**Advancements in electromagnetic interference shielding behaviour of carbonaceous composites**

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**Abstract:** With the advancement of modern technology, there has been a rapid rise in the electronic devices, and along with this growth, there has been an increased concern over the electromagnetic (EM) radiation emitted by these devices. Traditionally, metals have been used as the ideal shielding material simply due to their high shielding effectiveness (SE) that arises as a result of their high electrical conductivity. However, due to a few undesirable characteristics of these metallic materials such as the corrosion, there have been novel experiments into the development of other materials that can be used as an effective EMI shield. While some of these research work focuses on developing carbonaceous composites, others have focused on creating lightweight polymer-based shielding materials. This paper reviews such novel cementitious composite materials which have been developed to shield against EMI.

**Keywords:** Carbon, Graphene, Electromagnetic Shielding, Conductivity.

* 1. **Introduction:**

In today’s society, the use of electronics and wireless communications are becoming common, and the environment around us is getting more and more polluted by the interference of electromagnetic interference. When the signal from the electronic equipments interfere with its operations or operation of other devices [1]. The electromagnetic shielding is one of the methods to overcome this problem in which a barrier is placed which hinders the electromagnetic wave to interfere with the performance of electronic equipments. The electromagnetic shielding is mainly done in three ways. Reflection is the primary mechanism of EM shielding. Reflection occurs when the shielding material have charge carriers such as holes and electrons which creates impedance mismatch between the impedance of free space and the impedance of shielding material. Metals are the shielding materials which were used and have good shielding effectiveness and mechanical properties [2, 3][3]. The metals are generally based on the faraday cage principle in which the metal shield is formed in which the EM wave creates the charges on the surface of cage which is cancel by the charges inside the cage. Metals are good conductors, thereby are best reflecting materials. But they have the disadvantage such as heavy weight, poor processibility, exposure to corrosion etc [4]. The secondary mechanism is absorption which is done by ohmic losses and the heating of material due to the induced current in the material. The mechanism of absorption has been evolved firstly back in 1936 in Netherlands in 1936, when a carbon black and titanium oxide (TiO2) has been used as an absorbing material for a resonant type quarter wave and was first patented as microwave shielding material.

For the reduction of EMI issues, many agencies such as CISPR (international special committee on radio interference) given in 1934 by the International electrotechnical commission (IEC) has given the rules for controlling the EMI in the electrical and electronic devises. According to the rules, EMI shielding effectiveness should be greater than 30 dB for commercial applications which corresponds to 99.9% of the incident radiation. In order to meet these extremely large values for EMI SE, the electronics must be entirely enclosed by the shield. Any penetration into the shield, unless appropriately treated, can significantly reduce the EMI SE.

**1.2 Theory of electromagnetic waves**

The electromagnetic wave travel in x-direction and the electric and magnetic vectors are in y and z directions respectively. The electromagnetic field has been described by Maxwell using these equations:

$$∇.D=δ$$

$$∇.B=0$$

$$∇XH=\frac{∂D}{∂t}+J$$

$$∇XE=-\frac{∂B}{∂t}$$

The solution of these equations can be given by following

$$D=εE=\left(ε^{'}+ε^{"}\right)E$$

$$B=μH=\left(μ^{'}+μ^{"}\right)H$$

$$J=σE$$

where B is the magnetic field, H is the magnetic field strength, E is the electric field, D is the displacement vector, ε is the relative permittivity, µ is the relative permeability, J is the current density and σ is the electrical conductivity of material. The changing electric field produce magnetic field and vice-versa and, the coupling of both fields leads to the generation of electromagnetic wave.

When the EM wave interact with the dipole, the dipole rotates itself to align according to the polarity. During the alignment, some energy is lost in the form of heat and acceleration or deceleration. The degree with which the dipole is rotated with the incident EM field depends on the frequency which determine the imaginary part of permittivity for electric field and the imaginary part of permeability for magnetic field. The imaginary permittivity and permeability are directly related to loss factor. Higher the imaginary values, more the energy is released during the alignment of dipole and less energy is left for the propagation of EM wave.

In case of harmonic EM field, the electric field equation can be given as

$$E\left(r,t\right)=E\left(r\right) e^{jwt}$$

$$∇^{2}\vec{E}+ω^{2}με\vec{E}=jωμ\vec{J}+∇(∇.\vec{E})$$

For free space, σ=0, then the above equation becomes

$$E\left(r,t\right)=E\_{0}e^{-j(k.r-ωt)}$$

Where K is the direction vector of EM wave propagating with wavelength λ=2π/ω.

The relevant solution for magnetic field is given as

$$H\left(r,t\right)=\frac{k}{ωμ}kx\vec{E}(r)$$

with $k=(ω^{2}με)^{2}$. From Maxwell equations, it can be concluded that the material depends on the electrical permittivity, magnetic permeability and the electrical conductivity of the material. The electric component of EM wave gets attenuated by conducting or dielectric material and the magnetic component gets attenuated by magnetic materials having hysteresis and resonance of absorbing material. The real part of permittivity and permeability give the stored energy and the imaginary part of permittivity and permeability give the loss of energy. The electromagnetic wave characteristics depends upon the distance from the source and the nature of source. The distance around the source is divided into two regions. The distance near the source is known as near field or induction field region where the region is less than λ/2π and the wave in near field region has spherical wave front. The region which is greater than λ/2π is known as far region or radiation field region. In case of far field, the radiated EM wave lose its curvature and become plane wave. The radiation field depends on the medium in which the electromagnetic wave is propagating. The medium at a distance λ/2π from the source which is between far field and the near field is called as the transition region. In this thesis, we are discussing about the plane electromagnetic wave for EM shielding applications.

The propagation of electromagnetic wave can be given by these equations:

$$\vec{E}=E\_{y}(x,t)\vec{j}=E\_{o}\cos((kx)-wt)\vec{j}$$

$$\vec{B}=B\_{z}\left(x,t\right)\vec{k}=B\_{o}cos⁡(kx-wt)\vec{k}$$

Where E0 and B0 are the amplitudes of electromagnetic wave. The angular wave number and the angular frequency are related to wavelength as

$$k=\frac{2π}{λ}$$

$$ω=kν=2π\frac{ν}{λ}=2πf$$

Where f is the frequency of EM wave. The propagation of EM wave depends on intrinsic impedance and the wave velocity. The intrinsic impedance is given as

$$η=\sqrt{\frac{jωμ}{σ+jωε}}$$

In case of dielectric material, $σ\ll jωε$

then $η=^{μ}/\_{ε}$ . This shows that the intrinsic impedance depends on the dielectric permittivity and the magnetic permeability.

In case of conductor, $σ\gg ωε$, $η=\sqrt{\frac{jωμ}{σ}}=(1+j)\sqrt{\frac{πμf}{σ}}$

Now, the propagation constant is defined as

$$γ=\left(α+iβ\right)=\sqrt{jωμ(σ+jωε)}$$

where α is the attenuation constant and β is the phase constant of EM wave.

In case of good conductor, $γ=\sqrt{jωμ}=(1+j)\sqrt{πμfσ}$

$α=β=\frac{1}{δ}=\sqrt{πμfσ}$ where δ is the skin depth of the material. Skin depth is defined as the distance in the material upto which the amplitude of EM wave decreases to 1/e of the wave.

For free space, the intrinsic impedance is nearly 377 ohm, the EM wave will be the plane wave. For radiated field, the EM wave depends on the characteristics of wave. For transition field EM wave, the wave depends on the source and the distance of wave from the source. In near field, if the voltage is high and the current is low, then the magnetic dominated field. If current is high and voltage is low, then the electric field is dominated.

The plane electromagnetic wave strike the interface between two media having different impedances. The reflection loss will be higher when the impedance mismatch between two media is higher.

**1.3 Mechanism of EMI Shielding**

When an electromagnetic plane wave impinge on the surface, then some wave is reflected back in same environment, some is absorbed in the another environment which re-reflected by the interfaces inside the material and rest is transmitted through the material that depends on the skin depth of the material.

The part of incident wave reflected by the surface of shield is given by reflection coefficient. The conducting material like metals are suitable for reflection as they contain mobile charge carriers. The mobile charge carriers create impedance mismatch between the impedances of free space and the shield. Because of the impedance mismatch, most of the incident EM wave is reflected from the shield. The part of incident wave is transmitted through the medium, the amplitude of the wave decreases by the factor e-α/z where α is the attenuation constant and is called as absorption loss. If the skin depth is less than the shielding material, the EM wave re-reflected by the surfaces of the material and finally, transmitted through the shield which is called as multiple reflection. So, the total shielding effectiveness is the total sum of reflection loss, absorption loss and the multiple reflection loss of the material.

SE = SER + SEA + SEM

**1.3.1 Reflection Loss**- Reflection is the primary mechanism of EM wave and it occurs when the shielding material have charge carriers such as electrons and holes which creates impedance mismatch between free space and shielding material. The reflection depends on the material and frequency of propagation. The reflection coefficient (R) for the normal incident would be calculated as:

$$SE\_{R}(dB)=10log\left(\frac{σ\_{ac}}{16ωε\_{0}μ^{'}}\right)$$

Where σ is the conductivity, f is the frequency and µ is the relative permeability.

Wave impedance presents how the relative permeability and permittivity (material properties) can affect the reflection coefficient.

**1.3.2 Absorption Loss** - Skin depth is the distance travelled by EM radiation inside the material upto which the wave amplitude reduces to the 1/e or 47%.

By comparing skin depth (𝛿) with thickness (t), the following two situations can be visualised.

1. When t << 𝛿, this situation occurs at low frequencies or in case of electrically thin sample where the thickness of shield is much less than the skin depth. In such cases, absorption is neglected and attenuation is done by reflection only.
2. When t >> 𝛿, this situation occurs generally at high frequencies or in case of electrically thick samples. In such cases attenuation is done by reflection, absorption and multiple reflections.

 The thickness should be greater than the skin depth of shielding material in microwave region. The ratio of impedance in air is 377. If the impedance become less than 377, the wave become

**1.4 Role of Permittivity and Permeability in EMI Shielding**

Permeability and permittivity are the important factors for shielding the EM wave. The conductivity and dielectric loss are the key factors for electrical shielding and magnetic loss is the key factor for magnetic shielding. Dielectric loss depends on the ionic, dipole, electronic and interfacial polarization.

According to free electron theory, the dielectric loss can be given as

$$ε^{''}=\frac{σ}{2πε\_{0}f}$$

Where dielectric loss is proportional to conductivity which shows that high conductivity material increases the dielectric loss. The ionic and electronic polarization generally occurs at terahertz frequency range and are neglected in microwave region. Interfacial polarization appears due to space charges at the interfaces and their respective relaxation occurs. The relaxation process can be investigated by cole-cole semicircle by using Debye relaxation process. The relationship between ε’ and ε” is given by

$$(ε^{'}-ε\_{\infty })^{2}+(ε^{''})^{2}=(ε\_{s}-ε\_{\infty })^{2}$$

where $ε\_{s}$ and $ε\_{\infty }$ are the static and infinite permittivity in microwave region [5]. The multiple relaxation phenomena can occur in multi interfaces composites.

On the other hand, magnetic loss occurs due to the eddy current loss, natural resonance and exchange resonance. For an good shielding material, magnetic shielding is attributed to high permeability in microwave region. Ferrites have good permeability due to high current loss. The variation of magnetic loss attains a multi resonance which is attributed to small size effect, surface effect and spin wave excitations where the resonance frequency is dependent on particle radius [6].

**2. Carbon based materials**

Carbon based nanomaterials with their unique characteristics such as high conductivity, low density, high permittivity, high thermal, chemical and mechanical stability are currently growing interest scientifically. These materials offer a great opportunity to fabricate a lot of varieties of new materials, with tunable electrical, optical, mechanical and magnetic properties [7]. The carbon contains mainly two main ordered lattice structures: diamond and graphite. Diamond has many industrial applications like cutting, and polishing of equipment, along with some scientific applications. Moreover, diamond is one of the hardest natural material and is electrically insulating with band gap of 5.5 eV, as well as valuable and venerable [8]. These properties of diamond make it unfavourable in potential energy applications. On the other hand, graphite is highly conductive in nature. Furthermore, carbon possesses various allotropes, comprising of graphite, graphene nanoplatelets, carbon nanotubes (single wall and multi wall). These lightweight carbonaceous materials and their derivatives with polymers serve as excellent candidates for the electromagnetic shielding materials. A brief introduction to some carbon materials which are usually used in EMI shielding applications are given below.

**2.1 Graphite/ Expanded Graphite**

Graphite is a 3-dimensional carbon material which has a layered structure consisting of hexagonal rings of carbon atoms attached due to weak van der Waals forces. The carbon atoms are joined together by covalent bonds. The graphite possesses good electrical conductivity, high aspect ratio, and good thermal and mechanical stability which have several potential applications in the electronic, optical and energy devices. However, graphite has major drawback of poor dispersion in solvents [9,10]. To remove this drawback, graphite is further converted to expanded graphite which is obtained by thermal treatment of graphite. It has many advantages, such as consisting of a small stack of graphite layers, low cost and has poor resistivity and high mechanical stability. The major problem of using these materials is their poor magnetic properties that restrict their practical application [11].

**2.2 Graphene**

Graphene is a 2-dimensional allotrope of carbon atom formed by a single atomic layer of a honeycomb hexagonal lattice which hybridizes by sp2 bonding. Graphene has a very good mechanical strength, excellent electrical conductivity, high thermal conductivity, very high surface area and amazing electrical and thermal stability [12]. Graphene has been synthesized from graphite by several methods including top-down or bottom-up approaches, chemical vapor deposition (CVD) [13–15]. However, these methods do not offer the large-scale production of graphene. Additionally, the lack of surface functionalities and the excessively high carrier mobility of graphene is also not very good for electromagnetic absorption. Hence graphene’s derivatives such as graphene oxide (GO) and reduced graphene oxide (RGO) are more broadly used as alternative to graphene in practical applications.

**2.3 Graphene oxide (GO)**

 When the graphite is oxidized with some strong oxidizing agents, the resulting compound shows the attached oxygen functionalities, carboxyl, carbonyl, hydroxyl and epoxy groups which expand the layer separation within graphite [16]. The most important property of GO is the good dispersion in either kind of solvent (organic or inorganic), because organic groups gives the way for GO to be modified easily by other materials. Moreover, GO can be well dispersed in a polymer matrix because of the strong and specific interactions among the organic groups on the GO surface and the polymers. Fe3O4–GO/PVDF composites show better electromagnetic microwave absorption than pure PVDF. GO in Fe3O4–GO/PVDF composites does not only affect the reflection loss and absorption bandwidth but also has a great impact on the phase transformation of the PVDF crystals. [17] The disruption of sp2 bonding in GO diminishes its electrical properties. Hence GO acts as an electrical insulator, directly this is not very useful. However, the Fe components improve its conductivity to a certain extent.

**2.4 Reduced graphene oxide (RGO)**

Among all the derivatives of carbon, reduced graphene oxide (RGO) is the most promising material with diverse applications. In RGO, the oxygen functional group is removed using a reducing agent such as hydrazine hydrate, NaBH4 or NaOH etc. [17]. Reduced graphene oxide (RGO) is the most studied carbon derivative due to its cost-effective preparation, good electric and thermal conductivity and attractive barrier properties. Moreover, RGO comprises remanent functional groups and defects within the sheet which improve impedance mismatch, defect polarization relaxation and electronic dipole relaxation [18]. All these groups and defects increase absorption rather than reflection. The microwave absorption properties of chemically reduced graphene oxide has been reported. They observed that residual defects and organic groups within RGO not only improved the individual impedance matching but also produced energy transitions from the continuous states to the Fermi level. Furthermore, these peculiarities introduce relaxation polarization, defect polarization relaxation and electronic dipole relaxation which increases the EM wave penetration and absorption [19]. Compared with graphite and carbon nanotubes, reduced graphene oxide has a higher dielectric/magnetic loss by means of microwave absorption. Thus, due to the unique properties of RGO and Fe-based materials, as well as the synergistic effect between them, many reduced graphene oxide/Fe based composites for EMI shielding have been investigated.

He et al. [20] has investigated the microwave shielding behaviour of reduced graphene oxide (RGO) nanosheets with the carbonyl iron (FCI). FCI/RGO composites showed the maximum shielding effectiveness due to absorption of 65.4 dB at 5.2 GHz at thickness 3.87 mm and the pure FCI showed the shielding effectiveness of 13.8 dB at 13.7 GHz at thick- ness of 2.28 mm. They used the delta-function method to see the contribution of typical dielectric dispersion behaviour in FCI/ RGO. Since FCI/RGO possesses a larger area close to zero, which can directly explain the better matching of the characteristic impedance in FCI/RGO composites. There- fore, recent investigations have mainly concentrated on RGO and Fe, Fe3O4 and Fe2O3 based composites due to their easy preparation.

**2.5 Carbon nanotube (CNT)**

Carbon nanotubes are the one-dimensional (1D) nano- structures. These nanotubes belong to the fullerene family. Structurally, CNTs are a long, hollow structure with cylindrical walls framed by a honeycomb lattice (similar to graphene). Carbon nanotubes shows many properties such as extremely good electronic, mechanical and thermal properties. Furthermore, the high aspect ratio, low mass density, and wall integrity of CNTs enable them to serve them as superb nanofillers for improving the properties of composites. There are two main types of carbon nanotubes: single walled carbon nanotubes (SWCNTs) and multi-walled carbon nano- tubes (MWCNTs). Single walled carbon nanotubes (SWCNTs) are an allotrope of sp2 hybridized carbon atom, similar to fullerenes. The structure of SWCNTs is a cylindrical tube including six-membered carbon rings similar to graphite. Single walled nanotubes are a crucial type of carbon nanotube owing to their good electric properties compared to MWCNTs [17]. The electrical properties of SWCNTs are distinctly different from their larger diameter MWCNTs counterparts due to their smaller diameters and larger aspect ratios.

**2.6 Multi-walled carbon nanotubes (MWCNTs)**

Multi-walled carbon nanotubes (MWCNTs) are one of the most preferable CNTs. Structurally, MWCNTs possess multiple layers of graphite superimposed and rolled in on themselves to make a tube shape. Moreover, these can be considered as a collection of concentric SWCNTs consisting of different diameters, lengths and natures. MWCNTs are the most promising -dimensional materials due to their attractive properties. The structural disorders, appearing in MWCNTs during their synthesis, are responsible for their electrical and optical properties of MWCNTs [21]. As the result of their high aspect ratio, large surface area and low percolation threshold, MWCNTs are favoured as more effective nanofillers rather than SWCNTs in terms of EMI shielding applications.

**2.7 Carbon fiber (CF)**

Similar to other carbon materials, the carbon fiber also possesses a high mechanical strength and a low density but has poor thermal expansion coefficient. CFs composed of fibers between 50 to 10 mm in diameter mainly consisted of carbon atoms. Their lower magnetism and high conductivity increase the impedance mismatching in EMI due to increase in their skin depth, similar to CNTs. Hence, modification of CFs with Fe, Fe3O4, Fe2O3 or alloys could be a useful approach to handle the above problem. Still, the high cost of CFs limits their potential for extensive use in potential applications. Apart from these nanofillers, graphitic carbon, carbon black and carbon coils have also been used for EMI applications.

Feng et al. [22] have investigated the EMI shielding behaviour of FeNi@C nano- composites which has shown the dual dielectric relaxation which occurs due to a cooperative consequence of the FeNi–C interfaces and dielectric carbon. Therefore, the synergy of dielectric and magnetic losses in FeNi@C provides excellent microwave absorption performance. Du et al. [23] prepared a core@shell Fe3O4@C structure with 500 nm Fe3O4 microspheres. Observation revealed that carbon coating on the Fe3O4 microspheres increased the complex permittivity, and improved impedance matching occurred due to multiple relaxation processes. On the specific thickness of shells, Fe3O4@C showed an unusual dielectric behavior that favored a strong reflection loss, even at high frequencies.

**3. Conclusions**

In brief, the carbon based materials are very useful from an applications points of view in the fields of energy, medical, research and many others. In this review paper, we explored carbonaceous composites containing graphite, graphene, reduced graphene oxide, carbon nanotube (single-walled and multi-walled), carbon fiber nanomaterials as important constituents for the prevention of electromagnetic interference (EMI) by reflection as well as by absorption. Two losses, dielectric and magnetic, are responsible for high microwave absorption and the total shielding performance. In this context, the carbonaceous materials would be useful for defence applications, microwave telecommunications.

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