ACOUSTICALLY EFFICIENT CONCRETES THROUGH ENGINEERED PORE STRUCTURE

Narayanan Neithalath, Jason Weiss, and Jan Olek

SYNOPSIS: Three classes of specialty cementitious materials were evaluated for their potential benefits in sound absorption including a Foamed Cellular Concrete (FCC) with density ranging from 400 – 700 kg/m^3, Enhanced Porosity Concrete (EPC) incorporating 20-25% open porosity, and a Cellulose Cement Composite (CCC) with density 1400 – 1700 kg/m^3. Cylindrical specimens of these materials were tested for acoustic absorption in an impedance tube. The FCC specimens showed absorption coefficients ranging from 0.20 to 0.30, the higher value for lower density specimens. The closed disconnected pore network of these materials hinders sound propagation, thereby resulting in a reduced absorption, even though the porosity is relatively high. The most beneficial acoustic absorption was observed for EPC mixtures. When gap-graded with proper aggregate sizes, these no-fines mixtures dissipate sound energy inside the material through frictional losses. The cellulose fiber cement composites use cellulose fibers at high volume fractions (~7.5%), which are believed to provide continuous channels inside the material where the sound energy can be attenuated. By engineering the pore structure (by careful aggregate grading as in EPC, or incorporating porous inclusions like morphologically altered cellulose fibers) cementitious materials that have the potential for significant acoustic absorption could be developed.

Keywords: Acoustic absorption, Porosity, Foamed Cellular Concrete, Enhanced Porosity Concrete, Cellulose Cement Composite, Impedance, Damping.

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INTRODUCTION

Noise pollution affects more people than any other kind of pollution in the modern industrialized world [1]. In the United States, more people are exposed to highway noise than from any other single noise source [2]. Noise pollution is especially annoying in densely congested urban settings where residents live near highways and main transportation thoroughfares. The need to control noise in such environments therefore offers an incentive to study the acoustic performance of cementitious materials. Conventional concrete is a preferred material for the construction of noise barriers due to its excellent performance as a sound reflecting material, but its sound absorbing capability is extremely limited. While the construction of sound barriers impedes the sound transmission path between vehicles and the residential and commercial development located alongside the highways resulting in noise abatement, they tend to be extremely costly, unsightly, and not practical for bridges and/or urban highways [3]. A better method to control noise is the use of sound absorbing materials, or pavement surfaces that result in less noise generation. It is common practice in noise control engineering to use reduced density porous materials to achieve sound absorption. Sound absorbing materials are used for walls, floors, and ceiling to reduce the noise that is generated from within an enclosure.

This paper describes the results of a research study aimed at developing concretes with specially engineered pore structure as materials for sound absorption. In general, sound absorbing materials are porous materials with reduced densities. The basic principle is that the acoustic energy is converted into heat energy in the open pores of the material, resulting in the reduction of perceived noise levels.

CONCEPT OF SOUND ABSORBING MATERIALS

Cementitious materials can be classified as “rigid-framed” (the rigidity or stiffness of the frame is much higher than that of air) materials where sound absorption is typically believed to occur in an array of tortuous pores in the material [4,5]. This acoustic loss is attributed to the adiabatic pressure changes due to air compression (as the air enters the pores) and expansion (as air leaves out of the pores). In addition, the frictional losses in the pore walls also contribute to the acoustic absorption.

MATERIALS AND MIXTURES CONSIDERED

Three different cementitious materials with different porosity were considered for this study. The method of manufacture and properties of these materials are described in this section.

Foamed Cellular Concrete (FCC)

Foamed cellular concrete is manufactured by mixing cement, sand, and a foaming agent. The material used in the study was a commercial product, and was pre-cast in the plant. The density of the material can be varied from 300 to 1200 kg/m^3. Three different densities, as provided by the manufacturer, were used in this study – 450, 560, and 700 kg/m^3. Figure 1(a) shows a cross section of foamed cellular concrete.

Enhanced Porosity Concrete (EPC)

Enhanced porosity concrete (EPC) is proportioned by gap grading the coarse aggregates and either eliminating (or limiting) the sand volume in the matrix. Figure 1(b) shows a typical cross section of EPC. The cement content is established by providing a sufficient amount of paste to coat the aggregates. An excessive amount of paste may drain through the pores of the material. The water-to-cement ratio is also kept low for the same reason.

Three aggregate sizes - #8, #4, and 3/8" were chosen for single sized aggregate mixtures. The aggregate sizes shown refer to the sieve in which they were retained (for instance, # 4 indicates that the aggregates passed through a 3/8" (9.5 mm) sieve and were retained on the # 4 (4.75 mm) sieve). In addition, binary blends of these mixtures were also considered. Blends were prepared by replacing 25, 50, and 75% by weight of the larger sized aggregates successively by smaller sized aggregates. The mixtures were prepared using a laboratory mixer in accordance with ASTM C 192-00 [6], cast in 150 x 150 x 700 mm beam molds and consolidated using external vibration. Cylindrical specimens, 95 mm in diameter were cored from these beams at a later age for acoustic absorption measurements in the impedance tube.

Cellulose Cement Composite (CCC)

Morphologically altered cellulose fibers were considered as an option to introduce sound absorbing channels in the material. The cellulose fibers used in this study were in the form of nodules, 2-8 mm in size, and are referred to as "macronodules"(Figure 1(c)). These nodules are aggregations of individual fibers and therefore are porous. A cement-sand mortar with 50% aggregate volume was used. The fiber volume adopted was 1.5, 3.0, 4.5, 6.0 and 7.5%.

Cement and sand were first mixed at low speed for one minute and then the fibers were added, during mixing. Approximately three quarters of the water was needed for proper mixing. The water was added and all ingredients were mixed at medium speed for two minutes. The remaining water was then added with water reducer and mixed until a uniform mixture was obtained (typically one minute). Care was taken to ensure that the mixer did not run at a higher than required speed (or for a longer than required duration) to avoid breaking down of fiber nodules in the mixer. For mixtures with high volumes of fiber (6.0 and 7.5%), an accelerator was added since it was noticed that there was considerable set retardation otherwise. Cylindrical specimens (95 mm in diameter) were prepared for acoustic absorption whereas beams (75 mm x 250 mm x 25 mm) were made for measurements of damping behavior.

EXPERIMENTAL PROCEDURES

Porosity Determination

Foamed Cellular Concrete (FCC) – The porosities of the FCC specimens could be related to their densities. FCC with a density of 450 kg/m^3 had a porosity of 0.75, the one with a density of 560 kg/m^3 had a porosity of 0.70 and the one with density 700 kg/m^3, 0.61.

Enhanced Porosity Concrete (EPC) – Because of the presence of large interconnected pores in the EPC system, the following procedure was adopted to determine the porosity. The cylindrical specimens (95 mm in diameter and 150 mm long) that were cored from beams were immersed in water for 24 hours to saturate the pores in the matrix. After this period, the sample was removed from water, and the excess water on the sides wiped to bring it to SSD condition. The sample was then enclosed in a latex membrane and the bottom of the cylinder was sealed to a stainless steel plate using silicone sealant. The mass of the sample, latex membrane, and the steel plate (M_1) was measured. Water was added to the top of the sample until it was filled, which indicated that all the interconnected pores were saturated. The mass of the system filled with water was taken (M_2). The difference in the mass $\Delta M = (M_2 - M_1)$ represents the water in the pores. This mass was converted into an equivalent volume of water, and expressed as a percentage of the total volume of the specimen to provide an indication of the total porosity.

Cellulose Cement Composite (CCC) – Porosity was determined on 75 mm x 75 mm x 25 mm prisms of composite specimens. Vacuum saturation (as described in RILEM CPC 11.3 [7]) has been followed to determine the porosity. The prisms were dried in an oven at $105 \pm 5^{\circ}$C until no change in measured weight was noticed. The specimens were then placed in a vacuum chamber for 3 hours before water was introduced to the chamber, under vacuum. The vacuum was maintained for 6 more hours after which time the specimens were left in water for additional 18 hours. The saturated surface dried weight was then determined. The water absorbed by the fibers was accounted for in the vacuum saturated weight so as to obtain the total porosity.

Determination of Acoustic Absorption Coefficient (α)

The acoustic absorption coefficient (α) is a measure of how well a material can absorb sound. When a sound wave strikes a material, a portion of the sound energy is reflected back while a portion is absorbed by the material. The absorption coefficient is the ratio of the absorbed energy to the total incident energy.

The acoustic impedance tube was used to determine the absorption coefficient (α) using the experimental set up as described in ASTM E 1050-98 [8] (Figure 2). The sample was placed at one end of the cylindrical tube with a rigid backing. The specimen was tested with a plane acoustic wave propagating along the axis of the tube. The absorption coefficient is calculated as:

$$\alpha = 1-|R|^2 \qquad \text{(Equation 1)}$$

where the reflection coefficient (R) is computed for frequencies ranging from 100 to 1600 Hz using the following equation:

$$R = \frac{e^{jkd_1} - e^{jkd_2}P}{e^{-jkd_2}P - e^{-jkd_1}} \qquad \text{(Equation 2)}$$

where d_1 and d_2 are the distances from the specimen surface to the first and second microphones respectively (Figure 2), j is $\sqrt{-1}$, k is the wave number (ratio of angular frequency to the wave speed in the medium), and P is the ratio of acoustic pressures.

Specific Damping Capacity for Cellulose Cement Composites

The Specific Damping Capacity (ψ) was determined on 75 mm x 250 mm x 25 mm beams according to the decaying sin wave method.

$$\psi = \frac{A_i - A_{n+i}}{A_i} \times 100\% \qquad \text{(Equation 3)}$$

where A_i is the amplitude of the i^{th} period and A_{n+i}, that of $(n+i)^{th}$ period.

RESULTS AND DISCUSSIONS

This section presents the results of the experimental investigations conducted on foamed cellular concrete, enhanced porosity concrete, and cellulose cement composites to ascertain their acoustical efficiency.

Foamed Cellular Concrete (FCC)

The acoustic absorption spectra (variation of acoustic absorption coefficient with frequency) of FCC are given in Figure 3(a). It can readily be noticed that the peak absorption coefficient is reduced with increasing specimen density. However, the maximum absorption coefficient (α) of FCC is higher than that of normal mortar or concrete. For the chosen specimen length (150 mm), the peak absorption coefficients occur at a frequency of 300 – 400 Hz. Figure 3(b) shows the maximum absorption coefficients of all the three FCC samples plotted against density. The maximum absorption coefficients are in the range of 0.20-0.30. Though the FCC specimens are very light and have a high porosity, the absorption coefficients are not particularly high due to their closed pore structure, even though they are superior to normal concrete, which has an α of about 0.05.

Enhanced Porosity Concrete (EPC)

The porosities of EPC (proportioned with single sized aggregates) are shown in Figure 4(a) and the acoustic absorption spectra of these mixtures in Figure 4(b). Though the porosities of these mixtures lie in a very narrow range (0.19-0.21), the mixture with larger aggregate size (3/8”) tend to be acoustically less efficient because of the large pore sizes in these materials which do not force the sound waves to alternatively compress and expand, which is the primary energy expending process in these materials. The acoustic performance of mixtures comprising of either #4 or #8 aggregates alone was comparable.

As described earlier, blends of two different aggregate sizes were also used to evaluate their efficiency in acoustic absorption. Blending of aggregates of different sizes is expected to generate optimal porosity and pore size in EPC thus aiding in acoustic absorption. A typical case of blending of #4 and #8 aggregates is described in this section. The porosities of the blended mixtures are shown in Figure 5(a). It can be seen that the highest porosity is achieved for a 50% #4, 50% #8 blend. This can be explained by the fact that there is an increased volume of voids in the interface in a mixture of coarse and fine particles [9]. The characteristic pore size (median of all pore sizes in the material, greater than 1 mm – [10]) of the EPC mixture with # 4 aggregate was found to be smaller than 2.36 mm, which is the size of # 8 aggregate. Therefore the smaller aggregate could not fit into the pore space of the mixture with larger size aggregates, resulting in a higher porosity. Similar explanation also applies for the 75% #4, 25% #8 blend. The acoustic absorption spectra for 150 mm long EPC mixtures with a blend of #4 and #8 aggregates are given in Figure 5(b). It can be seen that for the 75% #4, 25% #8, and 50% #4, 50% #8 blends, the maximum acoustic absorption coefficients are higher than those for single sized aggregate mixtures. This is partly because of the higher porosity in the former mixtures, but more importantly, blending of the aggregates creates a more acoustically efficient pore structure (with respect to pore size and tortuosity). A thorough treatment of the acoustic absorption characteristics of EPC with different aggregate sizes and blends could be found elsewhere [10].

Cellulose Cement Composite (CCC)

The use of morphologically altered cellulose fibers for acoustic effectiveness was based on the premise that these fibers, because of their physical nature, could provide continuous pathways inside the material through which sound waves can propagate, and attenuate [11]. Originally, three different morphologies of cellulose fibers were considered, but only the macronodule fiber, which was the most acoustically effective, is discussed.

The porosity of the composite was found to increase with an increase in volume of the fiber phase, as shown in Figure 6(a). The relationship between the porosity of the composite ($\phi_{composite}$) at any fiber volume and the porosity of the fiber free mortar matrix (ϕ_{mortar}) can be given by:

$$\phi_{composite} = \phi_{mortar} (1 + A V_f) \qquad \text{(Equation 4)}$$

where the value of the constant A can be considered as an indicator of the contribution of the fiber phase to the total porosity of the composite.

The acoustic absorption spectra for CCC with macronodule fibers are shown in Figure 6(b). For these 75 mm long specimens, the absorption peak occurs at a frequency of approximately 500 Hz. It can be seen that an increase in fiber content increases the maximum absorption coefficient. For a sample with no fibers, the maximum absorption coefficient (α) is approximately 0.05 and it steadily increases to approximately 0.40 for the composite with 7.5% volume of macro nodules. The macro nodules appear to provide porous channels inside the specimen where the incident sound energy can enter and attenuate. With an increase in fiber volume, it is expected that there is an increase in the number of connected porous channels, leading to an increase in sound absorption.

The energy dissipation capacity of a material can also be defined in terms of its specific damping capacity. This parameter is very useful in characterizing materials like CCC where an inclusion phase is present, the stiffness of which differs from that of the matrix by more than one order of magnitude (the modulus of elasticity of normal mortar is approximately 30 GPa, where as the cellulose fibers have a modulus of 1-2 GPa). The acoustical mismatch of impedance at the interface of the constituent phases contributes significantly to damping [11,12].

For specimens with macronodules, Figure 6(c) shows the relationship between fiber content and specific damping capacity for two different ages of curing and three different moisture conditions (wet, dry, and rewetted). An increase in fiber volume results in an increased damping capacity, especially for wet specimens. This may be attributed to the fact that an increase in volume of macro nodules increases the stiffness mismatch, resulting in higher energy dissipation in the material than it would have for a sample without fibers. These results are also in line with observations from a study on damping mechanisms in hardened pastes, mortar and concrete which indicated that the damping capacity is related to the percentage of water-filled pores in the system [13], with increased moisture leading to a higher degree of damping. Higher volumes of macro nodules effectively increase the amount of water filled pores in the system, thereby resulting in high damping capacity values. For the same curing conditions (7 day and 14 day wet), it can be observed that the damping capacity decreases with age, probably due to reduction in porosity and pore water content as a result of cement hydration. The reduction, though, is not very large in this case.

SUMMARY AND CONCLUSIONS

Three porous materials, having different pore volume fractions, and vastly varying pore structure characteristics have been studied for their effectiveness in acoustic absorption. It has been found that the pore structure could be tailored to achieve desirable acoustic absorption characteristics. In the case of EPC, this could be accomplished by blending different aggregate sizes in chosen proportions, whereas for CCC, the use of morphologically altered fibers to provide continuous channels in the material is an option. The closed cell structure of FCC is not as effective as the other two materials in acoustic absorption.

The conclusions from this study can be summarized as follows:

(i) FCC though having a higher porosity, has a maximum acoustic absorption coefficient (α) in the range of only 0.20-0.30 because of its closed cell structure. However, this value is higher than that of normal concrete (~ 0.05). CCC incorporating high fiber volumes show α values of about 0.40, where as the α values of EPC were observed to be as high as 0.80.

(ii) Acoustic absorption coefficient of EPC with larger sized aggregates is found to be typically lower, since the pore sizes also tend to be large. Larger pore sizes are acoustically inefficient.

(iii) Blending of selected aggregate sizes in chosen proportions is found to create pore sizes in EPC that are acoustically efficient. Higher porosity of the blends, along with a pore structure that is tortuous enough to absorb sound waves, is believed to be the reason for the improved acoustic absorption. The acoustic absorption of EPC with properly chosen aggregate blends is around 0.80.

(iv) The use of morphologically altered cellulose fibers results in a moderate acoustic absorption. The porous macronodules are expected to provide interconnected channels inside the material where the sound waves can attenuate. The absorption coefficient increases with an increase in fiber volume, possibly due to increased porosity, and the generation of increased number of interconnected porous channels in the matrix.

(v) Specific damping capacity increases with an increase in fiber content, presumably due to an increased impedance mismatch between the cementitious matrix and the cellulose phases.

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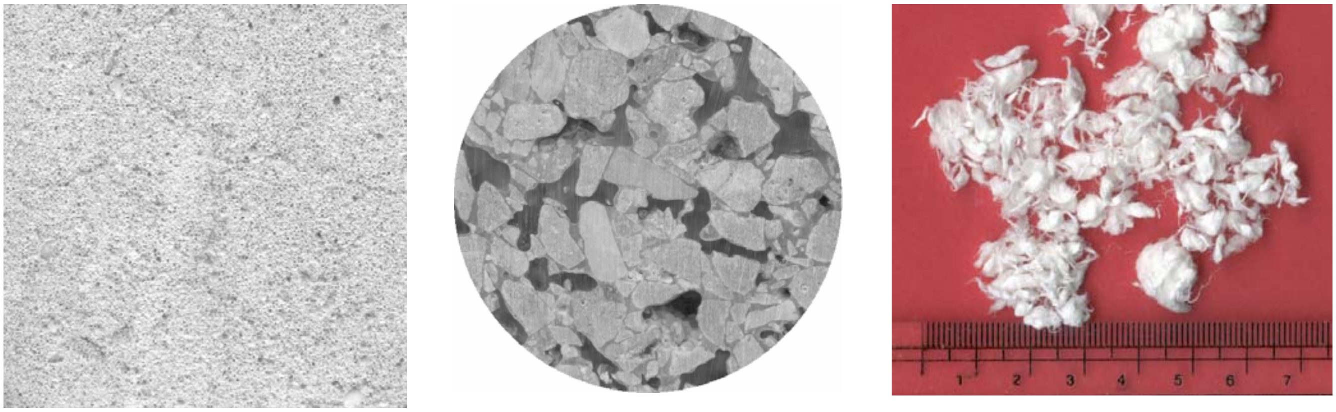


(a)

(b)

(c)

Figure 1: (a) Typical cross section of FCC, (b) Typical cross section of EPC, (c) Macronodule fibers used to manufacture CCC

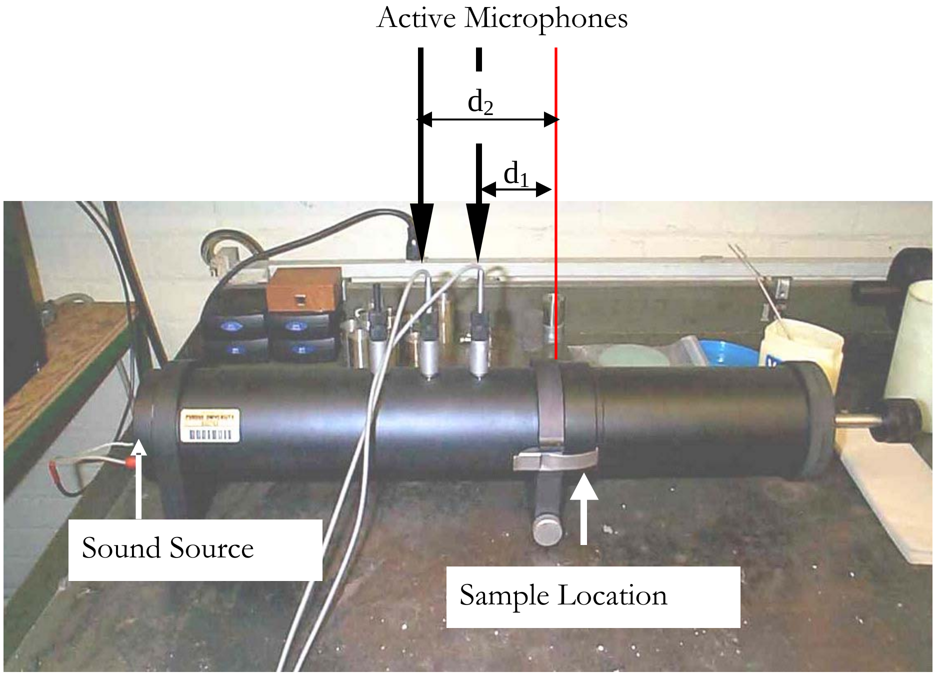
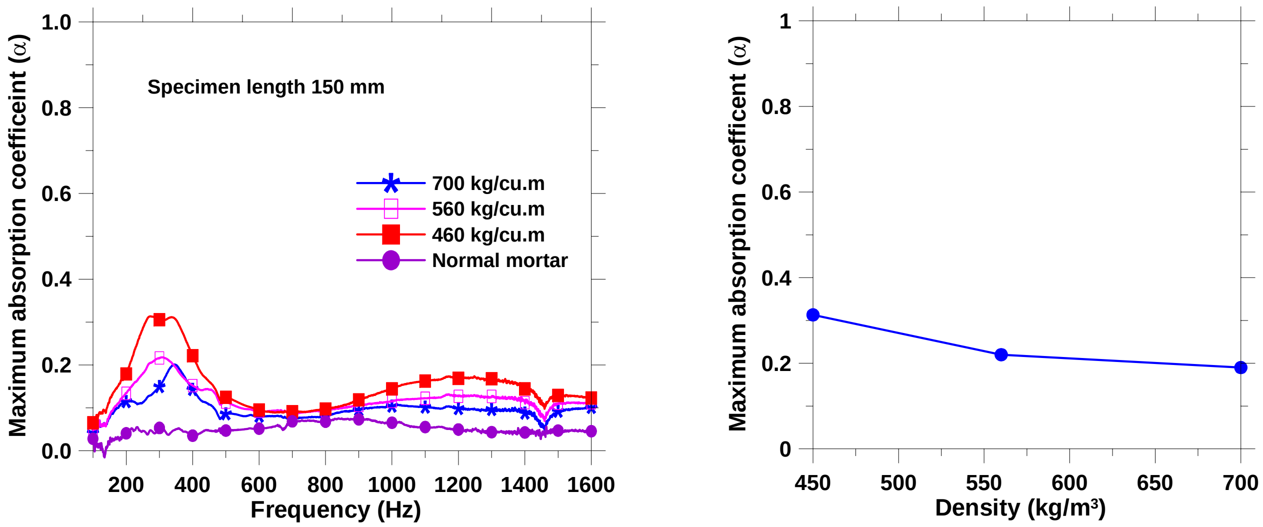


Figure 2: Impedance tube set up to measure acoustic absorption



(a)

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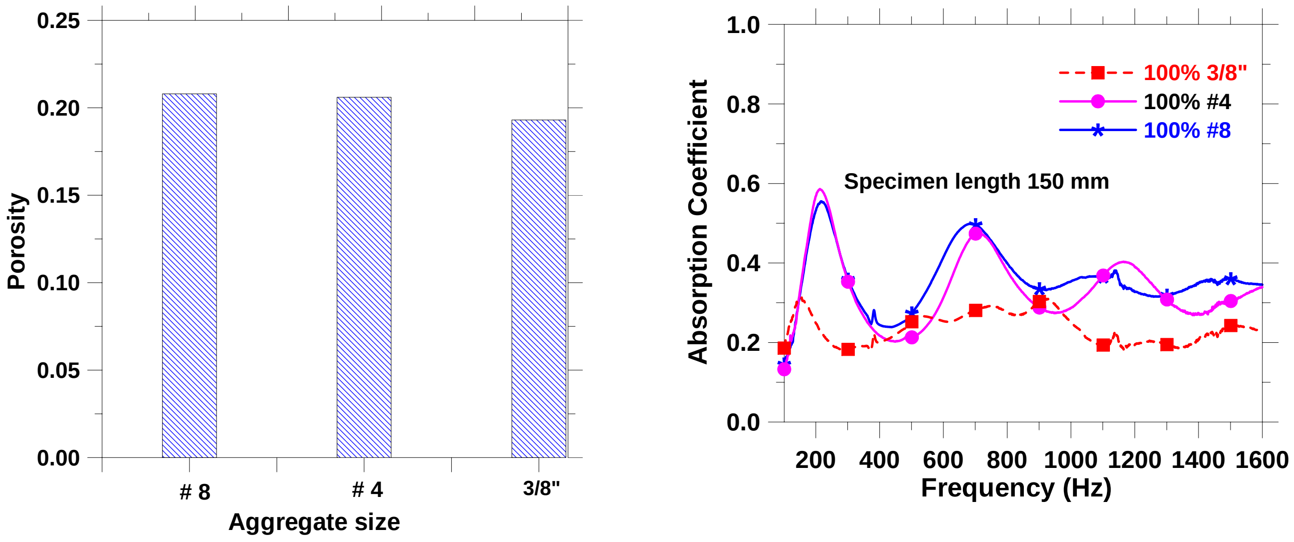
Figure 3: (a)Acoustic absorption spectra of FCC, (b) Variation of maximum absorption coeffieint of FCC with density



(a)

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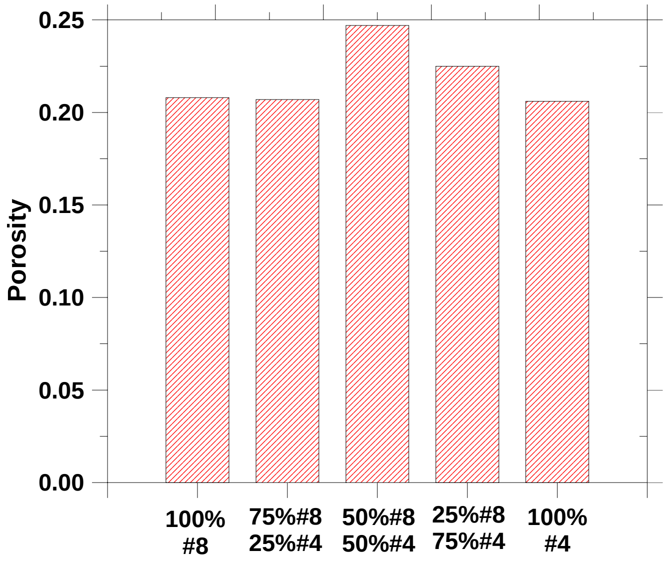
Figure 4: (a) Porosity of EPC with single sized aggregates (b) Acoustic absorption spectra of EPC with single sized aggregates



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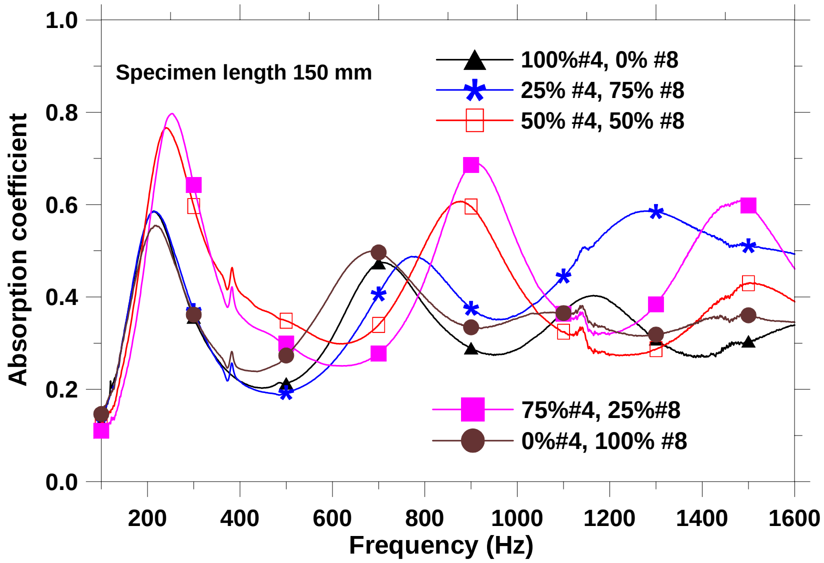
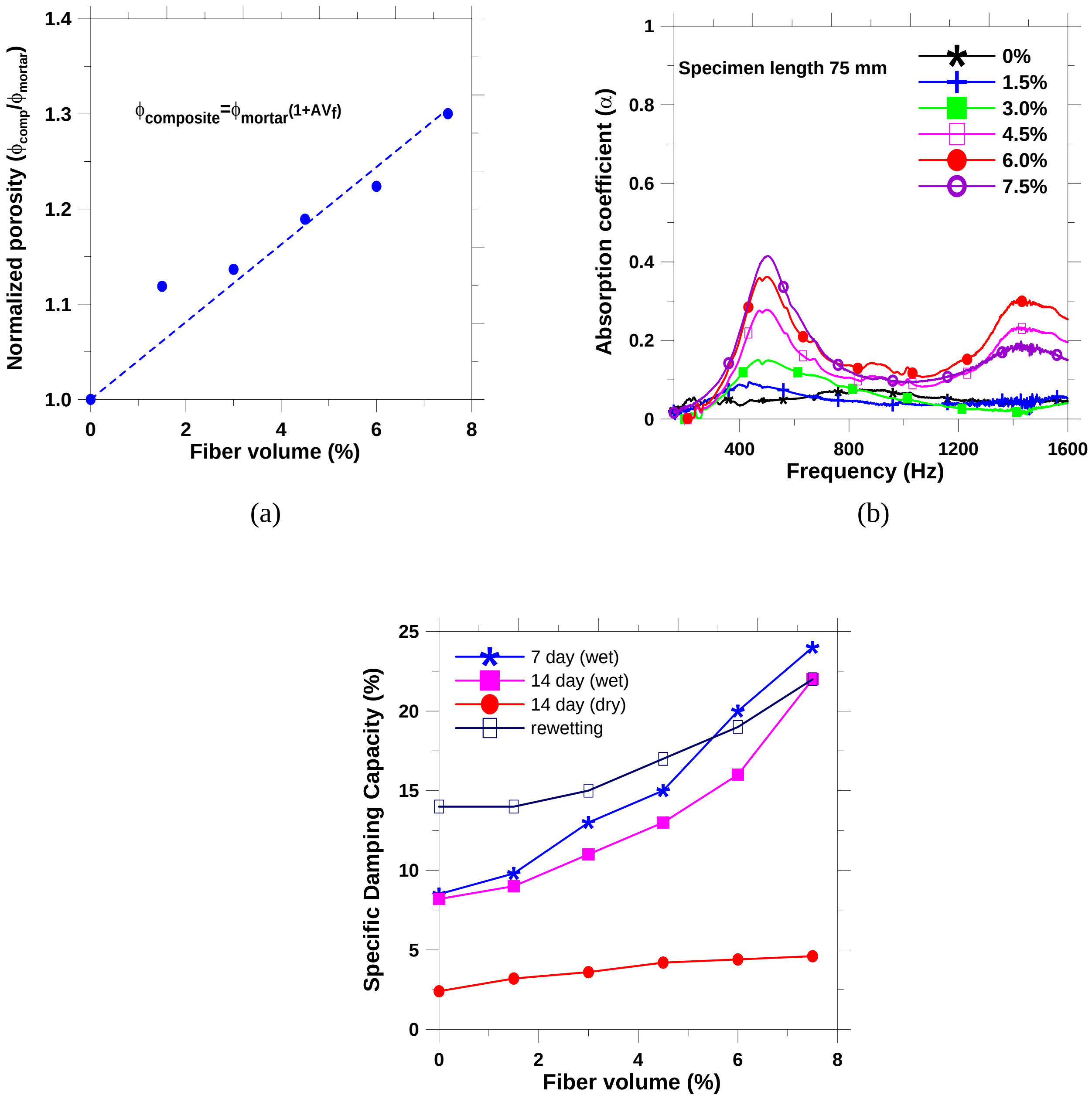


(b)

Figure 5: (a) Porosity of EPC with a blend of #4 and #8 aggregates (b) Acoustic absorption spectra of EPC with a blend of #4 and #8 aggregates



(a)

(b)

(c)

Figure 6: (a) Influence of fiber volume on the porosity of CCC (b) Acoustic absorption spectra of CCC with varying fiber volume (c) Relationship between fiber volume and specific damping capacity of CCC