Investigation of electromagnetic shielding and absorbing capabilities of cementitious composites with waste metallic chips

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ABSTRACT
Electromagnetic shielding has become more important in recent years as a result of increased electromagnetic environment pollution, its long-term health effects and information security in buildings. Therefore, the studies on building materials that can prevent electromagnetic emission have caused great attention. Additionally, accurate measurements of electrical characteristics properties of materials can provide scientists and engineers with valuable information to properly incorporate the material into its intended application for more solid designs or to monitor a manufacturing process for improved quality control. This paper mainly focused on the progress and prospective future of cementitious building materials by using waste metallic chips as a constituent for the purpose of electromagnetic shielding, wave absorbing activities and electrical properties of materials. For this purpose, natural sand was replaced in volume provided from different industrial areas in the production of cementitious composite, and these materials were examined to determine their electromagnetic shielding, absorbing capabilities and dielectric constants. As a result, although reference sample has almost 7 dB shielding efficiency, sample having iron chips (60%) has 18 dB shielding efficiency which is known as good shielding material property value.

KEYWORDS
Electromagnetic shielding; absorbing capability; waste material chips; cementitious composite, dielectric constant

1. Introduction
Uncontrolled electromagnetic emissions have two major problems; first one is related to electronic devices mainly known as electromagnetic compatibility problem. In particular, this problem is called as electromagnetic interference) problem. Electromagnetic emissions from any electronics may interfere other electronics or equivalently electronics may be interfered from the other emitting sources such that interference may cause malfunctions in the system. In order to prevent electronics and electronics’ sensitivity, one needs to control electromagnetic emissions in both ways (towards electronics or from...
electronics). Second problem is related to public health. In order to save people (patients and/or babies) in hospitals or in dwellings, one needs to control electromagnetic field emission through the buildings to guarantee acceptable specific absorption rate (SAR) levels (Xiang et al. 2001; Ozen & Ari 2008; Helhel 2015). Increasing both reflection and absorbing capabilities of materials are two major methods to control electromagnetic emission in both ways which are from electronics or to electronics, and for low SAR value originating from low level electric field intensity.

Since cementitious composites (CCs) have rich resource and good environmental adaptability, it is one of the most common structural materials used in engineering constructions (Helhel 2015). CCs are not only structural materials themselves, but they have also electromagnetic shielding effectiveness and wave absorbing properties more or less. The CCs which are basically dielectric materials having small conductivity has normally very low absorbing properties. Conductive fillings and ingredients of CCs allow us to increase its shielding effectiveness (SE). In the literature, there are different studies, one of these works that carbon was filled in cement material. When the volume was increased to 3.0 vol%, a specimen with about 3 mm thickness raised a SE of 10–40 dB in the frequency range 200–1600 MHz (Hongtao et al. 2006). In another study, %, a specimen with about 4.4 mm thickness and the SE (1 GHz) is 22 dB at a solid graphite content of 0.92 vol.%, compared to 15 dB for 15-μm-diameter carbon fibres and 35 dB for 0.1 μm diameter carbon filaments, both at similar volume fractions (Cao & Chung 2003a). They mainly address carbon materials as an additive for improving reflection capabilities of CCs. Nickel plated carbon fibres (Lu et al. 1996; Cao & Chung 2003b), nickel coated mica (Jiang et al. 2002), conductive papers (Shinagawa et al. 1999; Shinagawa et al. 1999), and magnetic woods (Nagasawa et al. 1999; Oka & Fujita 1999; Oka et al. 2002), and simulation-based microwave imaging of plain and reinforced concrete for nondestructive evaluation are the samples of conductive fillers. They are not only high in cost, but also complicated in processing, so they are not commonly used in cement matrix composites (Chung 2001).

Aggregates, usually provided from natural resources, occupy up to 80% of CCs by volume (Kockal 2015). Therefore, the dominating constituent in properties of CCs is aggregate due to this large volumetric occupation (Kockal & Ozturkan 2010). In recent years, industrial waste materials have been widely used in the construction field due to the increasing need to recycle these materials in order to protect the environment (Kockal 2013). In addition, due to the shortages of raw materials and high energy consumptions, construction companies are in search of alternative cheaper materials such as waste materials (Kockal 2012). There are millions of tons of WMCs generated all over the world and have caused great pollution, and the consumption of waste materials can be increased manifold if these are used as aggregate into cement mortar and concrete (De Brito & Sai-kia 2013). The use of waste aggregates can also reduce the cost of the CC production. As the aggregates can significantly control the properties of concrete, the properties of the aggregates have a great importance. Additionally, characterization of a wireless communications channel that includes man-made structures requires knowledge of the reflection and transmission properties of commonly used building materials (Dalke et al. 2000). Therefore, evaluating the SE capability of CCs by replacing natural sand with WMC is major aim of this study. Electromagnetic shielding capabilities of standard CCs, prepared by mixing waste iron chips in varying rates and substitution of crushed sand by waste chrome and steel chips with a rate of 10% by volume, have been investigated.
2. Materials and methods

2.1. Properties and production of CCs and their ingredients

Seven different types of CC mixes were prepared in this study. The w/c ratio was 0.60 and aggregate/cement ratio was 4.7. Cement used in the mixtures was CEM I 42.5R complying with TS EN 197-1 with a specific gravity of 3.06. Natural crushed sand was replaced with waste iron chips in varying proportions (10%, 30%, 40% and 60% by volume) and volumetric replacement of natural sand with waste chrome and steel chips was also made by a ratio of 10%. Figures 1–3 show the morphology and waste chip concentration of some selected samples.

All sample preparations were processed in a similar manner, according to European Standard EN 196-1. The mortars were cast into 100 × 100 × 7.6 mm steel plate moulds for 24 h and hardened samples were then demoulded, reduced to sample holder dimensions by cutting and tested for determination of shielding capabilities.

Natural sand, iron, chrome and steel chips used as aggregates in CCs have specific gravity values of 2.71, 6.53, 7.83 and 7.62, respectively.

2.2. Definition and properties of electromagnetic SE

It is well known that ES is directly related to materials’ properties, and it is a measure of difference between the incident and transmitted waves, and dominant component is reflection rather than absorption. Meanwhile, these two components (absorption and reflections) are two main segments of ES (Basyigit et al. 2011; Tosun et al., 2013).

In order to get more reflected waves, shielding material must have load carriers (electrons and holes) interacting each other. Though the shielding relevant with electrically conduction, electrical connectivity is not the scientific criterion. Basically, as much as

Figure 1. Microstructure of reference sample.
conduction requires connectivity in the conduction path, whereas shielding does not. Most commonly, metals are used for electromagnetic shielding due to their free electrons. The other segment of ES is absorption. For absorption, materials have dipoles (electrical and magnetic) interacting with electromagnetic fields in radiation. Materials possessing a high value of the magnetic permeability may supply magnetic dipoles (Balanis 2012) resulting in absorption.

**Figure 2.** Microstructure of sample having 10% volume of waste iron chip.

**Figure 3.** Microstructure of sample having 40% volume of waste iron chip.
The complex electric permittivity and magnetic permeability of a planar specimen in free space are given by Equations (1) and (2) (Kocakusak et al. 2016). Diffraction effects at the edges can be neglected since it is assumed the planar specimen is infinite extent.

\[ \varepsilon = \varepsilon' - j\varepsilon'' \]  
\[ \mu = \mu' - j\mu'' \]  

Equations (3) and (4) are related to the transmission and reflection coefficients.

\[ S_{11} = \frac{\Gamma(1 - T^2)}{1 - \Gamma^2 T^2} \]  
\[ S_{21} = \frac{T(1 - \Gamma^2)}{1 - \Gamma^2 T^2} \]  
\[ \Gamma = X \pm \sqrt{X^2 - 1} \]  

where

\[ X = \frac{S_{11}^2 - S_{21}^2 + 1}{2S_{11}} \]  
\[ T = \left( \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \right) \]  

Reflection losses are independent of the thickness of the shield and depend entirely on the reflection coefficient given by Equation (5). But the absorption loss is directly proportional to the thickness of the shield given by Equation (6) (Miyashita & Imai 1993; Sau et al. 1997; Xing et al. 1998). Multi-reflections in various surfaces (interfaces) through the shield are another ES mechanism. SE can be classified in two groups as electric field SE and magnetic field SE (Chiou et al. 1989; Li & Chung 1993; Li & Chung 1994; Shui & Chung 2000). SE including reflection, absorption and multi-reflections is commonly expressed in terms of dB, and SE_E is given by Equation (7) and SE_M is given by Equation (8).

\[ SE_E = 20\log \left( \frac{\vec{E}^{\text{inc}}}{\vec{E}^{\text{tran}}} \right), \text{(dB)} \]  
\[ SE_M = 20\log \left( \frac{\vec{H}^{\text{inc}}}{\vec{H}^{\text{tran}}} \right), \text{(dB)} \]  

where \( \vec{E}^{\text{inc}} \) and \( \vec{E}^{\text{tran}} \) are incident and transmitted electric field intensities (V/m), respectively. \( \vec{H}^{\text{inc}} \) and \( \vec{H}^{\text{tran}} \) are also incident and transmitted electric field intensities (A/m), respectively. In shielding, the attenuation of electromagnetic waves from the air/conductive surface and with regard to the interaction enters the screen conductor takes place in three stages. These are reflection losses (\( R_{dB} \)), absorption losses (\( A_{dB} \)) and multiple reflections losses (\( M_{dB} \)) and finally SE can be denoted as the summation of those three components as in Equations (9) and (10).
Traditional wave absorbers can be divided into three types as electric loss, magnetic loss and dielectric loss materials with respect to wave absorbing mechanisms. Conductive polymers are electric attenuation absorbent materials having higher electric loss tangent \((\tan \delta_e)\), and the electromagnetic energy is mostly attenuated as heating in a resistor. Ferrites and fine chips are magnetic loss absorbents having higher magnetic loss tangent \((\tan \delta_m)\), and polarization process (hysteresis loss and magnetic domain resonance) are dominant factors to attenuate and absorb electromagnetic energy. There are smart ceramics and metal fibres behave like dielectric loss absorbents and they attenuate electromagnetic energy by electronic and ionic polarization (Hongtao et al. 2006; Balanis 2012; Michelia et al. 2014).

Microwave techniques are capable of determining the properties and quality of materials. Determination of the dielectric properties of materials is necessary for microwave propagation modelling to improve indoor wireless communication systems. When external electrical field is applied, all materials named as dielectric store energy. It can be modelled as shown in Figure 4.

The complex dielectric constant \(\varepsilon_r\) consists of two parts; one of them which is real part \(\varepsilon_r'\) represents the stored energy, the other is imaginary part \(\varepsilon_r''\) and represents the loss energy.

### 2.3. Measurement set-up

Measurements were conducted at Industrial and Medical Application Based Microwave Research Center (EMUMAM) at Akdeniz University. A vector network analyser (VNA) operating in frequency range of 10 MHz–9 GHz (Anritsu MS4624B), control software
and computer, adaptors (2xWR-159) and wide band coaxial cables were used. Transmission line method was preferred to measure the attenuation upon reflection and transmission, and a sample holder for F band measurements was designed and combined with standard adaptor as shown in Figure 5.

Own computer graphical interface was used as main control unit. Used network analyzer was calibrated before each measurement, and set-up frequency range was in between 4.9 and 7.05 GHz. During measurements, dry bulb temperature was kept in the range of 22–24°C and dew point was measured as 100°C, and room humidity has been estimated as 41%.

Samples were fitted inside the holder having dimensions of 0.386×20.193 in mm. Waveguides were connected to the ports of VNA through wideband coaxial cable, and measurements were repeated at 401 points between 4.9 and 7.05 GHz. 201 points, refer to 5.36 MHz step size which is quite enough frequency resolution for such kind of studies. VNA reads both reflection and absorption loss components that $S_{11}$ is the input port voltage reflection coefficient and $S_{21}$ is the reverse voltage gain. Control software collects those readings ($S_{11}$ and $S_{21}$ parameters) in order to calculate reflection, absorption, multi-reflection losses and dielectric parameters. Seven different samples of 7.6±0.1 mm thickness were selected in order to investigate composites’ performance. Sample without metallic chips was coded as RS for reference sample, and other samples were coded by considering their WMC volumetric content so that the notations of samples containing 10% steel, 10% chrome, 10% iron, 20% iron, 30% iron, 40% iron and 60% iron waste chips were SS10, CS10, IS10, IS30, IS40 and IS60, respectively.

3. Results and discussion

The C-band is a name given to certain portions of the electromagnetic spectrum, including wavelengths of microwaves that are used for long-distance radio telecommunications. The IEEE C-band (4–8 GHz) and its slight variations contain frequency ranges that are used for many satellite communications transmissions, some Wi-Fi devices, some cordless telephones and some weather radar systems. For satellite communications, the microwave frequencies of the C-band perform better under adverse weather conditions in

![Figure 5. Measurement set-up. (a) General view. (b) Accessories.](image)
comparison with the Ku band (11.2–14.5 GHz), microwave frequencies used by other communication satellites. Since the term shielding has negative sense, results must be indicated in positive value, and throughout the manuscript one need to take into account it. Dielectric constants of samples are measured and shown in Figure 6 after calibration was done. Figures 7 and 8 indicate the total SETSE and its components referring to wave absorbing components were coded as $A_{dB}$ and the reflection components coded as $R_{dB}$ for all

Figure 6. Dielectric constants of all samples.

Figure 7. Parts of SE for RS, SS10, IS10 and CS10.
samples. $A_{db}$ of RS is nearly 2 dB in this study similar to another study published by Roberto Pastore et al. (Michelia et al. 2014). Real part of dielectric constant associated stored energy so the real part of dielectrical constant of material is the bigger, it has better absorbing ability.

4. Conclusions

Using metallic chips as additives (conductive inclusions) in the cement-based building materials can be offered in order to dispose wastes in practical and economical way and to obtain better electromagnetic SE and wave absorbing functions.

Developing new construction materials having electromagnetic wave absorbing and shielding capability has been a great concern in recent years. Parallel to this concern including the need of information security and health risks, standards defining the structure of buildings as well as equipment establishment procedures have been regulated. Obtaining these properties with WMCs is comparably a new approach, and the dominance of absorbing component as a constituent besides reflection component in TSE is an important outcome of this study in order to remain within the limits specified by the relevant standards.

Other properties of CCs such as porosity and unit weight will be investigated in further studies to determine their behaviour and effect on TSE.

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Disclosure statement

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