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Acoustic properties of cenosphere reinforced cement and asphalt concrete

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Abstract

A detailed experimental study has been conducted to determine the effect of adding hollow ceramic-micro balloons, also known as cenospheres, on the acoustic properties of cement matrix and asphalt concrete. The motivation for this study was to explore the feasibility of using cenospheres in developing lightweight sound absorbing structural materials. Cement and asphalt concrete specimens with different volume fractions of cenospheres and varying diameter and thickness were tested to determine their acoustic characteristics over the range of frequencies (0–4000 Hz). Experimental results showed that a 40% volume fraction addition of cenospheres to cement matrix increased the Noise Reduction Coefficient by 100%. In contrast to cenosphere rich cement, the sound absorption coefficient of asphalt concrete decreased with an increase of cenosphere, volume fraction.

Keywords: Cenospheres; Cement; Asphalt; Sound absorption coefficient; Lightweight materials; Noise reduction coefficient

1. Introduction

Noise is becoming an increasingly significant concern because of its adverse effects on the lives of many people in urban societies and in rural areas. Noise arising from different sources such as vehicles, aircrafts, power plants and machinery is not only uncomfortable but also hazardous to health. These concerns have led to major

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developments in the field of sound absorbing materials. For homogenous and isotropic materials, acoustic performance is defined by a set of experimentally determined constants, namely: absorption coefficient, reflection coefficient, acoustic impedance, propagation constant and noise reduction coefficient (*NRC*).

In recent years extensive research studied the usages of various types of materials in making sound barriers. Wolfe et al. [1] investigated the usage of cement-wood composite as highway sound barriers and established the effectiveness of such sound absorbing materials in reducing traffic noise. Watts et al. [2] studied the effects on roadside noise levels by applying sound absorptive materials to the traffic face of noise barriers. Watts et al. [3] also studied the combined effects of porous asphalt surfacing and noise barriers on traffic noise using the boundary element method.

Significant research efforts have also examined noise reducing mechanisms in order to develop new design recommendations for pavements. Iwase et al. [4] performed an estimation of road traffic noise reduction by measuring the basic acoustic properties of porous pavement. Yamaguchi et al. [5] studied the sound absorption mechanisms of porous asphalt surface by comparing it with other porous sound absorbing materials, such as mineral wool and synthetic foam. They also investigated the relationship between void ratio and sound absorption properties of porous asphalt pavement. Meiarashi et al. [6] and Oshino et al. [7] studied noise reduction mechanisms and characteristics of asphalt pavement, and proposed a model for predicting vehicle noise propagation on asphalt pavement. However, studies involving the use of cenospheres for sound absorption applications have not yet been reported.

In this work the effect of the addition of cenospheres on the acoustic properties of cement matrix and asphalt concrete was studied to determine the feasibility of using cenosphere enrichment as a counter measure against noise. Cenospheres [8] are hollow micro balloons made of aluminum silicate. Being a waste product of thermal power plants, they are relatively inexpensive and their use has the added benefit of decreasing the strain on the environment. The focus of this study is to characterize the sound absorption parameters of cement matrix and asphalt concrete as a function of cenosphere content and material thickness over the frequency range of 0–4000 Hz, and to identify the optimum amount of cenospheres required to maximize sound absorption.

2. Theoretical considerations

The absorption of sound results from the dissipation of the sound energy as heat. The dissipation mechanisms are mainly due to one of two phenomena. The first is the energy loss due to flexural vibrations in the specimen. The second is porosity effects, where energy is dissipated due to multiple reflections of sound waves within the voids in the structure. For most porous materials like synthetic foam and mineral wool with interconnected pores, incoming sound is reflected within the pores, causing them to vibrate and convert sound energy into heat.

The sound absorbing performance of a material is defined by its sound absorption coefficient (α), which is the ratio of the unreflected sound intensity at the surface to the incident sound intensity. Other important acoustic parameters include the sound reflection coefficient (R) which is a ratio of the amount of total reflected sound intensity to the total incident sound intensity, and the acoustic impedance (Z_n) which is defined as ratio of sound pressure acting on the surface of the specimen to the associated particle velocity normal to the surface. These properties vary with frequency and are also a function of material thickness, density and pore size.

The measurement method used in this study employs an Impedance tube with a speaker at one end, and a specimen on the other end (discussed in detail in Section 4 of this paper). The interference of an incident wave and the reflected wave from the specimen creates a standing wave in the Impedance tube as shown in Fig. 1. Using the standing wave apparatus, the standing wave ratio (n) in the tube can be measured as:

$$n = \frac{P_{\mathrm{MAX}}}{P_{\mathrm{MIN}}} \tag{1}$$

where P_{MAX}, P_{MIN} are the maximum and minimum sound pressures in the impedance tube. The absorption coefficient (α) and the reflection coefficient (R) can be calculated from the knowledge of standing wave ratio using the following relationships:

$$\alpha = 1 - \left(\frac{n-1}{n+1}\right)^2 \tag{2}$$

$$R = \sqrt{1-\alpha} \tag{3}$$

Since the sound pressure and the particle velocity are not always in phase at the surface of a specimen the *Normal Acoustic Impedance (Z_n)* is a complex quantity

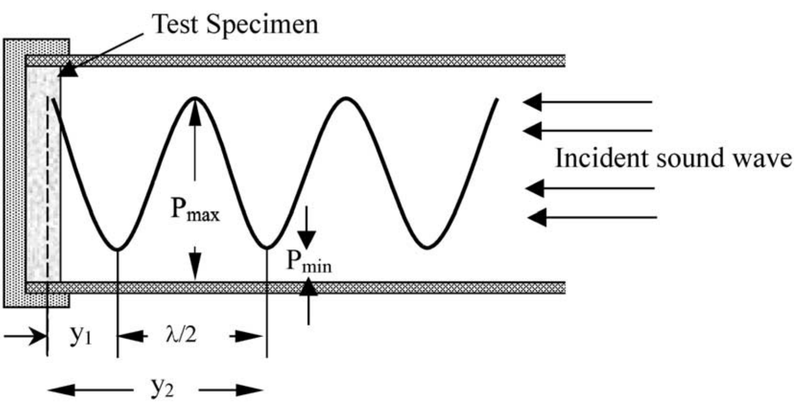

Fig. 1. Cross-section of impedance tube showing variation of pressure as a function of distance from the specimen.

which can be written as the sum of real and imaginary parts corresponding to the resistive and reactive components respectively

$$Z_n = (\text{resistive component}) + j\,(\text{reactive component}) \tag{4}$$

Where $j = \sqrt{-1}$

$$Z_n = (\mathrm{Re}(Z_n) + j\mathrm{Im}(Z_n)).\rho c \tag{5}$$

$$\frac{Z_n}{\rho c} = \sqrt{\mathrm{Re}^2 + \mathrm{Im}^2} \tag{6}$$

where ρ is the density and c is the velocity of sound in the material. The real and imaginary parts are related to the reflection coefficient R as:

$$\mathrm{Re}(Z_n) = \frac{1 - R^2}{1 + R^2 - 2R\cos\theta} \tag{7}$$

$$\mathrm{Im}(Z_n) = \frac{2R\sin\theta}{1 + R^2 - 2R\cos\theta} \tag{8}$$

where θ is the phase angle between the incident and reflected sound pressure, given by following relation:

$$\theta = \left(\frac{4y_1}{\lambda} - 1\right)\pi \tag{9}$$

$$\lambda/2 = Y_2 - Y_1 \tag{10}$$

where Y_1 and Y_2 are the distances of first and second minima from the specimen as shown in Fig. 1.

3. Specimen fabrication

3.1. Fabrication of cenosphere-rich cement specimens

Cenospheres are hollow spherical particles formed during the coal burning process by gaseous combustion products getting trapped in a viscous molten matrix. A *scanning electron microscope* (SEM) micrograph of cenospheres is shown in Fig. 2. Cenospheres were considered for this study because of their hollow nature and low specific gravity (approx. 0.67). These properties make cenospheres an ideal aggregate for lightweight cementitious materials.

Specimens of cenosphere-rich cement were made using Portland cement and cenospheres of size ranging from 10 to 300 μm in diameter. Several volume fractions of cenospheres (0–70%, increment of 10%) and different specimen dimensions were

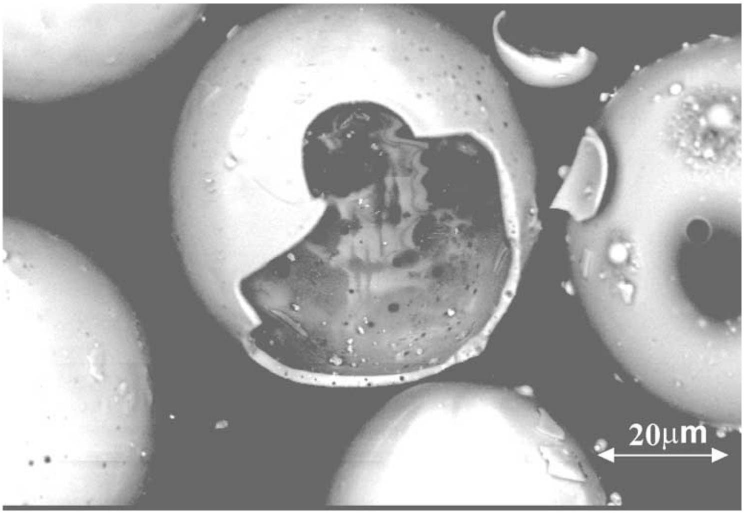

Fig. 2. SEM micrograph of broken cenosphere showing its hollow characteristics and porous walls.

considered in this study. For each volume fraction of cenospheres, cylindrical specimens of three different lengths (25, 50, and 75 mm) and two different diameters (30 and 100 mm) were fabricated. For all the cement specimens, the water to cement ratio was maintained at 0.4. At higher volume fraction of cenospheres (above 50%), wet cenospheres were used to obtain adequate workability of the mixture. In addition from the specimens for the standing wave apparatus, sheets of 300 mm×300 mm×13 mm dimension with different cenosphere volume fractions were also cast for measuring the dilatational wave speed. The specimens were allowed to harden for 24 h at room temperature and then placed in a water bath to cure for 28 days, before they were tested.

3.2. Fabrication of cenosphere-rich asphalt specimens

Highway surface course (class-1) design was used for making the cenosphere-rich asphalt concrete specimens. It consists of coarse aggregates and fine aggregates (sand) in different gradations and asphalt binder (6% by weight). In designing cenosphere asphalt concrete only fine aggregates of diameter less than 300 μm were replaced with an equivalent volume of cenospheres (0–100%, increments of 10%). Thus, the volume fraction of cenospheres mentioned in the subsequent sections for asphalt concrete indicates the volume replacement of fine aggregates. Cylindrical specimens of diameter 102 mm and thickness 64 mm were used in this study.

Before making the mix, the aggregates, molds and hammer were air dried, at 325 °F for 12 h to remove moisture completely. The asphalt was also preheated for one hour before starting the mixing process. Both the aggregates and asphalt were mixed together thoroughly in a metal bowl kept on a hot plate. The mix was then pored into the compacting mold and was compacted with 50 impacts on each side of the specimen as per the Marshal compaction method [9]. After compaction, the specimens were allowed to cool in the mold for 24 h before they were taken out.

4. Experimental procedure

The experimental setup used for acoustic characterization is shown in Fig. 3. It consisted of a B&K standing wave apparatus (Type 4002) with a crystal type microphone (25 mV/Pa, 2nF), frequency generator (Bendix advance technology center 343), four-channel phosphor oscilloscope (Tektronix TDS 3014) and a low noise preamplifier with band pass filter (Model SR560, Stanford research systems). The operation of the standing wave apparatus is based on the interference of two plane waves. The incident wave generated from the loudspeaker situated at one end of an acoustically rigid tube and the reflected wave coming from the test specimen, placed at the other end of the tube. This interference between incident and reflected waves generates a standing wave pattern within the tube. From the measurement of the maximum and minimum sound pressure intensities, and their position with respect to the specimen, the absorption coefficient, reflection coefficient, and the acoustic impedance of the test specimen can be determined using the relations given in Section 2.

The desired frequencies were generated in the tube by supplying a pure tone signal to the speaker from the frequency generator at a constant voltage. The microphone probe was positioned in such a way that it could be moved longitudinally along the tube while remaining coaxial. An amplifier and filters were used to enhance the signal and reduce noise while the digital oscilloscope was used for recording the output signals from the microphone. With the test specimen in the holder, sound levels at the point of maximum and minimum sound intensity in the tube and their corresponding location with respect to the specimen were recorded. As per ASTM C-384 [10] standard, absorption coefficient, reflection coefficient and acoustic impedance at third octave band center frequencies from 100 Hz to 4 kHz were determined for all the specimens.

A special adapter was designed for the asphalt specimens, as the diameter of standard marshal specimen is slightly bigger then the largest diameter (100 mm) that can be used in the impedance tube available. In order to prevent sound leakage and obtain a proper

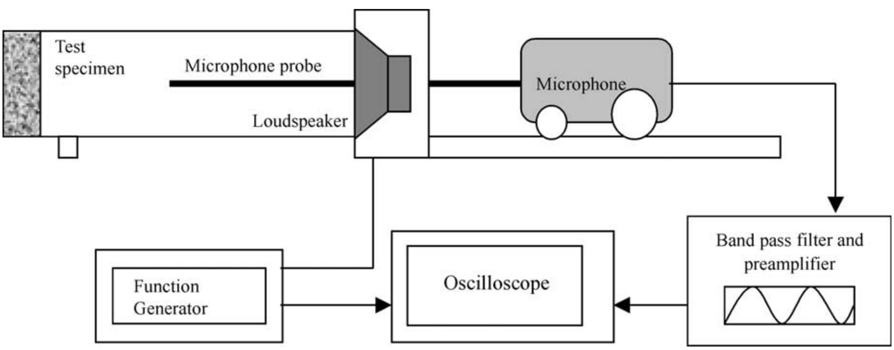

Fig. 3. Schematic of experimental setup used for acoustic characterization.

fit between the holder and the tube, their contact area was wrapped with the adhesive synthetic tape. Clamps were also used to hold the adapter firmly against the tube.

4.1. Experimental setup for measuring dilatational wave speed

The experimental setup used to measure the dilatational wave speed in the cenosphere-rich cement specimens (300×300×13 mm) consisted of two accelerometers (PCB model 303M7) mounted 100 mm apart from each other on the sheet specimens using wax. Both accelerometers were connected to a digital oscilloscope through the power supply. The free edge of the specimen was then impacted by a steel projectile falling from a small drop tower. The height of projectile drop was kept constant for consistent impact. The point of impact was in line with the accelerometers. To avoid the effect of speed gradient that may exist along the thickness, a high aspect ratio (width / thickness ratio was 24) was used for all the specimens. The time taken by the wave to travel between the two accelerometers was calculated from the arrival time of the pulses registered by the accelerometers. Ten experiments were performed for each volume fraction, and average wave speeds were calculated.

5. Results and discussions

Results of acoustic characterization of the cenosphere-rich cement and asphalt materials considered in this study are discussed in the following sections.

5.1. Density characterization

The density of cenosphere enriched cement matrix was determined for the different volume fraction of cenospheres. It was found that the mass density decreases from 1900 to 1110 kg/m^3 as the volume fraction of cenospheres increases from 0 to

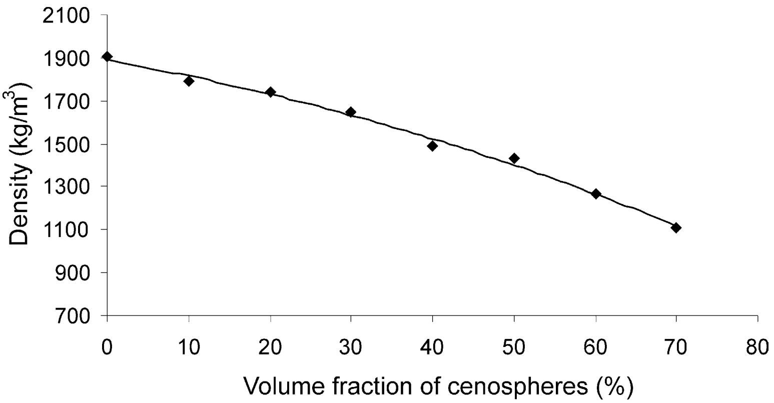

Fig. 4. Mass density of cenosphere-rich cement concrete specimens as a function of volume fraction of cenospheres.

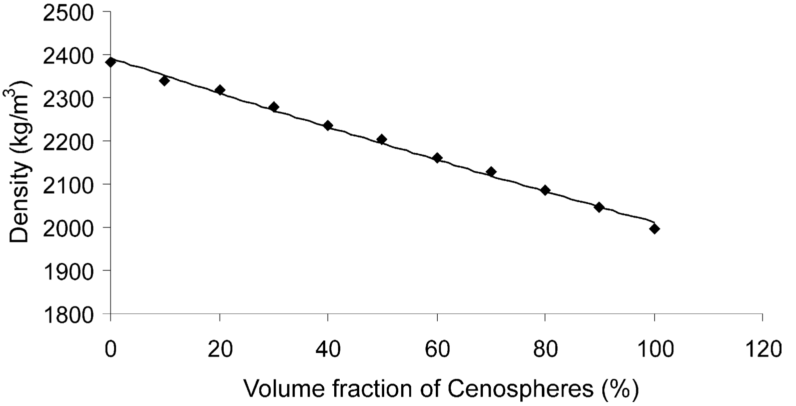

Fig. 5. Mass density of cenosphere-rich asphalt concrete specimens as a function of volume fraction of cenospheres.

70% as shown in Fig. 4. This corresponds to nearly a 40% decrease in mass density at highest volume fraction used.

In the case of the cenosphere enriched asphalt concrete, the mass density was observed to decrease from 2400 to 1990 kg/m^3 as the volume fraction of cenospheres increases from 0 to 100%, as shown in Fig. 5, which corresponds to a 17% decrease in density. This density reduction is less than that for the cement composite because in the case of asphalt concrete, only fine aggregates with a size range 300 μm or smaller were replaced with cenospheres.

5.2. Dilatational wave speed

For cenosphere rich cement concrete, it was observed that wave speed remains relatively insensitive (approx. 3200 m/s) to the change in cenosphere content as shown in Fig. 6. Though there is a decrease in the density of the material with

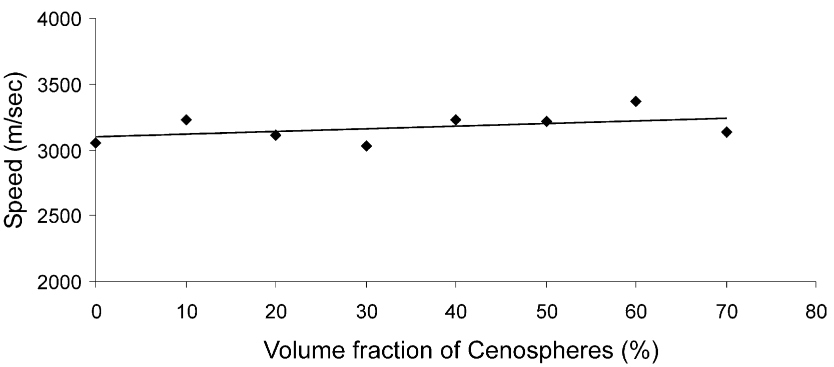

Fig. 6. Dilatational wave speed as a function of volume fraction of cenospheres in cenosphere-rich cement specimens.

increase in volume fraction of cenospheres, modulus of elasticity also changes correspondingly to maintain a constant wave speed. This is in accordance with the definition of wave speed in a bar, $V=\sqrt{\frac{E}{\rho}}$, where E is the effective modulus and ρ is the density of the bar material.

5.3. Characteristics of cenosphere-rich cement

The effect of volume fraction of cenospheres on sound absorption characteristics of 25 mm thick specimen is shown in Fig. 7. With increase in volume fraction of cenospheres from 0 to 20 to 40%, there is successive increase in sound absorption. With a further increase in the volume fraction of cenospheres from 40 to 60 to 70%, a systematic decrease in sound absorption was observed. This indicates that sound absorption properties peak at 40% volume fraction of cenospheres. The same variation was observed in case of 50 and 75 mm thick specimens.

Fig. 8 shows the normal acoustic impedance as a function of frequency for the 25 mm thick cement specimen at 0, 40 and 70% volume fraction of cenospheres. The minimum impedance is at 40% volume fraction of cenospheres. It can also be observed that the normal acoustic impedance of the specimens decreases with the addition of cenospheres up to 40% and increases thereafter with further addition of cenospheres. Though results for all the volume fractions were obtained, only the impedance at 0, 40 and 70% are reported in these figures (for the clarity of graph). Results obtained from both the 50 and 75 mm thick specimens exhibit similar behavior and follow the same trend of variation of impedance with respect to volume fraction of cenospheres.

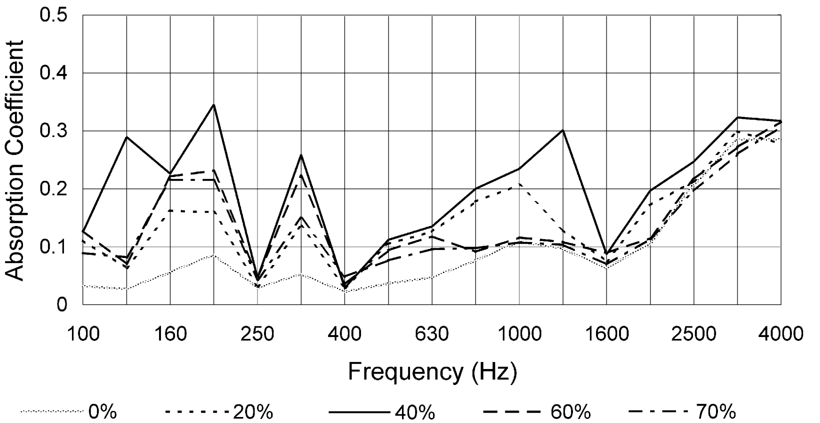

Fig. 7. Absorption coefficient as a function of volume fraction of cenospheres for 25 mm thick cenosphere-rich cement specimen.

5.4. Noise reduction coefficients for cenosphere-rich cement specimens

Noise reduction coefficient (NRC) represents a single number, which is the average value of the absorption coefficients of the material at the frequencies 250, 500, 1000, and 2000 Hz. Noise reduction coefficients as a function of cenosphere volume fractions for different thickness of cement specimens is shown in Fig. 9. It can be observed from this figure that for all the thickness, maximum absorption is achieved

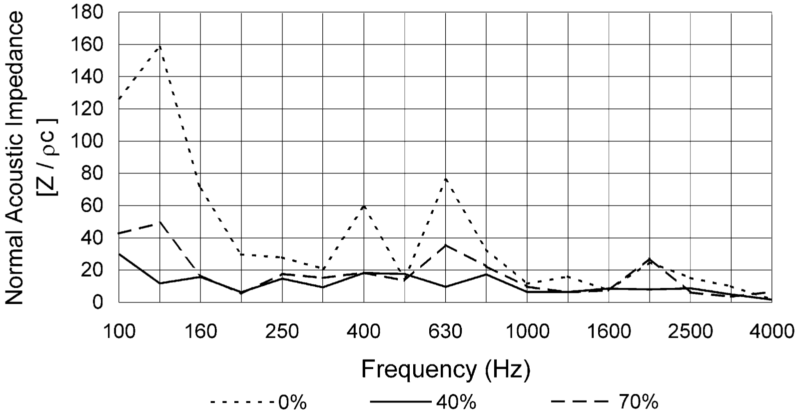

Fig. 8. Normal acoustic impedance as a function of frequency for 25 mm thick cenosphere-rich cement specimen at different cenosphere volume fractions.

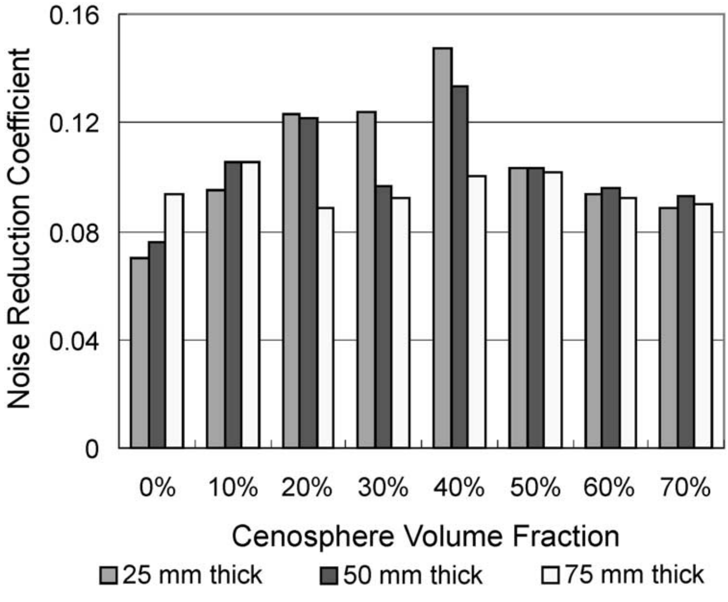

Fig. 9. Noise reduction coefficient as a function of cenosphere content for different thickness of cenosphere-rich cement.

at 40% cenosphere volume fraction. In addition the NRC for all the specimens with cenospheres was greater than the specimens with no cenospheres. It can also be seen that noise reduction coefficient for 25 mm thick and 40% volume fraction specimen is twice the NRC of 25 mm thick specimen with 0% cenosphere content.

5.5. Characteristics of cenosphere-rich asphalt concrete

The effect of addition of cenospheres to asphalt concrete on its absorption characteristics is shown in Fig. 10 for 0, 40 and 100% volume fraction of cenospheres. The absorption characteristic at 0 and 40% are nearly same, however it continues to decrease with the further addition of cenospheres. This decrease is not significant for the lower range of frequencies, i.e. 0 to 315 Hz. The decrease in the absorption properties is due to the fact that being spherical in nature, cenospheres can easily slip into the voids (as shown in Fig. 11) and reduce the number of pores in the asphalt concrete. Since sound absorption in the asphalt concrete is mainly due to the dissipation of the sound energy within the pores, the absorption coefficient decreases as the volume fraction of cenospheres increases.

Normal acoustic impedance as a function of frequency at different volume fractions of cenospheres for asphalt concrete is shown in Fig. 12. In contrast to absorption coefficient, acoustic impedance increased with an increase in the volume fraction of cenospheres. This trend also supports the conclusion that there is a decrease in sound absorption with an increase in cenosphere content as discussed.

6. Conclusions

A study of acoustic properties of cenosphere-rich cement and asphalt concrete was conducted. The following conclusions were deduced from the observations of this study:

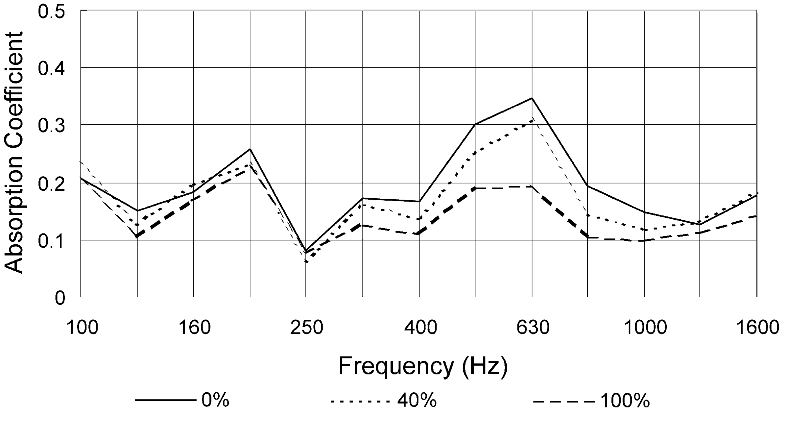

Fig. 10. Absorption coefficient as a function of frequency for 64 mm thick cenosphere-rich asphalt concrete specimen at different cenosphere volume fractions.

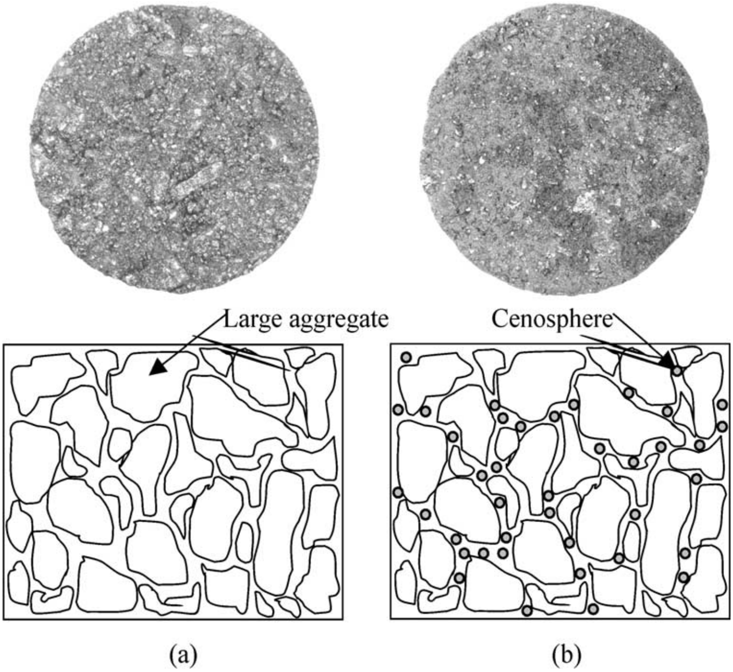

Fig. 11. (a) Structure of asphalt specimens without cenospheres (b) Structure of cenosphere-rich asphalt specimens.

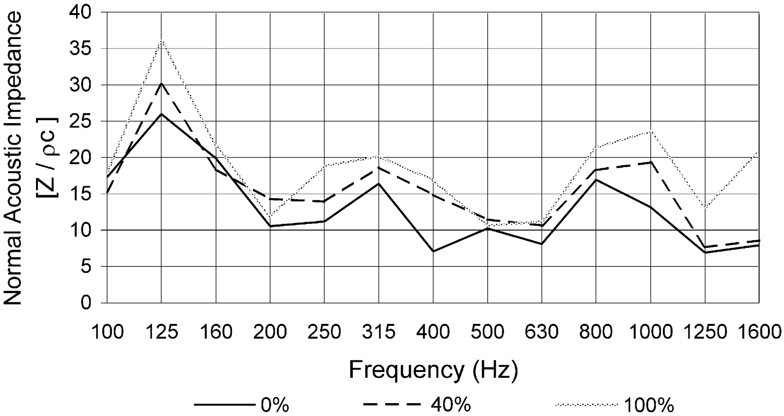

Fig. 12. Normal acoustic impedance as a function of frequency for 25 mm thick cenosphere-rich asphalt concrete specimen at different cenosphere volume fractions.

- Mass density of cement concrete decreased by 40% as the volume fraction of cenospheres increases to 70%.
- Sound absorption of cement concrete increases with the addition of cenosphere up to 40% volume fraction and decreases with further addition of cenospheres.

- No significant change in sound absorption characteristics of cement concrete was observed with change in specimen thickness
- Mass density of asphalt concrete decreased by 17% when all the fine aggregates (0–300 μm) were replaced by cenospheres.
- Sound absorption by asphalt concrete decreases with an increase in cenosphere content, and normal acoustic impedance increases with an increase in cenosphere volume fraction.
- Further studies to characterize the mechanical properties of cenosphere-rich cement and asphalt concrete will be helpful in determining its use as light weight construction and highway material.

Acknowledgements

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