in Section 2.3.

3.2 Experimental design for performance evaluation of open-graded asphalt mixtures containing seashell

To investigate the feasibility and optimal design of incorporating seashell materials as partial coarse aggregates in open-graded asphalt mixtures, experiments were designed and conducted in the laboratory.

3.2.1 Materials

Three types of materials are mainly used in the experiments: asphalt binder, aggregate, and seashell.

One Superpave performance-graded (PG) asphalt binder, PG 76-22, was selected for this study. It is a styrene-butadiene-styrene (SBS) modified binder and was obtained from a local asphalt supplier in Tampa, Florida. The PG 76-22 asphalt is widely used in the open-graded friction course mixtures on Florida highways. The optimum binder content (OBC) of the PG 76-22 asphalt in open-graded asphalt mixtures was determined following a binder draindown test specified in the Florida test method FM 5-588 (*68*).

Aggregates of a granite type were obtained from a local pavement construction company in Tampa, Florida and used in the study. Its resistance to degradation measured using a Los Angeles testing machine in accordance with American Association of State Highway and Transportation Officials (AASHTO) T 96 (*69*) has an average value of 14.9%.

The seashell material was obtained from a local supplier in Tampa, Florida. It had been washed at least twice before it was supplied for use, so it is named as Florida washed shell in this study. The shell material mainly consists of calcium carbonate (about 95%), which is similar to the calcium carbonate in limestone, and a small amount of protein. After receiving, the shell was dried under the sun for more than 24 h and then some of them were crushed into small particles in the Los Angeles abrasion machine. The shell particles were then grouped into four coarse aggregate sizes (12.5, 9.5, 4.75, and 2.36 mm), as shown in Figure 1, for use in the mixture preparation. These seashell particles tend to be flat with irregular shape.

Figure 1. Florida washed shell particles of various sizes used in this study

3.2.2 Mixture designs and specimen preparation

A total of 15 mixture designs are considered in this study, which are the combinations of five contents of Florida washed shell (0, 15, 30, 45, and 100%) and three open-graded aggregate gradations named as NMAS 12.5, NMAS 9.5, and NMAS 4.75, as shown in Table 2. The three gradations have different NMASs (i.e., 4.75, 9.5, and 12.5 mm). The mixtures with 0% shell are essentially conventional open-graded asphalt mixtures. Table 2 also shows a gradation of an NMAS of 19.0 mm. This will be used in the analysis of noise exposure and health impact.

Table 2. Gradation and binder content for different open-graded asphalt mixtures

Sieve size (mm)	**NMAS 19.0 (% Passing)**	**NMAS 12.5 (% Passing)**	**NMAS 9.5 (% Passing)**	**NMAS 4.75 (% Passing)**
25.0	100	100	100	100
19.0	95	100	100	100
12.5	54	92.5	100	100
9.5	36	65	95	100
4.75	20	20	32.5	90
2.36	15	7.5	12.5	13
1.18	10	5	5	11
0.6	7	5	5	9
0.3	5	4	4	7
0.15	4	3	3	5.5
0.075	2	3	1.5	4.5
Binder Content (% by aggregate mass)	5.0	5.5	6.0	7.5

The optimum binder contents of the mixtures were determined to be 5.5, 6, and 7.5% (by mass of aggregate) for the NMAS 12.5, 9.5, and 4.75 gradations, respectively. The shell particles of sizes in the range of 2.36 mm to 12.5 mm were used to replace the granite aggregates. The percentage of the flat and elongated particles in the combined coarse aggregates (granite and seashell) in various gradations was controlled below 10%.

To prepare test specimens, the proportioned aggregates, asphalt binder, and Florida washed shell were first mixed in a mechanical mixer at 160 ± 2.5°C for five minutes, then compacted at 155 ± 5.0°C into cylindrical specimens of a diameter of 101 mm and a nominal height of 63.5 mm using a Marshall compactor. During compaction, 50 blows were applied on each side of the specimens. After compaction, the specimens were allowed to cool down at a room temperature of 25°C for 24 h and then extracted from the molds. A prior study has shown that for open-graded asphalt mixtures, specimens compacted by the Marshall compactor are comparable to those compacted by a gyratory or a roller compactor (*7*).

3.2.3 Test methods

For the Florida washed shell, its physical properties, including bulk specific gravity, saturated surface dry (SSD) bulk specific gravity, apparent specific gravity, and water absorption were measured following the procedures in AASHTO T 85 and AASHTO T 96 (*69*, *70*).

The following properties of open-graded asphalt mixtures were evaluated by testing the compacted specimens: stability and tensile strength, durability in terms of resistance to raveling, air-void content, permeability, acoustic absorption, and macrotexture. By default, three replicate specimens were tested under each combination of testing conditions and test methods.

The Marshall stability test was performed according to AASHTO T 245 (*71*) to measure the stability of asphalt mixture specimens, which is related to the load-carrying capacity of the mixture. Specifically, a compressive load is applied in the diametrical direction of a cylindrical specimen of a diameter of 101 mm at a loading rate of 51 mm/min until specimen failure, and the maximum load is recorded. In this study, this test was conducted at 25°C instead of 60°C to prevent excessive creep deformation in the open-graded asphalt specimens during the high temperature (60°C) conditioning process.

The Cantabro test was conducted to measure the raveling resistance of open-graded asphalt mixtures according to American Society for Testing and Materials (ASTM) D 7064 (*72*). In the test, one compacted specimen was placed in the Los Angeles abrasion machine drum without abrasion loads (balls), and the drum was rotated at a speed of 30 revolutions per minute for 300 revolutions. The weight of the specimen was measured before and after abrasion in the drum and used to calculate the percentage of mass loss as the test result.

The indirect tensile strength test was conducted to evaluate the mixture tensile properties, which are related to cracking resistance, according to ASTM D 6931 (*73*). Similar to the Marshall stability test, this test was conducted at 25°C at a loading rate of 51 mm/min.

The air-void content of each specimen was calculated from its bulk specific gravity and theoretical maximum specific gravity, which were measured in accordance with AASHTO T 166 and AASHTO T 209, respectively (*74*, *75*).

The coefficient of permeability of each specimen was measured using a falling head permeability test according to Florida test method FM 5-565 (*76*).

The acoustic absorption coefficient of specimens was measured according to ASTM E 1050-12 [34] using an impedance tube system built in the laboratory, as shown in Figure 2. The built impedance tube device was validated by comparing its measurements on a number of asphalt mixtures with those from a reference Brüel & Kjær impedance tube.

The surface macrotexture of the specimens was characterized by the mean texture depth (MTD) as measured by a sand patch method according to ASTM E 96 (*77*).

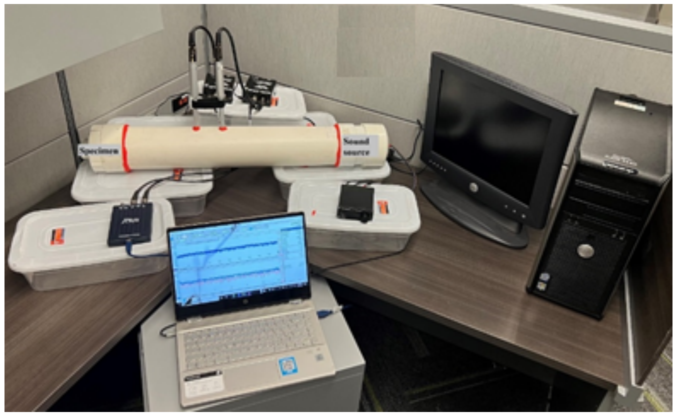

Figure 2. Impedance tube test system built in the laboratory

4 Result analysis and discussion

The analysis and test results are presented and discussed in this section.

4.1 Estimation of noise exposure and health impact from mixture design

The noise level perceived by a receiver is affected by a wide range of factors, such as the type, speed, and volume of vehicles, ground surface condition, environmental condition, distance and barrier between vehicle and receiver, and position within a building. Since the main purpose of this study is to compare different OGAC mixture designs in terms of their impact on perceived noise level and resulting health issues, many factors will be fixed at certain (usually worst) levels.

4.1.1 Noise exposure and impact from four typical OGAC mixture designs

In the analysis of the traffic noise level perceived by a receiver, we make assumptions as follows:

- The roadway is an infinitely long straight segment with a 1-year-old pavement surface, and the receiver is at 15 m from the roadway.
- The traffic on the roadway is passenger cars with a volume of 2000 per hour. This volume is near the capacity of a highway lane (*78*), so it may represent the worst noise scenario.
- The traffic speed is 96.6 km/h, which equals the speed of the test vehicle that was used in the OBSI measurement. If other vehicle speeds are to be considered, the OBSI at those speeds need to be first estimated or measured. This is out of the scope of this study.

Four typical OGAC mixture designs covering a wide range of NMAS, as shown in Table 2, are compared. From the aggregate gradation, the fineness modulus is calculated to be 4.65, 5.43, 5.98, and 6.54 for NMAS 4.75, NMAS 9.5, NMAS 12.5, and NMAS 19.0, respectively. The thickness of the OGAC layer is assumed to be 30 mm for all mixtures. Following the procedure described in Section 3.1, the A-weighted sound level emitted by a vehicle pass-by (dBA) was calculated by Equation (23) for the four mixtures. The results are 76.53, 76.16, 76.79, and 78.81 dBA for NMAS 4.75, 9.5, 12.5, and 19.0, respectively.

In the FHWA TNM, the maximum A-weighted vehicle noise emission level (dBA) for the i[th] vehicle type, $L_A(s_i)$, recorded at 15 m from the vehicle is

$$L_A(s_i) = 10 \cdot \log_{10}\left((0.6214 s_i)^{A/10} 10^{B/10} + 10^{C/10}\right) \text{ dBA} \quad (26)$$

where, s_i is the speed of vehicle type i (km/h); A, B, and C are constants that vary with vehicle type, pavement type, and throttle condition, respectively. For automobiles on OGAC pavements with cruise throttle, the values of A, B, and C are 41.740807, -1.065026, and 50.128316, respectively. For automobiles on OGAC pavements with full throttle, their values are 41.740807, -1.065026, and 67, respectively (*32*). Therefore, at the speed of 96.6 km/h, L_A is 73.19 dBA for cruise throttle and 74.11 for full throttle. Since most OGAC pavements in the U.S. have an NMAS of 9.5 mm or 12.5 mm, the noise level predicted by the TNM model is slightly lower than the values (76.16 and 76.79 dBA) predicted by the procedure proposed in this study. One potential cause is the difference in measurement distance: 7.5 m in this study's procedure while 15 m in the TNM procedure. Since a shorter distance from the noise source leads to a higher noise level, the above discrepancy seems reasonable. Other discrepancies in the two procedures may also contribute to this difference. For example, the "automobile" vehicle type in TNM refers to all vehicles having two axles and four tires, including cars and light trucks while the vehicle in Equation (23) is a passenger car used in the OBSI measurement. Environmental conditions (e.g., air temperature and humidity) may also differ during the field measurements of noise data used to develop Equations (23) and (26). With these considerations, we think the noise levels predicted by this study's procedure are acceptable and therefore we may proceed to estimate the noise level at the receiver and analyze the impact of OGAC mixture designs on noise-induced health issues.

The noise levels perceived at the receiver were estimated using Equations (1) and (24) for the four mixture designs and the results are shown in Figure 3. As can be seen, the noise level at the receiver varies in the range of 76.12 dBA to 78.77 dBA when the pavement surface mixture varies among the four OGAC designs with different NMAS values, with the NMAS 9.5 mixture exhibiting the lowest noise level and the NMAS 19.0 mixture showing the highest noise level. Another observation is that generally the noise level decreases with the reduction of NMAS, except that when the NMAS is reduced from 9.5 mm to 4.75 mm the noise level increases slightly instead.

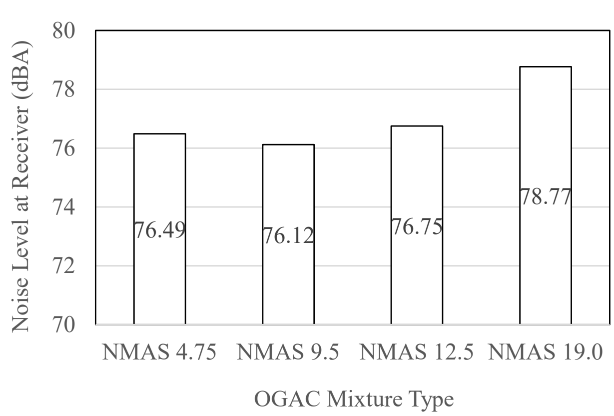

Figure 3. Noise levels at the receiver for four OGAC mixture designs

For the public health in terms of annoyance and sleep disturbance, Equations (10) and (11) are used to estimate the impact of noise level on them. To simplify the analysis, we assume that the day-night traffic noise level and nighttime traffic noise level are identical. The results are shown in Figure 4.

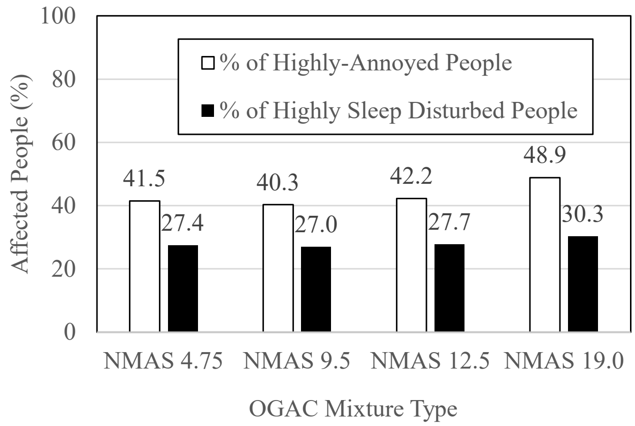

Figure 4. Percent of people affected by noise for four OGAC mixture designs

As can be seen from Figure 4, the percent of people highly annoyed by road traffic noise varies between 40.3 and 48.9 for the four mixtures while the percent of highly sleep disturbed people varies between 27.0% and 30.3%. This indicates that significantly changing the OGAC mixture design in terms of aggregate gradation may cause a change of 8.6% people who are highly annoyed and a slight change of 3.3% people who are highly sleep disturbed.

For the public health in terms of other symptoms such as hypertension, cardiovascular disease, high blood pressure, and mental health, the literature reviewed in Section 2.3 generally differentiated the noise impact for every 5 or 10 dBA change in the noise level. Since Figure 3 shows that changing the OGAC mixture design among the four gradations does not lead to a 5 dBA change in the noise perceived by a receiver, it is concluded that adjustment in the OGAC mixture design may not have a noticeable impact on those aspects of public health.

It should be noted that in this analysis the receiver is located near the roadway. For people living further away from the roadway with potential shielding (e.g., trees and buildings) in between, the difference in the perceived noise levels from the four mixture designs should be even less.

4.1.2 Noise exposure and impact from variations in OGAC mixture design

A prior study (*9*) on the OGAC mixture design for traffic noise reduction has suggested that within allowable ranges, the selection of mixture design may go towards a lower percentage passing the 4.75 mm (No. 4) sieve, a lower percentage passing the 2.36 mm (No. 8) sieve, or a lower binder content. In this section, we analyze the impact of variations in these design parameters on traffic noise level and health.

For the impact of percentage passing the 4.75 mm sieve (P4.75), this value was varied for each of the four gradations in Table 2 within ranges acceptable by other mixture design objectives. Results are similar among different NMAS gradations. Therefore, only the results for the NMAS 9.5 gradation are presented and discussed here. For this gradation, its P4.75 was varied in an increment of 3% from 28% to 37%, which is an allowable variation range in some state agency specifications (*9*). Fineness modulus was recalculated accordingly while other parameters including the binder content were kept constant.

The noise levels perceived at the receiver were estimated following Equations (1) and (24) for the four P4.75 values and the results are shown in Figure 5. As can be seen, the noise level at the receiver varies slightly in the range of 76.13 dBA and 76.25 dBA when the percent passing the 4.75 mm (No. 4) sieve decreases from 37% to 28%.

For the public health in terms of annoyance and sleep disturbance, Equations (10) and (11) are used to estimate the impact of noise level on them and the results are shown in Figure 6. As can be seen, when the percent passing the 4.75 mm (No. 4) sieve decreases from 37% to 28%, there is a very slight change (0.4%) in the percent of people who are highly annoyed and a very slight change (0.1%) in the percent of people who are highly sleep disturbed. For the public health in terms of other symptoms, variation in P4.75 in the OGAC gradation may not have a noticeable impact on them since the resulting variation in the noise level is less than 5 dBA.

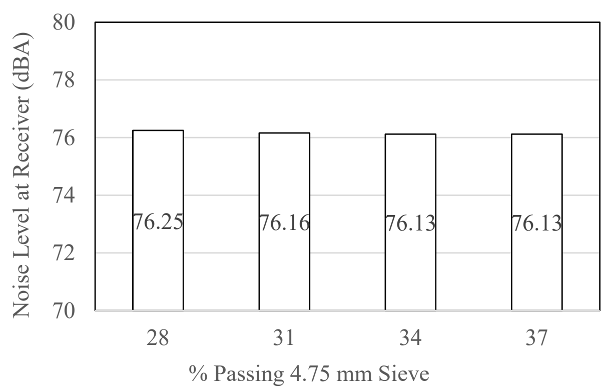

Figure 5. Noise levels at the receiver versus percent passing 4.75 mm sieve

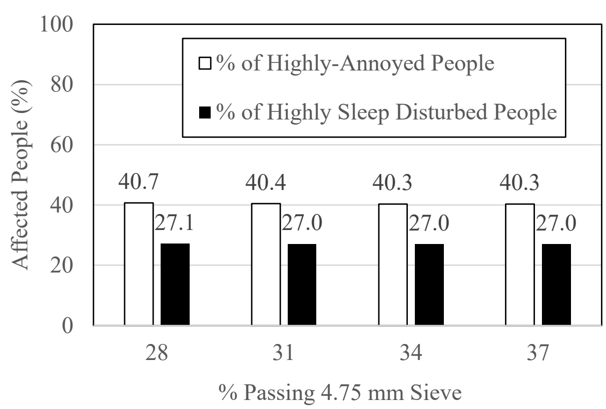

Figure 6. Percent of people affected by noise versus percent passing 4.75 mm sieve

For the impact of percentage passing the 2.36 mm sieve (P2.36), results from the NMAS 9.5 gradation in Table 2 are also presented and discussed. Its P2.36 was varied from 7% to 18%, as typical in road agency specifications (*9*). All other parameters except the fineness modulus were kept constant.

The noise levels perceived at the receiver for different P2.36 values are shown in Figure 7. As can be seen, when the percent passing the 2.36 mm (No. 8) sieve decreases from 18% to 7%, the noise level at the receiver varies very slightly in a narrow range of 76.12 to 76.26 dBA.

The corresponding impacts on annoyance and sleep disturbance, as shown in Figure 8, are therefore also very small, and the impact on other health symptoms is not noticeable.

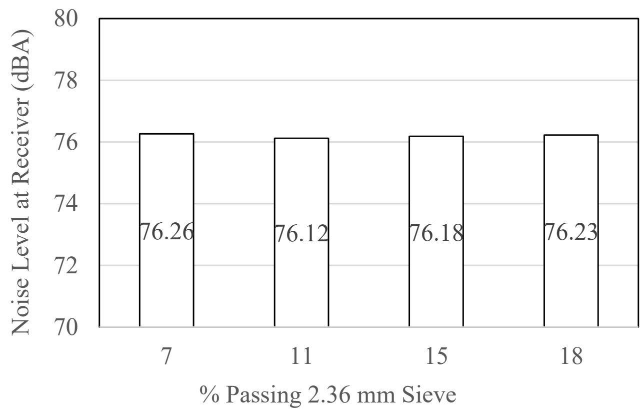

Figure 7. Noise levels at the receiver versus percent passing 2.36 mm sieve

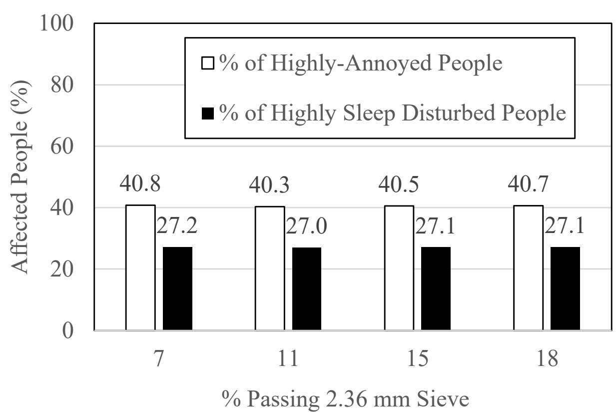

Figure 8. Percent of people affected by noise versus percent passing 2.36 mm sieve

For the impact of binder content, the binder content of the NMAS 9.5 gradation in Table 2 was varied around the optimum binder content of 6.0%, from 5.5% to 6.4% All other parameters were kept constant. The noise levels perceived at the receiver for different binder contents are shown in Figure 9. As can be seen, when the binder content changes in the range of 5.5% to 6.4%, there is no noticeable change in the noise level at the receiver. Therefore, there would be no change in the noise impact on public health.

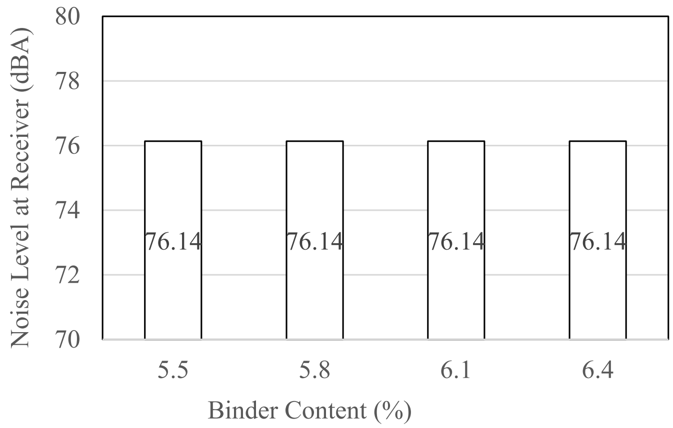

Figure 9. Noise levels at the receiver versus binder content

4.1.3 Summary

The analysis results show that for OGAC mixtures that are typically "quieter" than DGAC when they used as pavement surface, reducing the NMAS from 19.0 mm to a smaller value has a noticeable impact on the car traffic noise level perceived by a receiver near the roadway and the resulting public health. The impact of variation of NMAS in the range of 4.75 mm to 12.5 mm, however, is small. For a given NMAS, variations in the mixture design do not cause significant change in the perceived traffic noise level and public health. Adjusting the OGAC mixture design under a given NMAS may not have practical significance in reducing the traffic noise impact on public health. This is consistent with observations made in a previous field study (*79*).

4.2 Performance evaluation of open-graded asphalt mixtures containing seashell

4.2.1 Properties of Florida washed shell

The measured properties of the seashell material along with those of the granite aggregate are summarized in Table 3. As can be seen, the seashell has a higher loss value in the Los Angeles abrasion test than the granite aggregate. Based on the experience gained in the U.S., LA abrasion loss values of 30 percent or less was recommended for aggregates used in the open-graded friction course (*80*). The LA loss value of the seashell, therefore, is still within the acceptable range. Table 3 also shows that the seashell has lower values of bulk specific gravity and bulk SSD specific gravity than granite but a higher water absorption value. This indicates that the seashell has more porous surface and may absorb more asphalt binder during mixing.

Table 3. Physical properties of granite aggregate and seashell

Property	Granite	Seashell	Method
LA Abrasion Loss (%)	14.9	28.4	AASHTO T 96
Bulk Specific Gravity	2.677	2.600	AASHTO T 85
Bulk SSD Specific Gravity	2.691	2.669	AASHTO T 85
Apparent Specific Gravity	2.716	2.792	AASHTO T 85
Water Absorption (%)	0.54	2.64	AASHTO T 85

4.2.2 Marshall stability

Figure 10 shows the average and the range of one standard deviation of the Marshall stability for 15 mixtures. There is no significant difference in the stability values among mixtures with 0, 15, 30, and 45% of seashell with 12.5 mm and 4.75 mm NMAS gradations. However, increasing the seashell percent seems to negatively affect the Marshall stability in mixtures with the 9.5 mm NMAS gradation.

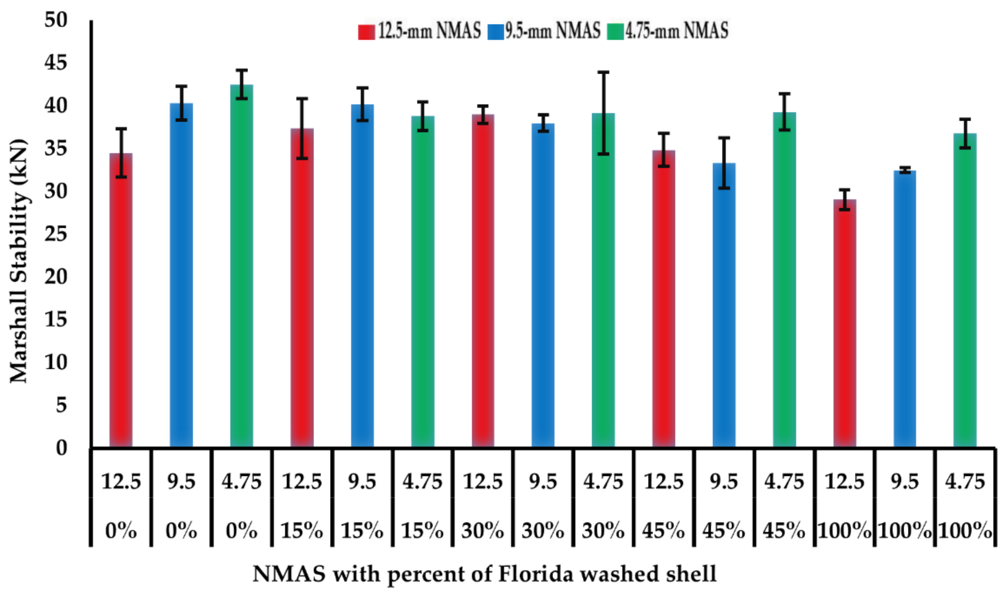

Figure 10. Marshall stability results of open-graded asphalt mixtures at 25°C

4.2.3 Cantabro loss

The Cantabro test results are summarized in Figure 11. A higher Cantabro loss value indicates a lower resistance to raveling. It can be seen that generally raveling resistance of open-graded asphalt mixtures decreased with the increase of NMAS, and the use of 4.75 mm NMAS significantly increased the raveling resistance. For the open-graded asphalt mixtures with the 12.5 mm NMAS gradation, the use of 30, 45, and 100% of seashell decreased the Cantabro loss compared to 0 and 15% seashell mixtures. This indicates that replacing a high percent of large-sized aggregates with Florida washed shell may improve the mixture raveling resistance. For mixtures with a 9.5 mm or 4.75 mm NMAS gradation, the Cantabro loss values were generally less than 20% and so in the acceptable range (*81*).

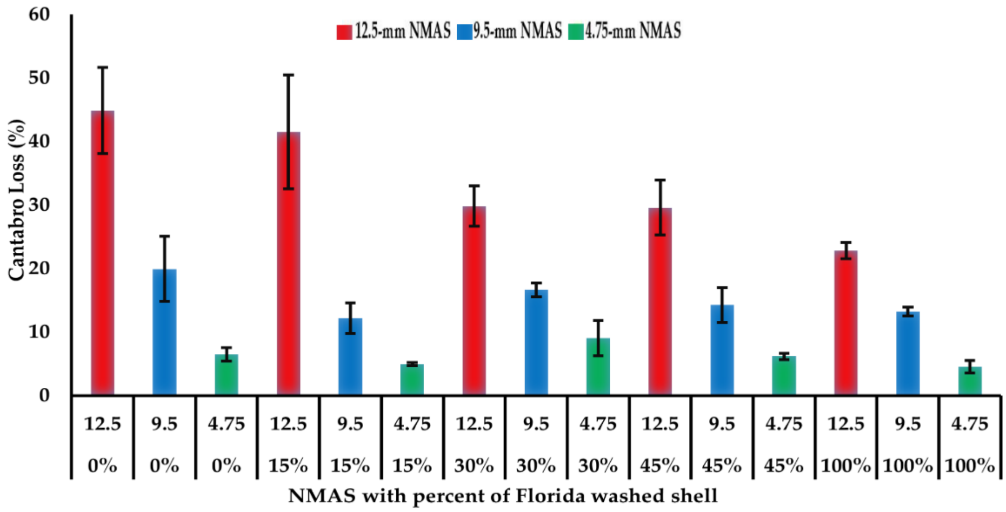

Figure 11. Cantabro loss results of open-graded asphalt mixtures

4.2.4 Indirect tensile strength

The indirect tensile strength (ITS) test results for the 15 open-graded asphalt mixtures are shown in Figure 12. There seems to be no significant difference in the indirect tensile strength values when the coarse aggregates were replaced with 15, 30, 45, or 100% Florida washed shell. It can be noticed that the indirect tensile strength of open-graded asphalt mixture decreased with the increase of NMAS, which is consistent with findings from a previous study (*7*).

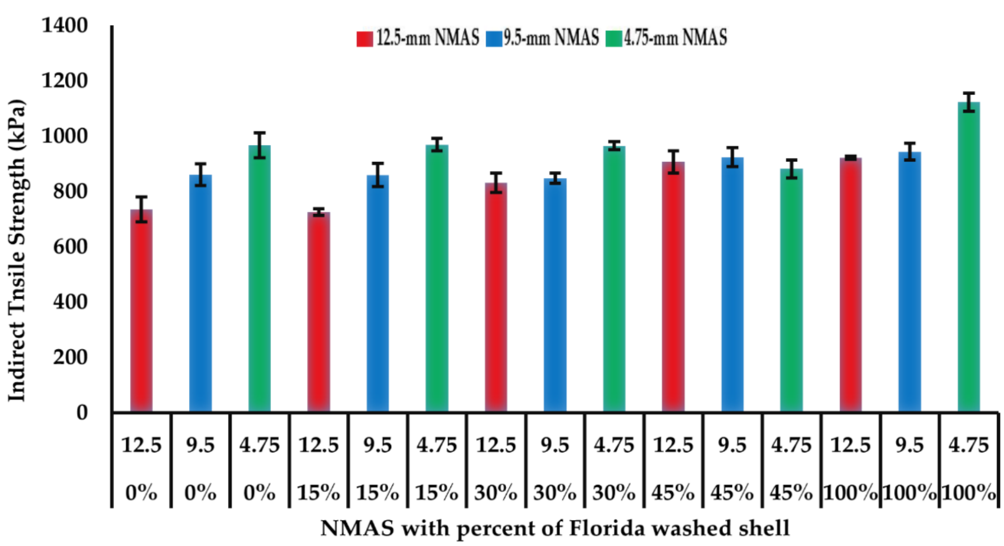

Figure 12. Indirect tensile strength results of open-graded asphalt mixtures at 25°C

4.2.5 Air-void content

Table 4 shows the average air-void contents of the 15 mixtures. The results show that the percentage of seashell does not have a significant effect on the air-void content of open-graded asphalt mixtures under the same compaction effort. The NMAS slightly affected the air-void content in the mixture. Nonetheless, all the mixtures are within the desirable air-void content range (18–25%) of open-graded asphalt mixtures (*81*). The results also support previous research findings that a coarser gradation in an open-graded asphalt mixture can result in a higher void content under the same compaction effort (*82*).

Table 4. Average air-void contents of 15 open-graded asphalt mixtures

NMAS (mm)	Seashell Content (%)	Air-void Content (%)
12.5	0	22.0
12.5	15	21.7
12.5	30	21.1
12.5	45	20.7
12.5	100	24.2
9.5	0	20.3
9.5	15	20.9
9.5	30	20.4
9.5	45	20.0
9.5	100	23.0
4.75	0	18.3
4.75	15	19.8
4.75	30	19.0
4.75	45	18.1
4.75	100	19.3

4.2.6 Permeability

The permeability test results for the 15 open-graded asphalt mixtures are shown in Figure 13. It can be seen that the permeability increases with the increase of NMAS. For the 12.5 and 9.5 mm NMAS gradations, the permeability decreases with the increase of seashell percentage. This indicates that the shape of large-sized seashell has some effect on the interconnected air void system and water conductivity in the mixture. Regarding mixtures with 4.75 mm NMAS gradations, the seashell percentage has no significant impact on the mixture permeability.

There was a noticeable disparity between the effects of seashell percentage on the air-void content and on the permeability. Using the 12.5 mm NMAS mixtures as an example, an increase in the percentage of seashell led to a decrease in the permeability but no significant change in the air-void content. This could be related to the shell impact on the three-dimensional distribution of air voids in the mixtures, as the addition of seashell may result in more isolated voids that do not contribute to effective porosity. There is still a research need to clarify the relationship between the structure and distribution of air voids in porous asphalt concrete (*83*).

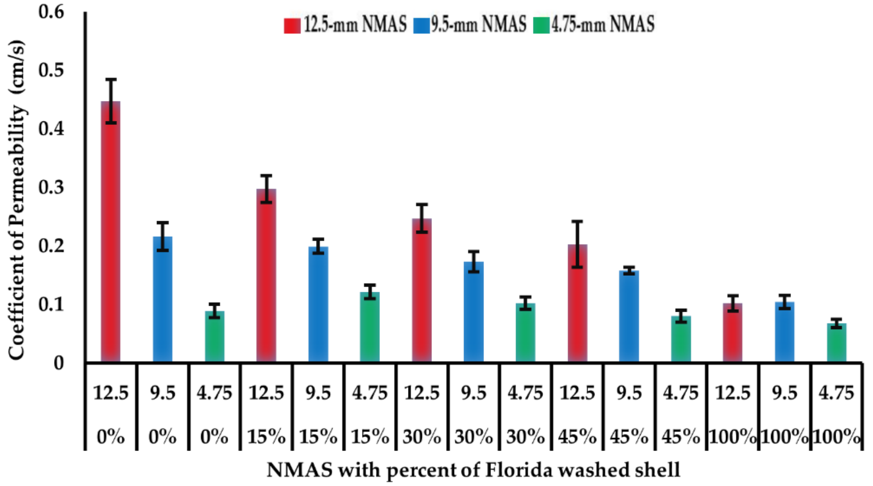

Figure 13. Permeability results of open-graded asphalt mixtures

4.2.7 Acoustic absorption

The impedance tube test results are shown in Figure 14 through Figure 16 for open-graded asphalt mixtures with 12.5 mm, 9.5 mm, and 4.75 NMAS gradations, respectively. In the figures, each curve is the average of the results from two specimens.

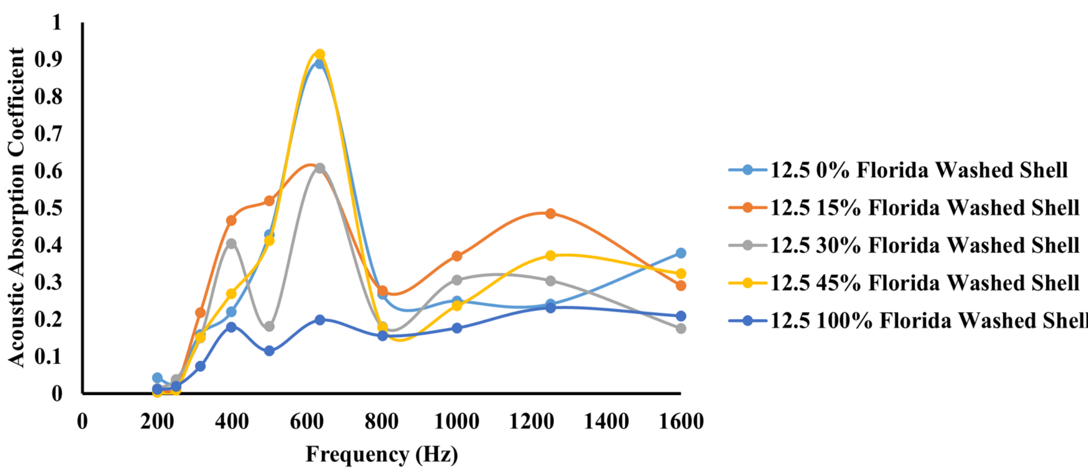

Figure 14. Acoustic absorption results of open-graded asphalt mixtures of 12.5 mm NMAS

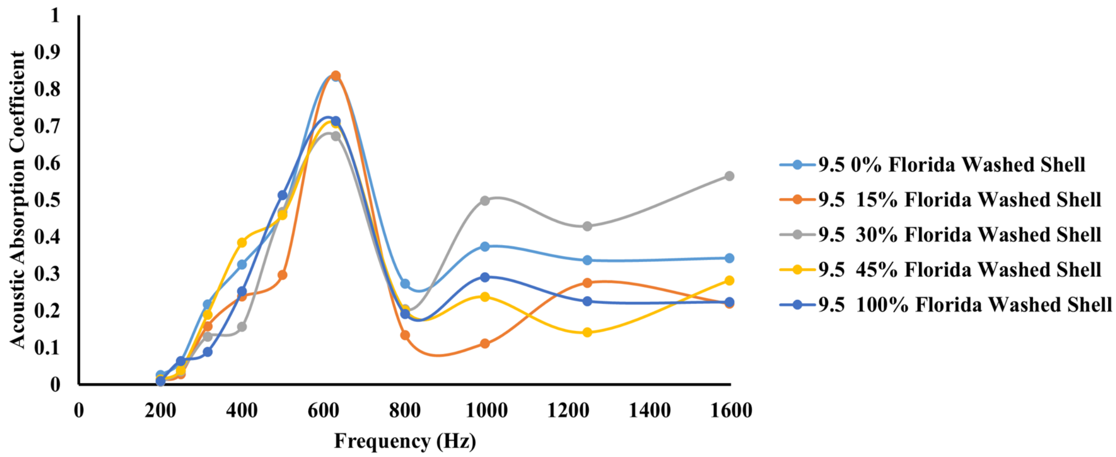

Figure 15. Acoustic absorption results of open-graded asphalt mixtures of 9.5 mm NMAS

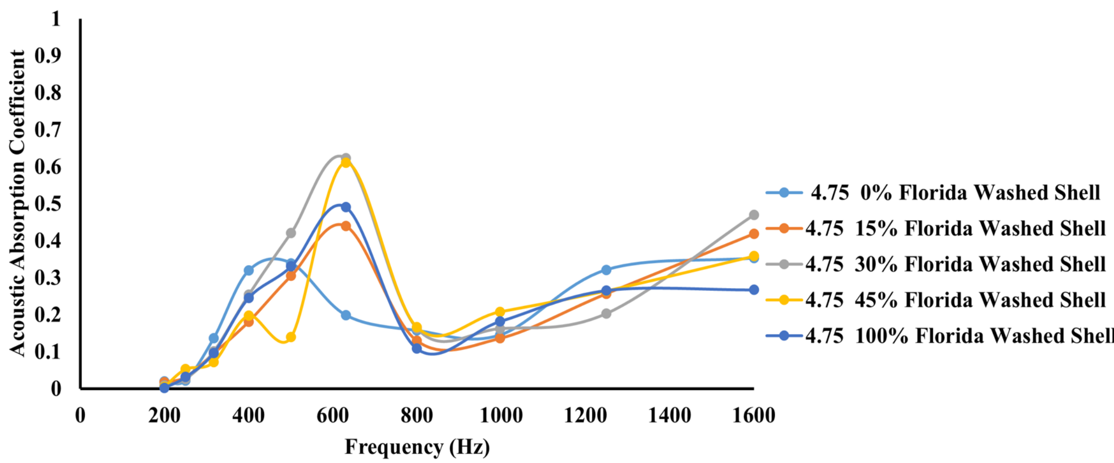

Figure 16. Acoustic absorption results of open-graded asphalt mixtures of 4.75 mm NMAS

Figure 14 shows that for the 12.5 mm NMAS mixtures, the mixture with 100% coarse aggregates being seashell had a lower acoustic absorption coefficient than other mixtures with no or partial coarse aggregates being seashell. A clear trend, however, cannot be observed in the relationship between the seashell content in the mixtures and the acoustic absorption coefficient.

Figure 15 shows that for the 9.5 mm NMAS mixtures, the acoustic absorption is similar among the five mixtures of various seashell contents when the frequency is lower than 800 Hz. The acoustic absorption showed a high variation among the five mixtures when the frequency is higher than 800 Hz. Again, there is no clear relationship between the seashell content and the acoustic absorption.

Figure 16 shows that for the 4.75 mm NMAS mixtures, the acoustic absorption is similar at most frequencies among the mixtures containing seashell. Compared to the mixture without seashell, mixtures with seashell tend to exhibit a higher acoustic absorption in the frequency range of 500 – 800 Hz.

From the above discussion, visual observation of the test data does not suggest a clear trend of impact of the inclusion of seashell in an open-graded asphalt mixture on the acoustic absorption performance of the mixture.

4.2.8 Macrotexture

Figure 17 through Figure 19 show the macrotexture results in terms of MTD for mixtures of 12.5 9.5, and 4.75 mm NMAS gradations, respectively. It can be seen that the macrotexture depth decreased with the increase of the percentage of Florida washed shell in the mixtures, and the rate of reduction was more significant in mixtures with larger NMAS. This indicates that the inclusion of seashell in the open-graded mixtures is beneficial for reducing the tire-pavement noise generated due to tire tread impact.

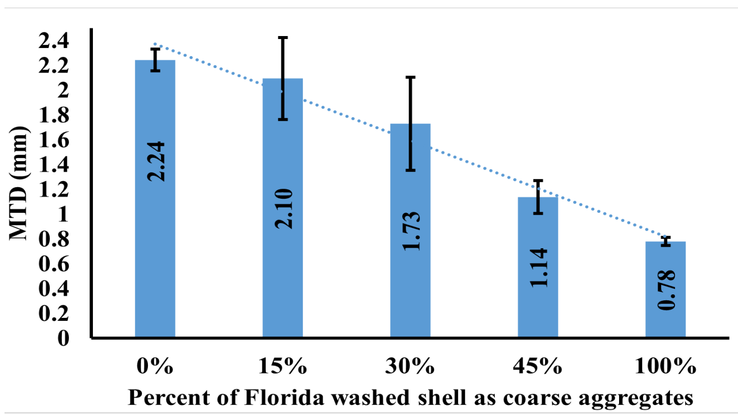

Figure 17. MTD results of open-graded asphalt mixtures of 12.5 mm NMAS

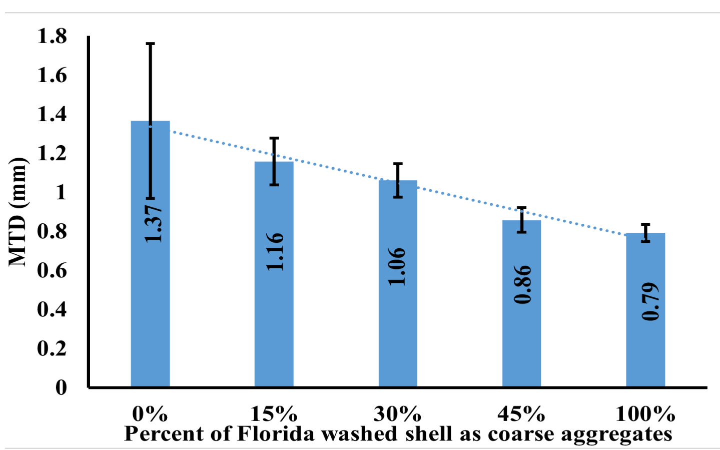

Figure 18. MTD results of open-graded asphalt mixtures of 9.5 mm NMAS

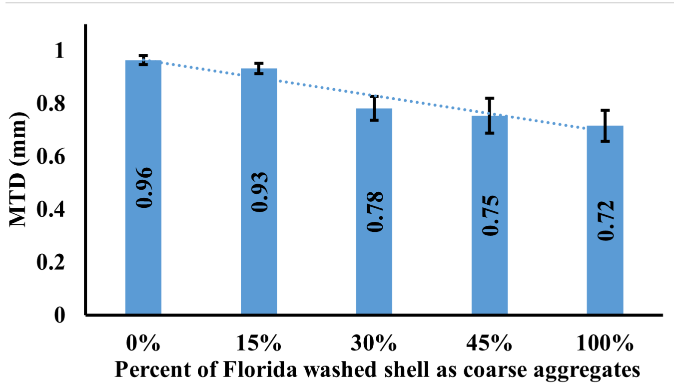

Figure 19. MTD results of open-graded asphalt mixtures of 4.75 mm NMAS

4.2.9 Statistical analysis

As a further step of analysis, a t-test was performed to compare the test results from mixtures with and without seashell and to determine the optimum content of seashell as coarse aggregate replacement in mixtures with different NMAS values. The optimum content was selected as the highest amount of Florida wash shell that does not cause significant change in the mechanical and volumetric properties of mixtures. A 5% significance level was used in the t-test and the test results are summarized in Table 5 through Table 7 for the 12.5, 9.5, and 4.75-mm NMAS mixtures, respectively. In these tables, "Yes" indicates statistical significance (i.e., the p-value is less than 0.05) while "No" does not.

Table 5. t-test results comparing 12.5-mm NMAS mixtures with and without seashell

Property	**15% Seashell**	**30% Seashell**	**45% Seashell**	**100% Seashell**
Marshall Stability	No	Yes	No	Yes
Cantabro Loss	No	Yes	Yes	Yes
Indirect Tensile Strength	No	Yes	Yes	Yes
Air-Void Content	No	No	Yes	Yes
Permeability	Yes	Yes	Yes	Yes

Note: "Yes" indicates statistical significance at the 5% significance level.

Table 6. t-test results comparing 9.5-mm NMAS mixtures with and without seashell

Property	**15% Seashell**	**30% Seashell**	**45% Seashell**	**100% Seashell**
Marshall Stability	No	No	Yes	Yes
Cantabro Loss	Yes	No	No	Yes
Indirect Tensile Strength	No	No	No	Yes
Air-Void Content	No	No	No	Yes
Permeability	No	Yes	Yes	Yes

Table 7. t-test results comparing 4.75-mm NMAS mixtures with and without seashell

Property	15% Seashell	30% Seashell	45% Seashell	100% Seashell
Marshall Stability	Yes	No	No	Yes
Cantabro Loss	Yes	No	No	Yes
Indirect Tensile Strength	No	No	No	Yes
Air-Void Content	Yes	Yes	No	Yes
Permeability	Yes	No	No	Yes

Table 5 shows that for 12.5-mm NMAS open-graded asphalt mixtures, the differences in the mechanical test results were statistically insignificant between conventional mixtures (i.e., mixtures without seashell) and mixtures with 15% coarse aggregates replaced with Florida washed shell. This indicates that replacing 15% coarse aggregates in the 12.5-mm NMAS open-graded asphalt mixture with Florida washed shell has no effect on strength and durability of the mixture. However, the effect on mixture permeability is significant. Overall, it is deemed that 15% can be the optimum content of Florida washed shell as coarse aggregate in the 12.5-mm NMAS mixtures.

Table 6 shows that for 9.5-mm NMAS mixtures, the differences in the mechanical test results were statistically insignificant between conventional mixtures and mixtures with 30% coarse aggregates replaced with Florida washed shell. Mixture permeability is again affected by Florida washed shell from a statistical significance perspective. The average change in the mixture permeability, however, is minor from an engineering application perspective. Overall, it is deemed that 30% can be the optimum content of Florida washed shell as coarse aggregate in the 9.5-mm NMAS mixtures.

Table 7 shows that for 4.75-mm NMAS mixtures, the differences in the mechanical test results and permeability were statistically insignificant between conventional mixtures and mixtures with 30% or 45% coarse aggregates replaced with Florida washed shell. Overall, it is deemed that 45% can be the optimum content of Florida washed shell as coarse aggregate in the 4.75-mm NMAS mixtures.

For the noise-related parameters (i.e., sound absorption coefficient and MTD), multiple regression models were applied to explore their relationships with mixture design parameters. The relevant data are summarized in Table 8, which are the averages of two replicate specimens. The average sound absorption coefficient is the arithmetic mean of the sound absorption coefficient values at different frequencies from 200 to 1600 Hz.

Other mixture design parameters, such as percentage passing No. 3/4 sieve size (P9.5), percentage passing No. 4 sieve (P4.75), percentage passing No. 8 sieve (P2.36), and percentage passing No. 200 sieve (P0.075) can be found from Table 2.

Table 8. Summary of properties of 15 open-graded asphalt mixtures with seashell

Mixture Type	NMAS (mm)	Seashell Content (%)	Thickness (mm)	Air-Void Content (%)	Binder Content (%)	MTD (mm)	Average Sound Absorption Coefficient
Mix 12.5 0	12.5	0	64.41	23.10	5.5	2.244	0.301
Mix 12.5 15	12.5	15	63.48	22.37	5.5	2.095	0.320
Mix 12.5 30	12.5	30	62.64	21.50	5.5	1.730	0.241
Mix 12.5 45	12.5	45	62.52	21.27	5.5	1.139	0.277
Mix 12.5 100	12.5	100	63.03	23.56	5.5	0.781	0.151
Mix 9.5 0	9.5	0	62.78	21.07	6.0	1.366	0.310
Mix 9.5 15	9.5	15	62.95	21.47	6.0	1.157	0.225
Mix 9.5 30	9.5	30	62.12	20.86	6.0	1.061	0.300
Mix 9.5 45	9.5	45	61.25	20.53	6.0	0.858	0.272
Mix 9.5 100	9.5	100	63.56	24.32	6.0	0.792	0.255
Mix 4.75 0	4.75	0	61.63	19.07	7.5	0.964	0.217
Mix 4.75 15	4.75	15	61.35	18.45	7.5	0.932	0.218
Mix 4.75 30	4.75	30	61.59	19.20	7.5	0.781	0.263
Mix 4.75 45	4.75	45	62.00	18.51	7.5	0.753	0.199
Mix 4.75 100	4.75	100	61.59	19.74	7.5	0.716	0.193

When the average sound absorption coefficient (i.e., arithmetic average over frequencies) was the dependent variable, the variables shown in Table 8 and P9.5, P4.75, P2.36, and P0.075 were used as the independent variables for the multiple linear regression model. The best subset model selected based on the maximum adjusted R^2 includes two variables that are statistically significant at a 5% significance level: the seashell content (Seashell) and percent passing No. 200 sieve (P0.075), as shown in Table 9. The adjusted R^2 for this model is 0.43.

Table 9. Multiple linear regression model for average sound absorption coefficient

Predictor	Estimate	Std. Error	t value	P-value
Intercept	0.3321610	0.0274197	12.114	<0.001
Seashell (%)	-0.0007356	0.0002777	-2.649	0.021
P0.075 (%)	-0.0182329	0.0078099	-2.335	0.038

The sign of the estimated coefficient for seashell content is negative, indicating that a higher percentage of Florida washed shell as coarse aggregates would reduce the average sound absorption coefficient. This agrees with the observation on the impact of seashell content on permeability and suggests that the addition of seashell may result in more isolated voids that do not contribute to sound absorption.

Similar statistical analysis was performed for the macrotexture in terms of MTD and the best subset model is shown in Table 10, which has a maximum adjusted R^2 of 0.81.

Table 10. Multiple linear regression model for MTD

Predictor	Estimate	Std. Error	t value	P-value
(Intercept)	-10.183802	5.371919	-1.896	0.085
Seashell (%)	-0.007525	0.001611	-4.670	<0.001
P9.5 (%)	-0.013058	0.004710	-2.772	0.018
Thickness (mm)	0.204288	0.081569	2.504	0.029

The sign of the estimated coefficient for seashell content is negative, indicating that a higher percentage of Florida washed shell as coarse aggregates would reduce the macrotexture of mixture surface and so may help reduce the tire-pavement noise generated due to tire tread impact.

5 Conclusions and recommendations

This study developed a procedure to predict the road traffic noise and resulting health impact from the design parameters of open-graded asphalt concrete (OGAC) that is used as pavement surface. This study also evaluated the incorporation of renewable seashell in OGAC as partial replacement of non-renewable natural aggregates for potential benefits of noise reduction and sustainable development.

Several empirical models were combined to correlate the mixture design parameters to the perceived road traffic noise and some health indicators. The scope of the models is limited to the following conditions: (1) OGAC as pavement surface; (2) traffic consists of only passenger cars traveling at a high speed of 96.6 km/h and with a high volume of 2000/h; (3) traffic noise is perceived near the roadway without considerations of barriers, trees, buildings and other items in between. Applications of the developed procedure to variations of several key design parameters of OGAC, including nominal maximum aggregate size (NMAS), percent passing No. 4 sieve, percent passing No. 8 sieve, and binder content, show that the NMAS has a noticeable impact on the car traffic noise level perceived by a receiver near the roadway and the resulting public health while other design parameters do not. In addition, the impact of variation of NMAS in the range of 4.75 mm to 12.5 mm is small. For a given NMAS, variations in the mixture design do not cause significant change in the perceived traffic noise and health. These results suggest that adjustments in the OGAC mixture design with an NMAS less than 19.0 mm may not have practical significance in changing the perceived car traffic noise and the health impact. This conclusion, however, cannot be extended to other pavement surface mixtures (e.g., ultra-thin wearing course, stone mastic asphalt, and thin overlay mixture) or truck traffic as they were not included in the scope of analysis in this study.

The laboratory evaluation of the incorporation of seashell in OGAC included three aggregate gradations, one PG 76-22 binder, Florida seashell and granite aggregates in the experiments. Test results showed that for different NMAS gradations, the coarse aggregates in OGAC may be replaced with seashell up to a certain percentage without causing statistically significant change in the mixture properties including Marshall stability, tensile strength, raveling resistance, and air-void content. With the increase of seashell content, however, the permeability, the acoustic absorption coefficient, and the macrotexture of OGAC were all generally reduced. This suggests that the inclusion of seashell in OGAC may increase the tire-pavement noise at high frequencies but reduce the tire-pavement noise at low frequencies.

With the above conclusions, the following recommendations are offered regarding the design of pavement surface mixtures:

1. When acoustic performance is to be included in the design objectives of an open-graded asphalt mixture, the NMAS should be selected in the range of 4.75 mm to 12.5 mm. Within this range, a smaller NMAS may be selected based on other mixture performance requirements such as raveling resistance.
2. For a given NMAS, the OGAC design may be optimized based on properties other than acoustic performance, such as permeability, friction, durability, tensile strength, and moisture resistance.
3. Wherever seashell is available, it is feasible to include it in OGAC as partial replacement of the coarse aggregates. It may not improve the mixture acoustic performance but helps sustainable development of the pavement.
4. Other pavement surface mixtures, such as semi-dense asphalt mixture, ultra-thin wearing course mixture, stone mastic asphalt, and thin overlay mixture, should be included in future studies for their design parameter impact on the perceived road traffic noise and public health when relevant field data become available.

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