ESTIMATION OF COMPRESSIVE STRENGTH OF CONCRETE BY MEANS OF MECHANICAL IMPEDANCE

Genki Kubo
Nitto Construction Inc.
9-8, Kitago3-4, Shiroishi-ku,
Sapporo, Hokkaido, 003-0833
Japan
genki@nittokensetsu.co.jp

Hajime Kubo
Nitto Construction Inc.
1344-5, Oumu, Town Oumu
Monbetsu, Hokkaido, 098-1702
Japan

Dr. Tomoaki Sakai
Applied Research Inc.
904-1, Tohigashi,
Tsukuba, Ibaraki, 300-2633
Japan

KEYWORDS: Mechanical Impedance, Compressive Strength, Rebound Hammer

ABSTRACT

In the case of actual aged concrete structures, the surface of the concrete might become plastic; therefore a method to measure the concrete strength while avoiding the surface condition of the concrete is needed. We paid attention to the force wave form of the hammer when the hammer strikes the concrete surface. The wave form can be divided into two parts, the first being the active part when the hammer makes plastic/elastic deformation on the concrete surface, and the other being the reactive part when the concrete surface pushes the hammer back by potential energy due to the elastic deformation of the concrete. It means that if the mechanical impedance of the reactive portion of the hammer blow is measured, the compressive strength of the concrete which is not affected by the surface condition of the concrete is obtained. In this paper, the applicability of the mechanical impedance for the aged concrete structure is examined as the results of the field test. Also the signal processing method to calculate the mechanical impedance of the deteriorated concrete is shown.

INDRODUCTION

NDT technologies to measure the state of actual concrete rapidly, precisely and inexpensively are required for the maintenance and long term usage of the concrete structures currently in use. Today, there is a rebound hammer method (RHM) for measuring the compressive strength of the structural concrete in NDT manner. RHM is widely used as defined in the national or international standards. However, there are many arguments and questions on the accuracy of estimation of the concrete strength. Especially in case of the concrete with deteriorated surface, RHM has theoretical limitation that it should be performed after removing the deteriorated layer of the concrete surface completely. Among the existing concrete structures, almost all of the concrete of the waterways have been deteriorated; therefore, it is difficult to employ RHM for strength estimation of the waterway concrete. On the other hand, the mechanical impedance method (MIM) developed by the authors employ the method to calculate the mechanical impedance using the reactive motion of the hammer blow on the concrete surface. Therefore the applicability and accuracy of MIM to the concrete with deteriorated surface is considered higher. In this paper, the theoretical consideration on the measurement method of MIM and the results of experiments of the strength estimation of the surface deteriorated actual waterway concrete are shown. The problems and their solutions when applying MIM to strength estimation of the actual concrete structures are discussed.

STRENGTH ESTIMATION OF CONCRETE STRUCTURES BY HAMMER BLOW

Rebound Hammer

RHM measures the rebound value. The rebound value is defined as the ratio of the rebounded hammer stroke and the initial stroke of the hammer. The theory of the rebound hammer is based on the energy equilibrium and the following equation stands good.

$$E_0 = E_P + E_R \quad (1)$$

Here, E_0, E_P, E_R are the initial energy of the hammer, energy lost by the plastic deformation of the concrete surface and the energy used for the hammer rebound respectively. From Eq. (1), the initial displacement of the hammer driving spring is x_0 and the spring displacement after the hammer rebounds is x_R, the rebound value becomes,

$$R = \left(\frac{x_R}{x_0}\right) = \sqrt{1 - \frac{E_P}{E_0}} \quad (2)$$

From Eq. (2), the energy consumed for the plastic deformation on the concrete surface is obtained. RHM is the method to calculates the Brinell hardness of the concrete surface form the plastic deformation energy and then to estimate the compressive strength of the concrete. Therefore, clean and fresh concrete surface is required by RHM to get the concrete strength. This means that RHM has theoretical limitation for applying the method onto the concrete with surface deteriorated itself.

MIM

On the other hand, MIM employs both of the mechanical impedance of the hammer contact with concrete surface when both of the hammer progressing process (Active part) and the hammer rebound process (Reactive part). And the mechanical impedance of the reactive part is used for the strength estimation to avoid the undesired influent of the deteriorated surface of the concrete structure.

FIELD EXPERIMENT USING ACTUAL WATERWAY CONCRETE

Outline of the structure

Photo.1 Tested Waterway (Bibai)

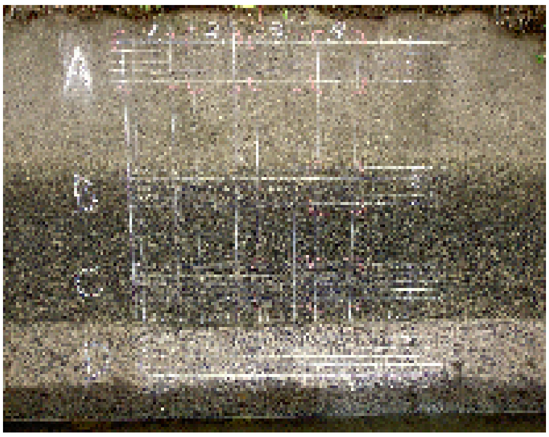


Photo.2 Measuring area

The overview of the waterway used for this field experiment and its measuring parts are shown in Photo (1) and Photo (2) respectively. The normal water level of this waterway was the level where the wall color was dark in Photo (1) and (2). The experiment was performed after its making water level lowered and dried up the measuring parts.

Measuring method

The measurements were preformed on the air exposed part (Photo 2 A-part), the part showing the boundary of air and water (Photo 2 B & C-part) and the underwater part (Photo 2 D-part). Both RHM and MIM were used to measure the strength of the concrete, and both the data were compared. In addition, for MIM, three masses of the hammer (190, 416 and 566 grams) were used to make experimental consideration on the influence of the hammer mass on the mechanical impedance value and their variations.

Results of experiment

(1) RHM

The results of RHM are shown in Fig. 1 and 2. Fig. 1 shows the relationship between the rebound values and thickness of the layer removed on the concrete surface at the part B. The maximum rebound value of RHM appears when removed off 2mm. This means that the surface deterioration depth of this waterway concrete was estimated around 2mm.Fig. 2 shows the relationship between blow count and the rebound value when RHM was continuously blown almost at the same spot. This test had two purposes, one was that the real rebound value of this concrete could be obtained or not by blowing continuously and the other was to examine the applicability of RHM onto the concrete without smooth surface. The blow tests were performed more than 20 times. The rebound values were fluctuating; however, the rebound value was rising with the rise in blow count and showing the trend to become the constant value. The rebound value becomes almost a constant value after seven to ten times of the blow in this experiment. The rebound value at the first blow was the half of the constant value at the final blow condition, thus it is considered that it is difficult to get the proper rebound value while avoiding surface abrasion processing.

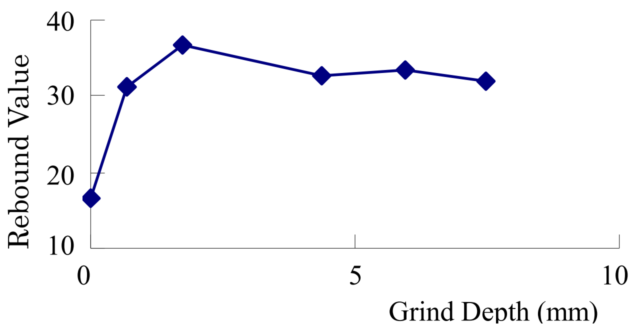


Fig.1 Rebound Value vs Grind Depth

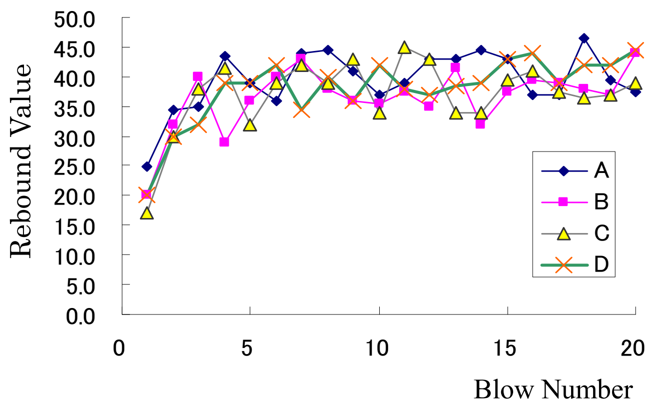


Fig.2 Blow Number vs Rebound Value

(2) MIM

Fig. 3 shows the relationship between the hammer blow count and the rebound coefficient measured by MIM. By MIM, both of the hammer speeds when the hammer collides with the concrete surface and when the hammer is pushed back from the concrete surface are measured. Therefore the rebound coefficient shown in Fig. 3 is the value theoretically defined. Also shown in Fig. 3, if the blow count number exceeded 10 times, the rebound coefficient became almost 1. The result of MIM for the rebound coefficient shows the same tendency as that of RHM. This fact shows that the plasticized surface layer of the deteriorated concrete could be removed by continuous hammer blowing and the rebound value of this method is almost as same as that of the concrete with the grained surface. However, in the case of RHM, the result shows the large variation on the rebound value and the coefficient of variance from 12 to 22%.

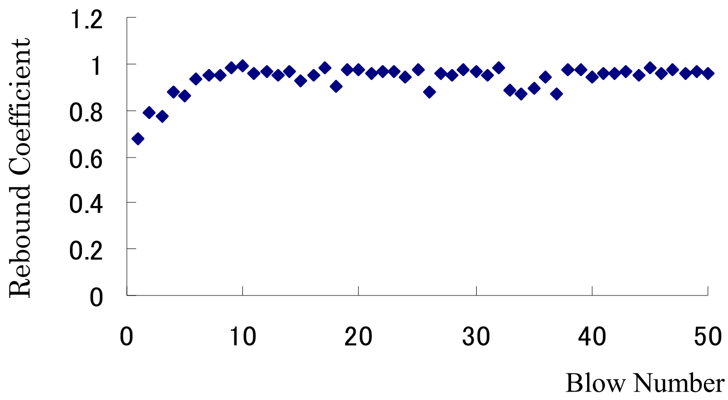
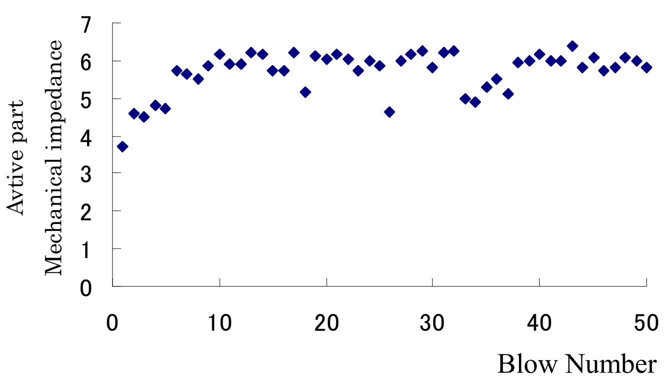


Fig.3 Blow Number vs Rebound Coefficient

Fig. 4 shows the variation of the mechanical impedance of the active part (when the hammer is pushing the concrete surface) and reactive part (when the hammer is pushed back by the concrete surface) in accordance with blow counts. On the active part, the mechanical impedance shows the tendency to become larger in accordance with blow count; however, the mechanical impedance of the reactive part does not change even if the blow count is smaller or larger. This fact confirms that the reactive mechanical impedance is not affected by the deterioration of the concrete surface.



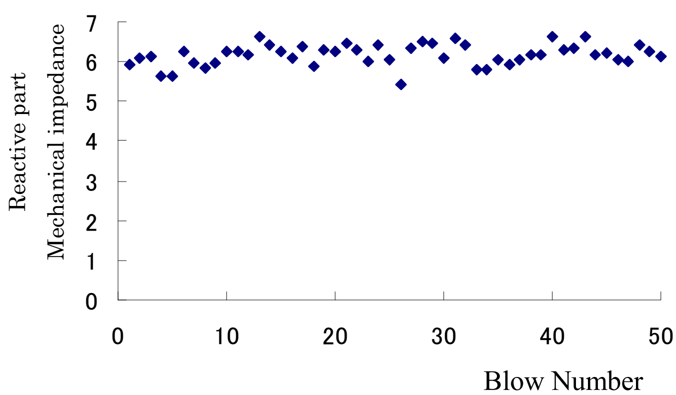


Fig.4 Blow Number vs Rebound Coefficient

(3) Consideration on the frequency range usage for signal processing

MIM is employing the digital signal processing unlike RHM; the values are deduced as the result of signal processing using the wave form in the time domain. In this case, the result will be changing with the used frequency range. Generally speaking, a low pass filter is commonly used for putting the limitation on the frequency range. To examine the proper frequency range for the impedance calculation of the concrete, that is comparing the original wave form and filtered wave form, the residual power and the correlation coefficient on the projected regression plane of the residual wave signal were used. The residual signal is obtained by

$$\varepsilon(t) = x(t) - \hat{x}(t) \tag{3}$$

Here, x is the measured wave form and $\hat{x}$ is the filtered wave form. Fig. 5 shows the original wave form obtained by MIM and the residual wave form filtered by 10 kHz of the low pass filter. And Fig.6 shows the power spectrum of the original wave. The frequency range of the measured wave form in this case is almost under 6 kHz. The frequency component beyond 15 kHz seems to be generated by the roughness of the concrete surface and mainly appears on the active part. And also 25 kHz is the resonant frequency of the hammer with mass of190 grams.

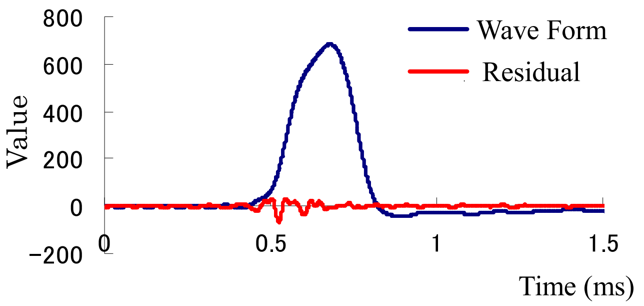


Fig. 5 Filtered and Residual Wave Form

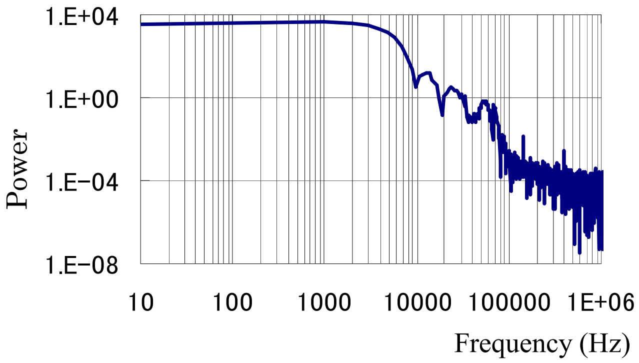


Fig. 6 Power Spectrum of Measured Wave

Fig. 7 shows the residual power versus the cutoff frequency of the low pass filter and Fig. 8 shows the correlation coefficient on the projected regression plane. The regression plane is constructed by the residual value at the time t and $t - \Delta t$. In this figure, the time difference is 50 micro second. The correlation coefficient of the projected regression plane shows that whether specific frequency components are contained in the residual signals or not.

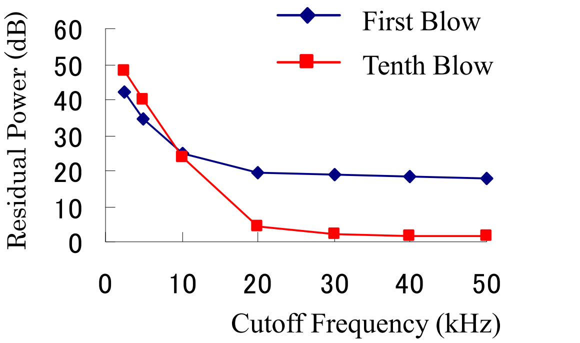


Fig.7 Power of Residuals depends Cutoff Frequency

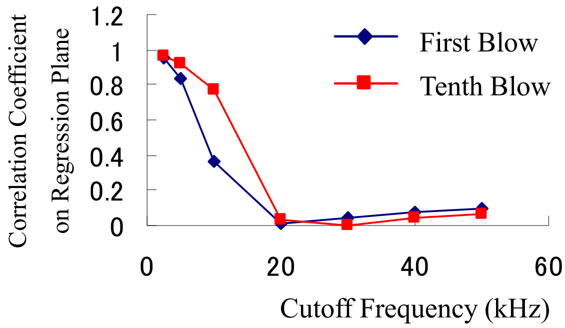


Fig.8 Correlation Coefficient on Regression Plane

In Fig.7 and 8, results of calculations were shown for the first blow and the tenth blow as a comparison. From the results shown in Fig. 7, the residual power becomes larger if the cutoff frequency chosen is less than 20 kHz. Fig. 8 shows the same trend as in Fig.7. This means that the necessary information to obtain the mechanical impedance of the concrete surface is in the frequency range up to 20 kHz. Comparing the first and the tenth blow, the residual powers of the first blow are larger than them of the tenth blow. This is due to the fact that the higher frequency noises were contained during the active process of the hammer blow and it is the same fact that the mechanical impedances of the active part were not stable before the tenth blow as shown in Fig. 4 (a). This is also due to the fact that the higher frequency noises were generated when loosened fine aggregates were broken by the hammer blows. Also, as shown in Fig. 8, if the cutoff frequency comes up to 20 kHz, the correlation coefficient of the projected regression plane suddenly becomes smaller. This means that there is no information on the mechanical impedance for up to 20 kHz.

(4) The effect of hammer mass

The effect of the hammer mass on the accuracy of the strength estimation of matured waterway concrete was also examined in this field experiment. As shown in Fig. 9, the variances of the mechanical impedance were changing by the mass of the hammer. The rebound coefficient and the mechanical impedance of the active part have a trend to become larger in accordance with the hammer mass. However, the mechanical impedance of reactive part becomes smaller when the hammer mass is 412 grams. Variances of the rebound coefficient and the mechanical impedance of active part are mainly induced by the influence of higher frequency noises generated by breaking of the fine aggregates on the surface of the aged concrete. And such influence must be small for the mechanical impedance of reactive part. However, the variance of the mechanical impedance of reactive part becomes higher if the hammer mass is 560 grams as shown in Fig. 9. The reason why such a result is obtained is that if the hammer mass becomes heavier, the broken region by the hammer blow becomes larger.

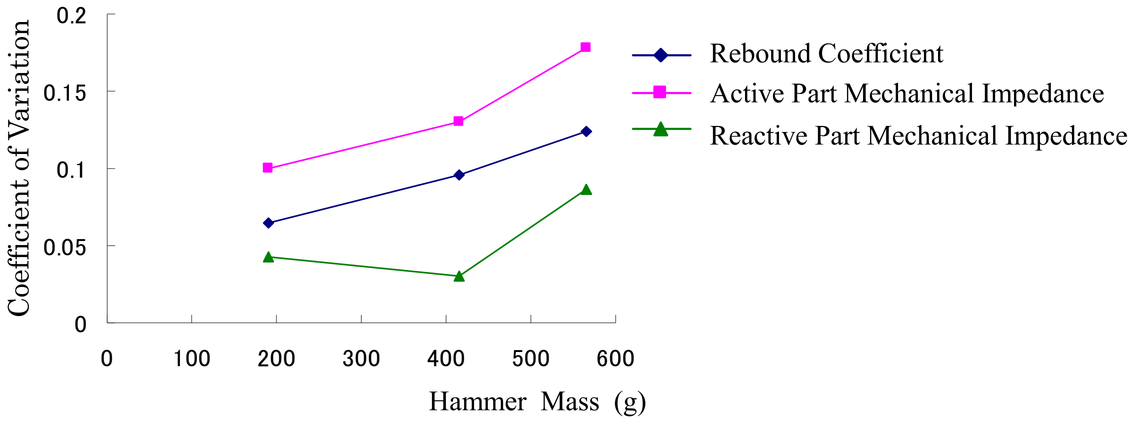


Fig.9 Hammer mass and coefficient of variation

Conclusions

The applicability of the strength estimation by RHM and MIM for the surface deteriorated concrete structure was examined by using the actual mature waterway concrete. If RHM was applied without surface treatment, the variance of the measured rebound value becomes larger and the estimated strength was smaller than the actual strength. In the case of MIM, such trend as obtained by RHM is small and the strength of the concrete could be estimated within the allowable variance if the mechanical impedance of the reactive part is used and several times of blows are employed. The frequency range which usable for strength estimation of the concrete is less than 20 kHz in case of the mass of the hammer is 190 to 566 grams.