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Electromagnetic response of Fresh concrete and its Ingredients

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Abstract - *Quality estimation of concrete is necessary and important part in any structural construction. Knowing the integral properties like moisture content of concrete, controlled monitoring can be done. Moisture effect on dielectric properties of fresh concrete remains as the focal point of research. Differentiation of Concrete grades based on its Dielectric parameters can be used for quality check, strength prediction and estimation of integrity of structure. Most of the works reported influence of moisture on limited range frequencies of Electromagnetic waves through GPR. This work explores the effect of fresh concrete parameters on a wider band of frequencies. Concrete ingredient and curing response of concrete for 28 days is presented. Vector Network Analyzer is used over whole X-band to measure the dielectric response which is calibrated using NRW method through MATLAB program. After adding water to the dry mix, the Dielectric Properties (Permittivity, Permeability) of fresh concrete remain practically unchanged for the first 24 hours. Measurement uncertainties are also discussed in terms of their causes and effects.*

Key Words**: Dielectric Response; NRW Method; Concrete; VNA**

1. INTRODUCTION

All materials can be electrically characterized in the frequency domain by their complex permittivity (ϵ) and permeability (μ), which influence their response to electromagnetic (EM) radiation. Not just for research but also for industrial applications, detailed knowledge of these constitutive properties is necessary. Due to the uncertainties in production processes, measuring a material's properties frequently is the only way to determine its framework.

Concrete is a dielectric material; various experiments are done based on dielectric response of concrete. Dielectric properties (Complex Permittivity and Permeability) represent the electromagnetic response when material is placed in electric field. The dielectric properties are based on the electrical polarization of a material. Due to Polarization, a material will store and absorb electrical energy when placed in an electrical field. Permittivity(ϵ) determines the amount of electrical energy that can be stored by a material. When permittivity is expressed with relative to the permittivity of vacuum is known as relative permittivity (ϵr). Relative Permittivity of Air is 1, Water is 80, Ice is 3-4, Sand is 3-5. As water is so called permanent dipole with highest relative permittivity, in a concrete mixture water can play huge role in changing its dielectric properties. Hence water content becomes influencing parameter while measuring dielectric property of concrete [1]. The microwave techniques have a great potential for quality assessment of cement-based materials due to a number of advantages; they are directly sensitive to water content and can be non-contact, remote, one-sided and wireless [2]-[5]. A wide range of investigations into microwave characterization of cement-based materials including determination of w/c ratio and dielectric property determination using different approaches have been conducted [6]-[10]. The dielectric response of M25 grade concrete according to curing days and response its ingredient is measured and presented in this paper.

1.1 Dielectric Properties and Scattering Parameters

Permittivity- "The absolute permittivity, often defined as permittivity or simply permittivity and symbolized by the Greek letter (ϵ), is a measure of the electric polarizability of a dielectric in electromagnetism". When an electric field is applied, a material with a high permittivity polarizes more than a substance with a low permittivity, allowing the material to store more energy.[11]

Permeability- Permeability is "the amount of magnetization that a material acquires in electromagnetism in response to an applied magnetic field. The (μ) Greek letter is commonly used to denote permeability".[11]

Scattering Parameters- The Scattering parameters are also known as 'S-parameters'. S-parameters are 'complex matrices that display the amplitude/phase (Reflection/Transmission) characteristics in the frequency domain'. S11,S12,S21,S22 are the scattering parameters. "The port where the signal emerges is designated by the first number after the "S," and the port where the signal is applied is designated by the second number. S21, then, is a measurement of the signal leaving port 2 in comparison to the RF stimulus going into port 1". Since the input and output ports are the same, it implies a reflection measurement when the numbers are the same (for example, S11). S11 and S22 denotes reflection of wave while S12 and S21 represent the transmission of wave [11].

2. OBJECTIVES

1. Formulation of problem statement, development of methodology, and possible validation with high quality research article.
2. To propose a monitoring technique for concrete.
3. Check dielectric response of fresh concrete and response with different days of curing.
4. To monitor setting and hardening using Ultrasound Pulse Velocity.

3. METHODOLOGY

The methodology includes creating a mould for fresh concrete testing and fixing the grade of concrete to test. Creating the MATLAB code for converting the response recorded by Vector Network Analyzer (VNA) into dielectric form. The wave is then passed through the sample and response is recorded, the recorded response is then run through MATLAB code and graphs of response is plotted and observation is concluded.

4. Nicholson-Ross-Weir (NRW) Method

This method provides a direct calculation of both the permittivity and permeability from the s-parameters. It is the most commonly used method for performing such conversion. Measurement of reflection coefficient and transmission coefficient requires all four (S11, S21, S12, S22) or a pair (S11, S21) of s-parameters of the material under test to be measured. However, the method diverges for low loss materials at frequencies corresponding to integer multiples of one-half wavelength in the sample which is due to the phase ambiguity. Hence, it is restricted to optimum sample thickness of λg/4 and used preferably for short samples. NRW method is divergent at integral multiples one-half wavelength in the sample. This is due to the fact that at a point corresponding to the one-half wavelength the s-parameter (S11) gets very small. For a small s-parameter(S11) value the uncertainty in the measurement of the phase of S11 on the VNA is very large. Therefore, the uncertainty caused the divergence at these frequencies. These divergences can be avoided by reducing the sample length, but it is difficult to determine the appropriate sample length when its(ϵ) and (μ) are unknown [10].

Advantages of NRW method

_ Fast, non-iterative.

_ Applicable to waveguides and coaxial line.

Disadvantages of NRW method

_ divergence at frequencies that are half wavelength times the length of a sample.

_Use a brief sample whenever possible.

_ Low loss materials are not appropriate.

The procedure proposed by NRW method is deduced from the following equations:

$S_{11=}\frac{\Gamma(1-T^2)}{(1-\Gamma^2T^2)}$ and $S21 = \frac{T(1-\Gamma^2)}{(1-\Gamma^2T^2)}$

The correct root and in terms of S-parameter.

$$X = \frac{S11^2 - S21^2 + 1}{2S11}$$

The Reflection Coefficient can be deduced as

$$\Gamma = X \pm \sqrt{x^2 - 1}$$

The Transmission Can be Written as

$$T = \frac{S11 + S21 - \Gamma}{1 - (S11 + S21)\Gamma}$$

The 'Permeability' is given as

$$\mu_r = \frac{1 + \Gamma}{\Lambda(1 - \Gamma)\sqrt{\left(\frac{1}{\lambda_o^2}\right) - \left(\frac{1}{\lambda_c^2}\right)}}$$

Where 'λ_o is Free Space Wavelength' and 'λ_c is the cut off wavelength' and

$$\frac{1}{\Lambda^2} = \left(\left(\frac{\epsilon_r * \mu_r}{\lambda_o^2}\right) - \left(\frac{1}{\lambda_c^2}\right)\right) = -\left(\frac{1}{2\pi L}\ln\frac{1}{T}\right)^2$$

The 'Permittivity' can be defined as

$$\epsilon_r = \left(\frac{\lambda_o^2}{\mu_r}\right)\left(\frac{1}{\lambda_c^2} - \left(\frac{1}{2\pi L}\ln\frac{1}{T}\right)^2\right)$$

By Solving with above equations Permittivity can be calibrated by

$$\epsilon_r = \mu_r\left(\frac{(1 - \Gamma)^2}{(1 + \Gamma)^2}\right)\left(1 - \frac{\lambda_o^2}{\lambda_c^2}\right) + \left(\frac{\lambda_o^2}{\lambda_c^2}\right)\left(\frac{1}{\mu_r}\right)$$

Here,

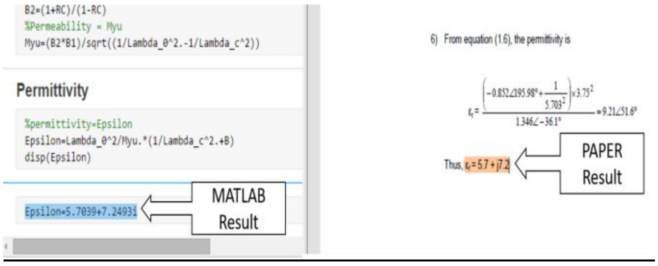
L=Material Length ϵ_r =Relative Permittivity

μ_r =Relative permeability λg =Wavelength in Sample

c =Velocity of light f= Frequency

Code Validation

The MATLAB codes for NRW method was created and verified with the results published in the verified paper [10].



```
B2=(1+RC)/(1-RC)
%Permeability = Myu
Myu=(B2*B1)/sqrt((1/Lambda_0^2.-1/Lambda_c^2))
```

Permittivity

```
%permittivity=Epsilon
Epsilon=Lambda_0^2/Myu.*(1/Lambda_c^2.+B)
disp(Epsilon)
```

```
Epsilon=5.7039+7.2493i
```

6) From equation (1.6), the permittivity is

$$\epsilon_r=\frac{\left(-0.852\angle 195.98^\circ+\frac{1}{5.703^2}\right)\times 3.75^2}{1.346\angle -36.1^\circ}=9.21\angle 51.6^\circ$$

Thus, $\epsilon_r=5.7+j7.2$

Fig -1: Code Validation

5. FABRICATION OF EXPERIMENTAL SETUP FOR FRESH CONCRETE TESTING

Need of mould which can hold the concrete in its flowing state and give easy access to the connection for VNA and UPV antennas and transducers respectively was noted. So accordingly, a wooden mould was prepared. A semi-circular wooden mould with flexi glass fixed inside to fix the antennas and transducers was made. The wooden mould with radius 150 mm and width of 100 mm was built. The mould was then cut to fix the flexi glass of 3 mm thickness to attach the antennas and transducers. Figure 2 shows the mould prepared to test the fresh concrete using VNA.

Fig -2: Mould for Fresh Concrete Testing.

5.1 Sample Preparation for Fresh Concrete Test

Tests were carried out on 10 cube of 150 mm casted with mould sample of M25 Grade Concrete. The concrete had W/C ratio of 0.55 to facilitate moisture movement and Cement, Sand,10 mm and 20 mm Aggregate mix ratio of "1:2:1.32:1.98". The constituents were OPC 43 grade cement, river sand and maximum 20 mm sized aggregates. The concrete mix was prepared in concrete mixer. After the concrete mix was prepared the cubes and mould were filled and to avoid the air gaps and honey combing kept on vibrating table for 5 minutes. The cubes then left for 24 hours in open air for setting of concrete. The sample mould was put to test under VNA and UPV for 24 Hours. Proposed experimental setup is shown in figure 3.

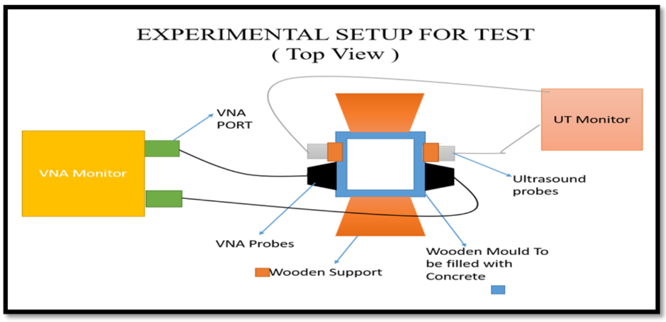


Fig -3: Experimental Setup Sketch for Testing Fresh Concrete

6. Experimental data collection and analysis

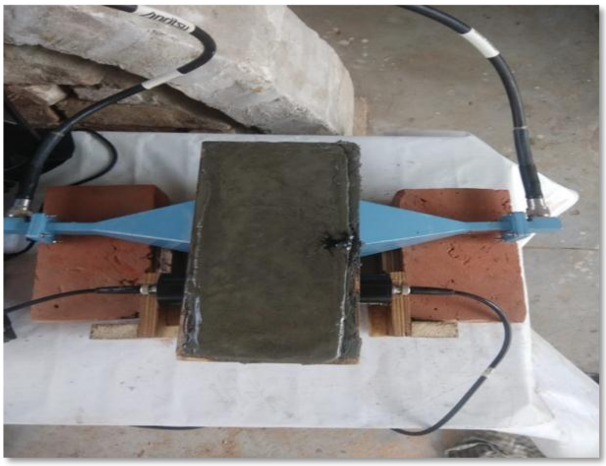


Fig -4: Experimental Setup Sketch for Testing Fresh Concrete

Fig -5: Experimental Setup for Testing Fresh Concrete

The VNA antennas and UPV transducers were fitted on the mould for proper readings and reducing errors. The UPV was connected to laptop with installed Pundit link software which recorded the readings automatically. The VNA readings were taken manually pressing the save button. The readings were recorded for every 5 minutes interval for 24 hours. Figure 4 shows the connection of Antennas and Transducers on the mould while figure 5 presents the actual setup with Laptop, VNA and UPV which records the data.

7. Results and Discussion

Material which was used for mould preparation and its dielectric response is also recorded before and after experiment is done. The response is plotted as shown in figure 6 and 7 for permittivity and permeability.

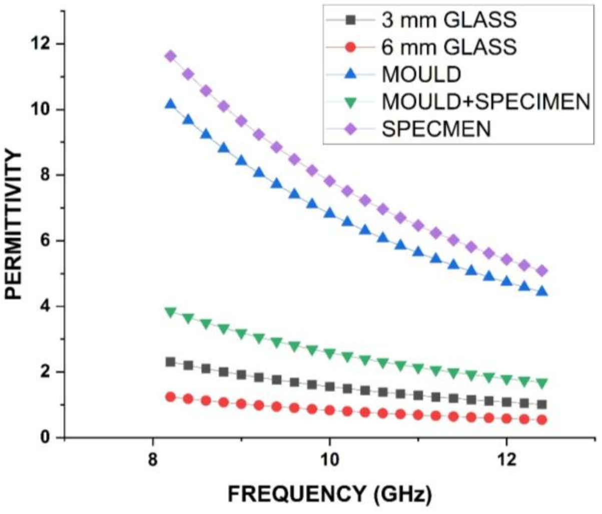


Fig -6: Permittivity vs Frequency for mould, flexi glass and Specimen

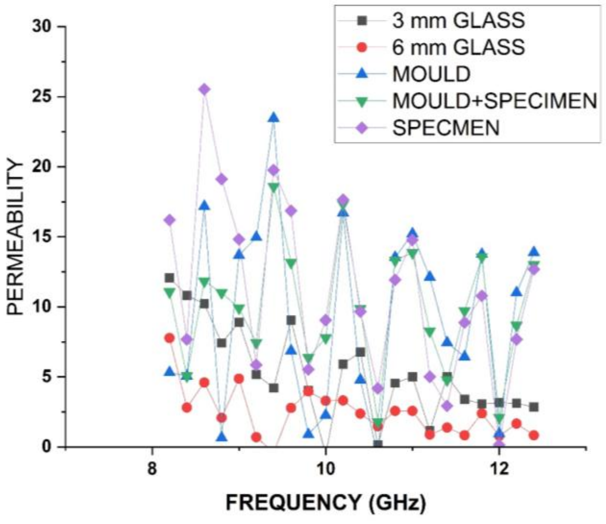


Fig -7: Permeability vs Frequency for mould, flexi glass and Specimen

The Specimen obtained from mould gives highest permittivity readings as water is present in it. Mould takes second place in permittivity value but when mould and specimen are tested together the wave absorption is more and permittivity value drops. The permittivity value for flexi glass is expected to fall when size is increased. Complicated results are obtained when permeability is considered.

Transmission coefficient (S21) and Reflection coefficient (S11) amplitude change was observed for 24 hours setting of concrete. The S11 amplitude changed from -7.75 dB to -10 dB over the period of 24 hours which was expected trend of high amplitude corresponding to high water content as discussed in Hardened concrete. The curve gradually decreases as concrete hardens. For transmission coefficient (S21) amplitude being sensitive to water content, ingredient setting showed continuous ups and down throughout the observation. The behaviour was shown in graph plotted in figure 8.

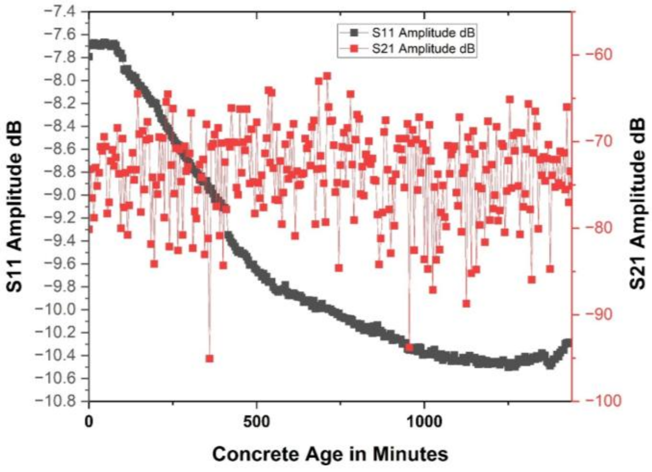


Fig -8: Reflection and Transmission Coefficient AMPLITUDE vs Age of Concrete

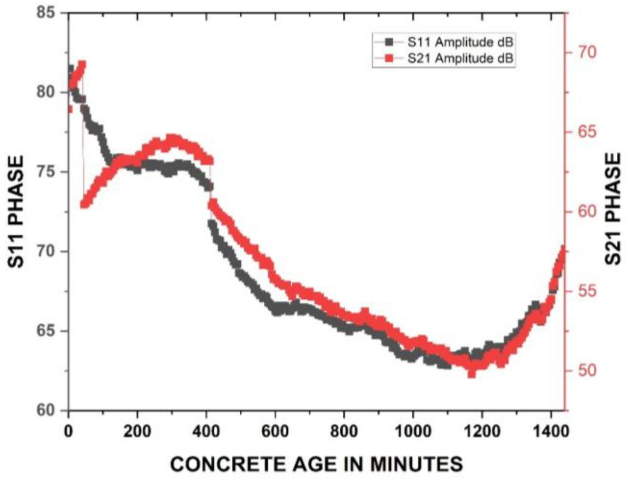


Fig -9: Reflection and Transmission Coefficient PHASE vs Age of Concrete

Also, the trend of S11 phase and S21 phase was observed. As shown in figure 9, the S11 phase and S21 phase curve nearly follows the same trend but value of S11 phase is higher than S21 phase.

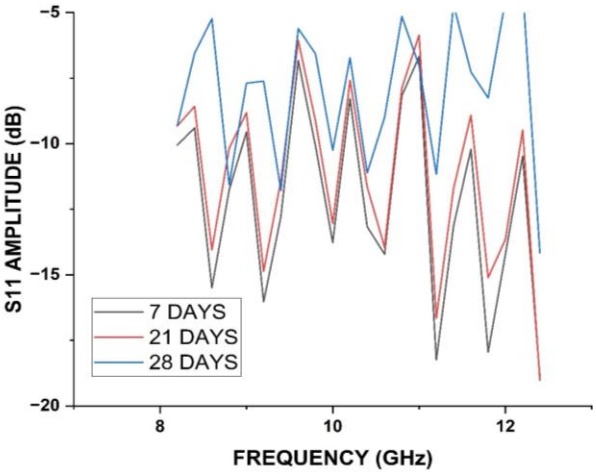


Fig -10: S11 Amplitude vs Frequency for curing days

S11 amplitude was also observed for different curing days. As from figure 10 we can conclude that S11 amplitude increases with curing days.

Table -1: Concrete Test Results for different days of curing

DAYS	WEIGHT (kg)	UTM Test (MPa)	Permittivity	Permeability
7 DAYS	8.25	21.20	0.9153	1.315
7 DAYS	8.40	24.20	0.9155	1.321
7 DAYS	8.80	14.64	0.919	1.326
13 DAYS	8.15	20.44	1.406	0.881
13 DAYS	8.25	24.24	1.405	0.880
13 DAYS	8.50	21.20	1.404	0.878
21 DAYS	8.25	20.44	1.440	1.220
21 DAYS	8.30	24.25	1.39	1.30
21 DAYS	8.15	27.49	1.47	1.15
28 DAYS	8.20	28.99	1.91	0.78
28 DAYS	8.20	28.34	1.41	0.669
28 DAYS	8.25	24.34	1.40	075

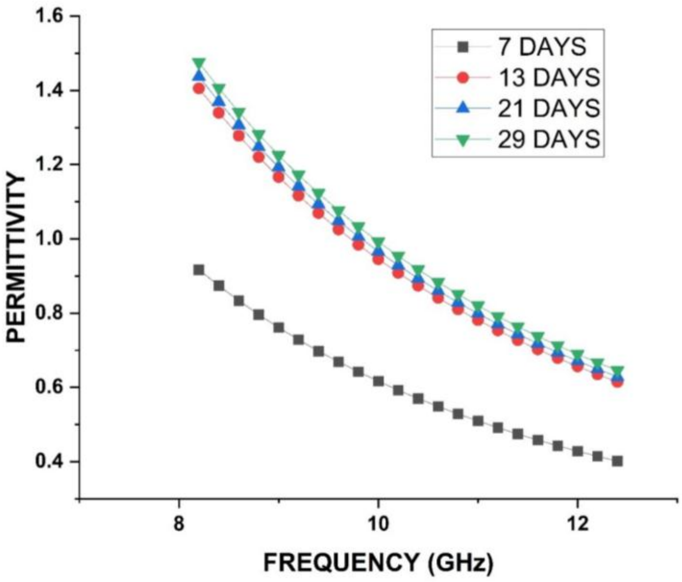


Fig -11: Permittivity at Different days of curing

Increase in permittivity with increase in curing days of concrete was noted. As concrete Hardens the permittivity increased. The results were plotted as shown in figure 11. The value of 7th day permittivity was observed less than 1. The permittivity value at 13, 21 and 29th days were close.

DIELECTRIC RESPONSE OF INGREDIENTS

The ingredients are tested for their dielectric response when taken for concrete mixture. The ingredients are poured in mould and their response is recorded. Figure 12 shows the permittivity response of ingredient while figure 13 shows the permeability response.

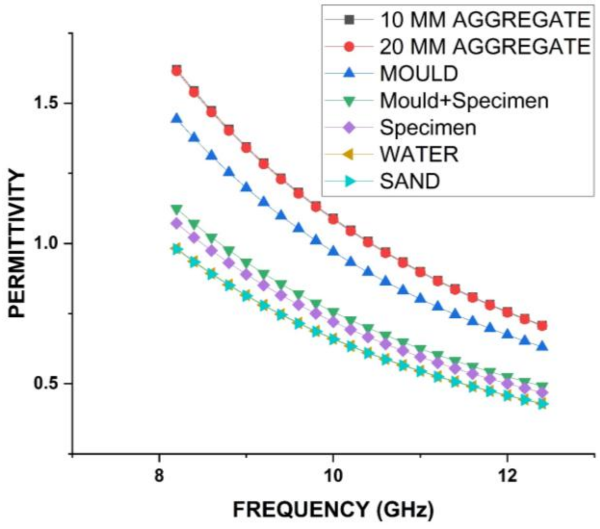


Fig -12: Permittivity vs Frequency for concrete ingredients

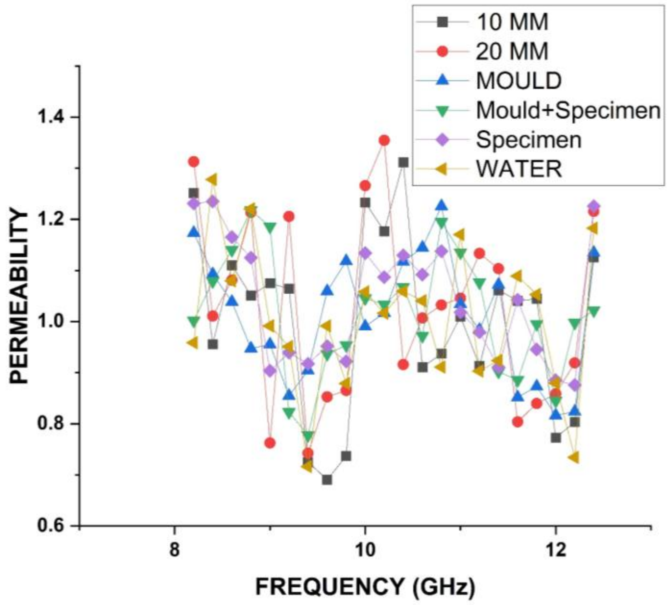


Fig -12: Permeability vs Frequency for concrete ingredients

Ultrasound Response of Fresh Concrete

The UPV observations were recorded for whole 24 hours of setting of concrete.

The velocity change with time was represented in figure 12 and 13. In addition, the UPV pulse was captured. The pulse data was gathered and processed using the MATLAB application. The velocity change per 5 minutes interval and hourly interval was noted. The velocity increase with age of concrete was recorded. There was slight dip in the curve from 10 hours of setting to 13 hours as result of loss of tight contact of transducers to the mould as lubricant connecting between released.

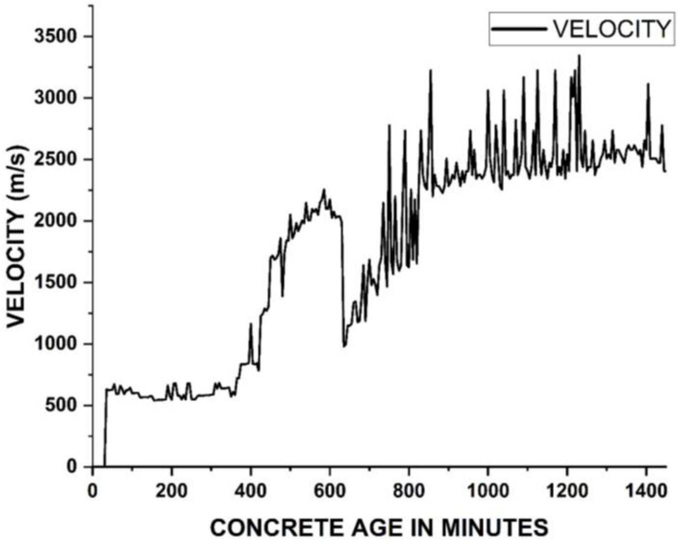


Fig -12: Velocity vs Age of Concrete (Minutes)

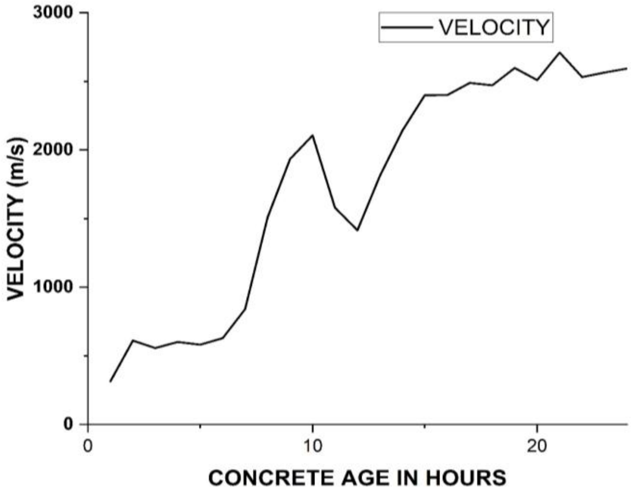


Fig -13: Velocity vs Age of Concrete (Hours)

8. CONCLUSIONS

i. The basic concept of Dielectric properties was discussed. The applications of Dielectric properties were presented and explained. The equations used to extract constitutive parameters from simulated S-parameters were described and programmed in MATLAB.

ii. Decrease in S11 amplitude as concrete changes phase from liquid to semisolid and semisolid to solid was observed. As age of concrete increased, increase in permittivity value and decrease in permeability value is observed.

iii. The total S11 amplitude change of 2.5 dB is observe for whole 24 hours of setting of concrete.

iv. With increase in curing days the Permittivity increases but the change in successive days results reduces.

v. The material result was also observed and influence water can be easily noted with high permittivity value of specimen.

vi. Differentiation of ingredients of concrete can be done based on the permittivity result.

vii. Magnetic aspect which is permeability gives complicated results but follows same pattern.

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