Determination of Physical Properties of Concrete by Using Microwave Nondestructive Techniques

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Abstract ─ Determination of the electrical properties of concretes with different water/cement ratios and investigation of the relationship between their electrical and mechanical properties is a promising technique towards improving novel nondestructive microwave based methods. In this study, this relationship between water-cement ratios/mechanical properties and electrical characteristics of various concretes is investigated in the frequency range of 3-18 GHz. The obtained data provides an accurate measurement results for the researchers to design microwave sensors operating at a constant frequency. Besides, the relationship between the electrical properties and the pressure applied to the concrete is also investigated experimentally for various cement types. The experimental study demonstrates the presumable mechanical characteristic of the concrete by using its dielectric constant values. The dielectric constant is retrieved from the reflection and transmission coefficients (which are more commonly known as scattering parameters) by using Nicolson Ross Weir (NRW) Technique. It is revealed that the most significant frequency point is 18 GHz to determine water/cement ratio and 17 GHz to differentiate applied pressure level by using dielectric constant values of the concrete.

Index Terms ─ Concrete, electromagnetic, Nicolson-Ross Weir, nondestructive testing.

I. INTRODUCTION

Concrete is one of the most commonly used materials in the construction industry. Cement powder, water, fine aggregate (sand), coarse aggregate (rocks) and air (porosity) are composition of concrete which is a heterogeneous material. Aggregate used in concrete is an inert filler material while the chemical reactions between cement powder and water generate a paste binder that holds filler materials together.

Detection of the aging and examining concrete effectively is possible by using nondestructive test (NDT) and nondestructive evaluation (NDE) techniques. These techniques are used for monitoring damages or examining the quality control of concretes [1]. In addition, NDT methods are used to predict premature collapses that the structures may have in future. Techniques and application of these methods are studied by various researchers [1,2].

Moisture content, cracks, voids etc. can be determined by radio and microwave nondestructive testing methods [2]. Conducting these methods provides advantages over the other NDE methods (such as radiography, ultrasonic, eddy current) since they are more reliable, cheaper and easier to apply on [3]. Nowadays, microwave nondestructive testing (MNDT) techniques (such as ground probing radar, free-space microwave techniques) are effectively used for quality control of concretes. Since MNDT techniques are fast, precise and reliable, these test methods have taken an important place in the construction applications [4].

Boiset et al. [5] studied microwave near-field reflection property analysis of concrete to correlate the analysis results with the strength of concrete, which is strongly influenced by water-to-cement (w/c) and coarse aggregate-to-cement (ca/c) ratios of concretes. In the study of Zoughi et al. [5], cement paste samples with different w/c are tested under different frequency ranges in microwave spectrum. According to their results, there is a correlation between the reflection coefficients of the samples and water-cement ratios. Thus, correlation between compressive strength and the reflection coefficient of these samples is also obtained.

A time domain reflectometry (TDR) and backscattering search optimization algorithm (BSA) based nondestructive approach for wiring diagnosis is also investigated by Boudjefdjouf et al. [6]. The results of proposed technique is realized by both simulations and experiments. It is concluded that the proposed

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approach can be used to determine complex wire networks. Signal inversion by using sensors is also carried out for eddy current (EC) nondestructive testing (NDT) method. The proposed technique characterizes surface cracks by using the reflected EC signals [7].

In the current study, reflection coefficients and dielectric properties of the concrete samples containing different types of cement with various water-cement ratio are determined by electromagnetic waves at microwave frequency range of 3.0–18.0 GHz and mechanical and transport properties of the samples are also examined. At the end of the study, a correlation between electrical parameters (dielectric constant) and mechanical/transport properties of the concrete samples are presented.

II. EXPERIMENTAL STUDIES

In order to characterize the electromagnetic behaviours of the concrete samples, we need to obtain the scattering parameters (also known as S-Parameters). For this purpose, a wideband Vector Network Analyzer (VNA) which is capable of measuring electromagnetic signals from 10 MHz to 43.5 GHz are used. Two wide band, linearly polarized, directional and high gain horn antennas are used by connecting VNA. Antennas have the operating frequency of 3-18 GHz which is quite enough to analyze the electromagnetic behaviors of the concretes under test. Analyzer with the antennas is used to measure transmission and reflection parameters to find the electromagnetic behavior of the concrete samples.

Nicolson Ross Weir (NRW) approach is used to determine the electromagnetic properties of the concrete samples with various w/c values [10,11] and many different types of materials [12-14]. This approach uses reflection and transmission values as well as the associated phases obtained from the network analyzer to characterize the electromagnetic response of the concrete sample. NRW method which is preferred due to its advantages on free space measurements. It is based on extracting the parameters by using two main scattering coefficients, namely the reflection from the port-1 (S11) and the transmission between port-1 and port-2 (S21) (Fig. 1). The electromagnetic parameters of any medium including the concrete samples can be extracted from the transmission and reflection values by using NRW technique. Some of these parameters are the electrical permittivity, permeability and loss factor values that we successfully obtained from experimental setup. The formulas of $\mu = \mu_0 \mu_r$, $\varepsilon = \varepsilon_0 \varepsilon_r$, $Z = \sqrt{\mu_r / \varepsilon_r}\, Z_0$ can be used to find magnetic permeability, dielectric constant and impedance of the medium, respectively. The details of the NRW method can be summarized for the general case as follows.

First, the reflection coefficient which is shown by Γ should be found:

$$\Gamma = \frac{Z - Z_0}{Z + Z_0} = \frac{\sqrt{\mu_r/\varepsilon_r} - 1}{\sqrt{\mu_r/\varepsilon_r} + 1}. \quad (1)$$

By using the sample thickness and medium parameters, wave decay (z) can be calculated for the medium inside the sample under test:

$$z = \exp - j\omega\sqrt{\mu\varepsilon} d = \exp[-j(\omega/c)\sqrt{\mu_r \varepsilon_r} d]. \quad (2)$$

By using the parameters found so far, it can be easily written the expressions for the reflection and transmission parameters as:

$$S_{21}(\omega) = \frac{(1+\Gamma)(1-\Gamma)z}{1-\Gamma^2 z^2} = \frac{(1-\Gamma^2)z}{1-\Gamma^2 z^2}, S_{11}(\omega) = \frac{(1-z^2)\Gamma}{1-\Gamma^2 z^2}. \quad (3)$$

While the impedance of the sample unit is:

$$Z = \pm \sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}}. \quad (4)$$

The relative permittivity and permeability can then be calculated using the formula below:

$$\mu_r \sim \left(\frac{2}{jk_0 d}\right) \frac{1-V_2}{1+V_2}, \quad (5)$$

$$\varepsilon_r \sim \left(\frac{2}{jk_0 d}\right) \frac{1-V_1}{1+V_1}. \quad (6)$$

Where k denotes wave vector in MUT which is $k \sim \frac{1}{jd} \frac{(1-V_1)(1+\Gamma)}{1-\Gamma V_1}$ and V1, V2 are defined for simplification as:

$$V_1 = S_{21} + S_{11}, \quad (7)$$

$$V_2 = S_{21} - S_{11}. \quad (8)$$

It should be noted that the derivation above is for the general case of the relative permittivity and permeability calculation. The software loaded onto the analyzer will choose the appropriate parameters while using NRW method. Therefore, the distance between the testing antennas and the sample under test as well as the thickness of the sample are extremely crucial in order to obtain more accurate results.

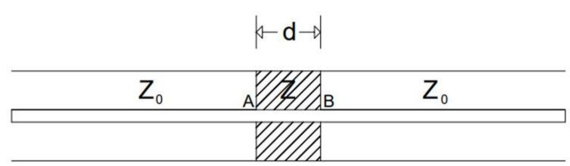

Fig. 1. Measurement configuration of S-parameters.

A. Materials and mixture proportions

An experimental analyze is conducted to determine the correlation between the effective electrical properties and mechanical/transport properties of different concrete mixtures. The materials used to prepare the concrete mixtures are portland cement, white cement, calcium alimunat cement, fine aggregate with a maximum grain size of 4mm, coarse aggregate with a maximum grain size of 16mm and tap water. The chemical composition of the portland cements used is presented in Table 1.

Table 1: Chemical composition of Portland cement

Chemical Properties	Analysis (%)
MgO	2.00
Al_2O_3	6.57
SiO_2	21.56
CaO	61.28
Fe_2O_3	3.00
SO_3	3.19
K_2O	0.69
Na_2O	0.27

The absolute volume method defined by ACI is used for mixture design. For the mixtures which contain Portland, white and calcium alimunat cement, the water-cement ratio is kept constant with a value of 0.5. In order to determine the effect of water-cement ratio, the traditional (Portland) cement containing concrete mixture is preferred as a control mixture and then samples with different w\c are produced. The details of mix proportions used in this study are given in Table 2.

Table 2: Mix design

W/C	Water (kg/m³)	Portland Cement (kg/m³)	Fine Aggregate Weight (kg) (0-4 mm)	Coarse aggregate Weight (kg) (4-11 mm)
0,4	200	500	672,39	693,79
0,5	250	500	617,39	637,04
0,6	300	500	562,39	580,29

B. Mix proportions

Five different mixtures are prepared as the material under test (MUT) with the consideration of the followings:

- Concrete mixtures containing three different cement types (Portland cement, white cement, calcium alimunat cement).
- Three different water-cement ratio for mixtures containing traditional cement (0.4, 0.5 and 0.6).

Fine and coarse aggregates are placed in concrete mixer and mixed for a minute, cement is then added and mixed for two minutes. Finally, tap water is added gradually and mixed up for the concrete to have plastic form. A speed controlled power-driven revolving pan mixer is used to mix the concrete. 15x15 cm^2 slap samples with 4 cm thickness to determine the electromagnetic (EM) behavior, 10x10x10 cm^3 cubes to conduct compressive strength, abrasion and absorption tests and 15x15x15 cm^3 cubes to perform tensile splitting and high water pressure tests are used. The mentioned dimensions are carefully selected to minimize the measurement errors and to provide adaptation for NRW limits. The correctness of the experimental results is provided by normalizing the results with respect to the results of both free space measurement in the same environment and the measurement performed by using metallic sheet between transmitter and receiver antennas. The specimens are demolded 24 hours after casting and cured in a water tank for 28 days.

C. Test methods

This study aims to determine the concrete properties of the samples with different mixtures by using a non-destructive electromagnetic based method. The proposed method retrieves the relative permittivity values from the scattering parameters, more widely known as S-parameters. These parameters characterize the reflected and transmitted electromagnetic signals between the ports. Two-port system is considered in the study. To find relationship between the mechanical characterization and the electromagnetic behaviour of the concrete samples will lead us to build various instruments including particularly microwave sensors and etc.

S-parameters can be measured by using a network analyzer within the operating frequency range of the analyzer. The instrument we have covers almost 43 GHz frequency band which is quite enough for our purpose as the results also support this statement. Although the range of the analyzer is high, it is observed that the relationship is obtained in the frequency range of 3-17 GHz. For this purpose, two linearly polarized horn antennas with very high efficiency and directivity is used in the measurement. The calibration is made by following the procedure suggested by the manufacturer which includes air for free space normalization and a metallic plate for full reflection calibration. After each calibration we have measured the testing setup for free space and no further work is done without confirming the calibration is accurate. Permittivity value of air is measured first for the calibration check and the values for air are always obtained before starting the concrete measurements. The separation distance and the sample thickness are measured and typed into the program and the corresponding subroutines tabulated the desired characteristics which will be shown in the following sections of the paper.

In case of determining the physical properties by using NRW free space method, each electromagnetic properties are determined with respect to the thickness of the samples as seen from Eq. (2), Eq. (5), Eq. (6) and Eq. (7). Hence, errors that can be occurred due to the thickness have been eliminated in the main equations. Beside this, diffraction errors are minimized by choosing the sample as large as the maximum wavelength of incident wave in the related frequency range.

The tests are conducted on 15x15 cm^2 concrete specimens with 4 cm thickness. Measurement setup and the schematic view of the experimental study is shown in Fig. 2. The measurement environment is set to minimize scattering and near field effects to enhance the accuracy of the experiments. The measurement environment should not include any other external electromagnetic wave transmitter in order to prevent any noise from the reflected and transmitted data. Therefore, all the instruments are switched off and removed from the testing area. The testing setup is prepared so that two horn antennas have the same orientation in order to measure the co-polarization measurement not the cross-polarization responses of the antennas. The separation distance between the antennas are calculated and precisely aligned so that reactive near field region effects are eliminated.

Tensile splitting tests are performed on 15x15x15 cm^3 cubes and compression tests are performed on 10x10x10 cm^3 cubes by a 1000 kN compression capacity testing machine. To conduct tensile splitting test on the cube, lines are drawn on the middle of two opposite faces of the cubes to ensure the applying load on the same axis. Two metal strips are then placed on the drawn lines. After that, approximately a 14-21kg/cm^2/minute load is applied. To estimate tensile splitting strength, Eq. (9) is used:

$$\sigma=2P/\pi a^2, \quad (9)$$

where

σ: Tensile splitting strength,
P: Load,
a: Length of the specimen.

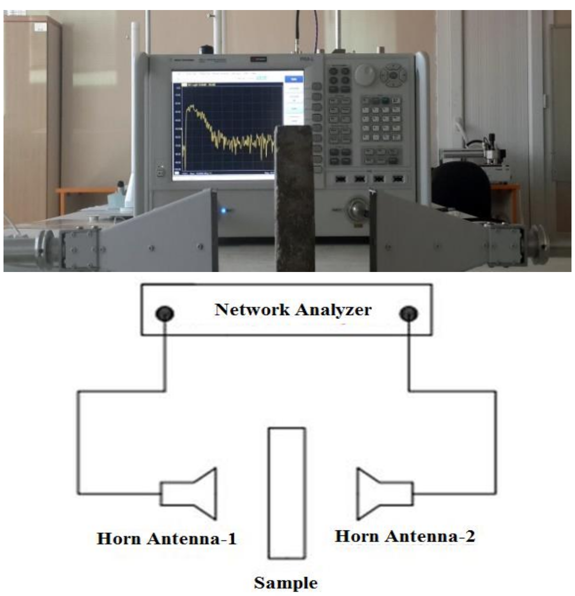

Fig. 2. Measurement setup and the schematic view.

Apart from applying a linear load in tensile splitting test to determine compressive strength of the concretes; a distributed load is also applied onto two opposite faces of the cube. To estimate compressive strength, Eq. (10) is used:

$$\sigma=P/a^2. \quad (10)$$

Determination of the abrasion resistance of the concrete, Vertical Abrasion Tester setup is used. Concretes having 10x10x10cm^3 dimensions are abbreviated by an abrasive dust. The dust is poured between the concrete sample and a metal disc, which rotates 75 times/min. For measuring abrasion amount, final (abbreviated) and first (not-abbreviated) weight of the samples are recorded. The weight difference between the final and first reading gives the abrasion resistance.

To determine water absorption capacity of the hardened concrete, 28 days water cured concrete samples are dried in an oven under the temperature of 105^{o}C for a day. Then, weight difference between fully saturated and oven dried concrete samples gives water absorption capacity of the concrete. For this test method, 10x10x10 cm^3 cubes are used.

High water pressure test is conducted to determine water penetration deepness of the concrete samples by applying 5 bar water pressure from bottom face. Before conducting the test procedure, concrete samples are dried in an oven under 105^{o}C for a day and then faces of the test specimen except top and bottom faces are coated with paraffin to control the water flow. A 5 bar water pressure is applied from bottom face of the 15x15x15 cm^3 cube samples for 72 hours. At the end of three days, the cube samples are split then the water penetration deepness is measured and recorded.

III. RESULTS AND DISCUSSIONS

Determining or predicting compressive strength of a concrete sample in terms of electrical properties provides a prediction of other mechanical and transport characteristics of the concrete under test with various properties. In order to provide this relationship, water-cement concrete mixtures with 0.4-0.5 and 0.6 ratios are prepared. The aim of the selection of these water-cement ratio values is to control compressive strengths of the samples so that the other mechanical and transport parameters would also be under control. Increasing water content in the concrete mixture causes weaker bond between cement paste and aggregates, bigger capillary pores and more heterogeneous mixture due to segregation compared to the concretes with lower water-cement ratio. Thus, as it can be seen in Table 3, higher values of w/c result in an increment in compressive strength, increase the splitting tensile strength and abrasion resistance; decrease the water absorption and high pressure water penetration.

The results of the strength and transport characteristics of the concretes containing different water content is illustrated and compared in Table 3. The prediction of compressive strength of the concrete will provide useful data to have a better idea about concrete properties for specialists.

Table 3: The relationship between mechanical properties of the concrete and water/cement ratios

Engineering Behaviors	W/C=0,4	W/C=0,5	W/C=0,6
Compressive strength (Mpa)	46,09	29,98	22,26
Splitting tensile strength (Mpa)	2,34	2,26	1,81
Abrasion resistance (weight loss (%))	0,04	0,08	0,09
Water absorption (%)	3,65	7,49	8,72
High pressure water penetration (cm)	0,5	3,5	5

In this study, both the concrete samples having different water contents and the concrete samples with different cement types are studied. Their compressive strengths and electromagnetic characteristics are tested and the results are then correlated. Each material has unique electromagnetic properties and responses when exposed to an electric field due to changing effective electromagnetic properties depending on the content of concretes. One of the parameters identifying the electromagnetic properties of a matter is the effective electrical permittivity. When electric field is applied to a material, it will interact and polarize depending on the amplitude, phase and direction of the field. Under the same condition, this parameter allows us to distinguish materials just by observing their electrical permittivity. Experimental studies are carried out by using a vector network analyzer in a significantly large frequency range between 3 GHz and 18 GHz. Two linearly polarized horn antennas with high gain and operating in the frequency range of 3-18 GHz are used in order to obtain the reflected and transmitted responses of the concrete samples.

Determination or observation of strength gaining of the concrete by using microwave test methods as a nondestructive method is carried out in this part of the study. In this respect, the effective dielectric constant values of the concrete samples with different water contents are investigated by using microwave measurement techniques at two different time lines. The measurements of the reflection and transmission coefficients and evaluation of the dielectric constant values are realized on the 28th day and in the 2nd month after casting. (The specimens are demolded 24 hours after casting and cured in a water tank for 28 days). As it is obvious in the literature that as the time passes, hydration reaction in the cement paste continues. Thus, concrete becomes denser and gains more strength [8]. The conducted studies showed that there is a correlation between the strength properties and effective dielectric constant values. As seen from Fig. 3 (a), the increment of the water/cement ratio reduces the effective dielectric constant in the entire frequency spectrum. Since the presence of water in cement reduces the effective density of the concrete, the dielectric constant reduces. The widest gap between dielectric constants occurs at the frequency of 18 GHz. The dielectric constants are 6, 2 and 0.65 for 0.4, 0.5 and 0.6 w/c ratios, respectively. Hence, a simple microwave device can be designed to determine the water content of concrete. Since, the increment of the water content in the cement decreases compressive strength and splitting tensile strength as dielectric constant, the relationship between w/c and dielectric constant can be used to estimate these two strength values. Beside this, the change of dielectric constant with respect to w/c ratio also helps to decide abrasion resistance, water absorption and high pressure water penetration properties of the concrete due to inverse relationship between these properties and dielectric constant of concrete. In addition, the concrete with 0.6 w/c ratio has zero dielectric constant in the frequency range of 9 GHz - 14 GHz. Hence, one can expect an enhancement of intensity in radiation mechanisms caused by scattering of pseudo photons [9]. Therefore, the mentioned concrete can be used to design novel radomes which are used to prevent radars and antennas from environmental conditions. As a result, determination of w/c, abrasion resistance, water absorption and high pressure water penetration properties, compressive strength and splitting tensile strength can be carried out by microwave technique at a constant frequency as a nondestructive method due to direct or inverse proportionality between these properties and effective electrical properties of the concrete.

The dielectric constant of concrete with different w/c ratios in the 2nd month after casting is shown in Fig. 3 (b). It is seen that the dielectric constant is inversely proportional with w/c ratios. The higher values of dielectric constants compared to the values on the 28th day after casting are due to the reduction of the water content in concrete with the elapsed time. Hence, the concrete w/c ratios can be determined by microwave measurement techniques as nondestructive method. Beside this, the relationship between w/c and mechanical properties also permits us to determine the mechanical properties of concrete by microwave techniques. The gap between dielectric constants is widest at 8.5 GHz at which the dielectric constants are 2.8, 6 and 9 for 0.6, 0.5 and 0.4 w/c ratios, respectively. In addition, determination of the w/c ratios of concrete can also be carried out in entire frequency spectrum. Therefore, a simple microwave device that operates at a constant frequency can be used to specify the mentioned mechanical properties of the concrete depending on the electrical properties.

As a final step, the electrical properties of different cement types under various pressures are evaluated from the free space measurement coefficients of the reflection and transmission in the frequency spectrum of 3 GHz-18 GHz as shown in Fig. 4.

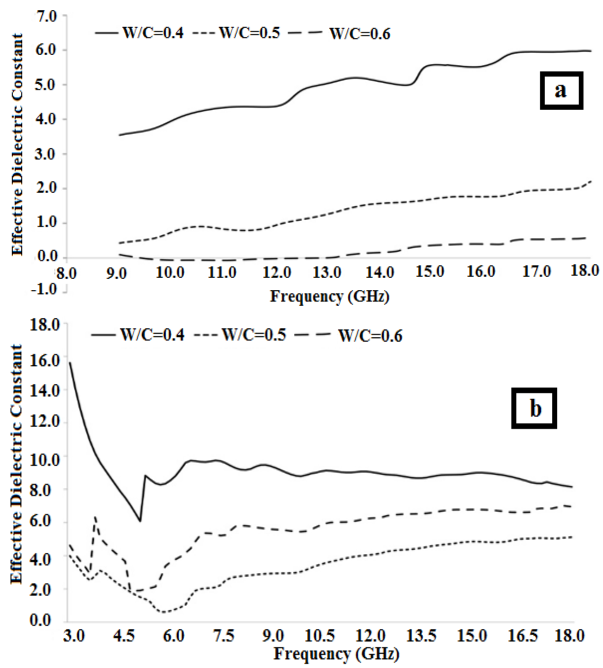

Fig. 3. Effective dielectric constants of cement with various w/c ratios for the: (a) 28th day and (b) 2nd month after casting.

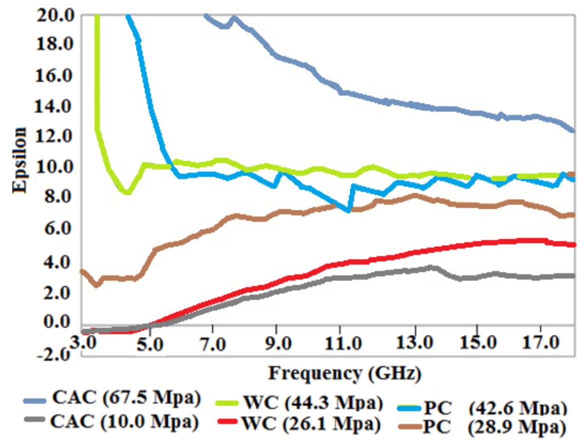

Fig. 4. Effective dielectric constants of different cement types under various pressures.

The measurements are carried out for calcium aluminat cement (CAC) under 67.5 MPa and 10 MPa pressure, white cement (WC) under the pressure of 44.3 MPa and 26.1 MPa and portland cement (PC) under the pressure of 42.6 MPa and 28.9 MPa. The higher values of pressure result in higher effective dielectric constants for each material under test for all types of cements. This is due to the increment of the density of the concrete. The reason is that the higher values of density results in higher values of dielectric constant. In addition, the effect of pressure on dielectric constant is much determinable with respect to the type of cement in concrete. Hence, it is possible to determine the applied pressure on concrete by microwave nondestructive method independent from the cement type. The effective dielectric constants at 17 GHz are around 14, 10, 9, 7.5, 4, 2 for calcium aluminat cement under 67.5 MPa pressure, white cement under 44.3 Mpa pressure, portland cement under 42.6 MPa pressure, portland cement under 28.9 MPa pressure, white cement under 26.1 MPa pressure and calcium aluminat cement under 10 MPa pressure, respectively. As a result, the cement type and pressure values can be determined by a microwave device operating at a constant frequency. Test results showed that there is a direct relation between epsilon values and compressive strengths. As seen in the figure, WQ increment in compressive strength causes increment in epsilon values (no matter which type of cement added into the concrete). Besides, as it can be seen in Fig. 4, the real part of dielectric constant is negative for two different types of calcium aluminat cement in the frequency range of 3 GHz-5 GHz. The negative value of dielectric constant is caused by the aluminat calcium aluminat cement with the metallic characteristics. With this novel measurement method, compressive strengths of the concretes are predictable and comparable without destructing concrete samples. In addition, having an idea about compressive strengths of the concrete samples allows predicting other mechanical and transport properties of the concretes as mentioned above.

IV. CONCLUSION

In this paper, Agilent brand 2-Port PNA-L Network Analyzer having the range from 10 MHz to 43.5 GHz is used for obtaining the scattering parameters and electromagnetic properties of the specially prepared concrete specimens. As it is well determined that the EM property of the concrete is one of the most important properties of the concrete that allows monitoring strength parameters and therefore, transport characteristics of the concrete because its EM characteristics is directly related to intensity of the sample which is concrete in this study. Although other traditional methods such as magnetic resonance imaging are also used to analyze properties of cement, the advantage of the proposed method is that the characteristic of the cement can be determined by a portable device which must be developed depending on the electromagnetic properties of the material under test.

According to test result, following conclusions can be drawn:

- A correlation between compressive strength and epsilon parameter is determined.
- Determining epsilon parameters would provide predicting strength of a concrete sample non-destructively. This nondestructive method provides faster determination of the strength of the concrete with respect to the destructive methods since this

procedure can be achieved in a few minutes.

- Correlation between compressive strength and epsilon parameters means also correlation between epsilon parameters and splitting tensile strength, abrasion resistance, water absorption, high pressure water penetration and other concrete properties.

Whereas concrete analysis and material content determination is realized by using microwave near field reflection property of the material under test in the study [4], the proposed method in this study get in contact with effective permittivity and mechanical properties of the material by using NRW method. Although the relationship between electrical and mechanical properties are also determined in another study by free space method up to 13 GHz [5], this study constitute this relationship by using another free space method (NRW method) in a wider frequency range up to 18 GHz. Nicolson Ross Weir method based microwave technique is used to characterize and retrieve electrical properties (dielectric constant) of concrete with various water/cement ratios and under different pressure levels in microwave frequency spectrum. The dielectric constant values for each material under test are evaluated from the measured values of reflection and transmission in the frequency range of 3 GHz-18 GHz. According to the results of the experimental investigations, the suggested nondestructive microwave method exhibits a reasonable difference and relationship between the mechanical and electrical properties of the concrete for the certain frequency points in the spectrum. Thus, the NRW technique is useful in the construction procedure of microwave devices/sensors operating at a constant frequency. In the case of water/cement ratio variation in concrete, the effective dielectric constant is inversely proportional within the entire frequency spectrum. Hence, the dielectric constant can be used to estimate w/c ratio in concrete. Besides, some of the mechanical properties related with w/c can also be determined. The effect of the ageing on the effective dielectric constant with respect to the water/cement ratio is also investigated for the 28 days and two months cured samples. The aging of the concrete sample results in an increment in the effective dielectric constants of the concrete with the same water/cement ratio due to settlement of density. The pressure effect on effective dielectric constant after the manufacturing process for different cement types in concrete is also carried out in the same frequency spectrum. It is also revealed that the increment of pressure also increases the effective dielectric constant due to higher density in unit cell. The pressure effect is more than the cement type. It is observed that a constant frequency of 17 GHz can be used to estimate the applied pressure by measuring the dielectric constant nondestructively. After all, microwave base techniques could be utilized more to be a good candidate for several nondestructive testing applications such as sensor, microwave devices, microwave tomography and so on.

REFERENCES

[1] P. C. Chang, A. Flatau, and S. C. Liu, "Review paper: Health monitoring of Civil infrastructure," *Structural Health Monitoring*, vol. 2, pp. 257-267, 2003.

[2] R. Zoughi, S. D. Gray, and P. S. Nowak, "Microwave nondestructive estimation of cement paste compressive strength," *ACI Materials Journal*, vol. 92, pp. 64-70, 1995.

[3] P. O. Moore, "American Society for Nondestructive Testing," Nondestructive Testing Handbook, 1999.

[4] M. Jamil, M. K. Hassan, H. M. A. Al-Mattarneh, and M. F. M. Zain, "Concrete dielectric properties investigation using microwave nondestructive techniques," *Materials and Structures*, vol. 46, pp. 77-87, 2013.

[5] K. J. Bois, A. D. Benally, and R. Zoughi, "Microwave near-field reflection property analysis of concrete for material content determination," *IEEE Transactions on Instrumentation and Measurement*, vol. 49, pp. 49-55, 2000.

[6] H. Boudjefdjouf, H. R. E. H. Bouchekara, F. de Paulis, M. K. Smail, A. Orlandi, and R. Mehasni, "Wire fault diagnosis based on time-domain reflectometry and backtracking search optimization algorithm," *ACES Journal*, vol. 31, pp. 340-347, 2016.

[7] B. Helifa, M. Feliachi, I. K. Lefkaier, F. Boubenider, A. Zaoui, and N. Lagraa, "Characterization of surface cracks using Eddy current NDT simulation by 3D-FEM and inversion by neural network, *ACES Journal*, vol. 31, pp. 187-194, 2016.

[8] A. M. Nicolson and G. Ross, "Measurement of intrinsic properties of materials by time domain techniques," *IEEE Transactions on Instrumentation and Measurement*, vol. 19, pp. 377-382, Nov. 1970.

[9] W. B. Weir, "Automatic measurement of complex dielectric constant and permeability at microwave frequencies," *Proceedings of the IEEE*, vol. 62, pp. 33-36, 1974.

[10] J. Němeček, V. Králík, V. Šmilauer, L. Polívka, and A. Jäger, "Tensile strength of hydrated cement paste phases assessed by micro-bending tests and nanoindentation," *Cement and Concrete Composites*, vol. 73, pp. 164-173, 2016.

[11] V. H. Arakelian and Z. S. Gevorkian, "Radiation in systems with near zero dielectric constant," *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, vol. 269, pp. 229-231, 2011.

[12] M. Esen, I. Ilhan, M. Karaaslan, E. Unal, F. Dincer, and C. Sabah, "Electromagnetic absorbance properties of a textile material coated using filtered arc-physical vapor deposition method," *Journal of Industrial Textiles*, vol. 45, no. 2, pp. 298-309, 2015.

[13] F. Dincer, M. Karaaslan, E. Unal, O. Akgol, and C. Sabah, "Multi-band metamaterial absorber: Design, experiment and physical interpretation," *ACES Journal*, vol. 29, no. 3, pp. 197-202, 2014.

[14] E. Dogan, E. Unal, D. Kapusuz, M. Karaaslan, and C. Sabah, "Microstrip patch antenna covered with left handed metamaterial," *ACES Journal*, vol. 28, no. 10, pp. 9999-1004, 2013.

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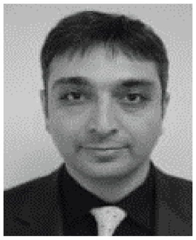

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