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Fast Estimate of Plane Wave Attenuation of Conductive Powders for Rapid Deployment of Customized Cement Based Microwave Absorbing Solutions

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Abstract—Enhancing the electromagnetic absorption properties of pozzolanic cement provides scope for low cost realisation of frequency screened buildings. Electromagnetic wave attenuation attribute of conductive filler inclusions determines the absorption properties of filler loaded cement mortar. A transmission line based rapid measurement technique for the speedy estimate of microwave attenuation of conductive fillers is presented, providing quick approximates of cement mortar thickness for realizing customized absorption loss. Ash from three units of steel plant including EAF, AoD, and ARS units is investigated. Coaxial transmission line supports TEM propagation, hence is well suited for estimating plane wave characteristics. Ash filled coaxial transmission structures are subjected to scattering matrix measurements in the frequency range 800 MHz–4 GHz. Plane wave attenuation is estimated from the scattering matrix transfer coefficient (S_{21}). Ashes guarantee minimum 10 dB/m attenuation in the specified frequency range with ash from ARS unit providing loss over 50 dB/m. The database of customized cement mortar (composite) thickness for realizing varied absorption losses, incorporating ARS ash, is projected. The presented technique reduces the requirement of anechoic chambers, broad band horns, and liability of prototyping large mortar samples (all frequency dependent), for estimating shielding properties of conductive filler loaded cement mortar composites, over wide band. Cement panels with customized absorption loss provide scope as low cost solution for managing device co-location issues encountered in evaluating EMI/EMC concerns is future IoT based systems.

1. INTRODUCTION

Enhancing electrical conductivity of composites employed in construction industry, including cement mortar and concrete, is an emerging low cost solution for realizing large area electromagnetic shielding applications [1, 2]. Cement mortar, an integral constituent of construction sector, employed as plaster or as concrete constituent, exhibits significant electromagnetic Shielding Effectiveness (SE) due to its inherent conductivity. Conducting Additives, referred as fillers, are mixed to enhance shielding effectiveness.

An entire gamut of materials ranging from fly ash from thermal plants, ash from steel industry, slags from copper smelter, carbon black, graphite, polystyrene beads have been investigated as conductive inclusions. Innovative fillers explored include CNTs [3], magnetitie gypsum plaster [4], medicinal package waste [5], and polymer based nano-composites [6]. Ocean of literature has been generated in this domain, exploring the effect of conductive fillers to enhance SE of cementitious composites [7].

Conventional SE measurement as per ASTM D-4935 mandates exposing the sample (cement mortar+conductive filler) to plane wave Transverse Electromagnetic Mode (TEM) scenario,

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necessitating huge sample sizes, broad band horns and anechoic chambers or Open Area Test Site (OATS) [5]. Guided wave techniques, conducted in laboratory scenario, to characterize microwave reflection/absorption properties of samples, thereby providing shielding effectiveness assessments, have been reported, to avoid sizable instrumentation required for plane wave scenario [6, 8]. Guided Wave techniques for direct estimation of SE has started gaining traction over the last five years [3, 4].

Plane wave absorption/reflection properties of conductive additives determine the shielding effectiveness of the cement mortar [7]. This work presents a transmission line based rapid technique to estimate the plane wave attenuation of powders (fillers) employed as conductive fillers in cement mortar composites. Mortar (composite) thickness required for realizing specific absorption loss is computed. Graphical data representing loss-thickness relation provide rapid assessments of shielding effectiveness and aid in speedy deployment of electromagnetic screened buildings, with specified absorption loss reducing the liability of prototyping large cement and concrete samples to determine shielding effectiveness.

The ash from steel plants is explored as a conducting filler. Ready mix cement panels [9] loaded with conductive fillers are proposed as sustainable customized electromagnetic absorber solutions. The knowledge of attenuation level of conductive fillers aids in estimating panel thickness required for realising customized absorption loss. The paper concludes with the discussion on employing cement panels as solutions for EMI/EMC issues expected in emerging systems including IoT and 5G.

2. STEEL ASH AS CONDUCTIVE FILLER

Steel manufacturing creates various types of ashes as byproducts. Ash disposal has been a perennial problem. Compared to the research on utilisation of fly ash from thermal plants, literature on steel ash utilisation is limited. Steel slag recycling and utilization in concrete applications in various sectors including civil, agriculture and marine have been explored [10, 11]. Steel based byproducts possess significant ferrous content that augurs well for electromagnetic wave absorption. Cement based slag loaded composites are subjected to electromagnetic absorption tests in the frequency range 1–18 GHz. Minimum reflectivity observed is −21 dB, indicating high absorption property [12].

The present work considers three types of ashes, including ash from Electric Arc Furnace (EAF), Argon-Oxygen decarburization (AOD) unit, and Acid Recovery Stations (ARS). The composition of each ash is provided in Table 1, as available from Salem steel plant. Plane wave attenuation of steel ash is investigated. Ash filled resonator is subjected to scattering parameter analysis in the frequency range 800 MHz–4 GHz. The results obtained present close consistency with microwave properties determined for steel slags reported in literature [12, 13].

Table 1. Component percentages of steel ash.

	Individual Constituents (percentage)					
	$\mathbf{Fe_2O_3}$	$\mathbf{Cr_2O_3}$	**MnO**	$\mathbf{Al_2O_3}$	**CaO**	**MgO**
EAF Ash	48	11	4	0.8	8	4
AoD Ash	40	8	2	1	29	5
ARS Ash	76.3	11.9	3.3	4.7	0.6	0.7

(Courtesy: Steel Authority of India, Salem Steel Plant, Salem, Tamilnadu, India)

3. METHODOLOGY

Plane wave absorption loss (AL) characterization is essential for estimating shielding effectiveness of electromagnetic absorbers [14]. Absorption loss is defined in Eq. (1).

$$AL = 20 \log_{10} \left(e^{\alpha t}\right) \tag{1}$$

Parameter "α" represents the attenuation offered by material to a Transverse Electromagnetic Mode (TEM) wave, and "t" represents the thickness of the material medium. The absorption loss of conductive powder, employed as a filler, determines the absorption loss of the final composite. Coaxial transmission line supports TEM wave propagation, hence the preferred device for estimating TEM parameters for materials in powder state. The input and output voltages of a coaxial line are related exponentially:

$$V_o = V_{in}\left(e^{-\gamma L}\right) \quad (2)$$

Parameter "γ" represents the propagation constant including the attenuation (α — dB/m)) and phase constant (β — radian/m) of the filled dielectric(conductive powder), and 'L' is the length of the coaxial structure. For heavily conducting powders, the attenuation property significantly governs the propagation constant value ($\gamma \sim \alpha$). The knowledge of ratio (V_o/V_{in}) provides estimate of the exponential term in Eq. (2). The transfer coefficient S_{21} of the scattering matrix measured employing Vector Network Analyzer (VNA) provides the output-input voltage ratio. The TEM attenuation parameter 'α' (dB/m), required for computing Absorption Loss in Eq. (1), is determined.

3.1. Coaxial Transmission Line Design

A 10 cm, copper coaxial transmission line is designed. The inner and outer conductor radii are 6.4 mm and 12.6 mm, respectively. The prototype coaxial structure is shown in Figure 1. The attribute shown in Figure 2 depicts the feature for conducting measurements by varying dielectric.

Figure 1. Coaxial transmission line.

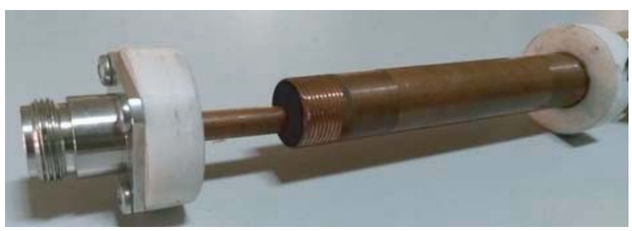

Figure 2. Design feature for varying dielectric.

4. SCATTERING MATRIX MEASUREMENT

The coaxial structure enables the measurement of plane wave parameters for conducting powders. The measured transfer coefficient of scattering matrix (S-matrix) relates to attenuation parameter in Equation (1). The S matrix of coaxial structure, with the three ashes filled is measured with Agilent Field Fox VNA (N9923A), with an operating range 100 MHz–4 GHz. Result analysis is restricted to the frequency range 800 MHz–4 GHz.

4.1. TEM Attenuation Constant Computation

The transfer characteristics of the coaxial structure represented by Equation (2) can be employed for determining the TEM attenuation of the powder material. For heavily conducting powders, the propagation constant $\gamma = \alpha + j\beta$ can be approximated as attenuation constant "α".

$$S_{21} = \frac{V_o}{V_{in}} = e^{-\alpha L} \quad (3)$$

where 'L' represents the length of the coaxial transmission line. The TEM attenuation constant can be computed as

$$\alpha = -\frac{\ln(S_{21})}{L}\,\mathrm{Np/m} \tag{4}$$

The attenuation values estimated through Eq. (4) possess unit Neper/m. The values multiplied by 8.686 provide the required estimates in dB/m. The attenuation values in dB/m are represented in Figure 3. The ash sample from Acid Recovery Station (ARS) exhibits high attenuation level over 50 dB/m, and the other ash samples provide minimum 20 dB/m in the adopted frequency range. The ferrous content (above 70%) in steel ash offers attractive scope as conductive filler for cement based wide band electromagnetic absorber, with minimum attenuation 10 dB/m, over entire frequency range.

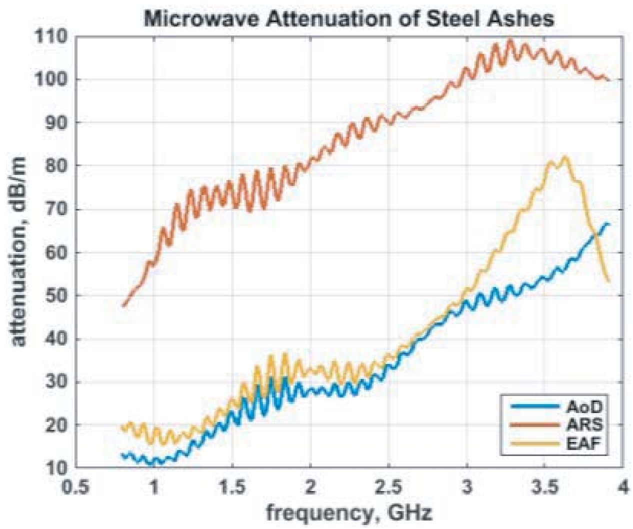

Figure 3. Microwave attenuation of steel ashes.

4.2. Comparison with Estimates from Material Studies

Literature on material analysis of ash from steel plants has witnessed steady growth over the last five years [10–13]. Estimates of electromagnetic parameters including permittivity and permeability have been documented through material studies [12, 13]. The attenuation computed through scattering matrix measurements is compared with the estimates computed employing material studies [12]. Attenuation values estimated through both approaches are provided in Table 2. Steel slag, a combination of ashes obtained from steel plants, is taken for studies in [12]. The measured results presented in this paper are exclusive to individual units of steel plants. The theoretical estimates bear close likeness to results for ashes from AoD and EAF unit. The high ferrous content of ash from ARS unit provides high attenuation levels.

Table 2. Comparison of measured attenuation (Np/m) with values estimated from [12].

Frequency (GHz)	Estimates — Material Studies (Np/m) [12]	Measurement Results (Np/m)		
		AoD	EAF	ARS
1	1.197	1.34	2	6.57
2	2.863	3.30	3.83	9.39
3	4.5646	5.55	5.93	11.77
4	5.498	8.29	5.80	12.06

5. DISCUSSION

5.1. EMC Issues in IoT

The futuristic communication scenario including Internet of things (IoT) is expected as the grand consolidation of all electronics and communication technologies. Successful IoT implementation necessitates the rugged and low cost deployment of communication systems, together with managing the complicated electromagnetic ambience in the environment. The major attributes in IoT deployment, which are of concern in evolving feasible EMC solution, are [15]:

a) Device Co-Location Density and Co-Location Distance:

The number of electronic devices, including sensors, actuators, transmitters, and receivers, presented per square km determines the size of IoT ranging from small, medium to Massive IoT. Estimates around ten thousand devices per square km are expected in Massive IoT scenario, necessitating challenging EMC solutions. Co-location distance refers to minimum distance between individual transceivers and is expected less than one meter in urban areas.

b) Shorter Range and Device Duty Cycle:

Energy conservation is an important attribute to be adopted in IoT design. Duty cycle refers to the transmitter ON time. Short bursts of ON time necessitate sufficient transient resilience in EMC solutions. Short range transmitter-receiver system is another aspect for enhancing energy efficiency. The high probability of receivers exposed to multiple transmitters is unavoidable.

c) Frequency of Operation:

Indiscriminate spectrum usage, by various service providers, in initial phase of IoT deployment may necessitate stringer EMC requirements in future, which may inhibit the very concept of massive integration of devices.

5.2. Electromagnetic Compatibility (EMC) Solutions for IoT

The primary component of any EMC solution, specifically in IoT scenario is a low cost, low weight, conformable and easily deployable electromagnetic (EM) absorber, at device level and structural level. Conductive filler loaded microwave composites offer feasible solutions for this scenario. Polymer based composite films as microwave absorbers have been aggressively researched and periodically reported over the past twenty years, the latest incumbent, combination of graphite and polyvinylidene fluoride (PVDF) [16] as thin film absorber for devices. Natural polymers including rubber sheets loaded with fly ash are good candidates for equipment level deployment [17].

The concept of Large Area Absorber (LAA) entails designing rugged, low cost, easily deployable electromagnetic absorbing solutions employing unconventional materials including cement, as replacement for conventional polymer and polyurethane based foam absorbers [1, 2, 5, 7, 8]. EMC solutions catering to IoT issues necessitate massive and fast deployment of conformal Large Area Absorbers. Electromagnetic Interference Shielding techniques employing cement based composites including plain mortar and concrete have been researched extensively over the last 15 years and are smart candidates for LAA deployment.

5.3. Cement Based EMC Solution

The researches on cement based electromagnetic interference (EMI) mitigation techniques have been reported extensively over last decade. The addition of conductive inclusions in cement composites, including plain mortar and concrete, enhances the EMI shielding property of cement composites. The conductive filler percentage and final composite thickness are important parameters that determine cost, deployment, and sustainability. Engineered conductive fillers including grapheme, multi-walled carbon nano-tubes (MWCNT), graphite, taconite, carbon black, carbon fibres, and steel fibres are attractive candidates for enhancing the shielding properties of cement composites [1, 2, 7, 8]. The emphasis on sustainable solutions has generated interest, in exploring industrial waste and byproducts including fly ash from thermal plants, medical package waste [5], and ash from steel industry [13], as conductive fillers. Important conclusion based on decade of research on enhancing EMI shielding properties of cement employing conductive fillers are [7]

- Responsibility to realize sustainable solutions employing industrial waste and byproducts to reduce negative environmental impact caused by indiscriminate disposal.
- The high volume fraction of fillers required to realize MIL STD -188-125-1, the earliest recommended standards on EMI/EMC, notwithstanding the stringent futuristic requirements mandated by widespread deployment of wireless systems.
- The unavoidable reduction in mechanical strength of the final product due to addition of conductive inclusions.
- Necessity to incorporate multiple fillers to enhance EMI shielding property, concurrently avoid degradation in mechanical properties.

5.3.1. Requirement of Fast Techniques to Characterize Absorption Loss

Conventional EMI characterization of cement based composites requires large prototypes with measurements conducted in anechoic chambers or Open Area Test Site (OATS) [5, 7], employing wideband horn antennas and associated instrumentation. The scenario is further complicated for lower frequencies with huge antenna sizes and subsequent increase in chamber dimensions. Wideband characterisation is extremely cumbersome due to the frequency dependent instrumentation and measurement systems.

The paper presents a fast technique to characterize the absorption loss of conductive fillers exploiting the frequency independent property of coaxial structure. The technique assumes significance in multi-filler scenario. Novel combination of fillers, including fly ash from different plants, ash mixes from thermal and steel plants, ashes with rice husk and agricultural byproducts, can be characterized for their shielding properties before-hand resorting to prototyping huge cement samples. Generating data on optimum mix ratio of conductive fillers and absorption loss estimates could be beneficial, for rapid field deployment of customized solutions. Preliminary discussion on design of customized cement based absorbing panel, based on employing coaxial techniques for filler characterization is presented in the succeeding section.

5.4. Sustainable Customized Cement Based Electromagnetic Absorber Panels

Sustainable ready-mix cement panels are recent innovations explored for incorporating thermal insulation to existing buildings [9]. Incorporating steel ash individually or in specific mix ratio could provide varying absorption loss, providing good value addition to the panel. Commercial realization of the proposed panel necessitates the estimate of two design parameters including panel thickness and filler percentage.

5.4.1. Panel Thickness

The knowledge of TEM attenuation values of conductive fillers provides scope for quick estimate of final composite thickness required for realising specific absorption loss, employing Equation (1). Thickness for specific attenuation levels, employing ARS ash, is provided in Figure 4. Panel thickness around 8 cm provides minimum 6 dB absorption loss in frequency range covering existing commercial wireless communication applications.

5.4.2. Determining Optimum Filler Percentage

The panel thickness depicted in Figure 4 assumes 100% filler concentration. Real time filler percentage in cement prototypes is restricted by the deterioration in mechanical properties. The optimum filler percentage reported in literature is around 40% [13]. Cement panels, compared to rubber sheet [16], possess higher inherent conductivity and could provide improved absorption loss compared to that presented in Figure 4. The thickness values shown in Figure 4 provide ***estimate*** of plaster thickness and probably serve as the plastering guideline for future constructions requiring electromagnetic shielding, employing steel ash loaded cement mortar.

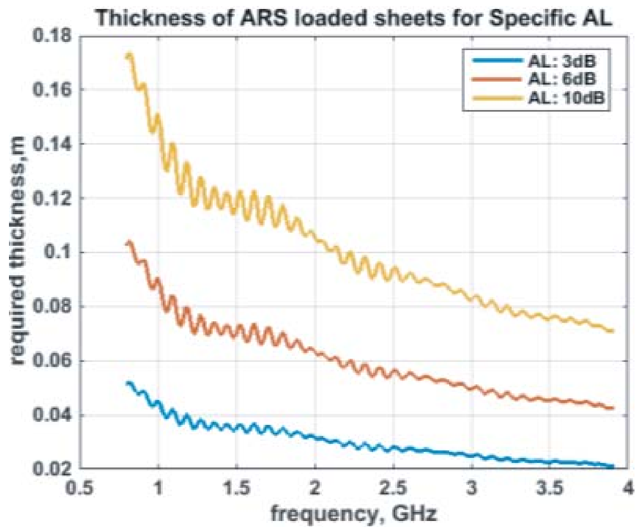

Figure 4. Thickness of ARS loaded panel for specific absorption loss.

6. CONCLUSION

Electromagnetically shielded buildings act as first line geo-fence against electromagnetic interference. Cement mortar and concrete loaded with conductive additives present a sustainable and low cost solution for realising electromagnetic screening. Ash waste from steel plants is investigated as a conductive filler for cement based composites. The transmission line based technique to estimate attenuation attribute of conductive fillers provides quick estimates of cement mortar thickness required to realise customized absorption loss in buildings, without massive conventional microwave instrumentation. Employing different steel ashes in varying composition in combination with reported low profile fillers [5, 7] provide scope for realising sustainable, low cost, custom-specific frequency screening walls and buildings vital for the complicated EM scenario resulting from 5G and advanced wireless sensor networks in future [14].

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