EVALUATION OF ACOUSTIC ABSORPTION CHARACTERISTICS OF ASPHALT MIXTURES

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by

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AUTHORIZATION TO SUBMIT THESIS

This thesis of Wahid Hassan, submitted for the degree of Master of Science with a Major in Civil Engineering and titled "EVALUATION OF ACOUSTIC ABSORPTION CHARACTERISTICS OF ASPHALT MIXTURES," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

Highways traffic noise is a major issue all over the world. It is annoying to the residents who live nearby major transportation corridors. Noise pollution adversely affects the quality of their life. It also causes sleep disturbance and anxiety. Some of the noise abatement techniques such as noise barrier walls are costly and not effective all the times. Reducing the tire-pavement noise at the source is viable alternative to cut down the noise level. This study examined the use of impedance tube to measure the acoustic absorption of asphalt mixtures in the laboratory. The effect of various parameters on the acoustic absorption was investigated including aggregate gradation, aggregate type, binder type, percent air voids, and sample thickness. In addition, factors that could affect the acoustical performance of asphalt mixtures after pavement construction was also investigated including air void structure, surface texture, temperature, and surface conditions. Percent air voids and layer thickness were found to have a significant influence on the acoustic absorption of asphalt mixtures. An analytical model was proposed to estimate the acoustic absorption coefficient of asphalt mixtures during the design stage. A good correlation was found between predicted and measured absorption coefficients in the laboratory. In addition, a double-layer system of asphalt mixtures was found to be effective in providing improved acoustical performance that overcomes the issues associated with the use of open graded friction course as a wearing surface.

Keywords: Acoustic absorption, impedance tube, PFC, and double layer.

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DEDICATION

To the memory of my father who always supported me and inspired me to be a good human being.

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CHAPTER 1 INTRODUCTION

1.1 Problem Statement

Highway traffic noise is major issue worldwide. Residents, who live near highways feel disturbance due to noise. Noise can cause stress that could lead to sleep disturbance and anxiety (WHO Regional Office for Europe 2009). Moreover, it may affect safe driving because it can disrupt the concentration of drivers. Excessive sound is annoying or objectionable to human. The unwanted or objectionable part of sound is termed as noise. Noise pollution becomes a major problem in the current world therefore many researchers and transportation agencies around the globe are actively performing research to find ways of reducing noise to an acceptable level. Traffic noise contributed the major source of total environmental noise. A sound pressure levels above 70 dBA is common for major highway inhabitants. At this sound level irreversible loss of hearing can occur (Rosenhall et al., 1990). Noise pollution increases with the increase of traffic volume therefore it is becoming an important environmental issue throughout the world (Bernhard and Wayson 2005). To mitigate traffic noise, engineers worldwide use costly noise barriers (Sandberg and Easement 2002; Rasmussen and Sohaney 2012). Noise barriers cost about $2 million or more per mile (Rasmussen and Sohaney 2012; Hanson et al. 2004). In addition to the cost, this is not always possible because gaps are required for side streets and driveways. Sound also tends to diffract over and around noise barriers (Rasmussen and Sohaney 2012).

Recently, engineers proposed alternative pavement types and surfaces to mitigate traffic noise. This research study evaluated the acoustic characteristics of asphalt mixtures during the design stage in the laboratory and factors that may affect the acoustical performance of asphalt mixtures in the field. In the first part of this study, the author conducted comprehensive laboratory experiments to determine the main parameters that affect the acoustic characteristics of asphalt mixtures. The second part of this study developed an analytical model to estimate the acoustic absorption of asphalt mixtures. Based on the results the author proposed alternative asphalt mixture composite to maximize the acoustic absorption and reduce traffic noise. The last part of this study evaluated the factors that may affect the acoustical performance of asphalt pavements after construction.

1.2 Goal and Objectives

Constructing pavements that provide a low level of noise can save millions of dollars by potentially eliminating the need to build costly noise barriers or lowering the height of noise barriers. In this study, comprehensive laboratory investigation was conducted to identify the main factors that affect the acoustic characteristics of pavements with the aim of designing asphalt composites that provide higher acoustic absorption. In order to meet this goal, the following objectives were achieved.

- Study the effect of various parameters that may affect the acoustic absorption of asphalt mixtures during the design stage. These parameters include percent air voids, layer thickness, aggregate type and gradation, and binder type.
- Develop an analytical model for the acoustic absorption of asphalt mixtures. Such model can be used to estimate acoustical performance of asphalt mixtures in the design stage and before constructing the pavements.
- Examine the effect various conditions that may influence the acoustical performance after construction and beyond the design process. Such conditions include air void structure of distribution, aging, temperature, moisture conditions, and surface conditions (e.g., presence of dust).
- Correlate the acoustic absorption properties of asphalt mixtures measured in the laboratory to the change in noise level measured in the field.
- Develop recommendations on asphalt mixture characteristics that provide high acoustic absorption coefficients to reduce the level of tire-pavement noise at the source.

1.3 Thesis Organization

The thesis has five chapters. The first chapter represents the problem statement, objectives of the study, and thesis organization.

The second chapter documents the findings of previous research on the effect of various parameters including air void, thickness, temperature, surface texture, aggregate gradation, etc. on the acoustic absorption of asphalt mixtures. In addition, the mechanism of noise generation and noise enhancement, noise regulation policy, and basic terms of acoustic absorption are also discussed Chapter 2.

The third chapter describes the experimental methods used to measure the acoustic absorption of asphalt mixtures in this study. A two microphone impedance tube was used to measure the acoustic absorption of asphalt mixtures in accordance with ASTM standard E-1050-12 (ASTM 2012). Test sample preparation, testing, and characterization are discussed in detail in Chapter 3.

Chapter 4 analyzes the acoustic absorption measurements to evaluate the effect of various parameters on the acoustical performance of asphalt mixtures. Statistical analysis tools such as R and SPSS programs were used to analyze the acoustic absorption measurements. Based on the results, an analytical model for the acoustic absorption is developed. The model estimates the acoustic absorption coefficients of asphalt mixtures as a function of percent air voids and sample thickness. In addition, the acoustic absorption coefficients obtained from laboratory are compared to the noise level measured in the field in a previous study.

Chapter 5 summarizes the main findings of the study and provides recommendations for the future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The acoustic absorption coefficient is defined as the ratio of absorbed energy to the incident energy (Muehleisen et. al 2005). When a sound wave hits an object, some of the acoustic energy is reflected, while the rest is absorbed by the object (Figure 2.1). The part of the energy absorbed by the object is called sound absorption (Ongel et al. 2007), and it depends on the frequency and angle of incidence of the acoustic waves (Hanson et al. 2004). Pavement constructed using materials with higher absorption coefficients provide less noise. When sound waves strike a porous medium, the sound energy is dissipated through the pores. According to ASTM E1050, the normal incidence sound absorption coefficient defined as given in Equations 2.1 and 2.2.

$$\alpha = 1- |R|^2 \quad \text{.......................................(2.1)}$$

$$\alpha = 1- \frac{|Z-\rho c\,|^2}{|Z+\rho c\,|^2} \quad \text{.....................................(2.2)}$$

where,

R = Complex acoustic reflection coefficient.

ρc = characteristic air impedance.

c = speed of sound.

ρ = density of air.

Z = ratio of sound pressure acting on the surface of the material to the particle velocity normal to the surface. Acoustic absorption of pavement can be improved by changing the pavement physical and material properties. Sound which is generated due to tire pavement interaction also depends on pavement surface texture, tire and speed of the vehicle.

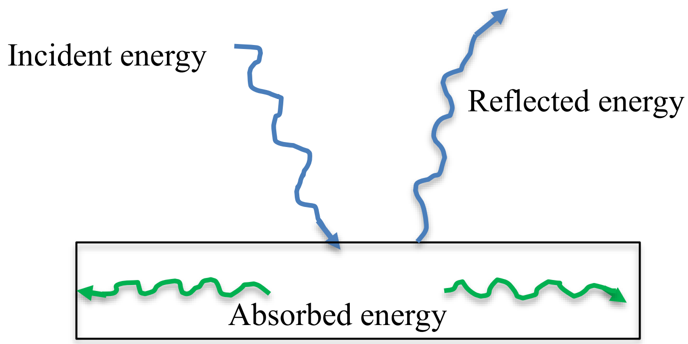


Figure 2.1 Acoustic absorption Mechanism

2.2 Sound and Acoustics Characteristics

2.2.1 Sound and Noise

In an elastic medium such as, air, water, and solids, sound is generated due to variation in pressure and this pressure variation is occurred by a vibrating surface (IEC 60050-801(1994)). As a result, pressure variation takes place. Sound propagates as a wave from the sound source at a speed of 343 m/s at 20 °C. Sound can be either desirable or undesirable. Undesirable sound is referred as noise (Rasmussen et al. 2007).

2.2.2 Frequency and Wavelength

Frequency is an important parameter to understand the perception of sound. Frequency is the number of cycles per second and is expressed in Hertz (Hz). Sound is usually composed of many frequencies combined together (Hansen 2001). Human with good hearing can hear the sound having frequency from 20 Hz (cycle/s) to 20000 Hz (cycle/s). Sounds below 20 Hz is called infrasound and above 20000 Hz is called ultra sound. Infrasound and ultra sounds out of human audible range. Therefore, sounds having those frequencies are not considered as a source of noise. Human sensitivity of hearing varies between 20 Hz to 20000 Hz. The peak sensitivity of human hearing is between 1000 and 4000 Hz. Noise in this frequency range is considered while strategies are applied to minimize noise (Bernhard and Wayson 2005). Wavelength is one of the important parameters for sound. It is defined as the distance between successive pressure pulses of a sound wave at a given frequency.

$$\lambda = \frac{c}{f}$$

where,

c = the speed of sound.

f = the frequency of sound.

2.2.3 Noise Metrics

Detailed representation of sound in terms of frequency and amplitude is very complex. Thus, to characterize noise simplified process has been developed. Noise is measured either by time-averaging or by taking maximum value. The choice between time-averaging and maximum value depends on the type of the event. For instance, in steady traffic flow time averaging value is considered, while for a single automobile maximum pressure is considered in measuring noise level. Human can hear sound having pressure amplitude with a factor greater than 10 million. Moreover, human response to sound pressure is not linear. Therefore, amplitude of the noise is represented in a logarithmic scale in terms of sound pressure level and is reported in decibels (dB). Mathematically, the definition of sound pressure level (SPL) is defined in Equation 2.3.

$$SPL = 20 \log (P_e/P_{ref}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.3)$$

Where, P_e is the effective pressure amplitude level in Pa and P_{ref} is the reference acoustic pressure level in Pa. The standard reference sound pressure level for sound in air is given in Equation 2.4.

$$P_{ref} = 20 \text{ X } 10^{-6} \text{ Pa} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.(2.4)$$

P_{ref} implies the smallest sound pressure that a healthy person can hear and in this pressure level the frequency is about 1000 Hz. Therefore, 1000 Hz frequency is the smallest frequency at which a person can hear sound. Since, sound pressure level is computed from a ratio and does not have unit so the reference sound pressure level should always be identified when reporting sound pressure level (Bernhard and Wayson 2005). Human can perceive 10 dB change in sound level. A 10 dB increment of sound pressure results twice as loud to normal human. Similarly, a 20 dB increase in the sound level is perceived as four times as loud by the normal human ear. The sensitivity of human ear to perceive noise makes noise mitigation challenging.

2.2.4 Octave Band and Weighting Scale

Analysis of sound source using frequency is very time consuming. To overcome this problem all frequencies are divided into different sets of frequencies which is called band. Each band has a specific range of frequencies. A band is called octave when its upper frequency is two times of its lower frequency. If the upper frequency of any frequency band is equal to cube root two times of lower frequency of that band then it's called one-third octave band (Equation 2.5).

$$f_2 = \sqrt[3]{2}\, f_1 \qquad (2.5)$$

where f_2 and $f_1$are upper and lower band frequency respectively. Each octave band represents the acoustic energy of that frequency range. For better understanding noise measurements are reported as octave band or one-third octave band (Bernhard and Wayson 2005).

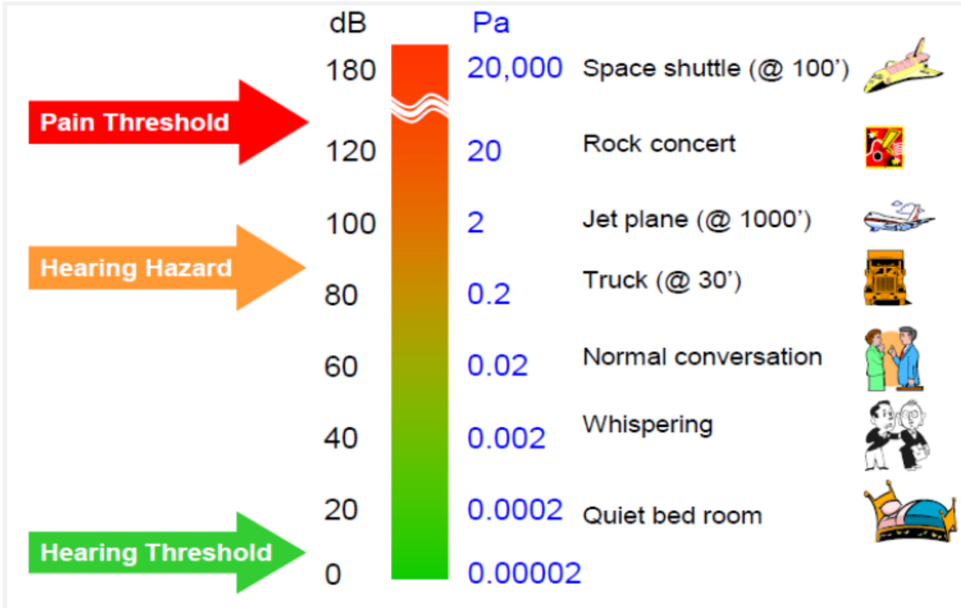


Figure 2.2 Common noise level (Bernhard and Wayson 2005)

2.3 Tire-Pavement Noise Generation Mechanism

Tire-pavement noise has been studying and analyzing since 1970. Noise generation due to tire-pavement interaction is a very complex mechanism. Therefore, to design quieter pavement better understanding regarding tire-pavement noise is necessary. When a tire rotates in pavement, some mechanisms radiates sound while some mechanisms amplify the sound (Ruhala 1999; U. Sandberg and Ejsmont 2002a) . There are several mechanisms that lead to noise generation including thread impact, air pumping, slip-stick, and stick-snap. In addition, there are other factors that contributes to sound enhancement including horn effect Helmholtz resonance, pipe resonance, cavity resonance, and carcass vibration. The reader is refereed to (Sandberg and Ejsmont 2002) for detailed discussion of these mechanisms.

2.4 Noise Abatement Techniques

A number of noise abatement procedures have been adopted by various transport authorities throughout the world to reduce the noise level at an acceptable limit. However, FHWA (2011) pointed out that there should be a strike balance between particular importance and feasibility. There are number of factors such as technical feasibility, the unique characteristics of highway generated noise, cost, overall public interest, aesthetic considerations should be taken into account before choosing a noise abatement technique (FHWA 2011). The noise abatement techniques include noise barrier walls, vegetation, buffer zone, private fencing, the use of insulating materials (in public or non-profit organizational structures such as places of worship, schools, hospitals, libraries etc.), in addition to traffic management. Traffic management can be used as a noise abatement measure which is used by most of the transportation agencies because of its effectiveness as well as less expensive in nature.

2.5 Noise Measurement Methods

Noise due to tire/pavement interaction should be measured accurately because the data which are collected from the measurement system will be used to understand the noise generation mechanisms and in identifying quieter pavement. Hence, numerous research studies have been devoted to developing tire/pavement interaction noise measurement method. In field, noise level can be measured by two methods: way side noise measurement and noise measurement at source (Bernhard et al. 2007).

2.5.1 Wayside Noise Measurement

Wayside noise measurement method measured noise form all the sources in roadway. This method measured the sound level using microphones. It considers traffic speed and classifications (Bernhard et al. 2007). There are three common types of wayside noise measurement method: Statistical Pass-by (SPB), Controlled Pass-by (CPB), and Continuous Flow Traffic Time Integrated Method (CTIM). Sound measurement techniques of these methods are similar.

Figure 2.3 SPB measurement apparatus (Rochat et al. 2010)

2.5.2 Noise Measurement at Source

Measuring noise at source i.e., 'noise near tire' is more accurate than the wayside measurement. Typically, there are two types of measurement techniques used all over the world for noise measurement at source. This includes Close Proximity (CPX) methods for sound pressure level (SPL) measurement and On Board Sound Intensity (OBSI) method. In CPX method, a test tire is mounted within a specially designated trailer that is towed by a passenger car. One or more microphones close to the test tire are located to measure the sound pressure level. Microphone position on the test tire according to ISO Standard is shown in Figure 2.4. The microphones are mounted inside an enclosed acoustical chamber to provide screening from winds and other traffic noise. In OBSI method, two pair of phase-matched microphones which are placed at both leading and trailing edge of the tire (AASHTO 2013a). The microphone is cabled to the interior of the vehicle where the signals are simultaneously captured on a recorder and processed by a real-time analyzer. The specially tuned microphone only picks up the noise of the tire-pavement interface; noise from other sources such as wind or other vehicles does not intervene.

A third category i.e., Acoustic Array Technology (AAT) method is also used for measuring tire/pavement interaction noise. This method is mainly used in laboratory with few on-road applications and exclusively used in research domain. There is no reported data available to correlate with in-situ measurement data in highway environment. Therefore, this method will not be elaborated in this paper, but details can be found elsewhere (Dumbacher et al. 1995).

Figure 2.4 NCAT close proximity trailer (Hanson et al. 2004)

Figure 2.5 OBSI testing setup

2.6 Relationship between source and wayside noise measurement

A number of studies have attempted to discover relationships between the source and wayside measurement techniques of tire-pavement interaction noise. This is particularly important when only one type of measurement technique available. Many researchers indicated a good relationship between CPX and SPB measurements if considered overall sound pressure levels (Sandberg and Ejsmont 2002). The relationship between CPX and SPB measurements was found to be on depended on both microphone position and frequency, but the two methods were shown to give similar rank orders of tires and pavement (Sandberg and Ejsmont 1985, Lédée 2004, Hanson 2004, Abbott and Watts 2004).

The first comparative data between pass-by and OBSI is presented by Donavon (1993). Tests were performed on DGAC surface with 7 different set of tire and sound pressure level was positioned 7.5 m from driving lane. From the linear curve fitting, difference between pass-by and OBSI data was observed 24.5 dBA. Similar difference also observed by later study (Donavan and Rymer 2003) who conducted both types of noise testing at test track in the state of California and registered that difference between sound pressure and sound intensity was 23.9 dBA. In this study, pass-by measurement was done 7.5 m from the driving lane. This study concluded that pass-by data can be predicted from OBSI data for a variety of pavement types within 0.5 dBA on average. When pass-by measurement was done 15m from the driving lane, the difference was 30.4 dBA. This indicates that propagation of noise is also a critical factor. This is in line with findings from the later study by Rasmussen and Sohaney (2012) which concluded noise difference between two measurement techniques was 28.2 dBA for pass-by measurement location of 15 m from the driving lane. A slightly higher offset value between two different types of measurement technique was observed by the recent study conducted by Florida Department of Transportation (Wayson et al 2009, 2014). Different value overserved for different researchers are probably due to site geometry, climatic conditions and distance from the road for microphone position. Furthermore, correlation between pass-by and OBSI method is depended on surface type. For concretes and dense graded asphalt surface, the relation is good while less favorable relation is overserved for porous asphalt pavement (Donavan 2011). This is because both noise generation and propagation to pass-by measurement location is affected by porous pavement.

Researchers also tried to correlate between CPX and OBSI data. Studies by (Donavan and Scofield 2004, Donavan 2005) showed that the difference between sound pressure and sound intensity is ~3 dBA. Although CPX method gives almost similar values of noise data but researcher encourage the use of OBSI technique because it can be used in continuous traffic stream.

2.7 Acoustic Absorption Measurement Method

There are several methods that are used to measure the acoustic absorption including:

- Impedance Tube – ASTM C 384/E 1050
- Impulse Response Measurements (Extended Surface Method) – ISO 13472-1
- Effective Flow Resistivity – ANSI S1.18; this technique is sometime preferred because the measurement is done at an angle from the pavement surface rather than perpendicular to it.
- Reverberation Time Method – ASTM C423-02; in this method the absorption coefficient of a test specimen is calculated by measuring the reverberation time before and after placing the specimen inside an enclosed space along with the noise source.

2.8 Effect of Air void and gradation on acoustic absorption

A pavement with higher percent air voids absorbs more sound, thus the higher the percent air voids, the quieter the pavement. Though air void in as a key factor in absorbing sound but also the size, connectivity and tortuosity of the voids affect the sound absorption. For dense graded mix with air void of 4% to 8% would have acoustic absorption coefficient between 0.1 to 0.2. Open graded and porous pavements with air void more than 15% would have acoustic absorption coefficient between 0.4 to 0.7 (Hanson et al. 2004). Interconnectivity of air voids affect the sound absorbed. As the interconnectivity of the voids increases, sound absorption increases (Hanson et al. 2004). For open-graded friction course (OGFC) surfaces, sound absorption increases as air void increases (Hanson and Waller 2006). There is a small correlation exists between air void content and noise level for DGA surfaces. In this section, previous studies regarding the effect of air voids on acoustic absorption is discussed along with their findings.

2.8.1 Kumar et al. 2011

In this study, the researchers measured the acoustic absorption of three different types of pavements referred as ISO test surface (asphaltic), state highway (asphaltic), and concrete road surface. An impedance tube was used for the measurements. Figure 2.6 shows the set-up in the field. The average acoustic absorption of the asphalt pavement was found to be about 39.13 % lower than the acoustic absorption of the concrete surface. They measured the maximum absorption over a frequency range of 400 Hz to 800 Hz and also from 800 Hz to 1600 Hz and they calculated the average acoustic absorption. The absorption coefficient values were found to be 0.019, 0.009 and 0.023 for ISO test surface, state highway and concrete road surface, respectively as shown in the Figure 2.7.

Figure 2.6 In-situ measurement of road sound absorption coefficient by impedance tube (Kumar et al. 2011)

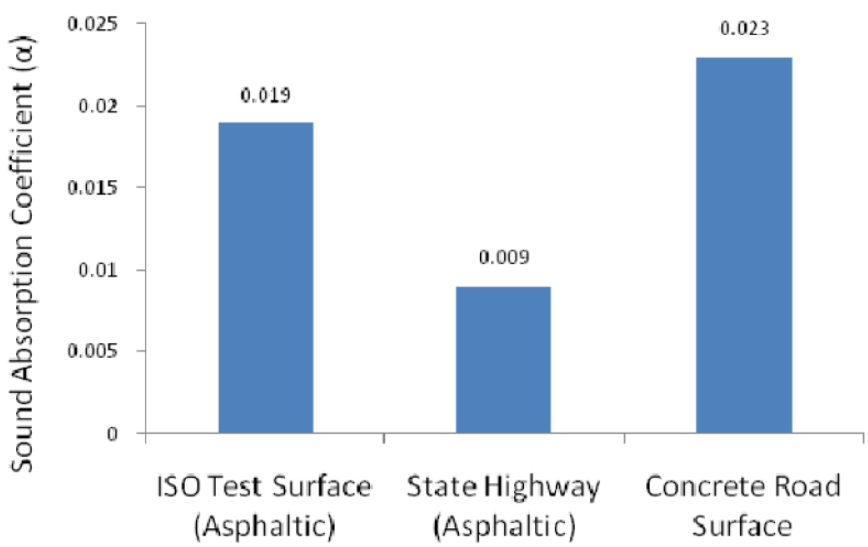


Figure 2.7 Comparison of sound absorption coefficients of three different road surfaces (Kumar et al. 2011)

2.8.2 Sandberg and Ejsmont (2002b)

In this study, the authors indicated that the open graded friction course (OGFC) or porous pavement had lower noise level compared to Dense Graded Asphalt (DGA). OGFC can reduce noise level by 3 to 5 dB(A) compared to non-porous HMA pavement. This is attained because porous asphalt pavement provides path for air trapped between the tire and the pavement surface to escape and thus reducing the horn effect and improving the sound absorption capacity. Pores are needed to be interconnected to achieve this objective. The additional advantages of these surfaces are reducing splash and spray and increasing frictional and hydroplaning resistance of HMA surface. From this study, it was also demonstrated that, the tire vibration is responsible for the noise at low frequency level (<1000 Hz). As the amplitude of the mega texture increased, the noise level also increased. Amplitude of the mega texture is mainly responsible for the noise level inside the vehicle.

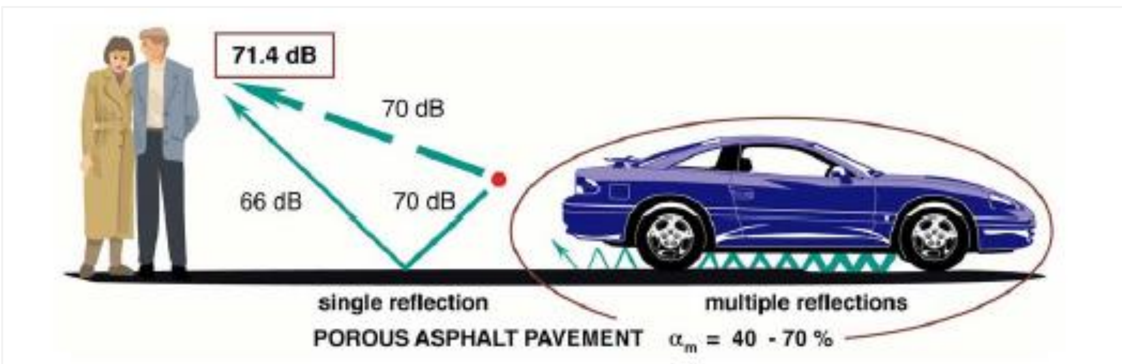


Figure 2.8 Sound absorption into a porous asphalt pavement (Sandberg and Ejsmont 2002)

2.8.3 Hanson et al. 2004

Hanson et al. (2004) conducted a study at National Center for Asphalt Technology to examine the effect of pavement type on the tire-pavement noise. They provided a review of a technical literature and analysis of the test results. Their report provided recommendations on the procedures for testing the noise level of pavement surfaces, in addition to the how to construct pavements with low noise level. The researchers tested OGFC in several states including Alabama, Nevada, Arizona, Texas, and Colorado. From their test, it was proved that OGFC can provide low noise level. In their study, the range of the thickness of test sections was between 3/4 in (19 mm) to 1 in (25 mm). The researchers examined nine sections with similar gradations. Field cores were obtained and the percent air voids was measured. The noise levels was measured using a close proximity method (CPX) trailer. CPX was developed in Europe and defined by ISO standard 11819-2 to measure the tire–pavement interaction noise at source (ISO 2000). In this method, a test tire is mounted within a specially designated trailer that is towed by a passenger car. One or more microphones close to the test tire are located to measure the sound pressure level. The microphones are mounted inside an enclosed acoustical chamber to provide screening from winds and other traffic noise. This acoustical chamber is particularly important to isolate the sound from other vehicles. The results showed that the noise level varied from 91.5 dB (A) (Arizona site) and 98.6 dB (A) (Alabama site). The researchers found that as the percent of air voids increases, the noise level decreases. Figure 2.9 represents the effect of percentage of air voids on noise level for the OGFC.

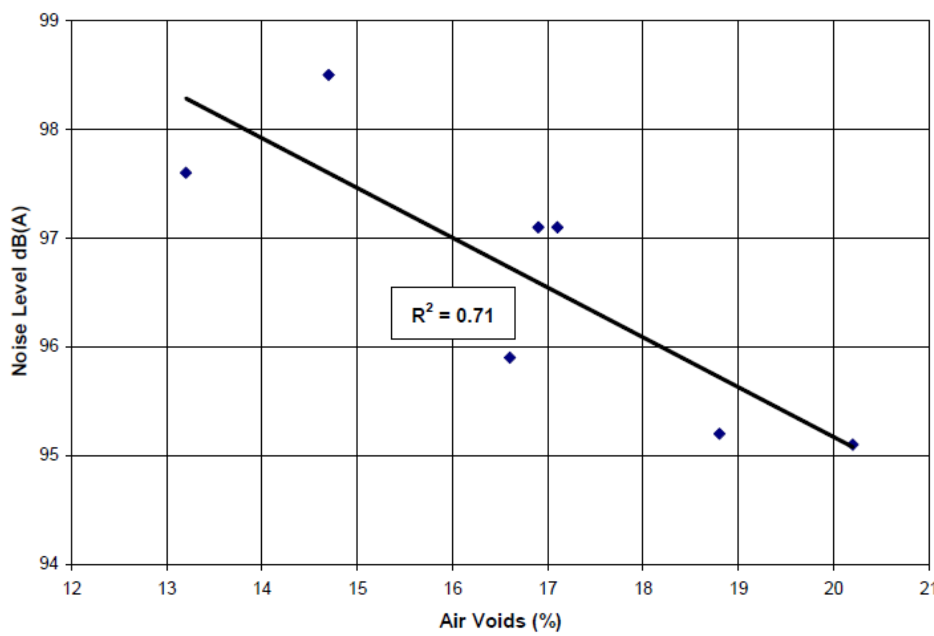


Figure 2.9 Effect of air void on noise level of OGFC (Hanson et al. 2004)

Unlike OGFC, the dense graded mix had a poor relationship between air voids and noise level (Figure 2.10)

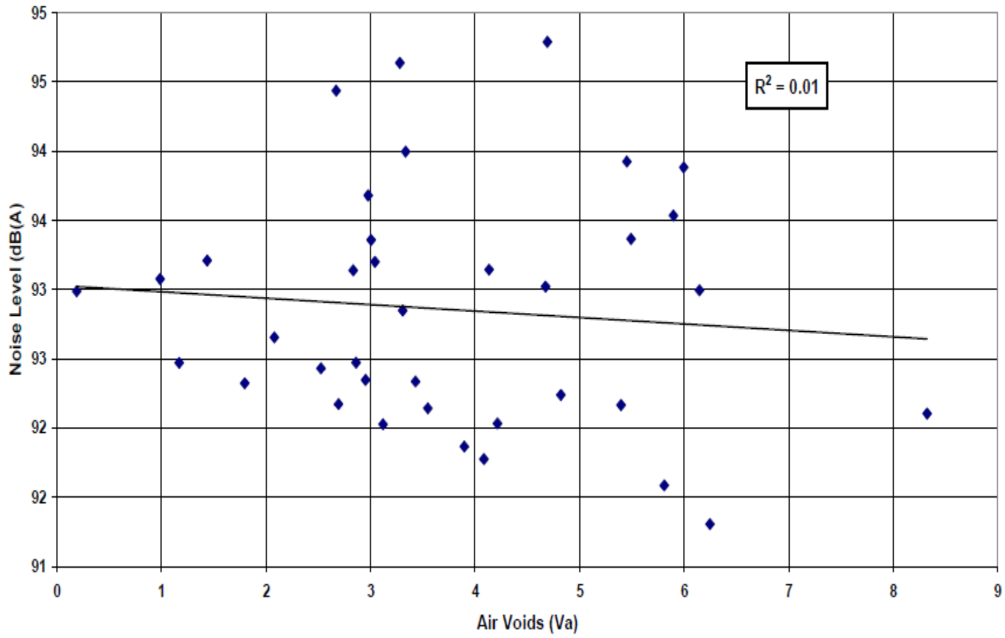


Figure 2.10 Effect of air voids on tire/pavement noise for dense graded HMA Mix (Hanson et al. 2004).

The researchers also measured the noise level on Stone Mix Asphalt (SMA) pavements in several states (Maryland, Colorado, New Jersey and Virginia). The average noise level for SMA mixes was between 96.8 dB(A) and 98.2 dB(A). Finally, the researchers recommended the use of impedance tube to measure the sound absorption in the laboratory. Sound absorption values from impedance tube can provide the material engineers with the capability to evaluate different mix design in the laboratory to optimize their noise reduction capability. Figure 2.11 is a schematic of the impedance tube built by NCAT for NCAT's noise studies.

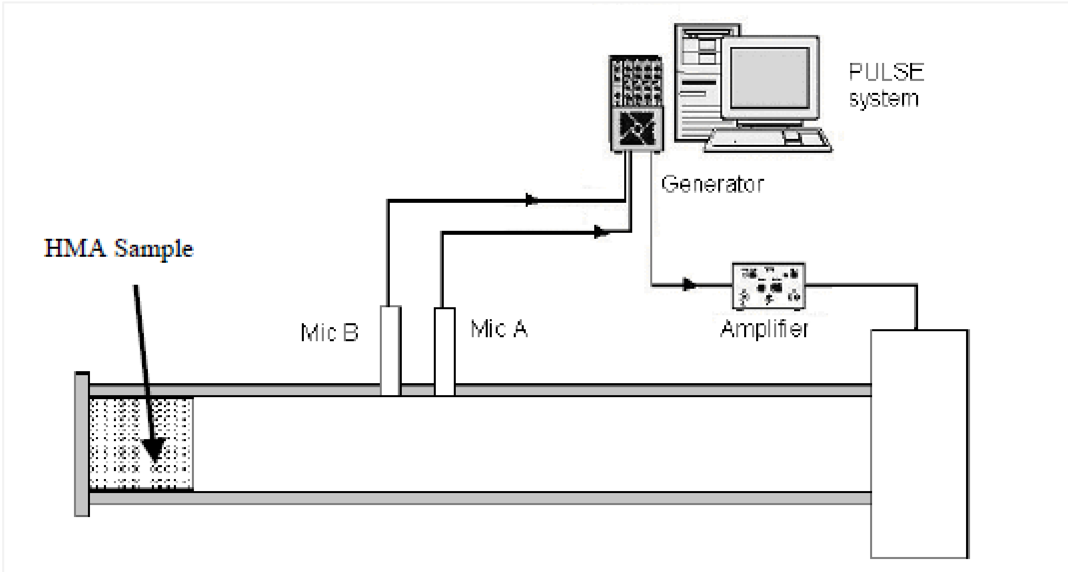


Figure 2.11 Experimental setup of sound absorption of HMA samples (Hanson et al. 2004)

2.8.4 Ongel et al. 2007

The researchers measured the acoustic absorption of 76 highway pavement sections in their study. Impedance tube was used for acoustic absorption measurements that allowed measurements from 200 to 1200 Hz. Figure 2.13 shows the impedance tube, microphones, analyzer, and speaker that used in this study. Four different asphalt mixture gradations were selected; dense graded, open graded, rubberized open graded and gap graded. The researchers found higher absorption values for open graded mixes compared to gap and dense graded mixes. The study found that the higher the air void, the higher the absorption. The acoustic absorption of open graded mix was found to be 0.20 while it was 0.04 for dense graded mix. The acoustic absorption is a good prediction of tire-pavement noise level especially at high frequencies. At frequency of 1600 Hz, the correlation between acoustic absorption and noise level was found 0.66 (Figure 2.12). They also found that, the porous asphalt pavements (10% to 20 % air void) reduced the noise level up to 4.5 dB compared to dense HMA surfaces.

They also found that there is a good correlation between acoustic absorption and noise level for frequencies over 1000 Hz for open graded mixes.

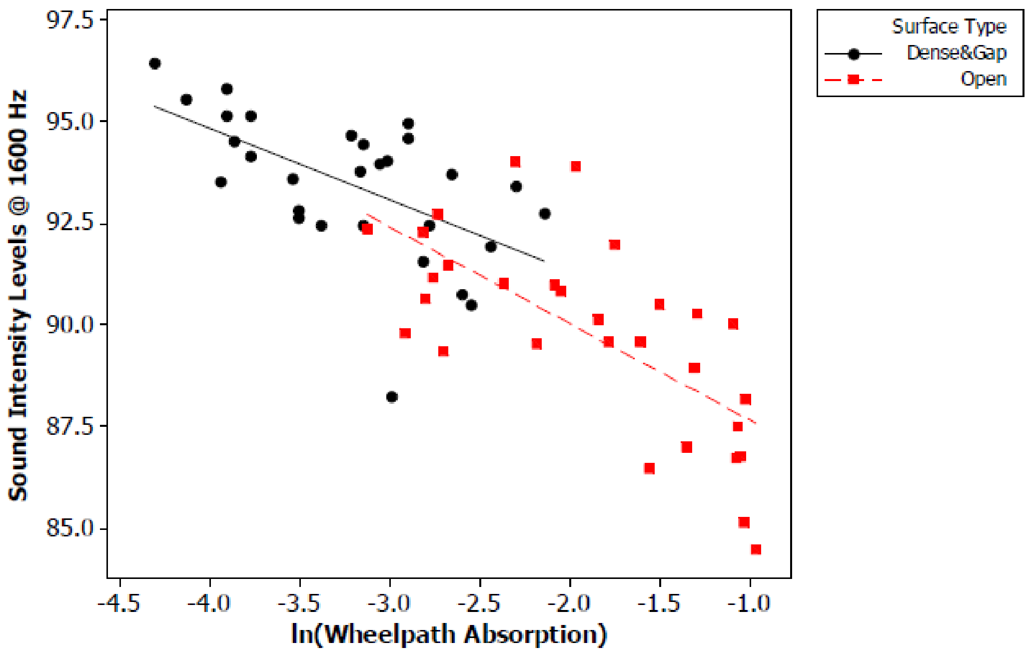


Figure 2.12 Sound intensity levels at 1,600 Hz versus the absorption values.

Figure 2.13 Impedance tube system (Ongel et al. 2007)

2.8.5 (Hanson et al. (2004) and Sandberg and Ejsmont (2002a)

Hanson et al. (2004) and Sandberg and Ejsmont (2002a) indicated that higher air void increases the sound absorption or decreases noise level due to two mechanisms. Firstly, the air trapped between the tire and the pavement surface moves through the void spaces in the porous pavement. As a result, horn effect of noise amplification is reduced. Secondly, higher air void provides increased sound absorption capability which reduces noise. However, higher porous surface is often exposed to clogging with dirt. At lower vehicle speed, voids are filled up with fine particles due to passing wheel which results in reduction of acoustic absorption of the pavement surfaces. To overcome this problem, European researchers recommended two-layer systems (Faure et al. 2000).

2.9 Effect of Thickness (Single and Double Layer) on Acoustic Absorption

Pavement layer thickness have also a significant effect on noise reduction. A relationship between the reduction in noise level (*ΔL*), the thickness of the surface layer (*e*), and the percent air voids (*v*) is given in Equation 2.6. (Sandberg and Easement 2002).

$$\Delta L = 0.005ev \qquad (2.6)$$

Asphalt samples with air void more than 20% are known as porous samples (Masondo et al. 2002). A single porous layer is very effective in reducing noise, but due to higher air void, porous surface is clogged easily by sand which reduces the sound absorption capacity of the porous surface (Masondo et al. 2002). In Europe, Twinlay porous asphalt was developed. Twinlay is made of two layers: coarse bottom layer and fine top layer. This section discusses the findings of some previous studies on Twinlay system.

2.9.1 DeMoss et al. (1999)

In this study, the researchers conducted the test using an impedance tube to determine the effect of layer thickness on acoustic absorption. The thickness of the layer varied from 1 to 3 in. It was observed that, for all aggregate sizes, the absorption coefficient peaked at lower frequencies as the thickness of the layer increased. In addition, while the 1 in-thick specimens had only one peak, the 3 in-thick specimens had two distinct absorption coefficient peaks, one at a lower and the other at a higher frequency as shown in the Figure 2.14. The effect of aggregate size had little to no effect on the measured absorption. The authors also explored the effect of the amount of fines in the mixture on noise absorption. They observed that with increasing percent of screenings, the absorption coefficient reduced or stayed somewhat constant but peaked at lower frequencies depending on the mixture type.

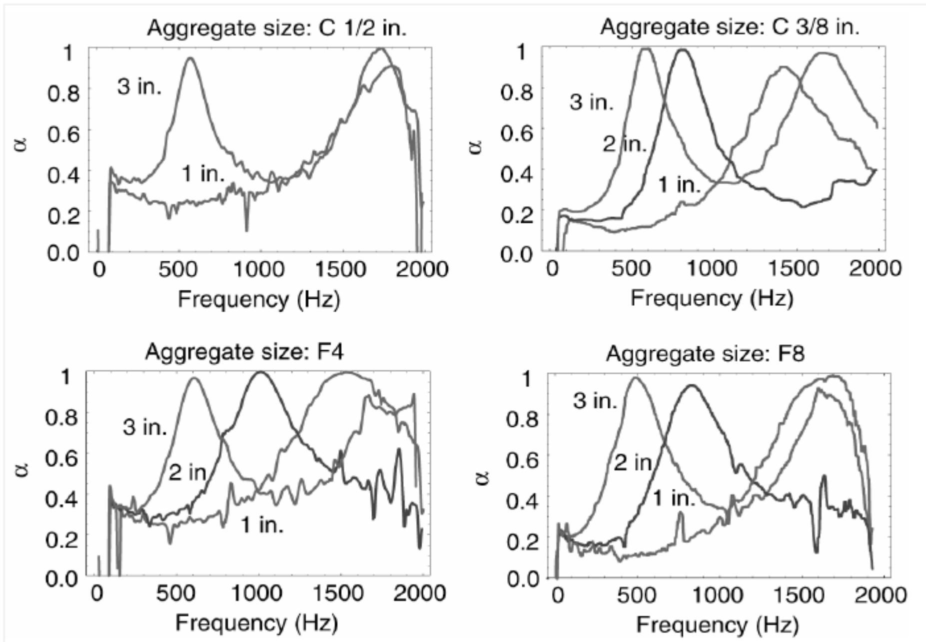


Figure 2.14 Effect of thickness on acoustic absorption (DeMoss et al. 1999)

2.9.2 (Masondo et al. 2002)

In this study, different types of mix design (as shown in Table 2.1) were chosen to find the acoustic absorption and compare the result of each mix design under consideration. For each type of mix design, experimental value was compared with the theoretical predictions. To calculate theoretical value Equation 2.7 and 2.8 were used (von Meier and Heerkens 1986).

$$\alpha = 1- \left|\frac{W-\rho c}{W+\rho c}\right|^2 \quad \ldots\ldots(2.7)$$

where,

$$W = -j\,\frac{\rho c}{\sigma}\sqrt{\left(1-j\,\frac{\Xi\,\sigma}{w\rho x}\right)x}\;.\;\cot\left[\,d\,\frac{w}{c}\sqrt{\left(1-j\,\frac{\Xi\,\sigma}{w\rho x}\right)x}\right] \quad \ldots\ldots(2.8)$$

σ : Porosity

ρ : Density of air (1.21 kg/m^3)`

Ξ : Specific flow resistance of the porous material

d : Thickness of the layer

χ : Configuration or structural factor of the porous material

Table 2.1 Mix design investigated

Mix Type	**Overall layer thickness**	**Top**	**Bottom**
1. Conventional Porous Asphalt	4 cm	-	-
2. Superfine Twinlay (proposed)	7 cm	2.5 cm	4.5 cm
3. Superfine Twinlay	8 cm	3.0 cm	5.0 cm
4. Superfine Twinlay	9 cm	3.5 cm	5.5 cm
5. Cityfalt	7 cm	2.5 cm	4.5 cm
6. Conventioanl Twinlay	7 cm	2.5 cm	4.5 cm
7. Fluisterfalt	7 cm	2.5 cm	4.5 cm

In this study, the influence of thickness on acoustic absorption was also investigated. In their analysis, 4 cm-thick porous layer shows higher absorption coefficient (α) at frequency 1000 Hz as compared to others. The 7 cm-thick Superfine Twinlay, 8 cm-thick Superfine Twinlay, 9 cm-thick Superfine Twinlay, Cityfalt, Twinlay and Fluisterfalt displayed more than two peaks over a broad frequency band. The 4 cm-thick porous asphalt layer displayed long wavelength compared to other double layers. Cityfalt, Twinlay and Fluisterfalt had higher acoustic absorption coefficients with shortwave-length over a broader frequency band than all the other mixtures under this study. A 4 cm-thick single layer of porous asphalt gave a high absorption at 1000Hz. Increasing the thickness from 7 cm to 8 cm resulted in higher sound absorption. Further increasing the thickness to 9 cm, the frequency of the first maximum point of absorption shifted further down to a lower frequency with a lower absorption at that point.

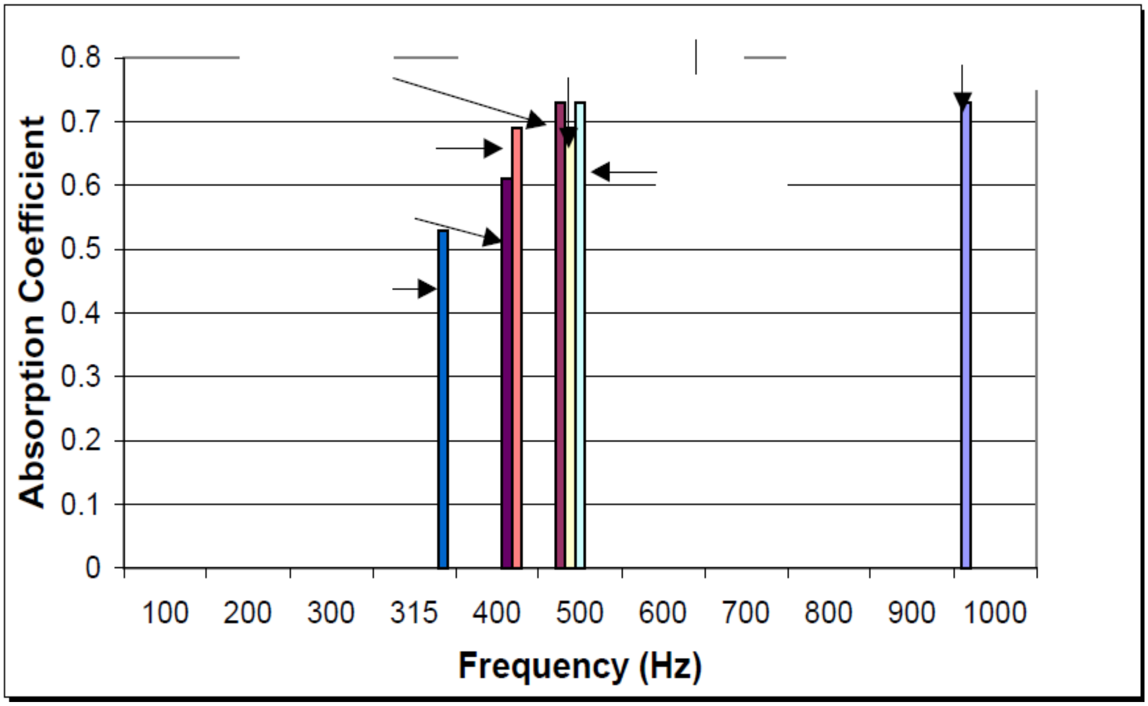


Figure 2.15 Absorption coefficient at various frequencies (Masondo et al. 2002).

2.9.3 (Bernhard and Wayson 2011)

Due to the problems associated with porous asphalt pavements in terms of surface clogging with dirt and winter maintenance (more amount of deicers is needed), the European researchers developed twin-layer system that can self-cleaning. In twin-layer system, top layer is constructed with small aggregate above porous layer to block the sand and dirt from penetrating into porous layer. The thickness of the overlay varies from 15 mm to 25 mm depending on the maximum size of the aggregate. The purpose of this type of gradation is to attain the gap-graded size distribution so that the finished pavement has the porosity that can manage the sand, dirt and water properly**.**

2.9.4 Gibbs et al. (2005)

In this study, several technologies were presented to construct quieter pavement in Europe including thin surfaced pavement, negatively textured gap-graded asphalt mixes, highly porous (more than 18% air void), single and double layer asphalt mixes and exposed aggregate concrete (EAC) pavement. In urban areas, where the speed of the vehicle is below 72 Km/h (45mph) and in the area which is subjected to heavy snow, thin surfaced, gap-graded mixes is used. Highly porous gap graded asphalt surface is used in high speed facilities area, rural area and in the area which has less or moderate winter condition. Highly porous surface becomes clogged under slow traffic. To gain noise reduction texture should always be negative. Positively textured surface such as chip seals increase noise.

2.9.5 (Smit and Waller 2007)

In this report, five types of pavements were constructed and assessed at NCAT test track with the aim of developing quieter pavement. Both single and double layer open-graded mixes were tested. Double layer of fine open-graded layer on top exhibited excellent quality in reducing noise. For double layer system, maximum absorption occurs between 800-1000 Hz, whereas for single system peak absorption occurred at high frequency. In a double layer system, a reduction in sound pressure level and intensity level is observed.

2.10 Effect of aging on acoustic absorption

Acoustic performance of the pavement decreases with time due to traffic and environmental effects. Porous pavement with initial low noise level may lose its acoustical performance with time as compared to dense pavement surface (Kephalopoulos et al. 2012). Trevino and Dossey (2009) showed that porous pavement gets louder with time. Researchers hypothesized that the air void in the porous surface gets clogged with dirt over the time. Therefore, sound level is increased. The researchers indicated that further research is required to validate their hypothesis. Correlation between noise level and aging of asphalt pavement was found to be significant where noise level increased with pavement age (Bennert et al. 2005).

Noise measurements were conducted on a high volume, multilane road in California for 12 years (Illingworth & Rodkin, Inc 2011). For pass-by noise measurements, continuous flow traffic time integrated method (CTIM) was used and on-board sound intensity (OBSI) method was used to measure the noise for tire-pavement interaction. Results from CTIM test showed that noise level increased by 3 dB(A) over 12 years as shown in Figure 2.16. Similar trend was also observed for the OBSI results as shown in Figure 2.17.

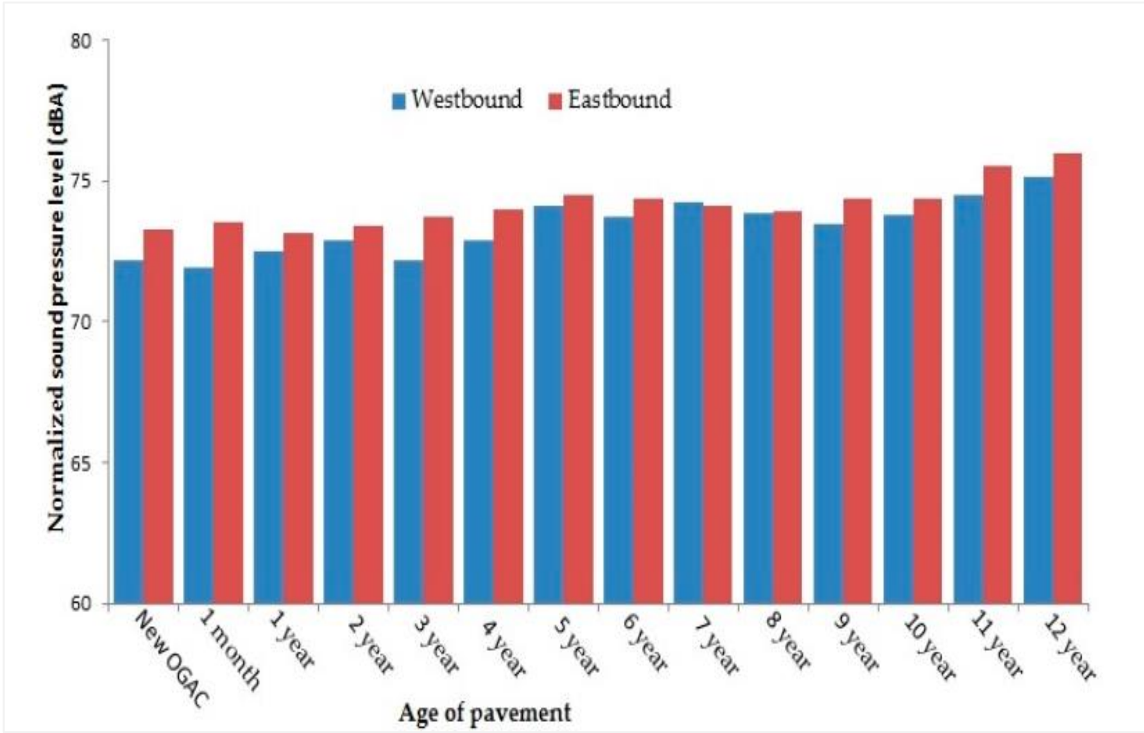


Figure 2.16 Noise level measurement using CTIM method (Illingworth & Rodkin, Inc 2011).

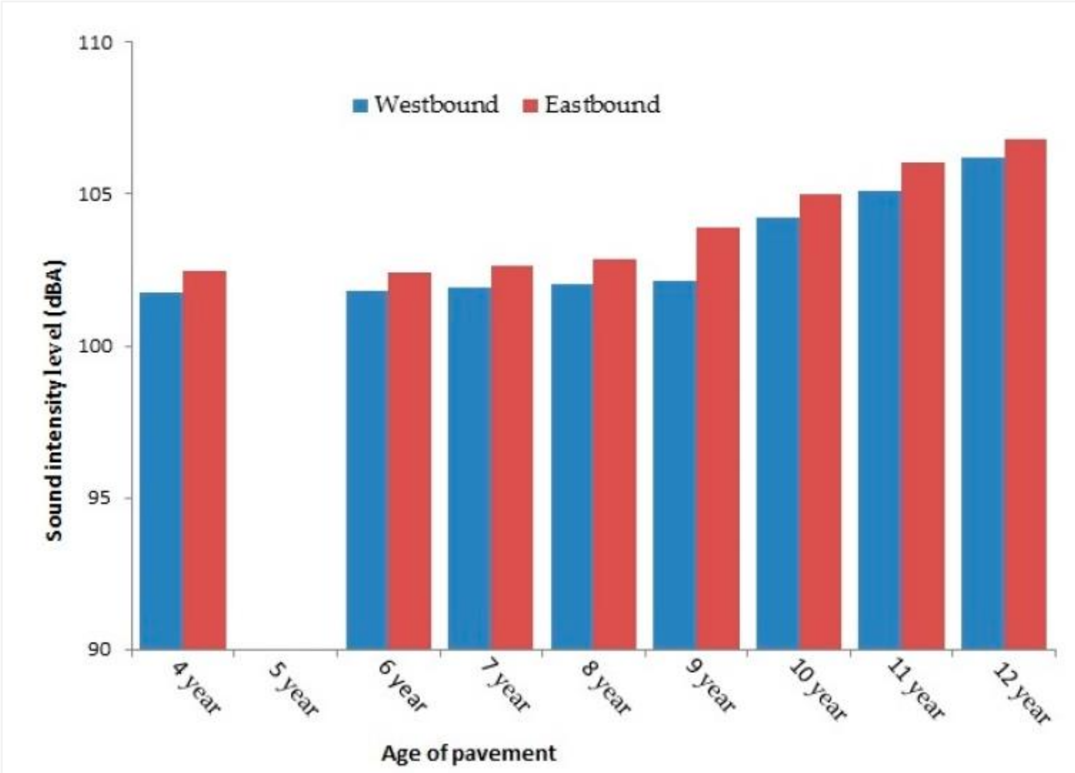


Figure 2.17 Noise level measurements using OBSI method (Illingworth & Rodkin, Inc 2011)

Scofield and Donavan (2003) used asphalt rubberized friction course (ARFC) was used as an overlay over a Portland cement concrete (PCC) surface with the aim of reducing noise level. Data was collected using NCAT CPX trailer and the results showed that the acoustical performance of ARFC reduced with time. To identify the acoustical longevity of ARFC surface, another study was performed by ADOT (Donavan 2012). Donavan (2012) used OBSI and wayside noise measurements and they found 0.7 dB(A) increment of noise level per year for ARFC surface.

NCAT conducted tire-pavement noise measurements in Colorado to determine the relationship between the noise level and pavement age. Ten dense graded HMA pavements were evaluated in this study. Figure 2.18 shows the results of noise level versus age of pavement. As expected, the older the pavement, the higher the noise level.

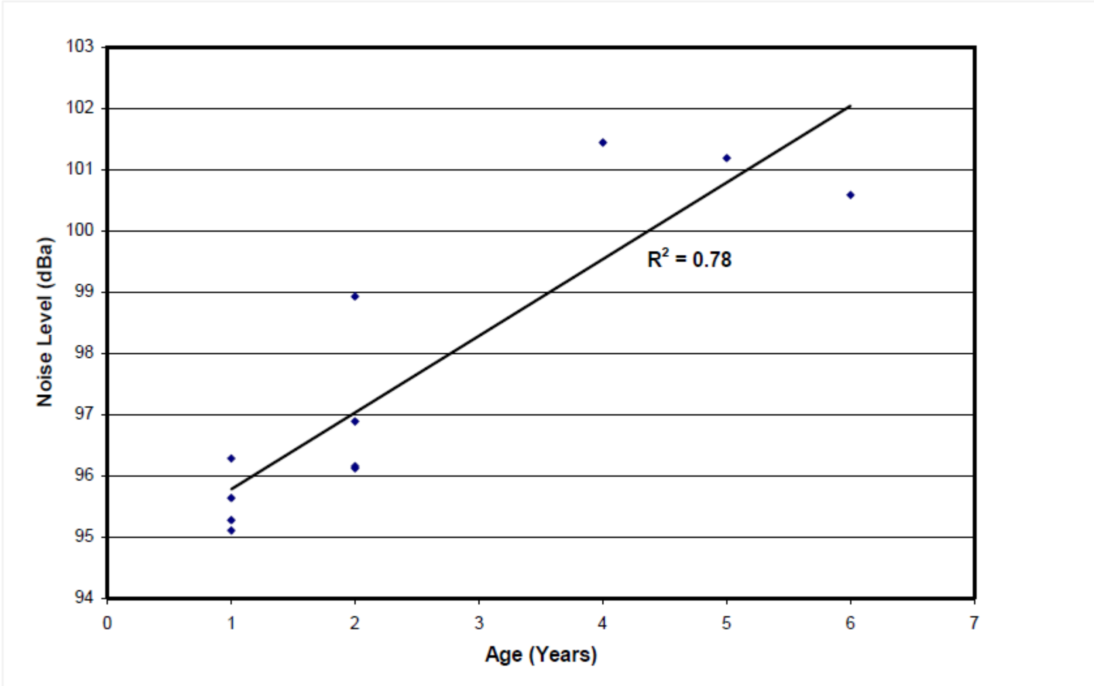


Figure 2.18 Effect of Age of Pavement on Noise (Hanson et al.2004).

2.11 Effect of Texture on Acoustic Absorption

The noise heard outside and inside the vehicle depends on the wavelength of the surface texture (Rasmussen and Donavan 2009). At highway speed, texture wavelength of 10 to 50 mm is responsible for the noise heard outside the vehicle while a texture wavelength of 20 to 200 mm is responsible for the noise heard inside the vehicle (Rasmussen and Donavan 2009). In general, it is widely accepted that pavements with a macrotexture of 0.5-50 mm (0.02 to 2 in.) wavelength are usually noisier, yet a microtexture less than 0.05 mm (0.02 in.) wavelength is usually beneficial as it provides paths for noise to escape.

Tire- pavement noise is greatly affected by surface texture. In general, surface texture helps to increase friction. Surface texture changes after the construction due to traffic, environment and the combination of both which referred as aging of texture (Kohler and Harvey 2010). Bernhard and Wayson (2011) showed that negative texture with characteristic length less than 10.0 mm tends to reduce noise. However, texture of other sizes and types tends to increase noise.

In general, the increase in microtexture decreases the tire-pavement noise (Abo-Qudais and Alhiary 2005). Abo-Qudais and Alhiary (2005) measured the skid resistance by using British Pendulum. However, traffic noise increases as the depth of the macrotexture increase (Gardziejczyk and Berengier 2000). Sandberg (1987) indicated that there is a strong correlation between road noise level and road texture. Such correlation can be positive or negative depending on frequency level. Sandberg (1987) also demonstrated that it is not possible to determine whether a rougher texture means a higher A-weighed noise level. At high frequency, noise level decreases as texture increases whereas at low frequency noise level increases as texture increases. The similar relationship between noise and texture was found for asphalt pavement in another study (Donavan and Rymer 2003; Hanson et al. 2004).

2.12 Effect of Pavement Stiffness on Acoustic Absorption

Effect of pavement stiffness on tire-pavement noise is not significant according to Sandberg (1987). Noise level can be minimized by constructing the pavement is such a way that it has same stiffness as tire (Rasmussen et al. 2007). This hypothesis was used to build asphalt pavements using rubber binders to reduce the level of tire-pavement noise. Sandberg (1987) indicated that stiffness may affect the noise generation. Stiffer pavements may have higher noise level. Concrete pavements are noisier compared to asphalt pavements since the concrete pavements have higher stiffness. Tire stiffness has also an impact on the overall pavement noise. If all the parameters are same, then softer tire results in less noise level (Rasmussen and Donavan 2009). Though effect of stiffness on tire-pavement noise generation is still a contentious fact (Descornet 2005) but data from various studies showed that noise generation is affected by pavement stiffness (Sousa et al. 2004).

2.13 Effect of Maximum Size and Gradation

Several researches and studies have been performed to identify effect of maximum aggregate size on noise mitigation of roads. Kowalski (2007) used tire-pavement testing apparatus (TPTA) to evaluate the effect of aggregate size on noise generation. The TATP consists of a fixed drum rotating on a fixed circular plate that has a diameter of 4.1 m. The test sample is about 1/6th of the circumference. This apparatus has two main limitations. First, the wheel cannot rotate at any speed above 48 km/h which is below the typical highway speed. Second, the test sample preparation is complicated. Another problem associated with this experiment was compaction of porous friction course (PFC) in the convex mold. Kowalski (2007) used near field noise measurement system to measure the tire-pavement noise using the TPTA. The results from this study showed that mixtures with 19 mm nominal maximum aggregate size (NMAS) had higher noise level compared to mixtures with 9.5 mm NMAS. Dense graded mix with coarser aggregates had 7dB(A) higher sound intensity level compared to dense graded with fine aggregates as shown in Figure 2.19 (Donavan 2006). Noise data obtained from four European countries showed similar trend as shown in Figure 2.20.

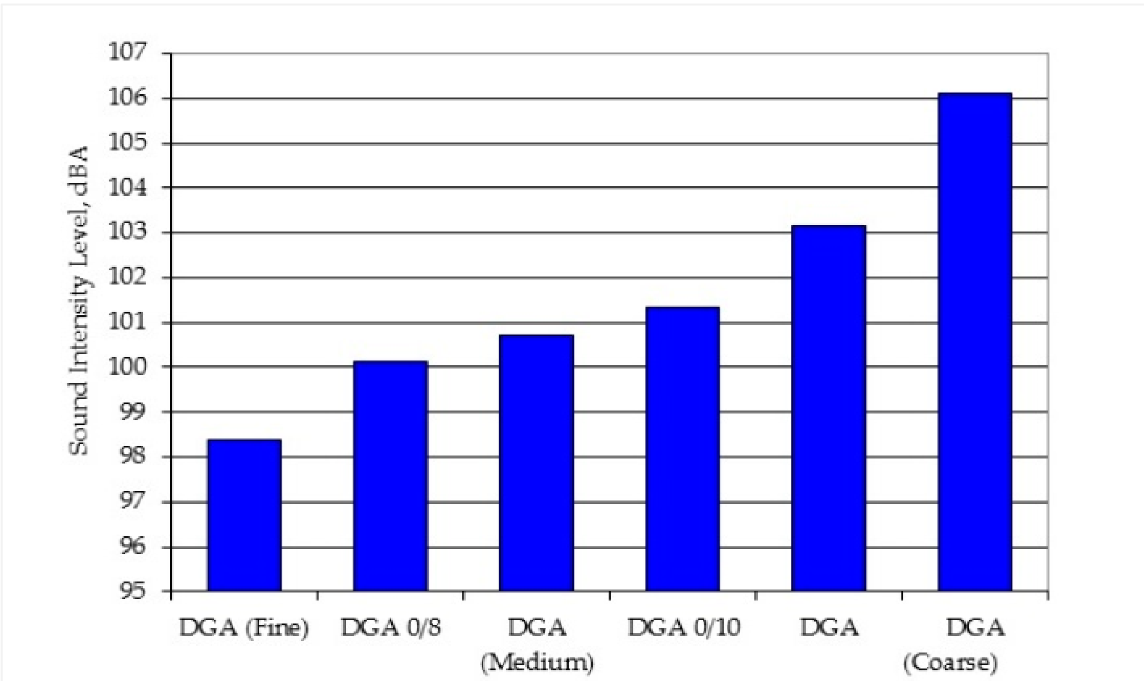


Figure 2.19 Noise performance of dense graded asphalt (DGA) pavements of varying aggregate size for four european countries (Donavan 2006)

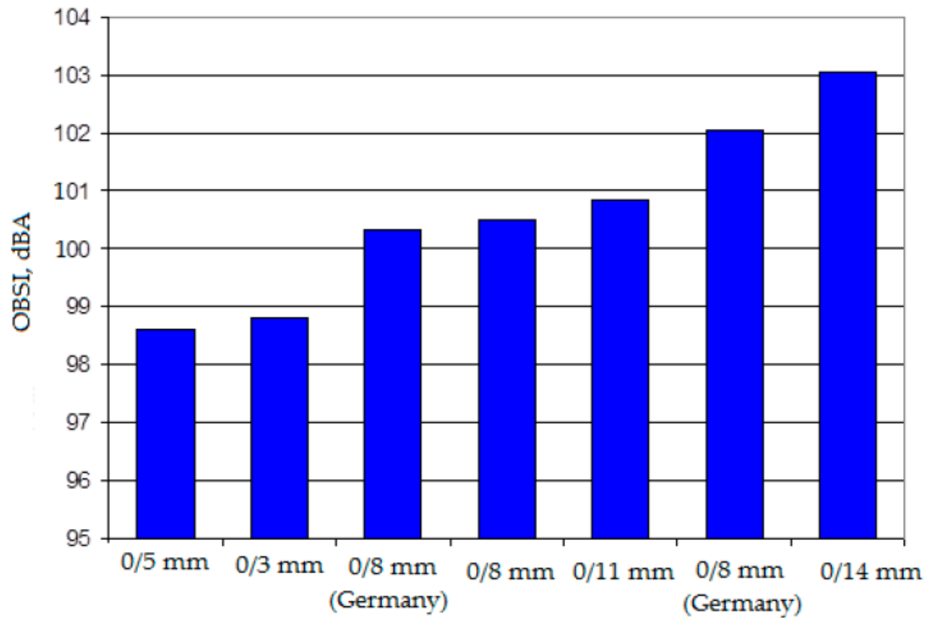


Figure 2.20 Noise performance of stone mosaic asphalt (SMA) pavements of varying aggregate size for four european countries (Donavan 2006)

Other studies also confirmed that fine graded pavement surface had lower noise level compared to coarse graded pavement (Timm et al. 2006). The tire experience less deformation on surface with small aggregates. Therefore, the air entrapped between the tire and pavement faces less squeezing which generates less noise as compared to larger aggregate surface. (Sousa et al. 2004). Meiarashi et al. (1996) observed that decreasing the NMAS would reduce the tire-pavement noise. Hanson et al. (2004) showed that open graded mixture with coarse aggregates gradation generates more noise than dense graded asphalt mixes. The study was conducted using NCAT CPX trailer. Open graded mixture with finer aggregates provided the quietest pavement among all the pavements in the study. Hanson and Waller (2006) performed noise analysis on HMA surfaces in Colorado. A CPX trailer was used for noise measurements. The results showed that the coarse graded asphalt mixtures produced higher noise. The fineness modulus, which is generally used for Portland cement concrete design can be used as an indicator of gradation of asphalt mix. The higher fineness modulus represents coarser mix which generates more noise due to tire-pavement interaction (Sandberg and Ejsmont 2002a)

2.14 Effect of Temperature

Effect of temperature on tire-pavement noise was investigated by Fabienne and Pichaud (2007). The temperature was varied from 5 to 10 °C during noise data collection and SPL method was used for noise measurements. It was found that the noise level decreases with temperature. For every 10 ° C increase in air temperature, the noise level was reduced by 1 dB(A) for dense asphalt pavements and 0.6 dB(A) for porous pavements. In this study, it was also found that the effect of temperature on acoustic absorption is dependent on frequency of noise. Rochat (2010) investigated the relationship between sound level and air temperature for data sets collected in three different studies. The data sets were collected using wayside measurement techniques. It was found that the effect of temperature on sound level can be affected by pavement type and vehicle type. For most of the data sets, it was found that the increase in temperature resulted slightly in a decreased sound level. However, there are some data sets that indicated slight increase in sound levels as the temperatures increased. The effect of temperature on sound pressure level is more noticeable for PCC pavements as compared to DGAC and OGAC with an exception for heavy trucks in the OGAC category which showed an increase in sound level with increase in temperature. This is contrary to research findings from other European studies, which showed the temperature effect is more prominent for DGAC surfaces than PCC surfaces(Bendtsen et al. 2009; Sandberg and Ejsmont 2002b).

2.15 Aggregate Type

Very few studies have been conducted to evaluate the effect of aggregate type on acoustic absorption and it was found that aggregate type does not have direct impact on the generation of traffic noise (Sandberg and Ejsmont 2002a). Although the aggregate type does not have an effect on absorption, the microtexture of the aggregate does (Gardziejczyk and Berengier 2000). Huang et al. (2007) indicated that binder produces different film thickness depends on aggregate type that may affects the noise level.

CHAPTER 3 MATERIALS AND METHODOLOGY

3.1 Introduction

Laboratory asphalt mixture test samples were prepared to evaluate various parameters (e.g., aggregate type, aggregate gradation, sample thickness, percent air void, and binder type). Four different types of aggregate were used in this study; gabbro, basalt, limestone and lightweight. Gabbro and limestone were obtained from the State of Qatar. Basalt was acquired from a source in Idaho and the lightweight aggregate was from Texas. Two binder types were used in sample preparation; unmodified binder (PG 64-28) and rubber modified binder (PG 76-22)

3.2 Aggregate Gradation

The research team selected two types of aggregate gradations to produce open graded and dense graded asphalt mixtures. The aggregate gradation for dense graded and open graded asphalt mixtures are presented in Table 3.1 and Table 3.2, respectively.

Table 3.1 Aggregate gradation for dense graded mixes

Sieve size	25mm (1in.)	12.5mm (1/2 in)	9.5 mm (3/8in.)	4.75 mm (#4)	2.36mm (#8)	0.3mm (#50)	0.15mm (#100)	0.075mm (#200)
Percent passing	100	100	100	85.6	38.4	15.4	11.9	7
	100	100	85.8	72.4	33.3	14.1	11	6.5

Table 3.2 Aggregate gradation for open-graded mixes

Sieve size	25mm (1in.)	12.5mm (1/2 in)	9.5 mm (3/8in.)	4.75 mm (#4)	2.36mm (#8)	0.6mm (#30)	0.3mm (#50)	0.075mm (#200)
Percent passing	100	100	59.7	31.6	18.9	14.3	2.2	2.7
	100	100	43.8	16.4	3.1	2	2	1.8

3.3 Aggregate Characteristics

Road texture is one of the primary factors that affects tire-pavement noise. Aggregate gradation and aggregate type influence the texture of the road and its ability to maintain the texture over time under traffic. Road macrotexture is associated with larger irregularities in the surface and is influenced by aggregate gradation and aggregate shape. In this study, the resistance of aggregate to abrasion and polishing was evaluated.

Los Angeles abrasion test was conducted to evaluate the resistance of aggregates to abrasion and breakage. Aggregate should be hard and tough enough to resist crushing, degradation and disintegration. The test was conducted in accordance with the ASTM C131 standard test "Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine". In this test, aggregate samples are placed inside Los Angeles Abrasion drum that contains a number of steel spheres. As the drum rotates, aggregate particles are crushed with steel spheres and other aggregates particles resulting in abrasion and grinding of the aggregate particles. The aggregate samples are sieved to measure the percent loss. Figure 3.1 shows the Los Angeles abrasion machine at the University of Idaho. Figure 3.2 shows the aggregate samples before and after Los Angeles abrasion test.

Figure 3.1 Los Angeles abrasion machine

(a) Limestone before L.A. test

(b) Limestone after L.A. test

(c) Basalt before L.A. test

(d) Basalt after L.A. test

(e) Gabbro before L.A. test

(f) Gabbro after L.A. test

(g) Light weight aggregate before L.A. test

(h) Light weight aggregate before L.A. test

Figure 3.2 Aggregate before and after abrasion test

The abrasion value (percent loss) for gabbro, basalt, limestone, and lightweight aggregate was 15%, 19%, 20%, and 54%, respectively as shown in the Figure 3.3. Gabbro has better resistance to abrasion and degradation compared to limestone and basalt. A Los Angeles abrasion value equal or less than 45% is suitable for base layers of lightly trafficked road. So, lightweight is not strong enough to resist abrasion. Aggregates with a Los Angeles abrasion value of less than 30 is considered strong enough for use in road wearing courses and surface treatments.

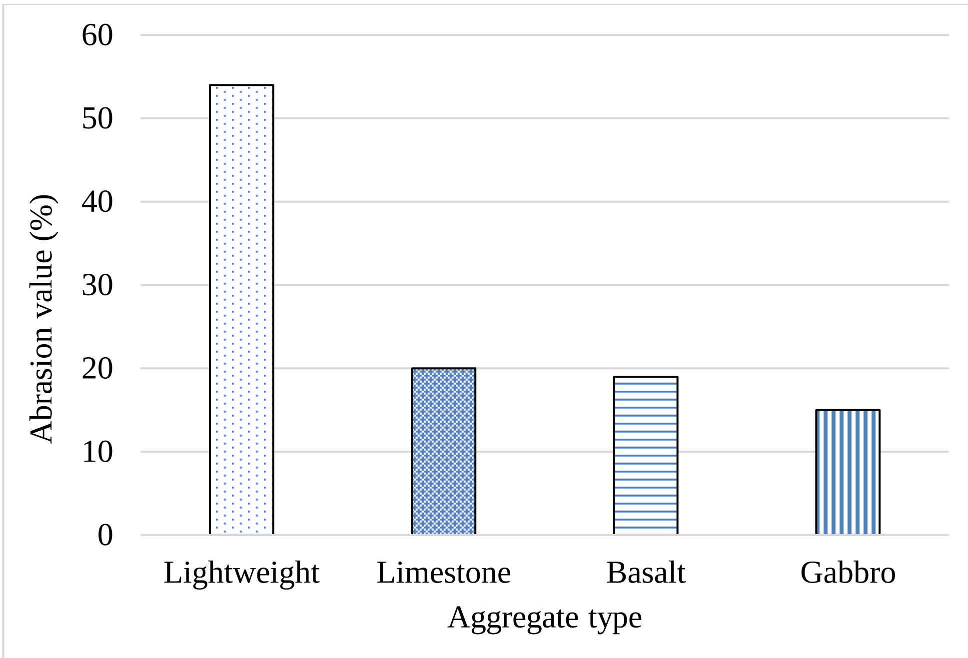
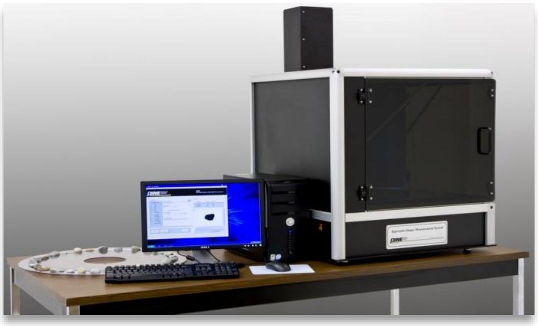
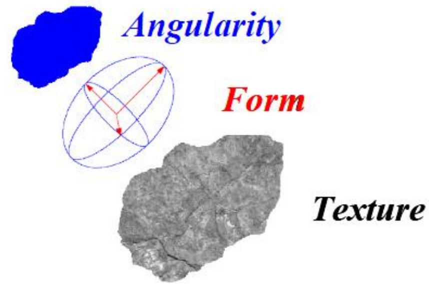


Figure 3.3 Abrasion value for different types of aggregate.

In a previous study (Masad et al. 2011), the aggregate imaging measurement system (AIMS) system and micro-Deval test were used to study the aggregates shape characteristics and abrasion resistance and durability of aggregates. Gabbro and limestone samples from two different sources in Qatar were tested. The AIMS was used to quantify aggregate shape characteristics (Figure 3.4a). The AIMS is an automated tool that is used to determine aggregate shape characteristics (form, angularity, and surface texture) through image processing and analysis methods (Figure 3.4b).



(a) AIMS



(b) Analysis properties (Pine 2004)

Figure 3.4 Aggregate image measurement system (AIMS)

In addition, the researchers (Masad et al. 2011) used the micro-Deval test to evaluate the resistance of the aggregate samples to abrasion and polishing. This test was conducted according to AASHTO (2002) standard procedure. In this test, the aggregates test sample is submerged in water inside a container and steel spheres are added. The container in placed in the micro-Deval machine that rotates at 100 rpm. The aggregate sample is then poured and washed over a 1.18-mm sieve, and the steel balls are taken out. The weight of aggregates retained on the 1.18 mm sieve is recorded, and the percent loss is calculated from the original weight of the aggregate sample. The results showed that gabbro aggregate had less percent loss after the micro-Deval abrasion test as shown in Figure 3.5. In addition, the gabbro rock was found to be more angular and had higher texture compared to limestone as shown in Figures 3.6 and 3.7.

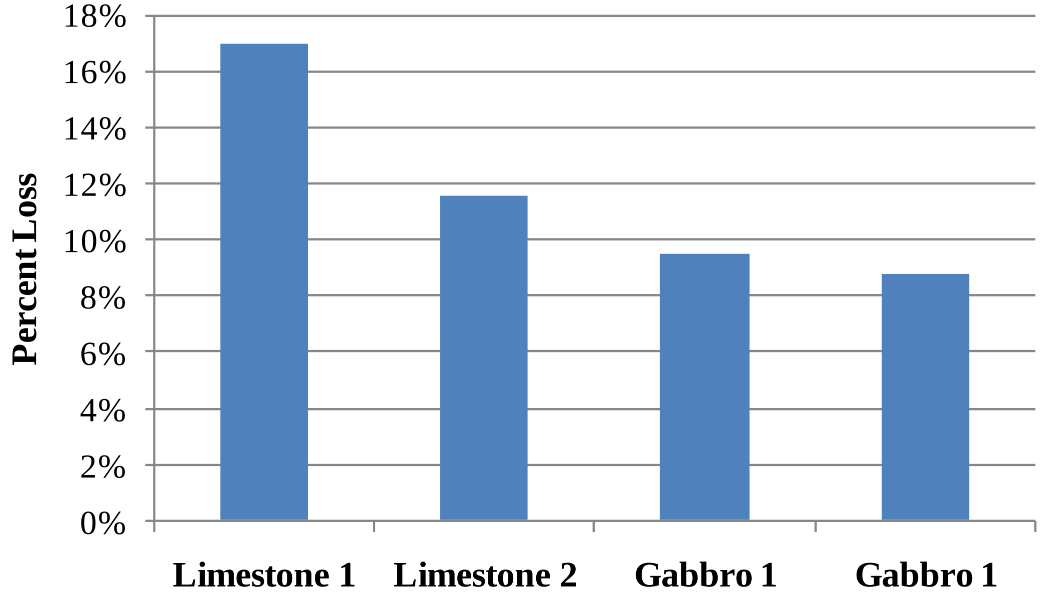


Figure 3.5 Micro-Deval abrasion loss (Masad et al. 2011)

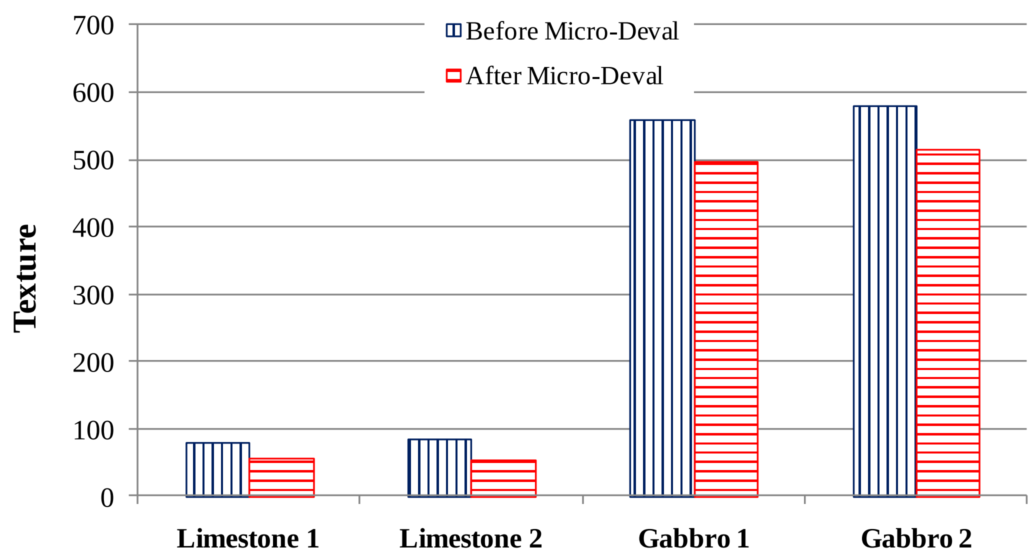


Figure 3.6 Average texture index before and after the micro-deval test (Masad et al. 2011)

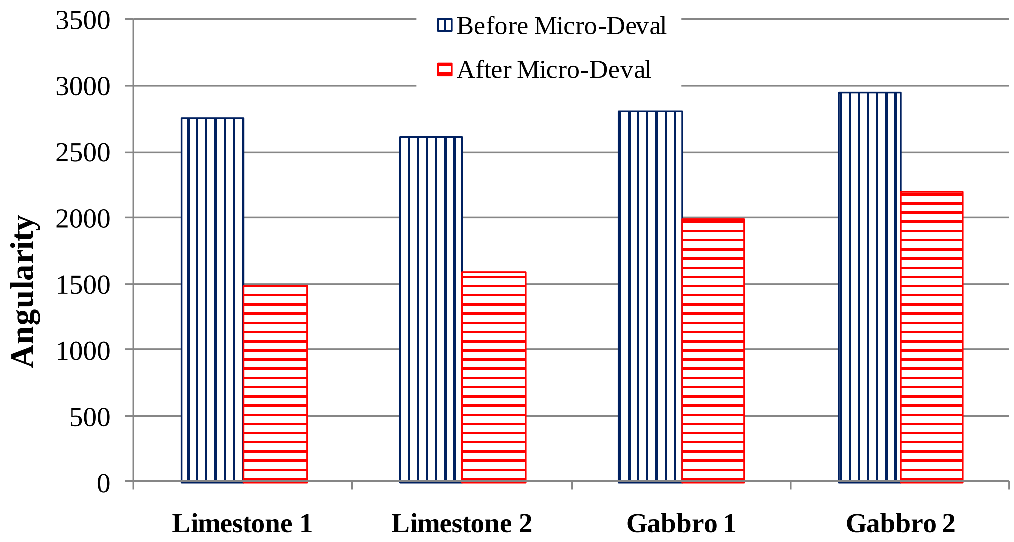


Figure 3.7 Average angularity index before and after the micro-deval test (Masad et al. 2011)

In addition to the gabbro and limestone aggregates, the researchers used the AIMS database at Texas A&M (Chowdhury et al. 2017) to determine resistance of the lightweight aggregates (used in this study) to abrasion and polishing. Figure 3.8 shows that the angularity of the lightweight aggregates decreased after the micro-deval test, while the texture increased. The texture may have increased due to creating more voids at the surface of the lightweight aggregates.

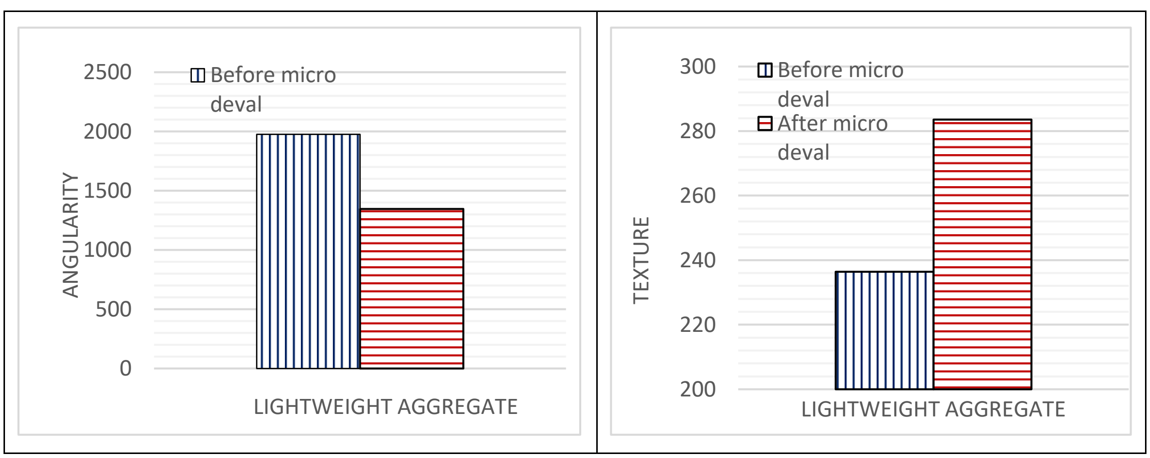


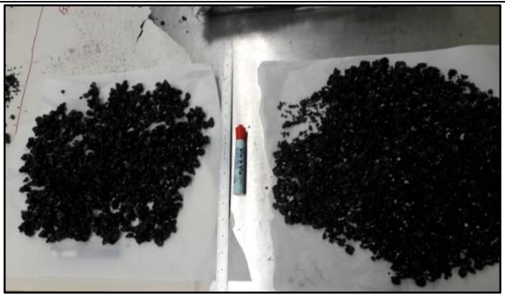
Figure 3.8 Average angularity index for lightweight aggregate before and after the micro-deval test

3.4 Sample Preparation

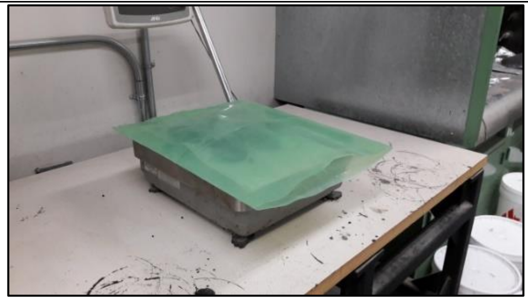
The laboratory test samples were prepared according to AASHTO T 312. A Superpave Gyratory Compactor (SGC) was used to compact the asphalt samples as shown in the Figure 3.9. The maximum theatrical specific gravity (Gmm) and bulk specific gravity (Gmm) were measured according to ASTM D6857 and ASTM D6752, respectively. The air void content was calculated based on the measured Gmm and Gmb according to Equation 3.1. Figure 3.10 shows the steps of air void calculations in the laboratory.

$$\text{Air Void (\%)} = \left(1 - \frac{\text{Gmb}}{\text{Gmm}}\right) \text{X } 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

Figure 3.9 A superpave gyratory compactor (SGC)



(a) loose asphalt mixtures



(b) recoding the weight of the CoreLok bag

(c) CoreLok Device

(d) recoding the weight of the test samples

Figure 3.10 Air void measurement in the laboratory

3.5 Measurement of absorption coefficient using Impedance tube

Acoustic absorption measurements can be conducted using an impedance tube. The impedance tube also known as Kundt Tube. The impedance tube consists of a large tube, a sample holder and microphones. There are various types of impedance tubes. In the laboratory experiments, a tube with two microphones was used. In this test, the sample is placed in the sample holder and then the sample holder is attached with the large tube. When test specimens are used, they are usually wrapped with stripping foam, rubber rings, Vaseline, or other material to prevent air gaps between the test specimen and the tube that may introduce measurement errors. In addition, the end of the tube is sealed with a metal plug to provide a hard-reflective surface (some researchers have used a second dense-graded specimen behind the test specimen to simulate more accurately the pavement structure). White noise is generated from the loudspeaker mounted at the other end of the tube. The sound waves propagate through the tube and reflected by the surface. Two microphones are used to measure the direct and reflected sound. These microphones are placed at a specific location along the length of the tube. The wave amplitude measured by the microphones depends on the diameter of the tube, length of the tube, distance between the microphones and the sample and the frequency. Same pavements can exhibit different absorption coefficient at different frequency. The tube amplitude and phase are calibrated by testing a completely acoustic absorbent material such as foam and a completely reflective material such as steel. A transfer function is measured with the two microphones in a standard position and in a reversed position allowing the estimation of the phase difference between the microphones and the internal losses of the impedance tube (Kumar et al. 2011).

The impedance tube can be used in laboratory as well as in the field. Although the impedance tube is not a true representation of actual tire-pavement noise, it is still an important tool to indicate differences in noise levels due to some characteristics of the pavement such as porosity, texture, and thickness. One of the disadvantages of this method is that the measurements are collected normal to the pavement surface and not at an angle as usually tire-pavement noise reaches the pavement.

3.5.1 Acoustic absorption measurement in the lab

This section discusses the steps taken by the researchers to measure the acoustic absorption in the laboratory.

(i) Software Set Up

Prior to making any measurements, the software (VA-LAB2), when using MC3522 sound card, should be installed properly. The VA-LAB2 software makes the use of a 2-channel data acquisition card. It is required for measuring absorption coefficient.

(ii) Hardware Set-up

The impedance tube consists of a loudspeaker and a sample holder. Loudspeaker end of the impedance tube should be connected to the MC3522 channel. The MC3522 needs to be connected with the two microphones and with a laptop in which the VA-LAB2 software is installed. Figure 3.11 shows configurations using MC3522 two channel card with a built-in amplifier.

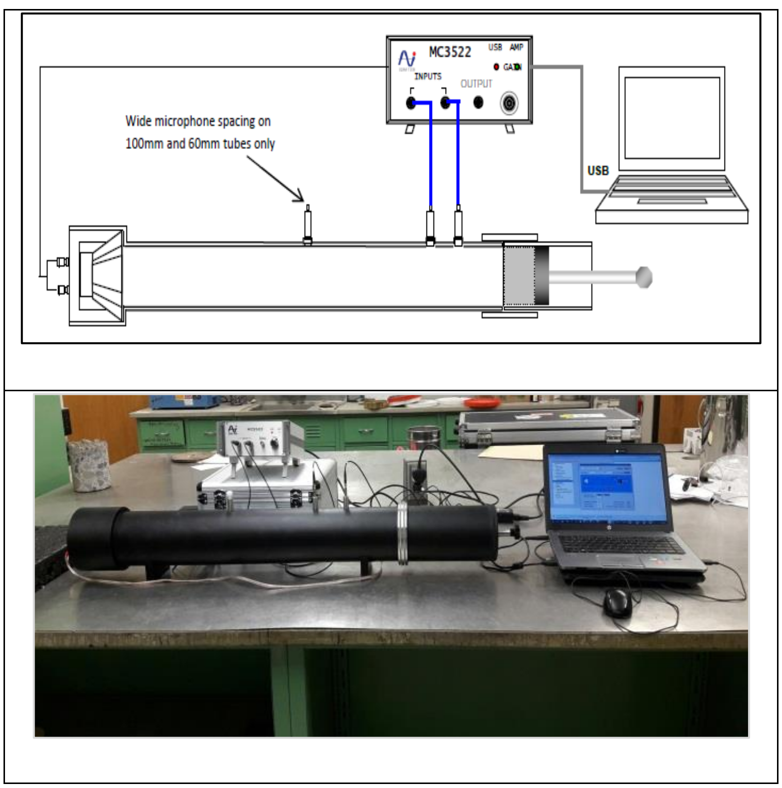


Figure 3.11 Impedance tube set-up

(iii) Sound card settings

The card MC 3522 was used as a signal input (Figure 3.12)

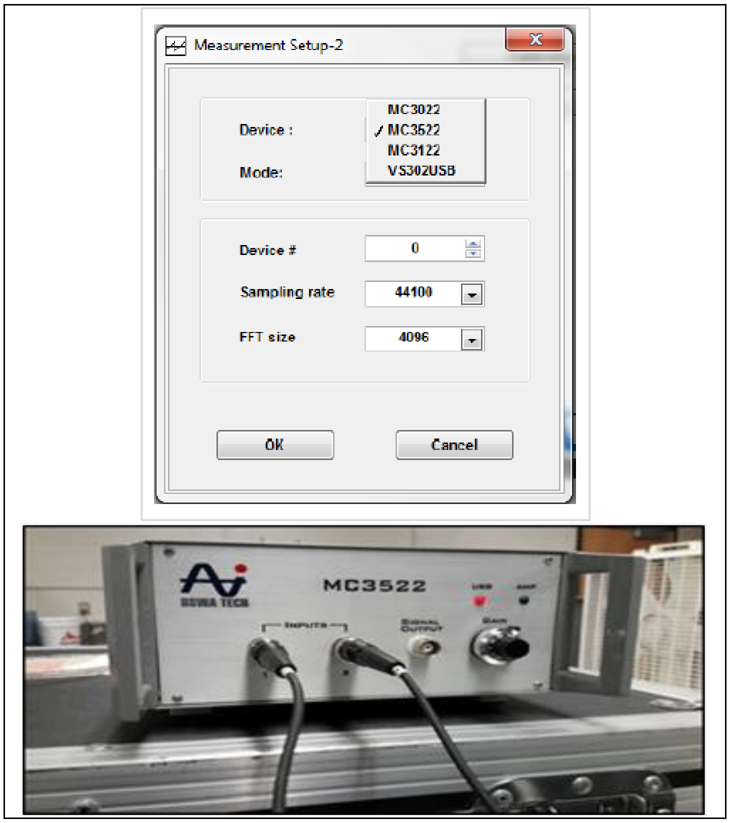


Figure 3.12 Sound card setting with MC 3522 channel

(iv) Microphone Calibration

In this step, the microphones were calibrated using VA-LAB and calibrator. In the Calibration Window, the frequency and the amplitude input should match with the frequency and amplitude of the calibrator. In this test, the BWSA CA115 calibrator was used (Figure 3.13). For the calibrator, the amplitude should be set to 114 dB and frequency to 1000 Hz (Figure 3.14). The sensitivity values used were shown in the right frame. In this frame, proper channel was selected to be calibrated. The corresponding channel was highlighted with red color. Microphone 1 was insert into the calibrator and there was a waiting time of 10 seconds for the pressure to equalize. Then the Calibrator was turned on. If the index value is equal to the actual value of the output of calibrator, it is not necessary to calibrate this channel again.

To calibrate the selected microphone, “Calibrate” option is selected. The same steps were repeated for the Microphone 2. Then calibration window is saved and closed.

Figure 3.13 CA 115 calibrator

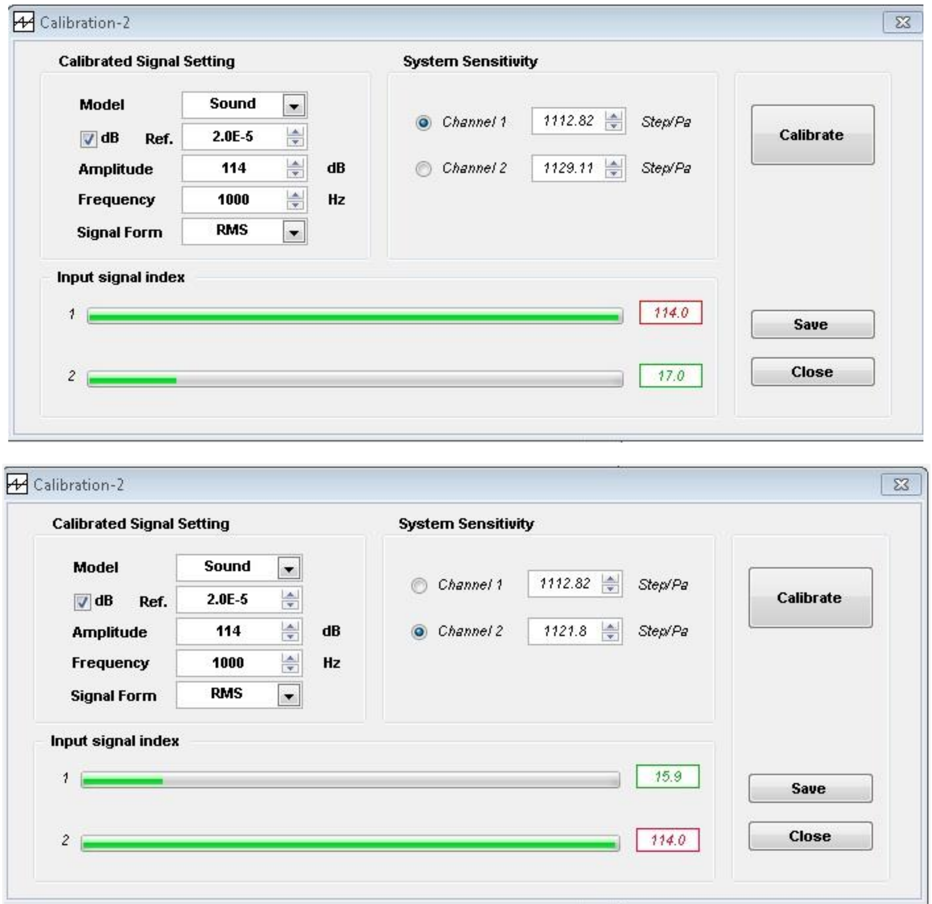


Figure 3.14 Microphone calibration window for channel 1 and channel 2.

(v) Channel Calibration

Calibration is needed to correct the measured transfer function data for mismatch in both the amplitude and phase responses of the measurement channels. It must be done before the test of specimen. Source tube was attached with the sample holder containing a highly absorptive material (as shown in the Figure 3.15) to prevent strong acoustic reflections and to obtain the most accurate correction factor possible.

Figure 3.15 Highly absorptive material inside the sample holder.

(vi) Taking Measurement

Before taking measurements, the channel calibration was completed. It should be ensured that microphone in Channel No. 1 is near the loudspeaker and the microphone in Channel No. 2 is near the sample. Any unused microphone port should be capped off.

The researchers measured the acoustic absorption of the field cores recovered from test sections in Qatar and laboratory-prepared test samples. The researchers conducted the following steps for measuring the acoustic absorption of the test samples:

- At first steel plate was attached to the impedance tube.
- The test sample was placed on a hard-reflective surface (a 25-mm thick steel plate).
- The test sample was surrounded by a steel mold. The purpose of this set up is to make the test sample insulated from the outside noise.
- A silicone polymer material was used to seal the gap between the top surface of test samples and the impedance tube.
- The tube was placed vertically on the top of test sample. System set up and acoustic absorption measurement process is shown in Figure 3.16 and 3.17.

(a) Test fixture for impedance tube

(b) Test fixture, attached with tube

(c) Lab sample above hard reflective surface

(d) Lab sample surrounded by steel mold

Figure 3.16 Fabricated test fixture (a) steel mold and (b) steel test fixture

(a) preparation of test samples

(b) measuring acoustic absorption

Figure 3.17 Acoustic absorption measurement

CHAPTER 4: ACOUSTICS ABSORPTION ANALYSIS

4.1 Effect of Different Parameters on Absorption Coefficient

This section discusses the absorption coefficient measurements and analyses to evaluate various parameters on the acoustical performance of asphalt mixtures. Table 4.1 presents the parameters and their levels evaluated in this study. These parameters include aggregate gradation (dense graded and open graded), aggregate type (gabbro, basalt, limestone, and lightweight), binder type (rubber-modified binder and unmodified binder (PG 64 -28), percent air voids (2% to 35%), and sample thickness (2 cm to 15 cm). These parameters can be modified during the mix design stage to produce asphalt mixtures with higher acoustic absorption.

Table 4.1 Parameters that affect the acoustic absorption of the asphalt mixtures in design stage.

No.	Variables	Levels
1	Aggregate gradation	Dense-graded and open-graded
2	Air void	2% to 35%
3	Thickness	2 cm to 15 cm
4	Aggregate type	Gabbro, basalt, limestone, and lightweight
5	Binder type	modified binder and unmodified binder

In addition to the parameters evaluated during the design stage, the researchers evaluated additional parameters that may influence the acoustical performance of asphalt mixtures after construction and during the service life as presented in Table 4.2. These parameters include pavement age (unaged and 3-month aged), air void structure (uniform and non-uniform), surface texture (positive and negative), temperature (0 °C, 20 °C, and 50 °C) and moisture conditions (dry and wet). Table 4.1 Parameters that affect the acoustic absorption of the asphalt mixtures in service life.

Table 4.2 Parameters that might affect the acoustic absorption of the pavement in service life.

No.	Variables	Levels
1	Aging	0 month and 3 months
2	Moisture level	Dry and wet
3	Temperature	0 °C, 20 °C, and 50 °C
4	Air void structure	Higher at top, Higher at bottom, and uniform
5	Texture	Positive and negative

4.1.1 Aggregate Gradation

Aggregate gradation has an important effect on acoustic absorption as discussed in Chapter 2. The acoustic absorption of pavements can be improved by modifying aggregate gradation. Lower noise level was found for fine pavement surface compared to coarse pavement surface (Timm et al. 2006). Hanson et al. (2004) showed that open graded mixtures with coarse aggregate gradation had higher noise compared to dense graded asphalt mixes. In the study herein, 34 test samples were prepared to evaluate the effect of aggregate gradation on acoustic absorption. Two types of gradations were considered; dense graded and open graded. Gabbro aggregate was used in preparing of these test samples. The thickness was 7.5 cm for all the test samples. The percent of air voids for dense-graded and open-graded mixes was 4% to 10 % and 15% to 25%, respectively. Figure 4.1 shows the asphalt samples of different gradations. Table 4.3 illustrates the experimental design. The average acoustic absorption for dense-graded mix and open graded was found 0.10 and 0.36, respectively. Table 4.4 presents the average value of acoustic absorption for dense and open-graded mixes. The research team conducted statistical analysis to evaluate the effect of aggregate gradation on acoustic absorption. Two sample t-test was performed in this regard using a statistical software R (version 3.4.2). It was found that, aggregate gradation was significant as the p-value was 2.641e-10. A p-value less than 0.05 means that the effect is significant. Table 4.5 presents the statistical analysis. Figure 4.2 shows the box plot of acoustic absorption of pavement for different gradations.

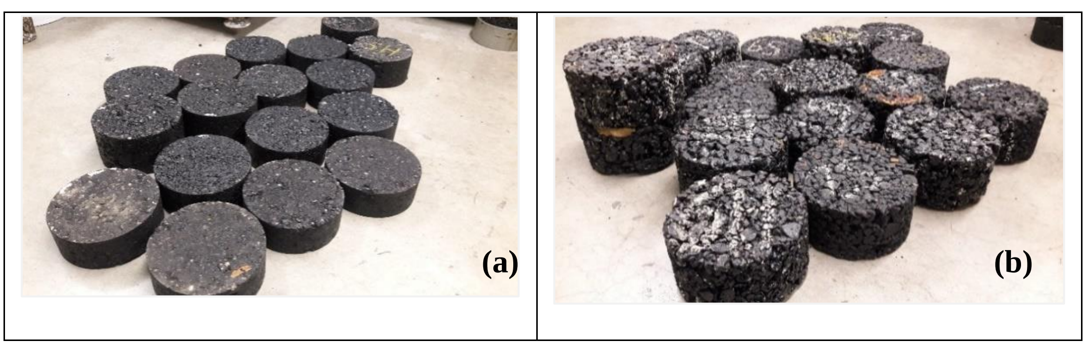


Figure 4.1 Asphalt samples of different aggregate gradation (a) well-graded and (b) open-graded

Table 4.3 Experimental design of acoustic absorption of pavement for open and dense graded mixture

Parameter	Aggregate	Gradation type	Thickness	Air void	No. of samples
Gradation	Gabbro	Dense graded	7.5 cm	4-8%	17 (1 replicate)
		Open-graded		> 15%	17 (1 replicate)

Table 4.4 Acoustic absorption for dense and open graded mixes

Aggregate Gradation	Acoustic absorption	Aggregate Gradation	Acoustic absorption
	0.11		0.23
	0.07		0.43
	0.1		0.39
	0.11		0.41
	0.1		0.43
	0.08		0.36
	0.11		0.36
Dense	0.10	Open	0.47
	0.11		0.48
	0.10		0.35
	0.10		0.27
	0.10		0.39
	0.12		0.40
	0.12		0.29
	0.11		0.31
	0.11		0.27
	0.10		0.30

Table 4.5 Statistical analysis of absorption coefficient for open and dense graded mixes

Gradation	Dense	Open graded
Average acoustic absorption	0.10	0.36
Standard deviation	0.012	0.076
T-test	2- sample t-test	
P-value	$2.641X10^{-6}$ < 0.05 Significant	

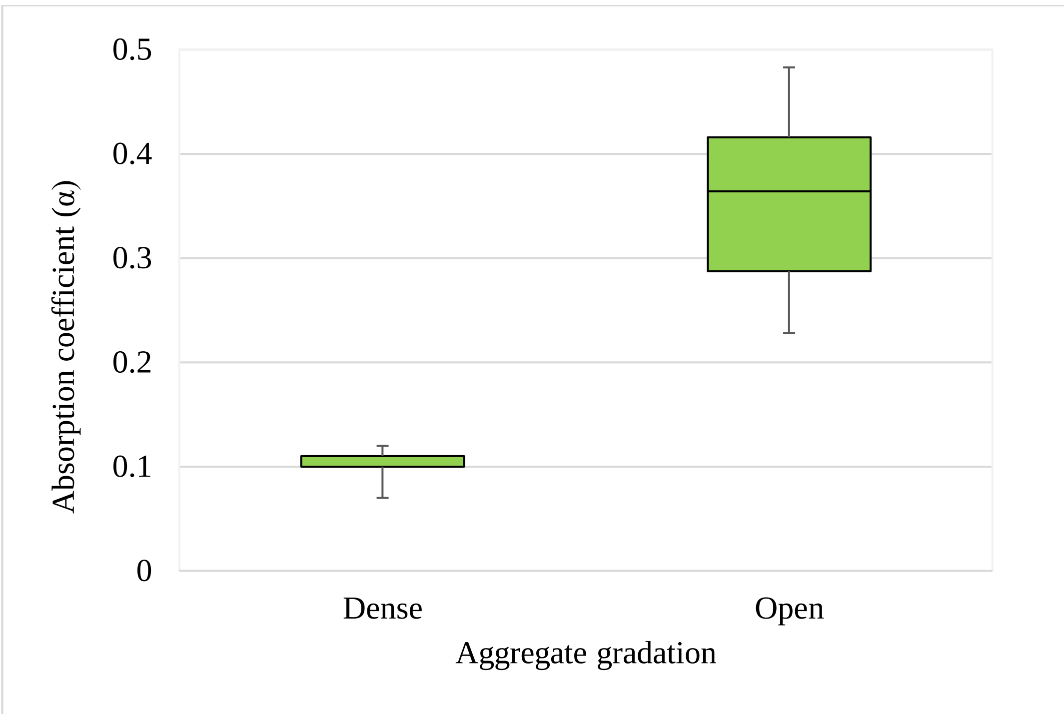


Figure 4.2 Boxplot of acoustic absorption of pavement for dense-graded and open-graded mixture

4.1.2 Air void

Air void is one of the key factors in designing quieter pavement. From the previous studies, it has been proved that higher air void is responsible for higher acoustic absorption. Dense-graded mixes with air void of 4% to 8% result in absorption coefficient of 0.1 to 0.2. Open-graded and porous pavement with air void more than 15% had absorption coefficients of 0.4 to 0.7 (Hanson et al. 2004). To analyze the effect of air void on acoustic absorption several types aggregate has been selected: gabbro, basalt, limestone, and lightweight. Table 4.6 presents the experimental design matrix.

Table 4.6 Experimental design matrix to determine the acoustic absorption of pavement for different air void

Aggregate	Air void range	Thickness	Number of samples
Gabbro	3 - 23 %	6.5 cm	10 (2 replicates)
Basalt	2 - 26%	6.5 cm	11 (2 replicates)
Limestone	5 - 21%	8 cm	8 (2 replicates)
Lightweight	30 - 36%	8 cm	9 (2 replicates)

At first, Gabbro was used to evaluate the effect of air void on acoustic absorption. Test samples were prepared to have different percent of air voids. The air void range under this study was from 3% to 23%. Thickness was kept constant for all the sample (6.5 cm). The average absorption coefficient for different air void is presented in the Table 4.7. For lower air void (4% to 8 %), the average absorption coefficient was 0.10 and for higher air void (>15%), the average absorption coefficient was 0.44. The results demonstrate that the air void has a significant effect on acoustic absorption (P-value is 1.129 e -7). Table 4.8 presents the statistical analysis. Figure 4.3 shows the box plot of absorption coefficient of pavement for different air voids. There is a good correlation between acoustic absorption of pavement and percent of air voids. In this study, this correlation was found 0.98 as shown in the Figure 4.4.

Table 4.7 Average absorption coefficient of pavement for different air void (Gabbro)

Sample No.	**Air void**	**Absorption coefficient**
1	3.56	0.09
2	4.14	0.11
3	5.82	0.10
4	6.35	0.10
5	6.71	0.11
6	16.8	0.388
7	20.3	0.427
8	21.09	0.406
9	22	0.483
10	22.4	0.474

Table 4.8 Statistical analysis of absorption coefficient for different air void (Gabbro)

Air void range	3-8 %	16-23%
Average acoustic absorption	0.1	0.44
Standard deviation	0.008	0.04
T-test	2- sample t-test	
P-value	1.129 e -7 < 0.05 Significant	

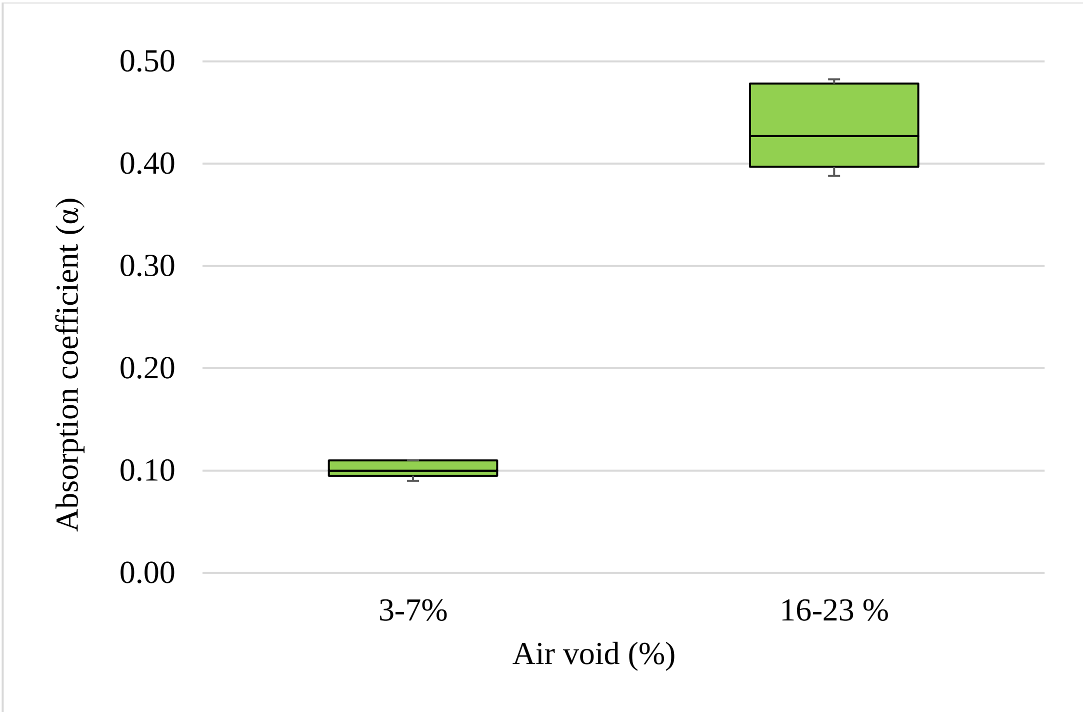


Figure 4.3 Box plot of absorption coefficient of pavement for different air void (Gabbro).

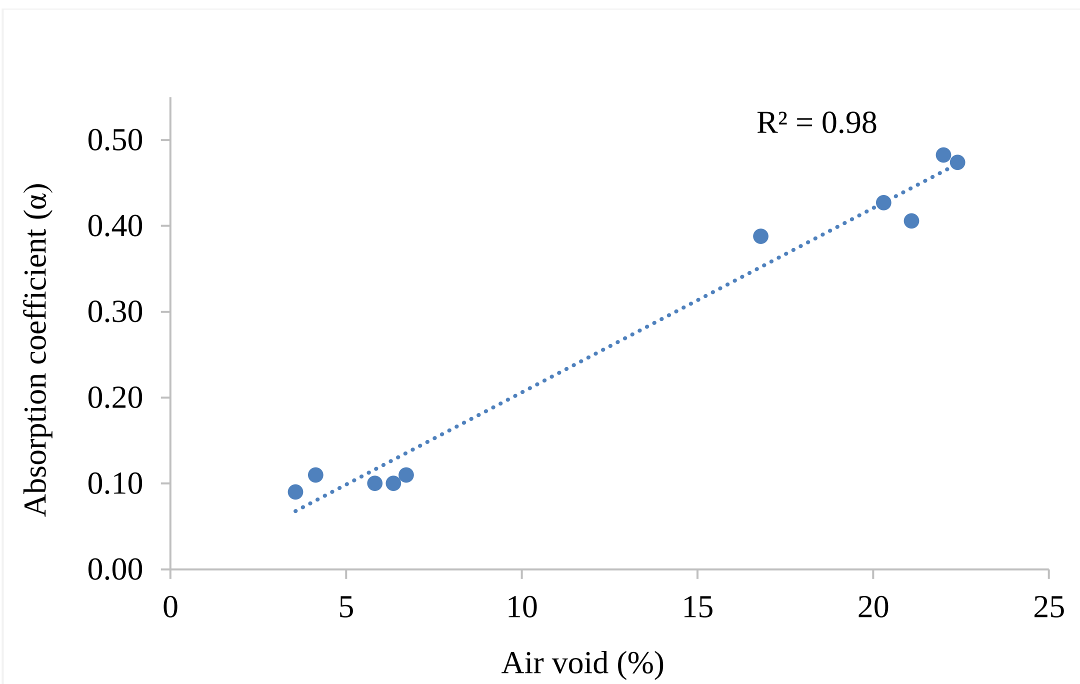


Figure 4.4 Correlation between absorption coefficient of pavement and air void (Gabbro)

Test samples were prepared using basalt aggregate. The basalt samples were also prepared to have different percent air voids while all other parameters such as thickness, maximum aggregate size, gradation, etc. were kept constant. The thickness of test specimens was 6.5 cm for all the samples. The average absorption coefficient for different air void is presented in Table 4.9. For lower air void (2% to 7%), the average acoustic absorption was 0.14 while it was 0.50 for test samples with higher percent air voids (>20%). The results showed that there is a good correlation between acoustic absorption and percent of air voids as shown in Figure 4.6 (R^2 = 0.92). Table 4.10 summarizes the statistical analysis of absorption coefficient for different air voids.

Table 4.9 Average acoustic absorption of pavement for different air void (Basalt)

Sample no.	**Air void (%)**	**Acoustic absorption (α)**
1	2.52	0.048
2	3.86	0.045
3	3.90	0.057
4	5.38	0.112
5	6.57	0.184
6	6.63	0.215
7	6.91	0.294
8	22.66	0.435
9	23.90	0.536
10	24.30	0.484
11	25.80	0.549

Table 4.10 Statistical analysis of absorption coefficient for different air void (Basalt)

Air void range	2-7 %	22-26%
Average acoustic absorption	0.14	0.50
Standard deviation	0.09	0.05
T-test	2- sample t-test	
P-value	0.000073 < 0.05 Significant	

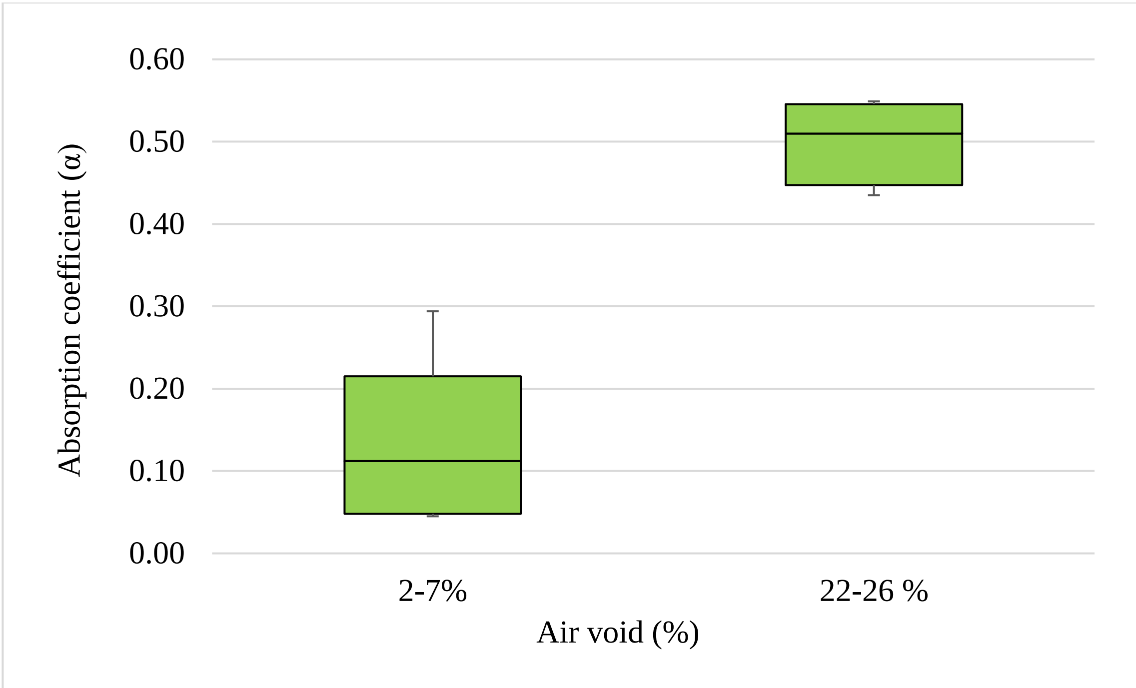


Figure 4.5 Box plot of absorption coefficient of pavement for different air void (Basalt).

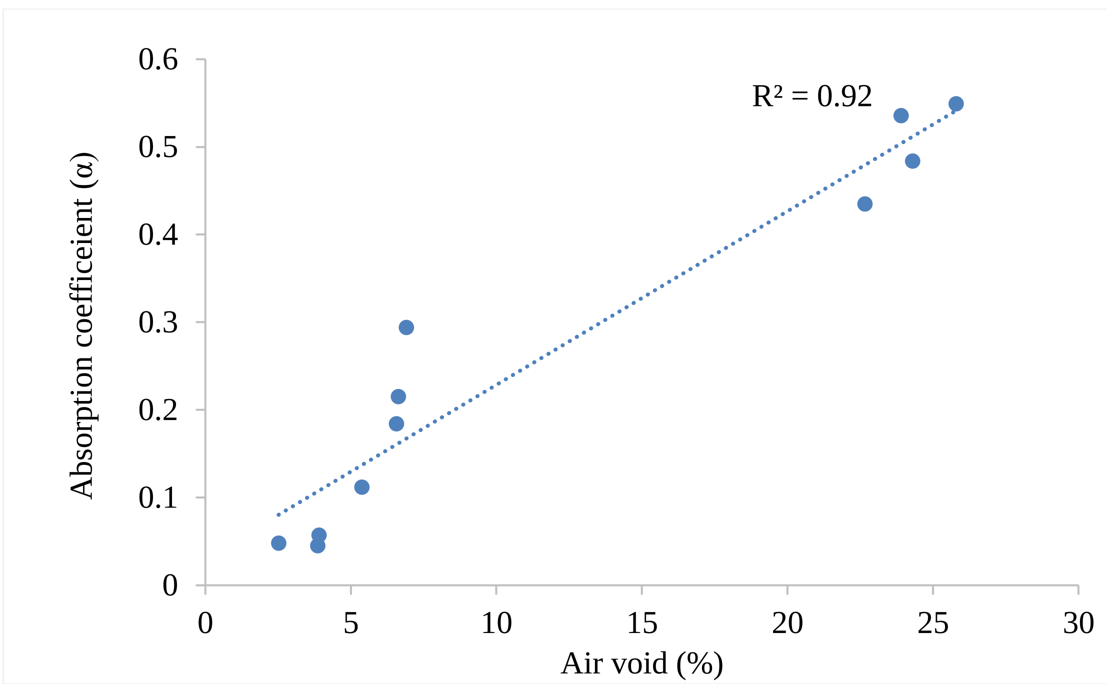


Figure 4.6 Correlation between acoustic absorption of pavement and air void (Basalt).

Test samples were also prepared using limestone aggregates. Similar to gabbro and basalt test samples, samples were prepared using limestone to have different percent air voids. All other parameters such as thickness, maximum aggregate size, gradation, etc. were kept constant. The thickness of test samples was 8 cm. The average acoustic absorption for different air void is presented in Table 4.11. For 5% to 9% air void, the average acoustic absorption was 0.07 and it was 0.44 for air void more than 15%. A strong correlation (R^2 = 0.98) was found between the percent air voids and acoustic absorption coefficient (Figure 4.8).

Table 4.11 Average absorption coefficient of pavement for different air void (Limestone)

Sample no.	Air void (%)	Acoustic absorption (α)
1	5.45	0.04
2	5.50	0.04
3	8.50	0.14
4	15.20	0.40
5	15.38	0.41
6	18.27	0.42
7	18.76	0.47
8	20.90	0.52

Table 4.12 Statistical analysis of absorption coefficient for different air void (Limestone)

Air void range	5-9%	15-21%
Average acoustic absorption	0.07	0.44
Standard deviation	0.06	0.05
T-test	2- sample t-test	
P-value	0.000073 < 0.05 Significant	

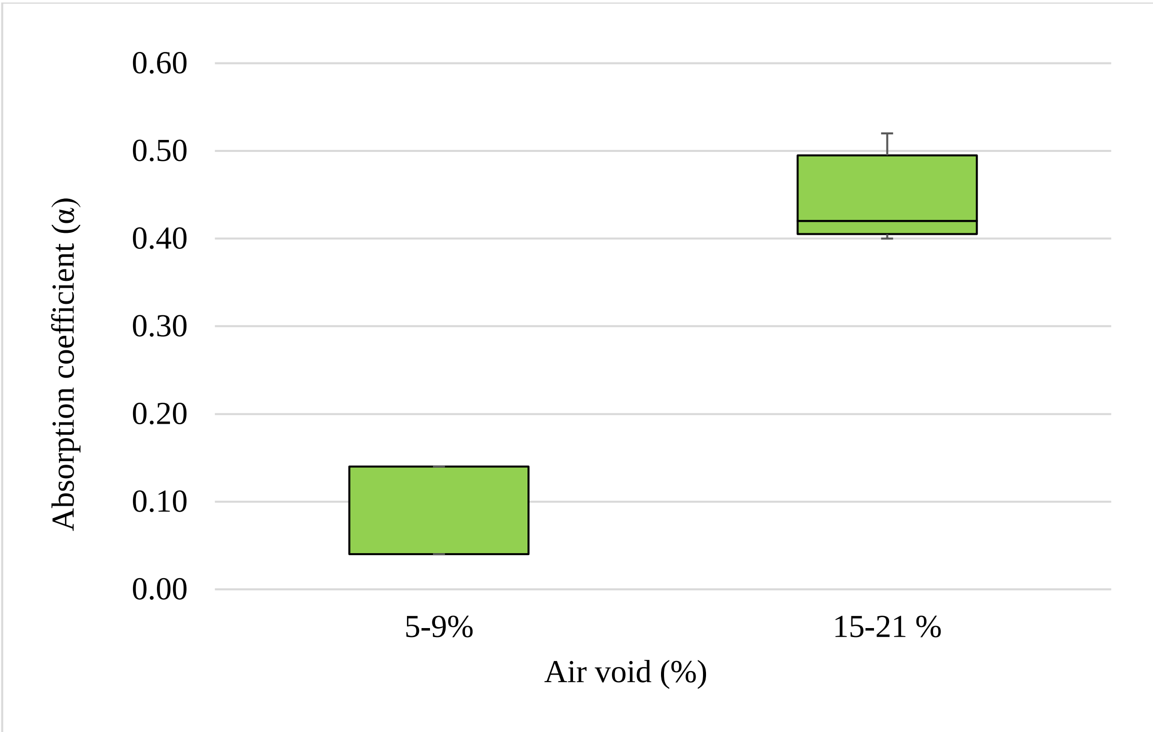


Figure 4.7 Box plot of acoustic absorption of pavement for different air void (Limestone).

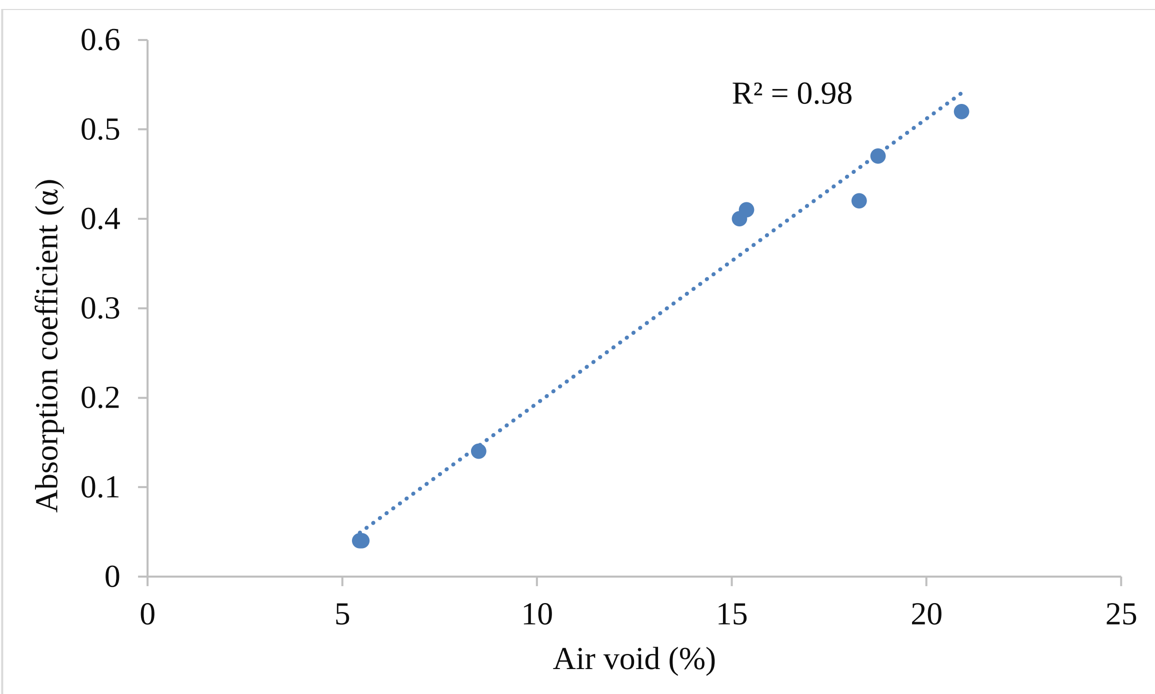


Figure 4.8 Correlation between acoustic absorption of pavement and air void (Limestone)

The lightweight aggregate was blended with rubber modified binder to prepare 8-cm thick test samples. The percent of air voids for the test samples prepared with lightweight aggregate was above 30%. The average acoustic absorption was found to be 0.51. Table 4.13 presents the acoustic absorption values for the lightweight aggregate test samples. Figure 4.9 shows the box plot of acoustic absorption results.

Table 4.13 Average acoustic absorption of pavement for different air void (Lightweight)

Samples No	Air void (%)	Absorption
1	34.71	0.50
2	32.46	0.46
3	36.50	0.50
4	35.98	0.54
5	33.90	0.47
6	35.36	0.54
7	35.97	0.57
8	33.42	0.48
9	35.06	0.53

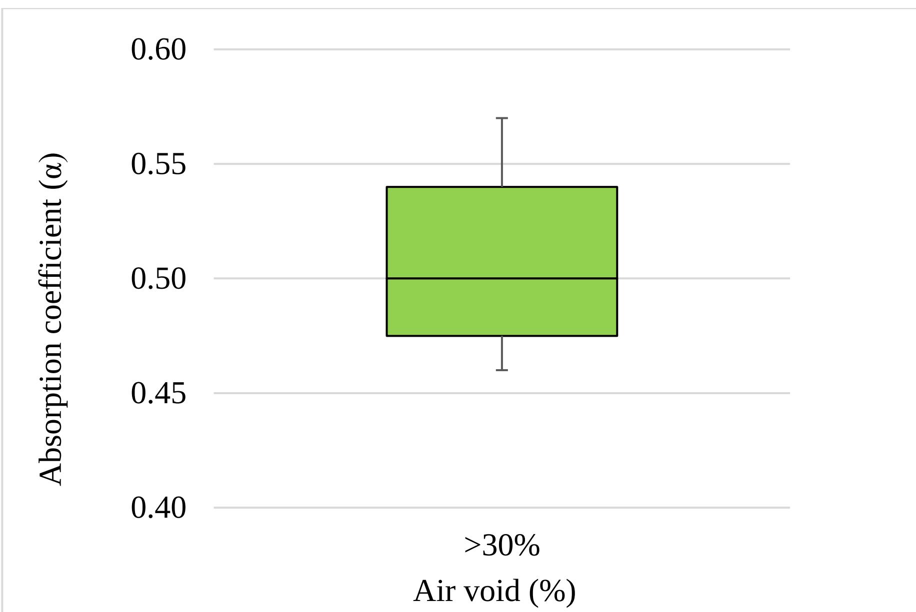


Figure 4.9 Box plot of acoustic absorption of pavement for higher air void (Lightweight)

4.1.3 Thickness

In this section, the researchers evaluated the effect of thickness on the acoustic performance of the asphalt mixtures. Test samples with various thicknesses and comparable percent air voids were evaluated. All other parameters were kept constant. Table 4.14 presents the testing matrix.

Table 4.14 Experimental design matrix to determine the acoustic absorption of pavement for different thickness

Aggregate	Air void range (%)	Thickness range (cm)	Number of samples
Gabbro	16-20	2-10	14 (1 replicate)
Basalt	20-24	5-10	14 (1 replicate)

A total number of 14 samples were prepared using gabbro aggregates to analyze the effect of thickness on acoustic absorption. The average acoustic absorption values of pavement for test samples are presented in Table 4.15. The results showed that as the thickness increases, the acoustic absorption increases. There was a good correlations between sample thickness and the acoustic absorption coefficients as shown in Figure 4.11 (R2 = 0.83). The effect of thickness was found significant (P-value is less than 0.05).

Table 4.15 Average acoustic absorption of pavement for different thickness (Gabbro)

Sample no.	Thickness (cm)	Absorption coefficient	Result from ANOVA (p-value)
1	2	0.228	
2	2.06	0.244	
3	2.4	0.323	
4	3	0.269	
5	5.7	0.388	
6	6	0.384	0.0004 < 0.05
7	6	0.312	
8	5.7	0.396	
9	5.3	0.352	
10	5.7	0.353	
11	9.74	0.437	
12	9.67	0.502	
13	13.88	0.439	
14	14	0.502	

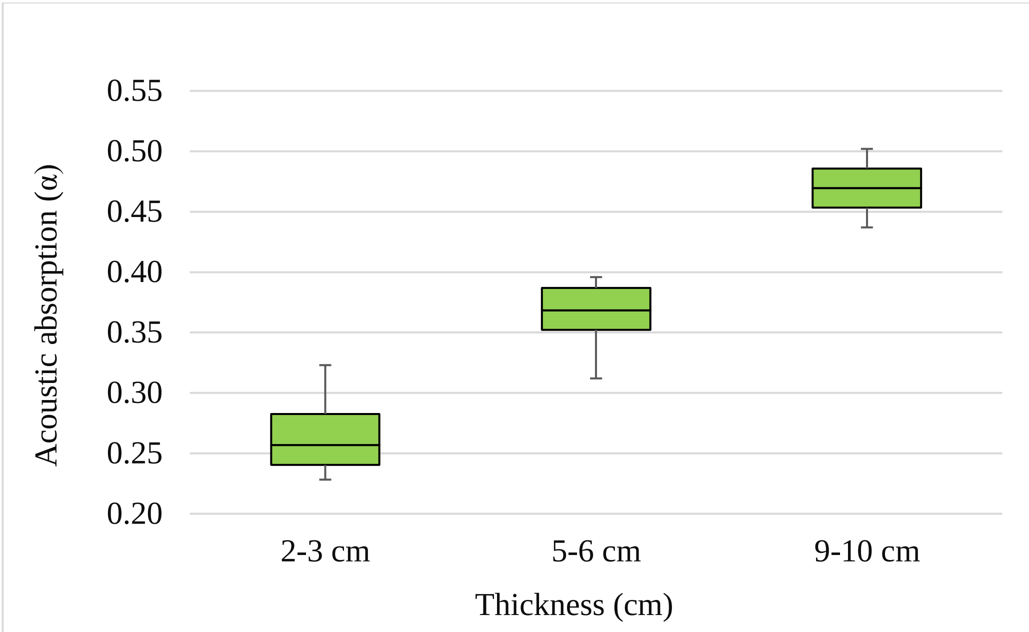


Figure 4.10 Box plot of acoustic absorption of pavement for different thickness (Gabbro)

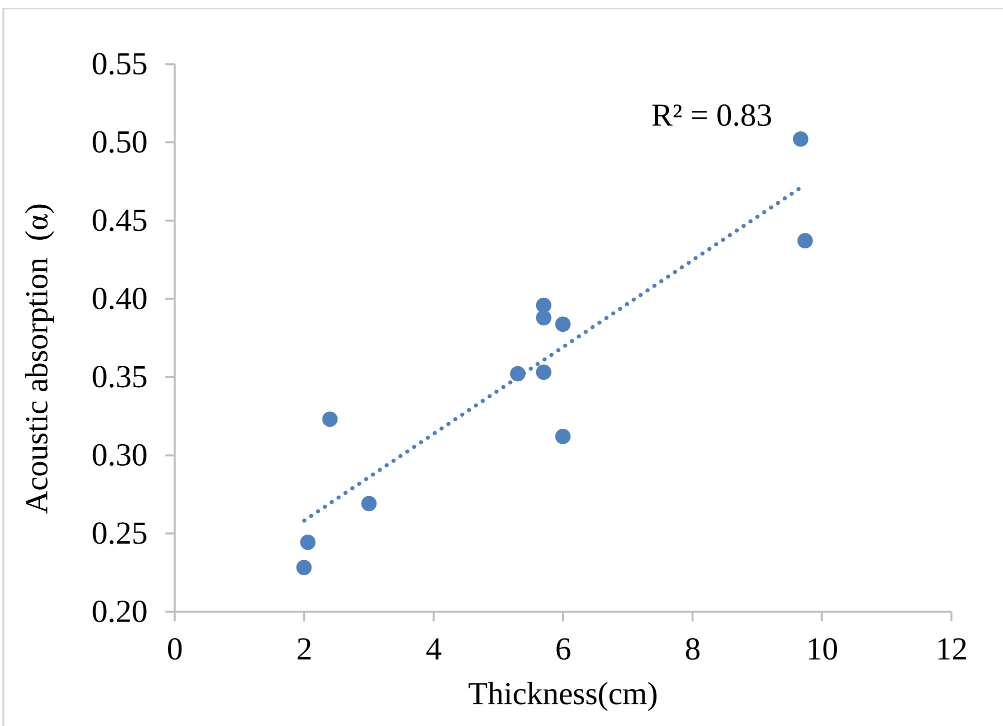


Figure 4.11 Correlation between acoustic absorption of pavement and thickness (Gabbro)

Additional 14 test samples were prepared using basalt aggregates. The average acoustic absorption coefficient of the test samples are presented in Table 4.16. The results showed a similar trend; the absorption coefficient increased as the thickness increased. In addition, the effect of thickness was found significant (the P-value is less than 0.05).

Table 4.16 Average acoustic absorption of pavement for different thickness (Basalt)

Sample no.	Thickness (cm)	Absorption coefficient	Result from ANOVA (p-value)
1	5.35	0.47	
2	5.57	0.43	
3	6	0.43	
4	6	0.41	
5	6	0.45	
6	7	0.48	0.000221 <0.05
7	7	0.5	
8	7.2	0.52	
9	7.5	0.55	
10	7.6	0.54	
11	7.8	0.49	
12	8	0.52	
13	9.9	0.53	
14	10	0.55	

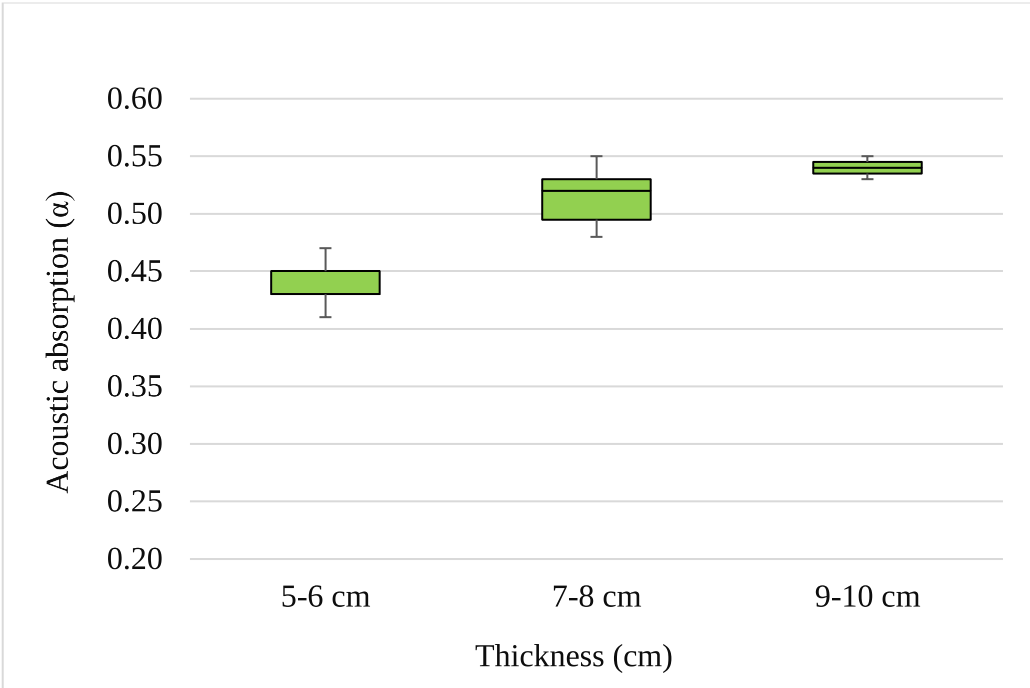


Figure 4.12 Box plot of acoustic absorption of pavement for different thickness (Basalt)

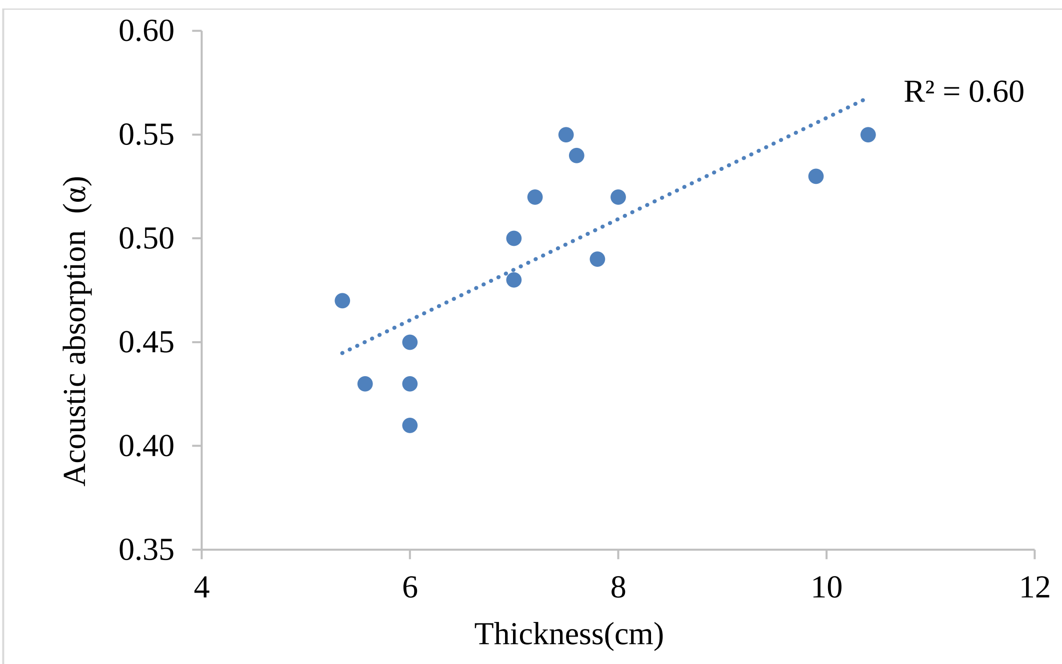


Figure 4.13 Correlation between acoustic absorption of pavement and thickness (Basalt)

4.1.4 Combined Effect of air void and thickness

The results showed that the acoustic absorption coefficients increase as the thickness of the test sample and percent air voids increase, therefore the combined effect of air void and thickness on acoustic absorption was analyzed. A linear relationship was found for all various aggregate types. The correlation between acoustic absorption and air void multiplied by the thickness was 0.67, 0.83, 0.50 and 0.64 for gabbro, basalt, limestone and lightweight aggregate, respectively. Tables 4.17 through 4.20 and Figures 4.14 through 4.18 show the results for test samples prepared using different aggregates.

Table 4.17 Combined effect of air void and thickness on acoustic absorption (Gabbro)

Sample no.	Thickness (cm)	Air void	Acoustic absorption	Thickness * Air void
1	1.30	0.192	0.249	0.228
2	2.4	0.156	0.374	0.349
3	4.2	0.189	0.792	0.302
4	5.7	0.168	0.958	0.388
5	5.80	0.224	1.299	0.474
6	5.9	0.064	0.375	0.100
7	5.99	0.203	1.216	0.427
8	6.13	0.220	1.349	0.483
9	6.3	0.058	0.367	0.100
10	6.5	0.067	0.436	0.110
11	6.5	0.170	1.105	0.228
12	6.56	0.208	1.361	0.364
13	6.77	0.211	1.428	0.406
14	7.1	0.197	1.398	0.363
15	7.1	0.036	0.253	0.090
16	7.7	0.041	0.319	0.110
17	9.67	0.229	2.212	0.502
18	9.74	0.223	2.170	0.437
19	13.88	0.173	2.404	0.439
20	14.1	0.176	2.486	0.502

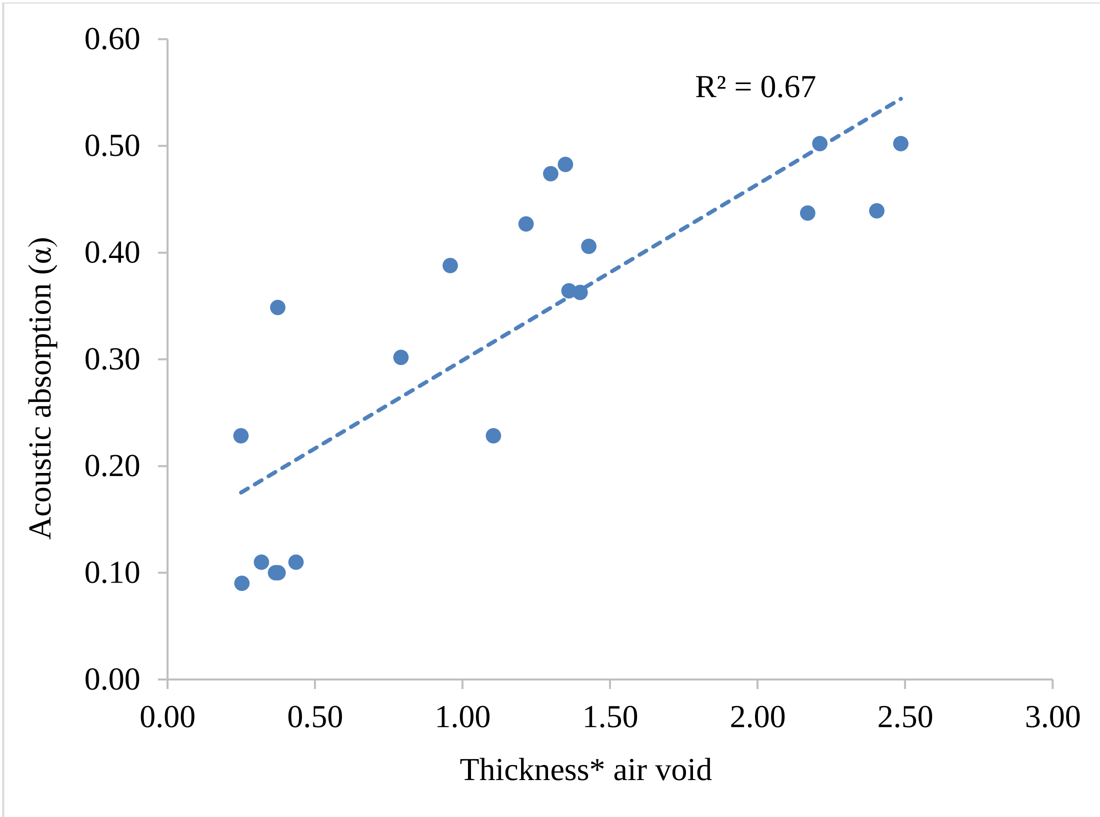


Figure 4.14 Correlation between acoustic absorption of pavement and thickness x air void (Gabbro)

Table 4.18 Combined effect of air void and thickness on acoustic absorption (Basalt)

Sample no.	thickness (cm)	Air void	t*void	Absorption
1	4.1	0.025	0.103	0.048
2	4.7	0.227	1.065	0.435
3	4.7	0.054	0.253	0.112
4	4.71	0.066	0.312	0.215
5	4.8	0.039	0.187	0.057
6	4.8	0.039	0.185	0.045
7	4.9	0.258	1.264	0.549
8	5.03	0.066	0.330	0.184
9	5.34	0.069	0.369	0.294
10	5.35	0.243	1.300	0.467
11	5.35	0.243	1.300	0.484
12	5.57	0.239	1.331	0.435
13	6.07	0.219	1.328	0.433
14	6.5	0.263	1.710	0.413
15	6.5	0.250	1.626	0.451
16	7	0.225	1.574	0.484
17	7	0.229	1.604	0.501
18	7.2	0.231	1.663	0.521
19	7.5	0.222	1.665	0.549
20	7.6	0.244	1.851	0.536
21	7.8	0.226	1.764	0.486
22	8	0.233	1.862	0.523
23	10.4	0.240	2.494	0.546

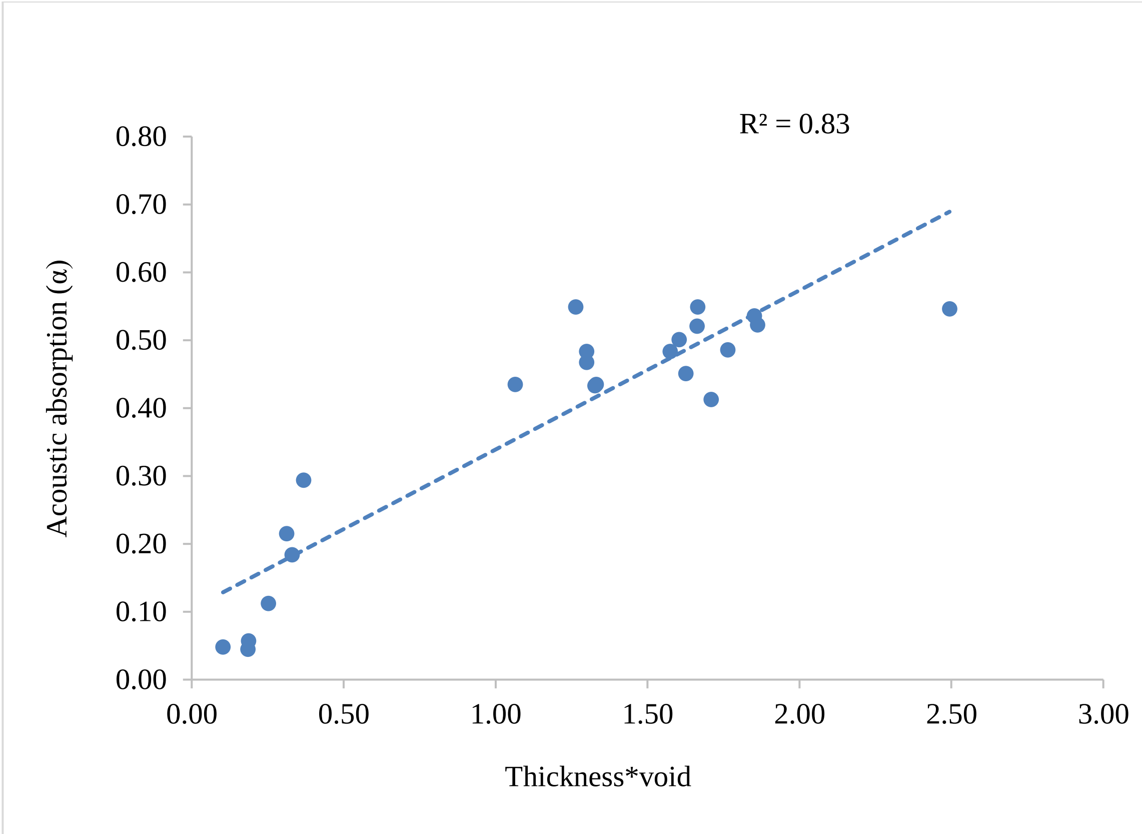


Figure 4.15 Correlation between acoustic absorption of pavement and thickness x air void (Basalt)

Table 4.19 Combined effect of air void and thickness on acoustic absorption (Limestone)

Sample no.	Thickness	Air void	Thickness*Air void	Acoustic absorption
1	2.14	0.1757	0.376	0.302
2	2.82	0.225	0.635	0.476
3	3.78	0.207	0.782	0.467
4	5.5	0.248	1.364	0.430
5	6	0.2085	1.251	0.322
6	6.5	0.2316	1.505	0.490
7	6.57	0.1827	1.200	0.422
8	6.6	0.209	1.379	0.522
9	6.9	0.085	0.587	0.143
10	7	0.152	1.064	0.403
11	7.5	0.1538	1.154	0.406
12	7.7	0.1876	1.445	0.469
13	7.94	0.055	0.437	0.039
14	8.1	0.2197	1.780	0.530
15	9.1	0.0545	0.496	0.041
16	10	0.211	2.110	0.480

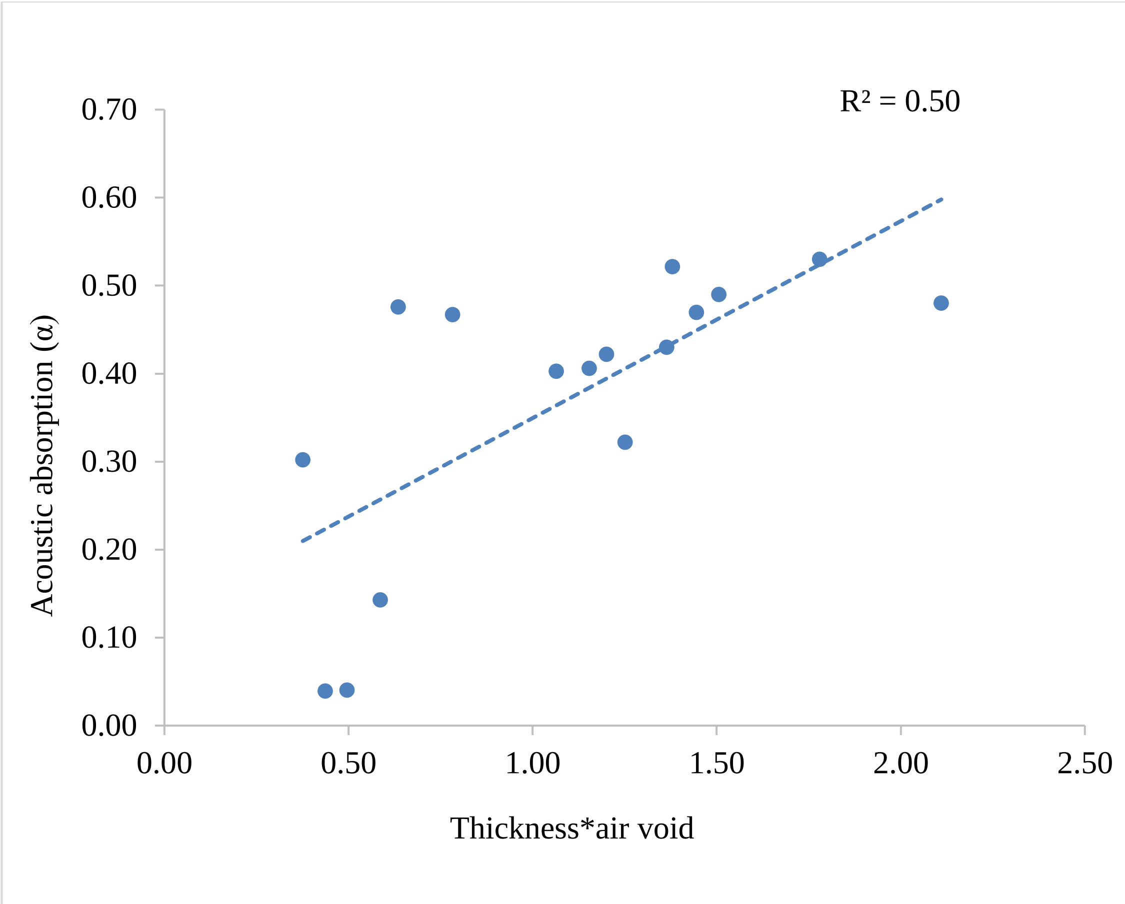


Figure 4.16 Correlation between acoustic absorption of pavement and thickness x air void (Limestone)

Table 4.20 Combined effect of air void and thickness on acoustic absorption (Lightweight)

Sample no.	Thickness (cm)	Air void	Thickness*void	Absorption Coefficient
1	5.2	0.356	1.852	0.509
2	5.2	0.362	1.882	0.577
3	5.9	0.365	2.154	0.500
4	6	0.251	1.504	0.490
5	6.2	0.339	2.102	0.470
6	6.2	0.354	2.193	0.536
7	6.2	0.360	2.230	0.567
8	6.8	0.360	2.447	0.540
9	8.5	0.284	2.413	0.510
10	9.56	0.373	3.570	0.641
11	10.3	0.337	3.469	0.627

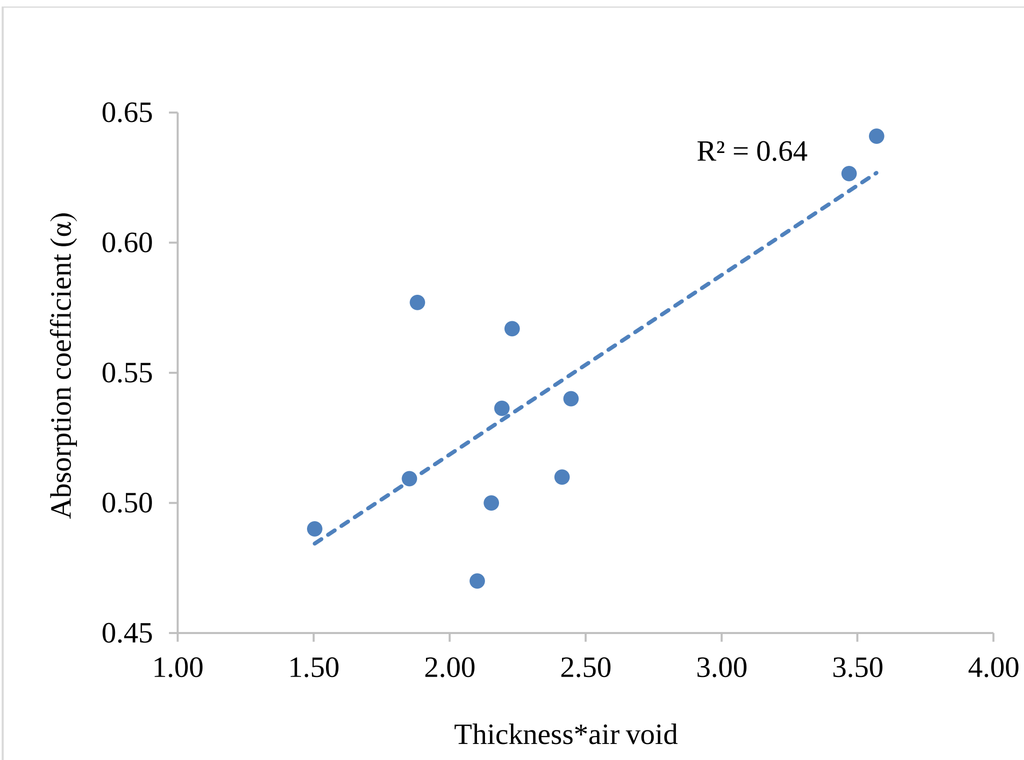


Figure 4.17 Correlation between acoustic absorption of pavement and thickness x air void (Lightweight)

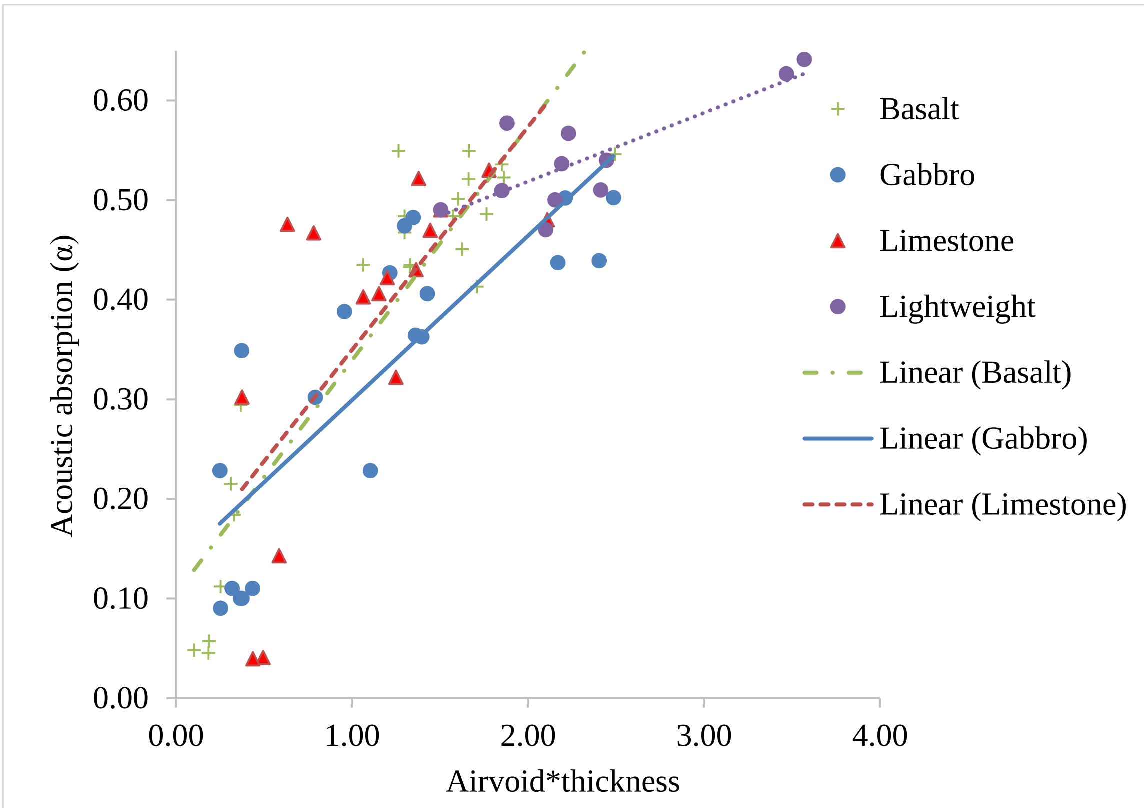


Figure 4.18 Correlation between acoustic absorption of pavement and thickness x air void

4.1.5 Aggregate Type

Aggregate type does not have a direct impact on traffic noise generation (Sandberg and Ejsmont 2002). Very few studies were performed in this regard. In the study herein, several samples were prepared using four different aggregate types: gabbro, basalt, limestone, and lightweight as shown in the Figure 4.19. All other parameters such as thickness, air void, and aggregate gradation were kept constant to evaluate the effect the aggregate type on acoustic absorption. The thickness of the test samples was 6.5 cm and the percent air voids was between 20% to 22%. The gradation was open graded for all the samples. Test samples prepared using lightweight aggregate had higher air void (>30%) compared to test samples prepared using other aggregates. The specific gravity (dry) of gabbro, basalt, limestone and lightweight aggregate was 2.90, 2.73, 2.60, and 1.42, respectively. Specific gravity was measured only for the coarse aggregate according to ASTM C127. Table 4.21 presents the experimental design. The average absorption coefficient of gabbro, basalt, limestone and lightweight was 0.40, 0.45, 0.42, and 0.52, respectively. ANOVA is performed for gabbro, basalt, and limestone. It is found that, the effect of aggregate type is not significant as the p-value is less than 0.05. Lightweight aggregate was not considered in ANOA analysis because for the same gradation and thickness lightweight aggregate showed higher air void. Higher air void leads to higher absorption coefficient. To evaluate the effect of aggregate type on absorption coefficient, air void should comparable to all types of aggregate. Figure 4.20 shows the box plot of average acoustic absorption of pavement for different types of aggregate.

(a)

(b)

(c)

(d)

Figure 4.19 Different types of aggregates, (a) gabbro, (b) basalt, (c) limestone, and (d) lightweight

Table 4.21 Experimental design of acoustic absorption of pavement for different aggregate type.

Parameter	**Aggregate**	**Gradation type**	**Thickness**	**Air void**	**No. of samples**
Aggregate type	Gabbro	Open graded	6.5 cm	20-22 %	16
	Basalt				9
	Limestone				14
	Lightweight*				16

* Lightweight aggregate shows higher air void (> 30%) for same type of gradation.

Table 4.22 Average acoustic absorption for different aggregate.

Aggregate type	**Number of samples**	**Average acoustic absorption (α)**	**Result from ANOVA**
Gabbro	16	0.40	P-value 0.01 > 0.05, insignificant
Basalt	9	0.45	
Limestone	14	0.42	
Lightweight*	16	0.52	

*Lightweight aggregate was not considered in ANOVA analysis.

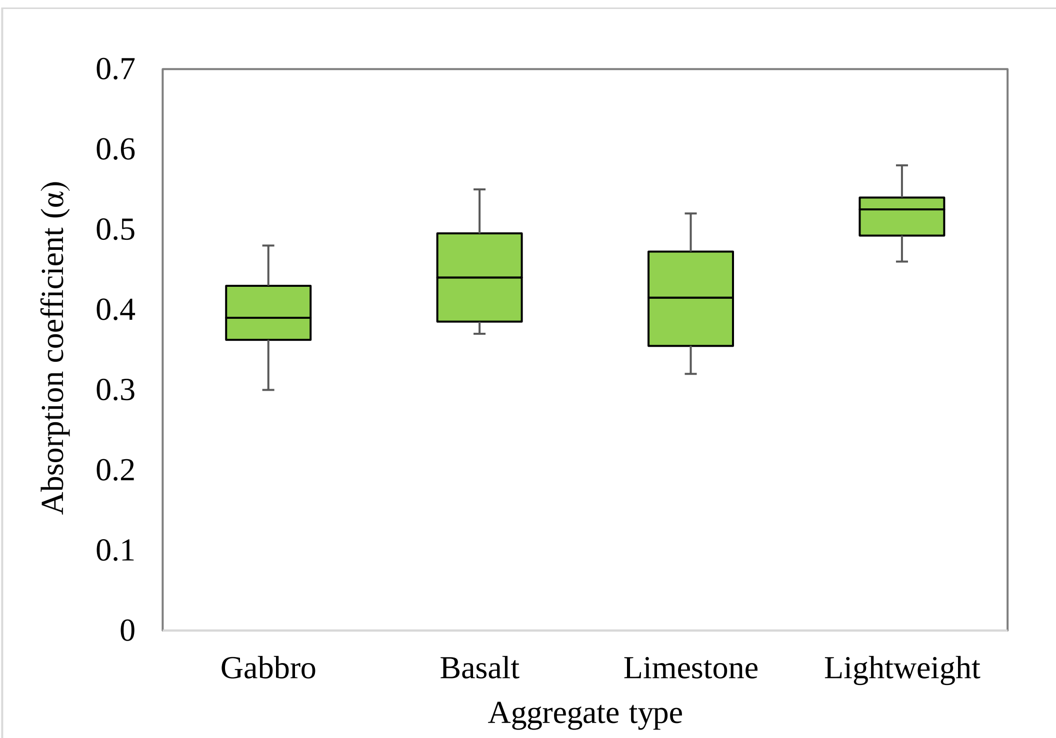


Figure 4.20 Box plot of acoustic absorption of pavement for different types of aggregate

4.1.6 Binder Type

To evaluate the effect of binder type on acoustic absorption, two different binder types were used: rubber modified binder (PG 76-22) and unmodified binder (PG 64-28). A total number of ten samples were prepared using basalt and the aggregate gradation was well graded. The thickness of the test samples was 7 cm. The percent air void of all the samples was between 5% to 8%. Experimental design for acoustic absorption of pavement for modified and unmodified binder is shown in Table 4.23. Average acoustic absorption of modified and unmodified binder was found 0.160 and 0.164, respectively. Table 4.24 presents the average acoustic absorption values. Statistical analysis showed that the use of rubber binder does not have any significant effect since the p-value is greater than 0.05 as shown in Table 4.25. Figure 4.21 shows the box plot of acoustic absorption of asphalt sample for modified and unmodified binder.

Table 4.23 Experimental design for acoustic absorption of pavement for modified and unmodified binder

Parameter	**Binder**	**Aggregate**	**Gradation type**	**Thickness**	**Air void**	**No. of samples**
Binder type	Unmodified	Basalt	Well-graded	7 cm	5-8%	5 samples
	Modified					5 samples

Table 4.24 Average acoustic absorption of pavement for modified and unmodified binder

Sample No.	Modified	Unmodified
1	0.15	0.16
2	0.16	0.17
3	0.17	0.18
4	0.14	0.15
5	0.18	0.16
Average	0.160	0.164

Table 4.25 Statistical analysis of acoustic absorption of pavement for modified and unmodified binder

Test	t-value	df	P-value	Significant/Insignificant
Two-sample t-test	-0.45883	8	0.6586 > 0.05	Insignificant

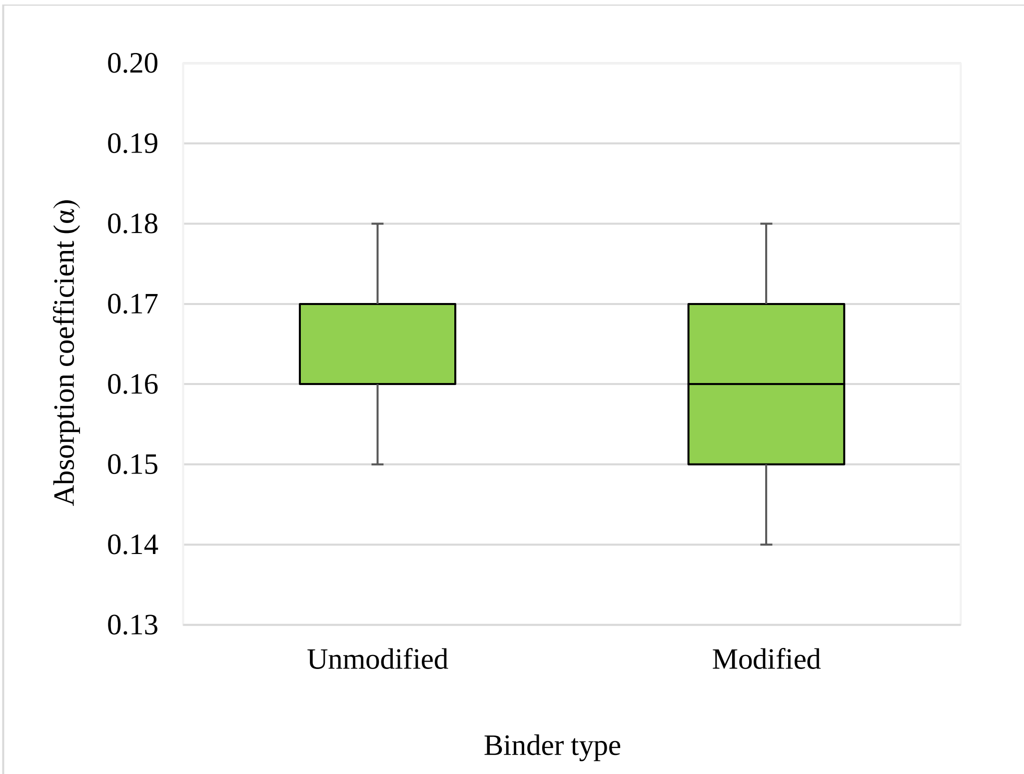


Figure 4.21 Box plot of acoustic absorption of pavement for modified and unmodified binder.

4.2 Analytical Model Development and Statistical Analysis

Based on the results of previous sections, the research team developed an analytical model for the acoustic absorption coefficient as a function of parameters that were found to affect the acoustic absorption coefficient during the mix design stage. These parameters include percent air voids, thickness, and aggregate gradation. The binder type and aggregate type were found insignificant on the acoustic absorption of asphalt mixtures. In order to consider aggregate gradation as a parameter, Weibull distribution function was used. The parameters from Weibull distribution function, describe the aggregate gradation (Masad et al. 2009). The two-parameter Weibull distribution is given in Equation 4.1.

$$F\,(x, \kappa, \lambda) = 1 - e^{-(\frac{x}{\lambda})^{\kappa}} \qquad (4.1)$$

where,

x = variable

κ = shape parameter

λ = scale parameter

To determine the κ and λ, MATLAB software (version 9.2.0.556344) was used. The obtained values are presented in Appendix A. Effect of air void, thickness, gradation and binder type on acoustic absorption are analyzed individually. It was found that, except binder type, all others parameters are significant in predicting acoustic absorption. So the parameters that are used in model development are air void, thickness, and gradation (κ and λ).

There are 153 data points for the model development which is shown in the Appendix A. A multiple linear regression analysis was performed using SPSS software (version 24) to develop an analytical model. The Acoustic model development process is described in the section below.

Step 1:

Dependent variable: absorption coefficient (α)
Independent variables: air void, thickness, κ and λ.

After analyzing 153 data points it was found that, κ and λ are not significant in predicting absorption coefficient as the p-value greater than 0.05 as shown in the Table 4.26. Variance inflation factor (VIF) was high for κ and λ, which indicate there are some collinearity issues for those variables.

Table 4.26 Coefficients for analytical model development

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
		B	Std. Error	Beta			Tolerance	VIF
1	(Constant)	-.081	.040		-2.037	.043		
	thickness	.001	.000	.133	3.407	.001	.843	1.187
	av	.021	.001	.905	21.911	.000	.757	1.321
	kp	.021	.027	.061	.753	.453	.197	5.071
	lm	-.006	.005	-.087	-1.131	.260	.220	4.535

a. Dependent Variable: alpha

Step 2:

Dependent variable: absorption coefficient (α)
Independent variables: air void and thickness.

In this step, κ and λ were removed from the data set and analyzed the data again. It is found that, air void and thickness are the key factor in predicting acoustic absorption and adjusted R^2 was found 0.81 as shown in the Table 4.28. Analysis of variance is presented in the Table 4.27. The final model for predicting absorption coefficient is given in Equation 4.2.

$$a = 0.026 * v + 0.001 * t - 0.189 \qquad (4.2)$$

where

a = absorption coefficient

v = Air void (%)

t = thickness (mm)

Table 4.27 Analysis of variance for analytical model development

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.514	2	1.757	330.672	.000[b]
	Residual	.797	150	.005		
	Total	4.312	152			

a. Dependent Variable: alpha

b. Predictors: (Constant), av, thickness

Table 4.28 Model summary of analytical model development.

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.903[a]	.815	.813	.07290	1.064

a. Predictors: (Constant), av, thickness

b. Dependent Variable: alpha

4.2.1 Regression Check List

Any linear multiple regression model should be checked considering the following criteria.

- Mean of residuals
- Constant variance
- Independence of residuals
- Normality of residuals

Mean of Residuals

Residuals should have a mean which is equal to zero. This criterion can be checked by analyzing the histogram plot of residuals. In our analysis, histogram of residuals is centered at zero as shown in the Figure 4.22.

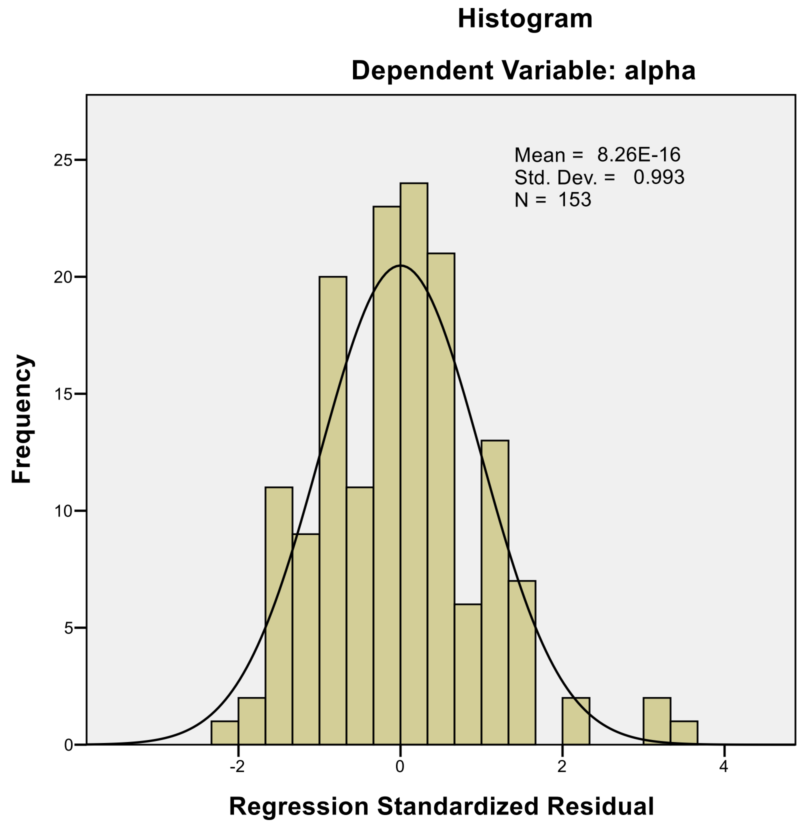


Figure 4.22 Mean of residuals

Constant Variance

This assumption states that variance should be constant. To check this assumption, residuals versus predicted plot should be analyzed. If no specific pattern is found, then it can be assumed that variances are constant for all output (acoustic absorption). In the developed model, no specific pattern was found in residuals versus predicted plot as shown in Figure 4.23.

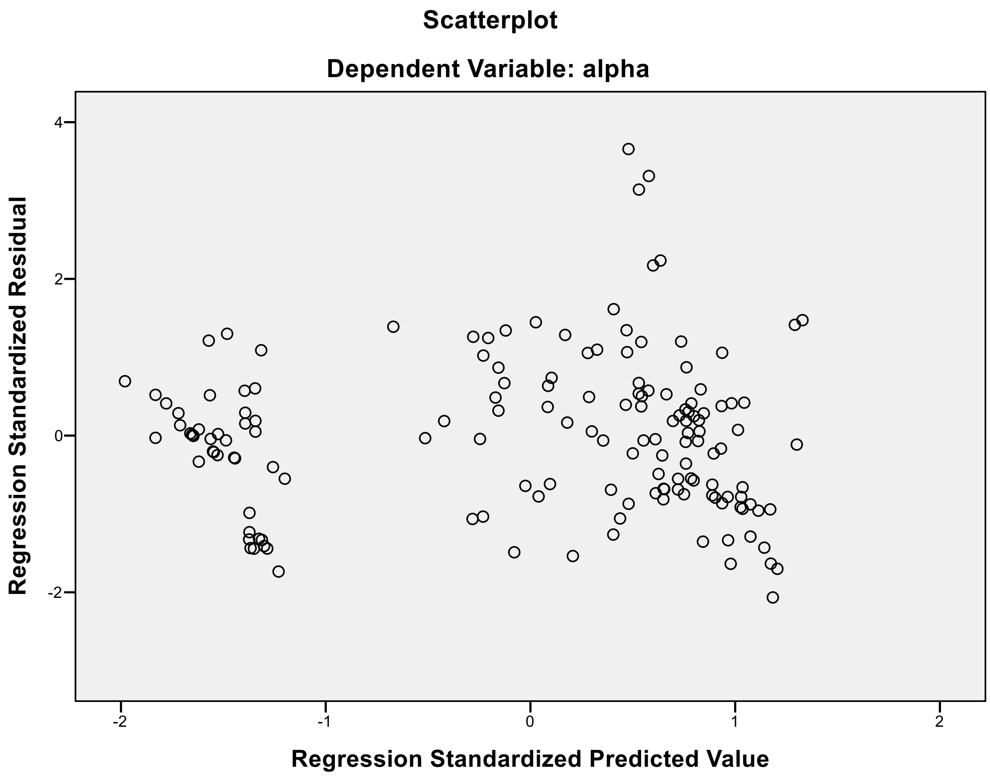


Figure 4.23 Constant variance

Independence of residuals

If covariance of any two errors is equal to zero, then this assumption is met. Generally, this assumption is met unless there is a time component in the data. In the analysis, there were no time component. So, this assumption has been met.

Normality of residuals

This assumption is met if residuals have an approximate normal distribution with mean equals to zero. This assumption can be checked by analyzing histogram of residuals plot or normality plot. The model satisfies this assumption as shown the Figure 4.24.

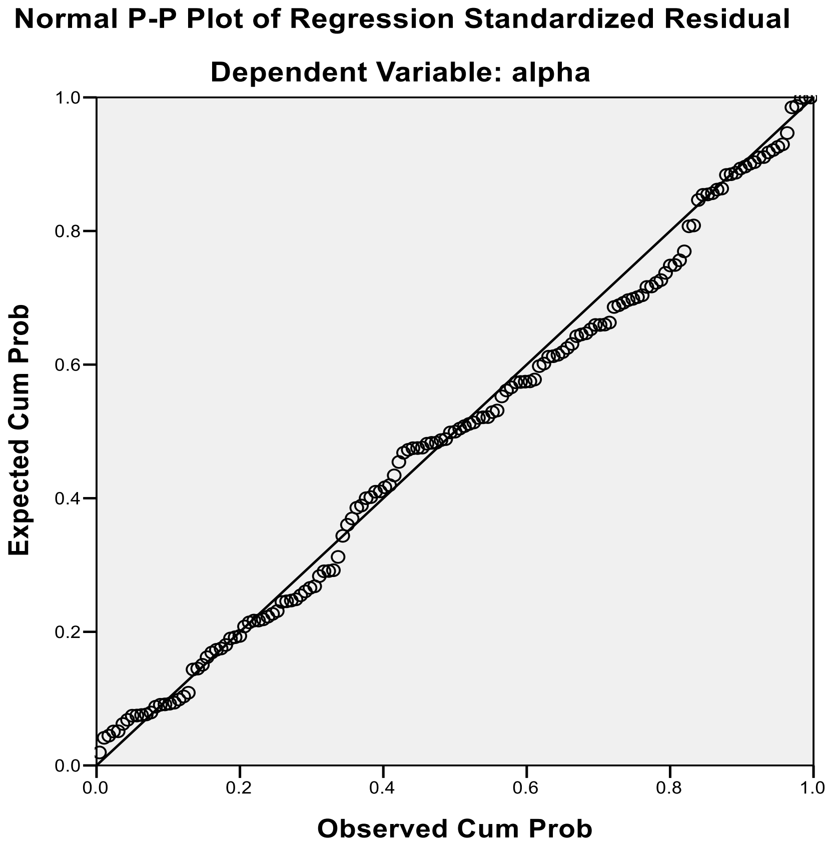


Figure 4.24 Normality of residuals

4.2.2 Model Validation

The analytical model was developed using 153 samples. Figure 4.25 shows the correlation between predicted and measured absorption coefficient. A good correlastion was found between the measured and predicted acoustic absorption coefficient (R^2 = 0.81). To validate the model, additional 17 data points were used from the lab experiment result. This data set is presented in Appendix A. It can be seen that the validation data points are lied very close to the model development line as shown in Figure 4.25. Figure 4.26 shows sensitivity analysis of the model parameters. The acoustic absorption increased with the increase in percent air void and sample thickness.

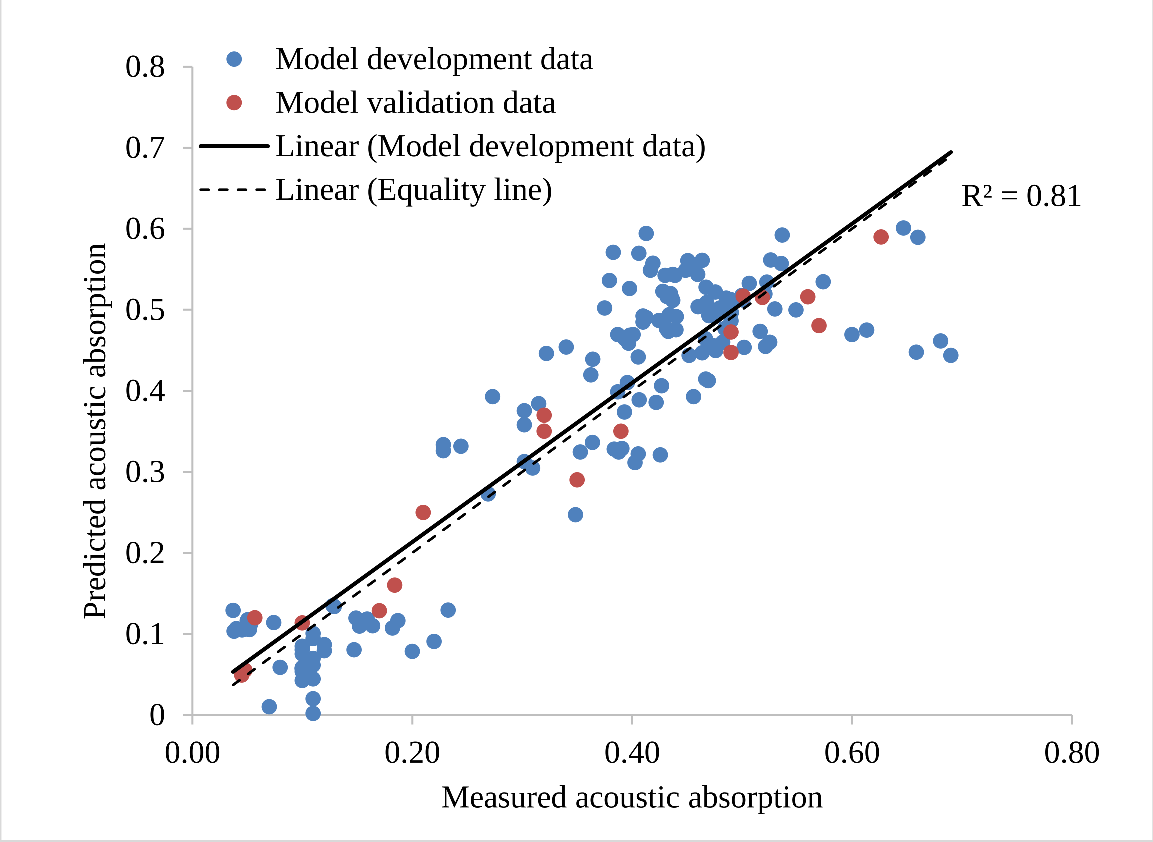


Figure 4.25 Model validation

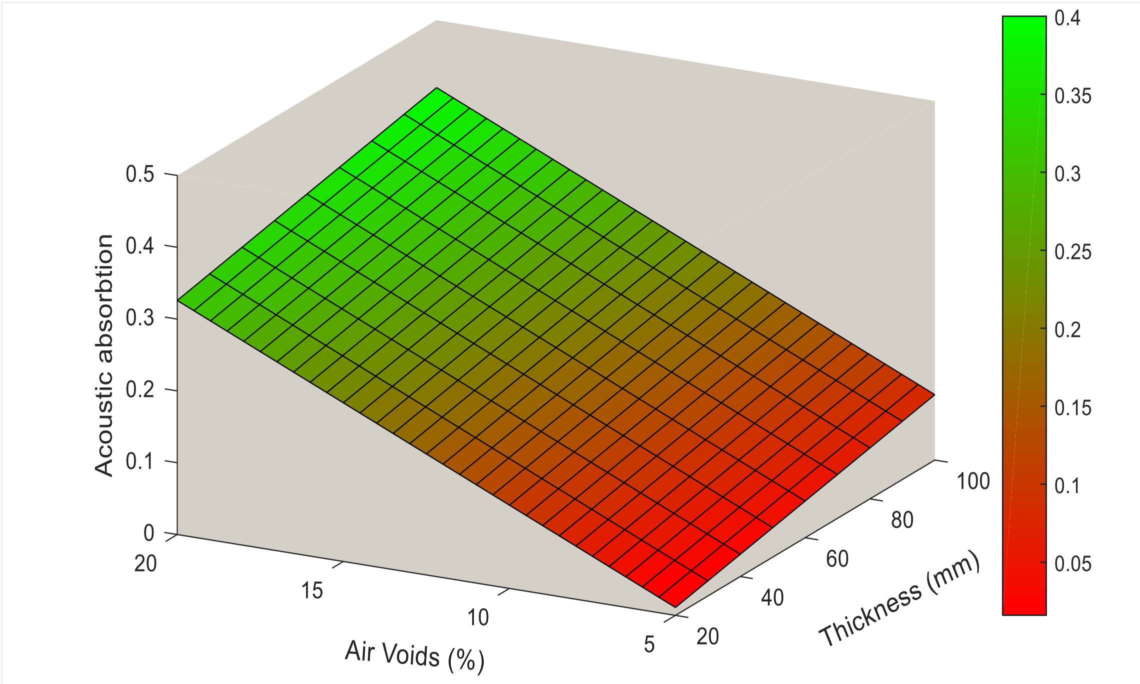


Figure 4.26 Sensitivity analysis

4.3 Acoustic Absorption and Noise Level

Sandberg and Easement (2002) demonstrated that variation in noise level, measured in the field, depends on both layer thickness and air voids based on research studies conducted in Belgium and Sweden. Sandberg and Easement (2002) developed an equation that relates the variation in noise level to the layer thickness and percent air voids as given in Equation 4.3.

$$\Delta L = 0.005\, e * v \qquad (4.3)$$

where:

ΔL = noise level, dB(A)

e = thickness of surfacing layer (mm)

v = air voids (expressed as a whole number)

In the study herein the acoustic absorption coefficient was also found be a function of layer thickness and percent air voids as given in Equation 4.2. The team correlated the acoustic absorption coefficients calculated using Equation 4.2 with the variation of noise level calculated using Equation 4.3. The percent air voids was varied from 2.50% to 27% and the thickness was varied from 13 mm to 100 mm. It was found a good correlation ($R^2 = 0.79$) between acoustic absorption and variation of noise level as shown in Figure 4.27. Such relationship demonstrates that there is a correlation between noise level in the field and acoustic absorption measured in the laboratory.

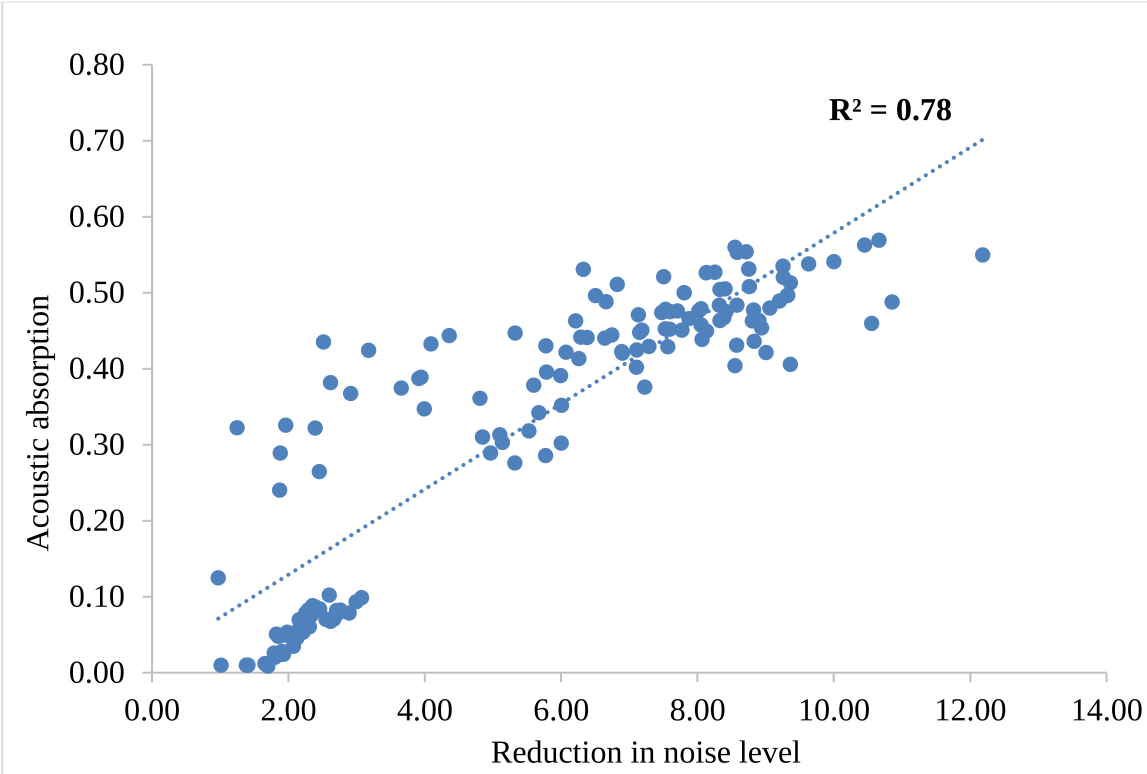


Figure 4.27 Correlation between absorption coefficient and noise reduction level

4.4 Double-layer System

Pavement layer thickness plays an important role in reducing tire-pavement noise. A single porous layer is very effective in reducing noise, but due to higher air void, porous surface is clogged easily by sand which reduces the sound absorption capacity of the porous surface (Masondo et al. 2002). Some European countries developed a two-layer porous system or twinlay. The top layer is made of finer material (0.04-0.08 in. [1-2 mm]) and is intended to protect the lower porous layer (0.4-0.5 in. [9.5-13 mm] material) from clogging with dirt and debris (Bernhard 2011). In addition, the top layer provides a fine surface texture that also helps in reducing noise. Typical thicknesses are about 1 in. (2.5 cm) for the top layer and 1.8-2 in. (4.5-5 cm) for the bottom layer (Masondo et al. 2002). This system demonstrated greater reduction in noise levels compared to single layer porous asphalt, especially on high-speed highways (Gibbs et al. 2005). On the other hand, a thin-layer of porous pavement seems to perform better on lower speed urban roads. Regarding aggregate size and gradation, some studies indicated that the maximum size of the aggregate should be limited to around 0.15 in to 0.4 in. (4mm to 10mm) in order to achieve the maximum noise reduction when open-graded pavements are used (Bernhard 2011; Gibbs et al. 2005; Hanson et al. 2004; Wayson 1998). The peak sound absorption is broader and occurs at a lower frequency for fine aggregates versus coarse aggregates (Leung 2007).

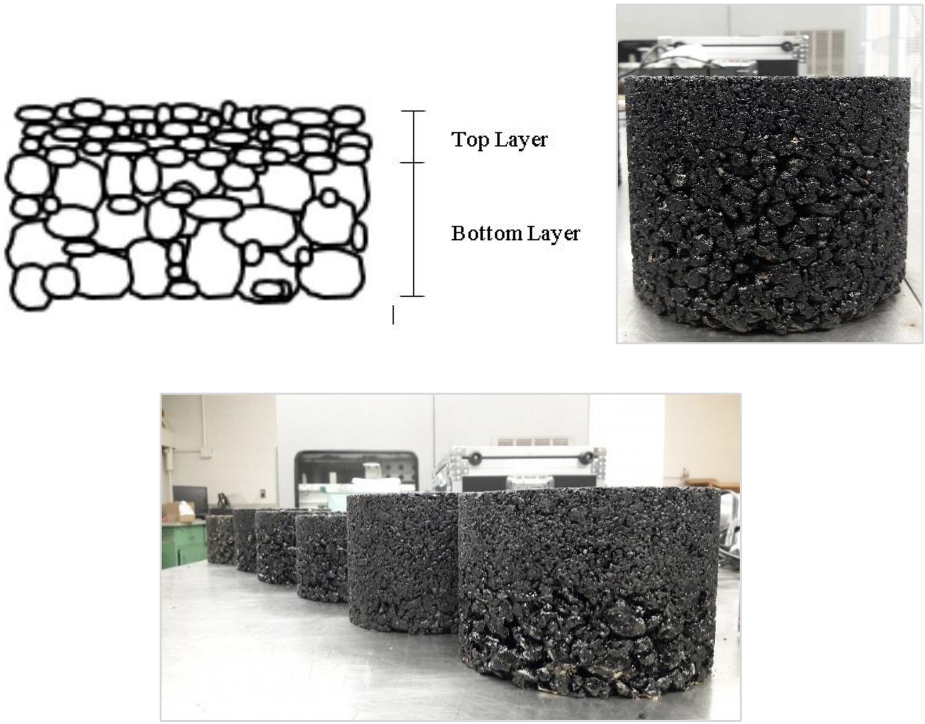


Figure 4.28 Double layer test samples

Open graded mix or porous friction course (PFC) has higher percent air voids which increases the acoustic absorption of asphalt mixtures. However, the voids at the surface may be clogged which would lead to a decrease in its acoustical performance overtime. In addition, PFC requires more amount of deicers in winter which is an added cost. The double-layer system can overcome these issues. In this study herein, the researchers investigated the optimum layer thickness of for improved acoustic absorption. In this section, five OGFC samples were prepared using gabbro aggregates. The nominal maximum aggregate size was 9.5 mm. The sample thickness was 10 cm. The thickness of the top layer was varied from 1 cm to 5 cm. The gradations of the fine top layer and coarse bottom layer are presented in Table 4.29 and shown in Figure 4.29. Table 4.30 presents the acoustic absorption coefficient of the test specimens.

It was found that, the double-layer system provides comparable acoustic absorption to OGFC and better than the conventional dense graded mixtures. The acoustic absorption of the double-layer samples are dependent on the thickness of top layer. As the thickness of the top layer increases, acoustic absorption decreases (Figures 4.30 and 4.31). When the thickness of the fine top layer remains 1 cm to 3 cm, the reduction in acoustic absorption due to adding fine top layer varies from 2% to 6% only. Any further increase of top layer thickness resulted in higher reduction of acoustic absorption. When the thickness of the fine top layer was 4 cm and 5 cm, the reduction in acoustic absorption was found between 11.6% to 15.9 %, respectively. These results demonstrated effectiveness of the double-layer system in overcoming the issues associated with using OGFC as a wearing course.

Table 4.29 Gradation for double layer

Top layer	Sieve size (mm)	25	12.5	9.5	4.75	2.36	0.3	0.15	0.075
	Percent passing	100	100	100	85.6	38.4	15.4	11.9	7
Bottom layer	Sieve size (mm)	25	12.5	9.5	4.75	2.36	0.6	0.3	0.075
	Percent passing	100	100	43.8	16.4	3.1	2	2	1.8

Table 4.30 Absorption coefficient of double layer

Sample no.	**Top layer thickness (t1), cm**	**Bottom layer thickness (t2), cm**	**Total thickness (tc), (cm)**	**ratio (t1/tc)**	**Acoustic absorption of double layer**	**Acoustic absorption of OGFC layer**	**Reduction in acoustic absorption (%)**
1	1	9	10	0.1	0.50	0.51	2.0
2	2	8	10	0.2	0.48	0.51	5.9
3	3	7	10	0.3	0.51	0.53	3.8
4	4	6	10	0.4	0.38	0.43	11.6
5	5	5	10	0.5	0.37	0.44	15.9

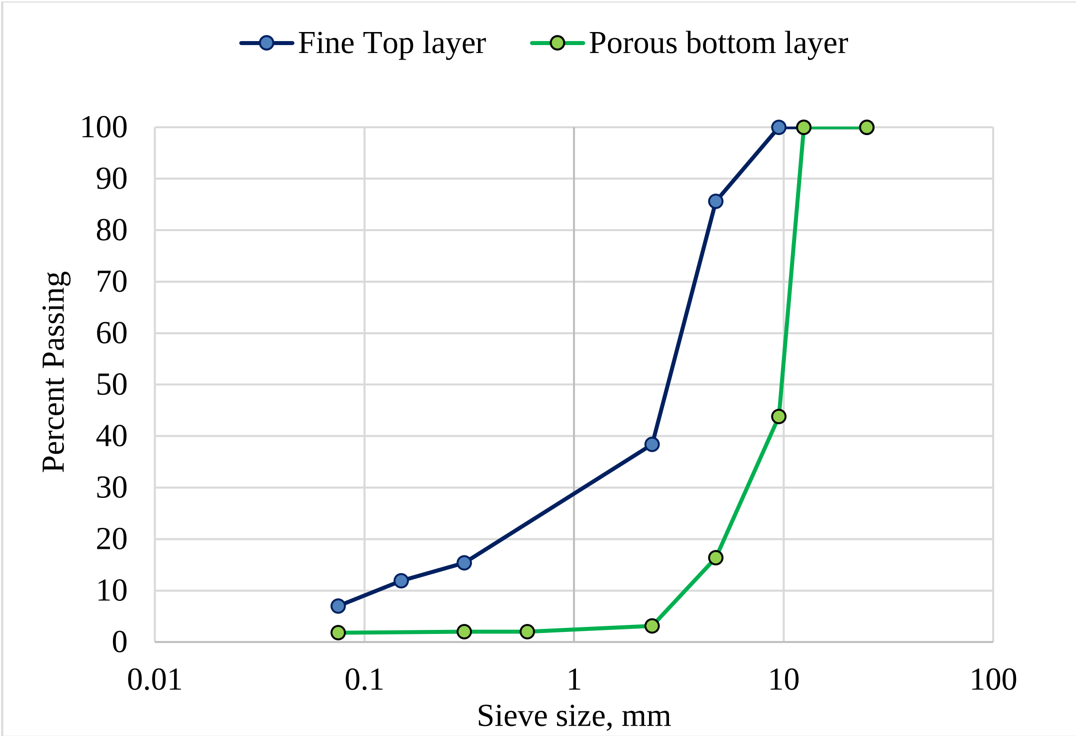


Figure 4.29 Gradation of top and bottom layer for the double layer pavement

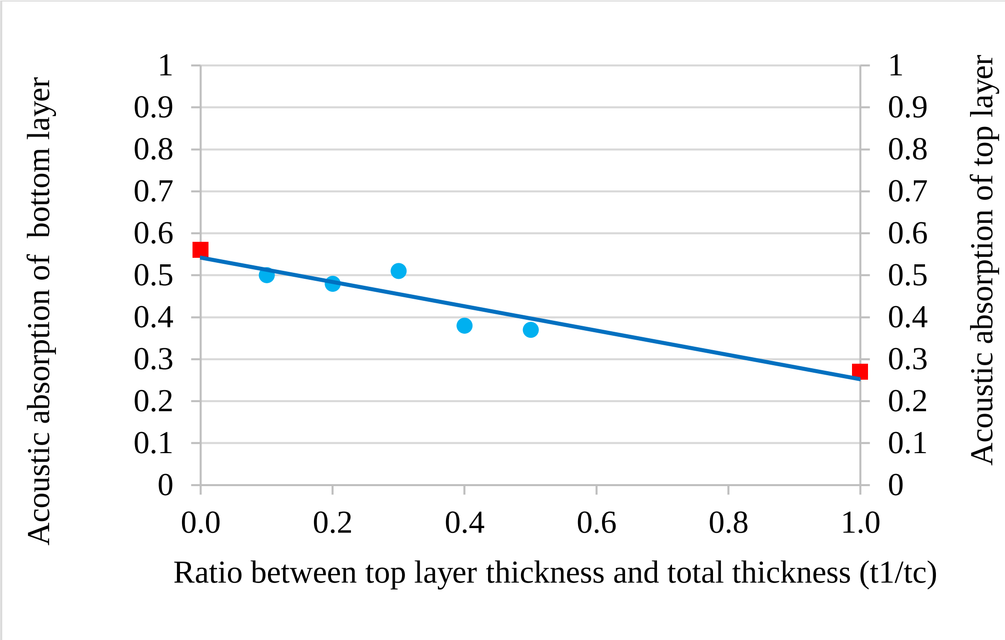


Figure 4.30 Change in absorption coefficient with the change in thickness ratio of the top and bottom layer of a double layer

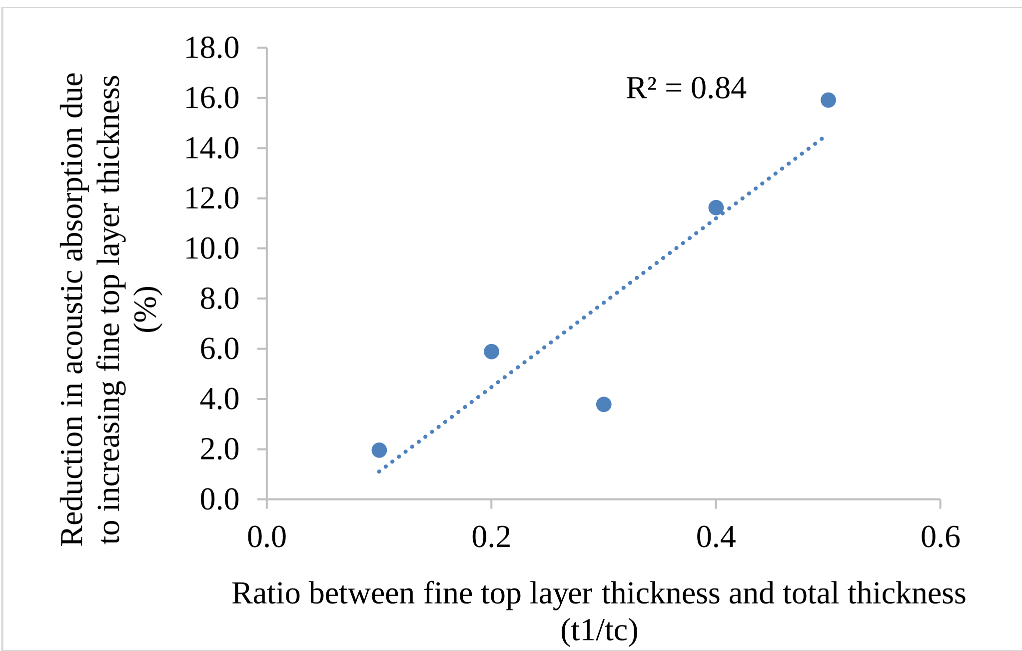


Figure 4.31 Reduction in acoustic absorption due to increase of top layer thickness of a double layer

4.5 Parameters that influence the acoustic absorption in the field

The acoustical performance of asphalt pavements may be influenced by several factors during the service life and after the construction. Table 4.2 presents the parameters evaluated in this study. These parameters include pavement age (unaged and 3-month aged), air void structure (uniform and non-uniform), surface texture (positive and negative), temperature (0 °C, 20 °C, and 50 °C), surface conditions (e.g., dust-free and dusty), and moisture conditions (dry and wet).

4.5.1 Aging

To evaluate the effect of aging on acoustic absorption of seven samples were prepared as presented in Table 4.31. The open and dense graded aggregate gradation were used. The acoustic absorption was measured for all the samples before aging (0 months) and after aging (3 months). The test specimens were aged for 3 months at a temperature of 60^{o}C to simulate the field aging. Table 4.31 and Figure 4.32 demonstrate the acoustic absorption results. It was found that the acoustic absorption increased with aging for open graded mixes. However, for dense graded mix aging does not have any specific effect on the acoustic absorption.

Table 4.31 Absorption coefficient at 0 month and 3 month.

Sample	Aggregate	Gradation	Acoustic absorption	
			0 months	3 months
1	Gabbro	Open	0.38	0.43
2	Gabbro	Open	0.47	0.49
3	Basalt	Open	0.44	0.48
4	Basalt	Open	0.38	0.41
5	Basalt	Dense	0.11	0.12
6	Gabbro	Dense	0.09	0.05
7	Gabbro	Dense	0.11	0.09

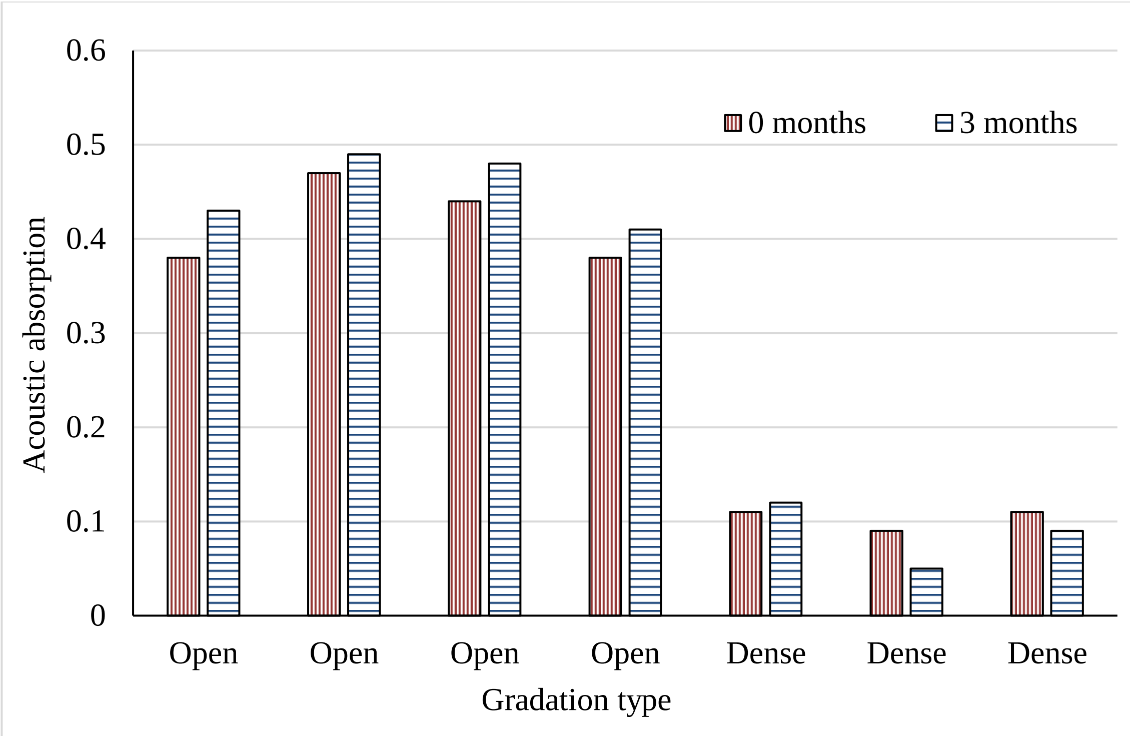


Figure 4.32 Effect of aging on absorption coefficient

4.5.2 Moisture Condition

To evaluate the effect of sample conditions (wet versus dry) on the acoustical performance, test samples were tested in dry and wet condition. The samples were submerged in water for 24 hours. Table 4.32 presents the acoustic absorption in different conditions, while Figure 4.33 shows the box plot of absorption coefficient in wet and dry conditions. The results demonstrated that wet sample had lower absorption compared to dry conditions. Water occupied the voids in the samples which may reduce the amount of noise absorbed leading to lower acoustic absorption.

Table 4.32 Absorption coefficient for different moisture

	Acoustic absorption	
Sample	**Dry**	**Wet**
1	0.23	0.08
2	0.53	0.46
3	0.65	0.41
4	0.47	0.46
5	0.66	0.47
6	0.69	0.55
7	0.52	0.33
8	0.44	0.34
9	0.37	0.19

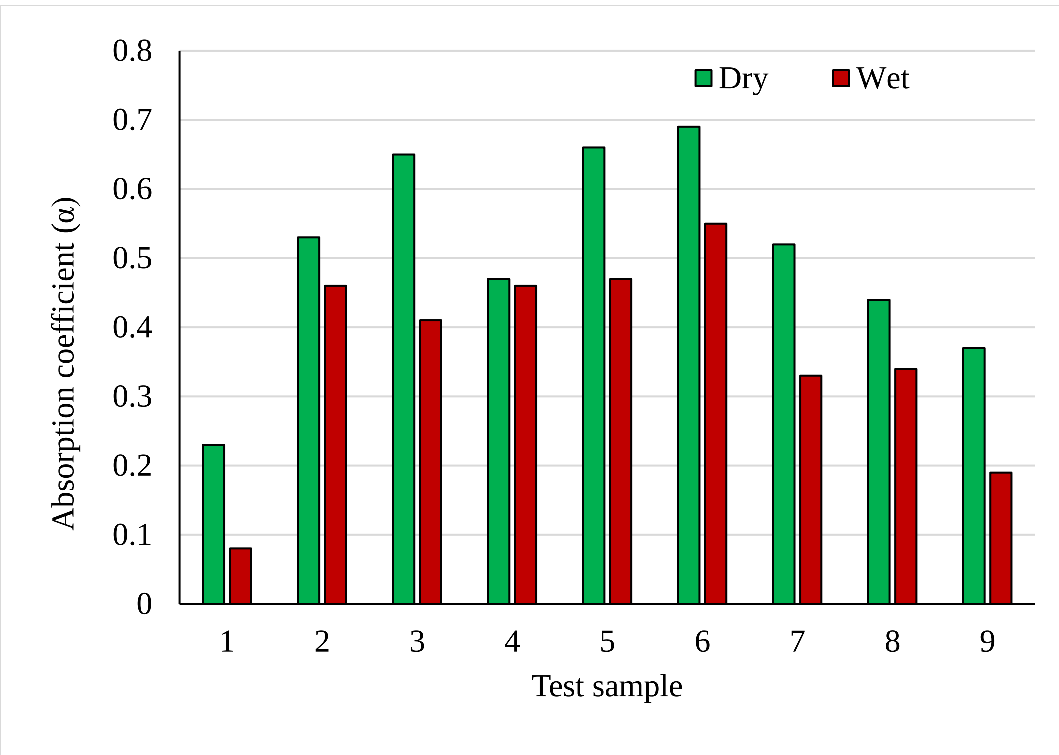


Figure 4.33 Box plot of absorption coefficient for different moisture conditions.

4.5.3 Temperature

Temperature is one of the important parameters that affect noise level. The noise level decreases as the temperature increases. For every 10 °C increase in air temperature, noise level decreased by 1 dBA for dense asphalt pavements and by 0.6 dBA for porous pavements (Fabienne and Yves Pichaud 2007). Reduced noise level implies higher acoustic absorption. In the study herein, 12 samples were prepared and tested at different temperatures (0°C, 20°C, and 50°C). The test samples were OGFC. It was found that the acoustic absorption was higher at 50°C compared to 20°C and the difference is significant as shown in the Table 4.33. However, no specific pattern was observed for acoustic absorption at lower temperature (0°C).

Table 4.33 Absorption coefficient of asphalt samples at different temperature.

Aggregate type	Acoustic absorption at 0°C	Acoustic absorption at 20°C	Acoustic absorption at 50°C
Gabbro	0.29	0.23	0.27
Gabbro	0.28	0.3	0.31
Limestone	0.5	0.41	0.43
Limestone	0.4	0.4	0.42
Basalt	0.52	0.47	0.58
Basalt	0.55	0.49	0.57
Limestone	0.58	0.62	0.64
Limestone	0.59	0.66	0.69
Limestone	0.62	0.52	0.65
Gabbro	0.58	0.57	0.6
Gabbro	0.39	0.46	0.42
Gabbro	0.4	0.43	0.51

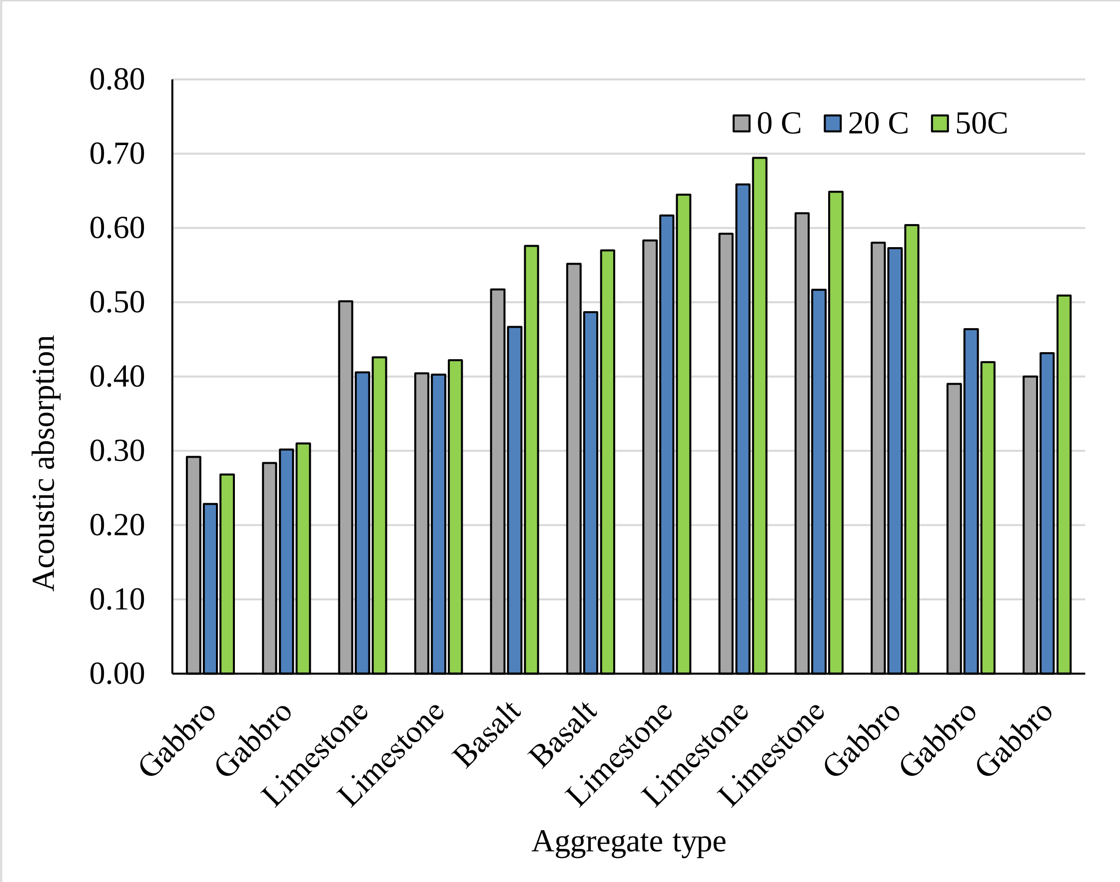


Figure 4.34 Absorption coefficient of asphalt samples at different temperature

4.5.4 Surface condition (dusty and dust-free)

To evaluate the effect of surface condition on acoustic absorption of eight samples were prepared as presented in Table 4.34. The open graded aggregate gradation was used. The acoustic absorption was measured for all the samples at dust free condition. Then some dust was inserted on the top surface of all the samples. The test specimens were kept outside for 3 months to simulate the dusty surface condition. Table 4.34 and Figure 4.35 demonstrate the acoustic absorption results. In the analysis, higher acoustic absorption was found in dusty-free surface condition.

Table 4.34 Absorption coefficient in dust free and dusty conditions

Sample	Aggregate	Gradation	Acoustic absorption	
			Dust-free	Dusty
1	Gabbro	Open	0.43	0.38
2	Gabbro	Open	0.41	0.38
3	Basalt	Open	0.51	0.49
4	Basalt	Open	0.49	0.47
5	Basalt	Open	0.52	0.50
6	Basalt	Open	0.48	0.44
7	Lightweight	Open	0.65	0.64
8	Lightweight	Open	0.51	0.47

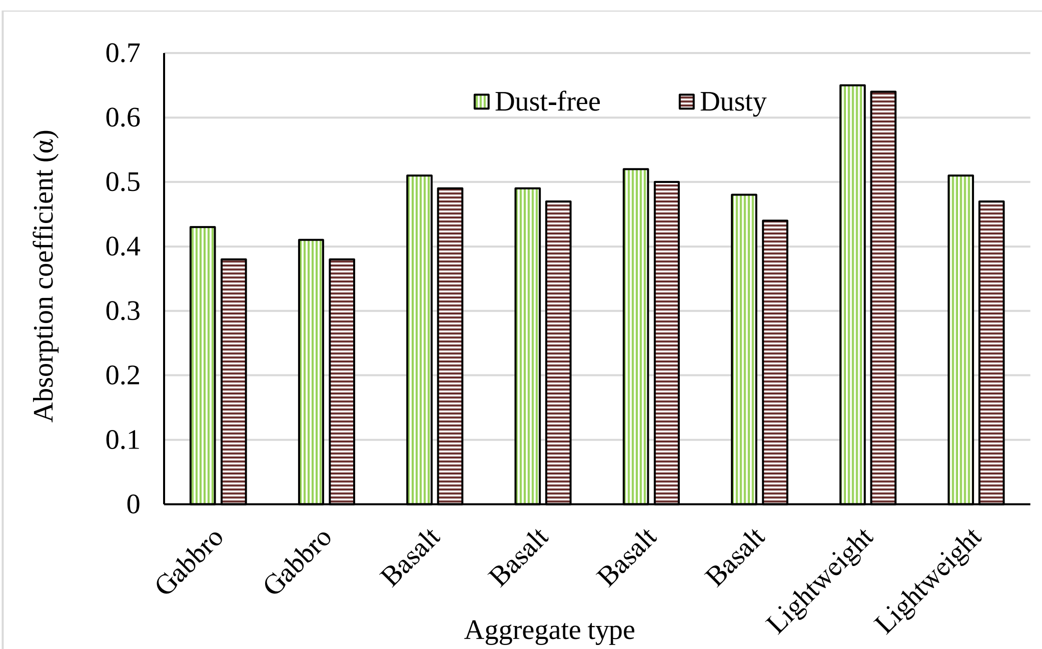


Figure 4.35 Absorption coefficient of asphalt samples at different temperature

4.5.5 Air void Structure

Air void distribution is not uniform along the sample height. There is higher air void content at the top and the bottom compared to the middle as shown in the Figure 4.36 (Masad et al. 1999). This is due to the laboratory compaction. Air void distribution and aggregate interlock are related to mixture performance (Shashidhar 1999). In gyratory compacted specimens, the middle part of the sample is more compacted than the top and the bottom parts (Partl et al. 2003 and 2007). Not only the level of porosity but also the size of the pore and the tortuosity has a strong effect on acoustical absorption (Nelson et al. 2008). To evaluate the effect of air void structure on acoustic absorption, test samples were prepared and cut to produce different air void distributions; however, the average percent air void is the same. Table 4.35 provides the characteristics of the test samples. Different air void distribution was achieved by cutting the specimens at different heights. The test samples were cut into three equal parts: top, middle, and bottom. The test samples were selected for the top, bottom and middle parts to have comparable air void. It was found that, the middle part showed higher acoustic absorption compared to top and bottom parts (Figure 4.37). The middle part has uniform air void distribution and thus higher chance for the air voids to be connected compared to top and bottom parts.

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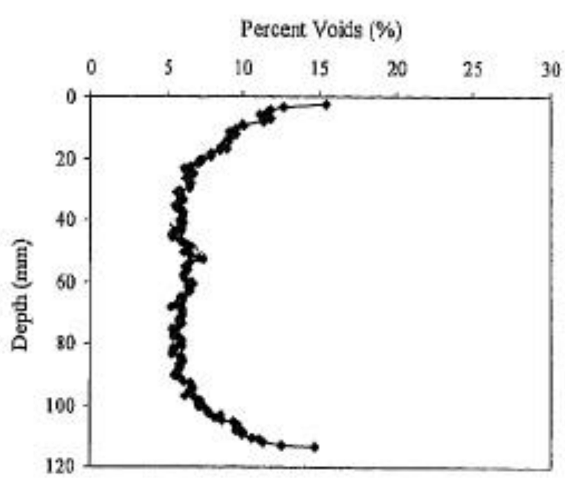

Figure 4.36 Air void distribution in superpave gyratory compactor (SGC) and linear kneading compactor (LKC) specimens (after Masad et al. 1999)

Table 4.35 Average acoustic absorption of different air void structure

Sample no.	Gradation	Part	Air void	Acoustic absorption
1	PFC	Top	21.09	0.38
		Middle	20.76	0.41
		Bottom	21	0.40
2	PFC	Top	16.59	0.27
		Middle	13.12	0.33
		Bottom	16.43	0.29
3	PFC	Top	21.79	0.40
		Middle	19.78	0.44
		Bottom	21.77	0.39
4	F	Top	8.7	0.16
		Middle	8.2	0.21
		Bottom	9.1	0.19
5	F	Top	7.0	0.11
		Middle	6.57	0.18
		Bottom	6.97	0.10
6	F	Top	7.5	0.17
		Middle	7.5	0.22
		Bottom	8.3	0.21

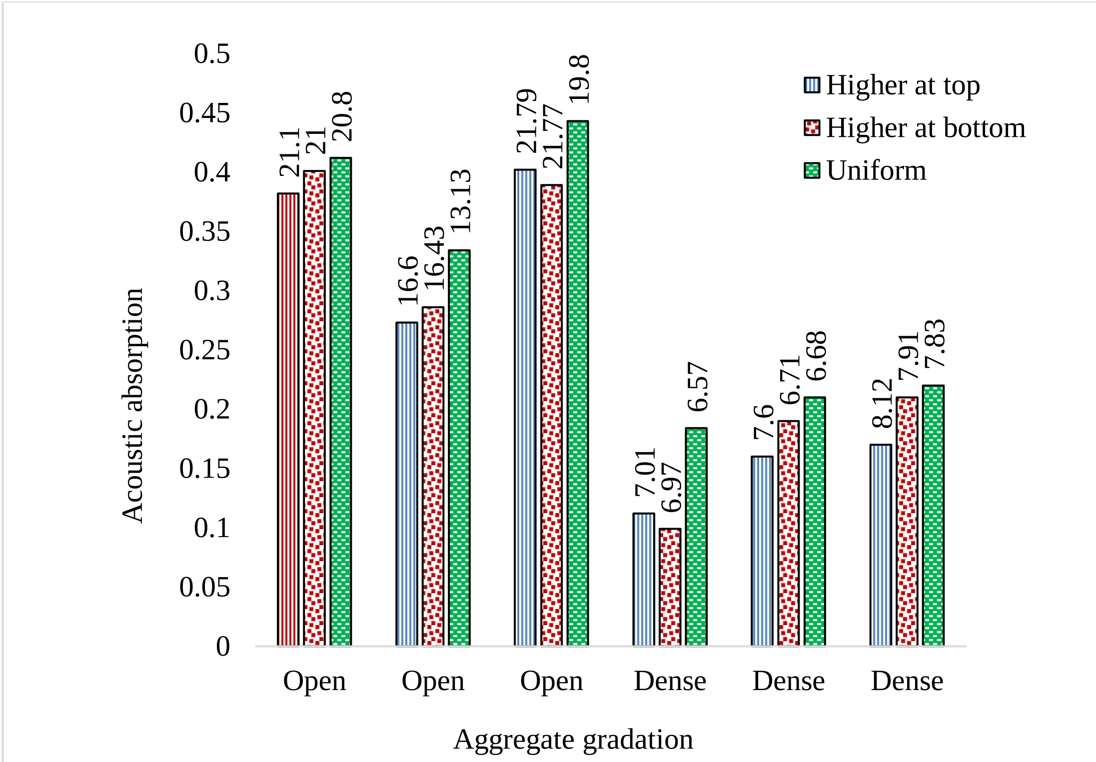

Figure 4.37 Absorption coefficient of asphalt samples for different air void structure

4.5.6 Texture

Tire-pavement noise is greatly affected by surface texture. Surface texture changes after the construction due to traffic, environment and the combination of both which referred as aging of texture (Kohler and Harvey 2010). Negative texture with characteristic length less than 10.0 mm tends to reduce noise (Bernhard and Wayson 2011). However, texture of other sizes and types tends to increase noise. In this study, the acoustic absorption was measured for two different types of textures: positive texture and negative texture as shown in the Figure 4.38. Sand patch method was used to determine the mean texture depth. Figure 4.39 shows that the samples with negative texture had higher acoustic absorption compared to samples with positive texture. These results are consistent with the noise measurements in the field where the seal coat surfaces (positive texture) are nosier compared to surfaces with negative texture (e.g., dense graded mixtures).

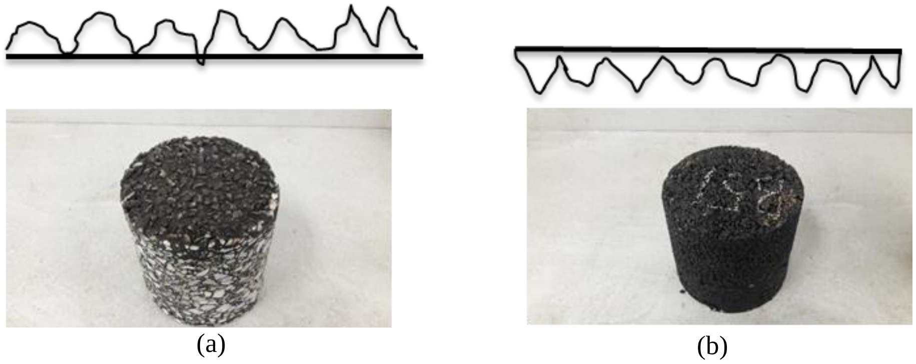

Figure 4.38 Surface texture, (a) Positive, and (b) Negative

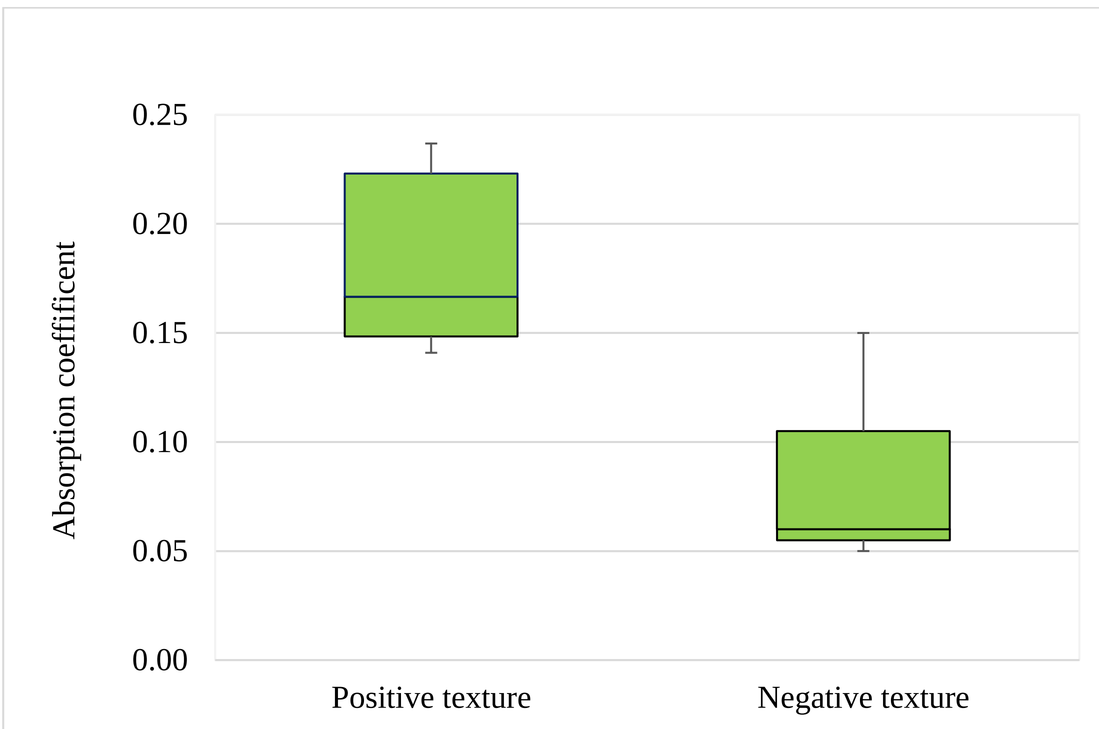

Figure 4.39 Absorption coefficient of asphalt samples for positive and negative texture

CHAPTER 5: CONCLUSIONS

This study focused on evaluating the pavement characteristics that influences the acoustic absorption of asphalt mixtures. The research team evaluate various parameters that could affect the acoustical performance of asphalt mixtures during the mix design stage. These parameters include aggregate gradation, aggregate type, binder type, percent air voids, and sample thickness. In addition to the parameters evaluated during the design stage, the researchers evaluated additional factors that may influence the acoustical performance of asphalt mixtures after construction and during the service life including pavement age, air void structure, surface texture, temperature, surface conditions, and moisture conditions. Based on the results the research team developed an analytical model for absorption coefficient as a function of percent air voids and layer thickness. The main findings of this study can be summarize as follows:

- The acoustic absorption of asphalt mixtures increase with the increase in percent air voids.
- Asphalt mixtures with 3% to 10 % air voids had low absorption coefficient (0.5 to 0.20).
- Open graded asphalt mixtures had higher acoustic absorption compared dense graded mixture.
- Samples prepared with lightweight aggregates had higher acoustic absorption.
- The acoustic absorption increased with layer thickness.
- Double-layer system would provide higher acoustic absorption and overcome the issue associated with using OGFC as a wearing course.
- An analytical model for the acoustic absorption was developed and found to correlate well with the experimental measurements in the laboratory.
- As the acoustic absorption increases the reduction of noise level increases.
- The acoustic absorption increased with age of asphalt mixtures and increase with temperature and air void uniformity.
- Dusty asphalt surfaces had lower acoustic absorption compared to dust-free surfaces.

5.1 Future Research

- Development a direct relationship between the acoustic absorption and tire-pavement noise could be a very helpful for pavement engineers.
- The acoustic absorption analytical model could incorporate parameters that describe the change in the acoustical performance after construction.

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APPENDIX A

Table A.1 Parameters (κ and λ) for aggregate gradation using MATLAB

Gradation	Kappa, κ	lamda, λ
1	1.594	11.32
2	0.271	6.354
3	0.468	7.989
4	1.282	11.29
5	1.305	11.17
6	1.112	9.587
7	1.334	11.74
8	0.9964	8.806
9	1.045	9.634
10	1.325	11.89
11	0.3775	8.94
12	1.1	9.775
13	0.7009	7.427

Table A.2 Model development data

Number	Air void (%)	Thickness (mm)	Absorption coefficient from the model	Absorption coefficient from the lab experiment
1	17.00	65	0.31	0.23
2	19.00	42	0.33	0.30
3	25.00	80	0.49	0.46
4	23.00	54	0.42	0.43
5	16.00	75	0.30	0.43
6	17.00	57	0.30	0.39
7	23.00	67	0.44	0.47
8	26.00	82	0.51	0.66
9	23.00	70	0.44	0.49
10	21.00	72	0.40	0.46
11	25.00	70	0.48	0.45
12	26.00	67	0.50	0.38
13	17.00	60	0.30	0.38
14	16.00	62	0.28	0.31
15	25.00	77	0.49	0.42
16	24.00	70	0.46	0.43
17	25.00	60	0.47	0.38
18	24.00	78	0.47	0.51
19	24.00	73	0.46	0.40
20	24.00	65	0.46	0.44
21	25.00	65	0.48	0.44
22	25.00	70	0.48	0.42
23	23.00	80	0.45	0.47
24	26.00	66	0.50	0.41
25	23.00	62	0.43	0.42
26	23.00	66	0.44	0.44
27	25.00	66	0.48	0.44
28	25.00	66	0.48	0.46
29	23.00	65	0.43	0.41
30	22.00	69	0.42	0.40
31	22.00	65	0.41	0.39
32	24.00	65	0.46	0.43
33	25.00	74	0.49	0.45
34	24.00	69.4	0.46	0.48
35	23.00	66.1	0.44	0.48

Table A.2 Model development data (Continued)

36	21.00	67.7	0.39	0.41
37	20.00	59.9	0.37	0.43
38	21.00	65.6	0.39	0.36
39	20.00	71	0.38	0.36
40	22.00	58	0.41	0.47
41	22.00	61.3	0.41	0.48
42	17.00	57	0.30	0.35
43	11.41	17	0.14	0.23
44	19.63	57	0.36	0.27
45	19.16	13	0.30	0.23
46	21.00	24.9	0.35	0.41
47	18.66	25.6	0.30	0.39
48	19.00	20.6	0.31	0.24
49	15.59	24	0.24	0.35
50	16.29	30.1	0.26	0.27
51	19.23	50	0.34	0.39
52	20.29	36	0.35	0.32
53	20.76	38	0.36	0.39
54	22.28	97.4	0.45	0.44
55	22.87	38.1	0.40	0.50
56	20.30	57	0.37	0.40
57	21.78	53	0.40	0.45
58	23.00	74.58	0.44	0.38
59	22.70	74.15	0.44	0.43
60	21.88	71	0.42	0.40
61	22.04	68.3	0.42	0.39
62	3.97	70	0.04	0.11
63	3.83	72	0.04	0.07
64	2.89	70	0.02	0.10
65	3.30	85	0.04	0.11
66	4.98	68	0.06	0.10
67	5.50	70	0.07	0.08
68	5.92	70	0.08	0.11
69	5.55	65	0.07	0.10
70	5.85	65	0.07	0.11
71	5.66	65	0.07	0.10
72	5.96	60	0.07	0.10
73	6.38	65	0.08	0.10
74	6.53	65	0.09	0.12
75	6.81	65	0.09	0.12

Table A.2 Model development data (Continued)

76	7.10	65	0.10	0.11
77	5.34	62	0.06	0.11
78	5.79	63	0.07	0.10
79	7.21	55	0.09	0.10
80	7.05	55	0.09	0.10
81	22.20	75	0.43	0.55
82	23.10	72	0.44	0.52
83	22.49	70	0.43	0.48
84	24.36	76	0.47	0.54
85	22.91	70	0.44	0.50
86	26.30	65	0.50	0.41
87	24.61	99	0.50	0.54
88	25.80	49	0.48	0.53
89	25.02	65	0.48	0.45
90	23.28	80	0.45	0.52
91	22.62	78	0.44	0.49
92	23.17	21.7	0.39	0.40
93	24.30	53.5	0.45	0.47
94	22.52	36.3	0.40	0.53
95	21.87	60.7	0.41	0.43
96	23.90	55.7	0.44	0.43
97	22.66	47	0.41	0.48
98	25.80	81	0.51	0.65
99	23.30	80	0.46	0.57
100	21.12	69	0.40	0.47
101	22.00	80	0.43	0.49
102	15.38	75	0.28	0.41
103	15.20	70	0.28	0.40
104	21.30	57	0.39	0.34
105	22.05	73	0.42	0.47
106	22.36	75	0.43	0.46
107	22.65	80	0.44	0.50
108	19.10	98	0.39	0.66
109	22.05	57	0.41	0.52
110	18.76	77	0.36	0.47
111	20.90	66	0.39	0.52
112	20.65	83	0.40	0.60
113	19.43	88	0.38	0.69
114	20.01	90	0.40	0.68

Table A.2 Model development data (Continued)

115	20.77	85	0.41	0.61
116	21.53	83	0.42	0.41
117	21.68	75	0.42	0.49
118	20.85	60	0.38	0.32
119	21.97	81	0.43	0.53
120	23.16	65	0.44	0.49
121	21.22	76	0.41	0.44
122	22.10	65	0.42	0.41
123	24.80	55	0.46	0.43
124	21.10	100	0.43	0.48
125	16.54	62.1	0.30	0.36
126	18.27	65.7	0.34	0.42
127	20.30	28.7	0.34	0.46
128	20.70	37.8	0.36	0.47
129	17.57	21.4	0.28	0.30
130	22.50	28.2	0.39	0.48
131	18.00	63	0.33	0.30
132	8.34	55	0.12	0.07
133	8.19	55	0.11	0.16
134	7.83	55	0.11	0.11
135	8.41	57	0.12	0.16
136	8.19	60	0.12	0.19
137	7.20	60	0.10	0.22
138	7.89	59	0.11	0.18
139	8.96	58	0.13	0.13
140	7.11	52	0.09	0.20
141	8.12	56	0.11	0.15
142	8.55	55	0.12	0.15
143	7.29	50	0.09	0.15
144	7.28	70	0.11	0.045
145	7.67	72	0.12	0.050
146	7.10	75	0.11	0.040
147	7.97	75	0.13	0.037
148	8.19	75	0.13	0.128
149	6.98	75	0.11	0.038
150	7.22	80	0.12	0.050
151	7.73	70	0.12	0.054
152	7.29	70	0.11	0.052
153	7.42	73	0.11	0.053