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Damage Prediction of Bacteria based Concrete Structure using Smart Sensor based EMI Technology

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Abstract

Construction of structures required environment-friendly biodegradable materials for clean and sustainable environment. The electro mechanical impedance (EMI) technique is sensor based technology, used for damage investigation. This research paper is motivated on damage prediction of environment-friendly bacterial concrete structure using EMI technique through PZT sensors. For the groundwork of bacterial concrete cube specimens the *Bacillus subtilis* bacteria has been considered with concentration of the 10^5 cells/ml. The damage was predicted in standard and bacterial concrete cubes with PZT sensors after 3, 7, 14, and 28 days of curing exposed to failure loads. The conductance and susceptance signatures were extracted by LCR meter with surface attached PZT sensors. The change in the optimum values of extracted signatures were evaluated, subsequently the variations in frequency at optimum signatures were determined. The correlations have been developed between the root mean square deviation and percentage change in parameters. The conclusion has been made that the bacterial concrete had superior performance than the standard concrete. Therefore, the developed concept is significant for damage detection of real-life infrastructures for sustainable environment.

Keywords EMI technique, Environment-friendly bacteria, Bacterial concrete, PZT sensor.

1 Introduction

In the present scenario of revolution the protection of environment is the worldwide challenge for clean and sustainable environment. All living things are surrounded by environment and facing problems with the industrialisation. The production of concrete making materials for the infrastructure development is one of environmental issue because the manufacture of cement alone produces about seven percent of the total global carbon di-oxide emission. The construction of structural systems needed materials like fly ash, silica fume, ground granulated blast furnace slag, metakaolin, and shurkhi with the fractional replacement of cement for environment concern [1–3]. Several factors viz., physical, chemical and biological affect the concrete systems [4,5]. These factors are responsible for beginning and growth of damages in concrete structures. Cracked concrete structures are required money and attention for the remediation. The structural damage causes loss of strength and integrity, thus the catastrophic failure may occur. To protect the structures from the damages the environment-friendly sustainable materials are required. The materials such as shortcrete, mortar, polymers, and epoxy raisins can be used for damage reduction. However, applications of these materials in the concrete systems are harmful for the environment because of these materials is non-biodegradable. Thus, novel concept is required for the damage reduction in the structural systems using biodegradable materials. The use of bacteria in the concrete matrix is novel concept for the sustainable structures [6,7].

Bacteria based concrete systems are environment-friendly and more durable than normal concrete systems, the motivation for that is the production of calcite ($CaCO_3$) in concrete matrix in presence of CO_2 and H_2O [8,9]. The formed calcite fills the pores present inside the concrete and developed higher strength, subsequently heals the cracks automatically without human involvement that provides structural integrity, thus the overall quality of the concrete can be improved. The quality of bacterial concrete is influence by several issues such as kinds of bacteria, nutrients used for culture, cell concentration, and the way of application. Numerous kinds of bacteria have been used in concrete for the sustainability; however some bacteria have positive impact and few of them show negative effect on the bacterial concrete properties. Based on the requirement, the optimal cell concentration of bacteria can be selected. Generally, for the optimum compressive strength the bacterial concentration of the 10^5 cells/ml can be considered, whereas the 10^7 to 10^9 cells/ml is used for self-healing of cracks [10]. The reason for the optimum compressive strength at optimal cell concentration is the filling of pores present inside and on the surface of concrete with calcite [11]. At the lower cell concentration than optimal lacks in the filling of all pores available in concrete leads lower compressive strength. Consequently, at the higher cell concentration than optimal the precipitation of calcite is much more on the surface of concrete and makes impervious layer, thus the required medium for the calcite precipitation inside the concrete is prevented, therefore the strength of concrete reduced. The healing of cracks needed large amount of calcite formation inside the cracks, hence higher bacterial cell concentration is required. The media used for the culture of bacteria such as peptone, sodium chloride, beef extract, yeast extract, urea, and calcium lactate etc. For the application of bacteria cells in the concrete matrix the direct or indirect method can be used. The bacteria cells can be added in the concrete matrix through the mixing water is referred as direct method, whereas the bacteria cells are added in the clay pallets and these can be used as the replacement of aggregates that is known as indirect method [12].

Generally, the bacteria used for improvement of concrete properties secretes urease enzyme and that is significant for microbial induced calcite precipitation. Based on the nutrients used for the growth of bacteria the bio-chemical reactions are summarized. The negatively charged bacteria are influenced by the positively charged calcium ion present in concrete and makes nucleic sites on the surface of bacteria. Further, the developed carbonate ion by the chemical reaction of moisture and carbon di-oxide reacts with calcium ion adhere on the bacterial surface, thus calcium carbonate induced on the surface of bacteria that is referred as bio-mineralization process [13–21].

For the sustainability and environment concern of infrastructures several authors incorporated bacteria in concrete matrix. De Muynck et al. studied the effect of bacterial calcite deposition in cementitious matrix for durability aspect. From results it was observed that the water absorption was reduced upto 90% due to calcite precipitation. Subsequently, the carbonation rate and chloride penetration have been reduced upto 30% and 40%, respectively. Thus, the developed concept can be used to construct the sustainable and durable structures [22]. Jonkers et al. investigated the significance of induced calcite precipitation for self-healing phenomenon to develop sustainable concrete. The *Bacillus* group of bacteria was used for experiment and observed that the pores of cement paste were reduced thus it was resulted integrity to structural systems [23]. Achal et al. studied bacterial concrete to enhance the durability of concrete building. From results it was observed that the compressive strength was increased by 36% and the water absorption was six times less than control concrete by addition of *Bacillus sp.* CT-5. The demonstrated concept was significant for preparation of bacterial concrete and provides a way to enhance the durability of concrete infrastructures [4]. Chahal et al. incorporated *Sporosarcina pasteurii* bacteria in silica fume based concrete and their consequence on compressive strength, water absorption, and chloride penetration were investigated. The maximum compressive strength was observed at the 10^5 cells/ml by 38.2 MPa at 28 days and 44 MPa at 44 days. The water absorption and chloride penetration were reduced due to the microbial induced calcite precipitation. Thus, the developed concept can be applied for sustainable and durable real-life infrastructures [24]. Xu and Wang investigated the self-healing phenomenon of cementitious materials by the application of alkali resistant spore forming bacteria. From the results it was observed that the crack was healed upto 0.417 mm after 28 days. Thus, from the developed concept the cracks can be healed of cementitious materials for sustainable environment concern [8]. Nguyen et al. studied self-healing and durability phenomenon of concrete matrix by application of *Bacillus subtilis* bacteria. At the 44 days the 0.40 mm crack was completely healed and developed integrity to structural systems [10]. Tayebani and Mostofinejad considered two types of bacteria named as *Sporosarcina pasteurii* and *Bacillus subtilis* for experimental investigation of concrete matrix. For durability aspects of concrete several parameters like permeability, corrosion and resistivity were evaluated and observed that the results were promising for concrete industry [25]. Therefore, the application of bacteria in concrete matrix is substantial for sustainable environment reason.

The revolutions of technologies needed non-destructive evaluation systems for structural health monitoring (SHM). The SHM concept is significant for investigation of structural health using smart materials such as availability of damage, damage location, damage severity, and residual life of structural systems. SHM covers several techniques for the identification of presence of damages in all kinds of materials and structures [26–31]. The technique is broadly classified as global and local techniques. Further, the global technique is divided into two parts named as global static and global dynamic response based techniques. The static loads are applied to the interrogated structures and corresponding structural parameters are evaluated in static response based technique, whereas in the global dynamic technique the host structures are exited with low frequency band and corresponding structural parameters are determined. These global techniques are very tedious and required lot of computational effort to acquire the data [28,30,32]. The local technique covers ultra-sonic pulse velocity meter, rebound hammer, acoustic emission, eddy's current, x-ray diffraction, and smart materials based techniques [26]. Electro mechanical impedance (EMI) technique is the conventional local technique which is based on the smart materials. Smart materials are the materials that change their properties under different stimuli. Thus, these materials are more susceptible to recognise the damages present in structures. The EMI technique is considered to measure structural parameters in terms of signatures and the deviation from the baseline signature results presence of damages. Therefore, the EMI technique can be used for non-destructive evaluation of structures through smart sensor based technology [33,34].

In this present scenario the application of EMI is not limited it can be used for monitoring of all kinds of materials viz., concrete, steel, timber, aluminium, and stones etc. Consequently, the monitoring of several structures such as buildings, bridges, tunnels, towers, water retaining structures, sewerage systems, and road networks can be completed using EMI technique [28,35–37]. Several researchers monitored the health of these materials and structures through PZT sensors bonded on surface/embedded. Lim et al. used EMI technique for structural identification and damage investigation using surface bonded PZT sensors. For verification of newly developed concept the lab sized engineering structures of different materials viz., aluminium truss, aluminium beam and concrete cube were considered. From the results it was observed that the concept was significant for damage identification and damage characterisation of all kinds of structures. For identification of structural systems the prior data has not been required, thus the method can be used for monitoring of real-life structures [38]. Yang and Divsholi monitored concrete structure using sub-frequency interval method in EMI technique. The proposed method can be used for damage identification to determine the location and severity of damages in concrete structures. Further, the correlation between the frequency and sensing zone of PZT sensor were presented [36]. Kaur et al. considered reinforced concrete specimens to determine damage and retrofitting accompanied by strength and fatigue monitoring using EMI technique with PZT sensors. The investigation was completed with CVS sensor used in RC structures under long term dynamic loading. The change in frequency was the first indicator of damage occurrence in both experimental and numerical investigations [39]. Ding et al. integrated the wave propagation method with EMI technique for damage detection of epoxied joint model in precast concrete segmental bridges using PZT sensors. The resistant curve and RMSD index were used for the location and quantification of damages [40]. Hence, the sensor grounded EMI technique is significant for structural damage detection along with location and severity identification.

Evaluation of bacterial concrete properties was made by many researchers in laboratory with destructive techniques. Damage in concrete structures reduces the strength along with durability, thus damage detection in structures is necessary so that the required actions can be applied within time interval. The health monitoring of bacterial concrete using don-destructive evaluation based EMI technique with PZT sensor has not been used till date. This research presented the application of EMI technique on bacterial concrete for damage identification using PZT sensors. The parameters were identified which was indicator of presence of damage. Variations in these parameters from baseline data designate presence damage. From the identified parameters the damage can be predicted of all kinds of structural systems.

2 Materials and methodology

2.1 Bacteria

The environment-friendly Bacillus subtilis bacteria with strain 441 were purchased from Microbial Type Culture Collection (MTCC) and Gene bank Chandigarh, India. These are rod-shaped and letting it to withstand rearward environmental situations because of the formation of tough and protective endospore. In this research the nutrients for culture of bacteria such as peptone, beef extract, sodium chloride, yeast extract and water have been considered in different proportions as 5.0, 1.0, 5.0, and 2.0 in grams/liter, respectively. To perform the experimental investigations the bacterial concentration of the 10^5 cells/ml has been considered. The cell concentration of bacteria has been calculated using the mathematical expression, cell concentration/ ml, $Y = 8.59 \times 10^7 X^{1.3627}$, where X is the reading at OD_{600} (optical density at wave length of 600 nm) measured by UV spectroscope [9].

2.2 Concrete constructing materials

Ordinary Portland cement (OPC) of grade 43 was used to perform the experiment in laboratory confirming IS: 8112-2013. Numerous tests have been completed to calculate the physical properties of cement such as consistency 28%, initial setting time 115 minutes, final setting time 223 minutes, fineness 2.8 %, specific gravity 3.15, and bulk density 1440 kg/m^3. These tests were performed in accordance with the IS: 4031-2005. The coarse aggregates retained on 4.75 mm and fine aggregates passed through 4.75 mm IS sieves have been considered, respectively in accordance with IS: 383-2016. The physical properties of coarse aggregate has been calculated by executing many physical tests like fineness modulus 7.37, bulk density at densest state 1659 kg/m^3, specific gravity 2.71, water absorption 0.5 % maximum and minimum size of aggregate 20 mm and 10 mm, respectively. The tests have been performed to calculate the physical properties of used fine aggregate and these properties have been found as fineness modulus 3.0, bulk density at densest state 1676 kg/m^3, specific gravity 2.68, water absorption 1.2% and lies in zone II. For the preparation of concrete mixture the fresh water was considered in accordance with IS: 456 – 2000 [41]. All the materials brought to room temperature 27 $\pm\pm$ $3^{℃℃}$ before the initiation of the experiment.

2.3 Preparation of specimens

Two kinds of concrete cubes of size 150 x 150 x 150 mm have been cast like control concrete cube (CCC) and bacterial concrete cube (BCC), respectively. The grade of M30 concrete has been considered. Total twenty four cubes were considered to conduct the experiment out of these twenty four cubes twelve were CCC (without bacteria cells) and twelve were BCC (with bacteria cells). For preparation of BCC the bacteria cells were added in concrete mixing water and that water was used for preparation of bacterial concrete. The prepared cube specimens were placed at 27 $\pm\pm$ $2^{℃℃}$ for 24 hours from the time of addition of water to the dry ingredients. Further, the cube specimens were removed from the mould and placed for curing until the commencement of the test within 24 hours. During the whole curing process the temperature 27 $\pm\pm$ $2^{℃℃}$ were maintained and checked has been applied the cube specimens were not dry at any time until they have been tested IS: 516.

2.4 EMI technique

The EMI technique is based on identification of incipient damages in high frequency band of 30 kHz – 400 kHz, whereas in global dynamic based technique the frequency gap is less than 100 kHz. Thus, the EMI technique is most reliable for incipient damage identification and the global dynamic technique is suitable for severe damage determination. In this technique the PZT sensors are used for health monitoring of interrogated structures in terms of signatures. These PZT sensors are attached with host structure using high strength epoxy adhesive and electrically excited via LCR meter. Structural admittance is extracted through LCR meter which consist of conductance and susceptance as real and imaginary part, respectively. The variation in signatures from healthy state condition directs presence of damages. The electro-mechanical admittance, $\overline{Y}\overline{Y}$ (unit Siemens) can be determined using equation (1) for square PZT patches of a 2-D systems by including the idea of 'effective impedance' which is inverse of mechanical impedance, ZZ. Where, GG is the conductance, $\omega\omega$ the angular velocity, jj the $\sqrt{-1}\sqrt{-1}$, ll the half-length of PZT patch, dd piezoelectric train coefficient, $\overline{Y^E}\overline{Y^E}$ the complex

Young's modulus of elasticity at constant electric field, v the poisson's ratio,, hh the thickness of PZT patch, B B the susceptance, kk the spring constant, $\overline{\varepsilon^T \varepsilon^T}$ [28,35–37,42].

$$\bar{Y} = G + B\,j$$

$$= 4\omega j \frac{l^2}{h}\left[\left(\overline{\varepsilon_{33}^{T}} - \frac{d_{31}^2 \overline{Y^E}}{1-v}\right) + \left(\frac{Z_{a,eff}}{Z_{s,eff}+Z_{a,eff}}\right)\frac{d_{31}^2 \overline{Y^E}}{1-v}\left(\frac{\tan \kappa l}{\kappa l}\right)\right] = 4\omega j \frac{l^2}{h}\left[\left(\overline{\varepsilon_{33}^{T}} - \frac{d_{31}^2 \overline{Y^E}}{1-v}\right) + \left(\frac{Z_{a,eff}}{Z_{s,eff}+Z_{a,eff}}\right)\frac{d_{31}^2 \overline{Y^E}}{1-v}\left(\frac{\tan \kappa l}{\kappa l}\right)\right] \quad (1)$$

2.5 RMSD Index

Variation in signatures from baseline data indicates existence of damage symptoms in structural systems. Damage changes signatures of structural system and signature shifts towards left side. Subsequently, the strength gain in structures also changes the structural signatures and signature shifts towards right side. The statistical index can be used for the quantification of structural damage and developed strength in structures. In this research the root mean square deviation (RMSD) index has been used for quantification of structural parameters changes in EMI technique such as damage and strength development. The RMSD index was developed by the Giurgiutiu et al. (1999) equation (2) [43]. Where, $G_i^1 G_i^1$ is the value of post damage /or strength conductance at i^{th} measurement point and $G_i^0 G_i^0$ is the corresponding pre-damage /or strength value. The 'n' represents number of observations.

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}\left(G_i^1 - G_i^0\right)^2}{\sum_{i=1}^{n}\left(G_i^0\right)^2}}\ X\ 100 RMSD = \sqrt{\frac{\sum_{i=1}^{n}\left(G_i^1 - G_i^0\right)^2}{\sum_{i=1}^{n}\left(G_i^0\right)^2}}\ X\ 100 \quad (2)$$

2.6 Experimental Setup

Experimental test has been performed on CCC and BCC by compression testing machine of 2000 kN capacity according to IS: 516. The experiment was conducted on prepared cubes after curing period of 3, 7, 14, and 28 days. The compressive load (failure load) was applied for the crushing of prepared cubes. Subsequently, for the extraction of structural signatures the PZT sensors (PIC151 purchased from Germany) were attached on the surface of these cubes using high strength epoxy adhesive. The conductance and susceptance signatures were extracted of these using PZT sensors at healthy and damaged (failure) state at 3, 7, 14 and 28 days of curing. The schematic representation of experimental setup for application of EMI technique to monitor the health of host structures using PZT sensors bonded on the surface has been presented in Figure 1. The soldering was performed on the top and bottom electrode films wrapped on top surface of PZT sensor with zero resistant wire. The LCR meter was used to measure the admittance signature and the processed data were collected in laptop using USB cable. Experimental setup for application of EMI technique to investigate health of concrete specimens was presented in Figure 2.

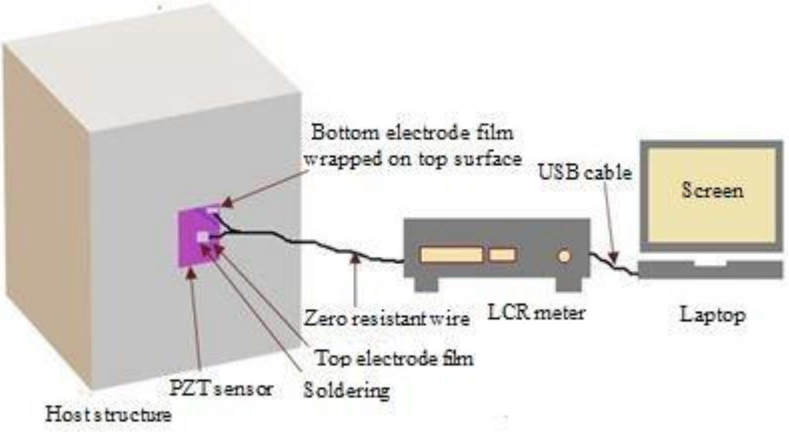


Fig. 1 Schematic representation of PZT sensor based EMI technique application

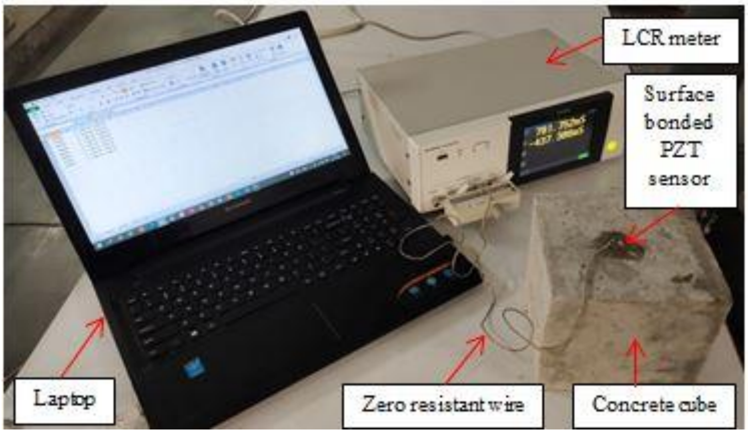
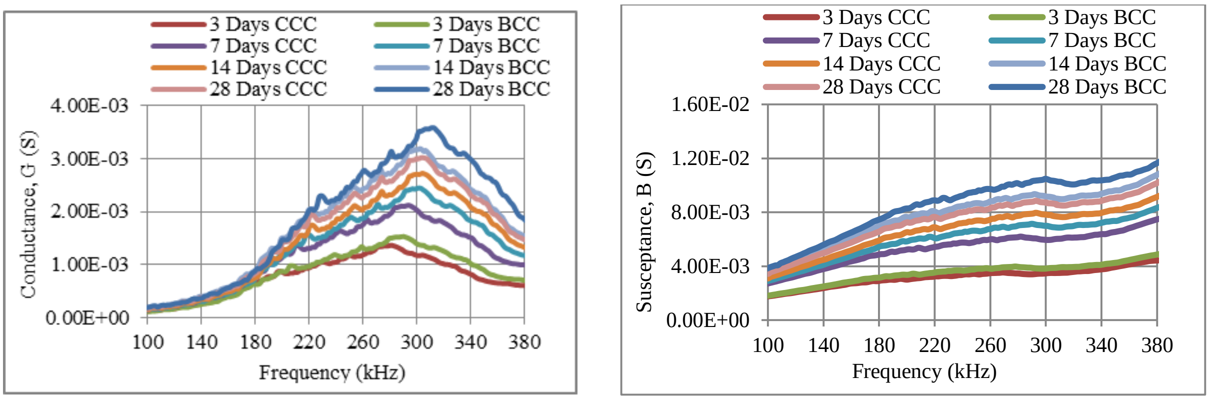


Fig. 2 The experimental setup for application of EMI technique to investigate the health of concrete specimens

3 Results and discussions

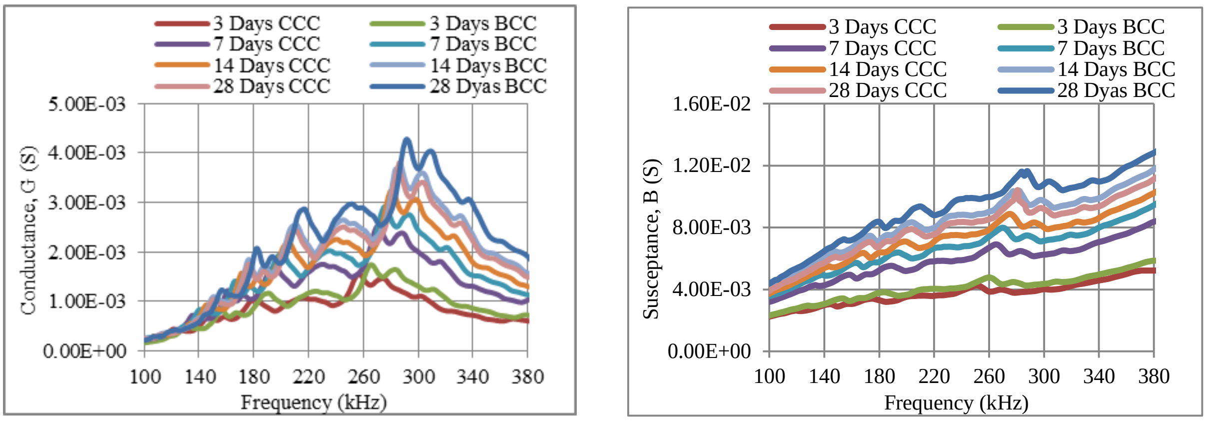
3.1 Extraction of signatures

The conductance and susceptance signatures have been extracted by surface bonded PZT sensors on host structure of CCC and BCC at healthy state (HS) and damaged state (DS) after 3, 7, 14, and 28 days of curing. Initially at HS the signatures of CCC and BCC were determined using LCR meter, further the failure load was applied for DS using compression testing machine and signatures were determined at all days. The evaluated conductance and susceptance signatures with respect to frequency at HS have been presented in Figures. 2 (a,b) for CCC and BCC. It was observed that the BCC signatures were shifted toward right side as compared with CCC signatures in HS at all ages. Further, the failure load was applied on both the cubes using compression testing machine and signatures were determined using surface bonded PZT sensors. The evaluated conductance and susceptance signatures in respect to frequency of CCC and BCC at DS have been presented in Figures. 3 (a,b). From the evaluated signatures at DS of CCC and BCC, it was observed that the signatures were shifted leftwards. The shifting of signatures towards left side was more in CCC, whereas lesser shifting was observed in BCC at all ages. The reason for that was the incorporation of bacteria in concrete matrix produces calcite in the pores of concrete that provide additional stiffness in BCC. Stiffness is the function of frequency, thus as stiffness increases the frequency increases. Therefore, the signatures of BCC were shifted rightwards due to strength gain. The damage in structural systems is cause of stiffness reduction and subsequently the frequency reduces, hence the signatures were shifted towards left side. The application of bacteria in concrete matrix is important to improve the quality of concrete and damage can be minimised.



(a) (b)

Fig. 2 Signature of CCC and BCC at healthy state (a) conductance v/s frequency (b) susceptance v/s frequency



(a) (b)

Fig. 3 Signature of CCC and BCC at damaged state (a) conductance v/s frequency (b) susceptance v/s frequency

3.2 Determination of structural parameters

Several parameters were considered for the determination of presence of damages viz., peak conductance value, peak susceptance value, frequency at peak conductance values, and frequency at peak susceptance values. The peak conductance and susceptance values of CCC and BCC at HS and DS have been presented in Table 1 and Table 2 at 3, 7, 14, and 28 days. The percentage changes were evaluated in CCC and BCC after damaged with respect to HS and changes were observed at all ages. Similarly, the frequency at peak conductance and susceptance values of CCC and BCC were evaluated at all days considering HS and DS that were presented in Table 3 and Table 4. The percentage changes after DS with respect to HS were determined and observed that the frequency values were reduced at all ages. The reduction in frequency indicates presence of damages in structural specimens. Thus, the changes in the considered parameters from the healthy state indicates occurrence of damages. The evaluated percentage changes in considered parameters after damage in CCC and BCC at all ages was presented in Figure 4. Damage in structures causes loss of stiffness which is directly correlated with frequency, thus the frequency was reduced after damage.

Further, to explore the effect of bacteria percentage changes in BCC with respect to CCC were evaluated considering HS and DS conditions at 3, 7, 14, and 28 days. The peak conductance and susceptance values of CCC and BCC at HS and DS have been presented in Table 5 and Table 6 at all days. The percentage changes were observed at HS and DS in BCC with respect to CCC at all ages. The changes were due to the application of bacteria in concrete matrix that produces calcites in concrete pores. Hence, the bacterial concrete was resulted higher strength than the control concrete. Similarly, the values of frequency at peak conductance and susceptance of CCC and BCC were evaluated considering HS and DS at all ages and presented in Table 7 and Table 8. It was observed that the frequency values higher in case of BCC as compared with CCC, because of higher strength gain due to bacterial incorporation. The formation calcites in bacterial concrete were resulted stiffer concrete than control concrete. The stiffness of the concrete system is function of frequency, hence as stiffness increases the frequency increases of bacterial concrete that indicates shifting of signatures towards right side than control concrete. The percentage change in BCC w.r.t. CCC considering peak conductance and susceptance values, and values of frequency at peak conductance and susceptance values with HS and DS at 3, 7, 14, and 28 days has been presented in Figure 5.

Table 1 Peak conductance values of CCC and BCC

Days	Specimens	Peak conductance value x 10^{-3}		% change w.r.t. healthy state
		Healthy state	Damaged state	
3	CCC	1.36	1.55	13.97
	BCC	1.53	1.74	13.73
7	CCC	2.12	2.53	19.34
	BCC	2.45	2.92	19.18
14	CCC	2.72	3.25	19.49
	BCC	3.03	3.61	19.14
28	CCC	3.19	3.81	19.44
	BCC	3.59	4.28	19.22

Table 2 Peak susceptance values of CCC and BCC

Days	Specimens	Peak susceptance value x 10^{-3}		% change w.r.t. healthy state
		Healthy state	Damaged state	
3	CCC	3.49	4.25	21.78
	BCC	3.92	4.77	21.68
7	CCC	6.10	6.91	13.28
	BCC	7.05	7.98	13.19
14	CCC	7.85	8.89	13.25
	BCC	8.72	9.87	13.19
28	CCC	9.21	10.42	13.14
	BCC	10.03	11.34	13.06

Table 3 Frequency at peak conductance values of CCC and BCC

Days	Specimens	Frequency at peak conductance value x 10^{3}		% change w.r.t. healthy state
		Healthy state	Damaged state	
3	CCC	282.04	256.3	-9.13
	BCC	290.65	265.3	-8.72
7	CCC	294.65	270.3	-8.26
	BCC	302.65	275.3	-9.04
14	CCC	304.65	280.3	-7.99
	BCC	305.65	285.3	-6.66
28	CCC	307.65	286.3	-6.94
	BCC	312.65	291.3	-6.83

Table 4 Frequency at peak susceptance values of CCC and BCC

Days	Specimens	Frequency at peak susceptance value x 10^3		% change w.r.t. healthy state
		Healthy state	Damaged state	
3	CCC	274.60	250.75	-8.69
	BCC	283.25	259.75	-8.30
7	CCC	287.25	264.75	-7.83
	BCC	295.25	269.75	-8.64
14	CCC	297.25	274.75	-7.57
	BCC	298.25	279.75	-6.20
28	CCC	300.25	280.75	-6.49
	BCC	305.25	285.75	-6.39

Table 5 Peak conductance values at HS and DS

Days	Condition	Peak conductance value x 10^{-3}		% change in BCC w.r.t. CCC
		CCC	BCC	
3	HS	1.36	1.53	12.50
	DS	1.55	1.74	12.26
7	HS	2.12	2.45	15.57
	DS	2.53	2.92	15.42
14	HS	2.72	3.03	11.40
	DS	3.25	3.61	11.08
28	HS	3.19	3.59	12.54
	DS	3.81	4.28	12.34

Table 6 Peak susceptance values at HS and DS

Days	Condition	Peak susceptance value x 10^{-3}		% change in BCC w.r.t. CCC
		CCC	BCC	
3	HS	3.49	3.92	12.32
	DS	4.25	4.77	12.24
7	HS	6.10	7.05	15.57
	DS	6.91	7.98	15.48
14	HS	7.85	8.72	11.08
	DS	8.89	9.87	11.02
28	HS	9.21	10.03	8.90
	DS	10.42	11.34	8.83

Table 7 Frequency at peak conductance values at HS and DS

Days	Condition	Frequency at peak conductance value x 10^3		% change in BCC w.r.t. CCC
		CCC	BCC	
3	HS	282.04	290.65	3.05
	DS	256.3	265.3	3.51
7	HS	294.65	302.65	2.72
	DS	270.3	275.3	1.85
14	HS	304.65	305.65	0.33
	DS	280.3	285.3	1.78
28	HS	307.65	312.65	1.63
	DS	286.3	291.3	1.75

Table 8 Frequency at peak susceptance values at HS and DS

Days	Condition	Frequency at peak susceptance value x 10^3		% change in BCC w.r.t. CCC
		CCC	BCC	
3	HS	274.60	283.25	3.15
	DS	250.75	259.75	3.59
7	HS	287.25	295.25	2.79
	DS	264.75	269.75	1.89
14	HS	297.25	298.25	0.34
	DS	274.75	279.75	1.82
28	HS	300.25	305.25	1.67
	DS	280.75	285.75	1.78

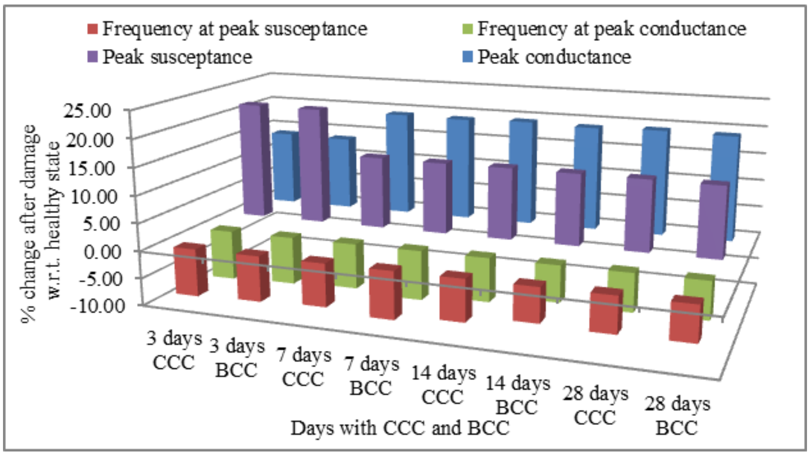


Figure 4 % change after damage w.r.t. healthy state

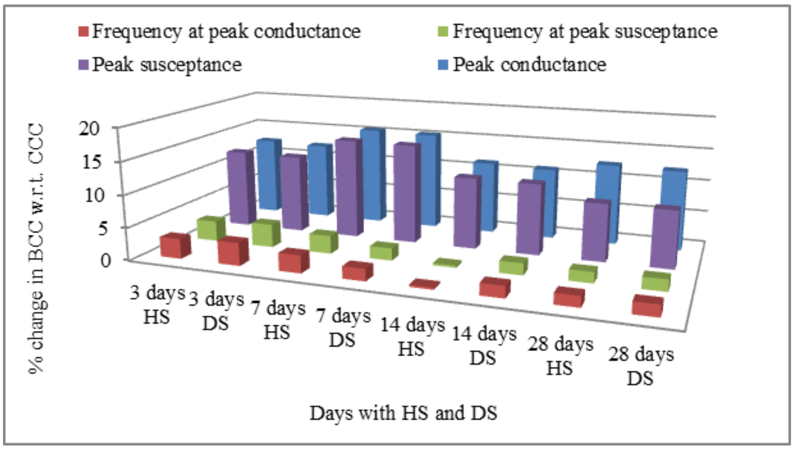


Figure 5 % change in BCC w.r.t. CCC

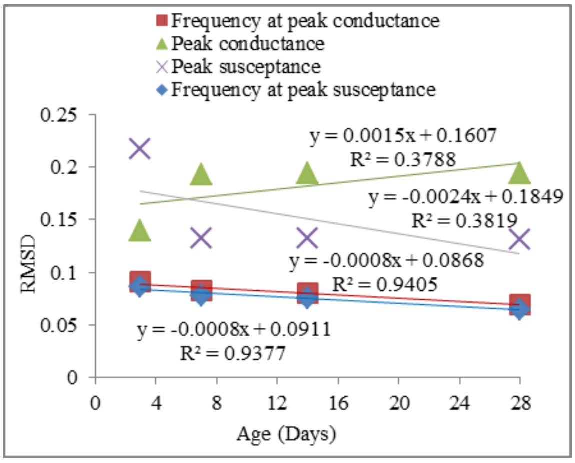
3.4 Investigation of RMSD statistical index

For the determination of damages present in considered structural specimens the RMSD index equation expressed in (2) has been applied. The damage was quantified using RMSD index for the parameters as peak conductance value, peak susceptance value, frequency at peak conductance values, and frequency at peak susceptance values. These evaluated plots for CCC and BCC were presented in Figures (6,7) considering HS and DS conditions at 3, 7, 14 and 28 days of curing. The trend line was determined for all the parameters and corresponding that the linear equations and R-values were evaluated of DS. Further, the strength at HS and DS of BCC with respect to CCC was quantified using RMSD index, which were presented in Figures (8,9) at all considered days. The trend line was determined for all the parameters and corresponding that the linear equations and R-values were evaluated of BCC. From the R-values, all the parameters were suitable to determine presence of damage; however the R-value was more in case of frequency at peak conductance and susceptance. Thus, the frequency was best suited for damage indicator of CCC and BCC. In case of strength evaluation, the peak conductance and susceptance were more significant based on higher R-value.

4 Conclusions

This study entails the damage prediction of environment-friendly bacteria based concrete and control concrete structures using smart sensor based EMI technology. The conductance and susceptance signatures of CCC and BCC were evaluated at HS and DS after 3, 7, 14, and 28 days of curing. It has been found that the signatures of bacterial concrete was shifted towards right side than the control concrete at HS, whereas at DS the shifting of signatures towards left side was lesser in bacterial concrete than control concrete. The reason for that was higher strength of bacterial concrete due to microbial induced calcite precipitation. Further, from the evaluated signatures the peak values of conductance, susceptance, frequency at peak conductance, and frequency at peak susceptance were determined and the percentage change of CCC and BCC at HS and DS calculated at all ages. The change in these parameters was indicator of damage presence in structural systems. The percentage changes in BCC with respect to CCC were determined at all ages in HS and DS considering structural parameters. Strength gain was observed in bacterial concrete due to the formation of environment-friendly biodegradable calcite materials in concrete pores by bio-mineralization chemical reactions. The equivalent structural parameters were extracted for CCC and BCC at all ages considering HS and DS conditions and it was resulted that the decrease in stiffness after damage, however bacterial concrete have more stiffness than control concrete.

The damage and strength were quantified using RMSD index considering investigated structural parameters of CCC and BCC seeing HS and DS at 3, 7, 14 and 28 days. Further, the trend line and R-value were determined considering RMSD values of all considered structural parameters for CCC and BCC at all considered days. The R-value for all considered structural parameters were suitable for damage prediction, however considered frequency at peak conductance and susceptance value was more significant for damage prediction. For the strength gain prediction the peak conductance and susceptance values was more significant because of higher R-value than the frequency at peak conductance and susceptance, whereas all considered structural parameters can be used. It was observed that the bacterial concrete have better performance than control concrete. The developed concept can be applied to real-life infrastructures for damage prediction as well as for strength evaluation.



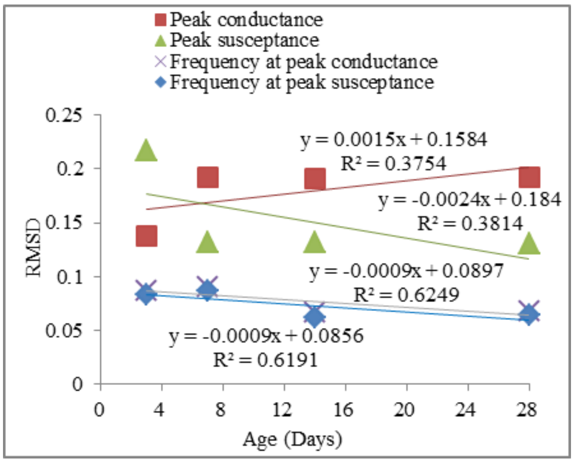
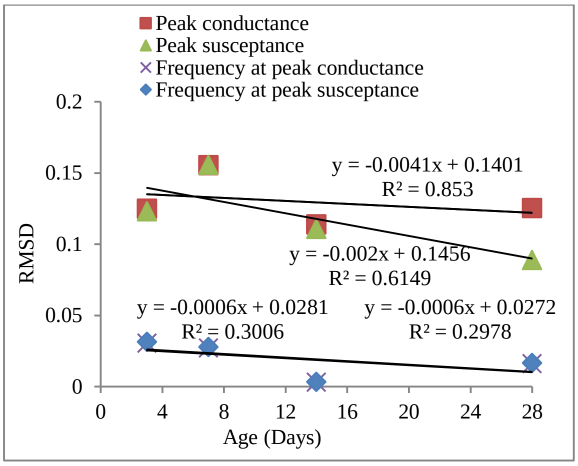


Fig. 6 RMSD *v/s* age for damage investigation of CCC

Fig. 7 RMSD *v/s* age for damage investigation of BCC



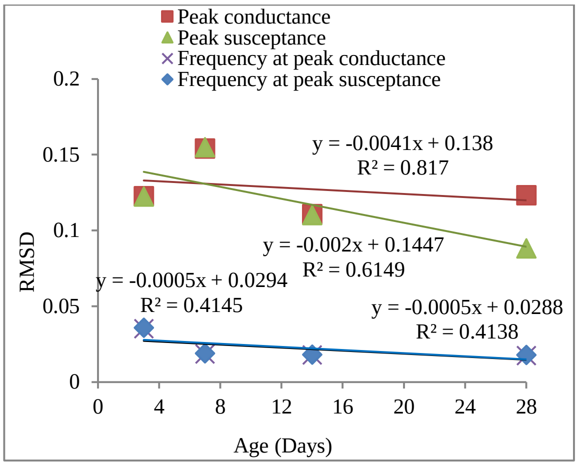


Fig. 8 RMSD *v/s* age for strength investigation of BCC at HS

Fig. 9 RMSD *v/s* age for strength investigation of BCC at DS

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