- *Technical Paper* -

# EXPERIMENTAL INVESTIGATION OF CONCRETE QUALITY CONDITION BY IMPACT WAVEFORM

Olatunde David OGUNSEYE[*1], Takeshi WATANABE[*2], Chikanori HASHIMOTO[*3]

## ABSTRACT

Mechanical Impedance`s capability of detecting deterioration near concrete surface, makes it more suitable method for periodical and routine inspection of concrete infrastructures. The Impact waveform from which mechanical Impedance is derived and could further be used to investigate the durability condition with respect to air permeability of concrete structure. Concrete damage by fire was simulated in this research. It was discovered that the mechanical Impedance parameters have good correlation with the air permeability condition of the concrete surface.

Keywords: Non-destructive testing, mechanical Impedance, fire damage, concrete durability, routine inspection.

## 1. INTRODUCTION

Cost of maintenance of infrastructure has been in the increase yearly. This had been a great concern to infrastructure asset managers, who are always trying to get good returns on investment while managing the current declining economy of the states [1]. A.E. Long et al [2], reported that Europe spends about 50% of all expenditure in the construction industry on maintenance, repair and remediation. Furthermore, the premature problem with durability of concrete structures is of great concern which requires urgent attention. Some developing countries with high infrastructural deficit is more greatly affected by this challenging increasing cost of periodic infrastructural maintenance. Those countries only carry out maintenance when infrastructural asset had experienced severe, visible and noticeable damage, this is not a good practice. Periodic maintenance activities are usually preceded by inspection. At this stage of maintenance, all performance requirement is being checked based on inspection results, and structural conditions can be evaluated. Routine and periodical inspection cost, detailed inspection and repair cost accumulates to the overall cost of maintenance.

This research is being carried out to investigate the capability of an impact waveform generated by a routine and periodical concrete non-destructive testing method called mechanical Impedance in detecting concrete durability condition with respect to air permeability by keeping the compressive strength relatively constant. Concrete deterioration will be simulated by heat action. Fire action is one of the most serious and rapid concrete deteriorating agent. As reported in many researches, the mechanical properties of concrete are affected at high temperature but due to impressive resistance of concrete at elevated temperature, concrete may experience marginal reduction in compressive strength to a maximum temperature 400°C, which is followed by a sharp decline in compressive strength thereafter. Concrete exposed to a maximum of about 400°C might be said to retain its one of the most desired properties which is the compressive strength but, its durability condition might be affected [3,4]. This situation is frequently encountered during routine and periodical inspection of concrete structures in which the compressive strength of maintained concrete structures are likely to be unaffected but other properties relating to its durability might be affected. Therefore, a device which could investigate the in-situ strength, deterioration, and durability condition of concrete structures, and thereby suggesting location on the concrete infrastructure to concentrate detailed inspection is of great importance. The Mechanical Impedance method of inspecting concrete is easy to use, with better efficiency over the surface hardness method.

## 2. METHODOLOGY

### 2.1 Research Background and Methodology

The method used in this study had been proven to be more effective in carrying out routine and periodical inspection over the well-known surface hardness method. because, in carrying out routine and periodical inspections not only compressive strength is desired, suggestive deteriorative condition is also important. The mechanical Impedance method estimates the in-situ compressive strength of concrete by hammering the concrete specimen/structure with a special hammer with installed sensor. The Mechanical Impedance method assumes Concrete to be as elastic body i.e. a spring system, therefore, on hammering the

*1 Graduate School of Engineering, Tokushima University, JCI Student Member.
*2 Associate Prof., Dept. of Civil Engineering, Tokushima University, JCI Member
*3 Professor, Dept. of Civil Engineering, Tokushima University, JCI Member

concrete surface both the Active and Reactive Mechanical Impedance values are generated based on the condition of the Concrete [5].

The Active Impedance is calculated when the hammer is pushed into the concrete, while the reactive Impedance is calculated as the reactive effect of the concrete pushing back the hammer. The Mechanical Impedance calculated by mathematically combining the impact force, $F_{max}$, velocity of the hammer on both active and reactive phase and also the contact time of the hammer during the two phases. Furthermore, an Impact waveform (as shown in **Fig. 1**) of hammer acceleration against time is generated for all impact on the concrete surface. The first-half of the waveform i.e, the rising phase to the peak of the waveform corresponds to the hammer pushing into the concrete which is the active Impedance, while the second half of the waveform which is the descending phase corresponds to the reactive response of the concrete pushing back the hammer denoting the reactive Impedance. In an ideal situation i.e. an un-deteriorated concrete, the generated waveform will be symmetrical with a high acceleration over a short time.

According to the device explanatory notes and reports, deviations from symmetrical shape of the impact generated waveform will suggest different grades of deterioration. Typical waveform suggesting deterioration and condition of the concrete structures are also presented in **Fig. 2** [5]. The ratio of the reactive mechanical Impedance to the active mechanical Impedance (ZR/ZA) is a deterioration index. An index value of close to 1 shows a deterioration for an ideal situation. Under real situation the active phase of an un-deteriorated concrete`s waveform will be bigger than the reactive phase. This is due to a phenomenon called specific damping of materials. Materials even metals below their yield points are not perfectly elastic [6]. Therefore, a damping condition and a plastic condition affect the duration of the active phase thereby increasing its contact time greatly higher than the reactive phase [7].

The Active and Reactive Impedance mathematical equation. [8]

$$ZA = \frac{F_{Max}}{V_A} \approx \frac{F_{max}}{\left(\int_{T_1}^{T_2} A(t)dt\right)^{1.2}} \qquad (1)$$

$$ZR = \frac{F_{Max}}{V_R} \approx \frac{F_{max}}{\left(\int_{T_2}^{T_3} A(t)dt\right)^{1.2}} \qquad (2)$$

Where:

$F_{max}$ : Maximum Impact Force,

M : Hammer Mass

$V_A$ : The velocity of the hammer as it pushes into the concrete.

$V_R$ : The Velocity of the Hammer as the concrete pushes back the hammer.

$A_{max}$ : Maximum Acceleration of the hammer

T : Time Interval

Recently, researches on the response of mechanical Impedance to concrete exposed to high temperature had proven that the reactive mechanical Impedance shows a very good correlation with increase in temperature [8].

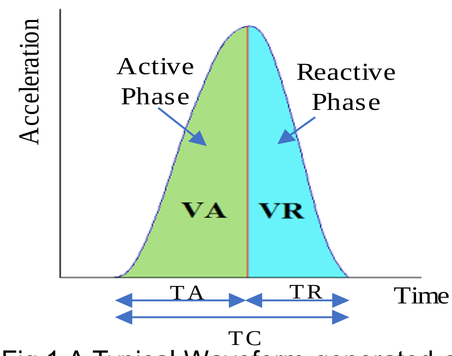


Fig.1 A Typical Waveform generated after impact [5]

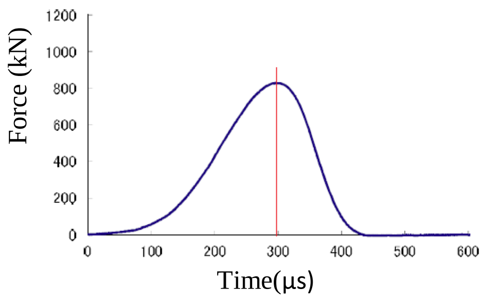


Fig.2 A Typical Waveform generated by deteriorated concrete [5]

This study investigates the response of the mechanical Impedance values and associated parameters in suggesting the durability condition of concrete structures by simulating a fire damage in which the compressive strength of the concrete is relatively constant, i.e. undergoes marginal change but the durability condition with respect to air permeability might have been greatly affected. Concrete specimen will be exposed to a maximum temperature of about 400°C. At this temperature it is expected that the residual compressive strength of the concrete will not have changed significantly, but its durability condition might have been affected. Therefore, the Mechanical Impedance values and associated parameters response will be investigated against concrete durability parameters.

## 2.2 Experimental Methodology

In this study, 3Nos 200x200x200mm Concrete cube specimen with standard 18Nos concrete cylindrical specimen of ϕ50x100mm were also prepared. The cylindrical specimen was prepared for the purpose of investigating the mechanical properties of the concrete while, the cubic specimen was to prepare impact test. As shown in **Table. 1** water to cement ratio of 0.5 was cast with the intension of producing a concrete to find a place between high and low compressive strength, also to be able to relatively maintain its compressive strength with the investigated temperature range. Concrete specimen was produced at a temperature of 20°C and a humidity of 60 mmHg. After cast, the concrete specimens were demoulded after 24 hours, cured in water for 28days, after which the experimental procedure to JSI standard in evaluating the mechanical properties of the concrete specimen were performed on the test piece to evaluate their compressive strength and some other mechanical properties. Test specimen were allowed to dry under natural environmental condition for 14 days in order to reduce the surface moisture content and also to reduce the possibility of surface indentation on the cube during impact test. It is therefore expected that during this 14 days waiting period the concrete will have gained additional strength due to the continuation of the hydration process, but the additional strength should not have significant effect on the experimental results.

Before exposing the concrete cubic specimen to fire damage, the concrete cubic surface as shown in **Fig. 3**, one surface of the cubic specimen will be divided into 4x4 grid. Furthermore, each grid will be further divided into two equal halves. The upper section of the grid was be tested before exposing the specimen to heat action while the other half will be tested after the heat action. This was done to reduce the possibility of error and also allow a new surface close to the earlier tested surface to be tested after exposure heat action.

In this research fire damage was simulated by placing the concrete specimen into an air tight electric furnace to a temperature of 200°C and 400°C. Although 600°C and 800°C were also intended but concrete surface was greatly impaired by surface spalling and explosion. Temperature gradient of 5°C/min was used in this research because Differential Scanning Calorimeter (DSC) test to map out heat transfer in solid used the same temperature gradient [4] and also to prevent rapid pressure build up in the concrete which could lead to rapid spalling or explosion of the concrete specimen. 1 Nos concrete cube and 6 Nos standard concrete cylinder were placed in the furnace and heated up to a with a temperature gradient of 5°C/ min until the desired temperature is attained i.e. 200°C and 400°C this temperature was maintained for 4 hours, in order to achieve even distribution of the heat effect throughout the concrete specimen, afterwards the concrete specimens were allowed to cool in the furnace gradually to 20°C so as not to induce further damage due to rapid Cooling. After 24 hours of cooling the concrete specimens, destructive mechanical properties were carried on the specimen and non-destructive test were performed on the cubic specimen by test hammer.

Table 1 Concrete Mix Proportion

| W/C (%) | s/a (%) | Unit Weight (kg/m$^3$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | W | C | G1 | G2 | SP | AE |
| 50 | 45 | 165 | 33 | 787 | 962 | 2.2 | 0.004 |

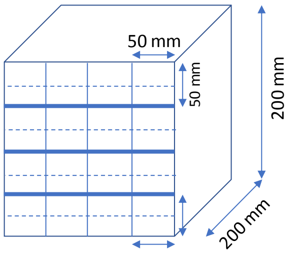


Fig.3 Cubic Specimen Preparation

On the first halve of each grid on the cubic specimen 20 hammering impact were carried out before and 20 hammering impact on the second half after fire action making a total of 640 blows before and after on the same concrete surface. The maximum force $F_{max}$, active phase and reactive phase velocities $V_A$ & $V_R$ respectively deterioration index which is the ratio of ZR to ZA, the Mechanical Impedance value ZR are read directly from the device when a concrete impact is made. The Active Impedance ZA and the contact time TC were thereafter calculated from the impact waveform generated by the device. The mean value of all parameter generated from the twenty hammering for each grid in the mean value of each grid.

Fig.4 Concrete Specimen in an electric furnace

The durability of the cubic specimen was evaluated by carrying out air permeability on one surface the specimen using torrent. Air permeability test was carried out on the un-deteriorated concrete. The concrete cube was exposed to 200°C and 400°C heating action. It was ensured that the surface water content of the specimen was below 5.0 as measured by a concrete surface moisture meter.

## 3 RESULTS AND DISCUSSIONS

### 3.1 Mechanical Properties and Impact Test Results.

The 28$^{th}$ day compressive strength of the concrete as measured by a destructive compressive strength test on the cylindrical specimen was 46.2 N/mm$^2$. After exposure to 200°C heating action, the value of the compressive strength increased to 48.3 N/mm$^2$, as summarized in **Table 2.** This increase in compressive strength value might be to a continuation of the concrete hydration process. A similar situation was reported by Neelam and Rafat [9], they investigated the influence of elevated temperature on self-compacting concrete and reported that there was a slight decrease in the compressive strength of the concrete at exposure between 100°C and 200°C, but there was a slight gain in compressive strength at 300°C temperature exposure. They further reported that the increase in strength after 200°C was due to the hydration of anhydrous cement which leads to the formation of hydrates with improved bonding properties. It was therefore concluded that high compressive strength does not relate to **good** durability condition. In this the cylindrical compressive strength shows slight decline to 47.3 N/mm$^2$ after exposure to 400°C heat action. Although it is expected that the compressive strength value will experience rapid drop when exposed to 600°C and 800°C heating action. The tensile strength value showed a slight increase and later dropped. The elastic modules showed a slight drop as the temperature increases, a similar situation had also been reported by Neelam and Rafat.

Table 2 Mechanical Properties

| Temperature (°C) | Compressive Strength (N/mm$^2$) | Elastic Modulus (kN/mm$^3$) | Tensile Strength (N/mm$^2$) |
|---|---|---|---|
| *20 | 46.2 | 23.8 | 3.3 |
| 200 | 48.3 | 22.3 | 3.9 |
| 400 | 47.3 | 15.7 | 3.0 |

*28days curing test values

The elastic modulus values of the cylindrical specimen did not increase in response to the increase in the compressive strength value as temperature increases. The fall in the elastic modulus value might be due to little changes in the microstructure of the concrete during exposure to the heating action. This phenomenon might be due to development of micro cracks, which would increase porosity of the concrete. It was also discovered that typical impact waveform at 20°C, 200°C, 400°C as presented in **Fig. 5-7**, does not show a deterioration condition situation as presented in **Fig. 2**, which suggests that the concrete had not experienced severe deterioration effect. As reported in recent researches [7], active and reactive mechanical Impedance results show decline with good correlation with temperature increases. Active Impedance shows a gentle rise with increase in temperature as shown in **Fig. 8**. It is due to the increase plastic strain at the surface. As the temperature increases the surface cohesive stress reduces, this leading to early attainment of the yield stress, with a corresponding increase in strain and also in contact time. The active phase could further be researched to understand the elastic-plastic phenomenon of this phase for better prediction of concrete durability. It had been reported and established that the reactive Impedance value as calculated by the impact hammer could be used in estimating to a greater accuracy the elastic modulus and further to estimates the compressive strength of concrete structures, but in this research, the reactive Impedance value decreases with temperature increase as shown in **Fig. 9**, which shows a good correlation with the elastic modulus of the concrete as presented in **Fig. 10**. Also, the compressive strength estimation might be affected by the surface condition of the concrete. This means that as the mechanical Impedance value which suggest the in-situ compressive strength of concrete it could also relate to the durability condition tested structure.

**Fig. 11,** shows the relationship between the contact time of the hammer with temperature increase. The contact time is the total time taken by the hammer to make a push into the concrete, and also the reactive action of the concrete on the hammer. The contact time of an impact system or bodies in contact had been related to the properties of the bodies in contact [9]. In this case the bodies in contact are the concrete surface and the hammer. The hammer head is made of steel material, and concrete a brittle material, therefore, to a larger extent the effect of the impact will be affected by concrete surface. The condition of the concrete`s surface can be related to the contact time of the impact hammer on the surface of the concrete. Since the contact time is the summation of TA and TR, the influence of each phase of the impact is investigated as shown in **Fig. 12**. The reactive phase was discovered to contribute more, with a more rapid increase over the active phase as temperature increase. The initial wide variance in the contact time of the two phase is due to the elastic-plastic condition of the active phase, as more time could be recorded during the plastic deformation. The further slight increase could be considered to be as a result of development of micro cracks leading to reduction as the exposure temperature increases. Reactive phase`s increase in contact time as shown could be explained as, the weakness on the concrete due to its inability to make a quick recovery after the hammer`s push.

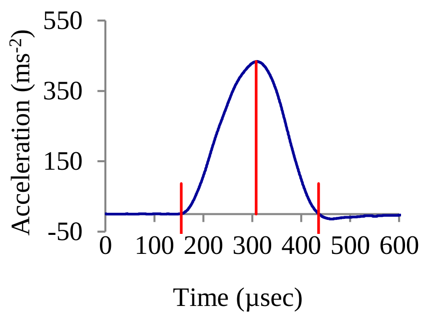


Fig.5 Impact Waveform at 20°C

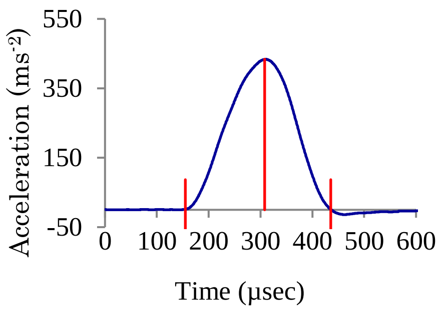


Fig.6 Impact Waveform at 200°C

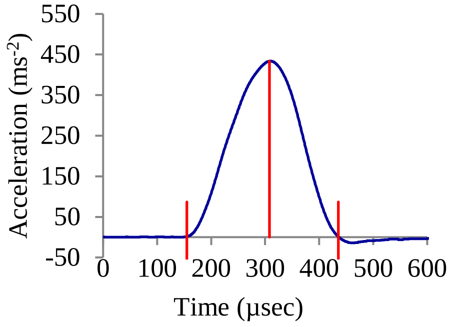


Fig.7 Impact Waveform at 400°C

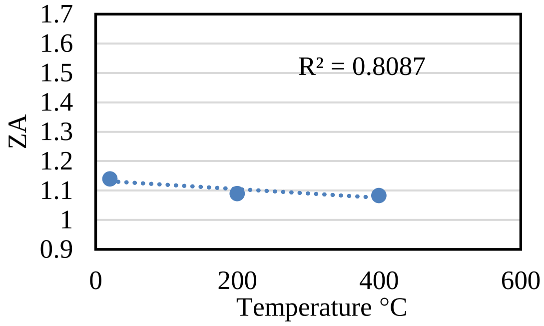


Fig.8 Active mechanical Impedance

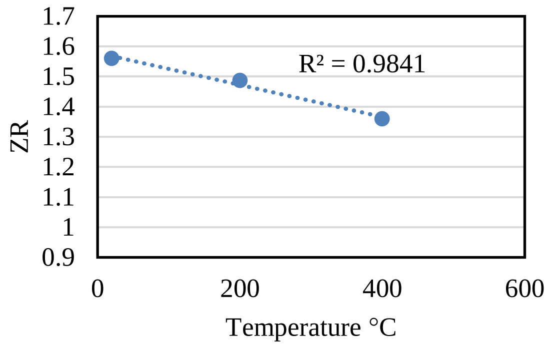


Fig.9 Reactive mechanical Impedance

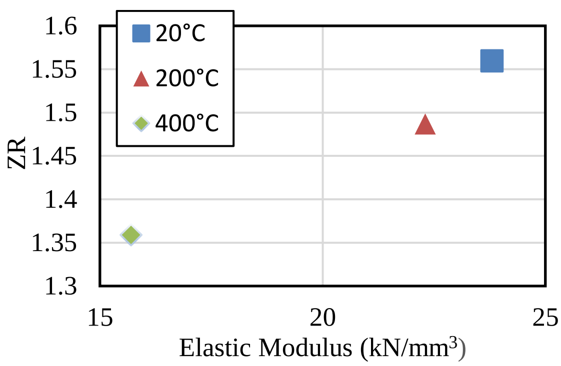


Fig.10 Elastic Modulus

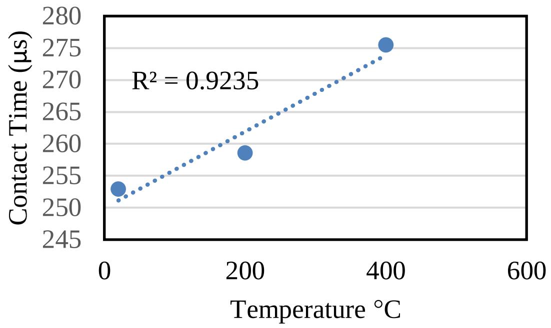


Fig.11 Contact Time

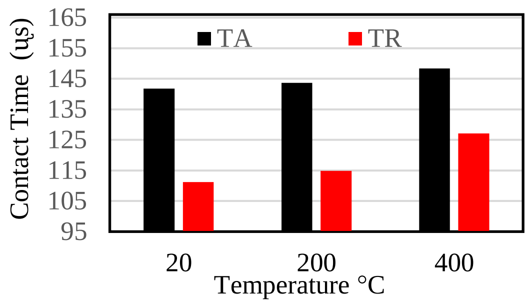


Fig.12 Contact Time

### 3.2 Concrete Durability Investigation

Lulu et. all [6] reviewed that the durability condition as it relates to long term performance of concrete structures is a function of the transport mechanism in concrete. The starting point of this transport process is the surface of the concrete. Depending on the driving force of this process and the nature of the transported material, the durability evaluated in terms of diffusion, absorption, and permeation. Furthermore, Lulu explained that the major cause of deterioration is the ingress of ions, liquids, gases from the environment directly or indirectly. It is very important to investigate the durability of concrete during routine and periodical inspection. Permeability is defined as the extent to which a fluid medium pass thorough a material under the action of pressure differential. As shown in **Fig 13**, visible change in the colour of 400°C specimen which suggest possible deterioration condition In this research, Air Permeability Test, concrete durability test was performed on the test piece is shown in **Fig.14** and correlated to the deteriorative parameters of the impact waveform. The result of this experiment is shown in **Fig.15.** As the exposure to temperature increases, the coefficient of permeability increases and also the permeability coefficient showed a correlative relationship. With respect to Concrete permeability coefficient scale, the concrete condition of the three-cubic specimen can be read from **Fig.15** in conjunction with **Table 3**.

Higher permeability coefficient value can be related to the development of micro cracks on the surface of the concrete. Much micro cracks were discovered on the surface of the cubic specimen exposed to 400°C heating action. In **Fig. 16,** the ratio of ZR/ZA as it tends 1 in an ideal situation should.

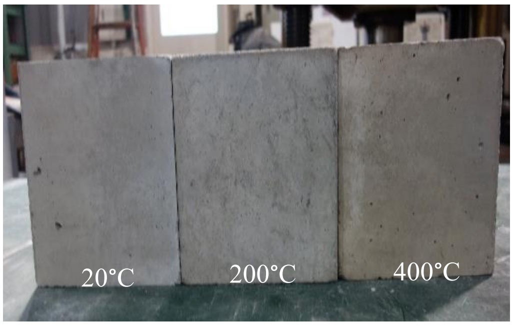


Fig.13 Surface Condition of Cubic Specimen.

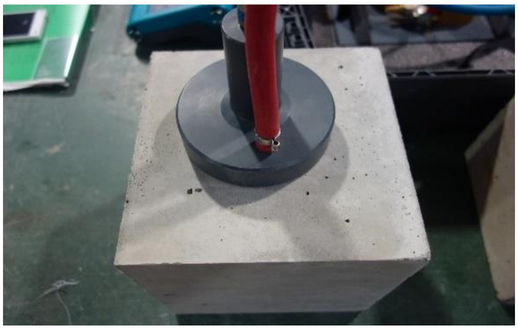

Fig.14 Air Permeability Experiment.

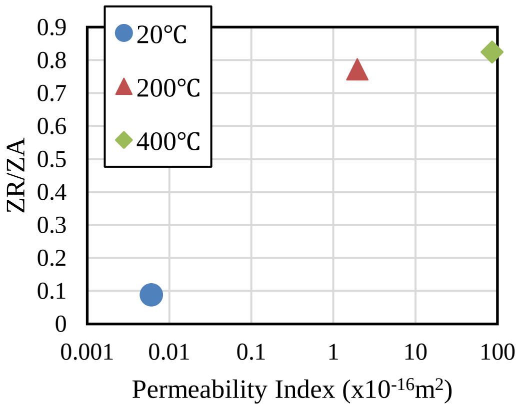


Fig.15 Air Permeability and Deterioration Index.

Table 3 Coefficient of Permeability Interpretation

| Coefficient of Permeability ($x10^{-16}m^2$) | Surface Condition |
|---|---|
| **10 - 100** | Very Bad |
| **1 - 10** | Bad |
| **0.1 - 1** | Normal |
| **0.01- 0.1** | Good |
| **0.001 - 0.01** | Very Good |

## 4. CONCLUSIONS

1. It was found that the surface condition of inspected concrete could affect the mechanical Impedance value.
2. The Active phase response to concrete surface condition as micro cracks could have affected the gentle decline in trends as temperature increases.
3. The mechanical Impedance parameters should be further investigated against different concrete quality conditions.

## ACKNOWLEDGMENT

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