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Research Article

Electromagnetic Shielding Characteristics of Eco-Friendly Foamed Concrete Wall

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The electromagnetic shielding characteristics according to the material composition of foamed concrete, which was manufactured to reduce environmental pollution and to economically apply it in actual building walls, were researched herein. Industrial by-products such as ladle furnace slag (LFS), gypsum, and blast furnace slag (BFS) were added to manufacture foamed concrete with enhanced functionalities such as lightweight, heat insulation, and sound insulation. The electrical characteristics such as permittivity and loss tangent according to the foam and BFS content were calculated and measured. Free space measurement was used to measure the electromagnetic shielding characteristics of the actually manufactured foamed concrete. It was confirmed that electromagnetic signals were better blocked when the foam content was low and the BFS content was high in the measured frequency bands (1–8 GHz) and that approximately 90% of the electromagnetic signals were blocked over 4 GHz.

1. Introduction

A number of users using a wireless service using a wireless communication system such as a wireless LAN and a Bluetooth in the 2.4 GHz/5 GHz band and a mobile communication system using the 3G and LTE are rapidly increasing. In addition, as the IoT age approaches, spectrum management is required to efficiently use limited frequency resources. In particular, various efforts are being made to improve the communication environment of buildings where wireless service users are concentrated, such as department stores, apartments, and companies. Generally there is interference between the same or adjacent channels. Studies on a frequency selective shielding space [1, 2] and a spectrum management technique capable of forming a wide coverage area according to a user's demand in the indoor space have been actively carried out [3, 4].

Recently, in order to improve the communication performance of the indoor space, it is becoming more important to analyze the electrical characteristics and electromagnetic wave transmission characteristics of the building materials constituting the building. In 2000, Cuinas and Sanchez [5] measured the propagation characteristics of the indoor of the building by measuring the reflection and transmission characteristics of wood, red brick, and glass as building materials in the 5.8 GHz band and measured the propagation characteristics of building materials for UWB channel modeling in 2003 [6]. Recently, to predict the signal coverage of 700 MHz~5 GHz wireless signal using free space measurement method, the propagation attenuation characteristics of real buildings were analyzed [7] and the propagation characteristics of building floors, glass, and bricks in the tens of GHz band were performed [8–10]. In addition, in 2015 [11], the electromagnetic reflection characteristics of the new building material, the thickness variation (10 mm–40 mm) of the foamed concrete, and the type of foaming agent (vegetable, animal foam) were observed for the 2–18 GHz frequency band. In this study, for the first time, electrical characteristics and electromagnetic transmission characteristics of eco-friendly foamed concrete that can be applied to various building materials such as flooring, wall, and roof material were analyzed.

Foamed concrete, which is manufactured by generating foam inside concrete, is lighter than ordinary concrete, is

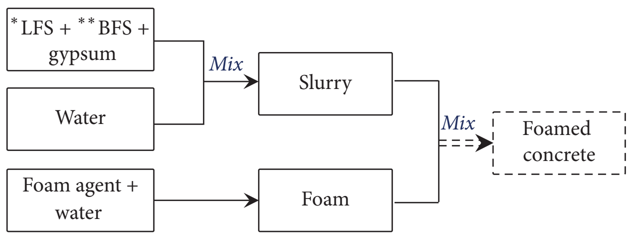


Figure 1: Manufacturing method of foamed concrete. *LFS: ladle furnace slag. **BFS: blast furnace slag.

convenient to construct, has high heat insulation effect, and has outstanding sound absorption and insulation; however, it has the disadvantage of low durability due to which additional additives such as blast furnace slag (BFS), which is an industrial by-product, must be used for production to strengthen concrete [12, 13]. BFS is a by-product that is created by finely splitting slag that is generated when producing pig iron with materials such as iron ore, coke, and limestone. Addition of BFS in concrete makes the material have large long-age strength, low hydration heat when water and cement react, and outstanding durability. In addition, it can reduce CO_2 generation, reduce cement consumption because inexpensive industrial by-products are added in production, and lower manufacturing costs and it is used not only in foamed concrete, but also in ordinary concrete [14, 15]. However, previous researches on concrete using BFS have used ordinary cement which generates CO_2 and causes environmental pollution. Instead of using recent concrete, researches on concrete that can reduce environmental pollution by using industrial by-products have been conducted [16, 17].

In this paper, we investigated the electromagnetic transmission of environmentally friendly foamed concrete walls by mixing industrial by-products with lightweight, fire resistance, heat insulation, and sound insulation effect. Eco-friendly foamed concrete was made by using industrial by-products such as LFS (ladle furnace slag), gypsum, and BFS (blast furnace slag) instead of cement, and electrical properties were measured according to the content of foamed concrete and blast furnace slag. Using the measured electrical properties, the electromagnetic characteristics of echo-friendly foamed concrete were simulated in the frequency range of 1~8 GHz and the electromagnetic transmission characteristics were measured and analyzed using free space measurement method.

2. Manufacturing of Foamed Concrete

Various functions of the foamed concrete are determined using the content of foam and BFS; thus, the ratio of foam and BFS varies depending on the purpose of application. In this paper, foamed concrete wall material with 20%, 40%, and 60% foam content and 0%, 20%, 40%, and 60% BFS content was produced. As shown in Figure 1, LFS, gypsum, and BFS, which are the main materials of foamed concrete, were mixed in water to produce the slag. Foam created by using a vegetable foaming agent mixed with 4% water was mixed with the slag to manufacture the foamed concrete. After complete drying for expression of high strength of the produced foamed concrete, measurement tests in this paper were conducted to investigate the electromagnetic shielding characteristics.

3. Electrical Properties of Foamed Concrete

In general, the electrical properties of a material are different from each other depending on the material constituting the material and composition ratio and are defined as complex values such as $\varepsilon_r = \varepsilon_r' - j\varepsilon_r''$. The dielectric constant and loss tangent are given by ε_r' and $\varepsilon_r''/\varepsilon_r'$, respectively. The electrical properties are expressed as a function of frequency, and the amount of electromagnetic waves passing through or reflecting the material, that is, the transmission and reflection coefficients, is known through electrical properties [18]. The relationship between the dielectric constant of the material for the loss tangent and the transmission coefficient T and the reflection coefficient Γ is given by the following equation [1]:

$$\begin{aligned} T &= \frac{\left(1-\Gamma^2\right)\exp\left(-jk_s d_s\right)\exp\left(-\alpha d_s\right)}{1-\Gamma^2\exp\left(-j2k_s d_S\right)\exp\left(-2\alpha d_s\right)} \\ \Gamma &= \frac{1-\sqrt{\varepsilon_r}}{1+\sqrt{\varepsilon_r}} \\ k_s &= \frac{2\pi}{\lambda}\sqrt{\varepsilon_r} \\ \alpha &= \frac{\pi}{\lambda}\frac{\varepsilon_r''}{\sqrt{\varepsilon_r'}}, \end{aligned} \tag{1}$$

where d_s is the thickness of the material and λ is the wavelength. In general, the electrical properties of building materials are calculated from reflection and transmission characteristics measured in free space or reflection and transmission characteristics using coaxial cables [1, 19, 20]. In this paper, to analyze the electromagnetic transmission properties of environmentally friendly foamed concrete, we measured the permittivity and loss tangent by using coaxial cable measurement method and calculated the electromagnetic transmission characteristics. The calculated results were compared with the electromagnetic transmission characteristics measured by the free space measurement method. Table 1 shows the eco-friendly foamed concrete measured in this study.

3.1. Dielectric Characteristics Measurements of Foamed Concrete. In order to verify the foam content and the electrical properties according to the blast furnace slag content of the echo-friendly foamed concrete, the permittivity for a solid material having a flat surface with a thickness of more than $20/\sqrt{|\varepsilon_r|}$ (mm), ε_r, and loss tangent ($\tan\delta$) were measured repeatedly by calculating the degree of reflection by placing a measuring probe on the upper surface of the foamed concrete as shown in Figure 2. The N1501A, a dielectric

Table 1: Experiment plan.

Method	Type	Content rate (%) Foam	BFS				Measurement	Results
Electrical characteristics	Cylinder	20	0	20	40	60	Coaxial cable measurement	ε_r
		40	0	20	40	60		
		60	0	20	40	60		$\tan\delta$
Electromagnetic transmission characteristics	Panel	20	0	20	40	60	Free space measurement	S_{21}

Table 2: Dielectric constant of materials sample.

Materials samples	Size	Permittivity Reference	Measured
Teflon [22]	40 mm × 30 mm × 20 mm	2.1	2.04
Wood (dry) [23]	28 mm × 28 mm × 20 mm	2	2
Soda-lime glass [22]	30 mm × 30 mm × 10 mm	6	6.1

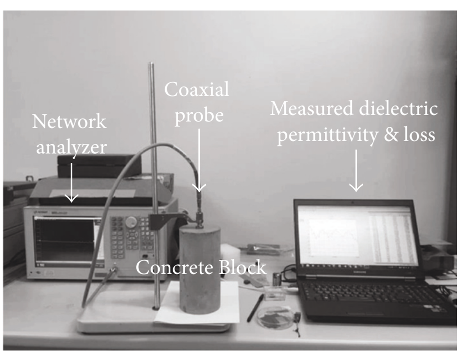


Figure 2: Environment of permittivity and loss tangent measurement.

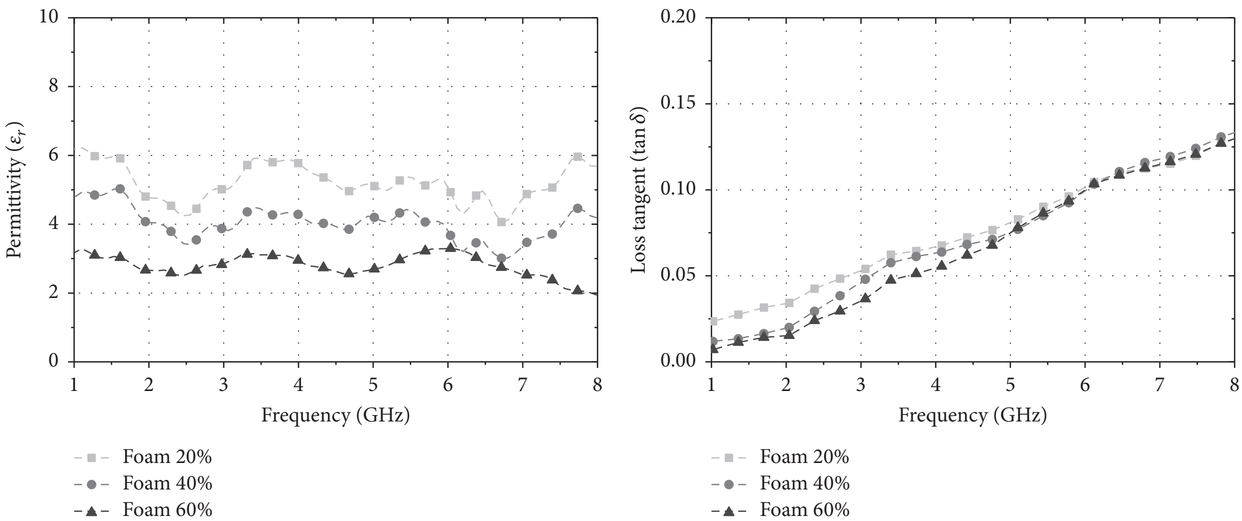
constant measurement device made by Keysight Co., used in this paper, can measure the permittivity of a solid material with smooth surface as well as liquid and semisolid for a broadband frequency band from 200 MHz to 20 GHz. In this paper, after calibrating to obtain accurate dielectric constant measurement value, we measured the dielectric constant of a solid which has already known the dielectric constant value and checked the accuracy and repeatedly measured the electrical properties of the foamed concrete. We measured and compared the dielectric constants of Teflon, wood, and soda lime glass, both of which are known for their permittivities. The results are shown in Table 2. It can be confirmed that the measurement result is very similar to the reference value.

Cylinder shaped foamed concrete with a radius of 10 cm and thickness of 20 cm was used for the measurements, and foamed concrete with 20%, 40%, and 60% foam without BFS was first measured. As a result, the mean permittivity at 1–8 GHz frequency bands decreased as the foam content increased to 20%, 40%, and 60% with values of approximately 5.24, 3.99, and 3.12 from Figure 3(a), respectively. From Figure 3(b), it can be seen that the loss tangent decreases with increasing foam content, and the loss increases with increasing frequency. Next, the permittivity and loss tangent were measured by fixing the foam content to 40% in order to investigate electrical characteristics (permittivity and loss tangent) of foamed concreted according to the BFS content. Figure 4 shows the measured results in which permittivity increases from approximately 3.99 at 0% BFS to approximately 6.12 at 60% BFS at higher BFS content, and the loss tangent also increases as the BFS content increases. As shown in Figures 3 and 4, the permittivity of the foamed concrete measured fluctuates with frequency variation because of measurement uncertainty. In this paper, the reflectance measurement method using coaxial cable, which is used to measure the dielectric properties, is unstable when an air layer is formed between the measurement probe and the surface of the measurement object. In this paper, the actual top surface of cylindrical foamed concrete has measurement uncertainty due to slight air gap between measuring probes due to slight irregularities of surface due to manufacturing tolerances.

3.2. Electrical Modeling of Foamed Concrete for Permittivity Calculation. To predict the effective permittivity according to the foam content and BFS content of foamed concrete, the permittivity prediction model of porous material can be modeled using (2) [21] as shown in Figure 5(b),

$$\varepsilon_{\text{eff}} = \frac{\varepsilon_m \varepsilon_{\text{air}} (1 + 3P) + 3\varepsilon_m^2 (1 - P)}{\varepsilon_{\text{air}} (1 - P) + \varepsilon_m (3 + P)}, \quad (2)$$

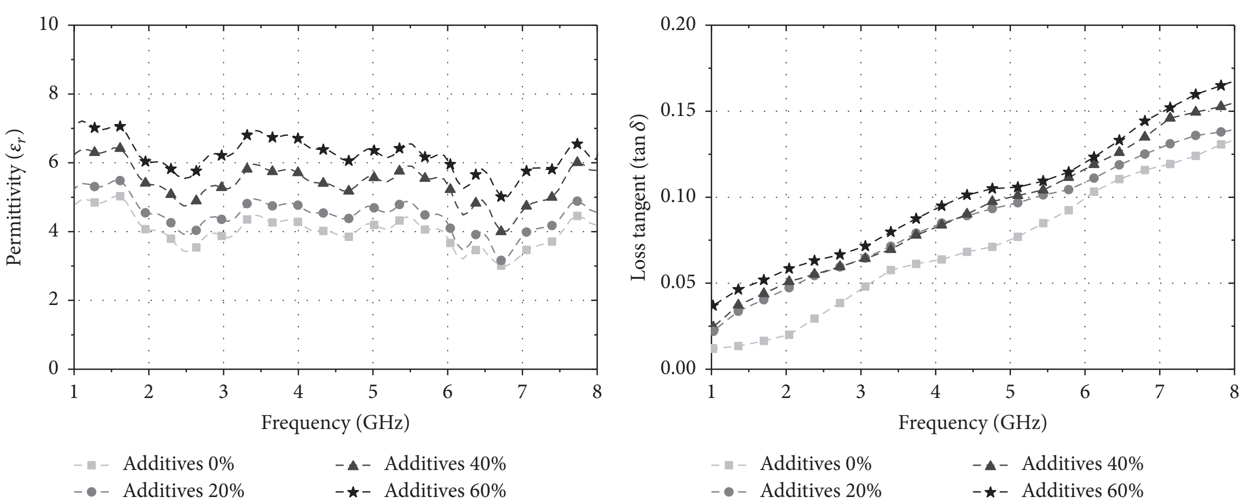
where ε_{eff} is the effective permittivity of the foamed concrete, ε_m is the permittivity of 0% foamed concrete, ε_{air} is the



(a) Measured results of permittivity (ε_{eff})

(b) Measured results of loss tangent

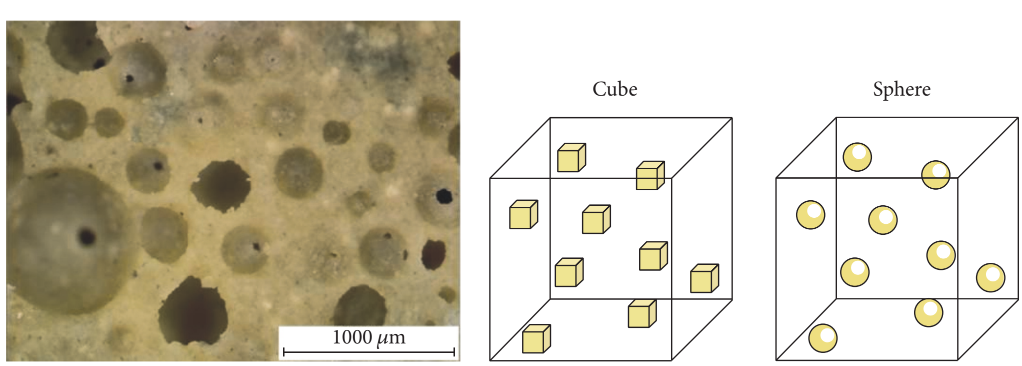
FIGURE 3: Measured results of electrical characteristics according to foam content.



(a) Measured results of permittivity (ε_{eff})

(b) Measured results of loss tangent

FIGURE 4: Measured results of electrical characteristics according to BFS content.



(a) Fabricated sample for permittivity measurement

(b) Foam concrete with BFS modeling

FIGURE 5: Modeling of foamed concrete.

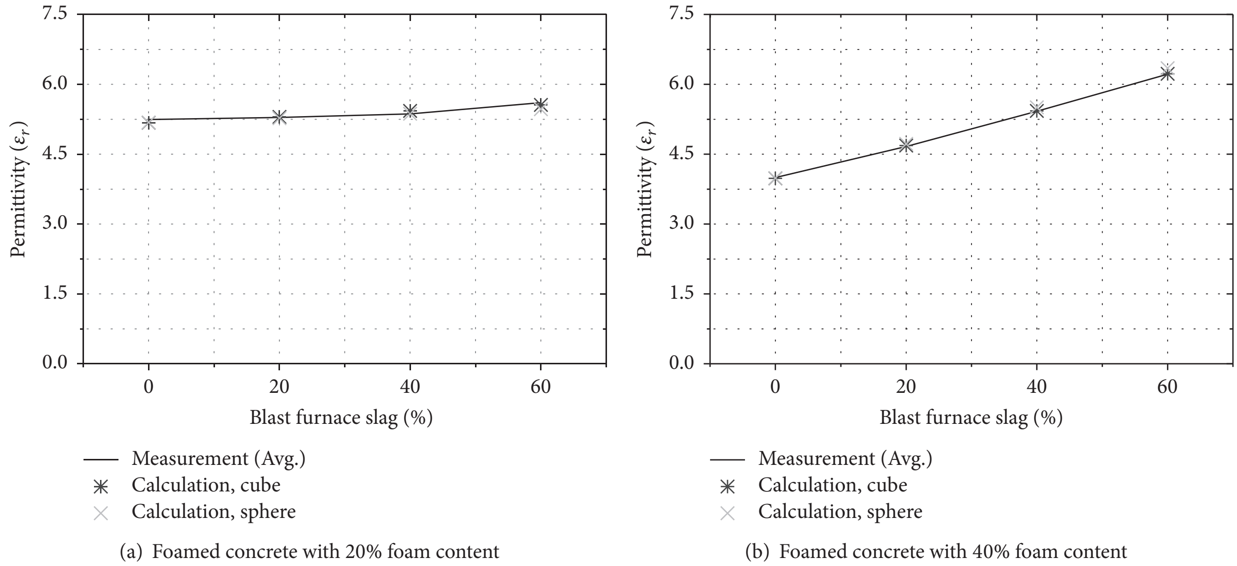


Figure 6: Comparison of calculated and measured permittivity of foamed concrete.

permittivity of air, and P is the volume of the total foam of the foamed concrete. Foam is randomly generated inside the actual foamed concrete when using foaming agents and micropores generated by evaporation of remaining water after hydration also exist. BFS is added for compensation and this has effect on the concrete strength. Therefore, the content of micropores due to BFS must essentially be considered in the volume of the total foam in the foamed concrete, and the accuracy of (2) can be improved through a correction equation like

$$P = V_1 \times N_1 - V_2 \times N_2. \quad (3)$$

Here, V_1 and V_2 are the unit volume of foam within the foamed concrete and the BFS, respectively, N_1 is the total amount of foam, and N_2 is the number of BFS.

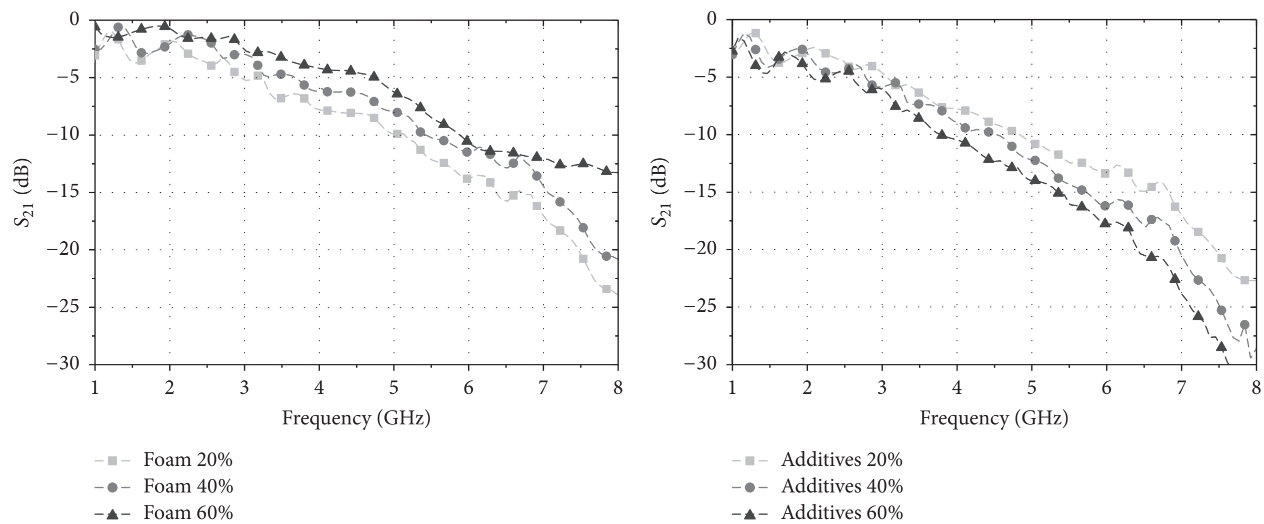
To verify (2) that is the permittivity modeling equation according to foam and BFS in the foamed concrete, a cylinder shaped foamed concrete was manufactured as shown in Figure 5(a) and measured. Measurements and calculations of permittivity according to the foam and BFS in the foamed concrete were compared and are shown in Figure 6. The results show good agreement between calculation of modeling and measurement.

4. Electromagnetic Shielding Simulation of Foamed Concrete

As discussed in Section 3, the electromagnetic transmission of a material is determined by electrical properties such as dielectric constant and loss tangent of the material. To simulate the electromagnetic transmission characteristics of indoor space in the 1–8 GHz frequency band, electrical property measurements should be used, as shown in Figures 3 and 4, depending on the foam content of the foamed concrete and the furnace slag content. In order to simulate the electromagnetic transmission of environmentally friendly foamed concrete, we confirmed the change of the electromagnetic wave transmission characteristics by using HFSS of Ansys, commercial three-dimensional electromagnetic field analysis software. In this paper, the electromagnetic transmission of 600 × 600 × 100 mm wall is estimated by applying permeability and loss tangent of 1~8 GHz band and assuming the incident of plane wave depending on foam content and blast furnace slag content. The transmission characteristics of the simulated foamed concrete are shown in Figure 7 as the transmission loss (S_{21}), which means the power ratio of the incident wave to the wave transmitted through the object. Based on −10 dB, electromagnetic waves were blocked above 4.9 GHz when the foam content was 20% and electromagnetic waves were blocked above 6 GHz when the foam content was 60%. This shows that signals are better blocked at lower foam content and higher frequency. In addition, higher blocking feature is shown when more BFS is used considering the shielding characteristics according to BFS content. It can be predicted through the simulation results that the electromagnetic shielding characteristics are better when there is a higher foam content with lower BFS content.

5. Measurements

In order to investigate the electromagnetic shielding characteristics in indoor space when applying foamed concrete in an actual building, 60 × 60 cm sized foamed concrete with a thickness of 10 cm was considered as the building wall, and a coaxial cable connected with a network analyzer was used. Two connected horn antennas were connected and a free space measurement method was used to investigate the electromagnetic shielding characteristics of the foamed concrete at 1–8 GHz frequency bands, as shown in Figure 8. Similar to measuring the electrical characteristics according to the foam content of foamed concrete above, measurements



(a) Simulated electromagnetic shielding according to variation of the foam content

(b) Simulated electromagnetic shielding according to variation of the BFS content

Figure 7: Simulated results of electromagnetic shielding characteristics of foamed concrete.

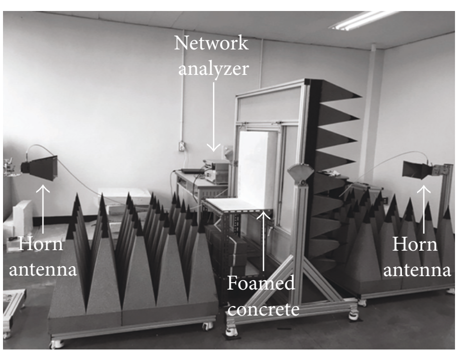


Figure 8: Environment of electromagnetic shielding characteristic measurement.

were conducted on three types of foamed concrete with foam of 20%, 40%, and 60% without BFS in order to investigate the electromagnetic shielding characteristics according to foam content. Figure 9(a) shows the measured shielding characteristics according to foam content based on −10 dB in which the blocking effect was observed above 3.55 GHz when the foam content was 20% and above 4.07 GHz when the foam content was 40%. Regarding 60% foam content, the absorption characteristics are observed at 1–8 GHz frequency bands. In addition, it can be seen in Figure 9(b) that the blocking feature is improved as the BFS content increases from 20% to 40% and 60% when the foam content is 40%. Compared with the simulation results, it can be seen from the measurement results that the foam size of the foamed concrete is uneven and the difference due to the loss occurs. In addition, the measurement results of the electromagnetic wave transmission characteristics in the Figure 9 show that a signal of −10 dB or more passes well at 2.4 GHz, which is the most widely used wireless LAN frequency band. This means that wireless LAN 2.4 GHz signals may interfere with wireless LAN signals in adjacent areas in indoor space where foamed concrete is applied as a wall, which may degrade reception performance. We will study a foamed concrete wall that can improve the indoor communication performance by selectively shielding the 2.4 GHz wireless LAN signal by applying a frequency selective surface (FSS), a spatial filter to block specific frequency bands.

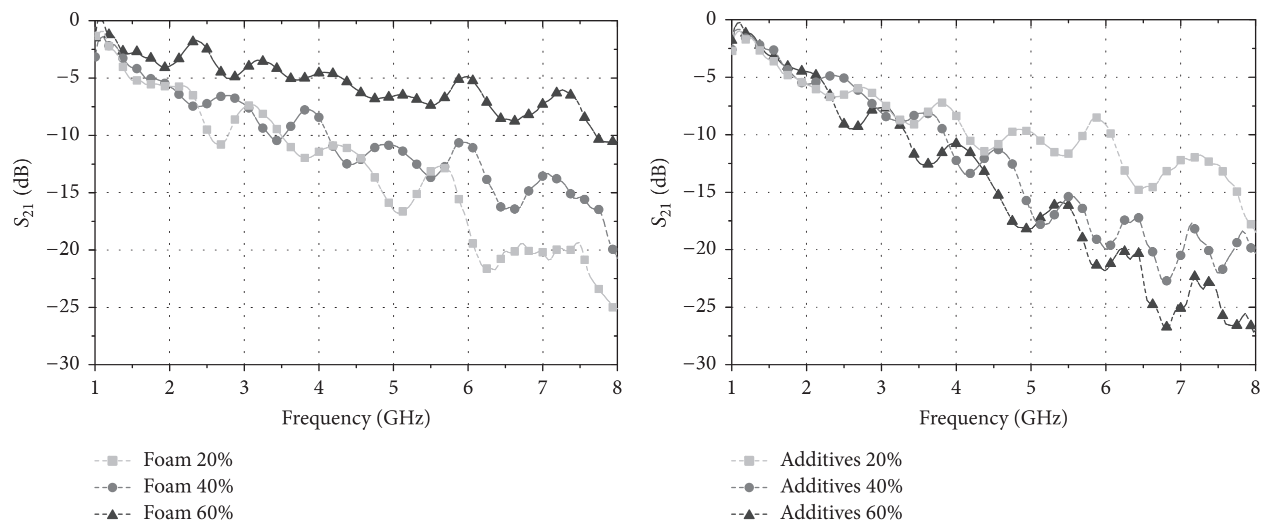
6. Conclusion

In this paper, the electrical characteristics such as permittivity and loss tangent according to the foam and the BFS content in foamed concrete and free space measurement were used to measure the electromagnetic propagation characteristics in indoor space with functional foamed concrete as wall at 1–8 GHz frequency bands. As a result of the measurements, electromagnetic waves penetrate at bands higher than −10 dB even if the foam and the BFS contents change below 4 GHz, but signals above 4 GHz pass when the foam content is high and the BFS content is low.

In this paper, the electromagnetic transmission characteristics of 100 mm thick eco-friendly foamed concrete, which can be applied to the inner walls of buildings, was measured and analyzed. The measurement results presented in this paper are expected to be used in various applications such as analysis of communication performance in indoor space and study of human influence by electromagnetic waves, and researches of foamed concrete wall with frequency selection characteristics are needed.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.



(a) Measured electromagnetic shielding according to variation of the foam content

(b) Measured electromagnetic shielding according to variation of the BFS content

Figure 9: Measured results of electromagnetic shielding characteristics of foamed concrete.

Acknowledgments

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