Master's Thesis

Performance Assessment of Concrete Crack Repairing Materials using PZT Transducers

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Department of Urban and Environmental Engineering
(Urban Infrastructure Engineering)

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2018

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A thesis/dissertation
submitted to the Graduate School of UNIST
in partial fulfillment of the
requirements for the degree of
Master of Science

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12. 04. 2017

Approved by

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Abstract

Concrete is a widely used material in construction of civil infrastructure engineering such as dams, houses, bridges, and energy plants. Due to shrinkage, rapid dry of the concrete, and overload, cracks are usually generated on the concrete structures and can possibly cause durability-related issues and structural damages. Thus, the concrete crack is an important indicator of potential durability degradation and damage, and the crack should be monitored and repaired through regular maintenance. Indeed, identifying and repairing the concrete cracks using healing materials is important. While most research efforts to date have been devoted to investigation of crack locations and sizes and effective repair, few are evaluating the repairing performance. Therefore, to find an effective nondestructive evaluation (NDE) method for assessing the repairing performance of different healing materials is necessary. Meanwhile, the electro-mechanical impedance (EMI) employing the Piezoelectric Ceramic Lead Zirconate Titanate (PZT) is widely used in structural health monitoring (SHM) as a NDE method in the civil engineering field. The PZT-based EMI is usually applied to detect and locate structural damage in operation. This study used PZT EMI to extract the impedance, which was used as the damage indicator to evaluate the repairing performance of three different materials of the healing cement material from Intchem company, superabsorbent polymer (SAP), and epoxy. A comparison study on the different computation methods of damage index (the root-mean-square deviation (RMSD), the shift of resonance frequency (SRF) and the mean absolute percentage deviation (MAPD)) is also conducted. Results show that the increase of crack depth level and the completing process of repairing crack can be carried out by the change rates of the impedance (admittance) and the shifts of the resonance frequency of PZT sensor in the selected frequency range clearly.

Key words: concrete damage, crack repairing, crack detection, PZT, structural health monitoring

Contents

INTRODUCTION

At present, the growing large-scale concrete structures are being constructed in civil infrastructures with the developed material technique and science. However, frost damage or chemical corrosion usually deteriorates concrete structures because of the water leakage through cracks. Thus, it is very important and necessary to find the cracks in a structure and repair them as soon as possible.

Nowadays, many nondestructive evaluation (NDE) methods for crack damage detection are developed, like ultrasonic pulse velocity (UPV) test, thermal field and radiography. Furthermore, these NDE methods are usually tedious and complex, and these methods also involve expensive and bulky equipment [1]. Therefore, with the increasing demands to adopt convenient, effective and unexpansive SHM and NDE technologies for civil infrastructure systems, the development of SHM technologies is soared rapidly, the piezoelectric ceramic material is one of these technologies. This material generates a change of voltage when it is applied a mechanical pressure. While, the PZT occurs the shape change when the electrical voltage is employed onto it, i.e., it can transfer the electrical power to the mechanical power, vice versa. Thereby, piezoelectric ceramic material can be utilized as sensors, transductors or actuators simultaneously for the SHM [2].

In SHM field, the Piezoelectric Ceramic Lead Zirconate Titanate (PZT) exhibits a bright prospective for damage detection and monitoring in civil engineering, because of its low cost, portability, high sensitive to local damages, and it can be used as sensors, actuators or transducers. This material has recently been developed as a brilliant tool for structural health assessments in real time [3], because of the PZT's impedance signals are sensitive to even small damages. This method uses the EM impedance of PZT, which is banded to the mechanical impedance of the target structure. The PZT plates' impedance (the inverse of admittance) signals were monitored and compared it with a baseline measurement that is the impedance of damage-free structure or a certain damage level structure. Subsequently, the damages in the target structure would be detected by monitoring the shift of the impedance signatures from PZT patches[4, 5].

The impedance technique of the PZT was first proposed by Liang [6]. Subsequently, the technique was introduced to aerospace and mechanical area to be used for SHM. The main indicators of structural damages on the impedance signatures of PZT are the vertical and horizonal shifting compared to the baseline measurements [7]. Statistical techniques and wave technologies are utilized to evaluate the damages by comparing the changes in the EM impedance, such as the RMSD [4], the change-in-stiffness method [8], the shift of resonance frequency (SRF) [9] and mode shape curvature method [10]. In 2008, Yang. studied the real applications of the electromechanical impedance technology in life and verified the phenomena observed previously by presenting the finite element simulations on the interaction between the sensor and the host structure[11, 12]. The good correlation between the changes of the impedance peaks and the stiffness of the concrete structure was discovered by Bhalla and Naidu in 2002 [13]. Xu et al. found out the relationship between RMSD of impedance spectra and different crack depth in concrete specimen, in 2010 [11]. Based on these, the piezoelectric-impedance technique can be a potential powerful tool to evaluate the performance of repairing materials, further, we can qualitatively determine that the relationship between damage indexes and the different structural damage levels and different repairing materials′ repairing quality.

For the above purposes, to find an adoptable convenient, effective and inexpensive SHM and NDE method for detecting the different damage levels and evaluating the repairing performance of repairing materials, the experimental study was carried out based on the concrete specimens with various crack damage depths and the evaluation for the healing performance of different repairing materials via PZT sensor. To make sure a high sensitivity to small-size cracks, the EMI signal was monitored in a wide frequency band (from 0 to 500 kHz), and the suitable frequency range would be selected based on a trail-and-error method. The PZT sensor was regularly placed and attached to the host structure to collect the EM impedance signals data of the PZT sensor. The damage indexes RMSD, MAPD and SRF were employed in analyzing the different damage levels and the healing performance evaluation.

BACKGROUND & RESEARCH METHOD

This chapter is about the basic background information and research method, such as PZT, RMSD, MPAD and SRF. First section in this chapter illustrates the background information of crack and crack repairing in concrete structure. Followed by, the development of impedance signal of the PZT sensors is explained. Finally, the damage indexes: RMSD, MPAD and SRF, are introduced and discussed.

2.1 Background

With the rapid growth of the infrastructure buildings during last decades, the concrete material has been becoming the widest utilized engineering material in construction engineering field. The development of a reliable and secure SHM system for the safety and integrity of in-service concrete structures remains a serious issue for researchers as well as maintenance personnel. Nevertheless, due to the combined effects of temperature variations, shrinkage, overloading, chemical corrosion and other degradation processes, the cracks may occur and become the most normally faced type of indictors of damages or durability in concrete structures. Although some cracks may do not affect the structural integrity, when the propagation and coalition of cracks happen, they will become a direct threat to structural safety and durability. Therefore, finding out the cracks and repairing them as soon as possible have become a necessary and important mission for preventing the structural failure. Meanwhile, it is necessary to find a cost-saving, high sensitive to local damages, and real-time SHM system for detecting the damage levels and evaluating the repairing effect of repairing materials in civil infrastructure area.

Within the SHM field, the variety of techniques and sensors for evaluating the cracks condition of various structures has boosted. Among them, the wave characteristics sensor is the most popular method, which is sensitive to the changes in the transit time, frequency content and energy of the wave in the structure [14-16]. Another widely used technique is Infrared (IR) thermography, which detects cracks by detecting the notches based on IR image rectification with the extraction of Isotherms. Yet, the wave characteristics sensors couldn’t work on its own and needs extra actuating systems, and the IR thermography and radiography involve expensive and bulky equipment. Fortunately, PZT plates sensitive to even small damages, and can be used as both sensors and actuators that are made in small sizes without high-cost. Thereby, the PZT is a promising alternative for generating the actuating signal and integration into structures [17]. In addition, in 2010, Xu applied surface-bonded PZT sensors on concrete specimen to estimate variations of crack depth in the certainly testing frequency ranges, this research result shows PZT is effective to quantify local damage and estimate the structural damage changing process by observing the change of the impedance spectra of the PZT transducers that relates to the host structure’s stiffness [11].

Therefore, setting up a feasible and efficient detection system for both crack damage detection and crack repairing performance become urgent in the SHM field. Specifically, my research purpose is to find and use some adoptable convenient, effective and real-time SHM and NDE methods for detecting the damage levels and evaluating the repairing performance of repairing materials. Simultaneously, to reduce the operation and maintenance cost, as well as the analysis time using the PZT sensors.

2.2 Research methods

2.2.1 Crack repairing in concrete

Concrete is becoming the most consumed constructing material in the world, because of it is inexpensive and has excellent compressive strength. However, the concrete's tensile strength and ductility is very limited. Thus, the cracks may occur frequently in concrete structures. The structural integrity would be affected by the propagation and coalition of cracks, although if the cracks do not propagate and coalesce, they still become a threat to structure due to the corrosive substances enter concrete inside along the cracks. Therefore, repairing the cracks as soon as possible is necessary and important for preventing the structural failure.

Nowadays, the material technologies have made significant development to solve many problems arising in civil engineering area. The effective repair techniques based on the material with the superior resistance to corrosion and the great mechanical properties are available. Currently, the common methods of repairing crack in concrete involve the cement injection, polymer epoxy [18-20] and the surface stuffs of fiber reinforced polymer strips [20]. Thus, in this study, after curing for 28 days of the identical concrete specimens, then cracks with different crack depths were simulated by using a cutting machine to cut through the width of the specimen. Meanwhile, the impedance signal of each depth would be detected by a impedance analyzer and recorded by a laptop. After that the three different materials of the healing cement material from Intchem company, superabsorbent polymer (SAP), and epoxy were used to repair the crack in concrete specimen. Finally, the repairing performance of each material would be evaluated depended on the analysis of the EMI signal that was monitored by the impedance analyzer.

2.1.2 EMI-based SHM method

Piezoelectric ceramics is one of the smart materials that have bidirectional piezoelectric effects and could be employed as both EMI sensor or transducers and actuator. The EMI transducers can be easy to be bonded to the structural surface or embedded into target structures. Meanwhile, the PZT material is low-cost, huge frequency bandwidth and lightweight. Thus, PZT material is widely used in SHM field. Liang developed the new EMI measurement technique for the damage monitoring of structures in 1994 [6]. Then, PZT carried out a series of researches on the specimens in lab and real building engineering.

The concept of MI of structure is similar to the theory of electrical impedance in the electrical circuit [32]. Reducing the differential functions of Newtonian mechanics into the simple algebraic equations is allowed to simplify assessment of complex mechanical systems by, because of the impedance method [33]. This study analyzed the EMI signatures of PZT plates that were bonded to structures based on the impedance method.

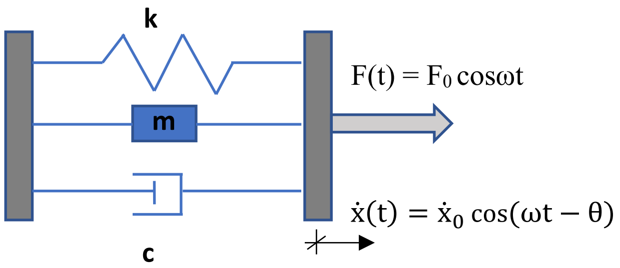

Figure 1. The SDOF spring-mass-damper system under a dynamic excitation

The single degree-of-freedom (SDOF) system can be employed to model the electro-mechanical system, which includes a PZT plate and a target structure [12]. So, the instantaneous velocity response is given as

$$\dot{x} = \dot{x}_0 \cos(\omega t - \theta) \tag{1}$$

Where ω is the angular frequency, $\dot{x}_0$ is the velocity and θ is the velocity's phase lag with the force. At the same time, the instantaneous acceleration and displacement response also can be gained by Equation (1).

The admittance signal (Y) that is the inverse of the impedance, then can be computed as the following Equation (2-4) [21]:

$$\overline{Y} = \overline{Y}_P + \overline{Y}_A \tag{2}$$

$$\overline{Y}_P = \omega j \frac{w_a l_a}{h_a}\left(\overline{\varepsilon}_{33}^{T} - d_{31}^2 \overline{Y}_{11}^{T}\right) \tag{3}$$

$$\overline{Y}_A = \omega j \frac{w_a l_a}{h_a}\left(\frac{Z_a}{Z + Z_a}\right) d_{31}^2 \overline{Y}_{11}^{E} \left(\frac{\tan(kl_a)}{kl_a}\right) \tag{4}$$

where $\overline{Y}_P$ is a function that only relate to the PZT parameters and referred to the negative admittance; $\overline{Y}_A$ is called the positive admittance; l_a indicates the length, ω_a is the width and h_a expresses the thickness of the PZT, respectively. $\overline{\varepsilon}_{33}^{T} = \varepsilon_{33}^{T}(1-\delta j)$ is the PZT's complex electric permittivity with the constant stress and d_{31} is the piezoelectric strain coefficient. ω represents the angular frequency, Z_a and Z indicate the PZT's mechanical impedance and short-circuited mechanical impedance of the target structure, respectively. $\overline{Y}_{11}^{T} = Y_{11}^{T}(1+\delta j)$ is the complex Young's modulus of PZT material at constant electric field, δ and η denote the dielectric loss factor and mechanical loss factor of the PZT. k is the wave number. Therefore, any change in admittance signatures can be used as the indicator of the change of the structural integrity that can be brought by the structural damages.

Thus, the EMI-based health monitoring method depend on measuring the PZT transducers' electrical impedances that are fixed on or embedded into the structures to monitor the structural changes. In his literature, the high-strength glue was used to fix the PZT plates onto the surface of the concrete specimen, which can be considered as a simple 1D model. If during the process of monitoring every parameter of PZT plates is keeping constant, then the electrical impedance of the PZT plates is directly related to the target structure's mechanical impedance. Thus, any EMI changes of the impedance signal can be expressed as the indicator of the changes of the integrity structure. By monitoring the admittance signatures and comparing them with the baseline case, the host structure's defect conditions can be identified qualitatively.

2.1.3 Damage indexes

Recently, many methods have been developed to quantify the changes in impedance spectrum signatures, for example, the RMSD, the MAPD, the correlation coefficient (CC) and the shift of resonance frequency (SRF) [9], [22]. Based on the results analysis of previous experiments, the RMSD, MAPD and SRF indexes are discovered that they are suitable for illustrating the expand of defect condition. Thus, in this study, the RMSD, MPAD and SRF were used as damage indexes to assess the change between the conductance signature of the baseline measurement and the conductance signals in the different damages' and repairing materials' states.

$$RMSD = 100 \times \sqrt{\sum_{i=1}^{N}\left(G_i^1 - G_i^s\right)^2 / \sum_{i=1}^{N}\left(G_i^s\right)^2} \tag{5}$$

$$MAPD = 100 \times \sum_{i=1}^{N}\left|\frac{G_i^1 - G_i^s}{G_i^s}\right| \tag{6}$$

Where G_i^s is the impedance (or admittance) of the PZT transducer that is measured at baseline measurement of the host structure, and G_i^1 is the corresponding impedance spectrum value of different damage cases at the i^{th} measurement point. That means the larger RMSD and MAPD are, the greater change of the structural damages over the baseline condition.

The shift of resonance frequency (SRF) is obtained by using a measure of centroid frequency of the resonant peak (RF) that is banded to the mechanical stiffness of the target structure in the impedance spectrum given as [9]:

$$RF = \frac{\int_{f_1}^{f_2} fGdf}{\int_{f_1}^{f_2} Gdf} \tag{7}$$

$$SRF = 100 \times \frac{|RF_1 - RF_s|}{RF_s} \tag{8}$$

where RF_1 is the centroid frequency of the spectrum and RF_s is the centroid frequency of the baseline measurement. G is the impedance at a given frequency, f_1 is the lower bound and f_2 is upper bound of each frequency range. Shift of resonance frequency (SRF) is computed by utilizing equation (8). The larger SRF is, the greater decrease in stiffness of the structural damages over the baseline measurement.

EXPERIMENTAL METHOD & MATERIALS

The piezoelectric ceramic plate (0.2mm × 25 mm × 25 mm) was employed as a sensing element to assemble the PZT transducer (PI Ceramic GmbH, Lindenstrasse, D-07589 Lederhose, Germany), the properties of the PZT material are shown in Table 1. A kind of waterproof glue was utilized as a binding material to fix the PZT transducer to cement concrete specimen, which is made by portland cement type 1 and fine aggregate and coarse aggregate. The identical concrete specimens were fabricated with dimensions of 250 mm × 125 mm × 150 mm. Then, the crack with different depths was simulated by cutting across the width of the specimen employing a WSQ50 diamond cylindrical cutting machine after curing for 28 days. Four different groups of crack depth (0, 5, 10, 15 and 20mm) were created on the concrete block. The simulated crack was lay in the middle of specimen with a depth variation from 0 to 20 mm with an interval of 5 mm, the PZT sensors located at the center of the specimen surface and 30mm away from the crack. The PZT sensors' layouts and the location of the crack are shown in Figure 2 and 3.

Table 1. Properties of PZT.

Properties	Value
Density ρp (g/ cm^{-3})	7.8
Poisson's ratio	0.34
Mechanical quality factor (Qm)	100
Piezoelectric strain coefficients, d31, d32 (×10-12 m v-1)	-210
Piezoelectric charge coefficient, d33 (×10-12 m v-1)	500
Dielectric loss factor, δ	0.2
Relative permittivity	2400

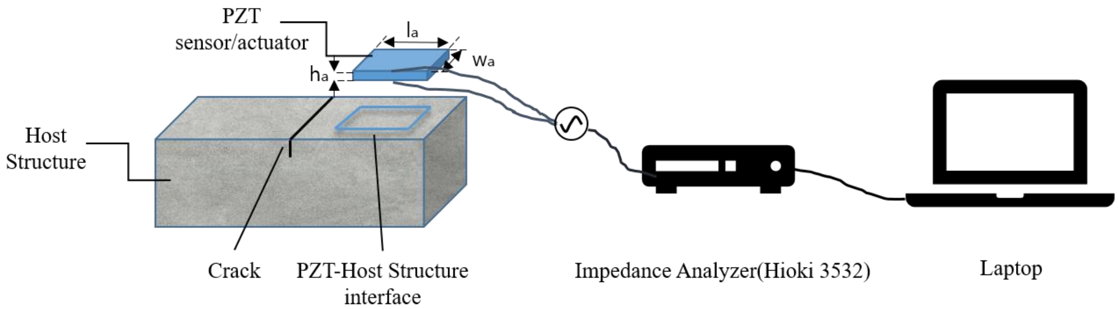

Figure 2. Schematic view of the set-up of the experiment to detect the crack in specimen.

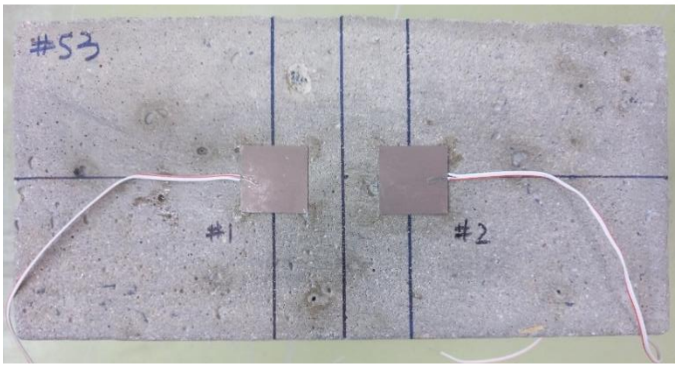

Figure 3. Layout of PZT sensors on the concrete specimen surface.

To minimize the extra influence of the surrounding temperature and vibration on the test result [23], the specimens were placed into the lab room without vibration interference with a constant temperature of 26°C. In this study, Hioki 3532 Impedance Analyzer was employed to detect the PZT transducer's electric impedance.

The impedance-based SHM method's sensitivity for damage detection was found to be related to the frequency ranges. I use a trial-and-error method to pick out the best frequency range for the host structure [24]. In the experiment, the PZT would be scanned over the frequency range of 0 - 500 kHz by a frequency interval of 100 Hz to pick out a suitable frequency range for calculating and assessing the change of the impedance signatures. The PZT transducer was excited by a 1 V alternating voltage from the Hioki 3532. The experiment was repeated five times to verify the stability. The average value to minimize the influence of random noise for further calculation was obtained. The impedance information from the PZT plate was collected by laptop and analyzed by MATLAB. The real impedance spectrum signal was plotted in each testing frequency range, and picked out the sensitive range around resonance frequency peaks in the frequency range from 30 - 400 kHz that Park et al. (2003) recommended [25]. Meanwhile, by comparing with different frequency ranges, the change in EM impedance signals of frequency range in the second peak to the fifth peaks were more obvious, therefore, the EM impedance spectrum signals in 56 to 61 kHz, 75 to 82 kHz and 176 to 193 kHz were picked out for performing the analysis in this study and based on the results to select the best one.

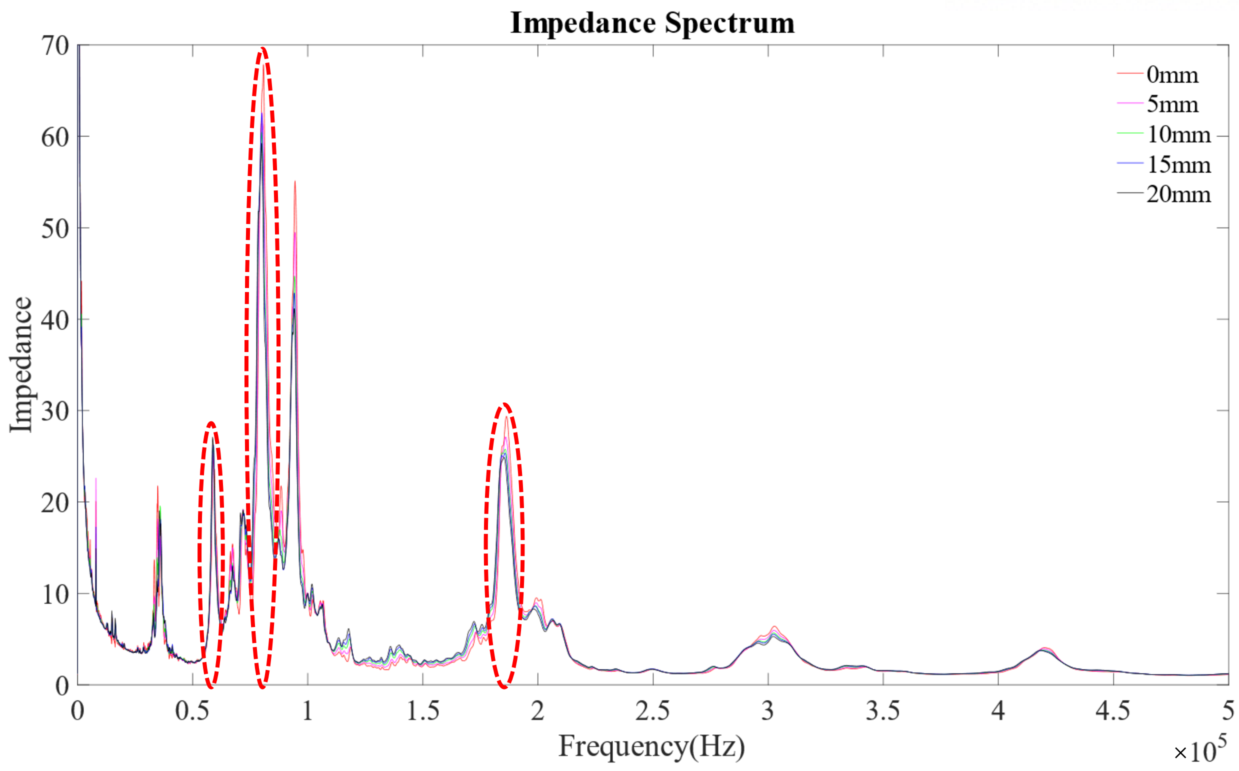

Figure 4. The three frequency ranges were selected in the impedance frequency domain.

To show how the damage cases affect impedance signal pattern, the impedance spectrum of the five damage cases have been averaged and plotted at each frequency in Figure 4. The desired damage cases between 0- and 20mm in the presence of impedance peaks, the 20mm case was shown in Figure 5. In this paper, 20mm crack depth case was set as baseline measurement.

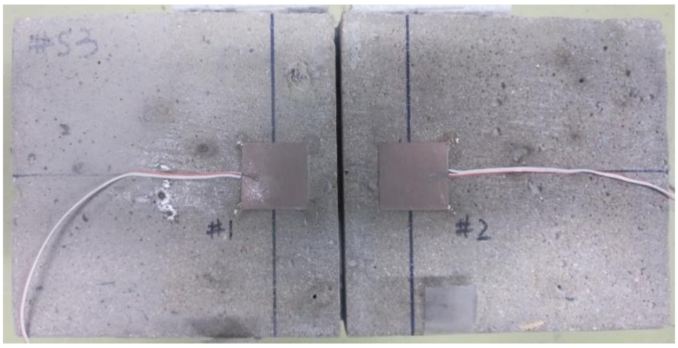

Figure 5. The layout of 20mm crack depth case.

On the other hand, many different kinds of materials are used for repairing concrete cracks, mainly including polymer-based material (like superabsorbent polymer) [26, 27] cementitious material (like cement material) [21], and organic-chemical grouting (like epoxy) [28]. In this study, the healing material supported by Intchem company as the cementitious material, superabsorbent polymer (SAP) as the polymer-based material and epoxy as the organic-chemical grouting material were used to repair the crack.

After getting the five damage cases' data, crack was repaired by the healing material supported by Intchem company first, and then the impedance data was collected by Hioki 3532 every day after repairing the crack until 28^{th} day. After that, the material was removed by cutting machine, the 20mm damage case should be detected again, and compared with the initial 20mm case, if they were very close, the previous 20mm case data was replaced by the new 20mm case data. After that we started to use superabsorbent polymer (SAP) to repair the crack, and collected the data again. When we used the epoxy to repair the crack, we repeated the whole process one more time.

RESULTS & DISCUSSION

This chapter covers the results of this study experiments and discussion based the damage indexes. The first section is about ascertaining the relationship between different damage cases and the corresponding damage indexes. The second section illustrates the repairing performance of different healing materials.

4.1 The relationship between damage cases and the damage indexes

According to the measured signatures, the PZT impedance of the five damage cases were calculated by Equations (5)-(8) and illustrated in Figures 6-11. As mentioned before, the changes in impedance and centroid frequency of the PZT transducer can be assessed by calculating the RMSD of the impedance spectrum among the different frequency ranges this is very helpful for detecting the structural crack damages [11]. According to the Figure 7, Figure 9 and Figure 11, we can find that when we set the 20mm crack depth case as the baseline measurement, with the crack depth increasing, the RMSD, MAPD and SRF are all decreasing along a linear downward trend.

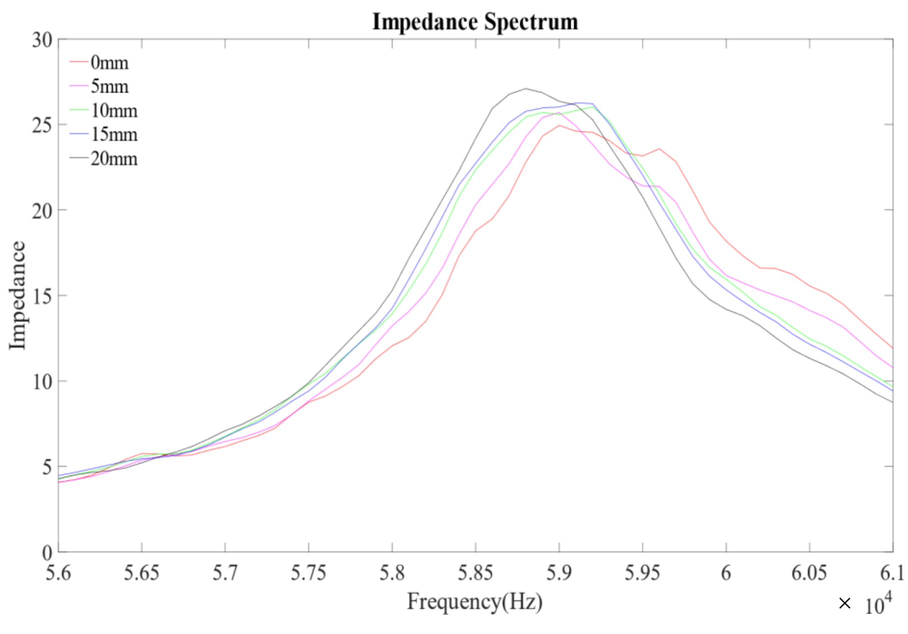

Figure 6. The impedance signatures of frequency range 56kHz-61kHz

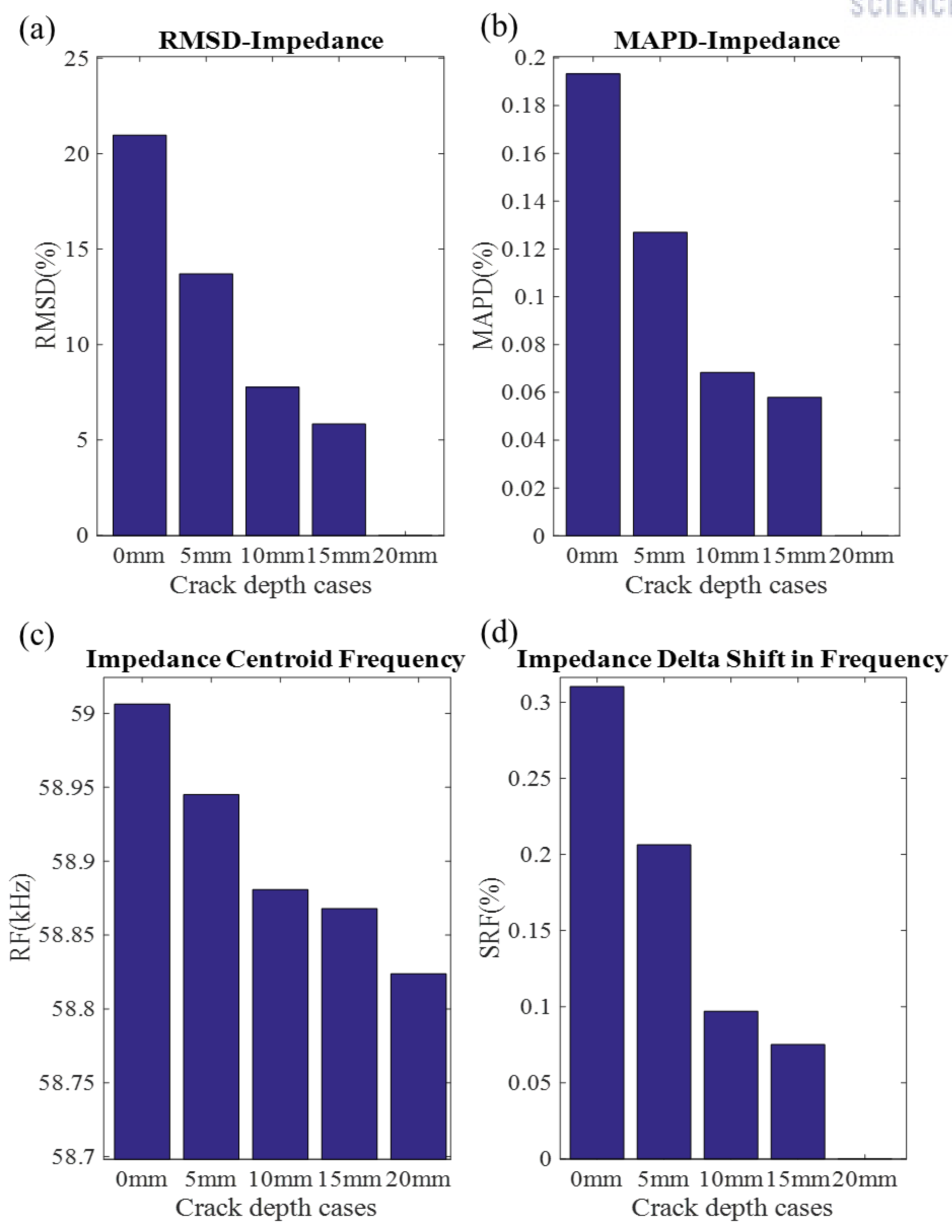

Figure 7. Damage indexes calculated in the frequency range of 56kHz-61kHz. (a) RMSD, (b) MAPD, (c) RF, and (d) SRF.

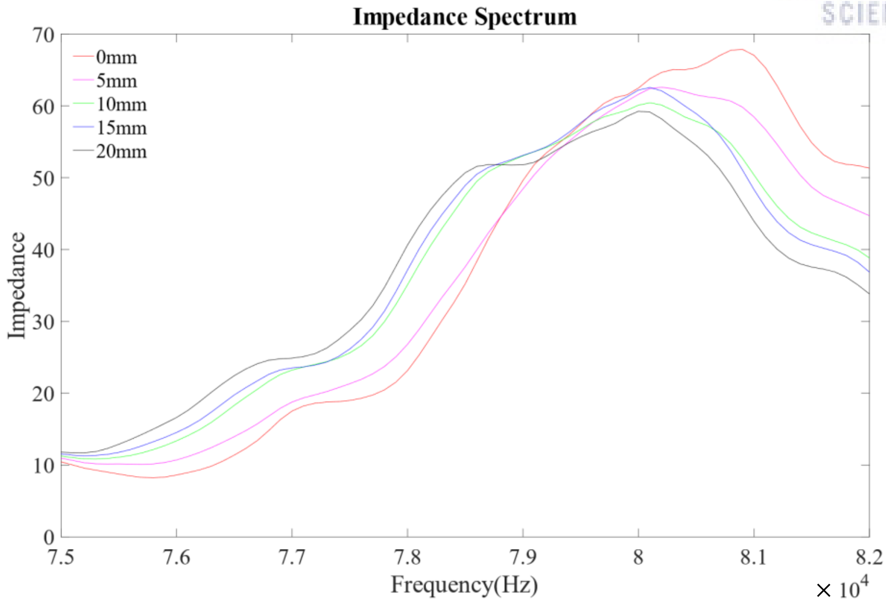

Figure 8. The impedance signatures of frequency range 75kHz-82kHz.

Due to increasing damage level in the structure, the progressive decrease in mechanical stiffness produces a centroid frequency shift to lower values. It can be seen in the Impedance Spectrum line chart such as Figure 8, and Impedance Delta Shift in Frequency bar chart in each frequency range. Therefore, the deeper crack, the more sensitive the PZT plate is. That means damage indexes RMSD, MAPD and SRF can illustrate the crack damage level very well, they can be used to evaluate the healing condition of the damage with different healing materials in these frequency ranges.

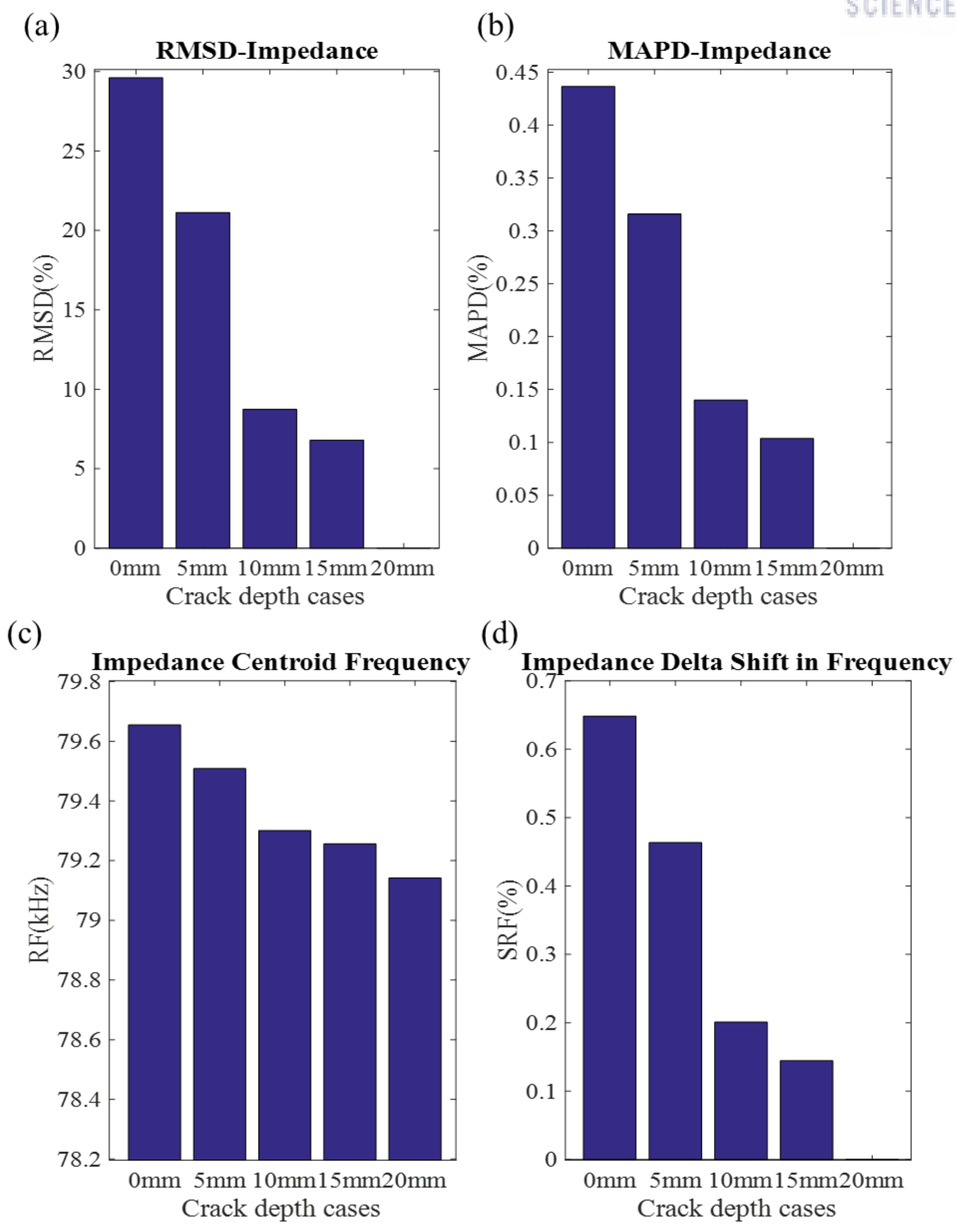

Figure 9. Damage indexes calculated in the frequency range of 75kHz-82kHz. (a) RMSD, (b) MAPD, (c) RF, and (d) SRF.

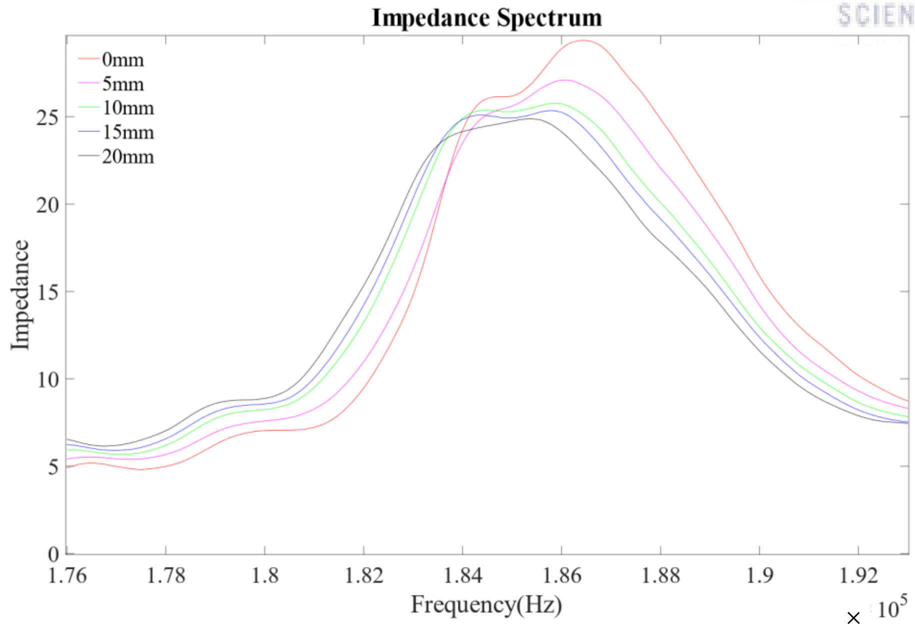

Figure 10. The impedance signatures and the RMSD, MAPD, SRF of frequency range 176kHz-193kHz.

For the further analysis, we picked out the 0mm crack depth case, 5mm crack depth case and 20mm crack depth case as the damage cases' delegates, and the 20mm case was also set as the baseline measurement in the following analysis. For the different healing materials, the different data monitoring periods would be chosen based on the properties of each materials. The minimum period was set as 7 days, the maximum period was set as 28 days. For the long period of collecting repairing data, we picked out the first 7 days' cases, and from the 8th day case to the 28th day case with an interval of two days as the damage cases' delegates.

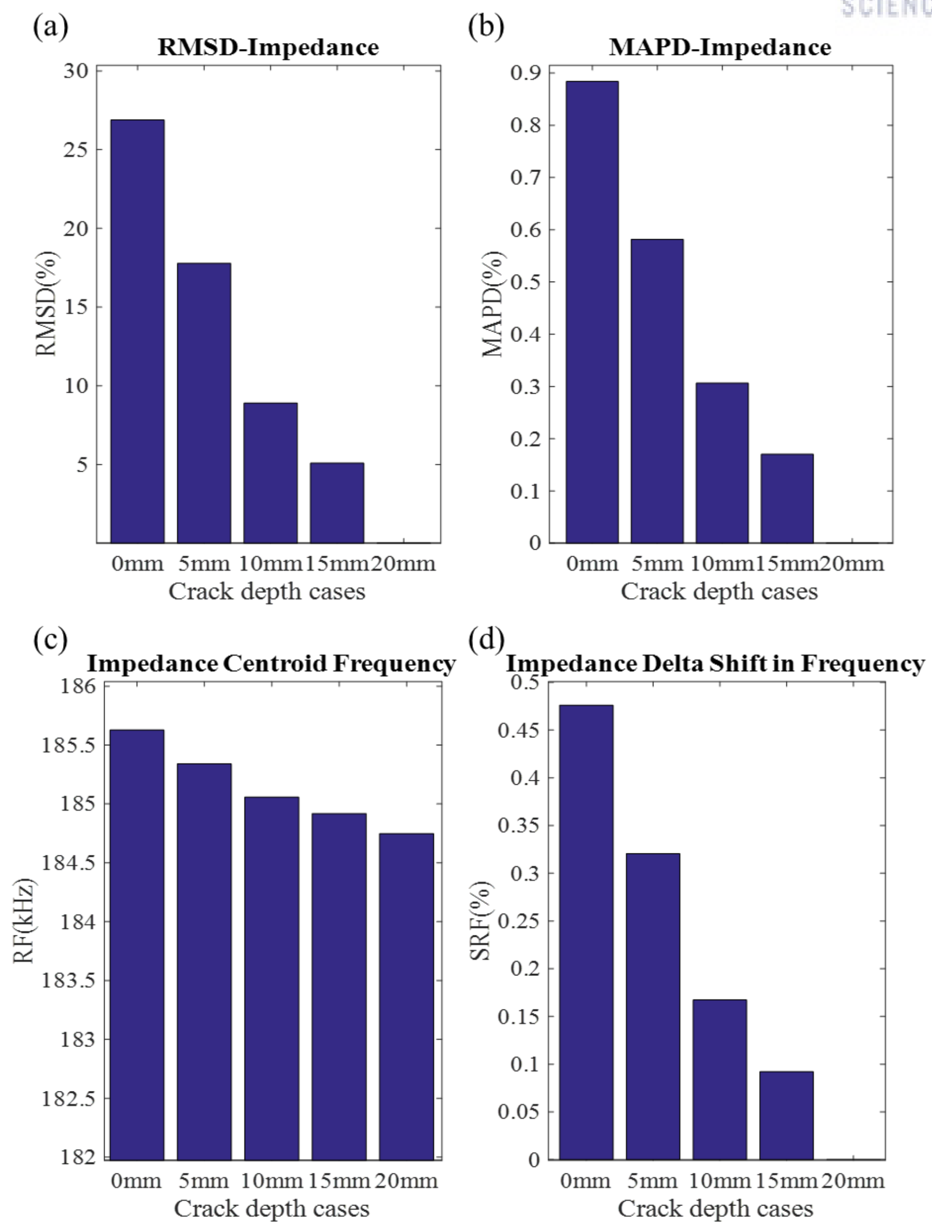

Figure 11. Damage indexes calculated in the frequency range of 176kHz-193kHz. (a) RMSD, (b) MAPD, (c) RF, and (d) SRF.

4.2 Evaluate the performance of the healing materials via PZT

In this part, we use three kinds of healing materials to test their healing performance by comparing the results with the material's performance data that is given from the companies or other papers.

First, we used the healing material from Intchem company to repair the crack in the specimen, as shown in Figure 12, and collected the data every day after repaired the crack for 28 days. For the repairing data, we picked out the first 7 days' cases, and from the 8th day case to the 28th day case with an interval of two days as the damage cases' delegates. From the Figure 13 - 19, it can be observed clearly that during the first 7 days, the RMSD, MAPD and SRF all rose back quickly. After the 7th day until 20th day, they increased more slowly than before, and after 20th day they all start to stay around a constant value. This is because of the curing process of the cement healing material, in which the stiffness strengthens soon in the early curing process, and then the speed of strengthening will slow down and finally be close to zero. This trend is clearly illustrated in Impedance Delta Shift in Frequency bar chart clearly. The changes in different damage cases produced changes in the resonant peak which are related to the influenced of different damages. With the more extreme damage level, the larger shift is observed in the RF, and after the crack was repaired, with the time going through, the RF regularly rising back over time. Therefore, the damage indexes RMSD, MAPD and SRF of the three frequency ranges can provide a good indication of the different degrees of healing performance. Because with the increasing strength of the cement healing material, the crack would be healed more solidly and integrally. However, among the three frequency ranges, the result of the frequency range 56kHz-61kHz is much better for evaluating the healing performance than the other two. Because there are fewer errors during the period of increase and less fluctuation during the steady period. Thus, the frequency range 56kHz-61kHz was selected as the only frequency band for the further analysis.

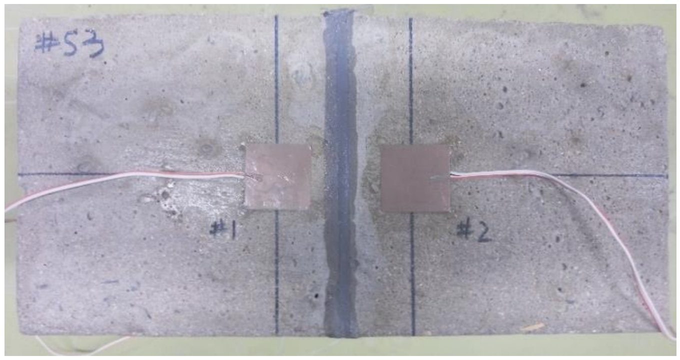

Figure 12. The layout after repairing the crack by cement healing material

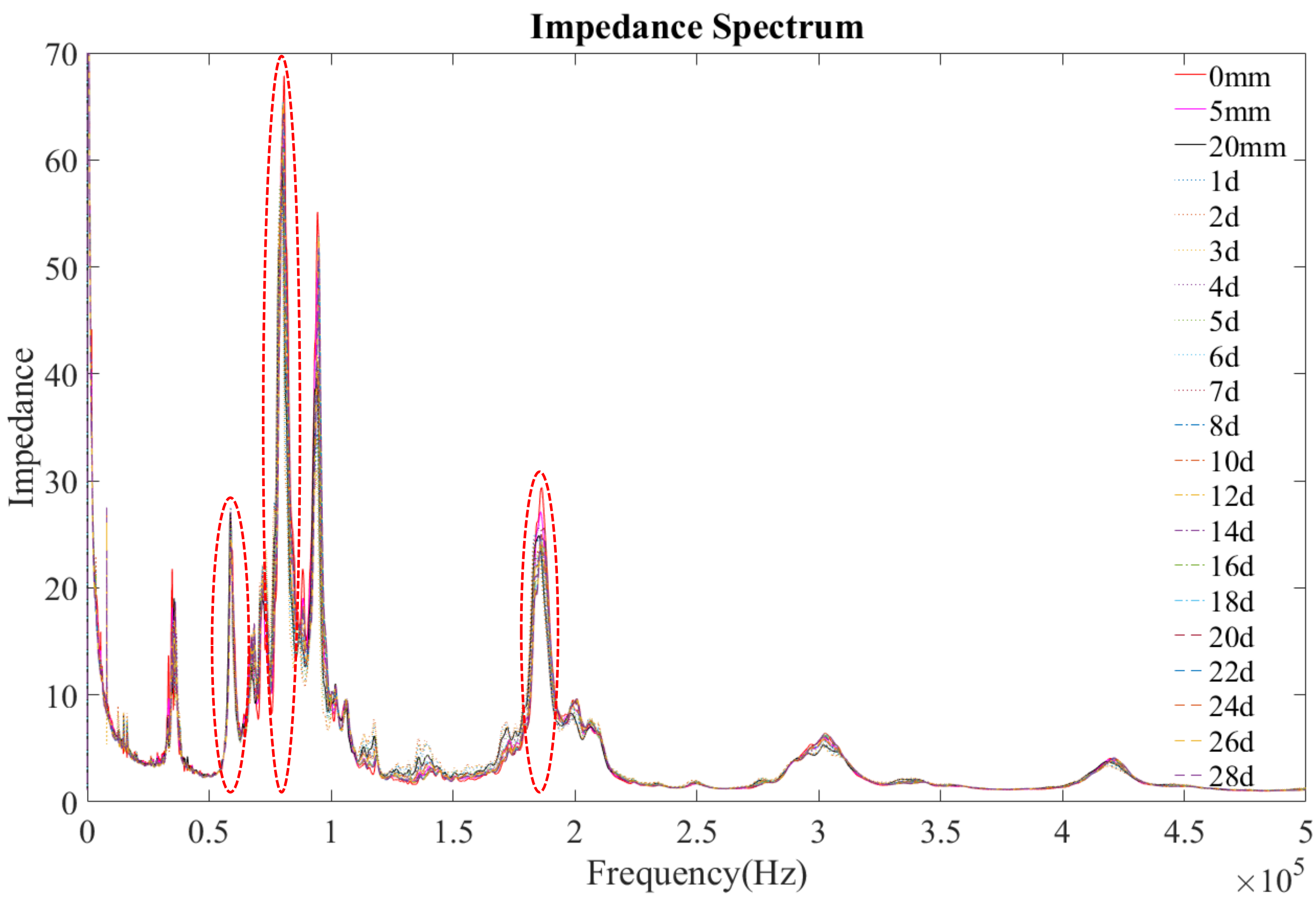

Figure 13. The three frequency ranges with cases were selected in the impedance spectrum.

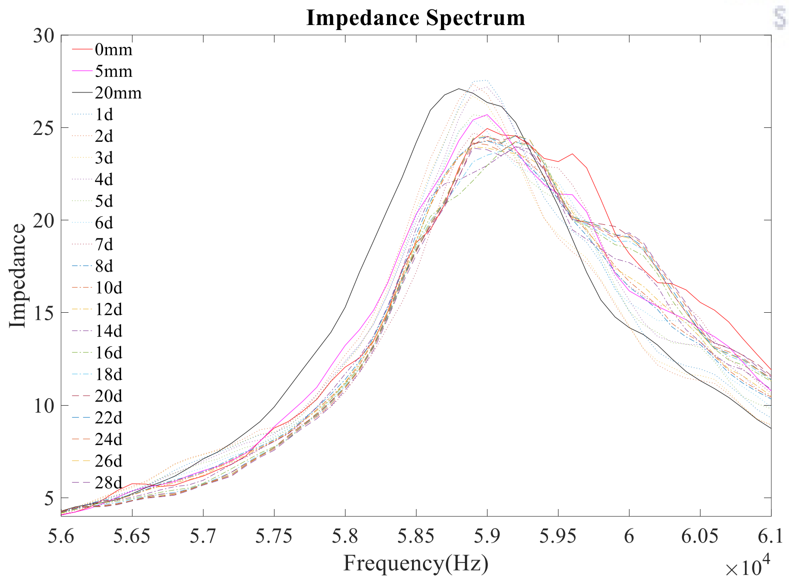

Figure 14. The impedance signatures of frequency range 56kHz-61kHz.

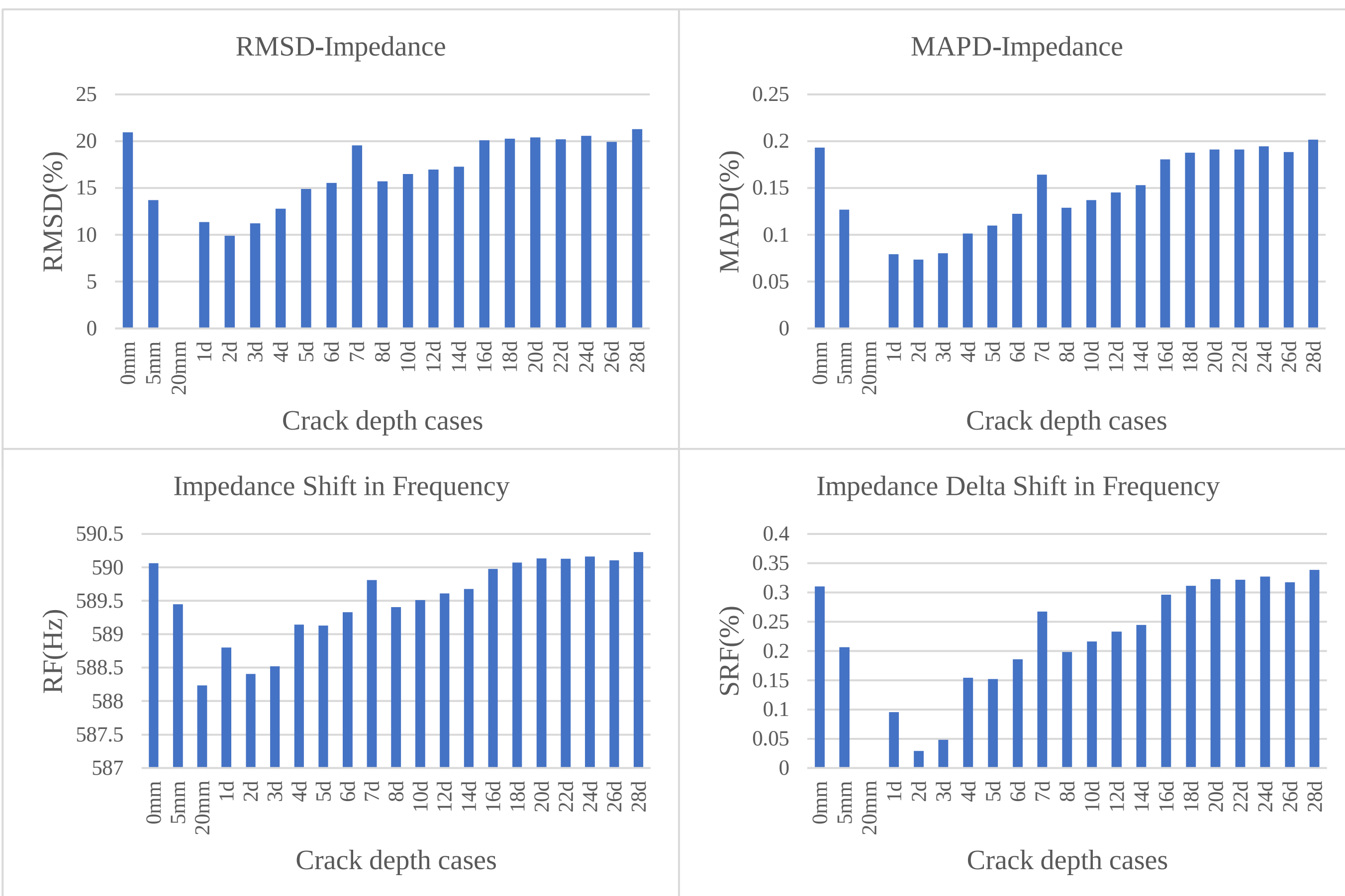

Figure 15. The RMSD, MAPD, SRF of frequency range 56kHz-61kHz.

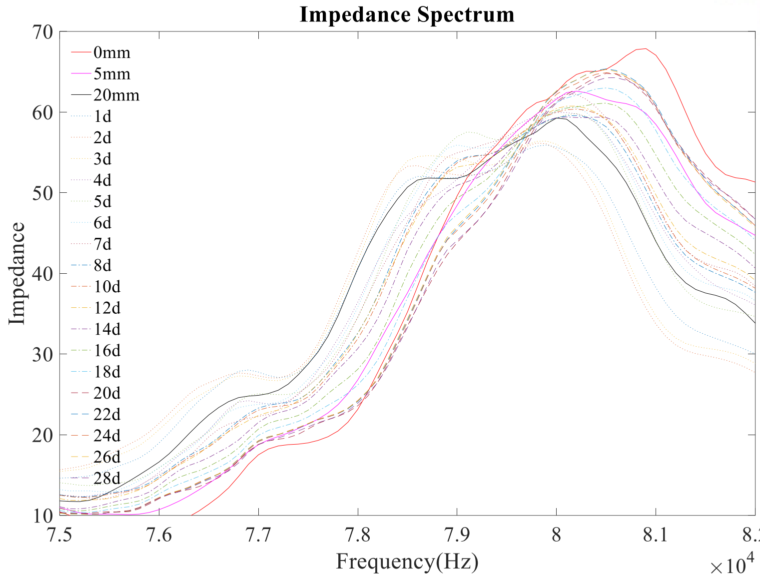

Figure 16. The impedance signatures of frequency range 75kHz-82kHz.

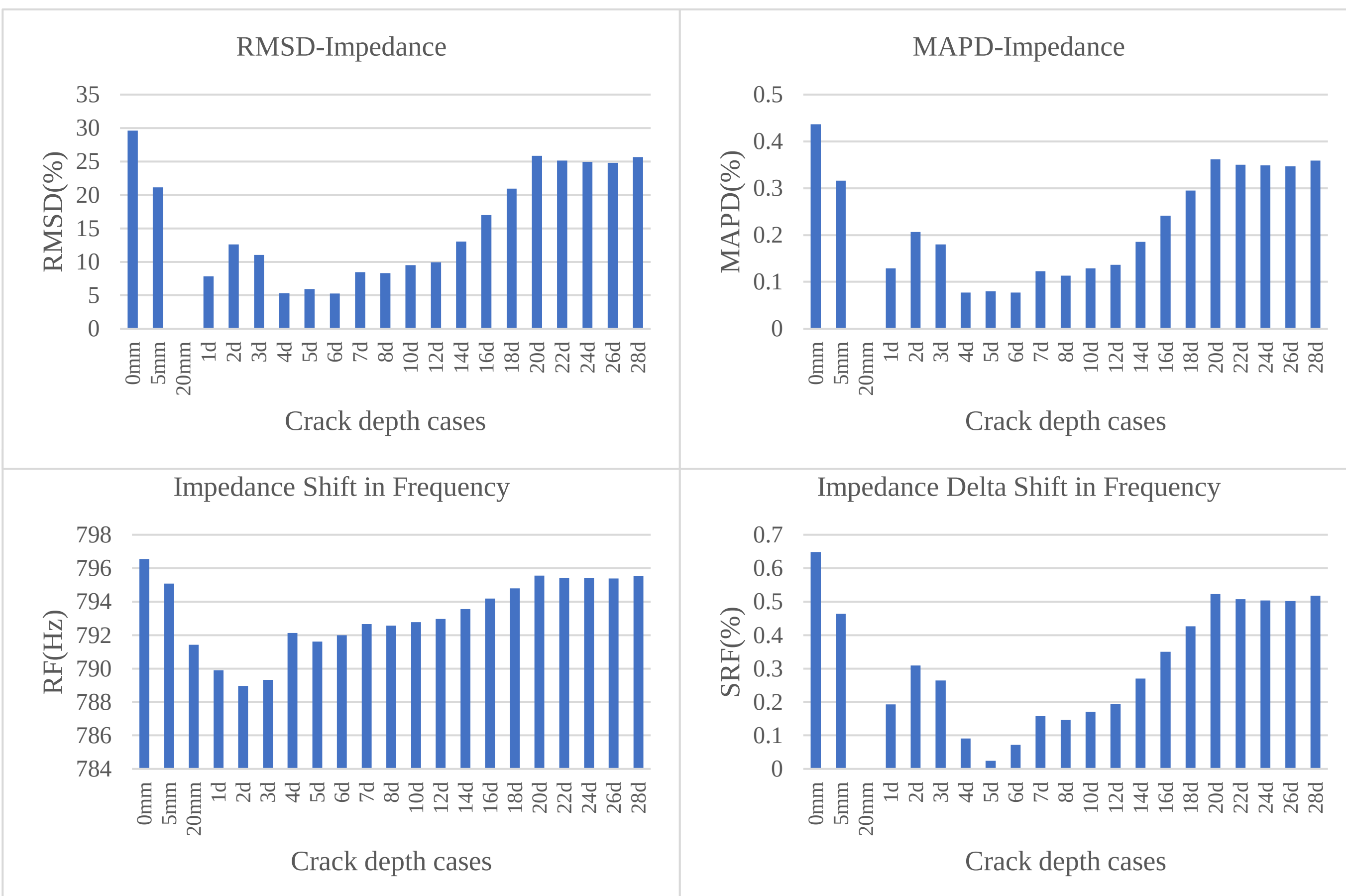

Figure 17. The RMSD, MAPD, SRF of frequency range 75kHz-82kHz.

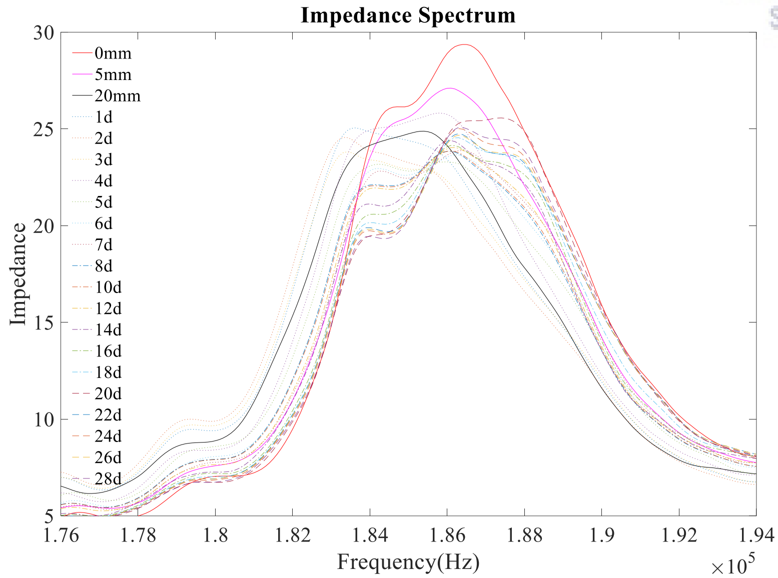

Figure 18. The impedance signatures of frequency range 176kHz-193kHz.

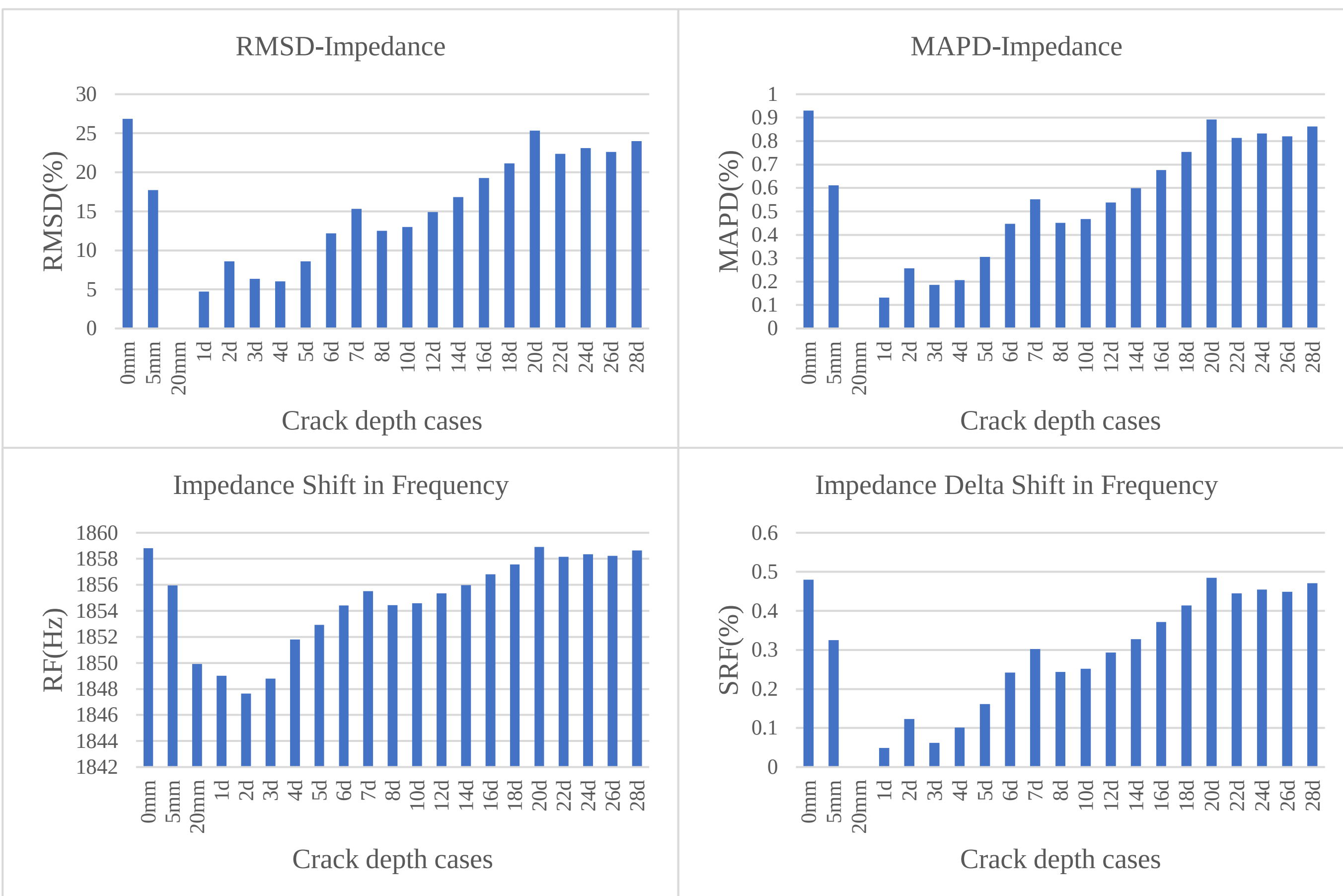

Figure 19. The RMSD, MAPD, SRF of frequency range 176kHz-193kHz.

The next stage of our analysis involved the healing material provided by Incan company was removed away from the crack by the WSQ50 diamond cylindrical cutting machine. The 20mm crack depth case would be detected again, and the data of the new 20mm crack depth case was took to replace the previous one for the following calculation. After that the 20mm depth crack was repaired by the SAP material, it was shown in Figure 20, and repeated the process of the previous experiment in the 56kHz-61kHz frequency range again. The results of 28 days' data are shown below:

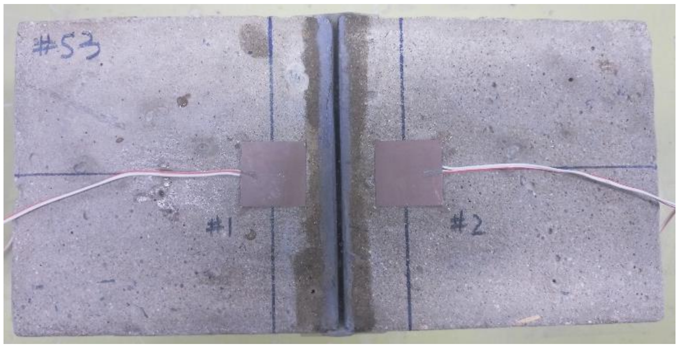

Figure 20. The layout after repairing the crack by SAP healing material

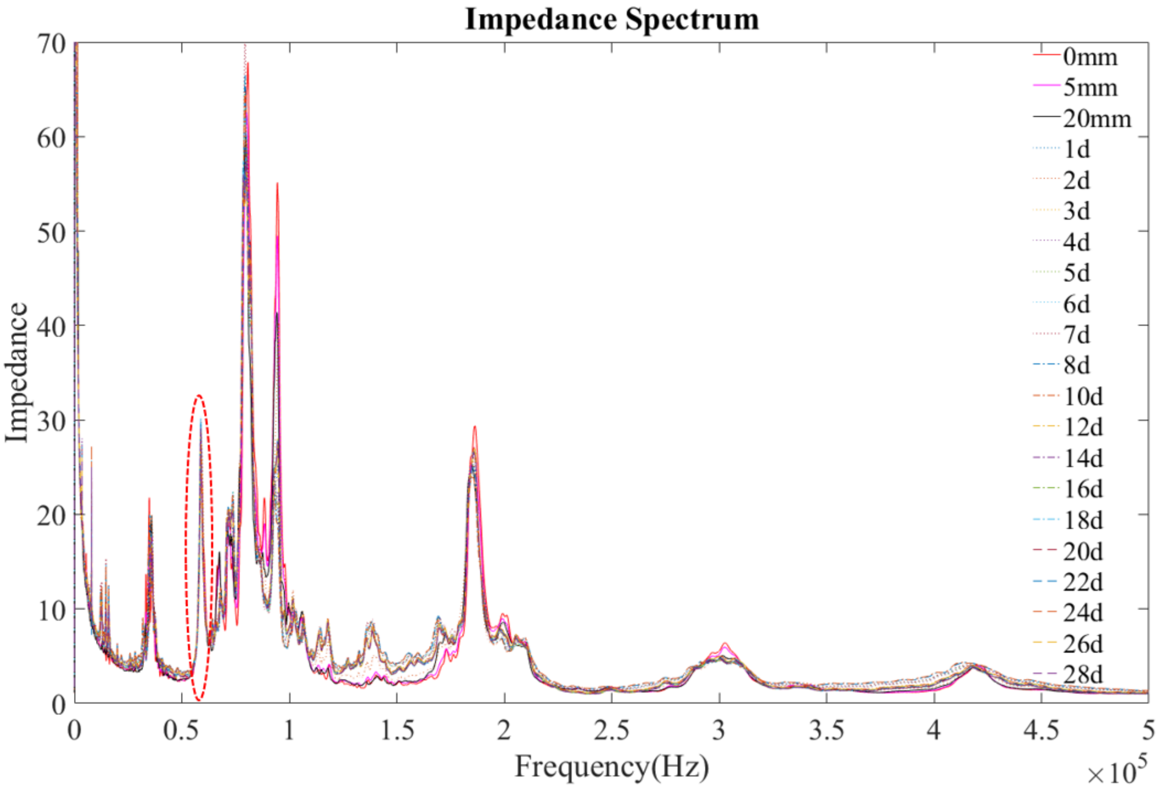

Figure 21. The frequency ranges with cases in the impedance spectrum with SAP material.

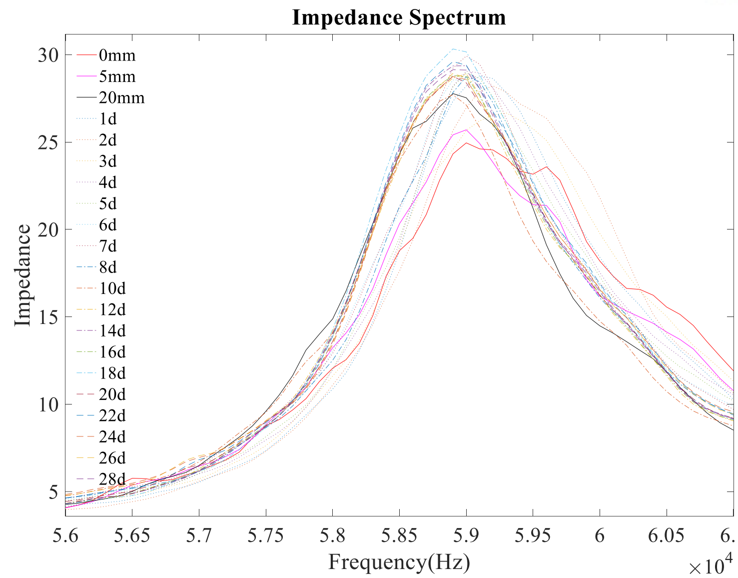

Figure 22. The impedance signatures of frequency range 56kHz-61kHz with SAP material.

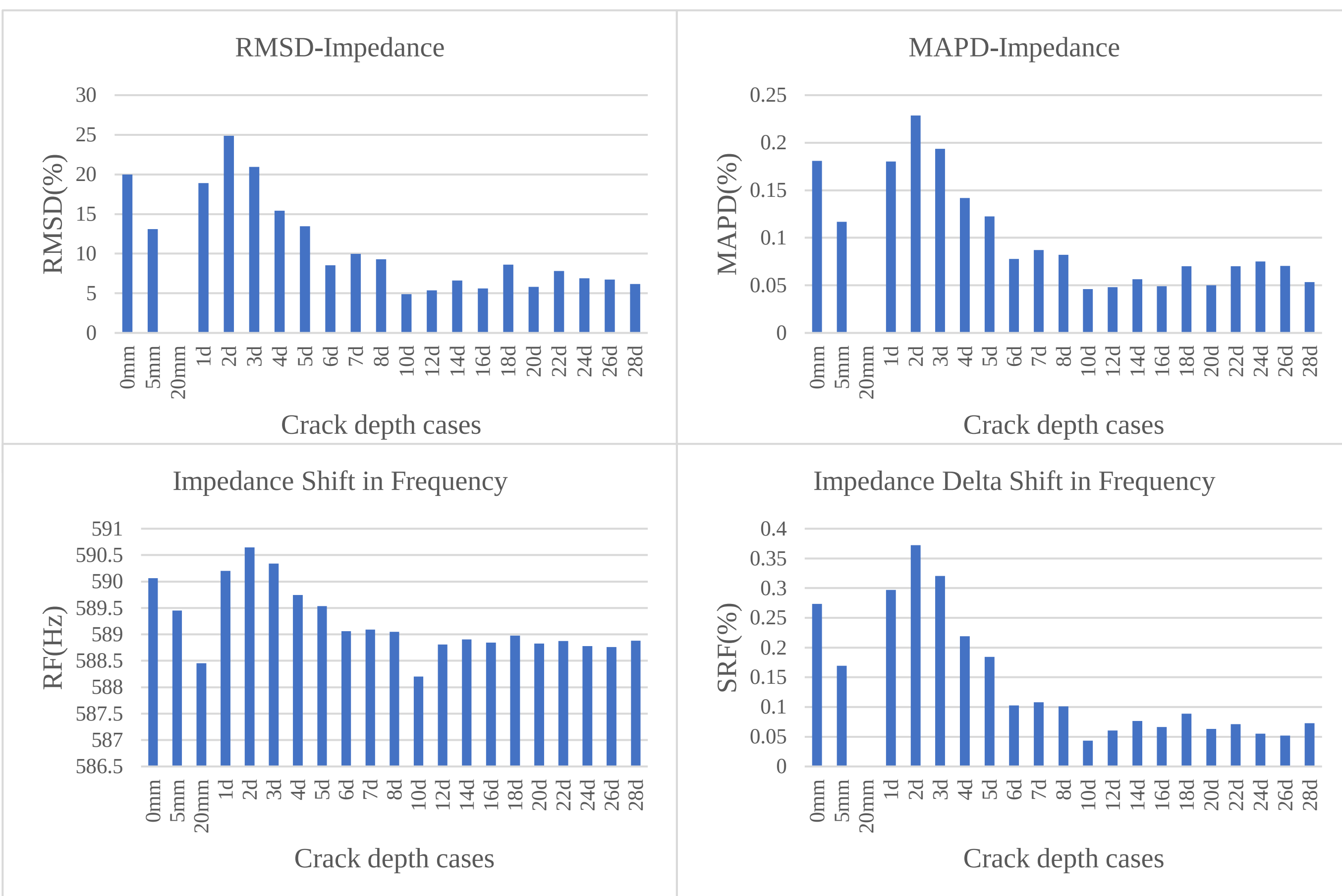

Figure 23. The RMSD, MAPD, SRF of frequency range 56kHz-61kHz with SAP material.

From the results, we can find that the PZT can indicate the healing process of the SAP material in crack very well. And the results also show that the SAP material is good for the temporary self-healing of the crack damage, but it is not suitable for long span period crack healing. The RMSD, MAPD and SRF charts of Figure 21 show good damage indication of the crack and the healing performance of the SAP material. They show that the SAP has a good performance at the first two days, because the SAP absorbed the water and swelled to fill the crack very well. However, after that its' performance has reduced very fast until the 7th day, because of the high PH value in the mortars, the polymerization occurred in the SAP material, which make it lose the ability to swell after absorbing water regularly. After completing the polymerization inside, its performance stays around a steady level, and we can find this phenomenon in all bar charts in Figure 21 after 7 days. J. Justs et al. also found this phenomenon of SAP material in concrete by another method (strain) in 2015 [29].

The results that shown in Figure 25 - Figure 27 indicated after the SAP experiment, the SAP material that was in the crack was removed, and the 20mm crack depth case was tested again and the data was used to replace the previous 20mm case, and then the crack was repaired with Epoxy material, as shown in Figure 24. The process of the previous experiment in frequency range 56kHz-61kHz was operated. However, for the epoxy material, we found that the after 2 days, the performance already became staid. Therefore, we just tested the impedance data of this healing material for 7 days after repairing the crack.

The impedance signatures measured from the specimen of the PZT patch at different damage levels are shown in Figure 25 - 26. These RMSD, MAPD and SRF charts of Figure 27 show a good indication of the healing performance of the epoxy material. We can find that after filling the crack, the epoxy started to harden and strengthen gradually with the accelerator by a tardiness speed and arrived at the best condition after about the 2nd day, and then kept around a consistent level. In 2008, Yan studied the healing efficiency of self-healing epoxy under different temperatures [30]. The healing efficiency in his paper has the same trend as our results. This suggests that the PZT can indicate the healing efficiency of the epoxy material in crack very well. The results also show that the epoxy material is good for the fast repair of the crack damage.

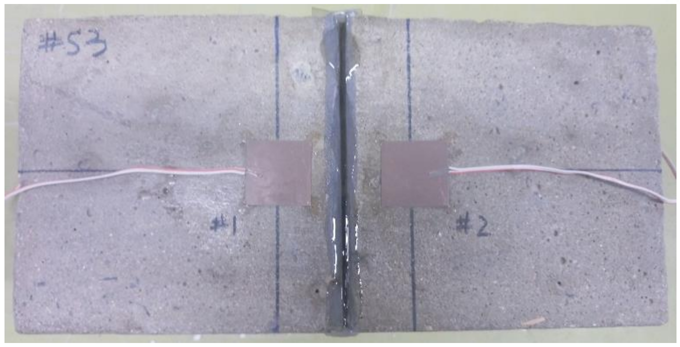

Figure 24. The layout after repairing the crack by SAP healing material

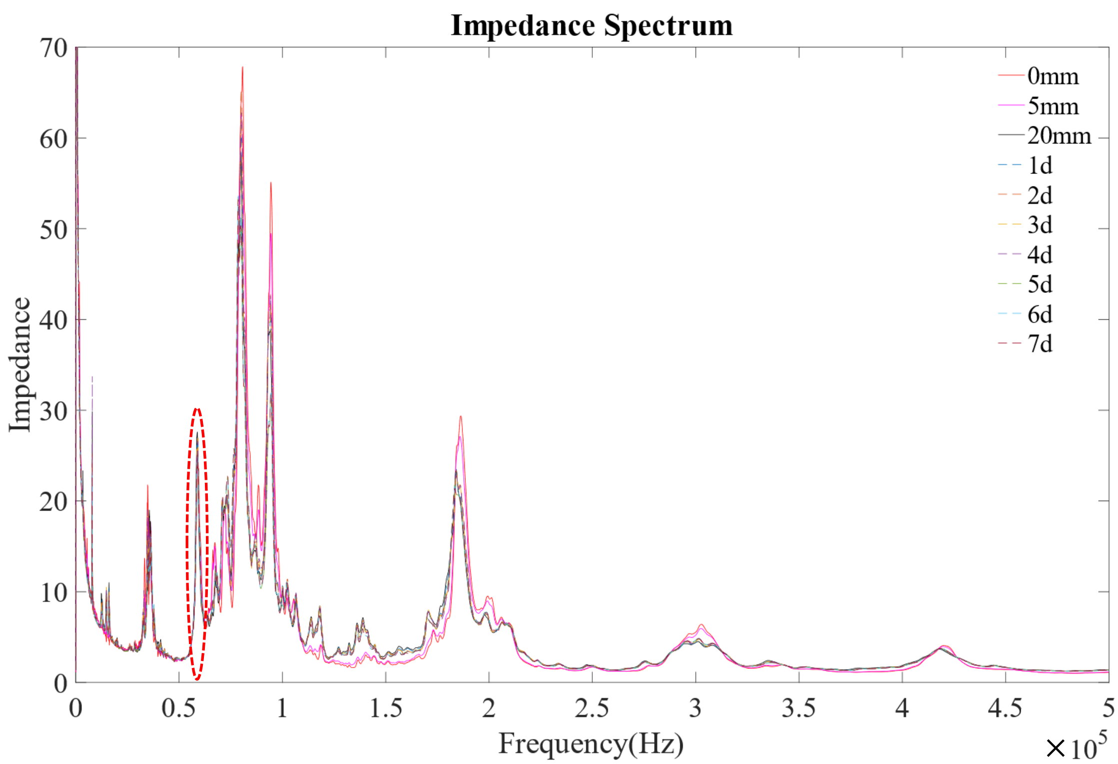

Figure 25. The frequency ranges with each case in the impedance spectrum with Epoxy material.

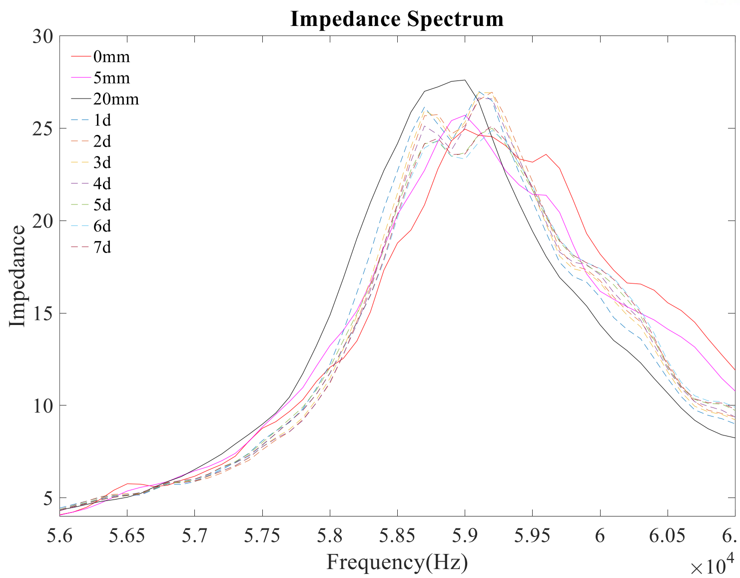

Figure 26. The impedance signatures of frequency range 56kHz-61kHz with Epoxy material.

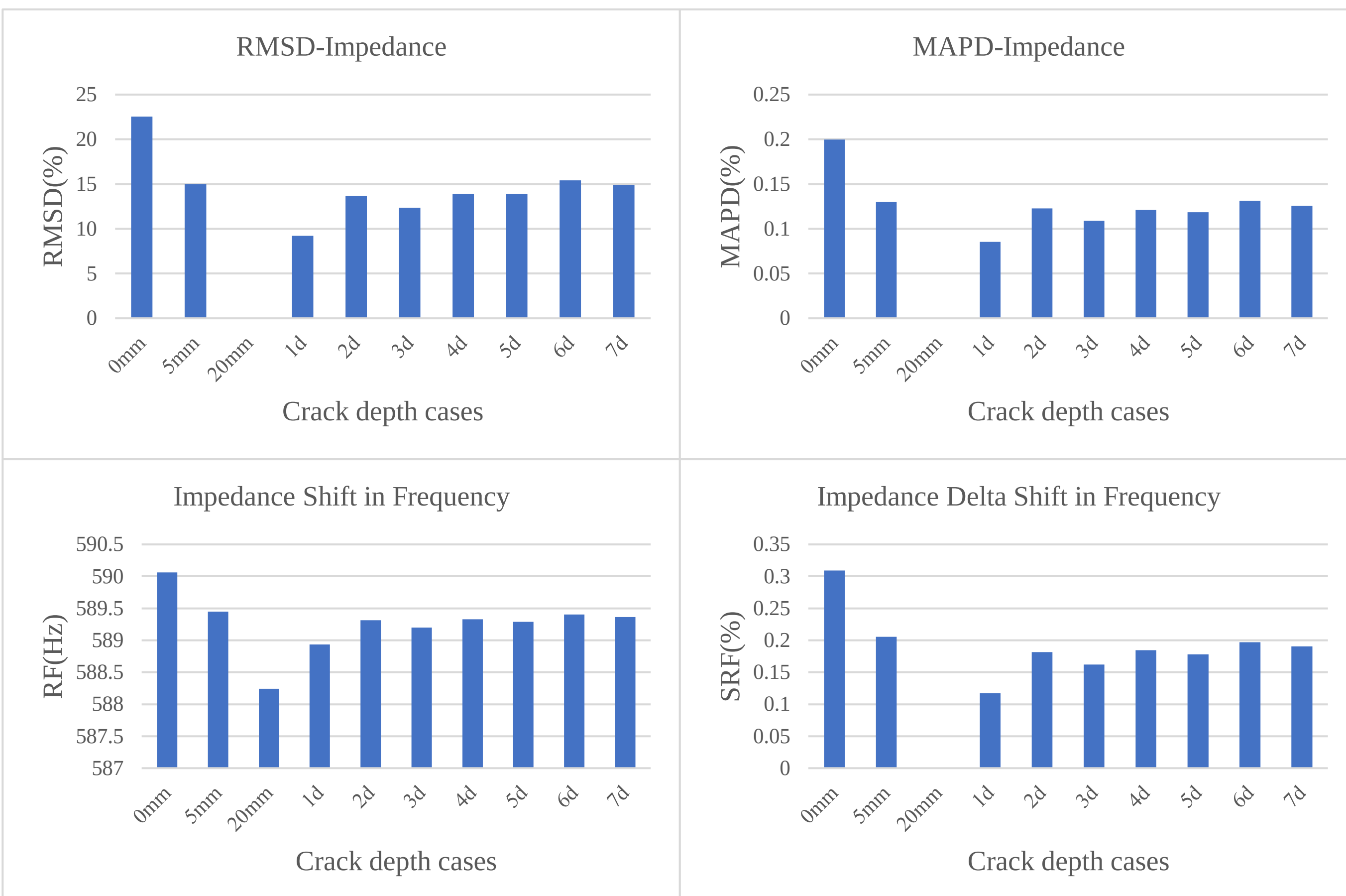

Figure 27. The RMSD, MAPD, SRF of frequency range 56kHz-61kHz with Epoxy material.

CONCLUSION & FUTURE RESERCH

In the study, the experimental investigations into the application of smart PZT sensor have been presented for damage detection and performance evaluation of healing materials. The results show that the RMSD, MAPD and SRF indexes can provide a good indicator to the severity condition of the damage, the PZT sensor appear capable of detecting the healing performance of different healing materials for healing damage in concrete successfully.

When we detected the extent of the damage, the 20mm crack depth case was set as the baseline measurement, due to increasing damage level in the structure. The progressive decrease in mechanical stiffness produced a less natural frequency, which made the centroid frequency shift to lower values in the impedance spectrum. The RMSD, MAPD and SRF are all sensitive to the different damage levels in the frequency ranges 56-61kHz, 75-82kHz and 176-193kHz, but only in the 56kHz-61kHz band. They performed well in both damage detection and healing materials' repairing performance assessment. Therefore, in 56-61kHz range, with the crack depth increasing, the RMSD, MAPD and SRF are all decreasing along a linear downward trend. So, the crack is deeper, and the PZT sensor is more sensitive. After repairing the crack, the centroid frequency moved back over time, the damage indexes also increased back, so that we could know the materials' repairing performance in the crack based on the value of the damage indexes.

From the experiments with these three kinds of healing material, the PZT can give us a good indication of the healing process of different materials after repairing the crack. The PZT sensor's damage index can show the cement healing material's curing condition for every day, and the best condition point after filling the crack for repairing. It can also quantize the period of the polymerization of SAP and the development of the self-desiccation in the concrete, and the process of hardening and strengthening of epoxy material in concrete. The results show that the cement material is good at repairing the damage in a structure, which is needed with a high physical requirement in the long term, but its process of curing is slow and long. Relatively, the SAP and epoxy are good for the temporary self-healing of the crack damage in concrete structure, but the SAP is not suitable for long term periods crack healing.

The study presents a strong prospect for utilizing PZT sensor in evaluating the extent of damage and the healing performance evaluation of healing materials for repairing the cracks in concrete. The results indicate that the EMI method has highly realistic value in the SHM of concrete structures, and provides a potentially valuable tool for researching the practical and new applications of the EMI method.

This study was successful in identifying the different crack depths and the repairing performance of different healing materials. However, there are still some concerns needing to be explored for the further research:

1. Optimize the array of the sensors on the host structure for decreasing the extra influence on the testing sensitivity because of the coupling vibration.
2. To optimize the method of frequency range choosing based on the properties of PZT's impedance mode.
3. To reduce the influence of complex surroundings on the sensitivity of the PZT sensor, such as the surrounding temperature and air humidity.
4. To combine the PZT sensors with other kinds of sensor based on outstanding their own advantages and avoiding their limitations.
5. To develop the multifunction of PZT in SHM field based on the property of PZT that it can be used as sensor and actuator.

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ACKNOWLEDGEMENT

Thanks to UNIST, I want to use this chance to express my best gratitude to everyone who supported me throughout the process of my thesis.

My deepest gratitude goes to my advisor, Prof. Sung-Han Sim. Thanks for his patience, constant encouragement and providing me with excellent guidance in doing research. He has companied me through all the stages of this thesis. The completion of this thesis could not have reached its present form without his consistent and illuminating instruction. I would like thank Prof. Sung Woo Shin who gave me so many helpful suggestions during the whole process of my experiment. I would like to thank Mr. Alan Stubbs for his kind help in my English writing skills. I also want to thank my research co-workers Hyunjun Kim and Eunjong Ahn, without their cooperation, my research could not be possible. I also prefer to thank my friendly colleagues Hyunjun Kim, Junhwa Lee, Seunghoo Jeong, Eunjin Kim and Sahyeon Lee for their support and help throughout my study and life.

Special thanks go to Hyunjun Kim, Junhwa Lee, So-Huei Kang, Feng Li and Kai Lou who are willing to help and support throughout my experience in Korea. I would not have so much unforgettable memory during my master study without them.

Further on, I would also like to thank my wife, my younger brother, my parents and my friends. They are the important inspiration for me, and always supporting me and encouraging me without reservation.