- Technical Paper -

CONCRETE DETERIORATION INVESTIGATION BY MECHANICAL IMPEDANCE METHOD

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ABSTRACT

The applicability of mechanical impedance method in evaluating the deterioration condition of concrete will improve its reliability. Three different grades of concrete were investigated. Concrete deterioration by fire damage was simulated on all grades of concrete in an electric furnace to an elevated temperature of 200°C, 400°C, 600°C, 800°C. A deterioration index by impact energy loss on hammering was formulated and proves to be very effective. Irrespective of the grade of concrete, the energy loss deterioration index value is the same for un-deteriorated concrete, and as induced deterioration increases, and later varies slightly with the respective grades of concrete.

keywords:Non-destructive testing, mechanical Impedance, fire damage, routine inspection, concrete deterioration, energy loss deterioration Index.

1. INTRODUCTION

Concrete, world most used construction material in infrastructural development owing to its low cost, ease of production, and its applicability in many infrastructural development of varying complexities, is challenged with various agent of deterioration under service life.[1] These agents of deterioration varies from mechanical, chemical, environmental or structural fatigue under service life. Apart from deterioration concerns, concrete is also challenged with the need to ensure a certain level of quality at both fresh and hardened state. The quality of concrete is very important as it has a great influence on ultimate, serviceability and also its durability conditions. Efforts have increased in recent times in accurately predicting the homogeneity and the residual compressive strength of concrete. Non-destructive methods of inspection are being preferred over destructive method because the investigated concrete components are unimpaired, wide arrears can be tested with a short period of time. Additionally, the reliability of various non-destructive methods have increased over the years. [1][2]

Concrete infrastructure maintenance cost is on the increase yearly owing to many aged, deteriorating and newly constructed concrete infrastructures. Shortage of experienced concrete inspector and cost of specialized concrete non-destructive inspection equipment and tools have been a major concern to concrete infrastructural maintenance.[3] These challenges have led to the development of mechanical impedance, a non-destructive method of estimating the compressive strength of concrete by hammering concrete surface.[4] This method is easy to use and have been proven to accurately estimate the compressive strength of concrete over the well-known rebound hammer method.[5] In-situ compressive strength of concrete is most desired when evaluating the integrity of existing Concrete structures,[1] therefore, non-destructive test methods tends to estimate the compressive strength based on regression models. Most regression models are formulated by correlating a particular non-destructive method parameter with elastic modulus of different grades of durable concrete to predict in-situ compressive strength. In most cases these models and compressive strength estimation tends to be confusing as undeteriorated concrete are usually used to develop those models. It was discovered that compressive strength and elastic modulus of concrete might not have a consistent degradation pattern when concrete deteriorates, also when investigating concrete infrastructure with limited historical information, as to its design strength, mix ratio, current service life etc. It's therefore important to determine whether the estimated in-situ compressive strength value had been affected by deterioration or a true representation of the concrete's design strength.

This technical paper seeks to present a tested hypothesis of evaluating concrete quality and deterioration by mechanical impedance. The fundamental principle from which mechanical impedance parameter of ZA and ZR was formulated will be investigated to develop a new index of deterioration. Three different grades of concrete were prepared under the same environmental condition. In this investigation, fire damage was simulated by heating the samples in an electric furnace up to a maximum temperature of 800°C. Fire damage is one

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of the most serious and rapid concrete deteriorating agent. Laboratory simulation of fire damage helps also to simulate a fast and steady deterioration as temperature increases, depending on heating gradient. Concrete experience marginal reduction in compressive strength with a significant drop in elastic modulus at maximum temperature 400°C, which is followed by a sharp decline in compressive strength thereafter. It is suggested that quality concrete should meet certain quality requirement irrespective of its grade if all quality assurance and quality control procedures are deployed from material preparation stage to placing and curing. As reported, ultrasonic pulse velocity method of concrete non-destructive inspection has given a range of velocity for undeteriorated concrete despite the grade of concrete ceteris paribus as quality requirements[6] This technical paper will also seek to develop a near concrete surface quality index using mechanical impedance model to measure the quality of concrete. This index value will help to suggest possible deterioration in Concrete and as a mean quality assurance.

2. METHODOLOGY

2.1 Research Background and Methodology

The Mechanical Impedance method assumes that concrete is an elastic body which could be represented with a spring model. Concrete stress strain curve during uni-axial compression test also confirms it. When concrete surface is hammered both the active and reactive mechanical impedance values are generated based on the near surface condition of the concrete. [4]

The active mechanical impedance represents the hammer pushing through the concrete, while the reactive impedance is calculated as the reactive effect of the concrete pushing back 4the hammer. The mechanical impedance values are calculated by mathematically combining the impact force, F_{max}, velocities of the hammer during both active and reactive phase and also the contact time of the hammer during the two phases. An Impact waveform (**Fig. 1**) of hammer acceleration against time is generated for all impact on the concrete surface is used to calculate the mechanical impedance values. 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 phase, 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 phase. In an ideal situation i.e. an undeteriorated concrete, the generated waveform will be symmetrical with a high acceleration value over a short period of time.

According to the explanatory notes, reports and codes, deviations from a symmetrical shape of the impact generated waveform will suggest different grades of concreten deterioration.[5] Although, metals also are not perfectly elastic below their yield points.[7] Therefore, damping and a plastic condition affects the duration of the active phase thereby increasing its contact time greatly higher than the reactive phase [8].

The Active and Reactive Impedance mathematical equation are presented in **Eqn. (1) and (2)**. [4]

$$Mechanical\ Impedance = \sqrt{MK} = \frac{F}{V^{1.2}} \quad (1)$$

$$ZA = \frac{F_{Max}}{V_A} \approx \frac{MxA_{max}}{\left(\int_{T_1}^{T_2} A(t)dt\right)^{1.2}} \quad (2)$$

$$ZR = \frac{F_{Max}}{V_R} \approx \frac{MxA_{max}}{\left(\int_{T_2}^{T_3} A(t)dt\right)^{1.2}} \quad (3)$$

Where:

F_{max} : maximum impact force,

M : hammer mass

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

V_R : the velocity of the hammer as the Concrete pushes back.

A_{max} : maximum acceleration of the hammer

T : time Interval (where T_1, T_2, T_3 are the contact time at the start, maximum peak, and end of the impact waveform)

K : spring constant

Recently, investigations on the response of mechanical Impedance to concrete exposed to high temperature have proven that the reactive mechanical Impedance shows a very good correlation with increase in temperature. [9][10]

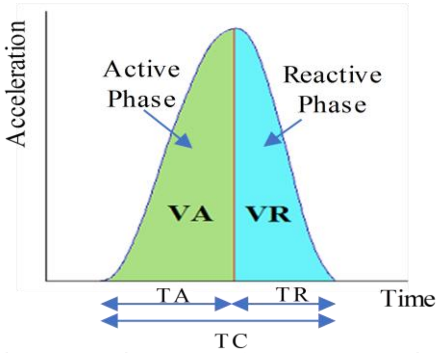

Fig.1 A Typical Waveform generated after impact [5]

2.2 Experimental Methodology

In this study, three grades of concrete classified by water cement ratio were investigated in this research. As shown in Table 1, water cement ratio of 0.4, 0.5, 0.6 were cast to capture different grades of concrete commonly used. Ordinary Portland cement(C), sand with an oven dry density and fineness modulus of 2.53 g/cm^3 and 2.2 respectively as fine aggregate(S), and granite as coarse aggregate(G) an oven dry density and fineness modulus of 2.54 g/cm^3 and 6.41 respectively. Superplasticizer and air entrainment agent as admixtures were used to ensure consistency of mix. For each grade, 5Nos 200x200x100mm concrete cube specimen were prepared with standard 18Nos concrete cylindrical specimen of ϕ50x100mm were cast and cured under also a controlled temperature of 20°C and a humidity of 60 mmHg. The cylindrical specimen was prepared for the purpose of investigating the mechanical properties of the concrete, while the cubic specimen for hammering test. Lesser thickness of the rectangular specimen compared to previous research was adopted in order to prevent high pressure build-up in the specimen at high temperature.[10] After concrete cast, the specimens were de-moulded after 24 hours, cured in water for 28days, after which the experimental procedure to JIS standard in evaluating the compressive strength and elastic modulus of the concrete specimen were performed on the cylindrical test piece to evaluate their compressive strength and some other mechanical properties.

In this research, all three investigated grades of concrete were exposed to elevated temperature to induce deterioration in them. The concrete specimens were placed into an air tight electric furnace and heated up to 200°C and 400°C, 600°C and 800°C, to induce increasing grade of deterioration. Temperature gradient of 2.5°C/min was used in this research because at higher temperature gradient rapid pressure build up in the concrete which could lead to spalling or explosion of the concrete specimen before 600°C mark is reached.[10] 1 Nos Concrete cube and 3 Nos standard Concrete cylinder specimen were placed in the furnace and heated up to a with a set temperature gradient of 2.5°C/min until the desired temperature is attained i.e. 200°C and 400°C,600°C, 800°C for each grade of concrete. When desired temperature is reached, temperature was maintained for 2 hours 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 48 hours or more of cooling, the concrete specimens, destructive mechanical properties were carried on the cylindrical specimen and non-destructive mechanical impedance impact test were performed on the cubic specimen. Un-deteriorated concrete test pieces were performed at 20°C.

Table 1 Concrete Mix Proportion

W/C (%)	s/a (%)	Unit Weight (kg/m^3)					
		W	C	S	G	SP	AE
40	45	165	413	757	925	1.3	0.005
50	45	164	327	790	965	1	0.005
60	45	175	292	790	965	0.8	0.003

As Shown in **Fig. 2,** on each concrete cubic specimen's surface, 20 hammering impact were carried out on each 50x50mm grid before and 20 hammering impact and after fire action making a total of 640 blows on the same concrete surface before and after heating. The maximum force F_{max}, active phase and reactive phase velocities V_A & V_R, deterioration index which is the ratio of ZR to ZA, the mechanical impedance value ZR are read directly from the device when an 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 was generated from the mean values of each twenty hammering of each grid.

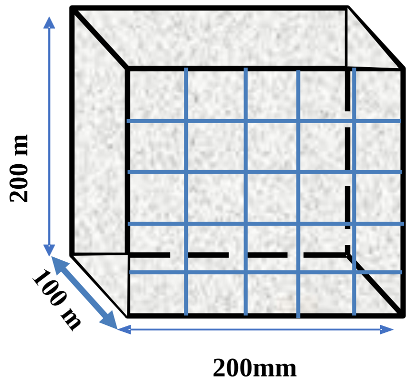

Fig.2 Cubic Specimen Preparation

Residual compressive strength in all concrete specimens was estimated by conversion table made available by Nitto Construction Inc. Residual compressive strength was estimated by reactive mechanical impedance values ZR.

3 RESULTS AND DISCUSSIONS

3.1 Mechanical Properties and Impact Test Results.

Figures 3-5, presents the uni-axial compressive Strength(STR), Elastic Modulus(EM), estimated residual compressive strength(EST. STR) based on available correlation curve, at all temperature range for the three investigated concrete grades. For w/c ratio 0.4 grade concrete all values decreases as temperature increases. At 20°C i.e. un-deteriorated state, the uniaxial compressive strength compressive strength values and CTS estimated were very close. But as deterioration sets-in, the estimated compressive strength begins deviate widely from the uniaxial compressive strength. It was also discovered that at the elastic modulus and the reactive mechanical impedance values seams to decline in similar pattern as temperature increases except at early temperature of 200°C as shown in Fig 6, which might be a situation peculiar to fire damage. Unlike w/c 0.4 grade, w/c 0.5 grade concrete estimated compressive strength tends to maintain a relative close values with the compressive strength up to about 600°C. This pattern is also similar with w/c 0.6 grade Concrete. It was observed that reactive mechanical impedance strength estimation have a high degree accuracy to crushing compressive strength when concrete is un-deteriorated. This makes this method adequate for in-situ quality assurance and control of newly constructed concrete infrastructures. The elastic modulus results of the cylindrical specimen in this investigation did not make regular pattern with uniaxial compressive strength as temperature increases. This might make it difficult to accurately estimate the compressive strength of deteriorated concrete. However elastic modulus values are very useful in investigating the concrete deterioration.

Fig.6&7 shows the response of active and reactive mechanical Impedance to increasing level of deterioration. All concrete grades show similar patterns as deterioration increases with a relative consistent trend between 400°C and 600°C. The massive drop of ZR after 400°C shows a response to severe deterioration of concrete specimen.

3.0 ENERGY LOSS INDEX VALUE.

3.1 Model Formulation

From first principle, mechanical impedance model is based on the elastic properties of concrete and therefore assumes that concrete is an elastic spring. It further assumes energy conservation when concrete surface is hammered; the kinetic energy of the hammer is equal to the energy stored in the spring as represented in **Eqn. (4).**

$$\frac{1}{2}MV^2 = \frac{1}{2}KX^2 \tag{4}$$

Where:
M : hammer mass
V : impact hammer velocity during impact
K : spring constant
X : spring displacement

From mechanical impedance theory it could be readily observed that the active phase of the mechanical impedance waveform is bigger that the reactive phase. Fundamental theory of impact had suggested that the active phase has both plastic and elastic component. If the reactive phase is perfectly elastic, the difference between the active and reactive phase could suggest energy loss due to plastic deformation (an unrecoverable deformation).

In a real case **Eqn. (4)** becomes **Eqn. (5)**

$$\boldsymbol{\frac{1}{2}MV^2 = \frac{1}{2}KX^2 + U} \tag{5}$$

Where:
U : energy loss

From Hooks Law,

$$X = \frac{F}{K} \tag{6}$$

Substituting Eqn. (5) to Eqn. (4)

$$MK = \frac{F^2 + 2KU}{V^2} \tag{7}$$

Squaring both sides

$$\sqrt{MK} = \sqrt{\frac{F^2 + 2KU}{V^2}} \tag{8}$$

Energy Loss is investigated at the Active Phase of the waveform

$$\therefore \sqrt{MK} = ZA \tag{9}$$

and $V = V^{1.2}$ (9)

Therefore, Eqn. (7) becomes

$$\boldsymbol{U = \frac{ZA^2V_A^{2.4} - F_{max}^2}{2K}} \tag{10}$$

The Reactive Impedance is assumed to be perfectly elastic, therefore the true springo/ stiffness is obtained from the reactive Impedance value.

$$\sqrt{MK} = ZR \tag{11}$$

Energy loss during impact as a deterioration index value (U) during impact at elevated temperature is presented in **Fig. 8**. The energy loss during hammering is virtually the same for all grades of concrete at 20°C i.e. un-deteriorated concrete. As concrete deteriorates it losses it elastic properties, this prevent the concrete from total recovery after deformation. As elastic properties of concrete decreases its plastic properties increases which result in an increase in energy loss. All concrete grades increases in the same pattern with little deviations with respect to concrete grades. At 400°C the energy loss value during impact for all the grades of concrete begins to falls drastically which reflects severe deterioration in the concrete as reflected in the mechanical properties values.

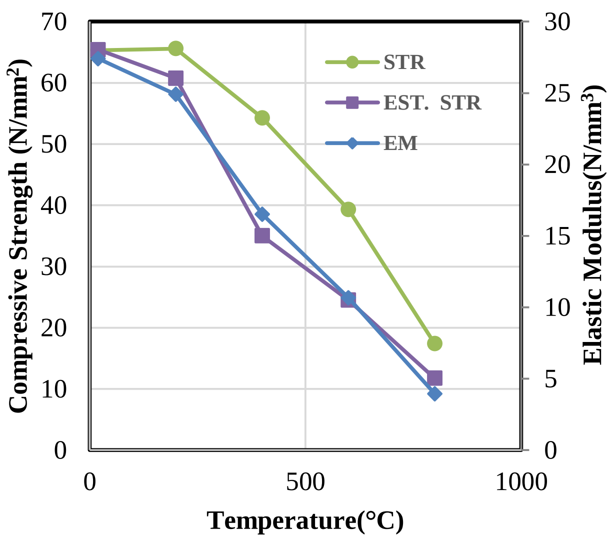

Fig.3: w/c 0.4 Concrete Mechanical Properties at Elevated Temperatures.

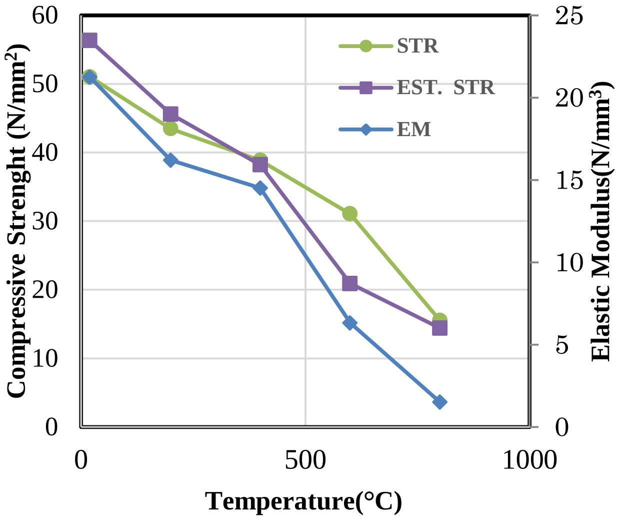

Fig.4: w/c 0.5 Concrete Mechanical Properties at Elevated Temperatures

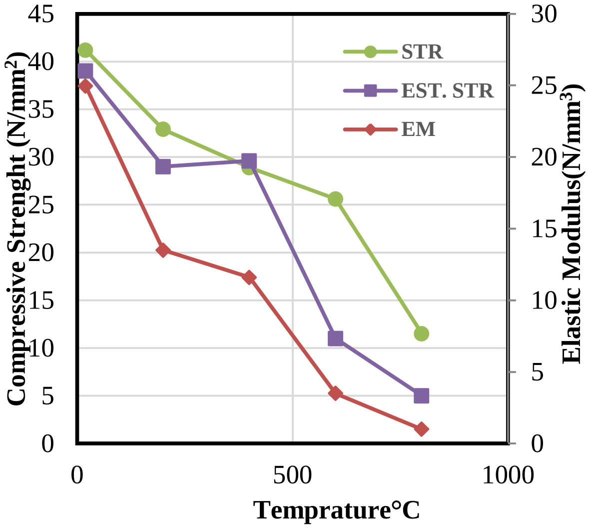

Fig.5: w/c 0.6 Concrete Mechanical Properties at Elevated Temperature

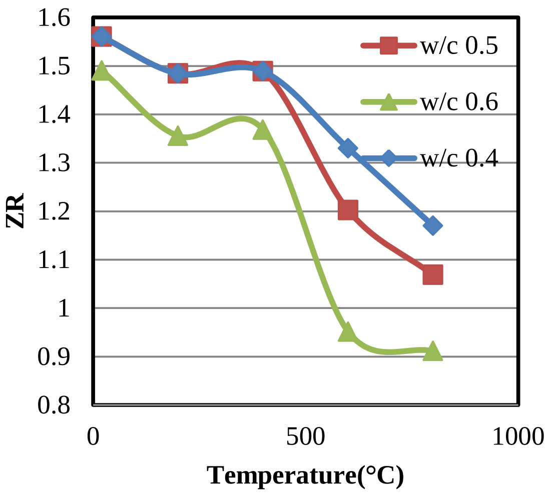

Fig.6: Reactive Mechanical Impedance at Elevated Temperature.

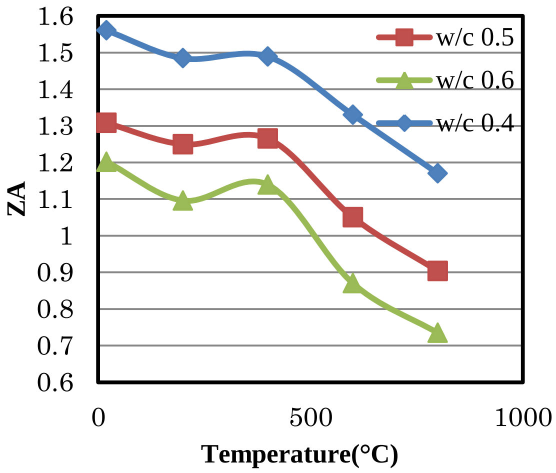

Fig.7: Active Mechanical Impedance At Elevated Temperature.

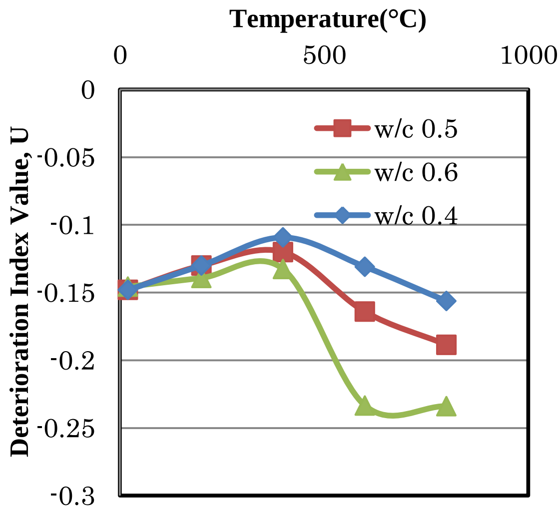

Fig.8 Energy Loss Deterioration index at Elevated Temperature.

4. CONCLUSIONS

Deterioration index defined by impact energy loss on hammering had proved to be simple and very effective of the grade of Concrete the Energy loss deterioration index value is the same for un-deteriorated Concrete this could be used to checkmate substandard Concrete. Energy loss Index within the range of -0.1 and -0.15 could mean a structurally-durable concrete. Further experimental trial is required to validate this index. The theory of Spherical Indentations could be used to improve the reliability of Mechanical Impedance because the hammer is a spherical indenter.

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