Applicability of Mechanical Impedance by Hammer blow for Estimation of Compressive Strength of Concrete*

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Abstract

It is known that the ultimate strain of the concrete within some range of compressive strength is almost 2000 to 2500 micro strain. This means that if the Young's modulus of concrete at a certain strain state is given, the ultimate compressive strength can be estimated by using measured Young's modulus within some accuracy allowance. Through the theoretical consideration and field examination, it is found that the mechanical impedance of the contact surface between hammer and concrete indicates the Young's modulus of the concrete if it is taken into account during reactive phase of the hammer blow. The mechanical impedance can be calculated by dividing the maximum force, when the hammer collides the concrete surface, with the initial velocity of the hammer rebound. This fact simplifies the mechanical impedance measurement process, i.e., the maximum force and rebound velocity can be calculated by using acceleration wave form.

This paper shows the theoretical background of the reactive mechanical impedance measurement and the results of laboratory and field tests on the compressive strength estimation of the concrete. The results of field tests show the accuracy of this method is within 15% for the normal concrete of fifteen to forty N/mm^2 strength range.

Key words: Mechanical Impedance, Young's modulus, Compressive strength, Rebound hammer

1. Introduction

Rebound hammer is commonly used for estimating the compressive strength of structural concrete in nondestructive manner, and Japan has the industrial standard (JIS) to specify the basic dimensions of the Rebound Hammer(1). The Rebound Hammer has more than 60 year history since it was developed by Dr. Schmidt in Switzerland and in Japan it has been used for more than 50 years. During this half century, various researchers and engineers performed many field tests and calibration tests with different considerations to clarify the relationship between rebound value by the Rebound Hammer and the compressive strength of the structural concrete. The basic theory of the Rebound Hammer is energy consume by plastic deformation of the concrete surface when the hammer collides the concrete. Therefore this method tend to be rather destructive test method.

As a substitute to the Rebound Hammer, we developed a method to measure the mechanical impedance or the spring coefficient of the concrete surface by the hammer blow, then estimating the compressive strength of the concrete applying the relationship between this elastic coefficient and strength of it. In this paper, we will call this method the Mechanical Impedance Method (MIM). The theoretical background, the difference between MIM and the Rebound Hammer and accuracy of the strength estimation are discussed.

2. Theory of the Rebound Hammer and MIM

2.1 Rebound Hammer

There are some theoretical difference between MIM and the Rebound Hammer. First of all, the method for generating an active force on to a concrete surface is basically different. In case of the Rebound Hammer, an impact force is generated when hammer collides on the top of a bar (plunger) and this force propagates through the plunger then reaches to the concrete contact point of the plunger. In case of MIM, hammer blows onto the concrete surface directly. Simply said, it is difference of two methods is the direct (MIM) and indirect (Rebound Hammer) blows.

The plunger can be assumed as the 1-dimensinal elastic bar and when the hammer with an initial speed V_0 (it is almost 3.47m/s calculated using the values specified in JIS) collides on the top of the plunger, the particle velocity of the plunger is

$$V_p = \frac{1}{1+\eta} V_0 \tag{1}$$

Where η is the mechanical impedance ratio between hammer and plunger. If two material are the same, the mechanical impedance ratio is in proportion of ratio to their cross sectional areas. If the cross sectional area of the hammer is three times of that of the plunger, the particle velocity of the plunger is estimated as 2.67m/s. The stress and the particle velocity are in proportional relationship for a plane wave as shown

$$\sigma = \rho c V \tag{2}$$

Where ρc is called the acoustic impedance, with ρ as the density, c as the elastic wave speed of the material. For structural concrete, if ρ were 2,300kg/m^3 and c were 4,000m/s the stress caused on the surface is calculated as about 25N/mm^2. If it is high compressive strength concrete, this value may not be strong enough to cause any destructive deformation to it Figure 1 shows the wave form of the top of the plunger when the hammer collides given by the stress wave equation, the end of the plunger here is supported by spring like concrete surface. The spring coefficient of the concrete surface is

$$K = 2\pi R H_B \tag{3}$$

Here R is the radius of the spherical plunger tip and H_B is Brinell hardness of the concrete. The 200N/mm^2 was used as the Brinell hardness of the concrete and this value indicates the compressive strength of 38N/mm^2 which is in accordance with Taniguchi's research results(2). As shown in Fig.1, the maximum force at the plunger top is 20kN and the reflected force is minus 26kN. It means that the point resistance of the plunger toe is too weak to produce the compressive force for making the hammer rebound. That is, if only Brinell hardness oriented resistance were working at the toe of the plunger, hammer is never rebounded. Fig.2 shows the calculated wave form where the spring coefficient is 400 times stiffer than in the case of Fig.1. It is easy to understand that both wave forms, before when the reflected wave at the toe of the plunger reaches the top of the plunger, are exactly the same. However, after 40 micro second spot, the wave forms are changed. If the spring coefficient value is larger, compressive force in reflected wave becomes larger and this results increase the possibility of the hammer rebound. Fig.3 shows the relationship between the spring coefficient of the concrete surface and rebound value calculated by the stress wave theory. The rebound value is calculated as the ratio of the impulse before and after 40 micro second, therefore these are not exactly theoretically accurate rebound values. However, it is obvious that the rebound value increases when the spring coefficient increases. And it seems that the rebound value shows the tendency to converge to the maximum limit value. This concludes that the Rebound Hammer is not suitable for estimating the compressive strength of the high strength concrete.

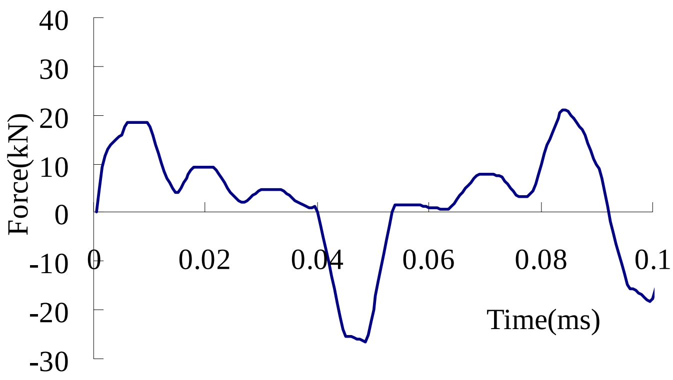

Fig.1 Calculated wave form of force on the top of plunger.
Plastic resistance

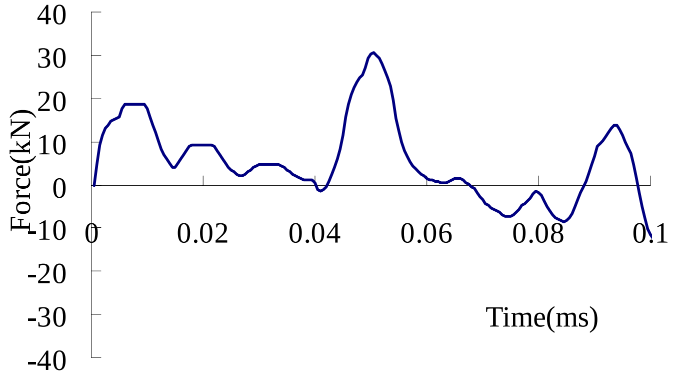

Fig.2 Calculated wave form of force on the top of plunger.
Elastic spring resistance

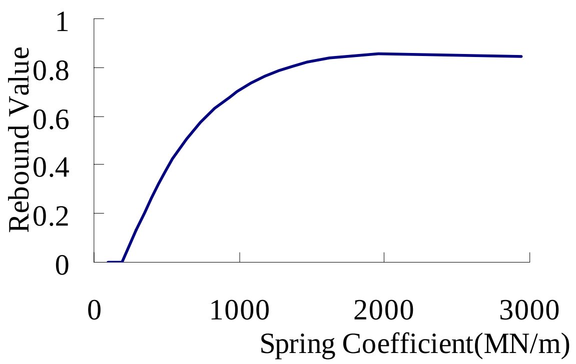

Fig.3 Relationship between spring coefficient and rebound value

2.2 Theory of MIM

In case of MIM, the hammer directly collides with the concrete surface with no plunger. The stress occurred on the concrete surface is in proportion with the product of the initial speed of the hammer and the acoustic impedance of the concrete.

$$\rho c = \frac{\sigma}{V} \tag{4}$$

However, it is not possible to measure the stress of the concrete surface directly. Therefore we employ the method to measure mechanical impedance of the hammer and concrete contact plane for determining the string coefficient of the concrete. If the initial speed of the hammer when it collides with the concrete surface is V_0 and mass of the hammer is M, the kinetic energy of the hammer is,

$$E_H = \frac{1}{2} M V_0^2 \tag{5}$$

And the potential energy of the concrete surface is

$$E_C = \frac{1}{2} K D_{\max}^2 \tag{6}$$

Here K is the spring coefficient, and $D_{\max}$ is the maximum elastic displacement of the concrete surface. From the energy equilibrium law, both energies should be equal then,

$$M V_0^2 = K D_{\max}^2 = \frac{F_{\max}^2}{K} \tag{7}$$

And considering the Hooke's law ($F=KD$), Eq.(7) becomes

$$K = \frac{1}{M} \frac{F_{\max}^2}{V_R^2} \tag{8}$$

Thus, it is clear that the spring coefficient of the concrete surface can be obtained by Eq.(8) if the maximum force $F_{\max}$ and initial speed of the hammer V_0 are measured. We install an accelerometer on the hammer body for measuring the maximum force and hammer speed as shown in the equations below.

$$\left.\begin{aligned} F_{\max} &= M A_{\max} \\ V_R &= \int_T^{\infty} A(t)dt \end{aligned}\right\} \tag{9}$$

Here A is the acceleration of the hammer. In Eq.(8) the hammer speed is denoted as V_R, One of main characteristics of MIM is measuring the hammer speed during the rebound phase, while avoiding the influence of energy loss caused by the plastic deformation of the concrete surface. T is the time when the force reaches its maximum value. At this moment, the elastic displacement of the concrete surface becomes maximum value and the hammer is just stopped to change the moving direction form downward to upward. MIM measures the spring coefficient of the concrete surface during when hammer is moving downward (Active phase) and moving upward (Reactive phase). The spring coefficients ratio between active and reactive phase indicates the degree of deterioration (plasticity) of the concrete surface. This is the second characteristics of MIM.

2.3 Estimating the compressive strength by MIM

From the theoretical consideration, the spring coefficient of the concrete surface is given by both Rebound Hammer and MIM. Next problem to be solved is estimating the compressive strength of the concrete by using the indexed values of the spring coefficient. The compressive strength of the concrete is the value when it is in ultimate plastic condition, where as the spring coefficient is the characteristics in the elastic region.

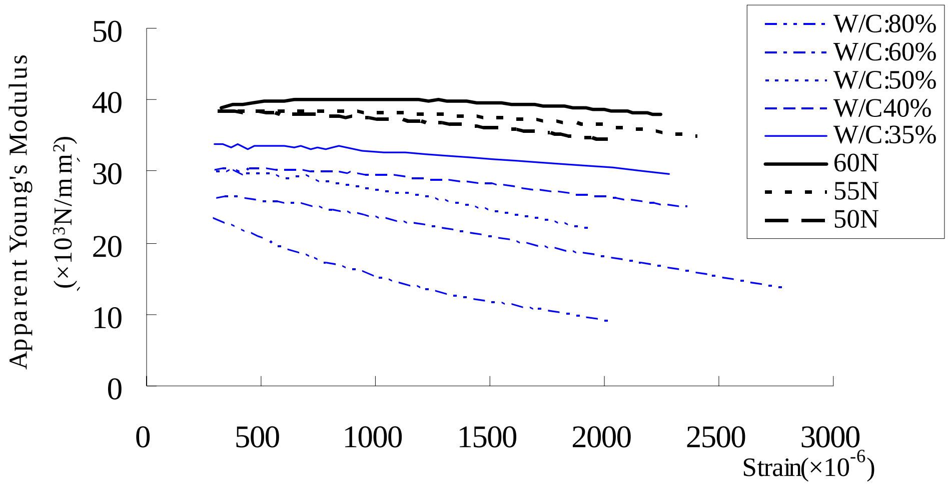

Fig.4 Strain and young's modulus of concrete

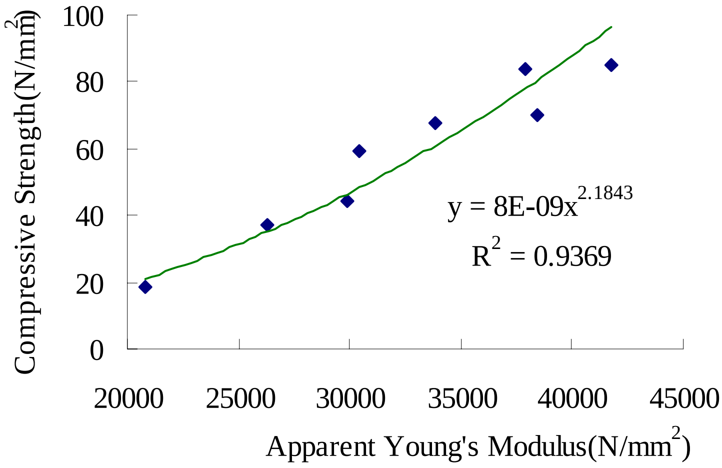

Fig.5 Relationship between the apparent Young's modulus at 200 micro strain and Compressive strength

Fig.4 shows the relationship between the strain and Young's modulus as secant incline of the stress strain curve of the concrete for different types of concrete. In Fig.4, two facts are found; one is that the maximum strain of the concrete will be between 2,000 to 2,500 micro strains regardless of a kind of the concrete, and the other is that strain dependency of Young's modulus of the concrete becomes smaller for higher strength concrete.

From this fact, if Young's modulus were given, compressive strength of the concrete will be given

$$\sigma_U = \varepsilon E \tag{10}$$

The spring coefficient is given, instead of Young's modulus, by MIM. Therefore the compressive strength of the concrete will be estimated by

$$\sigma_U = aK \tag{11}$$

However, in case of the Rebound Hammer there are no linear relations between the rebound value and the spring coefficient of the concrete, Eq.(9) should be rewritten as

$$\sigma_U = bf(R) \tag{12}$$

Here a,b are proportion coefficients, and R is the measured rebound value. In case of the MIM, the accuracy of the estimated compressive strength is within 11% depending on the error of used and actual maximum strain. The dependency of apparent Young's modulus of the concrete is larger for weak concrete; therefore the correction factor should be introduced. In Fig.5, the compressive strength shows a tendency of becoming large in accordance with square value of the apparent Young's modulus at 200 micro strains.

2.4 Speed dependency of impact force

The previous discussion was based on the vibration theory of mass spring system. However, the speed dependency characteristics of the mass - elastic body system should be considered. The maximum force value depends on the initial speed of the hammer to the power 1.2 as well known as the Hertz's law. This fact means that it is necessary to modify the equations of the mechanical impedance measurement.

To make clarify this phenomenon, the experimental study was performed using the test anvil made from MC nylon with various initial velocities of the hammer. Figure 6 shows the typical wave form of the hammer acceleration. The wave form is almost in line symmetry as the shape of hanging temple bell.

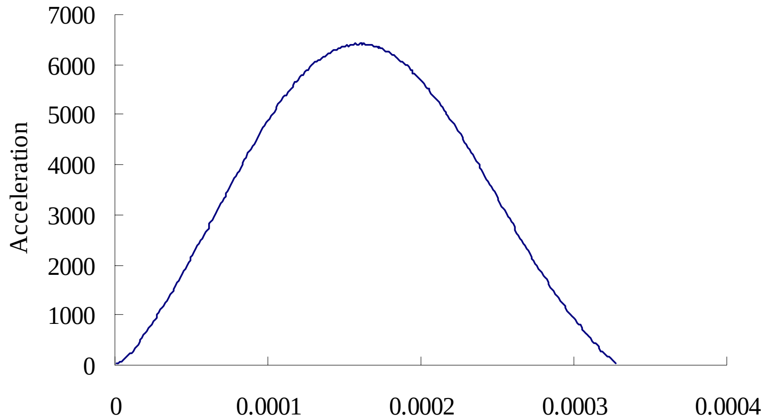

Fig.6 The typical wave form of the hammer acceleration for MC nylon

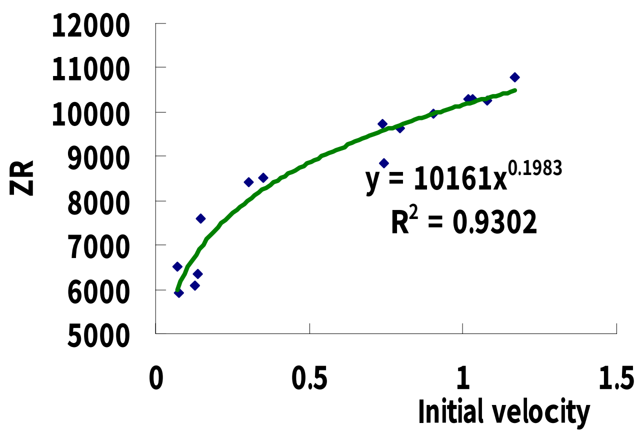

Fig.7 Relationship between Z_R and initial velocity

Figure 7 shows the relationship between the mechanical impedance of the reactive portion and the initial speed of the hammer. Here, the mechanical impedance depends upon the initial speed to the power 0.198. and it can be said that the value of 0.198 is the actualized value of the theoretical value of 0.2.

2.5 Estimation of compressive strength of concrete by MIM

The experimental works to find the relationship between the index value of the mechanical impedance of reactive phase (Z_R) and the compressive strength of the actual concrete were performed using concrete specimens of 0.5m width and length and 0.2m thickness, with the designed strength range of 15N/mm^2 to 36N/mm^2 stepping 3N/mm^2. Three test pieces for each designed strength specimens were made and cores of 0.1m diameter 0.2m length were drilled out from the each specimen. After MIM tests, uni-axis compressive tests were performed on there test pieces.

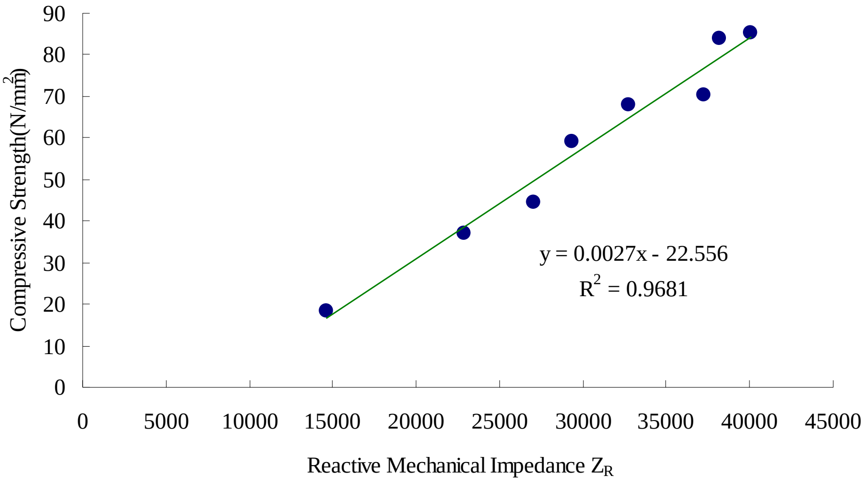

Fig.8 Relationship between compressive strength and Z_R

Fig.8 shows the relationship between the corrected Z_R and the compressive strength of the concrete. And it signifies the higher correlation between them is obtained. Therefore it is concluded that the corrected index value Z_R can be the index value of the compressive strength of the concrete.

3. Conclusion

The driving mechanism of the Rebound Hammer was analyzed by using the numerical solution of the stress wave equation. It is found that the rebound value of the Rebound Hammer depends on the spring coefficient of the concrete surface. That is, both of MIM and the Rebound Hammer have the same way of estimating the concrete strength. The both methods are measuring the spring coefficient related value and then estimate the strength of the concrete. However, the difference of the driving mechanisms in two methods brings out a substantial influence on the accuracy of the strength estimation. In case of the Rebound Hammer which has indirect driving system, there is some limitation of the maximum force; therefore it seems to cause some difficulty on applying to the high strength concrete. And also because of non linear relationship between the rebound value and the spring coefficient of the concrete surface, it seems that more discussions is necessary on the accuracy of strength estimation by the Rebound Hammer. In case of MIM, the direct driving system is employed and the spring coefficient of the concrete is measured directly. The high applicability for estimation of the high strength concrete is obtained.

4. References

(1) JIS A 1155, Method of measurement for rebound number on surface of concrete, Japanese Standards Association , (2003)

(2) Taniguchi, H, Study on Estimating Method for Concrete Strength by Test Hammer, Report of Technical Research Institute of Sumitomo Mitsui Construction, No.5, (2007)