

METHODS

Method for Optimization of a Shielding Effectiveness Measurement System Using Shielding Concrete Blocks for IEMI

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This work was supported by the Construction Technology Research Project through the Ministry of Land, Infrastructure and Transport of the Korean Government, under Grant 22SCIP-B146646-05.

ABSTRACT The recent digitization of many technologies has made information communication facilities vulnerable to intentional electromagnetic interference (IEMI) and electromagnetic pulses (EMPs). Concrete with shielding capability is being studied to protect entire information facilities or security facilities from these threats. Although the conventional standards ASTM D 4935 and MIL-STD-188-125-1 provide guidelines with regard to the assessment of the shielding effectiveness (SE) of materials, these standards are not applicable to concrete owing to the thickness of concrete, particularly when reinforced with rebar, the composition of building materials, time, and cost. To solve this problem, this paper proposes a method for measuring the SE of concrete used for building construction. The proposed measuring method is based on the MIL-STD-188-125-1 standard. Small concrete blocks are used as specimens for testing the suggested SE measurement method, which is designed to operate in the frequency range of 600 MHz to 1.5 GHz. The accuracy of the proposed method is optimized by varying parameters such as the size of the concrete blocks, incidence angle of electromagnetic waves, fixture materials, and the use of absorbers. The results of the proposed method are compared with those of the ASTM D 4935 standard. The SE of concrete blocks, concrete walls, and concrete buildings is also tested using the proposed method and MIL-STD-188-125-1. Similar results were obtained with all of these methods. Therefore, the proposed method to measure the SE of concrete blocks might be suitable to ascertain that buildings constructed with the same concrete could be expected to have the same SE.

INDEX TERMS Shielding concrete, electromagnetic shielding, shielding effectiveness test.

I. INTRODUCTION

The digitization of devices is rapidly progressing as a result of recent technological advancements. Additionally, automation technology that uses wireless connectivity to operate facilities or equipment is becoming more widespread. This phenomenon complicates the wireless environment and causes electronic devices to malfunction and experience failure due to interference. Particularly with regard to digital infrastructure, the ensuing problems may be disruptive. This

The associate editor coordinating the review of this manuscript and approving it for publication was Kwok L. Chung.

threat originates from the production of powerful electromagnetic waves such as intentional electromagnetic interference (IEMI) or electromagnetic pulses (EMPs). Electronic devices are already shielded against such powerful electromagnetic radiation using a variety of methods. For example, shielding sheets, electromagnetic filters, metal enclosures, shielding chambers, and electromagnetic absorbers have been used as technologies for controlling the electromagnetic environment. However, conventional technologies can only protect a limited field space. The disadvantages of currently available technologies are their inefficient use of space and the high costs associated with these technologies. To overcome these

disadvantages, a reinforced concrete structure that offers the necessary shielding has been studied. The rebar incorporated in concrete structures constitutes a shielding network. The shielding concrete is manufactured by combining a shielding material with the concrete mixture. The resulting reinforced concrete structure would deliver good shielding performance and would enable an electromagnetically independent space to be created. This technology is expected to make it possible to build facilities protected against IEMI and EMPs for private buildings, traffic control rooms, military bunkers, and control rooms.

Because a building has many apertures, windows, doors, and vents, it is impossible to create a shielded space using only shielding concrete. Other technologies being researched for use in conjunction with shielding concrete include paints, films, and sheets. The shielding effectiveness (SE) of these supporting technologies can be evaluated according to the ASTM D 4935 standard. However, the standard is not applicable to concrete because of limitations regarding the physical characteristics of concrete. Therefore, a measurement method applicable to concrete was developed by referring to the standard test methods MIL-STD-285 and MIL-STD-188-125-1 [1], [2], [3].

To ensure that the proposed measurement method is comparable with the conventional standard measurement method, the proposed method was designed to operate in the 1.5 GHz frequency band or lower. Even though the measurements are limited to this frequency range, the properties of concrete are expected to compensate for the shortcomings of the method. In recent years, the frequencies at which electronic devices and equipment operate have increased by tens of GHz. Therefore, the SE of many shielding materials is being studied at these frequencies. However, unlike these shielding materials, the thickness of concrete structures provides natural SE when the frequency increases to 300 MHz or more, and the SE increases in proportion to the frequency. Shielding concrete that offers satisfactory SE capability at low frequencies is expected to offer satisfactory SE even at high frequencies when the characteristics of the concrete are taken into account [4], [5]. Consequently, shielding concrete containing a large amount of conductive material is expected to be the basis for protecting information facilities and electronic equipment from EMP and IEMI threats.

In this study, we have developed a method to measure the shielding effectiveness by referring to the MIL-STD-188-125-1 standard with the aim of shielding concrete buildings. In Section II, we propose a measurement method using small concrete blocks to measure the SE. Experiments have been conducted to optimize the method to enhance its accuracy. The SE results of the proposed measurement method and the ASTM D 4935 standard method are compared. In Section III, we discuss the deficiencies of the proposed measurement method and present the simulation results of our analysis of the EM penetration paths. The measurement system was supplemented by using metal covers. In Section IV, we discuss the measurements of the SE of concrete blocks, concrete

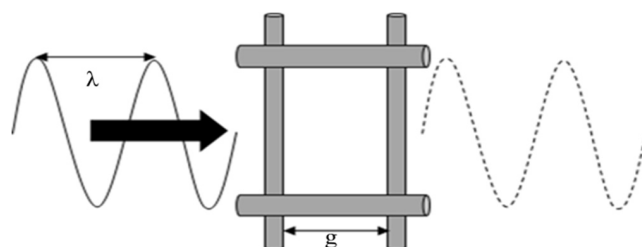


FIGURE 1. SE of reinforcement bars.

walls, and buildings and compare the results obtained with the different methods to verify that the results of the proposed measurement method are accurate.

II. SHIELDING EFFECTIVENESS OF A CONCRETE BLOCK

A. SELECTING A CONCRETE BLOCK

The size of a concrete block is an important factor influencing the electromagnetic wavelength and resonance effect. As shown in Fig. 1, structural SE occurs at a frequency with a wavelength longer than the rebar interval, g . Therefore, the lowest frequency that can be measured is determined by the size of the selected concrete block. The formula for calculating the SE and minimum frequency is as shown in (1) [6]. To indirectly confirm the SE of a building, the size of the concrete blocks can be selected such that it corresponds to the size of the cell between the reinforced steel bars in reinforced concrete.

$$SE_{dB} \approx 20 \log\left(\frac{\lambda}{2g}\right) \quad (1)$$

$$\lambda = c/f \quad (2)$$

The frequency-dependent shielding effectiveness (SE_{dB}) can be calculated using the interval g and wavelength λ . The minimum spacing between reinforcement elements in reinforced concrete structures is 250 mm. Therefore, when calculated using (1), the minimum frequency for SE is 600 MHz. The SE of this concrete block was measured in the range of 600 MHz to 1.5 GHz. This range can be compared and analyzed by using a frequency range that overlaps with that of ASTM D 4935 of 30 MHz to 1.5 GHz [7]. The thickness of the concrete block also needs to be considered for the resonance frequency. Based on the upper limit of the measurement frequency range of 1.5 GHz, the thickness of the concrete block is determined to be 200 mm from (2). Thus, the concrete block should be 250 mm in length and width and 200 mm in thickness to enable the SE to be measured.

Finally, the weight of the concrete block must be considered. The weight of the concrete block is restricted by transportation and safety considerations, and is calculated using the average density of concrete ($1 \text{ m}^3 = 2,300 \text{ kg}$) to ensure that the concrete block can be moved by humans. As shown in Figs. 2 and 3, the concrete block needs to be installed on the fixture. Therefore, the dimensions of the concrete block for measuring the SE were selected to be $300(\text{W}) \times 300(\text{L}) \times 200(\text{T}) \text{ mm}^3$. This concrete block weighs about 41.4 kg. This

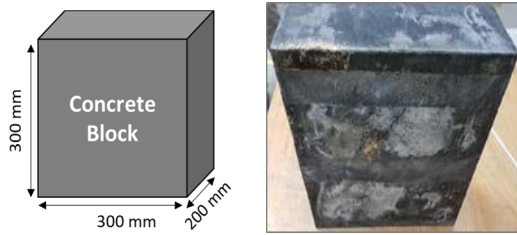


FIGURE 2. Concrete block for SE measurement.

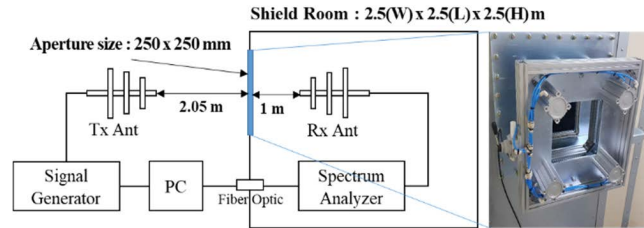


FIGURE 3. Configuration of SE measurement system for concrete block.

allows for a slight increase in the weight of the additional material in the concrete for shielding purposes.

The SE measurement environment was prepared by cutting a $250 \times 250 \text{ mm}^2$ square hole and installing a concrete block fixture in the wall of the shielding room. The SE measurement system is configured as shown in Fig. 3.

B. IMPROVING THE SHIELDING ROOM ENVIRONMENT

1) COMPARISON OF RESONANCE EFFECT OF THE SHIELDING ROOM WITH AND WITHOUT ABSORBER

A conventional shielding room is constructed of metal, and the square aperture acts as a slit. Therefore, an incident electromagnetic wave resonates several times internally in the shielding room, which reduces the accuracy of the measurement results. This necessitates the use of an absorber in the shielding room to reduce the resonance effect. As shown in Fig. 4, the absorber is located on the sides and the rear, which are the areas where most of the reflection occurs in a small space. Absorbers are not installed on the floors and ceilings because even partial absorption is sufficient to reduce the resonance effect such that the SE can be measured [9], [10]. The size of the movable absorber installed on the side is $1.2 \times 2.3 \text{ m}^2$, and that of the movable absorber installed on the rear wall is $2.4 \times 1.8 \text{ m}^2$. The absorber and transceiver antennas are positioned as shown in Fig. 4. The aperture is in one wall of the shielding room, and the block fixture is installed in this aperture.

The signal intensity that was detected inside the shielding room before and after installation of the absorber was recorded and is shown in Fig. 5. The absorber has the effect of greatly reducing the intensity deviation of the received signal. However, the received signal underwent attenuation in the range 900 MHz to 1.1 GHz up to 20 dBm and solutions to this problem are discussed in Section II-C [11], [12].

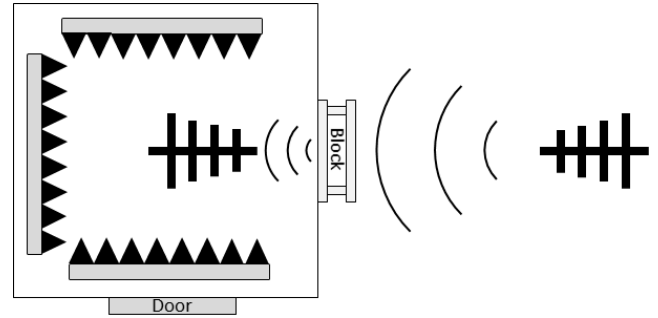


FIGURE 4. Movable absorber in shielding room.

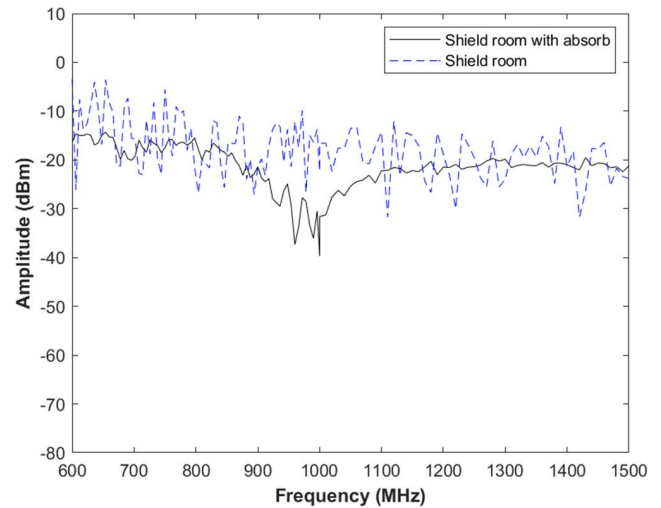


FIGURE 5. Comparison of resonant effect on shielding room without or with absorber.

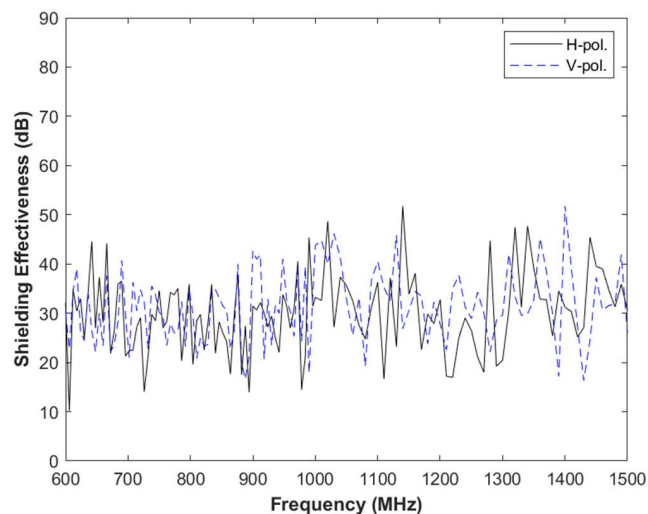
2) SE MEASUREMENT OF CONCRETE BLOCK

The proposed measurement system was used to determine the SE by comparing the measurements recorded in the absence and presence of the concrete block. Measurements recorded without the concrete block are the reference values (V_{ref}), whereas those recorded after installation of the concrete block in the fixture are the received values (V_{rev}). Then, using these two values and (3), the SE (Shielding Effectiveness) is calculated [13], [14].

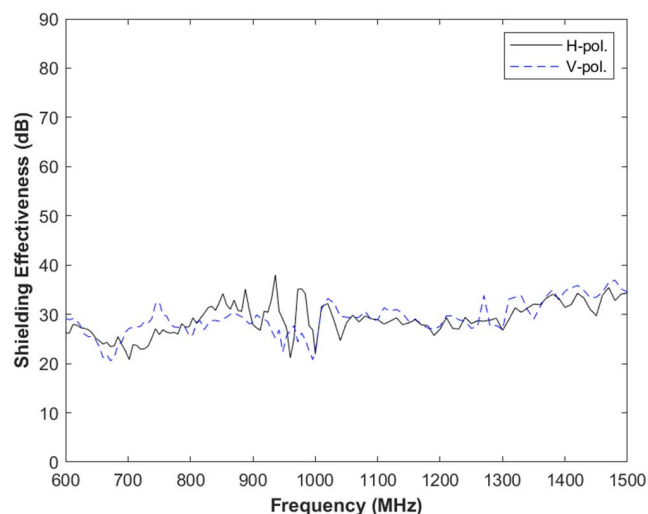
$$SE (dB) = 20\log\left(\frac{V_{ref}}{V_{rev}}\right) = 10\log\left(\frac{P_{ref}}{P_{rev}}\right) \quad (3)$$

Here, P_{ref} and P_{rev} are the power value of V_{ref} and V_{rev} , respectively. The SE of the concrete block was determined to assess the effect of the absorber. The configuration of the measurement system is shown in Fig. 3, and the concrete block is placed on the fixture. The calculated SE based on the measurements without and with the absorber is shown in Fig. 6 (a) and (b), respectively. The graph confirms that the measurement results have been improved as a result of the absorber.

The deviation is calculated by the difference between two successive measured values. These calculations showed that when measuring the SE of the concrete block in the shielding



(a) without absorber



(b) with absorber

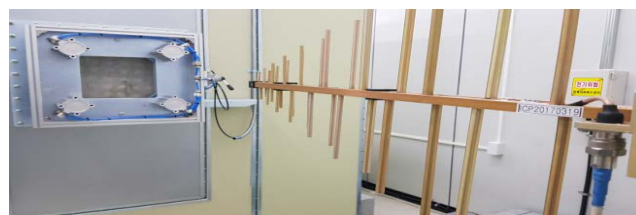
FIGURE 6. SE results with concrete block in shielding room.

room without an absorber, the received signal deviates by as much as 33.4 dB. On the other hand, in the shielding room with an absorber, the received signal has a maximum deviation of 9.9 dB. By reducing the resonance effect inside the shielding room, the absorber therefore decreases the maximum deviation of the measured values [9], [10]. In addition, the difference in polarization also decreased by about 70%, when the absorber was installed.

C. ANALYSIS OF SE AFFECTED BY FIXTURE COMPOSITION SUBSTANCE

1) METALLIC FIXTURE FOR CONCRETE BLOCK

The fixture used to hold the concrete block in position is constructed of metal, as shown in Fig. 7. The metallic fixture is configured as follows. The fixture consists of a square frame, which firmly holds the concrete block in position in the



(a) installed metallic fixture



(b) removed metallic fixture

FIGURE 7. Effects of the metallic fixture on electromagnetic waves.

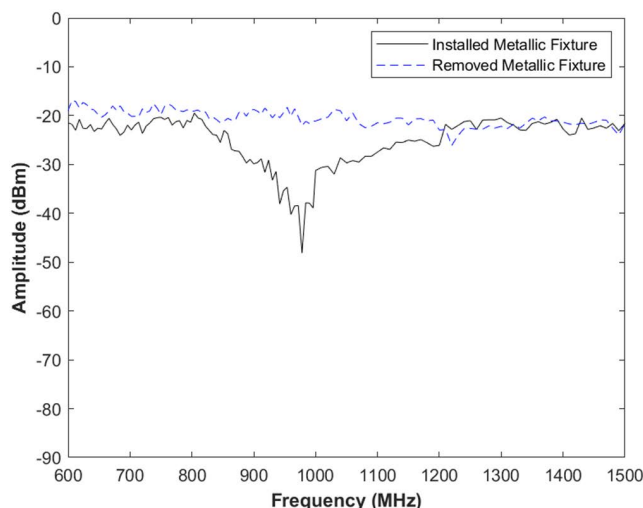


FIGURE 8. Dependence of the measurement results on the installation of the metallic fixture.

wall. A narrow gap exists between the concrete block and the wall, and a gasket is installed at the corners of this aperture.

In this experiment, the effect of the metallic fixture was measured without the concrete block. The transmission signal is a CW signal of 20 dBm in the frequency range of 600 MHz to 1.5 GHz. As shown in Fig. 8, the amplitude of the signal varies depending on whether the metallic fixture is installed. Because the metallic fixture reduces the dynamic range performance of the SE measurement, the SE of a concrete block with a high SE may not be accurately measured.

2) BAKELITE FIXTURE FOR CONCRETE BLOCK

A new fixture was constructed for the concrete block with the major components consisting of Bakelite (synthetic resin) to compensate for the problems with the metallic fixture, as shown in Fig. 9. Although metals were excluded from the new fixture as much as possible, the bolts, pillars, and

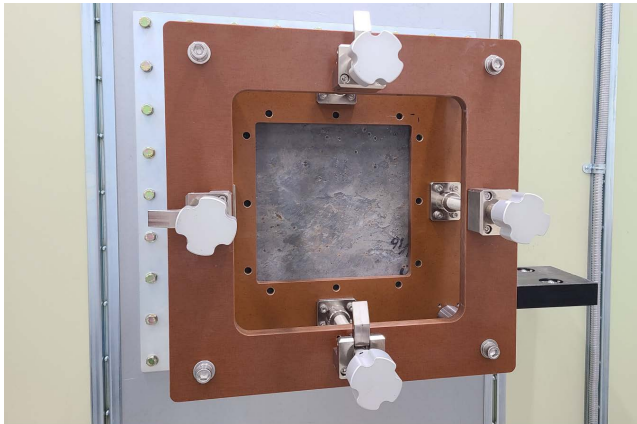


FIGURE 9. Bakelite fixture to hold the concrete block.

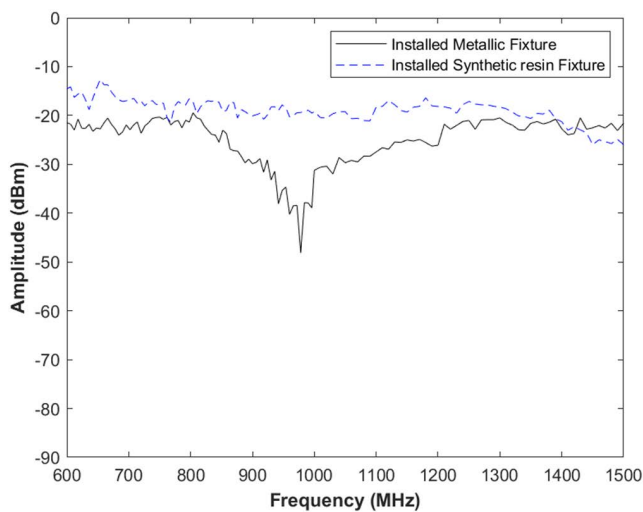


FIGURE 10. Comparison of measurement results between metallic & Bakelite fixture.

supports still contained metal. These metal parts were necessary to support the weight of the concrete block, which varied from 40 to 50 kg.

The measurement results of the signal received for each of the two different concrete block fixtures are shown in Fig. 10. In the case of Bakelite, the electromagnetic wave attenuation band has disappeared. Therefore, the use of Bakelite changes the electromagnetic properties by reducing the attenuation and shifting the attenuation band. Consequently, measurements in bands from 600 MHz to 1.5 GHz were conducted using the Bakelite fixture to hold the concrete blocks in position in the SE measurement system.

D. COMPARING MEASUREMENTS OF SHIELDING EFFECTIVENESS USING ASTM D 4935

The proposed measurement system was validated with the standard ASTM D 4935, which is a method for testing the SE of planar materials [7], [8]. For this comparison, the concrete block was replaced with two types of shielding sheets and measurements were carried out in the frequency range

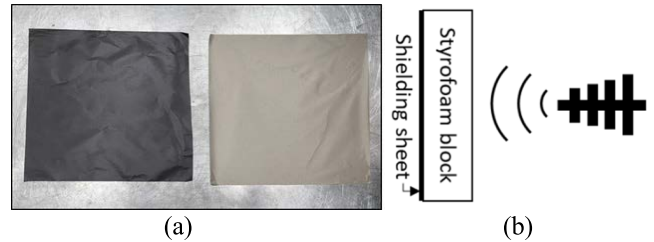


FIGURE 11. Photographic image of the shielding sheets: (a) carbon-coated sheet (left) and normal sheet (right); (b) experimental configuration with Styrofoam block.

of 600 MHz to 1.5 GHz. Both of the shielding sheets were plated with copper and nickel, but only one of these sheets was coated with an additional layer consisting of carbon. Because a thin shielding sheet cannot be installed directly in the block fixture, the shielding sheets were attached to a Styrofoam block of the same size as the concrete block, as shown in Fig. 11 (b).

The SE measurement results obtained with the two shielding sheets are shown in Fig. 12 (the carbon coated shielding sheet in Fig. 12 (a) and the normal shielding sheet in Fig. 12 (b)). Similar curves were recorded for both of the sheets but the SE of the proposed fixture measurement system is higher than that of the conventional ASTM D 4935 system.

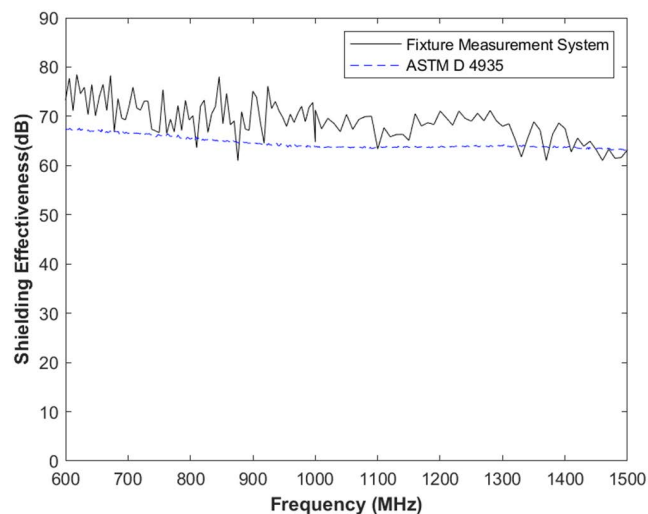
III. VALIDATION OF PROPOSED MEASUREMENT SYSTEM

A. SE MEASUREMENT SYSTEM USING METAL COVER

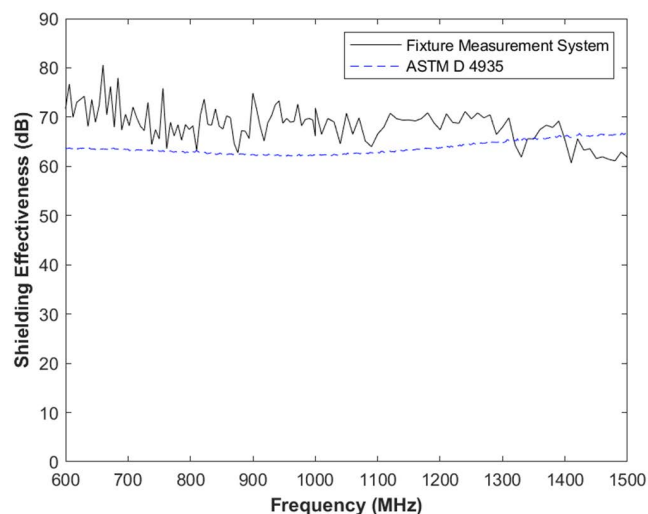
1) ELECTROMAGNETIC WAVE PENETRATION THROUGH THE SIDE SURFACE OF THE CONCRETE BLOCK FOR SIMULATION ANALYSIS

The proposed measurement system was found to be unable to measure SE of more than about 40 dB, the SE value that typically prevailed regardless of whether additional metallic materials were added to the concrete mix to increase the measured SE value [15], [16], [17], [18]. This problem was analyzed as being caused by electromagnetic waves entering via the side surface, whose path is shorter than the path followed by entering through the front of the concrete block. In particular, an increase in the SE of concrete is expected to strengthen the effect of electromagnetic waves incident from the side. The electromagnetic waves were simulated to analyze the problem. The simulation for electromagnetic wave analysis was conducted by building two models of the experimental environment: the first involved a concrete block and the second a concrete block with a metal cover, as shown in Fig. 13.

The simulation was performed by using an incident planar wave with a frequency of 1 GHz. The size of the shielding room was set to PEC of $2.5 \times 2.5 \times 2.5 \text{ m}^3$. The concrete block was $0.3 \times 0.3 \times 0.2 \text{ m}^3$ in size. In the case of the shielding concrete, the following settings were used: dielectric constant of 7 F/m, electrical conductivity of 1 S/m, and loss tangent of 2.57 (@ 1 GHz). The settings for general concrete were: dielectric constant of 7 F/m, electrical conductivity



(a) Carbon-coating shielding sheet



(b) Normal shielding sheet

FIGURE 12. Comparison of SE results of the proposed measurement system with those of the ASTM D 4935 method for the different shielding sheet.

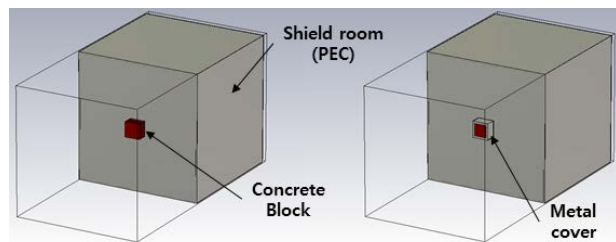


FIGURE 13. Modeling for SE simulation of concrete block.

of 5.56×10^{-2} S/m, and loss tangent of 0.13 (@ 1 GHz). Analysis of the penetration of the side of the concrete by electromagnetic waves was conducted by running the simulation without a fixture. The tool used in the simulation is CST Studio.

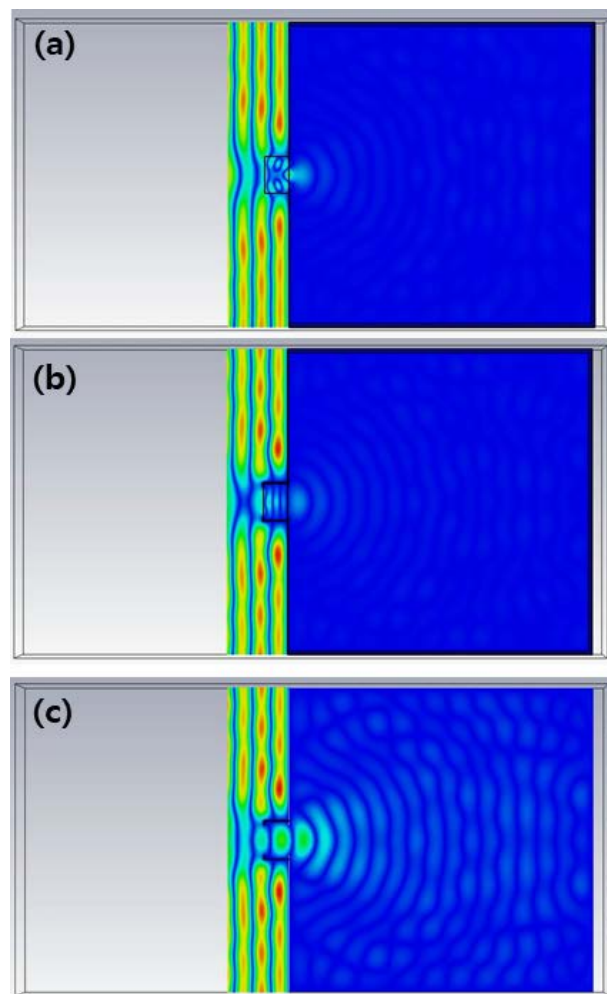


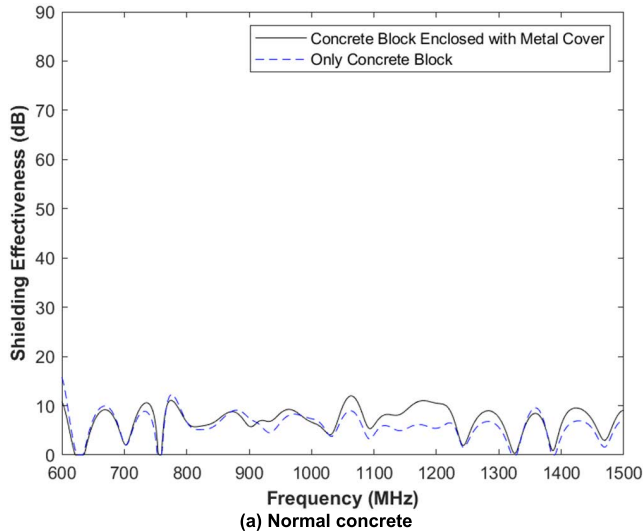
FIGURE 14. Simulation result of plane wave monitor in shielding room with metal cover and concrete block: (a) concrete block, (b) concrete block with metal cover, and (c) only metal cover.

In Fig. 14 (a), because the side is not shielded, electromagnetic wave penetration takes place through shorter path. In the presence of the metal cover, it seems that electromagnetic waves are incident on the front, as shown in the simulation results in Figs. 14 (b) and (c).

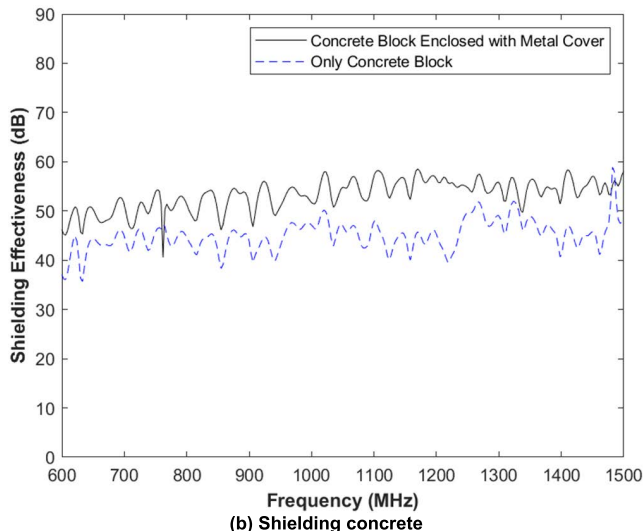
The simulated SE of the shielding concrete block in this environment is shown in Fig. 18. Shielding the side surface with a metal cover can be expected to increase the SE compared with using no metal cover. On the other hand, the simulation result of the normal concrete block reveals low SE, as shown in Fig. 15, where a metal cover has no beneficial effect on the normal concrete block. Accordingly, the metal cover is concluded to make a valid contribution to the SE of the high-performance shielding concrete block.

2) USE OF METAL COVER OPTIMIZED TO MEASURE SE

The metal cover was designed to surround the sides of the concrete block such that a margin of 0.1 to 0.3 mm existed between the cover and the block. Taking into account the unevenness of the surface of the concrete block, a gasket was



(a) Normal concrete



(b) Shielding concrete

FIGURE 15. SE simulation results for concrete blocks with and without a metal cover.

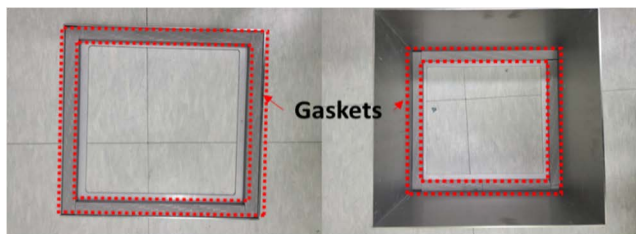


FIGURE 16. Metal cover for shielding side surface of concrete block.

installed to compensate for the gap between the metal cover and the block. The position of the gasket is shown in Fig. 16.

A metal cover was fitted to both sides of the concrete block, after which the opening between the sides of the two metal covers was sealed with copper tape, as shown in Fig. 17. This was intended to act as a shield to prevent electromagnetic waves from penetrating through the slit.



FIGURE 17. Copper tape sealing the gap between the upper and lower metallic covers.

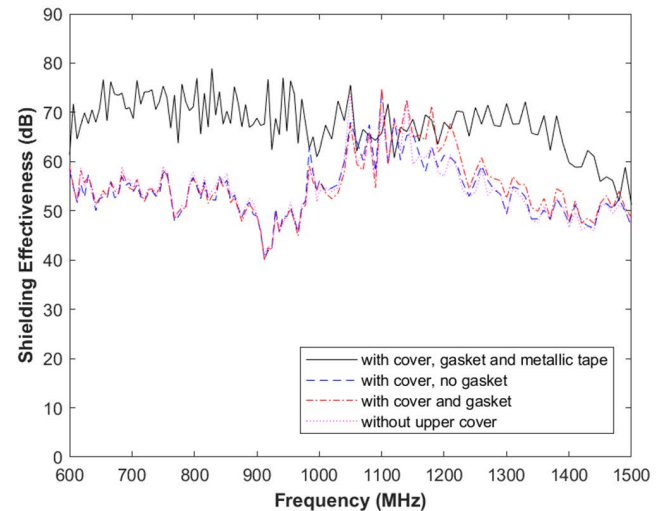
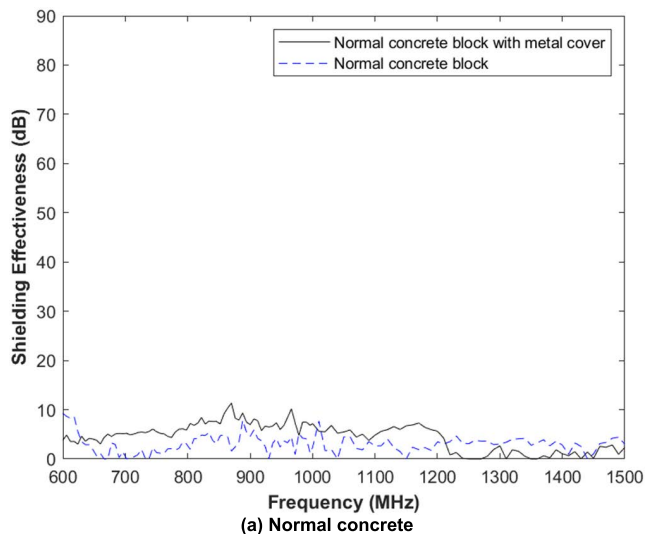


FIGURE 18. SE measurement results to determine the effect of the gaps between the metallic cover and concrete block.

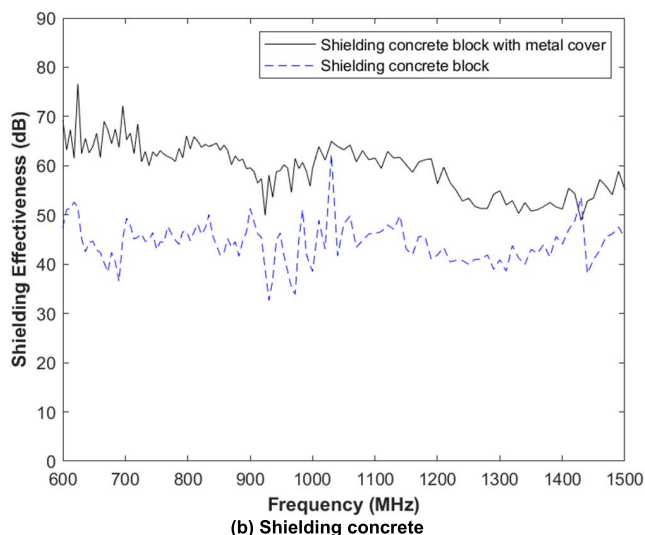
The effects of the upper cover, gasket, and copper tape were compared by measuring the SE by removing each of these conditions. In addition, a high-performance shielding concrete block was used to verify its effect. The results are shown in Fig. 18. The highest SE was measured when the metal covers, copper tape and gaskets were all used. On the other hand, in the absence of any of the metal covers, gasket, or upper cover, the SE was low [19], [20]. However, the higher the SE, the greater the error becomes, even with weak electromagnetic waves penetrating through small gaps.

3) SE RESULT USING THE PROPOSED MEASUREMENT SYSTEM

Experiments were conducted to measure the SE with the metal cover and these results were compared with the simulation results. Shielding concrete blocks with normal and high SE values were measured to have SE levels, which are similar to those in the simulation. These shielding blocks contained metal slag (generated as an industrial by-product) as the shielding material incorporated in the concrete. Metal slag possesses high conductivity and hardness, and has both shielding properties and architectural properties. The compressive strength of concrete is 24 MPa on the 7th day and 38 MPa on the 28th day. The slump and air content of



(a) Normal concrete



(b) Shielding concrete

FIGURE 19. Results of SE measurements of concrete blocks.

concrete are 210 mm and 3.5%, respectively. The diameter and strength of the rebars are 10 mm and 400 MPa, respectively. The covering depth is 30 mm.

As shown in Fig. 19 (a), the SE of ordinary concrete is not affected by the metal cover. On the other hand, as shown in Fig. 19 (b), the shielding concrete block had low SE without the metal cover. The SE of the shielding concrete block with and without the metal cover differed by about 10 dB across all frequency bands.

The experimental SE results for the concrete block are similar to the simulation results. Therefore, measurement of the SE with the metal cover may yield more accurate results. This approach is related to the method that was used to calculate the SE using (3), as described above. The reference signal is measured only with the metal cover, and the received signal is measured by positioning the concrete block inside the metal cover. In both cases, the SE is calculated by (3). This approach made it possible to measure the SE by reducing

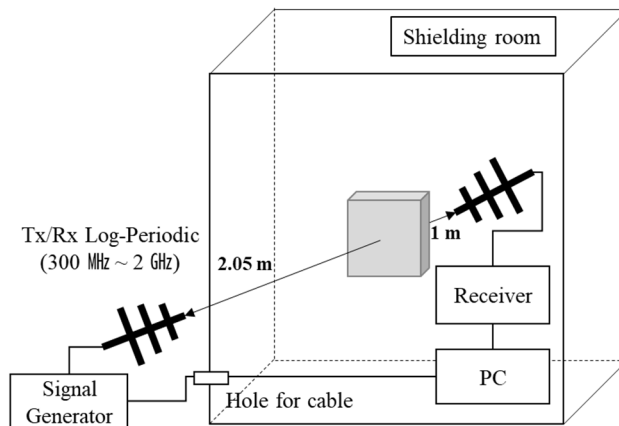


FIGURE 20. Configuration of SE measurement system with concrete block.

the effects of the experimental environment. The results of the proposed measurement system were verified to be more accurate.

B. CONFIGURATION OF SE MEASUREMENT SYSTEM FOR SHIELDING ROOM

1) CONCRETE BLOCK

The SE of the concrete block was measured by using the proposed measurement system. The size of the concrete block was 300(W) × 300(L) × 200(T) mm³, and the block was inserted into an aperture (sized 250 × 250 mm²) in the wall of the shielding room. The concrete block was designed larger than the aperture to attach it to the wall of the shielding room without passing through the aperture. The SE was measured in the frequency range of 600 MHz to 1.5 GHz. The experimental configuration for the measurements is shown in Fig. 20.

The experimental configuration was referenced by the MIL-STD-188-125-1 standard. The distance between the transmission and reception antenna was 3.05 m without including the thickness of the concrete block. The reference value (V_{ref}) was determined by measuring the SE of the metal cover without the concrete block. The received value (V_{rev}) was measured after positioning the concrete block in the metal cover. The SE was calculated by (3). The actual environment is shown in Fig. 21.

2) CONCRETE WALL

The system configuration for the second stage of the SE measurement is shown in Fig. 22. A concrete wall (2.2 × 2.2 × 0.2 m³) was installed in a square aperture (2 × 2 m²) that was created in the sidewall of an anechoic room. The concrete wall was constructed using metal frames as a part of the mold. This metal frame, which is similar to a metal cover, prevents electromagnetic waves from penetrating sideways. The concrete wall was reinforced at intervals of 250 mm such that it resembled the concrete block as closely as possible. The diameter of the reinforcement was 10 mm. The measurement system was designed to be similar to the concrete block



FIGURE 21. Environment for testing the SE of the concrete block.

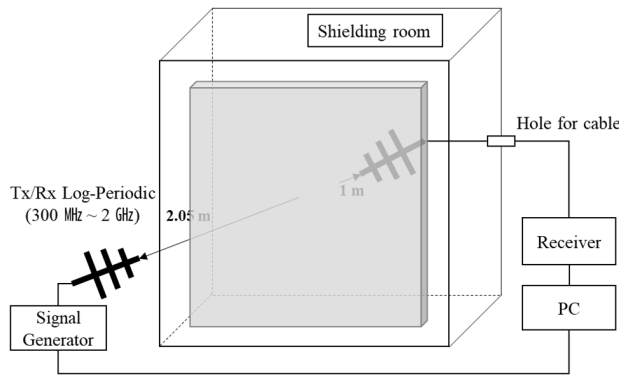


FIGURE 22. Configuration of SE measurement system with concrete wall.

fixture. The reference value (V_{ref}) was measured without the concrete wall, and the received value (V_{rev}) was measured after installing the concrete wall in the shielding room. The SE was also calculated by (3).

The concrete wall was fitted with a gasket and swung into position in the aperture using a pneumatic machine. This ensured that the concrete wall was positioned tightly in the aperture in the outer wall of the anechoic chamber.

3) CONCRETE STRUCTURE

The concrete structure used as the anechoic room had the same enclosure as a conventional shielding room except for the thickness of the walls. Therefore, the SE was measured with the standard MIL-STD-188-125-1 method rather than with the ASTM D 4953 method. The size of the concrete structure was $2.9 \times 3.4 \times 2.9 \text{ m}^3$. The wall thickness of the structure was 0.2 m. Reinforcement in the concrete structure was arranged at intervals of 250 mm to ensure the structure was similar to that of the concrete block. The diameter of the reinforcement bars was 10 mm. The measurement system was configured as shown in Fig. 24. With this configuration, the reference value (V_{ref}) was measured across the same distance in empty space. The received value (V_{rev}) was measured by placing the measurement system inside the concrete structure. The SE was calculated by (3).

The actual concrete structure that was constructed as the measurement environment is shown in Fig. 25, which shows



FIGURE 23. Construction of the anechoic room for testing the concrete wall.

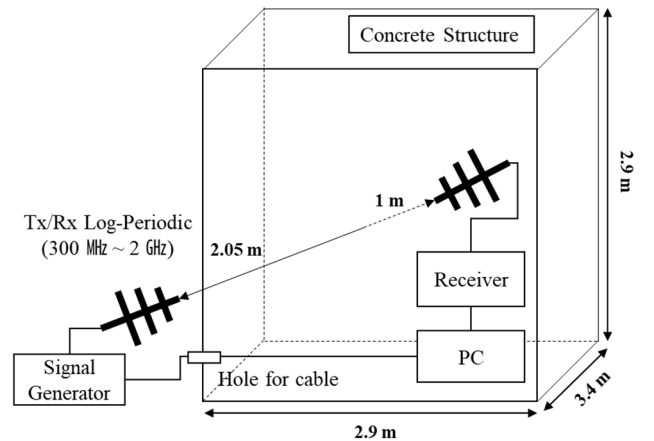


FIGURE 24. Configuration of SE measurement system for measurements in a concrete structure.

the shielding door that was installed to enter the structure. This shielding door, with an SE of 80 dB or more, was designed so as not to affect the SE measurement of the concrete structure. The door is positioned on the rear side of the anechoic room, opposite the shielding wall, to enable the SE of only the concrete to be measured.

IV. RESULTS OF SE MEASUREMENTS

The results of 6 samples were compared by measuring the SE of concrete walls, blocks, and structures using normal and shielding concrete. The transmission output power is 20 dBm, and the frequency range for transmission and reception is 600 MHz to 1.5 GHz. The transmission and reception antennas are log-periodic antennas for frequencies from 300 MHz to 2 GHz.

The results of the SE measurement of normal concrete are shown in Fig. 26, which shows that the SE measurements of

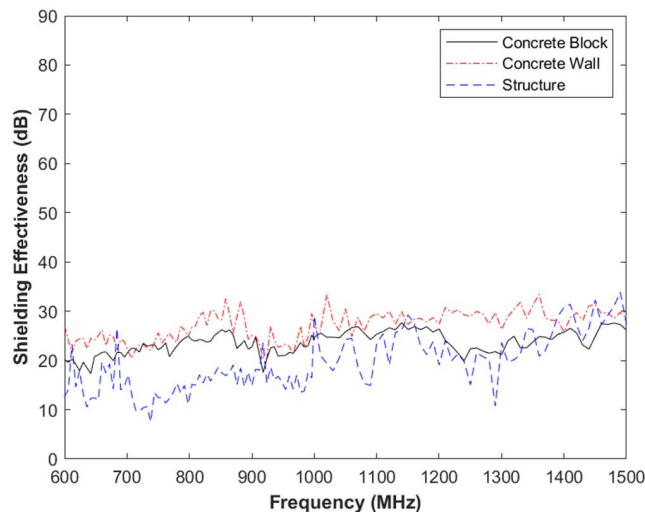


FIGURE 25. Concrete structure showing the shielding door in the rear side of the concrete structure that forms the SE test environment.

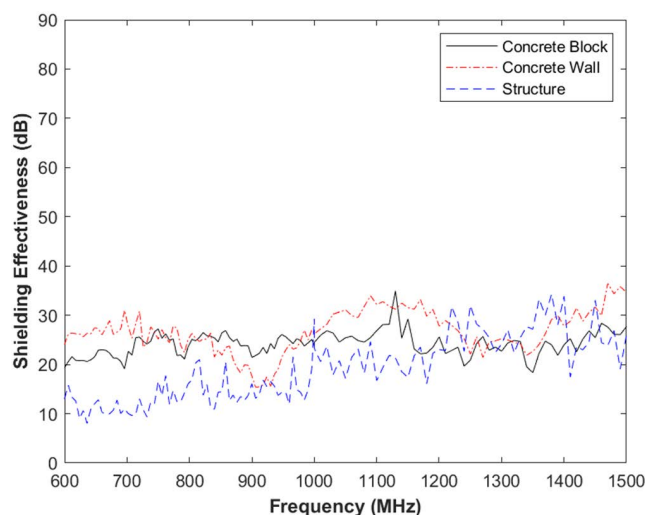
the concrete block, wall, and structure were similar regardless of the polarization. Although the results were generally similar across all frequency bands, but a large difference in SE occurs at 800 MHz or less. The different environments and measurement systems in Figs. 21, 23, and 25 would be expected not to produce exactly the same SE results.

The SE measurement results for the shielding concrete are shown in Fig. 27. These results confirm that shielding concrete containing conductive materials has higher SE than normal concrete. In addition, the measurement results for the three structures are similar across the entire frequency band.

A comparison of Figs. 26 and 27 shows that the SE results for the three normal concrete structures (block, wall, and structure) deviate to a larger extent than the SE results of the shielding concrete. In the case of structures with low SE such as normal concrete, the deviation would be expected to be large due to the effects of the composition and homogeneity of the concrete, and the environment. On the other hand, for structures with high SE such as shielding concrete, the deviation would be expected to be low as the dominant effect in materials with high shielding properties. The SE results of the



(a) Horizontal polarization



(b) Vertical polarization.

FIGURE 26. Test results for normal concrete with concrete block, concrete wall, and structure.

two types of concrete have similar values irrespective of the deviations. Therefore, when shielding concrete is developed, the SE of concrete blocks would be expected to be similar to that of walls and structures.

On the other hand, the time required and cost incurred to manufacture concrete blocks, walls, and structures differ considerably. Concrete blocks require a minimum of two weeks to manufacture and are inexpensive. In contrast, manufacturing a concrete wall requires more than a month and is costly with additional transportation costs. A structure takes more than two months to build, is highly expensive, and is also impossible to build without a construction expert. When shielding concrete is developed, the proposed measurement system using concrete blocks can achieve significant time and cost savings. In addition, high-accuracy SE measurement results could be expected to be obtained.

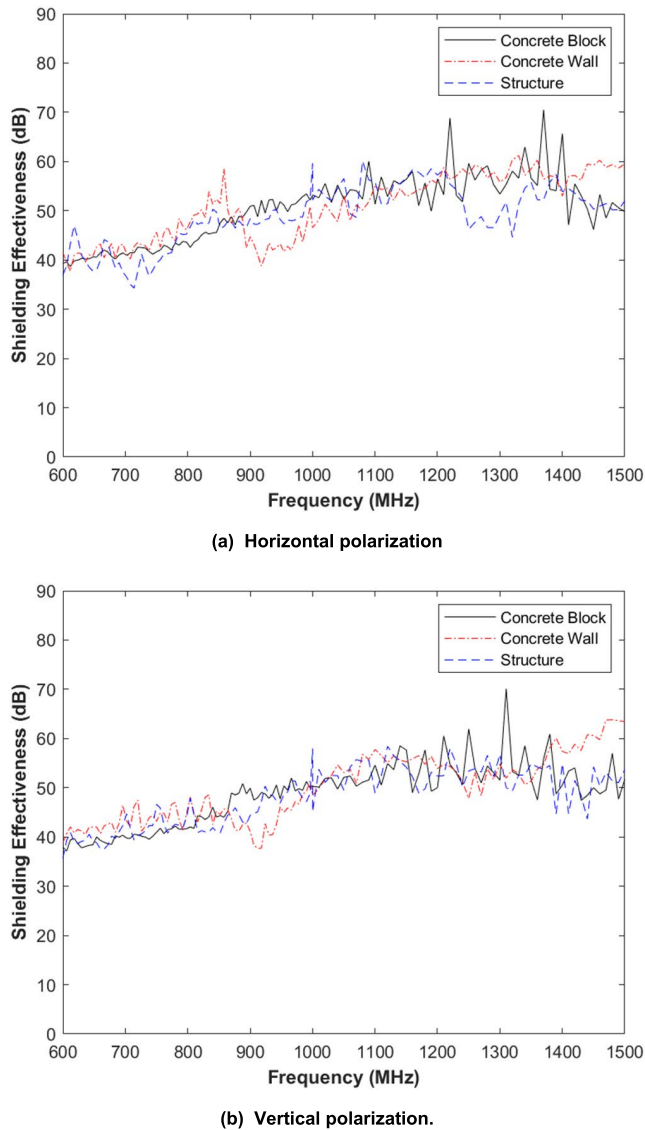


FIGURE 27. Test results for shielding concrete with concrete block, concrete wall, and structure.

V. CONCLUSION

The proposed method was started to measure the shielding effectiveness with the same sample for ASTM D 4935 method. And this measurement method applicable to concrete blocks was proposed by modifying the conventional standard method, MIL-STD-188-125-1. Therefore, the methods that were used to measure the SE of concrete blocks, walls, and structures are similar, and thus can be intuitively and easily understood. However, the application of the structure measurement method to concrete blocks proved to be problematic, and led us to propose a method to solve this problem. To verify the accuracy of the proposed method, we have measured and analyzed concrete blocks, walls, and structures produced with the same material.

Constructing a structure or a large sample is expensive and time-consuming and moreover requires space. In addition,

building structures require the expertise of construction professionals and additional tasks such as industrial safety, structural analysis and so on. However, by using the proposed method, specialist expertise is not required to produce concrete blocks. And small concrete blocks allow a laboratory to quickly manufacture and test different combinations of concrete mixture. Moreover, the use of the proposed optimization method has resulted in more accurate SE measurements. Also, the proposed measurement system might offer a powerful method for developing shielding concrete.

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