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RESEARCH

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Evaluation of Electromagnetic Pulse Shielding Performance of Carbon Fiber-Mixed Cement Paste

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Abstract

This study investigated the physical properties and electromagnetic pulse (EMP) shielding performance of cement paste containing small-diameter carbon fibers to develop an EMP-shielding cement. Small-diameter carbon fibers were used as a cement admixture because the powders were approximately 100 µm in length and were visually powder-shaped. As a result of the experiment, it was indicated that ordinary Portland cement do not have shielding performance. However, cement paste with 5% carbon fibers showed effectiveness in compressive strength and EMP shielding. However, the shielding performance did not increase when the cement contained more than 5% carbon fibers. Furthermore, a review of the EMP shielding performance relative to the thickness of the specimen showed that the plain cement without small-diameter carbon fibers did not increase the shielding performance with an increase in thickness, but the shielding performance of the specimens with small-diameter carbon fibers increased with an increase in thickness. Therefore, it was more effective to increase the thickness of the cement containing 5% carbon fibers rather than increasing the carbon fiber content.

Keywords: cement, EMP shielding, milled carbon fiber, concrete

1 Introduction

North and South Korea are neighboring countries with a complicated recent history, and it has been reported that North Korea owns nuclear weapons. Since the first nuclear test in 2006, North Korea has conducted more than five nuclear tests, and the associated national security issues have drawn global attention (Chun, 2016). Nuclear weapons generally explode in the air and generate heat, energy, and radiation, but those developed by North Korea are modified nuclear weapons that generate a high-altitude electromagnetic pulse (HEMP), supposedly meant to paralyze national infrastructure, such as power grids, communication networks, and electronic equipment (Lee, 2013). In response, nationally critical facilities in South Korea have, or are building, EMP shielding rooms. Existing shielding rooms are composed of enclosed conductor compartments inside the structures, as shown in Fig. 1 (Kim, 2013). The shielding plates are constructed through the assembly or welding of metal plates with excellent conductivity (Chung, 2001; Kim & Yi, 2015). However, this method has drawbacks, including low economic efficiency due to high construction costs, difficulty in processing, and the possibility of the ingress of EMP at the welded and bolted joints (Chen & Yao, 2004; Dai et al., 2010). Additional research is required to solve these issues, but research on the development of shielding methods and materials is currently insufficient.

To solve the abovementioned problems by imparting EMP shielding performance to cement, this study evaluated the shielding performance of ordinary Portland cement (OPC), one of the most commonly used cements

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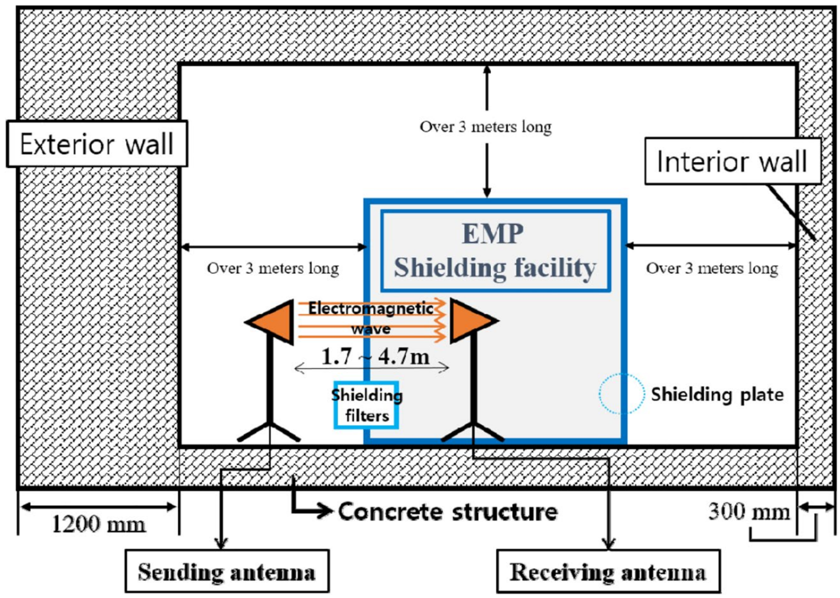


Fig. 1 Concept of a typical EMP shielding room.

in construction, mixed with small-diameter milled carbon fiber (MCF). MCF can be produced with special plastics or high-strength plastics, but the components of MCF are carbon-based. EMP shielding methods often use metals or carbons, but metals are not suitable for use as cement admixtures because they have a high specific gravity and suffer from the risk of corrosion (Park et al., 2021; Yuan et al., 2021a, 2021b). Therefore, this study selected MCF as a cement admixture and aimed to present basic data for developing a cement with EMP shielding performance.

2 Experiment Overview and Method

2.1 Experiment Overview

EMP shielding is generally achieved by considering three principles: return loss, transmission loss, and multiple reflection loss. First, return loss is caused by the impedance of a shielding material to radio waves passing through the surface air layer of the material (Dou et al., 2007; Xu & Hao, 2014). Second, transmission loss occurs when electromagnetic waves are converted to heat due to resistive loss while passing through a shielding material, typically consisting of carbon-based or magnetic materials. Third, multiple reflection loss is caused when electromagnetic waves are reflected back into the shielding material or in different directions (also known as EMP scattering) because they cannot penetrate through the shielding. Among these three losses, the most effective is multiple reflection loss, which shows greater EMP shielding effectiveness when the conductive material content is higher (Choi et al., 2019; Jin et al., 2014; Kim & Lee, 2008). The decibel (dB) unit is used to measure the EMP shielding performance.

Table 1 lists the experimental factors and their levels. The specimens were fabricated with cement paste, and the inherent performance of the cement was evaluated. In addition, to evaluate the small-diameter carbon fibers and EMP shielding performance, fiber-mixing ratios of 1, 5, 10, and 20% relative to cement were tested to determine the optimal carbon fiber admixture. Table 2 shows

Table 1 Experimental design.

Item	Factor		
Compressive strength, EMP shielding performance evaluation	W/C: 40%		
	Series 1	MCF mixing amount (%)	1, 5, 10, and 20
		Thickness (mm)	100
	Series 2	MCF mixing amount (%)	5
		Thickness (mm)	100, 200, and 300

Table 2 Mixing design of cement paste.

Specimen	W/B	Unit weight (kg/m^3)		
		Water	Cement	MCF (cement * %)
Plain	40%	720	1800	0
MCF 1				1
MCF 5				5
MCF 10				10
MCF 15				15
MCF 20				20

Table 3 Characteristics of milled carbon fiber.

Characteristic	
Filament diameter (μm)	7
Bulk density (g/ml)	0.22—0.28
Tensile strength (MPa)	3150
Young's modulus (GPa)	210
Elongation at break (%)	1.1–1.4
Carbon content (%)	> 90
Sizing content (%)	0.5–1
Mean fiber length (μm)	100

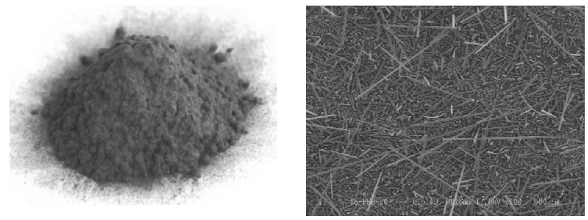


Fig. 2 Appearance of milled carbon fiber.

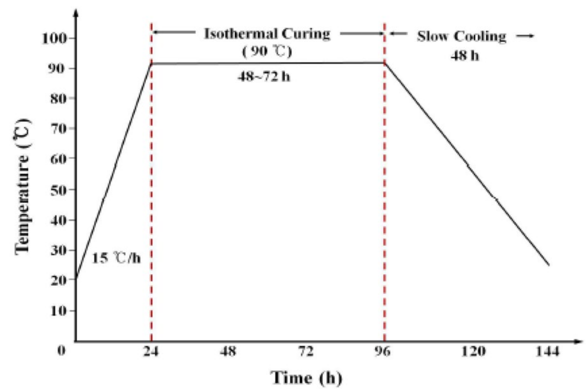


Fig. 3 Curing temperature and time.

the mixing designs of the pastes used in this experiment. Furthermore, after reviewing the EMP shielding performance of a cement layer with a thickness of 100 mm to determine the optimal MCF mixing amount, the EMP shielding performance was evaluated based on the thickness of the concrete mix with the optimal MCF admixture. The shielding performance was evaluated in a dual-shielded room with thicknesses of 100, 200, and 300 mm.

2.2 Materials and Specimen Fabrication

In this study, Type 1 OPC that complied with KS L 5201 and MCF in the form of fine particles with an average length of 100 μm were used. The MCF length was selected because the maximum size of the carbon fibers that could be pulverized was 100 μm, and it was expected that the best mixing performance could be achieved if cement was mixed with MCF powders. Table 3 lists the characteristics of the MCF. Fig. 2 shows a photograph at the naked eye scale and an X100 photograph magnified using a scanning electron microscope (SEM). MCFs with an average length of 100 μm appear as powders to the naked eye, and a fiber shape is observed when magnified with the SEM equipment.

To measure the shielding performance of varying thickness, cement pastes were produced using casting modes of 300 mm × 300 mm × 100 mm—300 mm. A cement paste with 40% water content (W/C) was mixed with a concrete mixer and poured into a casting mold. Subsequently, 2 h after pouring, steam curing was performed for 7 days according to the heating temperature curve shown in Fig. 3. After steam curing, the specimens were dried in a dryer at 60 °C for 2 weeks. Steam curing and drying were performed to eliminate the effect of moisture as much as possible because moisture in specimens has a significant effect on the EMP shielding performance.

The EMP shielding test method complied with United States (U.S.) military standard MIL-STD-188-125-1. Fig. 4 shows the layout of the EMP shielding test equipment, and Fig. 5 shows the antennas based on the measurement frequency. Different antennas must be used when measuring the EMP shielding performance because each antenna has its own measurement frequency range. Typically, three antennas are used. The measurement ranges of the loop antenna, biconical antenna, and log periodic antenna were 10 kHz–20 MHz, 20 MHz–300 MHz, and 300 MHz–2 GHz, respectively.

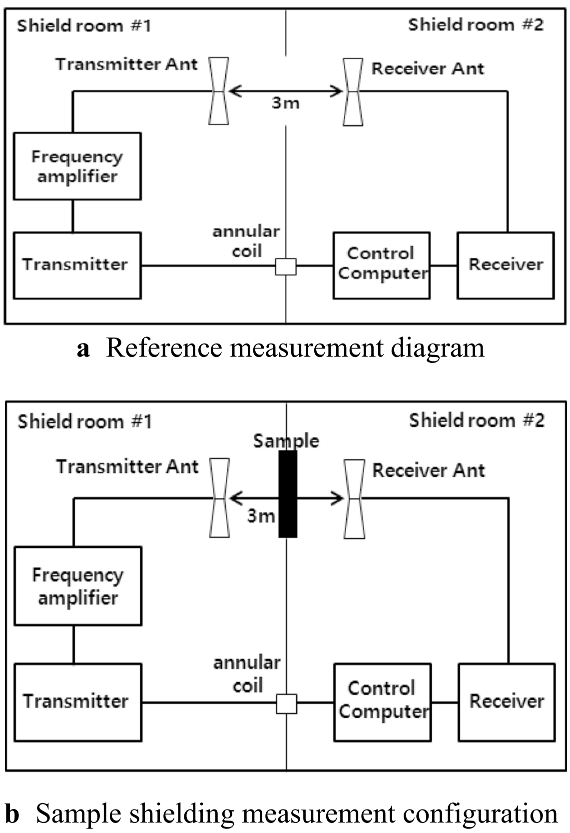


Fig. 4 EMP shield measurement concept.

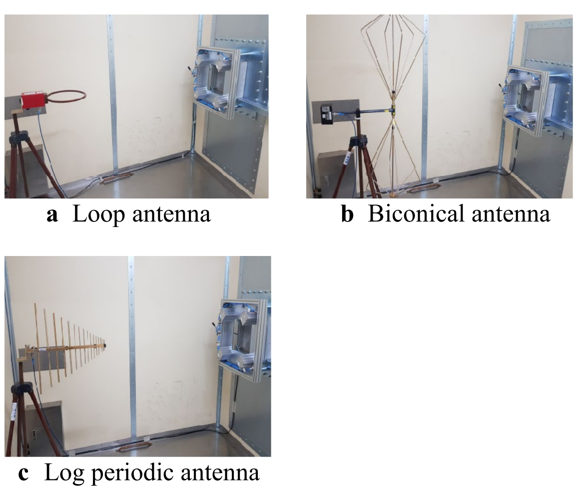


Fig. 5 EMP shield test equipment.

3 Results and Discussion

3.1 Evaluation of Physical Performance of Cement Paste

Fig. 6 shows the results of the flow tests. The flow was

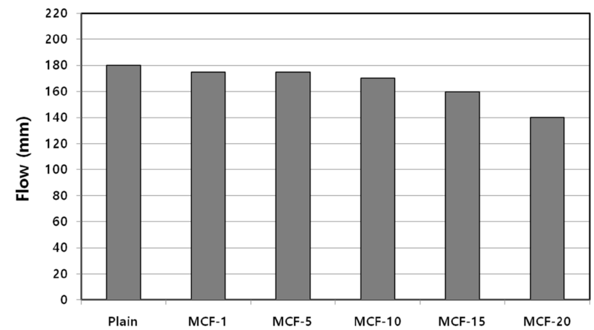


Fig. 6 Results of flow test.

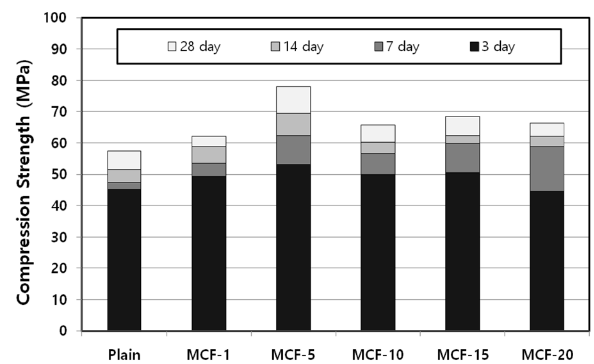
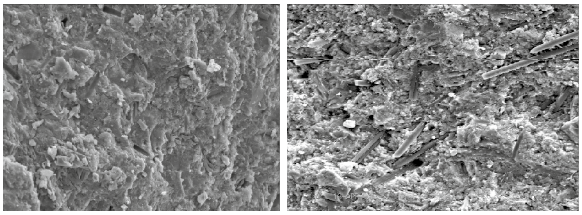


Fig. 7 Result of compressive strength tests.

measured according to KS L 5111. The flow did not change significantly until the MCF mixing amount was 10%. However, the flow decreased rapidly at MCF mixing amounts of 15% or higher. This suggests that, because the MCFs are fine particles with a size of 100 µm or less, the flow decreased as the fine particles of MCF were adsorbed into the mixing water.

Fig. 7 shows the results of the compressive strength measurements. When MCF was mixed with cement, high compressive strengths were observed. Specimen MCF-5 showed the highest compressive strength. However, MCF-10, MCF-15, and MCF-20 showed higher compressive strengths than the plain specimen. Furthermore, the compressive strength of the specimens with an MCF admixture of 10% was lower than that of the specimen with an MCF admixture of 5%; this is because the MCF mixing amount exceeded that of the cement paste, which resulted in lower strength.

Fig. 8 shows the morphologies of the plain and MCF-5 specimens, affording an examination of the distribution of MCFs among the hydrate tissues via the SEM. In the case of the plain specimen, MCF was confirmed to be absent in the specimen, whereas in the MCF-5 specimen, MCFs existed among the hydrates as if they were interconnecting the cement paste tissues. This suggests that



a Plain (X350) **b** MCF (X350)

Fig. 8 Results of SEM analysis.

the compressive strength increased owing to the MCFs interconnecting the cement hydrate tissues; in this case, the tensile strength is also expected to increase.

3.2 Evaluation of EMP Shielding Performance

The final setting time is the time elapsed between the moment the water is added to the cement, and the time when the paste has completely lost its plasticity and has attained sufficient firmness to resist certain definite pressure. Fig. 9 shows the results of the evaluation of the shielding performance according to the MCF mixing amount by frequency band over the frequency range of 0.75−2.0 GHz, in accordance with U.S. MIL-STD-188-125-1. Based on the results of the shielding performance experiment, the plain specimen showed an average shielding performance of 20 dB or less, indicating that there was no shielding, which is consistent with the results in literature. The MCF-5, MCF-10, MCF-15, and MCF-20 specimens exhibited a shielding performance of at least 50 dB. The MCF-5 specimen showed the highest shielding performance of 70 dB at a frequency of 1.3 GHz. The plain and MCF-mixed specimens exhibited a difference of approximately 30 dB or higher in terms of the shielding performance.

Fig. 10 shows the average shielding performance with respect to the MCF admixtures at 0.75–2.0 GHz. The shielding performance measurements did not indicate significant differences in the shielding effectiveness for MCF mixing ratios of 5−20%. Based on these results, 5% was determined to be the optimal admixture of MCF for EMP shielding. In the future, shielding performance needs to be analyzed for MCF mixing amounts ranging from 1 to 5%.

Fig. 11 shows the EMP shielding performance based on the thickness of the plain and MCF-5 specimens. The plain specimens exhibited low shielding performance regardless of the thickness. This suggests that, for cement without a shielding additive, the thickness has no effect on the shielding performance. The MCF-5 specimens showed shielding performances of 40–60 dB, 50–75 dB, and 65–85 dB at thicknesses of 100 mm, 200 mm, and 300 mm, respectively. The thicker material demonstrated a higher shielding performance. It is believed that the inclusion of an MCF admixture with an increase in thickness generated an increase in the time and range of the transmission of the EMP spectrum, thus resulting in higher shielding performance. Furthermore, the shielding performance was analyzed when varying the direction of EMP penetration by generating EMP spectra horizontally (marked as H after the specimen name) and vertically (marked as V after the specimen name). The MCF-5–100 mm, MCF-5–300 mm, and plain specimens did not show any difference in shielding based on the direction of the EMP spectrum. However, the MCF-5–300 mm specimen showed higher shielding effectiveness for the horizontal spectrum. However, this appears to be an experimental error due to the homogeneity of the specimen or the direction of the antenna that generated the EMP spectra.

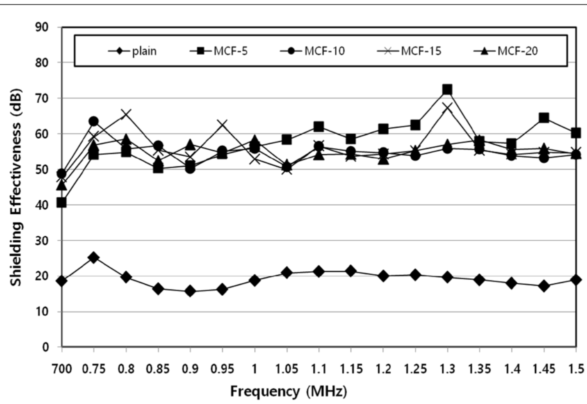


Fig. 9 EMP shielding performance according to MCF content.

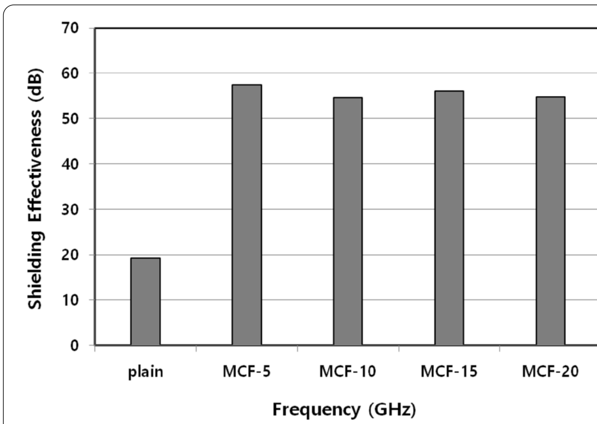


Fig. 10 Average EMP shielding performance.

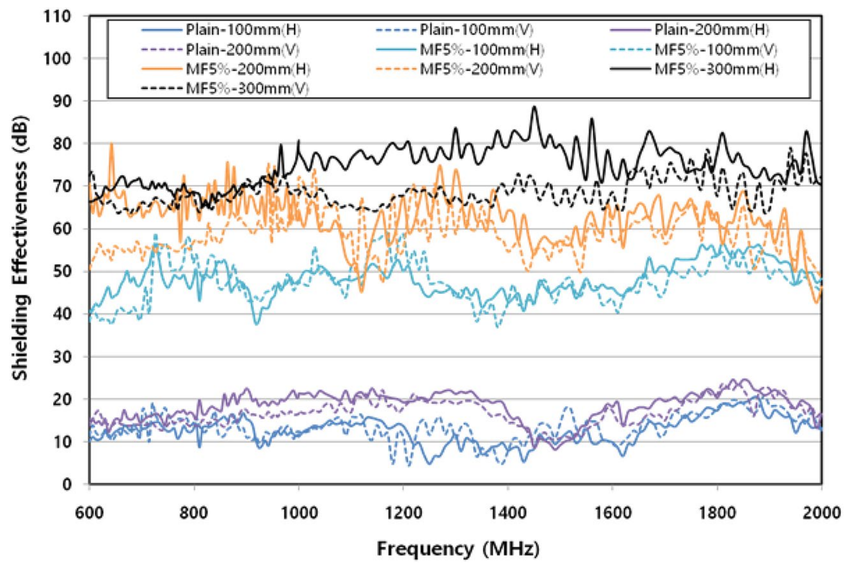


Fig. 11 EMP shielding performance according to thickness.

As shown in Fig. 11, the shielding performance did not improve significantly with larger MCF admixtures at a constant thickness. However, the shielding performance improved with increasing thickness for an MCF content of 5%. This suggests that, when EMP shielding is implemented via MCF addition, increasing the thickness is more effective than increasing the mixing amount.

4 Conclusions

Basic experiments were conducted using MCFs to develop an EMP-shielding concrete, and the following conclusions were obtained:

1. For the MCF-mixed cement, a decrease in flow was observed at an MCF admixture of 15% or higher. This decrease in flow is attributed to the adsorption of the mixing water by the MCFs.
2. The compressive strength increased with the inclusion of MCF. This was likely because the fine MCFs interconnected the tissues of cement paste hydrates, making them stronger. However, when the MCF admixture was higher than 5%, the compressive strength decreased. Thus, the optimal MCF mixing amount was determined to be 5%.
3. The MCF-5, MCF-10, MCF-15, and MCF-20 specimens showed shielding performances of 50 dB or higher in the set frequency range. MCF-5 exhibited the highest shielding effectiveness.
4. Analyses of the EMP shielding performance of specimens with varying thickness showed that the plain specimen did not demonstrate an increase in the EMP shielding effectiveness as the thickness increased. However, the specimens with MCFs exhibited a greater shielding performance as the thickness increased.
5. The optimal MCF mixing amount for increasing the EMP shielding performance is 5%; moreover, increasing the specimen thickness is believed to be most effective for improving EMP shielding.

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Authors' contributions

Each author has made substantial contributions to the conceptualization. TBM; investigation, writing—original draft. HKC; writing—review and editing. Both authors read and approved the final manuscript.

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Availability of data and materials
Some all data, models, or code that support the findings of this study are available from the Corresponding author upon reasonable request.

Declarations

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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