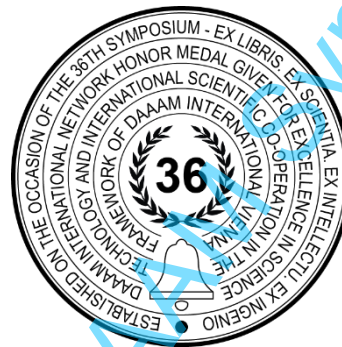


INFLUENCE OF STEEL MICROWAVE RESONATORS ON THE ELECTROMAGNETIC SHIELDING EFFECTIVENESS OF REINFORCED CONCRETE SLAB SPECIMENS

Stanko Colak, Damir Varevac, Ivana Milicevic & Slavko Rupcic



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Abstract

Research on reinforced concrete structural elements with enhanced resistance to electromagnetic (EM) radiation penetration remains insufficiently investigated. In this study, reinforced concrete slab specimens measuring 60×60 cm and 15 cm in thickness were fabricated and experimentally tested. The specimens were reinforced with Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer, with steel cross-shaped microwave resonators embedded beneath the top reinforcement layer. Reference specimens with the same reinforcement configuration but without microwave resonators were also fabricated and tested. The electromagnetic shielding efficiency of the specimens was evaluated over the frequency range from 50 MHz to 1 GHz in order to determine the effectiveness of the embedded microwave resonators in attenuating the transmission of EM waves. The results demonstrated that the reinforced concrete slab specimens incorporating welded wire mesh reinforcement in both the top and bottom reinforcement layers, together with embedded steel microwave resonators beneath the top reinforcement layer, exhibited significantly improved electromagnetic shielding effectiveness compared with the reference specimens. These findings indicate that the embedded steel cross-shaped microwave resonators provide a significant enhancement of the electromagnetic shielding performance of reinforced concrete structural elements.

Keywords: concrete slab; electromagnetic radiation; microwave resonators; transmission coefficient; shielding efficiency.

1. Introduction

Modern society largely depends on the continuous flow of information, which is predominantly transmitted through wireless communication systems. The most common sources of electromagnetic (EM) radiation include Wi-Fi access points, mobile communication networks, radio and television broadcasting systems, as well as low-frequency electromagnetic fields generated by electrical power networks. Electromagnetic radiation is a form of energy that propagates through space as waves travelling at the speed of light (approximately 300,000 km/s in a vacuum). It consists of mutually perpendicular electric and magnetic fields, both of which are perpendicular to the direction of wave propagation. Electromagnetic radiation is generated when a charged particle (e.g., an electron) is accelerated, producing time-varying electric and magnetic fields that propagate through space as electromagnetic waves [1].

One of the major challenges facing modern society is the excessive exposure of the population, particularly children and the elderly, to electromagnetic radiation. A comprehensive review of the available literature indicates that reinforced concrete (RC) structural elements with enhanced resistance to electromagnetic radiation penetration remain insufficiently investigated. Therefore, this study focuses on evaluating the capability of reinforced concrete slab specimens incorporating embedded steel cross-shaped microwave resonators to improve protection against electromagnetic radiation [2].

The improvement of material performance with respect to protection against electromagnetic radiation penetration is commonly evaluated by the electromagnetic shielding efficiency (SE), which is defined as the sum of the attenuation resulting from wave absorption within the shielding material and the attenuation caused by wave reflection at its surfaces.

In general, two principal mechanisms contribute to the attenuation of electromagnetic waves:

- reflection loss occurring at the surface of the shielding material,
- absorption loss occurring during wave propagation through the material [3].

The overall attenuation of electromagnetic waves passing through a shielding material is expressed as the shielding efficiency (SE) and is determined as the sum of the reflection loss (R) and the absorption loss (A). Electromagnetic shielding of a material is defined as the combined amount of electromagnetic radiation reflected by the material and absorbed within the material at a given frequency. Shielding efficiency is generally expressed in decibels (dB).

The electromagnetic shielding efficiency is calculated using the following expression:

$$SE = R + A \quad (1)$$

where:

- SE - electromagnetic shielding efficiency, representing the total amount of electromagnetic radiation prevented from penetrating the tested specimen,
- R - reflection loss, representing the amount of electromagnetic radiation reflected from the surface of the tested specimen,
- A - absorption loss, representing the amount of electromagnetic radiation absorbed by the tested specimen.

The decibel (dB) is a logarithmic unit used to express the ratio of voltage, power, or electromagnetic radiation intensity. Frequency represents the number of oscillations of an electromagnetic wave per second and is measured in hertz (Hz). Since materials do not exhibit identical shielding performance over the entire frequency spectrum, the electromagnetic shielding efficiency is frequency-dependent. Consequently, shielding efficiency is commonly presented graphically by plotting frequency (typically in MHz or GHz) along the horizontal axis and the corresponding shielding efficiency (dB) along the vertical axis [3].

The primary objective of this study was to investigate the potential for enhancing the broadband electromagnetic energy absorption capacity of reinforced concrete structural elements through the incorporation of materials capable of improving protection against electromagnetic radiation. Prior to these tests, a review was conducted of existing research materials that improve the shielding efficiency from EM radiation [4].

For this purpose, reinforced concrete slab specimens reinforced with welded wire mesh and incorporating embedded steel cross-shaped microwave resonators were fabricated. The electromagnetic interference shielding effectiveness (EMI-SE) of these specimens was experimentally evaluated by measuring the transmission of electromagnetic waves. Shielding effectiveness was determined using an Anritsu MS2038C vector network analyzer in combination with a Bicollog antenna, capable of measuring the reflection and transmission of electromagnetic radiation within the frequency range from 50 MHz to 1 GHz.

Future research will investigate the same reinforced concrete slab specimens at higher frequencies using a Hyperlog antenna, which measures the reflection and transmission of electromagnetic radiation into the 0.5–18 GHz frequency range using Hyperlog antennas, alongside flexural/structural testing of the slabs, provides a clear future research trajectory.

2. Materials and experimental methods

Reinforced concrete (RC) slab specimens with plan dimensions of 60×60 cm and a thickness of 15 cm, corresponding to the typical thickness of a reinforced concrete floor slab, were fabricated and experimentally tested to evaluate their resistance to electromagnetic (EM) radiation penetration. A total of four slab specimens were produced. Two specimens incorporated embedded steel cross-shaped microwave resonators, while the remaining two served as reference specimens without microwave resonators [5].

All specimens were reinforced with Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer, representing the reinforcement configuration commonly used in conventional reinforced concrete floor systems. The tested specimens are summarized in Table 1.

Specimen	Description
PP1	reinforced concrete slab specimen ($60 \times 60 \times 15$ cm) reinforced with Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer, incorporating embedded steel cross-shaped microwave resonators
PP2	reinforced concrete slab specimen ($60 \times 60 \times 15$ cm) reinforced with double Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer, incorporating embedded steel cross-shaped microwave resonators
PK1	reinforced concrete slab specimen ($60 \times 60 \times 15$ cm) reinforced with Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer, without microwave resonators (reference specimen)
PK2	reinforced concrete slab specimen ($60 \times 60 \times 15$ cm) reinforced with double Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer, without microwave resonators (reference specimen)

Table 1. Tested reinforced concrete slab specimens

The electromagnetic shielding performance of the specimens was evaluated using an Anritsu MS2038C vector network analyzer (Fig. 1) in combination with a Bicollog antenna operating within the frequency range from 50 MHz to 1 GHz (Fig. 2) [6]. The Anritsu MS2038C is a vector network analyzer capable of performing measurements over the frequency range from 5 kHz to 20 GHz. The experimental setup consisted of two antennas connected to the network analyzer. During testing, the analyzer measured the reflection coefficient S11 and the transmission coefficient S21 of the electromagnetic waves interacting with each tested specimen.



Fig. 1. Anritsu MS2038C vector network analyzer



Fig. 2. Bicol antenna (operating frequency range: 50 MHz–1 GHz)

Specimen PP1 was reinforced with Q335 welded wire mesh in the bottom reinforcement layer. The reinforcement consisted of 8 mm diameter reinforcing bars spaced at 150 mm, providing load-carrying capacity in both orthogonal directions, with identical bar diameters and spacing in each direction. The top reinforcement layer consisted of Q196 welded wire mesh, composed of 5 mm diameter reinforcing bars spaced at 100 mm, also providing bidirectional reinforcement with identical reinforcement characteristics in both directions. In addition, steel cross-shaped microwave resonators were embedded within the top reinforcement layer. A schematic illustration of specimen PP1 is presented in Fig. 3, while Fig. 4 shows the experimental setup used for evaluating the electromagnetic shielding performance of the specimen.

During testing, each reinforced concrete slab specimen was placed on a wooden support frame. The surrounding area was enclosed by an aluminium shielding panel coated with three layers of YSHIELD HSF54 electromagnetic shielding coating. The coating was applied to minimize unwanted reflections from the aluminium panel, thereby ensuring that the majority of the transmitted electromagnetic energy propagated through the tested specimen rather than around it. One antenna was positioned on one side of the specimen and served as the transmitting antenna, while the second antenna was positioned on the opposite side and functioned as the receiving antenna. A controlled electromagnetic signal was emitted towards the specimen. The electromagnetic radiation received by the transmitting antenna after reflection from the specimen represented the reflected electromagnetic radiation, quantified by the reflection coefficients S11 and S22. The electromagnetic radiation detected by the receiving antenna represented the portion of the signal transmitted through the reinforced concrete slab specimen and was quantified by the transmission coefficients S21 and S12. The remaining portion of the incident electromagnetic energy was absorbed within the specimen and is referred to as the absorbed electromagnetic radiation.

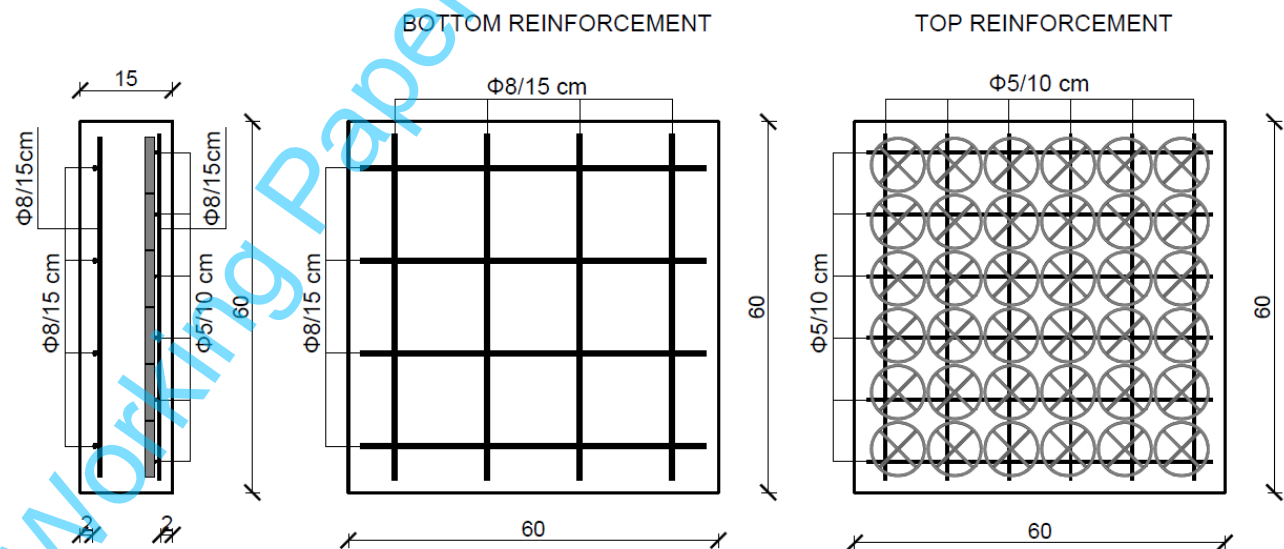


Fig. 3. Schematic illustration of reinforced concrete slab specimen PP1

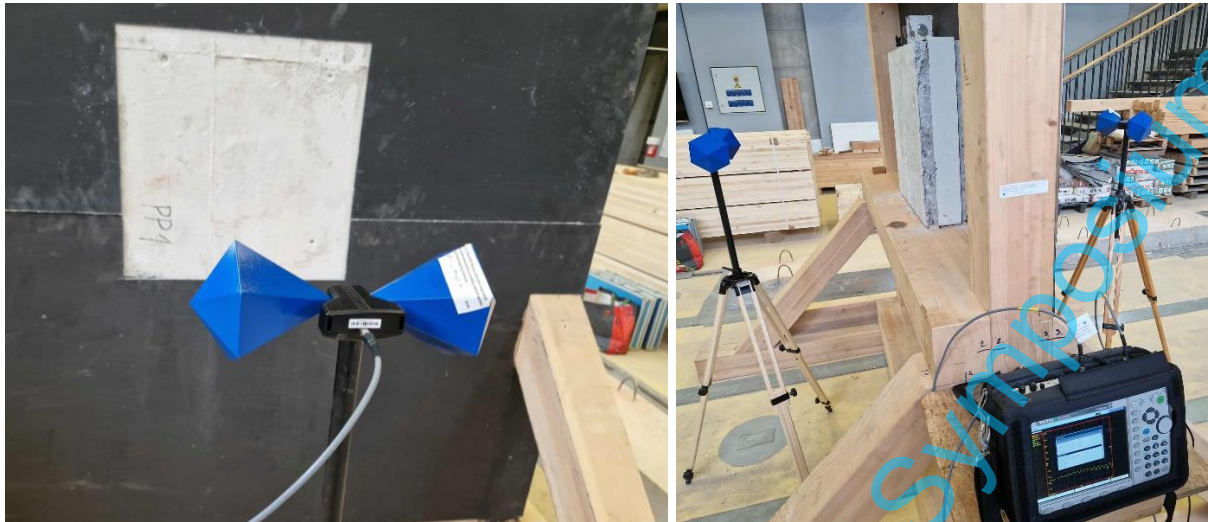


Fig. 4. Experimental setup for electromagnetic shielding measurements of specimen PP1 using the Bicollog antenna

Specimen PP2 was reinforced with double Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer. In addition, steel cross-shaped microwave resonators were embedded within the top reinforcement layer. A schematic illustration of specimen PP2 is presented in Fig. 5, while the experimental setup used to evaluate its electromagnetic shielding performance using the Bicollog antenna is shown in Fig. 6.

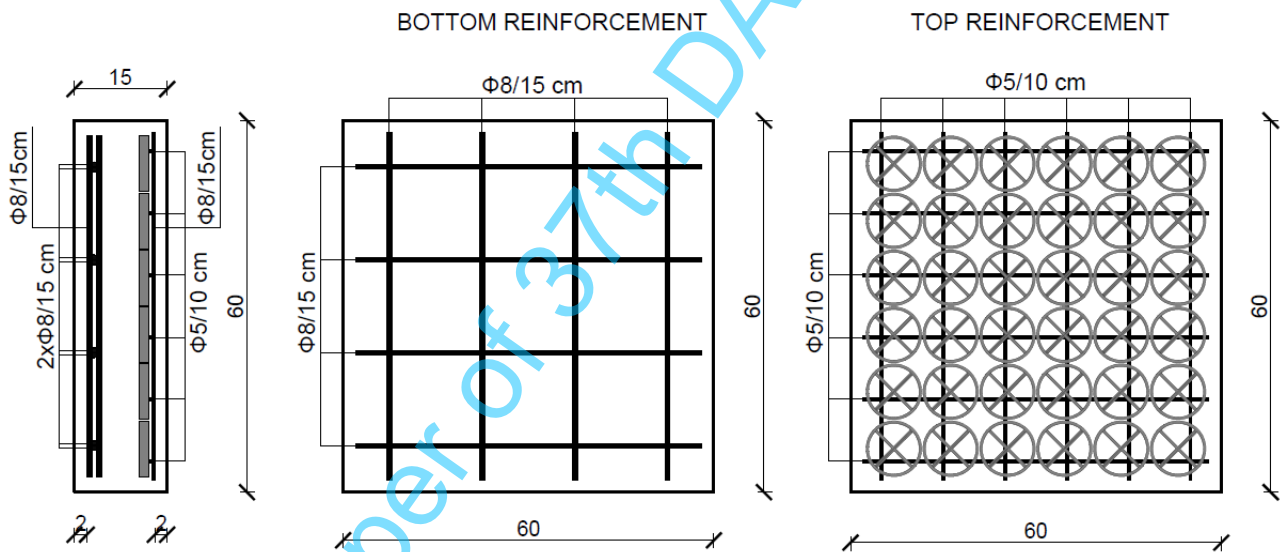


Fig. 5. Schematic illustration of reinforced concrete slab specimen PP2

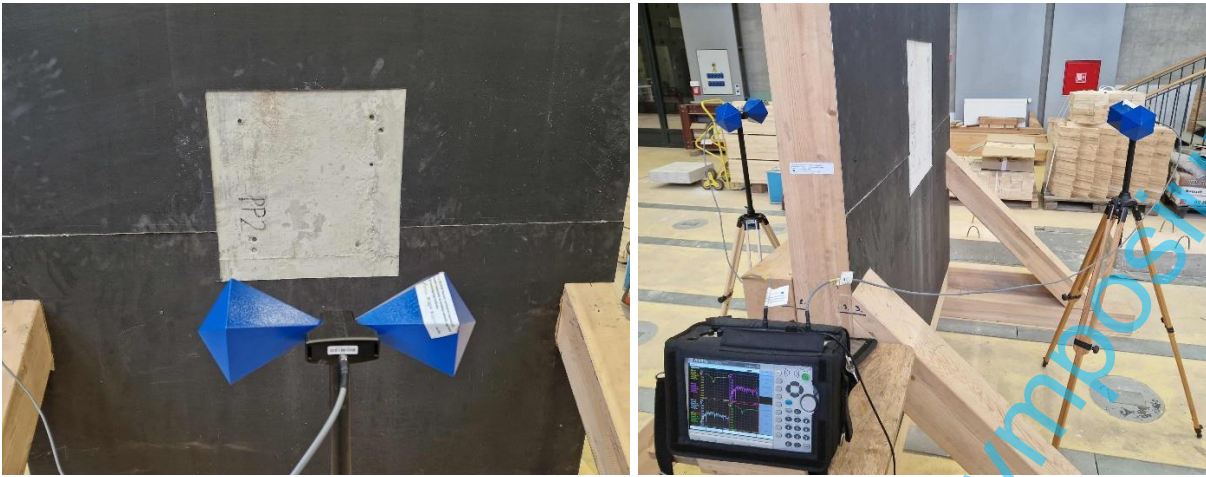


Fig. 6. Experimental setup for electromagnetic shielding measurements of specimen PP2 using the Bicolog antenna

Specimen PK1 was reinforced with Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer. Unlike specimens PP1 and PP2, specimen PK1 did not contain embedded steel cross-shaped microwave resonators and therefore served as a reference specimen. A schematic illustration of specimen PK1 is presented in Fig. 7, while the corresponding experimental setup for electromagnetic shielding measurements using the Bicolog antenna is shown in Fig. 8.

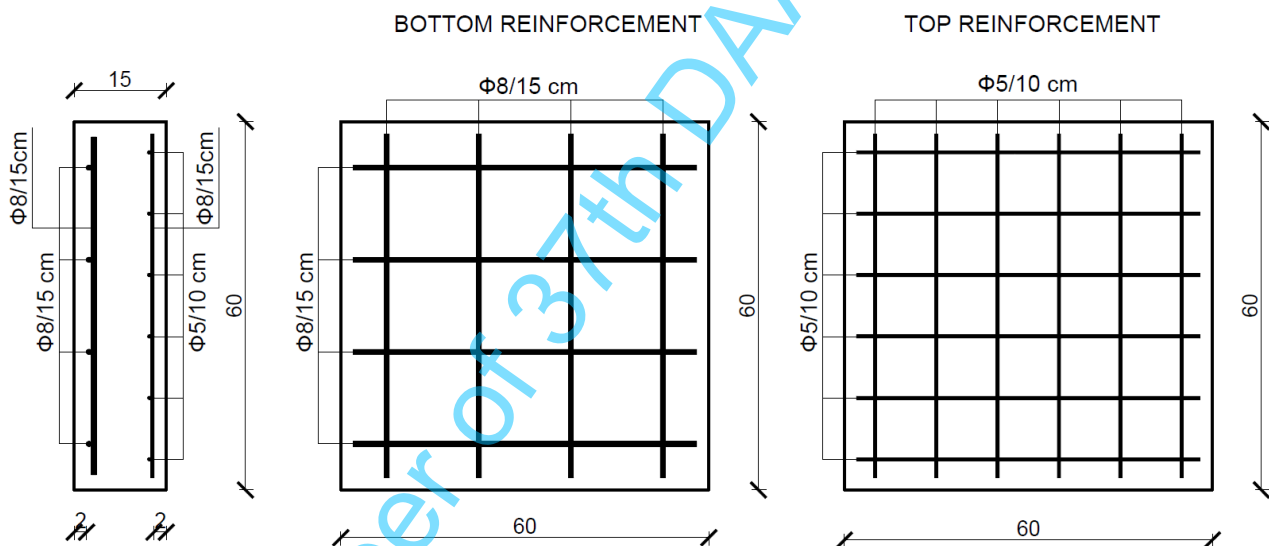


Fig. 7. Schematic illustration of reinforced concrete slab specimen PK1



Fig. 8. Experimental setup for electromagnetic shielding measurements of specimen PK1 using the Bicolog antenna

Specimen PK2 was reinforced with double Q335 welded wire mesh in the bottom reinforcement layer and Q196 welded wire mesh in the top reinforcement layer. Similar to specimen PK1, no steel cross-shaped microwave resonators were incorporated, making PK2 the second reference specimen. A schematic illustration of specimen PK2 is presented in Fig. 9, while Fig. 10 illustrates the corresponding experimental setup used for electromagnetic shielding measurements employing the Bicolog antenna.

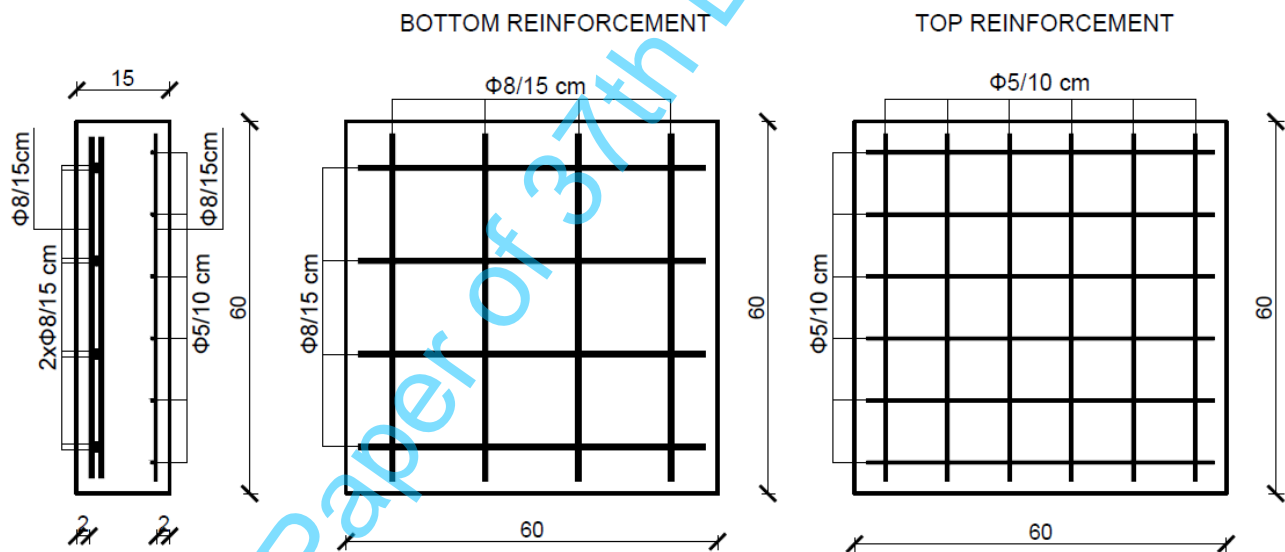


Fig. 9. Schematic illustration of reinforced concrete slab specimen PK2



Fig. 10. Experimental setup for electromagnetic shielding measurements of specimen PK2 using the Bicolog antenna

In addition to the reinforced concrete slab specimens, an empty test frame was also evaluated using the Bicolog antenna. This measurement served as a baseline (reference) condition, enabling comparison between the shielding performance of the reinforced concrete specimens and the absence of any shielding material. The experimental arrangement for the empty frame is presented in Fig. 11.

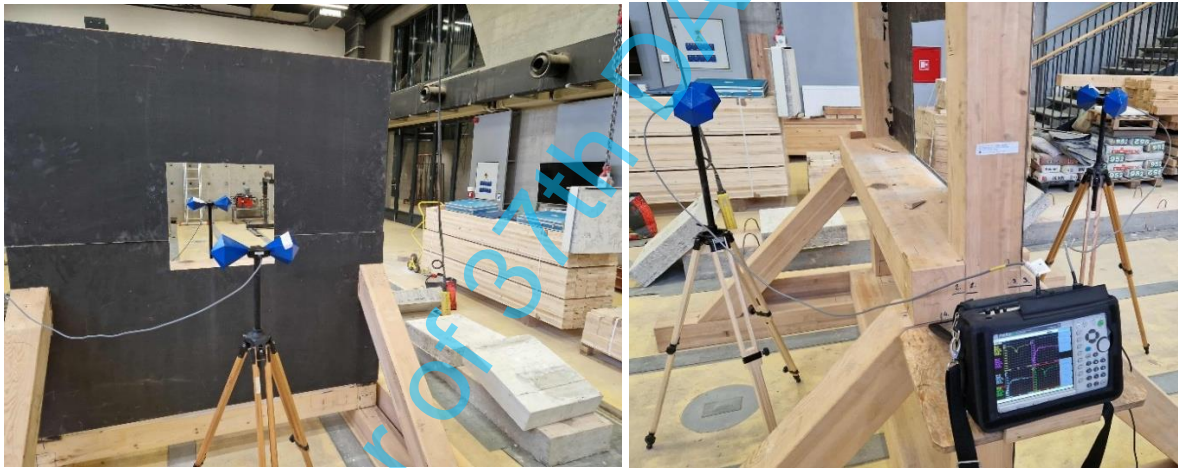


Fig. 11. Experimental setup for the empty reference frame

In the present study, the electromagnetic shielding efficiency was evaluated on the basis of the transmission coefficient (S21) according to the following expression:

$$S21 = 20 \cdot \log \frac{E_2}{E_1} \quad (2)$$

S21 is the transmission coefficient, representing the proportion of electromagnetic radiation transmitted through the tested specimen. The electromagnetic radiation is emitted by Antenna 1 (E_1), while Antenna 2 is positioned on the opposite side of the specimen and measures the electromagnetic radiation that has propagated through the reinforced concrete slab (E_2).

For the purposes of this investigation, the transmission coefficient S21 represents the most significant parameter because it directly quantifies the amount of electromagnetic radiation transmitted through the reinforced concrete slab relative to the total emitted radiation. Consequently, S21 serves as the principal indicator of the electromagnetic shielding performance of the tested specimens.

A lower value of the transmission coefficient S21 indicates that a smaller proportion of electromagnetic radiation penetrates the specimen and reaches the receiving antenna. Therefore, lower S21 values correspond to higher electromagnetic shielding efficiency and improved protection against electromagnetic radiation penetration.

3. Results and discussion

The results of the electromagnetic wave transmission coefficient S_{21} measurements obtained for the reinforced concrete slab specimens with different reinforcement configurations, together with the empty reference frame, using the Bicolog antenna, are presented in Fig. 12. Since the radio-frequency spectrum (below 0.3 GHz) is generally considered to present negligible health concerns, the discussion presented herein focuses on the microwave frequency range (above 0.3 GHz), where enhanced electromagnetic shielding is of greater practical importance.

As illustrated in Fig. 12, the reinforced concrete slab specimens incorporating embedded steel cross-shaped microwave resonators exhibited superior electromagnetic shielding performance compared with the reference specimens without microwave resonators. This improvement becomes particularly evident at frequencies above 0.5 GHz, where the transmission coefficient of the reinforced specimens decreases significantly. These results demonstrate that the embedded steel cross-shaped microwave resonators substantially enhance the electromagnetic shielding performance of reinforced concrete slab specimens by reducing the transmission of electromagnetic waves through the structural element.

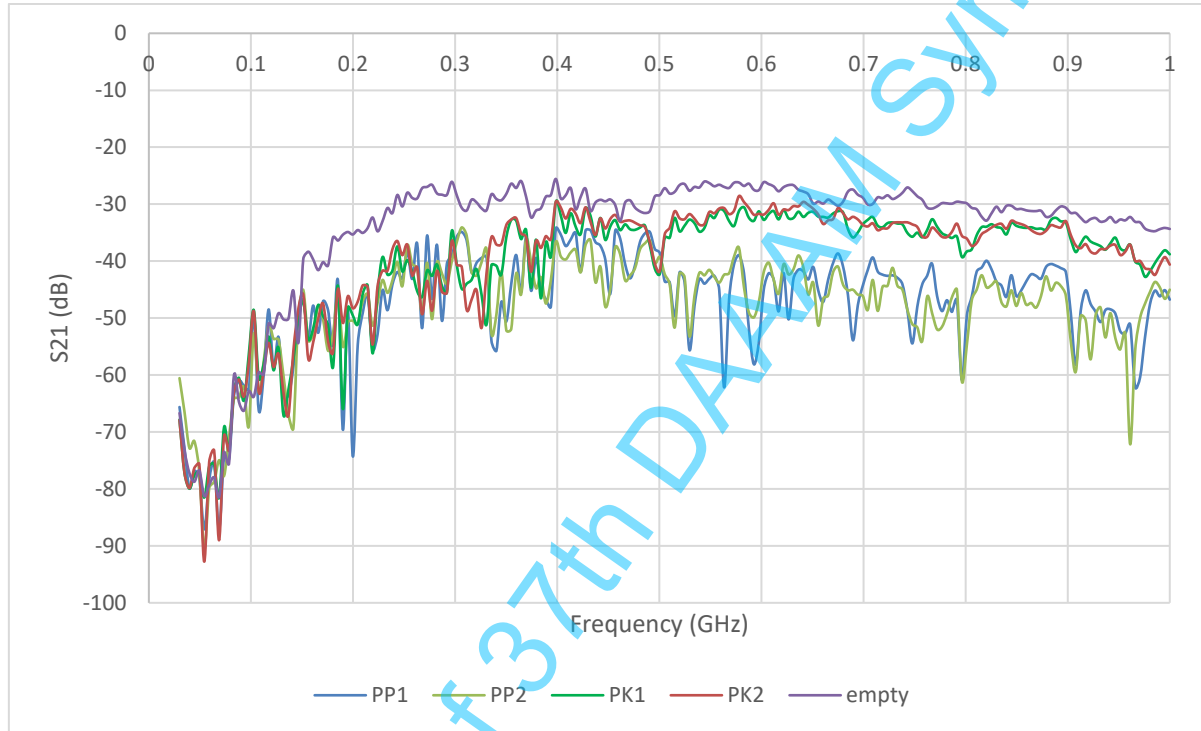


Fig. 12. Comparison of the transmission coefficient S_{21} for the tested reinforced concrete slab specimens measured using the Bicolog antenna

Within the ultra-high-frequency (UHF) range measured by the Bicolog antenna (0.3–1.0 GHz), specimen PP1 exhibited its highest shielding performance at a frequency of 0.56 GHz, corresponding to a minimum transmission coefficient S_{21} of -62,18 dB. Specimen PP2 achieved the best electromagnetic shielding performance at 0.96 GHz, where the minimum transmission coefficient S_{21} reached -72,15 dB. Among the reference specimens, PK1 exhibited the best electromagnetic shielding performance at 0.33 GHz, where the minimum transmission coefficient S_{21} reached -51,17 dB, whereas specimen PK2 exhibited the best electromagnetic shielding performance at 0.33 GHz, where the minimum transmission coefficient S_{21} reached -51,75 dB. The empty frame achieved the best electromagnetic shielding performance at 0,99 GHz, where the minimum transmission coefficient S_{21} reached -34,74 dB.

A comparison of these minimum transmission coefficients S_{21} clearly demonstrates that all reinforced concrete slab specimens provide a measurable degree of protection against electromagnetic radiation when compared with the empty reference frame. Furthermore, specimens incorporating steel cross-shaped microwave resonators consistently exhibited substantially lower transmission coefficients S_{21} than the corresponding reference specimens without resonators, indicating significantly improved electromagnetic shielding performance. The experimental results therefore confirm that the incorporation of embedded steel cross-shaped microwave resonators considerably reduces the transmission of electromagnetic radiation through reinforced concrete slab elements, particularly within the ultra-high-frequency spectrum that were measured by the Bicolog antenna.

Specimen	Minimum transmission coefficient S21	Frequency	Best EM shielding performance
PP1	-62,18 dB	0,56 GHz	PP2
PP2	-72,15 dB	0,96 GHz	
PK1	-51,17 dB	0,33 GHz	
PK2	-51,75 dB	0,33 GHz	
Empty frame	-34,74 dB	0,99 GHz	

Table 2. Minimum values of the transmission coefficient S21 measured in the ultra-high-frequency spectrum using the Bicollog antenna

The experimental investigation demonstrates that reinforced concrete slab specimens provide an inherent level of electromagnetic shielding compared with the empty reference frame. Moreover, the incorporation of steel cross-shaped microwave resonators resulted in a substantial improvement in shielding efficiency compared with otherwise identical reinforced concrete specimens without resonators. The reduction in the transmission coefficient S21 confirms that these resonators significantly increase the attenuation of electromagnetic waves propagating through reinforced concrete structural elements.

4. Conclusion

Experimental investigations demonstrated that all reinforced concrete (RC) slab specimens provided a measurable level of protection against the penetration of electromagnetic waves compared with the empty reference frame. Consequently, reinforced concrete itself contributes to electromagnetic shielding, while the incorporation of additional shielding components further enhances this performance. The RC slab specimens incorporating embedded steel cross-shaped microwave resonators consistently exhibited superior electromagnetic shielding effectiveness compared with the corresponding reference specimens without resonators. This confirms that the embedded steel resonators significantly improve the attenuation of electromagnetic waves propagating through reinforced concrete structural elements.

The experimental results further indicate that, throughout most of the ultra-high-frequency (UHF) spectrum measured using the Bicollog antenna, the difference in shielding efficiency between the RC specimens containing microwave resonators and the corresponding reference specimens was greater than the difference between the reference specimens and the empty frame. This finding demonstrates that the embedded steel cross-shaped microwave resonators contribute more substantially to electromagnetic shielding than the reinforced concrete slab itself.

Provided that subsequent mechanical testing confirms that the incorporation of the steel cross-shaped microwave resonators does not adversely affect the structural performance or load-bearing capacity of reinforced concrete slabs, these resonators may be considered a promising solution for practical application in buildings where enhanced electromagnetic shielding is required. Such applications include kindergartens, nursing homes, residential buildings, hospitals, research facilities, and structures located in the vicinity of nuclear power plants or other installations requiring increased protection from electromagnetic interference.

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