CORRIGENDUM

Corrigendum: A theoretical model for the electromagnetic radiation emission from hydrated cylindrical cement paste under impact loading (2018 J. Phys. Commun. 2 035047)

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Few errors in the equations (equations (12) to (17)) used were discovered after the paper described above got published.

Equations starting from 12 up to equation (17) and the text contained in between should be written as mentioned below.

(i) the radiation fields

\[
\begin{align*}
\vec{E}_1(\vec{r}, t) &= \frac{\mu_0}{4\pi r} \left\{ \left[ \dot{\rho}(t_0) \sin \theta \cos \theta \right] \hat{a}_\varphi + \left[ \dot{\eta}(t_0) \sin^2 \theta \right] \hat{a}_z \right\} \\
\vec{B}_1(\vec{r}, t) &= \frac{\mu_0}{4\pi \epsilon_0 r} \left[ \dot{\rho}(t_0) \sin \theta \right] \hat{a}_\varphi 
\end{align*}
\]

(ii) the induction fields

\[
\begin{align*}
\vec{E}_2(\vec{r}, t) &= \frac{\mu_0 \epsilon_0}{4\pi r^2} \left\{ \left[ 3\dot{\rho}(t_0) \sin \theta \cos \theta \right] \hat{a}_\varphi + \left[ 2 \cos^2 \theta - \sin^2 \theta \right] \dot{\rho}(t_0) \hat{a}_z \right\} \\
\vec{B}_2(\vec{r}, t) &= \frac{\mu_0}{4\pi \epsilon_0 r} \left[ \dot{\rho}(t_0) \sin \theta \right] \hat{a}_\varphi 
\end{align*}
\]

(iii) the static dipole fields

\[
\begin{align*}
\vec{E}_3(\vec{r}, t) &= -\frac{\mu_0 \epsilon_0}{4\pi r^3} \left[ p(t_0) \hat{a}_\varphi \right] \\
\vec{B}_3(\vec{r}, t) &= 0
\end{align*}
\]

Thus the total electric and magnetic fields are:

\[
\begin{align*}
\vec{E}(\vec{r}, t) &= \vec{E}_1(\vec{r}, t) + \vec{E}_2(\vec{r}, t) + \vec{E}_3(\vec{r}, t) \\
\vec{B}(\vec{r}, t) &= \vec{B}_1(\vec{r}, t) + \vec{B}_2(\vec{r}, t) + \frac{1}{\epsilon_0} \hat{a} \times \left[ \vec{E}_1(\vec{r}, t) + \vec{E}_2(\vec{r}, t) \right]
\end{align*}
\]

Now, the total electric field \( \vec{E}(\vec{r}, t) \) and total magnetic field \( \vec{B}(\vec{r}, t) \) in terms of three components in cylindrical co-ordinate system is given as:

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The changes made above in the equations have no effect on the main conclusion of the paper. The main idea and conclusion of the manuscript will remain exactly the same.

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PAPER

A theoretical model for the electromagnetic radiation emission from hydrated cylindrical cement paste under impact loading

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Keywords: cement paste, theoretical model, impact loading, electromagnetic radiation (EMR)

Abstract

This paper presents the detection of the electromagnetic radiation (EMR) from the hydrated cement paste samples when impacted by dropping weight. Cylindrical cement samples cured for 28 days emit EMR in the range of 44 mV to 95 mV as the height of impact is varied from 6 cm to 21 cm. The EMR voltage increases linearly as the height of impact increases. This suggests the suitability of the EMR measurement for the structural health monitoring under dynamic loading conditions. A theoretical model has been presented to explain the occurrence of the EMR under impact. The ions present in the capillary pores of the hydrated cement paste lead to the formation of dipoles at the solid liquid interface. When impact is applied the separation distance between the opposite charges of the dipoles undergoes transient variation causing the EMR. Theoretically calculated EMR voltages are in good agreement with the experimental results in nature as well as magnitude.

1. Introduction

Electrical effects due to fracture and deformation of materials have been in limelight for a long time and have been explored for numerous materials. Interest in this field got an impulse when electrical effects associated with the plastic deformation of the ionic crystals were reported by various authors \cite{1,2,3}. Later study on electromagnetic radiation (EMR) emission from fracture of rocks was also explored for developing the technique for earthquake prognosis \cite{4,5}. EMR emission from wide variety of rocks subjected to varying load conditions, during micro cracking and fracture has been observed and reported \cite{4,6,7,8,9,10,11}. Misra (1975) reported the preliminary investigations of electromagnetic radiation (EMR) emission from metals \cite{12}. Later this phenomenon was explored and reported by various authors \cite{13,14,15,16,17,18,19,20,21}. Coal has been investigated widely for the electromagnetic emission phenomenon for monitoring the stress state in the coal mines \cite{22,23,24,25,26}. Electromagnetic emission from ice under compressive load has been studied widely to develop a clear understanding of stress states in large ice glaciers which are not stable and are prone to failure \cite{27,28}. Dickinson and co-workers have extensively studied fracture emissions from polymers and polymer composites \cite{29,30}. Recently Sharma \textit{et al} have reported the electromagnetic emission from lead-free and lead-based ferroelectric materials subjected to externally applied alternating electric field and impact loading, respectively \cite{31,32}. Theoretical models for the electromagnetic emissions from metals, rock, ice and various other materials has been proposed earlier alongside the experimental studies \cite{21,33,34,35}. Misra \textit{et al} proposed a theoretical model which concludes the vibration of pinned dislocations as the genesis for EMR emission from metals and alloys \cite{16,21}. According to the model proposed for the EMR emission from rocks formation of parallel plate capacitor due to charge separation and change in potential due to crack movement leads to EMR emissions \cite{11}. Steven O’Keefe \textit{et al} have also explained the observed EMR emission from ice and coal based on parallel plate capacitor model \cite{36}. Rabinovich \textit{et al} and Frid \textit{et al} reported that oscillations of the ions formed at the adjacent sides of cracked surface leads to electromagnetic radiation (EMR) which is different from the earlier proposed capacitor based model \cite{35,36}. This surface oscillation model has been adopted by Lacidogna \textit{et al} for describing the EMR signal observed during compression of different types of brittle materials \cite{37}. Recently Sharma \textit{et al}...
have proposed a theoretical model which considers the 180° oscillations of dipoles under the effect of applied alternating electric field as the genesis for the observed electromagnetic emissions [39].

Electrical signals from cement and cement based materials have been an active research area from the last half century and has been explored widely [40–44]. F H Whittman tested the cement paste specimen during bending and recorded the electrical signals from the electrodes fixed on the two opposite sides [40]. A direct proportionality has been obtained between the applied load and the voltage recorded [40]. Li et al studied the electromechanical effect of hardened cement paste [41]. During this study shape change due to the applied electric field has been observed in wet samples only and electro-osmotically induced swelling of pores has been considered as the reason for the observed phenomenon [41]. Kyriazoopoulos et al have detected the electric current signals from the concrete specimen subjected to uniaxial compression and three-point bending [45].

The current signals were detected through the gold electrodes mounted on the stressed sample’s surface and the technique has been named as pressure stimulated current (PSC) technique. During the experiments maximum value of PSC (PSC_{max}) are found to be proportional to the strain rate (dε(t)/dt) [45]. Sklarczyk and Altpeter reported the electrical emission from mortar and concrete when subjected to impact loading. Movement of double electric layers under the impact loading has been considered as the reason for the observed emissions [46]. Mingqing Sun and co-workers studied electrical emissions from cement under compressive loading [47, 48]. Sun et al measured the voltage by subjecting carbon fibre reinforced cement to compressive loading [49].

Literature suggests that the most of the studies (e.g. metals, rock, coal, ice, glass and various brittle materials) have largely been concentrated on the signals emitted during the occurrence of permanent damage to the material [8, 16, 30]. Being a constructional material EMR emission from rocks, granites etc has received considerable attention while EMR emission from piezoelectric ceramics needs to be further explored. Cement being a ubiquitous structural material should be explored for EMR emission characteristics. As per the authors’ knowledge a proper theoretical model explaining the electromagnetic emissions from cement still lacks in literature. Thus in the present study 28 days cured cement samples have been studied for EMR emission under impact loading and a mathematical model explaining the physics involved has been presented for the same.

2. Experimental procedure

2.1. Sample preparation

Samples were prepared using Portland Pozzolana Cement (PPC). Water was added to the cement using pipette keeping the water to cement (w/c) ratio of 0.33. Cement and water were mixed thoroughly for 5 min. After mixing properly, cement paste was poured into cylindrical moulds of internal diameter and height of 22 mm and shaken for 5 min to reduce the air trapped in the mixture. Samples were demoulded after curing in air for one day. Then the cement paste samples were allowed to cure in water for 28 days. It was made sure during the process that demoulded samples had diameter (D) and height (L) of 22 mm.

2.2. Instrumentation

The schematic diagram of experimental set up is shown in figure 1. Two parallel plates made of bakelite were used which were separated by bolts and nuts. Sample was placed between these two parallel plates. A steel rod having equidistant holes to mount weight was fixed centrally to the upper bakelite plate. Slotted cylindrical weight of 0.5 kg was used to apply impact from different heights marked on the rod. The bakelite plates avoided any electric discharge between sample and the weight.

One Rohde and Schwarz make digital oscilloscope HMO2524 having specification 250 MHz/2.5 GSa/4MB was used to capture the EMR signals. An antenna was made from copper strip of length 150 mm and width 18 mm and thickness 0.1 mm. This rectangular copper strip was folded into a circular loop having diameter of 47 mm and was placed around the sample to capture EMR signals emitted from the sample. One end of the measuring probe of the oscilloscope was connected to the antenna and another one was grounded.

Cured samples taken out of water after 28 days and then dried in oven at 100 °C for 6 h have been used for experiments. To study the electromagnetic radiation response, the tests were performed by dropping the weights from different heights on the specimen. To ensure repeatability of the results, 6 sets of samples were prepared for each height and 7 readings were taken for each height on each sample.

3. Results obtained

Figure 2(a) shows the variation of maximum EMR voltage with respect to the height of impact for 28 days water cured (and then oven dried) cement samples. Maximum peak voltage is found to vary from 44 mV to 95 mV. EMR signal amplitude increases as the height of the impact loading increases. Oscillating damped EMR signals
are obtained for impact from different heights. Figure 2(b) shows the typical EMR waveform of the signal for height of impact of 21 cm. The proportional variation of maximum EMR voltage with height of impact suggests that the extent of deformation of cement structures under impact loading may be obtained by measuring EMR voltage. A comprehensive discussion of experimental and theoretical results is being made in the Results and discussion section (section 6). As mentioned in section 2.2 during EMR measurement the annular loop antenna was hanging freely around the sample and was not touching the bakelite plate. Also, bakelite is one form of thermosetting plastic (a type of polymer) and will not emit EMR until subjected to very high strain rate and plastic deformation [30, 31, 50]. Moreover, the EMR emissions from set up were checked separately and no emissions were detected from the same. Thus the EMR emissions from experimental set up are neglected in the present study.
4. Physical mechanism

Before formulating a model for the occurrence of the EMR for the present set of experiments, it is worthwhile to consider the experiments conducted earlier and proposed theoretical models discussed in section 1 (Introduction). Till now most of the studies on deformation induced emissions are primarily related to the emissions occurring during permanent damage to the materials such as plastic deformation, crack propagation or fracture. Because of this theoretical models proposed earlier are mostly centred around the phenomena related to plastic deformation or crack propagation involving movement of dislocations causing the accelerated movement of charges or the redistribution of charges on the newly formed crack surfaces. In the experiments presented in this paper the deformation is produced due to the impact caused by the weight drop. Even weight dropped from the small height of 6 cm causes EMR. Further the signals from the same sample can be obtained by dropping the weight again. Considering this the genesis of the EMR from the hydrated cement paste under impact should have a mechanism which can be repeated many times without causing serious damage to the material.

Cement has remained a popular area of investigation because of change in physical and chemical properties exhibited by cement when mixed with water. To understand the cause of electromagnetic radiation from a cement sample it is imperative to discuss about the internal structure of hydrated cement paste. In hydrated cement paste there are two kinds of pores: (a) gel pores, which are characteristic feature pertaining to the structure of gel and (b) capillary pores or cavities which are the regions not filled by gel during hydration. Water tends to reside in these pores [51]. The water present in the pores can be evaporable and non-evaporable. The evaporable water is assumed to reside partly in capillary pores and partly in gel pores. Ions such as Ca$^{2+}$, Mg$^{2+}$, Na$^+$, K$^+$, OH$^-$ etc are generally present in the water and thus it acts as an electrolyte. In any such solid-electrolyte system there is a specific liquid region in contact with the solid surface referred to as electrical double layer or diffuse layer [40].

Formation of electrical double layer and electrification of cracked surface has been studied extensively with respect to electrical emissions from cement based materials [40, 52–54]. Mingqing Sun et al have considered the formation of electrical double layer and motion of ions under compressive load as the cause for the observed electrical signal from cement [47, 48].

Consider a cylindrical cement sample containing capillary pores as shown in figure 3(a). Capillary pores are depicted in exaggerated size for visualization. Expanded view of a capillary pore is shown in figure 3(b). The ions present in the water residing in the pores have a tendency to get adsorbed on the solid surface adjacent to them, the oppositely charged ions get lined up in the liquid phase [50, 51]. Figure 3(b) depicts ions of a type adsorbed on the capillary surface whereas oppositely charged ions get lined up in the liquid region. This leads to the formation of dipoles as depicted. The impact applied through the weight drop will produce a strain wave in the sample. This strain wave will cause variation in the separation distance of the dipoles formed in the capillary pores. The transient variation in the separation distance leads to the variation in the dipole moment with time which subsides after a very short duration. Thus the vibrations set up in the sample due to applied impact will lead to the EMR because the time varying dipole moment causes EMR [55].
5. Mathematical model

5.1. Formulation of electric dipole under impact loading

As discussed in the physical mechanism the adsorption of ions presents in the capillary pores in the solid surface and the lining up of the ions of opposite charges in the liquid phase causes the formation of dipoles. If \( n \) is the number of ions each with charge \( q \) adsorbed in the solid surface, then charge on the dipole will be \( nq \) and let the separation distance between the opposite charges be \( d \). Then the dipole moment for each dipole when there is no external force acting on the sample will be \( p = nqd \). When impact is applied through weight drop then the separation distance will fluctuate for some time until the vibrations in the sample stop. Let the variation in the separation distance be represented by \( d_d \) so that the total dipole moment when sample is under the effect of impact is given by:

\[
p = nq(d + d_d)
\]  

(1)

Whenever an impact is applied to a body such that it can deform the body within the limits of linear elasticity vibrations are set up in the body.

Assuming that the whole of kinetic energy of the applied weight was converted into strain energy absorbed by the sample. Thus for elastic deformation of the structure, the maximum value of strain energy can be expressed as:

\[
U_{\text{max}} = \int \sigma_{\text{max}}^2 dV
\]

(2)

where \( E \) and \( V \) are the elastic modulus and volume of the sample respectively.

In case of uniform cylindrical samples, it can be assumed that stress distribution is uniform when the impact is applied. Therefore, equating the kinetic energy of the weight dropped to the strain energy of the sample:

\[
\frac{1}{2}mv^2 = \frac{1}{2} \sigma_{\text{max}}^2 \varepsilon_{\text{max}} V
\]

(3)

where \( m \) and \( v \), are mass and velocity of the striker.

Polymeric materials are known to absorb energy during impact and dynamic loadings which leads to their usage in different areas [56–58]. Bakelite is a polymer categorized as a thermoset plastic and elastic modulus of polymers generally lies in the range of 3450 MPa [59] which is less than elastic constant for cement. Thus bakelite plates are likely to absorb energy during impact and reduce the extent of transfer of the impact energy to the cement sample. Moreover, in the experimental set up two bakelite plates were used where the bottom plate was fixed with nut and threaded rods whereas the upper one was mobile through the rods which were movable through the holes drilled in the upper bakelite plate. Friction is also one of the factor which can hamper the movement of bakelite plate during the impact loading.

Thus considering the materialistic aspects and constraints of the experimental set up it is logical to expect that only a part of the impact energy will actually be transferred to the sample. For the initial approximations seeing the polymeric behavior of bakelite and not so smooth movement of bakelite plate during impact loading only 50% energy transferred has been considered. In light of this assumption maximum strain value is obtained as:

\[
\varepsilon_{\text{max}} = \sqrt{\frac{1}{2} \frac{mv^2}{EV}}
\]

(4)

Where, \( \varepsilon_{\text{max}} = \frac{n_{\text{max}}}{E} \)

Now if it is assumed that the distribution of the normal strain is uniform throughout the sample then the variation in the dipole separation distance can be proportionately expressed as:

\[
d_d = \varepsilon_{\text{max}}d
\]

Now, depending on the damping offered by the intermolecular friction of the sample the strain will subside when the systems attains equilibrium after some oscillations. The transient fluctuation in the separation distance can then be expressed as:

\[
d_d = d_0e^{-\omega_d t} \sin(\omega_d t)
\]

(5)

Substituting the value of \( d_d \) in equation (1)

\[
p = nq(d + d_0e^{-\omega_d t} \sin(\omega_d t))
\]

(6)

where \( d_0 \) is the separation distance of the dipoles, \( \omega_n \) is the natural frequency, \( \omega_d \) is the damped natural frequency and \( \zeta \) is the damping factor.

Differentiating this with respect to time we get the first and second time derivatives of the dipole moment as given below:
A detailed derivation of electric field, magnetic field and power radiated due to EMR may be obtained from Griffiths and Misra \cite{16, 21, 55}. Some basic safe assumptions are made there like motion of charges is arbitrary and all charges are confined in a volume which is very small compared to the dominant wavelength of radiation. Also the charges are assumed to be moving slowly as compared to the speed of light. The charge element is positioned at $r \rho$ where origin is considered inside the small volume. It is considered that the field point $P$ is at distance $r \rho$ from the origin and auxiliary distance is $R = \rho - \rho'$ as can be seen from figure 4. It is also assumed that point $P$ is far away as compared to source distribution i.e. $\rho' \ll \rho$.

The electric and magnetic fields represented by $E$ and $B$ respectively, at point $P$ are as follows \cite{21}:

(i) the radiation fields

\[
\begin{align*}
\vec{E}_r(\vec{r}, t) &= \frac{\mu_0}{4\pi \rho} \left\{ \vec{a}_r \times \{ \vec{a}_r \times \vec{p}(t_0) \} \right\} \\
\vec{B}_r(\vec{r}, t) &= -\frac{\mu_0}{4\pi c_0 \rho} \{ \vec{a}_r \times \vec{p}(t_0) \}
\end{align*}
\]

(iii) the static dipole fields

\[
\begin{align*}
\vec{E}_d(\vec{r}, t) &= \frac{\mu_0 c_0^2}{4\pi \rho^3} \left\{ \vec{a}_r \times \{ \vec{a}_r \times \vec{p}(t_0) \} + 2\{ \vec{a}_r \cdot \vec{p}(t_0) \} \vec{a}_r \right\} \\
\vec{B}_d(\vec{r}, t) &= 0
\end{align*}
\]

where $\vec{E}_d(\vec{r}, t)$ varies as $1/\rho^3$ and depends on $\vec{p}(t_0)$.

In the above expressions, $\mu_0$ is the permeability of free space; $t_0 = (t - \rho/c_0)$ is the retarded time; $c_0$ is the speed of light in free space and $\vec{p}(t_0)$ is the dipole moment at retarded time $t_0$.

In the present case cement sample and antenna used are of cylindrical shape so coordinate transformation is used to convert electric and magnetic field into cylindrical coordinate system. Figure 5 represents a vector $\vec{A}$ in spherical coordinate system given by equation:

\[
\vec{A} = \vec{a}_r + \vec{a}_\theta + \vec{a}_\phi
\]

where $\vec{a}_r$, $\vec{a}_\theta$ and $\vec{a}_\phi$ are the unit vectors in $r$, $\theta$ and $\phi$ directions.

Vector $\vec{A}$ in spherical coordinates can be transformed to cylindrical coordinates using following transformations:
The formation of the dipoles is depicted in the figure 3. The directions of the dipole moment and its two derivatives are considered as $\vec{p}(t) = p(t) \hat{a}_r$, $\vec{\dot{p}}(t) = \dot{p}(t) \hat{a}_r$ and $\vec{\ddot{p}}(t) = \ddot{p}(t) \hat{a}_z$. The considered orientation is depicted in figure 6. The orientation of dipole moment $\vec{p}(r', t)$ is taken along $\phi$ direction while for small oscillations direction of $\vec{p}(r, t)$ and $\vec{\dot{p}}(r, t)$ may be assumed to be along $z$ direction. The discussion for choosing the same has been incorporated in the section 5.2.

Using the equation (11) for conversion of the equations of electric and magnetic fields from spherical coordinates to cylindrical coordinates the electric and magnetic fields in cylindrical coordinates are obtained given below:

\[
\begin{bmatrix}
\hat{a}_r \\
\hat{a}_\theta \\
\hat{a}_\phi
\end{bmatrix} =
\begin{bmatrix}
\sin \theta & 0 & \cos \theta \\
\cos \theta & 0 & -\sin \theta \\
0 & 1 & 0
\end{bmatrix}
\begin{bmatrix}
\hat{a}_r \\
\hat{a}_\phi
\end{bmatrix}
\]

(11)
(i) the radiation fields

\[
\begin{aligned}
\vec{E}_1(\vec{r}, t) &= \frac{\mu_0}{4\pi r} \left[ \{ \vec{p}(t_0) \sin \theta \cos \theta \} \vec{a}_\rho + \{ \vec{p}(t_0) \sin^2 \theta \} \vec{a}_z \right] \\
\vec{B}_1(\vec{r}, t) &= \frac{\mu_0}{4\pi r} \left[ \{ \vec{p}(t_0) \sin \theta \} \vec{a}_\phi \right]
\end{aligned}
\]

(ii) the induction fields

\[
\begin{aligned}
\vec{E}_2(\vec{r}, t) &= \frac{\mu_0 c_0}{4\pi r^2} \left[ \{ 3\vec{p}(t_0) \sin \theta \cos \theta \} \vec{a}_\rho + \{ 2\cos^2 \theta - \sin^2 \theta \} \vec{p}(t_0) \vec{a}_z \right] \\
\vec{B}_2(\vec{r}, t) &= \frac{\mu_0}{4\pi r^2} \left[ \{ \vec{p}(t_0) \sin \theta \} \vec{a}_\phi \right]
\end{aligned}
\]

(iii) the static dipole fields

\[
\begin{aligned}
\vec{E}_3(\vec{r}, t) &= -\frac{\mu_0 c_0^2}{4\pi r^3} \{ \vec{p}(t_0) \vec{a}_\rho \} \\
\vec{B}_3(\vec{r}, t) &= 0
\end{aligned}
\]

Thus the total electric and magnetic fields are:

\[
\begin{aligned}
\vec{E}(\vec{r}, t) &= \vec{E}_1(\vec{r}, t) + \vec{E}_2(\vec{r}, t) + \vec{E}_3(\vec{r}, t) \\
\vec{B}(\vec{r}, t) &= \vec{B}_1(\vec{r}, t) + \vec{B}_2(\vec{r}, t) + \frac{1}{c_0} \vec{a}_r \\
&= \times [\vec{E}_1(\vec{r}, t) + \vec{E}_2(\vec{r}, t)]
\end{aligned}
\]

Now, the total electric field \( \vec{E}(\vec{r}, t) \) and total magnetic field \( \vec{B}(\vec{r}, t) \) in terms of three components in cylindrical coordinate system is given as:

\[
\begin{aligned}
\vec{E}_1(\vec{r}, t) &= \vec{a}_\rho \left[ \frac{\mu_0}{4\pi r} \{ \vec{p}(t_0) \sin \theta \cos \theta \} \right] + \vec{a}_\phi \left[ \frac{\mu_0 c_0^2}{4\pi r^3} \{ \vec{p}(t_0) \vec{a}_\rho \} \right] \\
&\quad + \vec{a}_z \left[ \frac{\mu_0}{4\pi} \{ 2\cos^2 \theta - \sin^2 \theta \} \vec{p}(t_0) \right] \\
\vec{B}_1(\vec{r}, t) &= \vec{a}_\phi \left[ \frac{\mu_0 c_0}{4\pi r^2} \{ \vec{p}(t_0) \sin \theta \} \right] - \vec{a}_z \left[ \frac{\mu_0}{4\pi r} \{ \vec{p}(t_0) \sin \theta \} \right]
\end{aligned}
\]

Electromagnetic waves carry energy with them. Energy radiated per unit time per unit area is given by pointing vector (S) and can be calculated as follows [55]:

\[
S(\vec{r}, t) = \frac{1}{\mu_0} \left| \vec{E}(\vec{r}, t) \times \vec{B}(\vec{r}, t) \right|
\]

5.2. EMR voltage

In the present work EMR voltage has been measured using a cylindrical copper loop antenna placed around the cylindrical cement paste sample. Considering this geometry, the EMR generated from the dipoles in the radially outward direction will be the significant part reaching to the cylindrical copper loop antenna. Figure 6 gives an insight of the spatial orientation of the capillary pores present in the cement paste where \( \rho \) component directs radially outward towards the antenna. However, the direction consideration of \( \vec{p}(t) = p(t) \vec{a}_\rho \) and \( \vec{p}(t) = \vec{p}(t) \vec{a}_\phi \) yields the electric field expressions only with \( \vec{a}_\phi \) components. Since the signals observed in the experiment are obtained using the cylindrical antenna and the signals are also transient in nature which die out with time. There is no continuous static component in the signal. Obtaining no static component in the \( \vec{a}_\phi \) direction is thus in line with the observed results. However, a radial component along \( \vec{a}_\rho \) direction must be obtained. Hence the directions of \( \vec{p}(t) \) and \( \vec{p}(t) \) are chosen as \( \vec{p}(t) = p(t) \vec{a}_\rho \) and \( \vec{p}(t) = \vec{p}(t) \vec{a}_\phi \). Further, the situation will be analogous to that of an annular cylindrical capacitor whose one surface is collecting the charge.
So using Gauss law of electrostatics, surface charge density $\rho_s$ can be calculated as:

$$\rho_s = \varepsilon_0 E_o$$  \hspace{1cm} (19)

The total charge collected over the surface can be calculated as:

$$Q(t) = \int S \rho_s dS$$  \hspace{1cm} (20)

Where $dS = 2\pi r^2 \cot \theta d\theta$ surface of cylindrical antenna on which charge is collected. Using value of $dS$ along with $\rho_s$ from equation (19)

$$Q = \int_{\theta_1}^{\theta_2} \frac{\varepsilon_0 \varepsilon_r}{4\pi \delta r} \left\{ \vec{p}(t_0) \sin \theta \cos \theta \right\} + \frac{\varepsilon_0}{r} \left\{ 3\vec{p}(t_0) \sin \theta \cos \theta \right\} \left[ 2\pi r^2 \cot \theta d\theta \right]$$  \hspace{1cm} (21)

Further EMR voltage so obtained from antenna can be given by formulation of cylindrical capacitor as:

$$V = \frac{\ln(b/a)}{2\pi l} Q$$  \hspace{1cm} (22)

where $a$, $b$ and $l$ are the inner radius, outer radius and length of the cylindrical capacitor.

**6. Results and discussion**

In the present study the EMR produced from the hydrated cement paste samples under the application of impact is being investigated. The generation of EMR is considered due to the time dependent variation in the dipole moment due to the vibrations in sample.

In order to calculate the EMR voltage using the formulated mathematical model following material properties and parameters are considered. A cement sample with diameter (D) and length (L) of 22 mm was taken for study. As per the literature the porosity of the cement sample cured for 28 days was taken as 0.26 [51, 60]. Whereas Young’s Modulus ($E$), damping factor ($\zeta$) and density ($\rho$) of the cement sample under consideration was 21 GPa, 0.04 and 2240 kg m$^{-3}$ respectively [61–66]. Based on the Young’s modulus and the dimensions of the sample the natural frequency ($\omega_n$) is obtained as 874 kHz and for a given damping factor ($\zeta$) of 0.04 damped frequency ($\omega_d$) was found to be 873 kHz. A rectangular array of the dipoles which can be considered as a giant dipole has been assumed to exist at the capillaries. For this the capillaries are assumed to have following dimensions length ($L_p$), width ($W_p$) and thickness ($T_p$) of 5 $\mu$m, 2.5 $\mu$m and 1000 nm (figure 3), respectively. An annular cylindrical antenna of copper was used to measure the voltage. Based on the radius and length of copper loop antenna the outer radius $b$ is taken as 23 mm and length $l = 18$ mm. The inner radius $a$ is taken 11 mm based on the radius at the surface of sample from which radiations start then travel. The total charge collected on copper antenna is calculated by integrating the equation (21) over from $\theta_1 = 30^\circ$ to $\theta_2 = 150^\circ$. This charge collected was used as input for equation (22) to compute the EMR voltage. However, this voltage was due to only one dipole in a single capillary. To consider the effect of all the dipoles contained in the capillary pores number of capillary pores contained in the sample were approximated by taking the ratio of porous volume and volume of one capillary pore. Consequently, the total number of dipoles contained in the capillaries were calculated by taking into consideration the dimension of largest ion i.e. $K^+$ with ionic diameter of 266 pm.

Further, EMR from any solid exhibits skin depth ($\delta$) characteristics which suggests that only the EMR emitted from the part of the material very near to the surface of the sample can travel outside the sample. The EMR generated in the depth of the sample gets absorbed within the material and gets screened out. The smaller depth/thickness of the sample which can be crossed by the EMR is termed as skin depth ($\delta$). The skin depth is considered as a small depth in the range of few microns by some researchers [21, 34, 67]. In the present study, skin depth was assumed to be 50 $\mu$m and accordingly the EMR voltage was calculated for different heights of impact using the proposed model. The theoretically calculated EMR voltage signals are presented in the figure 7 along with the experimentally obtained signals. It can be observed in the figure 7 that damped oscillating signals are obtained experimentally as well as theoretically. The variation in the maximum amplitude of the EMR as the height of impact is varied is shown in figure 8. Though the theoretical and experimental results are in close agreement yet the magnitude of the theoretical and experimental values shows some difference. This variation in the theoretical and experimental values of EMR signal can be attributed to the fact that there are many contributing factors for the observed emissions such as no. of pores, no. of ions contained in pores, no. of dipoles formed etc. Also the measurable EMR is generated by ionic dipoles formed within the skin depth of the sample. The ionic concentration and number of dipoles formed within pores lying in skin depth may vary with location. Exact estimation and incorporation of the local variations in these internal contributing factors for the theoretical model is difficult. The more closer estimations of these contributing factors can provide nearly
matching results. Also it would be interesting to study in future, the effect of different shapes of arrays of ions on the EMR emission. This may allow obtaining a combination of different shapes to be considered for the results in closer agreement with the experimental observations. However, theoretically obtained EMR in present study shows a linear variation with the increase in the height of impact which is in agreement with the experimentally observed results. This linear increase in EMR voltage with increase in height suggests the suitability of EMR for deformation monitoring. Further the amplitudes of EMR signals obtained theoretically are in close agreement with the experimentally obtained values.

**Figure 7.** (a) Experimentally obtained typical EMR Voltage vs time responses by dropping weight from different heights. (b) Theoretically obtained EMR Voltage vs time responses for impact loading from different heights.

**Figure 8.** Comparison of peak EMR voltage values obtained theoretically and experimentally.
References

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Acknowledgments

7. Conclusions

Electromagnetic radiation has been recorded from hydrated cement paste samples subjected to impact loading. EMR in the range of 44 mV to 95 mV has been observed as the height of impact varies from 6 cm to 21 cm. The EMR voltage shows a proportional increment with the increase in the height of impact. This suggests the suitability of the EMR measurement for the structural health monitoring under dynamic loading conditions. A theoretical model has been presented to explain the occurrence of the EMR under impact. The ions present in the capillary pores of the hydrated cement paste lead to the formation of dipoles at the solid liquid interphase. When impact is applied the separation distance between the opposite charges of the dipoles undergoes transient variation. This cyclic change in the dipole moment leads to the observed EMR. Theoretically calculated EMR voltage matches well with the experimental results in nature as well as in magnitude.

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