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Correlating the Cellular Network, in Foamed Concrete Containing Ash, with their Physical Properties

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Abstract

Cellular concrete is a lightweight solid cementitious foam that is used mainly for thermal insulation and sound absorption. Either partially or wholly, when the Portland cement in the binder is replaced with ash, the environmental impact of the material is reduced. However, the resulting changes in the cell structure and their subsequent impact upon the physical properties of the material have not been well examined. In this study, cellular concrete was prepared from alkali activated fly ash binders and separately, from Portland cement binders blended with wood ash. The cell structure was photographed using laser confocal microscopy and the images were analyzed to quantify the cellular network in terms of the porosity and the fractal dimension of the porous phase. Alongside, the cellular concrete specimens were tested for their thermal constants and sound absorption. The results show that there was an increase in the fractal dimension and an associated drop in thermal conductivity for an increase in the porosity.

Keywords:

alkali-activation; fly ash; foamed concrete; fractal dimension; sound absorption; thermal conductivity; wood ash

1. Introduction

Foam concrete is a lightweight cementitious composite, cast to densities ranging from 300 kg/m³ to 1900 kg/m³ (Fouad 2006). An optimal balance between the mechanical strength and requirements of thermal insulation is typically found for densities around 1000 kg/m³ (Fouad 2006). While the higher densities are almost always lightweight mortars with fine aggregate, the lighter mixtures are essentially highly air-entrained paste systems, useful for non-structural functions including thermal and acoustic insulation. The internal cellular network is typically created by introducing gas bubbles to a fresh cementitious paste, either by mixing in a preformed foam or by adding chemicals that react to produce gas in the freshly formed paste (Zhang et al. 2014).

It is well recognized that the production of Portland cement results in the emission of large amounts of carbon dioxide. For every 1000 kg of Portland cement produced, over 900 kg of carbon dioxide is emitted from the calcination of the raw materials and the burning of fossil fuels for energy to produce the clinker (NRMCA 2012). For this reason, it has become necessary to investigate materials that can function as alternatives to Portland cement. Various kinds of ash, resulting either as combustion by-products or industrial waste have been identified as supplementary cementing materials that can partially replace the Portland cement in a concrete mix. As reliance on coal powered plants is reduced, the availability of fly ash will decrease, further necessitating the shift to other supplementary cementitious materials. For long, fly ash from coal combustion in thermal power plants has been widely used, but nowadays bio-sourced ash from the combustion of wood or agricultural by-products have been identified as possible supplementary cementitious materials (Garcia and Sousa-Coutinho 2013; Hussain et al. 2017; Madrid et al. 2017; Othuman Mydin et al. 2014; Setayeshgar et al. 2017). At present, these ash outputs are primarily disposed of in landfill, which makes their possible use as supplementary cementitious materials serve the dual purpose of diverting them from landfills and also reducing the carbon footprint of construction materials. And, although lower ash fusion temperatures result in morphologies that are less suitable as a cement admixture than say, fly ash (Yao et al. 2019), the authors showed in a recent study that wood ash can replace up to 20% of the Portland cement in concrete without any significant loss of

strength (Setayeshgar et al. 2017). It has also led to lower thermal conductivity of the resulting concrete (Madrid et al. 2017).

As against its partial replacement, Portland cement may also be wholly substituted with a class of alkali-activated materials, known as geopolymers (Davidovits 2011). It involves a precursor that is rich in alumino-silicate, which is chemically activated with a strong alkaline agent. Fly ash, metakaolin, and blast furnace slag are commonly used as the source of alumino-silicates, while the alkali activator is typically a blend of sodium or potassium silicate with sodium or potassium hydroxide (Provis et al. 2014).

There has been much research characterizing the mechanical and thermal properties of cementitious foams, but the actual structure of their air-void network has not received as much attention. A better understanding of the pore structure in cellular concrete and how it affects those physical properties of that concrete could lead to optimization of the cellular concrete's properties by tailoring the air void network. Prior work by others has characterised the cellular network and its relation with the strength of the foams, finding that as the density decreases, there is an increase in the porosity and the median pore size, but a drop in the pore sphericity and their spacing. This combination of rising pore size and falling pore spacing manifests in a reduction in strength (Hilal et al. 2015; Kearsley and Wainwright 2001; Nambiar and Ramamurthy 2007; Wee et al. 2006). The authors' associates have found that the thermal conductivity of cement-based foams increases with a decrease in the porosity and that a higher median pore size corresponds to a drop in thermal conductivity (Batool and Bindiganavile 2017; Batool and Bindiganavile 2018). However, to the authors' knowledge, there is very little information on the cellular structure of foamed alkali-activated systems.

Sound absorption is an important factor when selecting building materials for occupant comfort. Here too, there is limited research that quantifies sound absorption in cellular concrete. The fractal dimension of the porous phase and the tortuosity of the cellular network are known to bear upon the thermal and mechanical properties in foams (Mamun and Bindiganavile, 2017; Bindiganavile et al., 2018). Accordingly, it remains to be seen whether these parameters also correlate with sound absorption.

Therefore, the present study investigates the structure of the cellular network in two foamed systems, one of which utilized wood ash as a supplementary cementing material while the other was prepared from alkali-activated fly ash (AAFA). Laser confocal microscopy was used to generate height maps of the cut surface of the foams. These were in turn analysed using digital image analysis techniques in order to quantify the cellular network.

2. Experimental Procedure

2.1 Materials and Sample Preparation

The foamed concrete mixtures were prepared using two series of binders namely, Portland cement and Alkali-Activated Fly Ash. The first series had three compositions, replacing Portland cement with Wood Ash at 0, 10% and 20% by mass. The second series was an alkali-activated Class C1 fly ash. In all cases, each mixture was cast to achieve three target densities, between 1000-1400 kg/m³. This range of densities is appropriate for use in non-load bearing walls. The Portland cement used was Type GU per CSA A3001 (CSA 2013). It corresponds to ASTM Type 1 (ASTM 2007). The wood ash was sourced from a local pulp and paper mill and a backscattered electron microscope (BSEM) image of the ash is shown in Figure 1. This ash appears as a mixture of small crystalline particles with larger irregularly shaped and fibrous structures. The wood ash has the composition shown in Table 1, as determined by x-ray fluorescence. Setayeshgar et al. (2017) found significant differences in the chemical composition and particle morphology of wood ash samples from different pulp mills across Alberta, Canada. This variation can have an impact on how the ash behaves in a cementitious system. The high calcium oxide content in this ash suggests that it will form hydrates, but will not likely have a pozzolanic effect. The mixture composition for the cellular Portland cement series is presented in Table 2. The Class C1 fly ash, shown in Figure 2, was sourced from a local coal-fired thermal power plant and has the composition shown in Table 3. It was activated with a combination of an 8M sodium hydroxide solution and sodium silicate. The sodium hydroxide solution was prepared by dissolving solid sodium hydroxide pellets in distilled water to the required molarity, while the composition of the sodium silicate solution is shown in Table 4. The use of

8M sodium hydroxide limited the alkalinity of the activator, improving user safety, while still delivering sufficient strength to the alkali activated fly ash. The mixture proportions for the cellular alkali activated fly ash is presented in Table 5. Given their low density, it is well known that reinforcing cementitious foams with brittle microfibres augments their strength with no increase in density (Hamad 2017, Jhatial et al. 2020). The same was undertaken here with all mixtures reinforced with glass microfibers at a dosage of 1% by volume. These microfibers had a diameter of 37 μm and length of 12 mm.

In order to prepare the foamed concrete, the liquid components of the binder were put into the drum of a concrete mixer and the ash or cement was gradually introduced while the mixer was left running. Once the mixture had fully combined to form a slurry, the glass fibers were sprinkled into the rotating drum of the mixture, and mixing continued until the fibers were well dispersed. At this point, a preformed foam was produced by running a diluted protein based foaming agent through a portable foam generator, shown in Figure 3. The preformed foam was gradually added to the drum of the mixer while it was still running, and was allowed to blend into the slurry. Periodically, a small sample was taken out in a graduated cylinder from the mixer and weighed to determine the current cast density. The preformed foam was continually added until the target cast density was reached. At this point, the foamed cementitious material was cast into cylindrical plastic moulds by pouring it in. The free flowing nature of the foamed concrete obviated any need for additional mechanical consolidation. The specimens were removed from their moulds after 24 hours and they were placed in a curing room at 21°C and 100% humidity for a further 24 days. Upon 25 days after casting, the specimens were removed from the curing room and the ends were cut and polished to expose the cellular structure of the material. The specimens were then left in ambient conditions to dry for 3 more days prior to further testing. This brought them to 28 days, as per the curing procedures specified in ASTM C495 for cellular concrete made with preformed foam.

2.2 Confocal Microscopy

Three-dimensional images of the top surface of each specimen were taken using an Olympus 3000 laser confocal microscope. The images were taken with a 1X objective lens, resulting in a resolution of 0.4 pixels/ μm . Each image covered a region 2560 μm x 1920 μm in area. At this level of magnification, the resolution was deemed satisfactory in order to clearly identify the macropores created in the foaming process while also capturing large connected regions in a single image. The 3D images were saved as colour coded 2D height maps for further processing. Nine images were taken for each mix design and at each density.

2.3 Image Processing

Image analysis was performed using the image analysis software, FIJI (Schindelin et al. 2012). First, colour thresholding was used to convert the coloured 2D height maps into binary images of the pores. An example of one such height map and the corresponding binary image can be seen in Figure 4. Each image was thresholded individually to ensure that the resulting binary image accurately captured the pores. These binary images could then be used for subsequent software based image analyses.

The fractal dimension, D_f , of the pores was determined using the box-counting method on the binary image of the pores. This involves dividing the image into a 2^n by 2^n grid of boxes and counting how many of the boxes contain any of the darker portions of the image. The logarithm of the number of boxes counted is plotted against the logarithm of $1/2^n$, and the slope of the resulting line is the fractal dimension, D_f . The fractal dimension of the solid phase was also determined by inverting the binary image of the pores, and again performing the box-counting procedure.

The tortuosity of the pore space was determined by measuring the geodesic diameter of each pore space and dividing this by the Euclidean distance between the endpoints of this diameter. This value was calculated for each region of interconnected pore space in an image, and the average tortuosity of all the pores was taken to be the tortuosity of that image. The MorphoLibJ (Legland et al. 2016) plugin for FIJI was used to determine the geodesic diameters and the coordinates of the endpoints of this diameter.

2.4 Determination of Thermal Conductivity

The thermal conductivity of the cellular cementitious materials was determined using the transient plane source method (ISO, 22007-2). For this, the specimens were cut into pairs of disks that sandwiched a sensor as shown in Figure 5. This sensor was a 3.189 mm radius double spiral, encased in Kapton. The technique requires electricity to be passed through the spiral, so that the change in resistance is measured over time. From this, the thermal properties of the specimen can be calculated. The thermal measurements were taken at an ambient temperature of 21°C. Each test was run for 180 seconds and the samples were heated using 51.33 mW of power.

2.5 Determination of Sound Absorption Parameters

The sound absorption of the foam concrete was determined using an impedance tube shown in Figure 6, as described in ASTM C384-04 (ASTM 2011). The specimen is placed at the end of a tube and a sound wave of a known frequency is sent down the tube to reflect off the specimen. The reflected sound forms a standing wave of sound intensity in the tube and the maximums and minimums of the intensity can be located and measured using a microphone probe. From the locations and intensities of these maxima and minima, the normal incident sound absorption coefficient can be calculated for a given frequency. The normal incident sound absorption coefficient, α_n , was measured for frequencies from 125 Hz to 6300 Hz. This absorption coefficient is a value from 0 to 1 where 0 implies that all sound is reflected off the material and 1 implies that all sound is absorbed by the material (Everest and Pohlmann 2009). As per ASTM C423, the Noise Reduction Coefficient (NRC), is defined as the average of random incident sound absorption coefficients, when taken at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz (ASTM 2017). In this study, instead of using *random* incident sound absorption coefficients, the *normal* incident sound absorption coefficients were used to obtain the NRC. This gives a similar measure of how well the material absorbs sound, while being much faster and cheaper to determine than using random incident sound absorption coefficients.

3. Results and Discussion

The porosity of the foamed concrete mixtures as determined by image analysis is presented in Figure 7. As expected, the porosity decreases with an increase in the density of the material. The 2-D fractal dimension, obtained using the box-counting technique described above, was calculated for the pore space and also for the solid phase. They are presented in Figure 8 a) and b), respectively. The values shown are the average of 9 measurements, and the error bars show the standard deviation of those 9 measurements. Across all binders and densities, the 2-D fractal dimension, D_f , of the pores ranged from 1.67 to 1.87. It is clear that the fractality of the pores decreases with an increase in the density of the foam concrete. It agrees with prior work on Portland cement based foam (Tian et al. 2011). The solid phases register an increase in D_f for an increase in the density. This too is in keeping with a prior study by Karam and Tonyan (1993). The type of binder used to produce the cellular material was seen to have insignificant effect on the fractal dimension, be it for the pores or for the solid phase. Figure 9 displays D_f of the pores as a function of the porosity of the cellular material. Note that D_f increases linearly with the porosity.

The tortuosity of the pore network is presented in Figure 10. Notice that there was little variation in tortuosity across densities or mixture composition. For the mixture containing 0% wood ash, there is an increase in tortuosity at 1000 kg/m³, but it is still a low value of tortuosity and this change is not seen for the other mixture designs. The low tortuosity is likely due to the large number of pores which are not interconnected. These pores individually have tortuosities very close to 1 because a straight path can be drawn across the near circular pores. As a result, the average tortuosity of all the pores is very low. Again, there is not much variation in tortuosity for mixtures with varying addition of wood ash, nor indeed within the alkali activated fly ash series.

In Figure 11, the thermal conductivity is plotted against D_f of the porous phase in the cellular cementitious materials. Note that there was a drop in the thermal conductivity with an increase in the pore fractal dimension, D_f , and this was true across all the mixture compositions. It is in keeping with that found for foams (Tian et al. 2011) and mortars (Mamun and Bindiganavile 2017) prepared with Portland cement. Mamun and Bindiganavile (2017) showed this trend to be true at a given density. However, in the case of foams, this relationship could be more a result of the changing porosity. Since an increase in the D_f of the

pores coincides with an increase in the total porosity, therefore the drop in the thermal conductivity may also be attributed to the increasing porosity.

Attempts were made to find a correlation between the noise reduction coefficient (NRC) of the foamed concrete mixtures and the microstructural parameters discussed above. In Figure 12a, the NRC is plotted against the porosity of the cellular systems. No clear trend is apparent from the data as the NRC values have very little variation with the porosity. Figure 12b plots the NRC against the fractal dimension of the pores. Again, most data points show little variation of the NRC with D_f , and no clear trend is visible. Figure 12c shows the NRC plotted against the tortuosity of the pores. The AAFA appears to have increasing NRC with increasing tortuosity, but this pattern is not seen with any of the other binder materials.

Therefore, across the range of materials and densities studied here, no definite conclusions could be made about the effect of structural parameters of the pore network on the noise reduction coefficient of the cellular system.

Existing models to predict the sound absorption coefficient of porous solids have been applied extensively to porous asphalt (Wang et al. 2016, Chen et al. 2018, Gourdon et al. 2018). These models aim to describe the propagation constant, k , and the characteristic impedance, Z_c , two functions of the material which, together, fully describe the acoustic impedance of such a material. Given these two functions, the surface impedance, Z , can be calculated for the material with known thickness, e , and a fixed rigid backing as in Eq. 1. From Z , the sound absorption coefficient, α , can be calculated using Eq. 2 in which ρ_0 is the density of air and c_0 is the speed of sound in air.

$$(1) \quad Z = Z_c \coth(-ike)$$

$$(2) \quad \alpha = \left| \frac{Z - \rho_0 c_0}{Z + \rho_0 c_0} \right|^2$$

Bérengrer et al. (1997) developed a three parameter phenomenological model for the sound absorption of porous asphalt based on the material's porosity, tortuosity, and air flow resistivity, called the Hamet model. This model is given by Eqs. 3-9.

$$(3) \quad k = k_0 \sigma^{1/2} F_\mu^{1/2} \left[\gamma - \frac{\gamma - 1}{F_\theta} \right]^{1/2}$$

$$(4) \quad Z_c = \left(\frac{\rho_0 c \sigma^{1/2}}{\phi} \right) F_\mu^2 \left[\gamma - \frac{\gamma-1}{F_\theta} \right]^{-1/2}$$

$$(5) \quad k_0 = \omega / c_0$$

$$(6) \quad F_\mu = 1 + i\omega_\mu / \omega$$

$$(7) \quad F_\theta = 1 + i\omega_\theta / \omega$$

$$(8) \quad \omega_\mu = (R_s / \rho_0)(h / \sigma)$$

$$(9) \quad \omega_0 = \omega_\mu \left(\frac{\sigma}{N_{pr}} \right)$$

Here, ϕ is the porosity, σ is the tortuosity, R_s is the air flow resistivity, γ is the specific heat ratio of air, N_{pr} is the Prandtl number of air, P_0 is the ambient air pressure, and ω is the frequency variable in radians.

Attenborough (2011) developed a model for k and Z_c of porous materials, assuming identical tortuous slit-like pores. It too is a three parameter model utilizing the porosity, tortuosity, and air flow resistivity of the specimen. This model is given by Eqs. 10-15 .

$$(10) \quad k = \omega \sqrt{\sigma \rho(\lambda) C(\lambda)}$$

$$(11) \quad Z_c = \frac{1}{\rho_0 c_0} \sqrt{\frac{\sigma \rho(\lambda)}{\phi^2 C(\lambda)}}$$

$$(12) \quad \rho(\lambda) = \frac{\rho_0}{G(\lambda)}$$

$$(13) \quad C(\lambda) = \frac{1}{\gamma P_0} \left[\gamma - (\gamma - 1) G(\lambda \sqrt{N_{pr}}) \right]$$

$$(14) \quad G(\lambda) = 1 - \frac{\tanh(\lambda \sqrt{-i})}{\lambda \sqrt{-i}}$$

$$(15) \quad \lambda = \sqrt{\frac{3\sigma\rho_0\omega}{R_s\phi}}$$

The air flow resistivity of porous materials can be estimated by image analysis as shown in Gourden et al. (2018). Assuming circular pores, the air flow resistivity can be estimated using the median effective pore radius, R_{eff} , the porosity, and the tortuosity as shown in Eq. 16 in which μ is the dynamic viscosity of air.

$$(16) \quad R_s = \frac{8\sigma\mu}{\phi R_{eff}^2}$$

If the pore size distribution follows a log normal distribution, the median effective pore size can be calculated using Eq. 17 where $\bar{R}$ is the mean pore size and σ^s is the standard deviation (Gourdon et al. 2018).

$$(17) \quad R_{eff}^2 = \bar{R}^2 e^{2(\sigma^s \ln 2)^2}$$

The air flow resistivities of the cellular concrete specimens were determined using this method and were found to be 10.626×10^6 Ns/m⁴ for the cellular AAFA system, and 7.252×10^6 Ns/m⁴, 12.991×10^6 Ns/m⁴ and 10.088×10^6 Ns/m⁴ for the cellular Portland cement systems with 0%, 10%, and 20% wood ash, respectively.

A comparison between the sound absorption coefficient of 1000 kg/m³ cellular concretes as predicted using the Hamet model, the Attenborough model, and that determined by measurement using an impedance tube is shown in Figure 13a-d. The Hamet model was unable to predict the high absorption coefficient at low frequencies, even when the input parameters were varied within the realm of realistic values. The sound absorption coefficient at moderate frequencies of 1000 and 2000 Hz are reasonably close to the values predicted by the Hamet model, but the actual sound absorption diverges at more extreme frequencies. The Attenborough model tends to provide a closer fit at very low frequencies, but the predicted sound absorption does not get as low as the measured values at moderate frequencies and does not predict the increase in sound absorption at higher frequencies. It is likely that the low connectivity of the pores in the cellular concrete results in a geometry very different from what is assumed by the models. These models assume that sound energy is dissipated through viscous and thermal effects as the sound waves travel through the medium. However, in the foamed concrete examined here, since the pore connectivity is low, the sound is not likely to penetrate deep inside the specimen.

Therefore, the absorption is primarily being caused by the rough surface of the cellular concrete, and not by its internal air-void structure.

4. Conclusions

Foamed concrete samples were prepared to achieve cast densities from 1000 kg/m³ to 1400 kg/m³. A preformed foam was employed in each instance, mixed variously with a blend of Portland cement and wood ash, or alkali activated fly ash as the respective binder. These foams were subsequently examined under laser confocal microscopy and the images so obtained were analysed to quantify the pore structure of the foams. Separately, both thermal and acoustic properties of these foams were experimentally measured and they were compared and correlated to the cellular structure. While the thermal conductivity was seen to correlate well with the air-void network, no trend emerged from this study to relate the latter with acoustic properties. Based on the results, the following conclusions are drawn:

- The fractal dimension of the porous phase, D_f , decreases with an increase in the density of the composite. No significant difference was noted for D_f with any change in the composition of the solid phase.
- The tortuosity of the pore network was low which indicates that although the number of pores in foamed concrete is large, they remain mostly as unconnected pores.
- The thermal conductivity of foamed concrete was found to decrease with an increase in the fractal dimension of the porous phase, D_f .

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Tables

Table 1: Composition of Wood Ash Determined by X-ray Fluorescence

Y ₂ O ₃	P ₂ O ₅	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	ZnO	SrO
2.21	1.62	1.22	5.29	4.69	82.7	0.28	0.38	1.05	0.23	0.34

Table 2: Mix Design of Cellular Cement

Target Density and Ash Content	Cement (kg)	Wood Ash (kg)	Water (kg)	Glass Microfibers (kg)
1000 kg/m ³ 0% Ash	575.9	0	397.3	26.8
1000 kg/m ³ 10% Ash	518.3	57.6	397.3	26.8
1000 kg/m ³ 20% Ash	460.7	115.2	397.3	26.8
1200 kg/m ³ 0% Ash	694.2	0	479.0	26.8
1200 kg/m ³ 10% Ash	624.8	69.4	479.0	26.8
1200 kg/m ³ 20% Ash	555.4	138.8	479.0	26.8
1400 kg/m ³ 0% Ash	812.5	0	560.7	26.8
1400 kg/m ³ 10% Ash	731.3	81.2	560.7	26.8
1400 kg/m ³ 20% Ash	650.0	162.5	560.7	26.8

Table 3: Composition of Fly Ash Determined by X-ray Fluorescence

MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	MnO	Fe ₂ O ₃	CuO	ZnO	As ₂ O ₃	Br ₂ O	SrO	ZrO ₂
0.9	15.57	50.16	1.63	1.82	17.6	1.93	0.13	9.61	0.04	0.04	0.02	0.07	0.35	0.11

Table 4: Composition of Sodium Silicate

Water (%)	Sodium Silicate (%)	Molar Ratio	Density (g/cm ³)	Si (g/L)	Na (g/L)
60*	40*	3.2*	1.4*	58.65	2.38

*From supplier’s Material Safety Data Sheet (MSDS)

Table 5: Mix Design of Cellular Alkali Activated Fly Ash

Target Cast Density (kg/m ³)	Sodium Silicate Solution (kg)	8M Sodium Hydroxide (kg)	Fly Ash (kg)	Glass Microfibers (kg)
1000	162	81	730	26.8
1200	195	98	880	26.8
1400	230	115	1030	26.8

Figure Captions

Figure 1: Backscattered Electron Microscope (BSEM) Image of the Wood Ash

Figure 2: Backscattered Electron Microscope (BSEM) Image of the Fly Ash

Figure 3: Foam Generator

Figure 4: 2D Height Map and Corresponding Binary Image of Cellular Concrete

Figure 5: Transient Plane Source Sensor between Cellular Cement Specimens

Figure 6: Impedance Tube Apparatus

Figure 7: Porosity of the Cellular Systems

Figure 8: Fractal Dimension of (a) Pores and (b) Solid Phase in the Cellular Systems

Figure 9: Fractal Dimension of Pores as a Function of Porosity

Figure 10: Tortuosity of the Pores in the Cellular Systems

Figure 11: Thermal Conductivity as a Function of Fractal Dimension of Cells in Cellular Cementitious Materials

Figure 12: NRC as a Function of (a) Porosity, (b) Fractal Dimension and (c) Tortuosity

Figure 13: Measured and Predicted Sound Absorption Coefficients for Mixtures with 1000 kg/m^3 Density, and based on (a) AAFA, (b) 0% Wood Ash, (c) 10% Wood Ash, (d) 20% Wood Ash

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Fig 1

86x65mm (300 x 300 DPI)

Figure 2: Backscattered Electron Microscope (BSEM) Image of the Fly Ash

Fig 3

115x73mm (300 x 300 DPI)

Fig 4

149x56mm (300 x 300 DPI)

Fig 5

47x62mm (300 x 300 DPI)

Fig 6

103x49mm (300 x 300 DPI)

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