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Non-Destructive Evaluation of Concrete Strength Grades Using Dielectric Permittivity Measurements

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Abstract

Concrete strength evaluation traditionally relies on destructive compressive testing, which is time-consuming and impractical for continuous monitoring. A review of on-going and current research on non-destructive testing of concrete is presented. This study investigates the use of dielectric permittivity as a non-destructive parameter for distinguishing concrete strength grades. Concrete samples with varying cement–sand–aggregate–water ratios corresponding to C16/20, C20/25, and C25/30 grades were prepared, cured, and measured using an open-ended coaxial dielectric probe connected to a vector network analyzer at ~2.0 GHz. Results show that dielectric permittivity decreases systematically with increasing strength grade, reflecting reduced water content and denser microstructure. Regression analysis demonstrated that exponential models achieved higher accuracy than linear models for concrete grades C20/25 and C25/30. The linear regression model is seen to be more suited for concrete grade C25/30, possibly due to its initial permittivity values are low compared to the other two concrete grades. The coefficient of determination, or $\mathbf{R}^2$ values for the linear regression models are 0.4971, 0.5761, and 0.4932, whereas for the exponential regression models are 0.5089, 0.5942, and 0.4757 respectively for the three concrete grades C16/20, C20/25, and C25/30. The research concludes that the experimental work demonstrated the measured real part of the complex permittivity values shows a distinguishable difference between each of the concrete grade. The trend in the values also show that they decrease drastically in the first 5 days, down to almost 50% of their initial measurements. The findings from this research have the potential to be investigated further, with the use of dielectric permittivity as a parameter to establish a microwave-based sensing system for monitoring of concrete samples or structures.

1. Introduction

This research paper presents findings from literature review and results and observations on the experimental study on measurements of the dielectric permittivity of concrete, based on several strength grades. The results are presented in measurements and plots where an appropriate regression model is used to fit the data obtained. Concrete strength is based on the mixture ratios of the materials used to create it, namely cement, sand and aggregates, plus water. Three mixture ratios of different concrete grades are used to produce concrete samples which are then moulded into cubes for experimental testing and measurement. The data is obtained using a dielectric probe in conjunction with a vector network analyzer to read the respective dielectric permittivity values. The readings are tabulated and plotted, then analyzed and compared with findings of other studies and research. The findings of this experimental work is to be used for the development of a sensor based system which can be used as a non-destructive testing method to determine concrete strength.

1.1 Background on Concrete Use

Concrete is a material widely used in the construction industry in modern times. The use of concrete can be traced back to the earliest human civilizations of the Greek and Roman Empires. Concrete is a composite material which is man-made. Typically, concrete is made from a mixture of cement, sand, and aggregates plus water. In modern times, the most commonly used concrete type is made from Portland cement. Cement comes from raw materials of limestone, clay and chalk that is then combined with other materials such as shale, silicon, sand, iron ore. These materials are crushed and grounded and fired in kilns. Then, the mixture is cooled and packed before being sold for use. In the local construction industry where concrete is and has been primarily used in buildings and structures, the demand for it has been ever increasing as there are more development in the sector in recent times.

In the local context, particularly the construction industry, the use of concrete is on the rise as the state undergoes rapid development and expansion of infrastructure. The use of concrete is expected to rise with the rising development. The need to have a method of testing the quality of concrete is seen as important to ensure that the infrastructure that are built or constructed would still be of good quality. This means that frequent testing of concrete would have to be applied to monitor the concrete quality. The common process for testing concrete is known to be a lengthy process, and time-consuming, in addition to the need to use laboratory based equipment for testing and measurement standards. In this research, the focus shall be on developing a method for testing concrete, which is proposed to be a non-destructive method, and aims to reduce the effort and time taken to perform.

1.2 Concrete Mixtures and Dielectric Permittivity

The hypothesis for this research study is that the concrete mixtures of varying ratio of materials can have different dielectric permittivity when measured. As reviewed in various literature, the concrete mixture is a ratio of cement, sand, aggregates and water. Varying the ratio of each of the material shall result in the different strength grade of the concrete. As it takes 28 days for concrete to set, which is often called the curing process, the final compressive strength that a certain mixture can be reached in four weeks.

The next method is to also take actual measurements from concrete samples itself. This serves to be the baseline data for concrete permittivity that can be used for further research in the future. The use of a dielectric probe connected to a network analyzer is able to obtain the dielectric properties for the concrete sample, hence both the real and imaginary values of the complex permittivity of the concrete can be measured.

1.3 Conventional Testing of Concrete Strength

The quality of concrete is determined by conducting compressive testing on it to obtain its strength value. Test samples require the concrete to be cast and moulded into shapes of either cubes, or cylinders. Thereafter, the samples are individually put through a machine that compresses the concrete until each of them fails (or breaks), as portrayed in Fig. 1.

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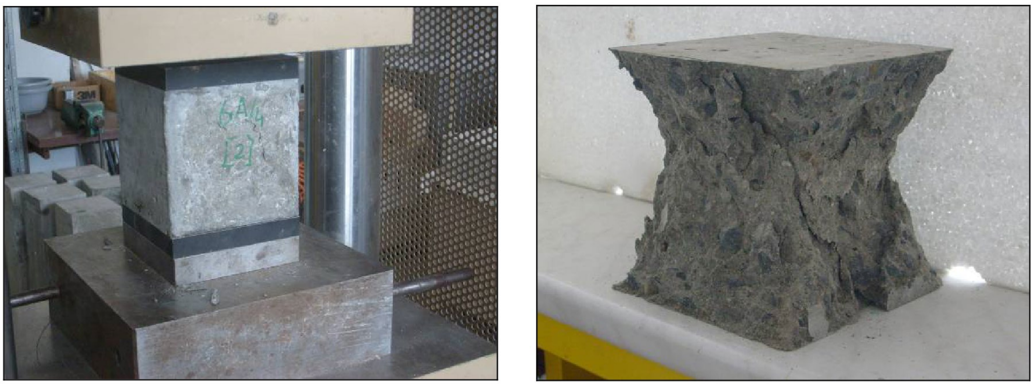


(a) **(b)**

Fig. 1 *Strength testing on concrete (a) Under compressive test machine; (b) Cube sample after testing [1]*

In the research by Sucharda et al., the authors show that the concrete samples used for testing in their research have been damaged i.e. broken after undergoing the compressive tests, [1]. Typically, the testing for the concrete strength is done in a laboratory environment. The common sizes and dimensions for the concrete samples are cubes with 10 cm or 15 cm sides, whereas for cylinders, they are of height 30 cm x diameter 15 cm.

2. Literature Review

There have been several types of research work and studies on the use of non-destructive testing (NDT) methods on concrete based materials, such as concrete strength, moisture content, and crack detection. There are many methods for NDT concrete testing, but there are challenges with each of them; typically requiring expertise in interpretation, analysis and automation in getting the data. While no single technique has been singled out as the most effective method, the fact that most are using sensors as the NDT tool which lead to lower monitoring costs and minimizing sudden failure accidents, according to Kot et al. [2].

2.1 Non-destructive Testing on Concrete

There are few techniques or methods for non-destructive testing on concrete. One such method uses radar on concrete to determine its dielectric properties. In this research, the proposed method of using sub-surface radar as an inspection method. The radar can detect reinforcing bars and ducts, voids, cracks and even moisture ingress into concrete. Multiple concrete samples of different strength grade levels are experimented on. As a result, the observation is that the moisture content affects the concrete permittivity the most. Apart from that, different mixture ratios do influence the conductivity of concrete more than on permittivity, according to Soutsos et al. [3].

In a research by Fares et al., the authors use capacitive probes as the method to test on concrete samples. The capacitive probes are connected to an oscillator, and electrodes are applied to the concrete surface to take measurements. The results show that the dielectric permittivity is affected by water content of concrete. Thus, there are results obtained using an inversion method to get the permittivity profile of reinforced concrete. The inversion process applied use two forms of parametrizations, i.e. discrete and continuous, with reference to the research literature by Fares et al., as shown in Fig. 2 [4].

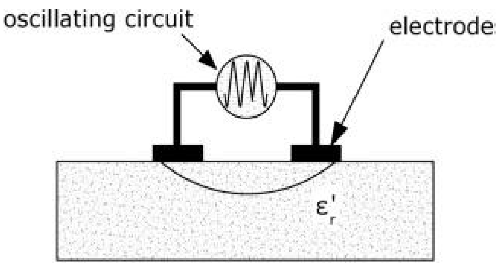


Fig. 2 *Use of capacitive probes on concrete sample [4]*

In another study on moisture content of cement based mortar, the NDT test method employs GHz dielectric resonator oscillator and horn antennas to demonstrate its viability. The conclusion made in the study is that moisture content can be related to the compressive strength of concrete, from the paper by Jusoh et al.; although establishing that relationship was not the focus of the study [5].

The following is a study by Vidal et al. uses an encapsulated UHF antenna to monitor concrete, whereby the setup is shown in Fig. 3. The measuring systems are connected to the vector network analyzer.

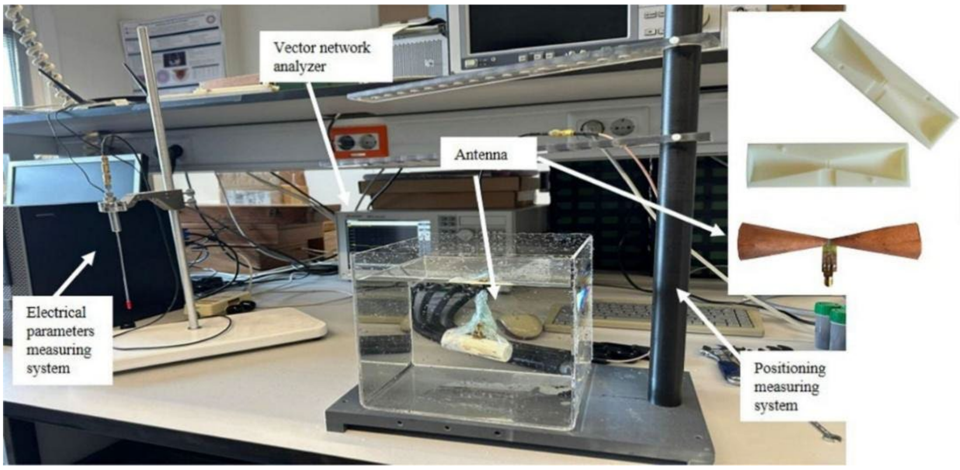


Fig. 3 *The encapsulated antenna undergoing test [6]*

The image of Fig. 3 is retrieved from the published research study. It also shows the antenna is embedded within the concrete to allow for a continuous measurement of temperature and humidity. The antenna itself is encapsulated into a casing together with other sensors before being incorporated into the concrete samples. The results presented in the paper showed conformity between the simulated and the actual testing of the setup [6].

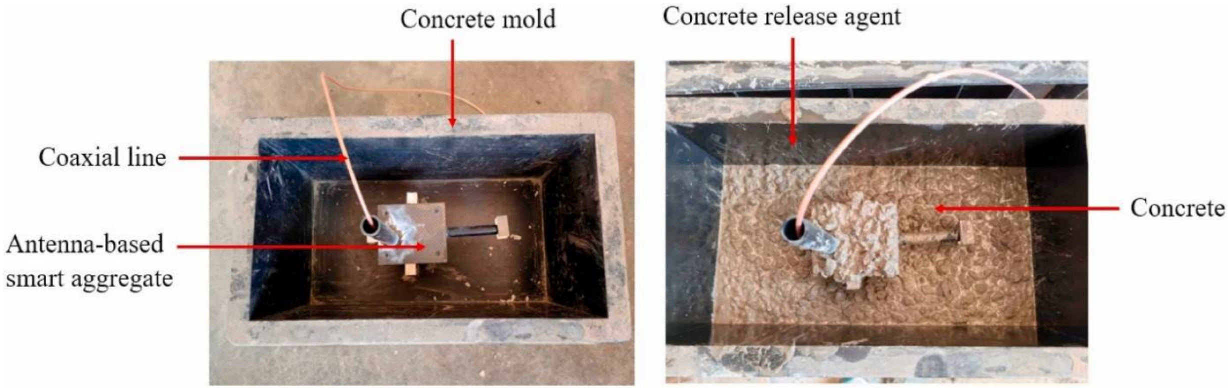


Fig. 4 *Patch antenna placed in a concrete mould [7]*

The use of permittivity and/or dielectric properties of concrete as a parameter to establish the relationship between their values with concrete strength has been used in several studies. In this particular study by He and Lu, shown in Fig. 5, ground penetrating radar is used to test concrete during the curing process, with the dielectric value of the material serving as the parameter to establish relationships for concrete strength, and its porosity [8]. The findings indicate that the water content in the concrete can be correlated to the dielectric property during the curing process. The authors also previously published a study whereby the experiments conducted showed dielectric constant is a good non-destructive testing method to evaluate the curing effectiveness of concrete [9].

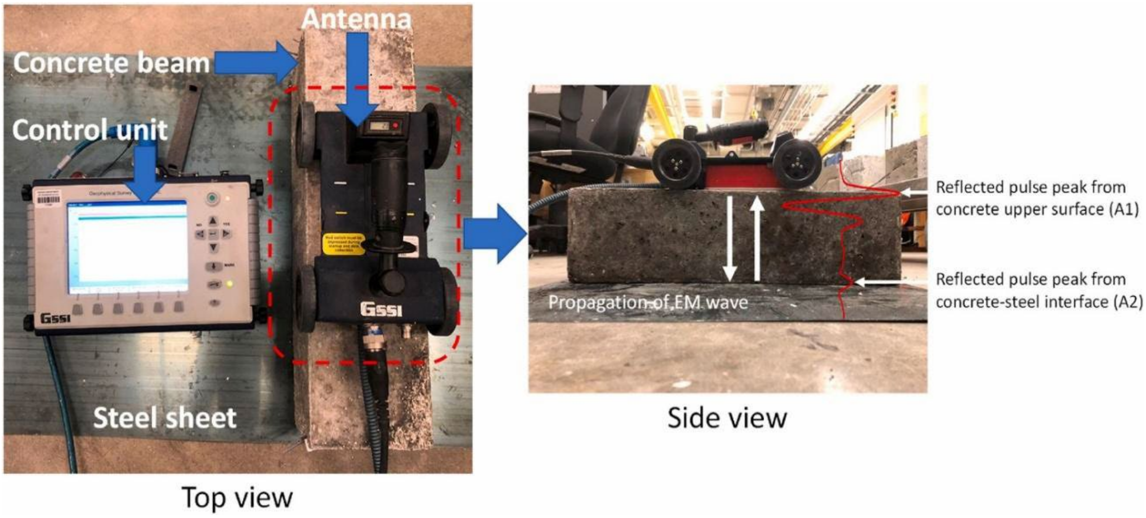


Fig. 5 *Use of ground penetrating radar on concrete sample [8]*

Consequently, the researchers in that study published another paper by Zhong et al., which is on investigating the dielectric properties of concrete in relation to the curing process [10]. Their radar system showed that there are other factors which may affect their testing results; namely the types of aggregate used, the environment and even electromagnetic interference, all of which do warrant further studies. Subsequently, several authors from that study [9] continued with further research on properties of asphalt concrete that found the dielectric constant of the material will vary when the ratio of the constituents are different [11].

In the study by Dinh et al., the researchers conducted microwave dielectric measurements on concrete of mixtures on the 28th and 100th day of the curing process [12]. Their findings showed that the mixtures produced different real and imaginary values of the dielectric permittivity at various frequencies ranging from 1 GHz to 10 GHz. They used varying aggregate sizes, water ratios, and curing methods in their research experiments.

3. Methodology

The proposed methodology here is to prepare three grades of concrete samples, then use the dielectric probe to measure the permittivity for each set of cubes of the grades. After that the concrete samples shall be tested using the compressive test machine, whereby the cubes are individually compressed until the point of breaking. This corresponds to the compression force in which the concrete can withstand before failing. If the samples have been casted from a mixture of known quantity of materials in the correct ratio, then the compressive strength obtained from physically breaking the concrete can be expected from the machine. At the same time, the readings from both the dielectric probe and the compressive test machine can be correlated, meaning that the permittivity values for each concrete grade can be matched to its compressive strength.

Another possible set of data that can be measured from the dielectric probe is the observation of the trend in the change of the permittivity during the concrete curing process. Since it takes 28 days for the concrete to be considered fully cured, which is when a mixture reaches its maximum strength, the permittivity of the concrete is expected to also decrease from the first day to the 28th day. This downward trend in the permittivity is due to the decreasing water content of the concrete as the curing process happens, as mentioned in the paper by Makul [13].

In this research, the main focus is to conduct testing, measurements and record data on concrete cubes based on the concrete mixtures that have been pre-selected prior, in order to study for possible correlation between the dielectric values with the concrete grades respectively. Three concrete mixtures are proposed to be created by varying the proportion of its components. There are many grades of concrete based on the commonly used standards by the British Standards Institution (2021) [14], and the selection for this research is chosen arbitrarily to be of three different grades with varying mixture ratios. There are several research on these grades of concrete, albeit focusing on different parameters and outcomes. One research is on the prediction of compressive strength of C16/20, C20/25 and C25/30 concrete grades using Adaptive Neuro-Fuzzy Inference System (ANFIS) and Artificial Neural Networks (ANN) [15], whereas another one is on the assessment of compressive strength of concrete using grades C20/25 and C25/30 [16].

The proposed mixtures chosen are in-line with concrete grades C16/20, C20/25 and C25/30, which in turn correspond to grades of strength values of 20 MPa, 25 MPa, and 30 MPa respectively. The purpose of choosing these three grades is based on the individual use case that each grade is meant for. Grade C16/20 is usually used non-structural and domestic purposes, whereas grade C20/25 is mainly used in the construction of floors or foundations of structures, and grade C25/30 is used for multi-purpose construction, and mainly for building foundations. Table 1 shows a summary of the use cases for the three concrete grades selected.

Table 1 *Concrete grades*

Concrete grade (MPa)	Use case
C16/20 (20 for cube)	non-structural and domestic use
C20/25 (25 for cube)	pavements and driveways
C25/30 (30 for cube)	foundations, floors, and stairs

For each grade of the concrete, three samples are made by mixing the various components of cement, sand, aggregates and water together and then poured into moulds to form the cubes. The mixture ratio of the components determines the concrete grades that are needed. Based on available literature and resources of concrete mixture ratios, the proportion of the materials are measured first before being mixed. As each cube is 15 cm x 15 cm x 15 cm in dimension, the amount of materials needed are calculated beforehand. Thus, for each cube it will have a volume of 3375 cm3 or 0.003375 m3. The calculations for the amount of materials needed for the components of the concrete are done based on the required mixture ratios of each grade, and they are presented in Table 2.

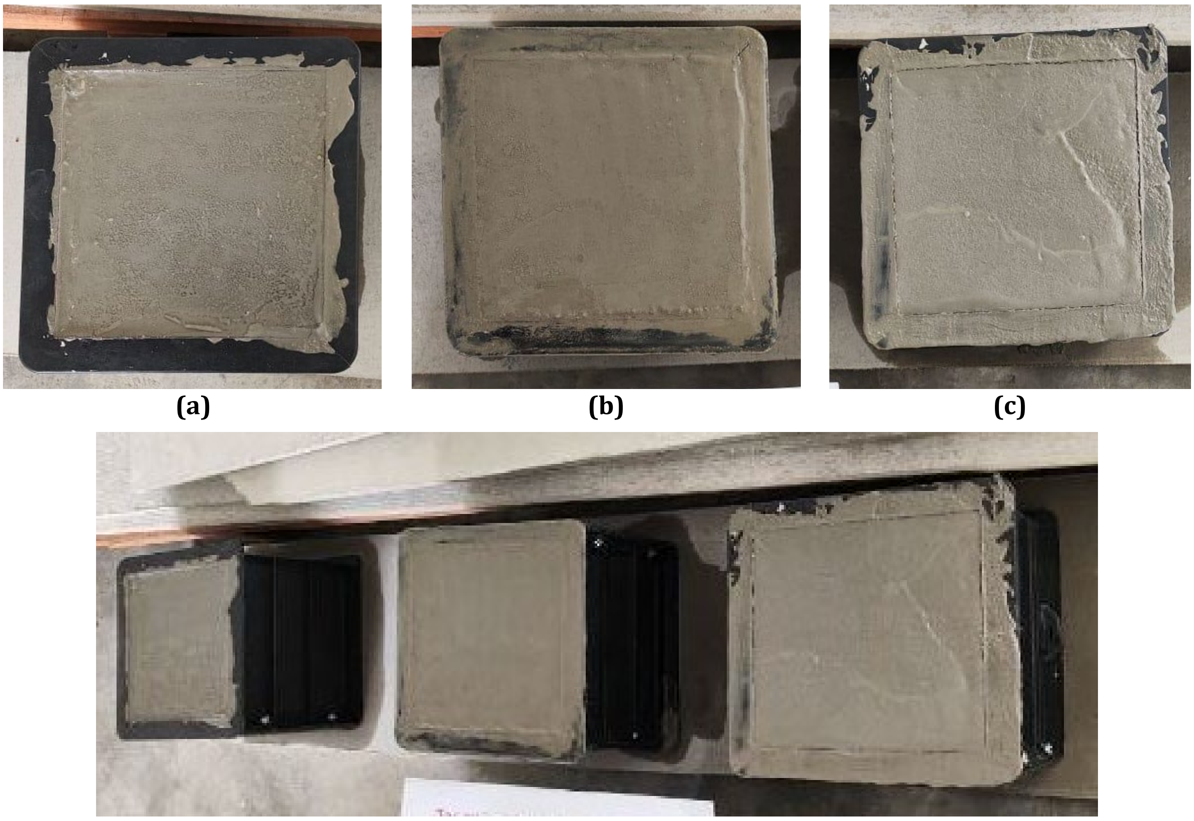
For concrete grade C16/20, the ratio for the materials is Cement:Sand:Aggregate of 1:1.5:3. Thus, each cube requires 1.08 kg of cement, 0.59 kg of water, 1.95 kg of sand, and 3.54 kg of aggregates. As each litre of water is equivalent to 1 kg, then the weight of water is equivalent to the volume required. For aggregates, a mixture of rocks no larger than 2 cm in size are used. To cater to some allowances, about 10% of materials have been added into the calculations for a cube. The weight for each material stated above already includes the extra material allowances. Next, to make concrete of grade C20/25, the materials needed are of Cement:Sand:Aggregate of 1:1:2. The amount of materials needed are 1.16 kg of cement, 0.59 kg of water, 2.00 kg of sand, and 3.44 kg of aggregates. For the third concrete grade option C25/30, the ratio of materials needed is Cement:Sand:Aggregate of 1:0.75:1.5, indicating that the amount of materials for a cube are 1.26 kg of cement, 0.59 kg of water, 1.91 kg of sand, and 3.43 kg of aggregates. Comparing these three concrete grades show that the amount of cement increases as the grade number goes up. The amount of water is similar across all three grades, whereas the amount of sand varies between the grades, albeit by a small quantity only. The amount of aggregates also decreases slightly as the grade number goes up. Overall, the variation of the quantity of each material of the concrete is in line with literature; the concrete strength goes up as more cement is added into the mixture, thus providing an increase in strength within a similar volumetric measurement.

Table 2 *Concrete mixture materials*

Concrete grade (MPa)	Cement (kg)	Water (kg)	Sand (kg)	Aggregate (kg)
C16/20 (20 for cube)	1.08	0.59	1.94	3.54
C20/25 (25 for cube)	1.16	0.59	2.00	3.44
C25/30 (30 for cube)	1.26	0.59	1.91	3.43

To make the concrete cubes for each grade listed above, the amount of materials is measured by weighing them one by one before mixing them together into a cement paste. The mixing is done using conventional tools, such as buckets and shovel. For small quantities of cement used, this method is the most suitable and does not incur a lot of costs, or use heavy equipment such as a cement mixing machine. Moreover, accurate measurements for the amount or quantities of each material can be done more accurately to produce the cube samples. Once the cement paste is produced, it is poured into the cube moulds. Each grade has three cubes being made. In line with industry practice of testing concrete strength, three cubes are required to have a reliable average measurement for the strength. If one of the cubes has defects or sustained failure, then the average strengths of two cubes would still be valid. Using three test cubes provides statistical reliability and quality control.

After the concrete cube samples are made, they are left to set overnight. The following day, the mould is opened and the cube is taken for measurements. A dielectric probe is used to measure the dielectric values from each cube. The dielectric probe is connected to a vector network analyzer. For each cube, readings are taken from 3 of the 6 faces and recorded. This process is repeated over a period of 28 days. Once the readings and measurements are recorded, the data is analyzed to review the pattern of the dielectric values from the concrete over the period taken from casting until fully cured. This corresponds to the 28 days mentioned, as typically in the industry, that is the amount of time taken for concrete to reach its maximum strength. Fig. 6 shows the concrete samples on the first day after being created in the moulds.



(a) **(b)** **(c)** **(d)**

Fig. 6 *Concrete cube moulds (a) C16/20 mixture; (b) C20/25 mixture; (c) C25/30 mixture; (d) A set of 3 cubes*

The dielectric probe is connected to a vector network analyzer and the output of each reading is saved onto a connected USB drive as a Comma Separated Values (CSV) text file. The flowchart in Fig. 7 summarizes the overall methodology in this research. It covers the preparation of the concrete samples based on the specified grades, the data collection process by taking measurements and readings using the dielectric probe, the analysis of data and the establishment of a regression model before presenting the findings, observations and comparisons.

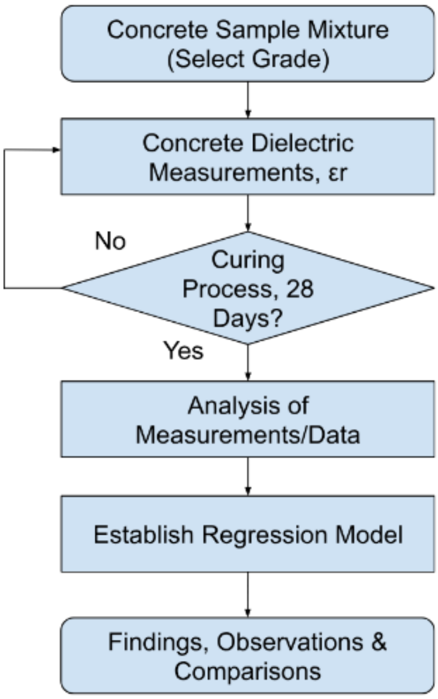


Fig. 7 *Flowchart of the overall methodology*

4. Results and Discussions

The process of collecting the measurements revolves around taking the dielectric readings from the concrete cubes daily from all the faces of the cube, and averaging the multiple readings before plotting out the data. The selected frequency for the dielectric measurements is selected to be as close as possible to 2.0 GHz based on an earlier simulation and modelling study conducted by the authors of the parametric study from this research paper [17].

For taking the readings, a dielectric probe connected to a vector network analyzer is used. Placing the probe directly onto the surface of the concrete cube allows the dielectric value of the material to be measured. This is demonstrated in Fig. 8.

(a) **(b)**

Fig. 8 *Dielectric probe in use to take permittivity measurements (a) From the top; (b) From the side*

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4.1 Results and Analysis

Each reading produces a standard CSV file which shows the frequency sweep, together with the information of the dielectric real permittivity εr', imaginary permittivity εr'', and loss tangent tan δe values, as shown in Fig. 9. The value on each face is averaged out over 5 readings. For each cube, 3 arbitrarily selected faces are chosen for the readings. During the 28 days, the key data points are those on the 1st, 7th day, 14th day, 21st day and 28th day as they correspond to the standard testing process for compressive machine testing of concrete samples. The data is then plotted to be studied, and observations are made on the trend and differences between each set of samples.

Essentially, the data collected comes from measurements conducted in accordance with this sampling method:

- 3 cubes of each concrete grade are created
- Dielectric measurements are taken from 3 faces of each concrete cube
- 5 readings are taken for each concrete cube face
- Readings are taken on the 1st, 7th day, 14th day, 21st day and 28th day
- Readings are averaged out for each cube

```
! Created Tuesday, 9 July, 2024 4:50:09 PM
! Hz ER
! freq  εr'     εr''    tan δe
!
1485025050     9.30169632020553      1.92992261649784      0.207480716426485
1530024900     9.25418827237134      1.90332179176673      0.205671392859939
1575024750     9.22673430285865      1.96279317735223      0.21272891501212
1620024600     9.2214586531975       1.95884498750476      0.212422466029876
1665024450     9.18171105969433      1.89788871289139      0.206703162466384
1710024300     9.14374874499876      1.85509772704445      0.202881529094849
1755024150     9.10955642279202      1.86187407786927      0.204386908808301
1800024000     9.09788370858456      1.81481362033149      0.199476458312945
1845023850     9.03944220280366      1.761072597245        0.194820936705452
1890023700     9.01266255368859      1.69944822521231      0.188562282798082
1935023550     9.01064956855081      1.69100995189819      0.18766792993484
1980023400     8.95675290328614      1.59152237372229      0.177689659512476
2025023250     8.93156184325639      1.55715453822252      0.174342916227828
2070023100     8.94468073655507      1.51610646584149      0.169498108484238
2115022950     8.9039247510574       1.54072284465062      0.173038619229981
2160022800     8.93801923289913      1.42508849303916      0.159441197865595
2205022650     8.88125322965598      1.42327586421363      0.160256196666151
2250022500     8.90060917060751      1.33498791238349      0.149988375716127
2295022350     8.88238651501291      1.28493170887799      0.144660638974245
2340022200     8.86694660575711      1.14472186300062      0.129099893559456
2385022050     8.94026057767354      1.16760716247731      0.130601021338591
2430021900     8.9485592965768       1.13376708759596      0.126698281815004
2475021750     8.91501197816964      1.16966895471156      0.131202174217572
2520021600     8.94442285884545      1.12206487815134      0.1254485499913167
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Fig. 9 *A CSV file of the measurements taken by the probe*

The plots for the real permittivity over the period of 28 days show a decreasing trend in the value, starting high and reduces over time, as shown in Fig. 10. There is a variation between each of the concrete grade as the concrete cures over time. It is observed that during the first 5 days, the real permittivity has a significant decrease in value to almost 50% of the initial measurements. Thereafter, the values slowly decreases until around the period of 21 days. After that, in the last 7 days, the real permittivity of each concrete grade sample remains almost in the same ranges.

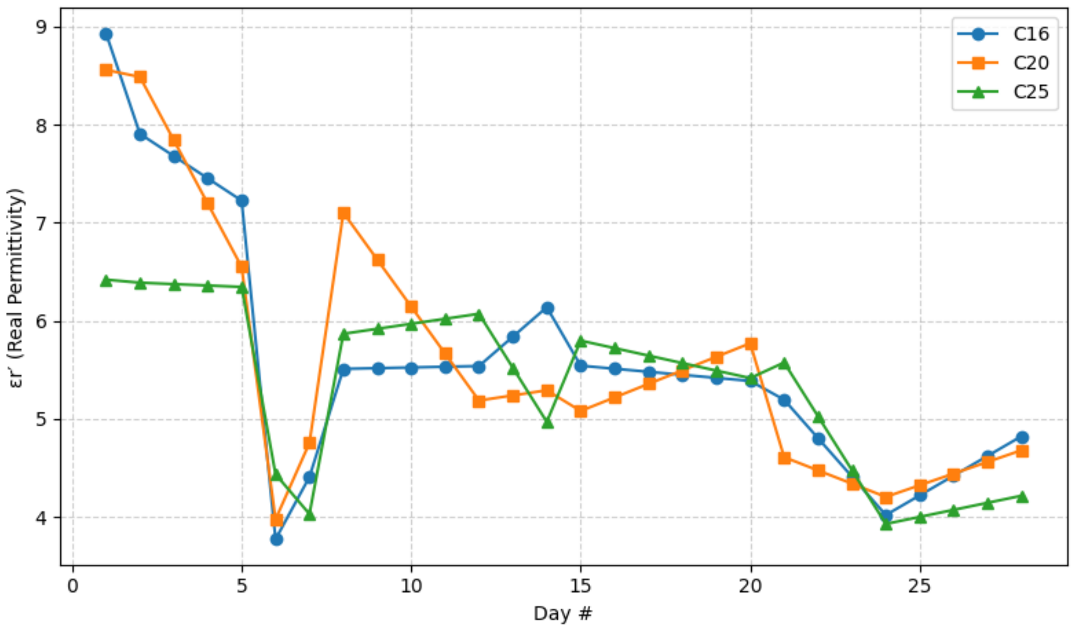

Fig. 10 *Real permittivity vs day*

In terms of the imaginary permittivity, there is also a downward trend from the first day until the last day the measurements are taken, as shown in Fig. 11. However, there appears not to be a distinguishing difference between the three grades of the concrete samples, unlike the real permittivity plot. The same is observed for the loss tangent plot too, as in Fig. 12.

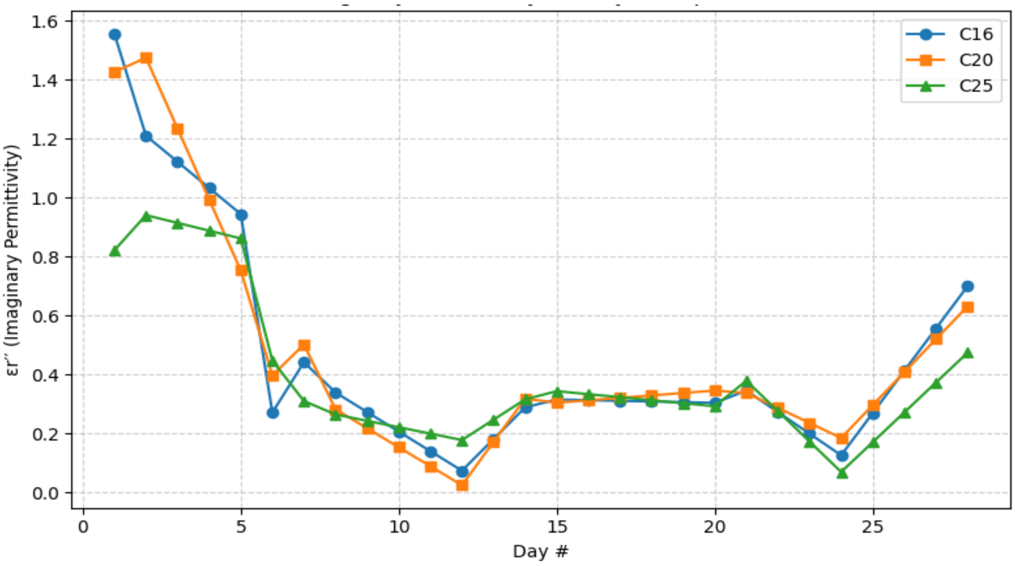

Fig. 11 *Imaginary permittivity vs day*

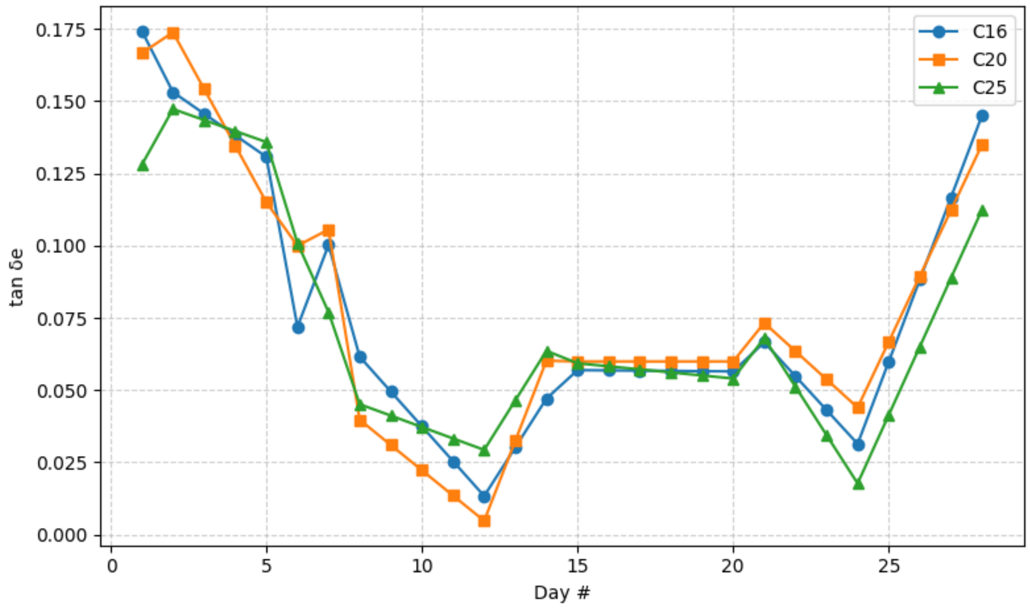

Fig. 12 *Loss tangent vs day*

Two types of regression model are applied to the plots of the real permittivity values for all the three grades of concrete. The respective regression equations (1), (2) and (3) for the linear model are for concrete grades C16/20, C20/25 and C25/30 respectively.

Concrete grade C16/20:

$$\varepsilon'_r = -0.1064 \cdot Day + 7.1243, \qquad R^2 = 0.4971 \tag{1}$$

Concrete grade C20/25:

$$\varepsilon'_r = -0.1179 \cdot Day + 7.3098, \qquad R^2 = 0.5761 \tag{2}$$

Concrete grade C25/30:

$$\varepsilon'_r = -0.0728 \cdot Day + 6.4035, \qquad R^2 = 0.4932 \tag{3}$$

Subsequently, the regression equations for the exponential model for concrete grades C16, C20 and C25 are in equations (4), (5) and (6) respectively.

Concrete grade C16/20:

$$\varepsilon'_r = 7.026 * e^{-0.01739 \cdot Day}, \qquad R^2 = 0.5089 \tag{4}$$

Concrete grade C20/25:

$$\varepsilon'_r = 7.267 * e^{-0.01956 \cdot Day}, \qquad R^2 = 0.5942 \tag{5}$$

Concrete grade C25/30:

$$\varepsilon'_r = 6.460 * e^{-0.01393 \cdot Day}, \qquad R^2 = 0.4757 \tag{6}$$

The linear regression model is shown in the plot of Fig. 13, and the exponential regression model is shown in the plot of Fig. 14.

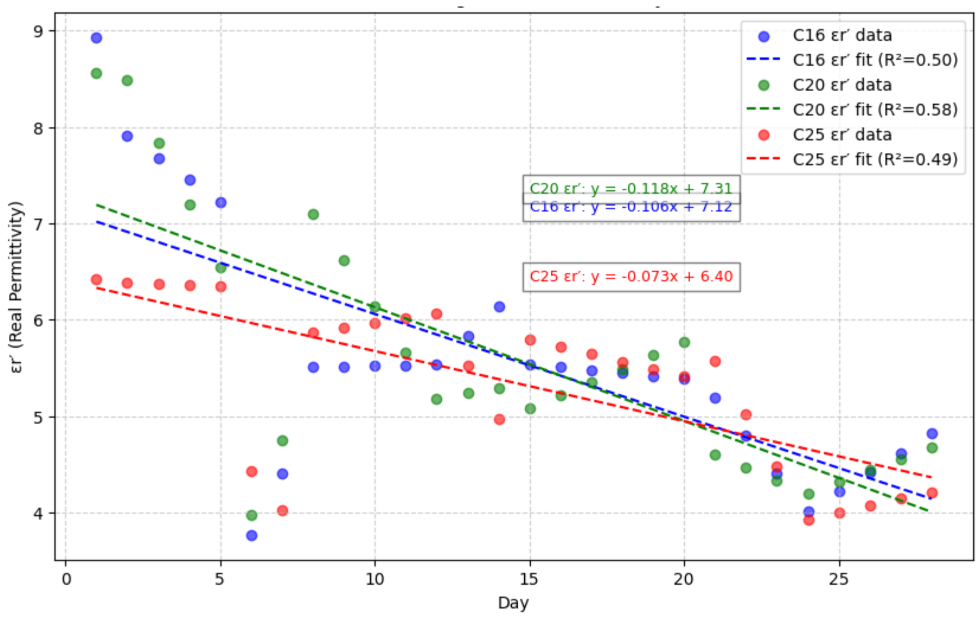

Fig. 13 *Linear regression of real permittivity*

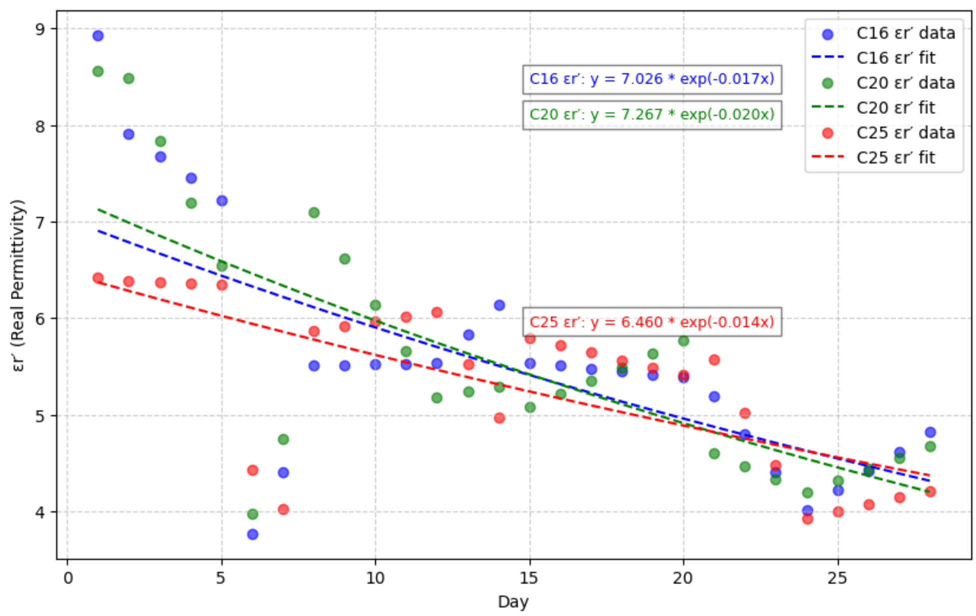

Fig. 14 *Exponential regression of real permittivity*

Next the $\mathbf{R^2}$ values for both models are compared across the three concrete grades. This is tabulated in Table 3. Overall, it can be seen that the exponential regression model is more suitable for all three grades as the $\mathbf{R^2}$ values are higher. For concrete grade C16/20, the exponential regression model can fit the decaying values of the real permittivity better as compared to the linear regression model. The same can be applied to concrete grade C20/25, where the model has a fit with a higher $\mathbf{R^2}$. For concrete grade C25/30, it may be seen that the linear regression model is more suitable. This may be due to the initial measured permittivity values starting lower as compared to that of concrete grades C16/20 and C20/25. Concrete of higher strength grades have a lower initial permittivity value compared to the grades that are lower. This observation can also be seen in the results presented in the research by Lai et al. [18]. Overall, for two of the concrete grades used in the experiments of this study, the exponential regression model is more suited. Further measurements on other concrete grades can be proposed to be conducted in order to evaluate their regression models too. Based on the findings of this research, for the correlation between dielectric properties of concrete and the compressive strength, an exponential regression model can be applied to estimate the real part of the permittivity during the curing process of the concrete.

Table 3 *R^2 values for linear and exponential regression models*

Concrete grade	Linear R^2	Exponential R^2
C16/20	0.497116	0.508881
C20/25	0.576109	0.594166
C25/30	0.493225	0.475745

4.2 Discussions of Findings

The results from the experiments and measurements indicate similar findings as the findings from Zhong et al., whereby their experiment on concrete compressive strength based on dielectric properties uses varying water to cement ratios during the preparation of their concrete samples [10]. However, the researchers are using concrete designed based on the standards of their own country for the experiment. Similar comparisons can also be made to the paper by Lai et al., whereby the authors experimented with light-weight and normal aggregate concrete, with the use of ground penetrating radar [18]. Their study showed that the permittivity values for their concrete mixtures also started high and have steep decline in the initial 20 days and gradually slowed to a steady value from 30 days onwards. Besides the effects of the types of aggregates used in the mixture for concrete, another research paper also investigated the effects of sand in the mixture ratios of concrete samples to Zhong et al. [19]. The authors found that the amount of sand used can also affect the dielectric properties of the concrete.

Therefore, a model for determining the concrete strength using the real part of the dielectric permittivity can be established to predict the compressive strength of concrete samples can be established in future work. Sensors can be designed to be used as a non-destructive testing method instead using a machine to test the concrete samples physically, as presented in this paper by Al–Mattarneh et al. [20]. The sensor used by the authors tracked the reflection coefficient values of the concrete, also during the curing process of the concrete. The values also show the decline is steeper during the first two weeks as compared to the last two weeks. Such sensors are suitable for use when on-site testing is not possible or when access to a compressive testing machine is not available. What is notable from the studies [18] and [20] above, is that the trend of the values measured follows a similar pattern to the measurements conducted under this research. The other studies use concrete mixtures of different constituents and materials such as silica fume, granite as aggregates, or steel fiber. These materials do affect the overall dielectric value when measured using a dielectric probe. The observation on the trend of the dielectric permittivity measurements do reflect the trend, as previously shown in Fig. 10 and Fig. 11 respectively. Structural health monitoring is an example of such application of using sensors in the non-destructive testing of concrete samples [21].

As a comparison to current methods of non-destructive testing that are in use, namely ultrasonic pulse velocity (UPV) test or rebound hammer test, the measurements of dielectric permittivity can be faster as it only requires 1 probe and readings can be obtained upon placement on the surface of the material. UPV testing sometimes require the extraction of the concrete samples from structural elements, which may imply the testing process is semi-destructive, as presented in this research [22]. As for the rebound hammer test, there could be factors which can affect the accuracy of the testing results, such as concrete surface moisture content, specimen size, or temperature, as observed in this research [23]. A summary of the comparison between this research and the UPV test, and rebound hammer test methods for non-destructive testing on concrete is shown in Table 4.

Table 4 *A comparison of dielectric permittivity measurement with ultrasonic pulse velocity [22] and rebound hammer [23] testing methods on concrete*

Testing Method	Ultrasonic Pulse Velocity	Rebound Hammer	Dielectric Permittivity (this research)
Advantage	Typically used in laboratory testing of concrete samples	Uses the correlation between the hardness of the material, e.g. concrete with its destructive strength	Use of dielectric measurements to determine concrete strength (sensor based)

Testing Method	Ultrasonic Pulse Velocity	Rebound Hammer	Dielectric Permittivity (this research)
Drawback	Concrete samples need to be extracted from structural elements, can be considered as a semi-destructive test	Many factors can affect the accuracy of the testing outcome, such as concrete surface moisture content, specimen size, or temperature	Proposed method needs further research and testing to determine its potential as an alternative non-destructive testing method for concrete strength

Future study and research on concrete strength determination using the dielectric permittivity measurements can extend from the findings of this paper. The authors propose an antenna based system that is able to predict the concrete strength based on the dielectric effects on an microstrip patch antenna, which has been modelled and simulated in a prior parametric study research [17].

5. Conclusion

In conclusion, this paper presented the findings of the experimental research work on the measurement of dielectric permittivity of concrete samples using three different mixture ratios which correspond to three grade strengths, C16/20, C20/25 and C25/30. Each concrete grade sample is measured to have a different dielectric permittivity value and the real part of the complex permittivity value shows a decreasing trend when observed for 28 days, during which the concrete samples undergo the curing process. This research also proposes two regression models to be evaluated on their suitability in fitting to the plots for the dielectric values. The findings from this experimental work can further support the implementation and design of a system to determine the compressive strength of concrete based on readings of dielectric permittivity. In this paper, the literature review is also done on several on-going and current research on non-destructive testing of concrete. As a summary, the paper has presented the following:

- A review of on-going and current research on non-destructive testing of concrete
- An experimental work on measuring the dielectric permittivity of concrete samples
- An analysis of the data collected from the readings and measurements of three concrete grade samples
- Proposed a linear and an exponential regression model to the data plots of the concrete permittivity

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Author 1, Author 2;* ***data collection:*** *Author 1, Author 2, Author 5;* ***analysis and interpretation of results:*** *Author 1, Author 2, Author 3, Author 4;* ***draft manuscript preparation:*** *Author 1, Author 2. All authors reviewed the results and approved the final version of the manuscript.*

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