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Experimental work on mechanical, electromagnetic and microwave shielding effectiveness properties of mortar containing electric arc furnace slag

Murat Ozturk [a], Oguzhan Akgol [b], Umur Korkut Sevim [a,*], Muharrem Karaaslan [b], Mustafa Demirci [a], Emin Unal [b]

[a] *Iskenderun Technical University, Department of Civil Engineering, Iskenderun, Turkey*
[b] *Iskenderun Technical University, Department of Electrical and Electronics Engineering, Iskenderun, Turkey*

HIGHLIGHTS

- Ordinary cement mortar specimens with Electric Arc Furnace Slag are investigated.
- Dielectric constant of permeability of the mortars improved with addition of EAFS.
- The minimum transmission is around −70 dB.
- Mortar including 40% EAF aggregate ratio has the best mechanical properties.
- The shielding effectiveness is excellent grade for 80–100% EAFS aggregates levels.

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ABSTRACT

It is well known that one of the widely used structural materials is ordinary cement mortar. Whereas the mechanical properties are sufficient as structural materials, its shielding effectiveness and prevention properties of microwave signal is insufficient due to the lack of electromagnetically conductive components. Electric Arc Furnace Slag (EAFS) is a by-product which is produced after the melting and the primary acid refining of liquid steel. It has potential to improve both mechanical and electrical properties of cement. In this study, ordinary cement mortar specimens with Electric Arc Furnace Slag are investigated. The EAFS used in this study takes part in the mortar specimens as aggregate. Electrical properties are measured by a vector network analyzer in the frequency range of 3–18 GHz. Both the reflection and transmission of the proposed specimens exposed to EM wave are evaluated by free space measurement techniques at the same frequency range. The compressive strength, flexural tensile strength and shielding effectiveness of mortars are also tested, respectively. The real part of permittivity increases with the increased EAFS content of the mortars up to dielectric constant of 40. Nearly constant and frequency independent characteristics of specimens have potential applications. Furthermore, the effective dielectric constant of permeability of the mortars is explicitly improved in the related frequency ranges with the addition of the EAF slags. The transmission prevention of the EAF slag mortars tend to increase significantly with the increasing ratio of EAF slag content. The minimum transmission is around −70 dB and the transmission below −10 dB for 40% EAF aggregate ratio in mortar which has the best mechanical properties in the entire frequency range and averagely and it is −10 dB lower than that of the cement without EAF aggregates. The shielding effectiveness is in excellent level for 80% and 100% EAFS aggregate levels and that of 40% aggregate ratio is still in a good level with a value varying between 15 dB and 20 dB. Besides, the mortars with 40% EAF slag content exhibit approximately 7 MPa higher compressive strength value and 0.9 MPa higher flexural tensile strength.

1. Introduction

In last decades, the pollution caused by electromagnetic (EM) radiation has been a great problem due to its damages on human

* Corresponding author.
E-mail address: ukorkut.sevim@iste.edu.tr (U.K. Sevim).

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being, animal and electronical devices [1,2]. Thus, researchers have paid more attentions on the ways of solving this issue [3]. Communication devices, which are widely used in daily life (e.g. mobile phones, displays, flexible devices, wireless network devices, and tablet personal computers), could be sources of the EM pollution in the frequency range of 3 kHz–300 GHz [4]. The large usage area of the communication devices causes EM radiation which results in an unwanted EM coupling between data paths and pollution.

Although cement based materials are widely used in construction area with high performance, EM wave absorbing ability of these materials is weak. The researchers have investigated and found some alternatives to enhance EM wave absorption capacity of the cement based materials by inclusion of TiO_2 [5], carbonized nano/microparticles [6], foaming agent [7] and carbon black [8]. In addition, there are some studies which are related to ferromagnetic inclusion for magnetic field shielding at extremely low frequencies. For instance, Laudani et al. made a research towards the development of a simple approach to model composite magnetic materials through Finite Elements Method (FEM) analysis [9]. Furthermore, they proposed a strategy to evaluate affective permeability of mortars containing ferromagnetic particles for magnetic shielding [10]. Despite these inclusions are effective to increase EM wave absorption capacity of the cement based materials, it is also important to find low cost materials with high absorption capacity.

Electric Arc Furnace Slag (EAFS) is a by-product which is produced after the melting and the primary acid refining of liquid steel. Sufficient durability, chemical and physical requirements must be satisfied before using a waste or by-product in cement based materials. According to the results of some studies in literature, cement based materials including EAFS perform satisfactory in the mentioned perspective [11–15]. Therefore, it could be said that EAFS is a sustainable and useful material when used to produce cement based materials in the scope of durability, chemical and physical requirements.

In the current study, EAFS electromagnetic wave absorption properties are investigated due to its high Fe (iron) content. EAFS is used as a substitute for natural sand and five different volume percentages of EAFS are used to study the effect of EAFS on mechanical and EM properties of cement mortars containing EAFS. The main aim of the current study is to carry out how EAFS behaves as an EM absorber in cement mortar and offer theoretical basis for enhancing microwave resistivity of cement mortar.

2. Preparation and experimental study on mechanical and absorption properties of the mortars

2.1. Raw materials

CEM I 42.5 R cement is used as a raw material. Nominal size of the fine natural aggregates (dolomitic limestone) and EAFS aggregates are 4 mm, natural and EAFS aggregate has a fineness modulus of 2.65–2.59, and specific gravity of 2.60–3.2, respectively. Tab water is used for mixing procedure for the preparation of the mortars.

2.2. Preparation of specimens

EAFS aggregate is replaced with natural sand by volume in cement mortar. The EAFS aggregate ratios in volume are chosen as 10%, 20%, 40%, 60%, 80% and 100%. Six different mixtures are designed as control specimens. The mass ratio of cement, water and sand is 1:0.485:2.75 in the control group, respectively. A speed controlled power-driven revolving pan mixer is used for mixing procedure. As the last step, mixtures are poured into 40 mm × 40 mm × 160 mm mold (mechanical tests) and 160 mm × 160 mm × 20 mm (EM tests) mold and vibrated for 30 s. 24 h after molding, the specimens are demolded and cured in a water tank for different curing time (7, 14 and 28 days for mechanical tests and 28 days for EM tests). Before conduction, mechanical and EM tests at the specified times, the specimens are dried in an oven under 40 °C until reaching a constant weight.

2.3. Characterization

2.3.1. Analysis and measurements of microstructures of cement mortar by XRD and SEM

The microstructure examinations of the samples selected from the produced mortar specimens are carried out by using an electron microscope. JEOL JSM-5610LV model Scanning Electron Microscope (SEM) equipment is used for observation of micromechanism of the specimens. The equipment has an accelerating voltage between 0.1 and 30 kV; Resolution in high vacuum mode is 5.0 nm, accelerating voltage is 30 kV-WD 6 mm, magnification is ×25–×300.000 and the probe current can be set from 1 pA to 1 μA.

Mortar samples containing EAF slag aggregate and aggregates are examined by RigakuSmartLab model X-ray diffraction device. X-ray diffraction (XRD) analyses are carried out by using a computer controlled Rigaku-SmartLab with Cu Kα radiation (40 kV, 30 mA) and 2θ angles ranging from 5 to 90.

2.3.2. Mechanical tests (flexural and compressive strengths) of cement mortar samples

Flexural tests are performed on 40 mm × 40mm × 160 mm prisms and compression tests are conducted on 40 mm × 40 mm × 40 mm cubes of cement mortar samples. Flexural and compression tests are conducted by considering the standards of ASTM C348 [16] and ASTM C349 [17] using testing machines with loading accuracy ± 0.5% of indicated load having the capacity of 1500kN (for Flexural tests) and 2500 kN (for Compression tests).

2.3.3. Microwave test to determine electromagnetic properties of samples under test

In order to understand the EM response of the samples, the scattering parameters, most commonly known as S-parameters are examined. To do so, a vector network analyzer, Agilent brand 2-Port PNA-L, and two wideband, high gain, linearly polarized horn antennas are used. In this experimental setup which is shown in Fig. 1, the samples are placed at the center of two horn antennas which are connected to the ports of the network analyzer through adaptors and testing cables. The operation frequencies of the antennas are the same and vary between 3 and 18 GHz, while the network analyzer is capable of operating from 10 MHz to 43.5 GHz. For the reflection, the electromagnetic energy reflected from the sample surface back to the antenna itself (S11 or S22) was measured. This parameter demonstrates how much energy is reflected from the sample within an electric field with frequencies varying from 3 GHz to 18 GHz.

Before conducting the measurement, the measuring tools need to be calibrated. The vector network analyzer (VNA) was calibrated by using a proper calibration kit for coaxial connection including open, short, load and transmission tools for two port system. In this way, all the affects coming from the cables, connectors and adaptors etc. are eliminated. The system was tested with two horn antennas only without placing the sample and it was ensured that the system is ready for the experimental tests.

The transmission behavior of the sample was measured by using the electromagnetic transmission between two ports which can be seen from S12 or S21 scattering parameters. As known, electromagnetic properties and responses are distinct characteristics of any material. These responses depend mostly on the electrical per-