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Estimation of Compressive Strength of Concrete Structures by the Impact Elastic Wave Method *

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Abstract

The test method for estimation of compressive strength of concrete structures by Impact elastic wave method is effective because it is able to evaluate directly and repeatedly the quality of structures. In this test method, the velocity of elastic wave is measured and the compressive strength of concrete is estimated from the relational expression which is calculated by relation between the velocity and the compressive strength. In this paper, firstly, to investigate the relation between the velocity and the compressive strength in case of different mix proportions, the velocity and the compressive strength of cylinder specimen were measured in 32 kinds concretes with different mix proportions. Secondly, to investigate the influence by reinforcing bar when the velocity of elastic wave is measured in reinforced concrete structures, various measurements were performed in concrete plate specimen. Thirdly, the measuring method for velocity of elastic wave which is applicable to deterioration assessments of established concrete structures was studied. From the results of above three experiments, the study for making the methodology and the applicable condition clear about this method was discussed. This paper reports on the results of this study.

Key words: Non Destructive Test, Concrete Structure, Impact Elastic Wave Method, Compressive Strength, Velocity

1. Introduction

Impact elastic wave method is known as Impact-Echo method and it is a non destructive test method for concrete structures. Impact elastic wave method has mostly been used for measuring thickness of concrete or for detecting flaws within concrete (1). In this paper, the test method for estimation of compressive strength of concrete structures by Impact elastic wave method has been studied. In general, the quality control about compressive strength of concrete structures has mostly been performed by compressive strength test of cylinder specimen or coring test. In these tests, it is an issue that the test of cylinder specimen is an indirect evaluation and the coring test is destructive test. On the other hand, the non destructive test method is effective because it is able to evaluate directly and repeatedly the quality of structures. However, in non destructive test, if the methodology and the applicable condition are not known well, the results of test would have a large range of error.

This paper reports on the result of study which is discussed from three experiments for making the methodology and the applicable condition clear about the method for estimation of compressive strength of concrete structures.

2. Measurement Principle

It is well known that velocity of elastic wave V_P is represented by Eq.(1)

$$V_P = \sqrt{\frac{E}{\rho}\frac{(1-\nu)}{(1+\nu)(1-2\nu)}} \qquad (1)$$

Where E is modulus of elasticity, ρ is density and ν is Poisson's ratio. Then, the modulus of elasticity E and the compressive strength f_C are able to link by the relational expression which is shown by Eq.(2) (2).

$$E = a \cdot f_C^{\,b} \qquad (2)$$

Where a and b are coefficient. The coefficient a and b are changed by unit weight, it is conceivable that the coefficient a and b are changed by difference of mix proportions of concrete. From Eqs.(1) and (2), the relational expression which is shown in Eq.(3) hold true.

$$f_c = \left\{\frac{\rho(1+\nu)(1-2\nu)}{a(1-\nu)}\right\}^{1/b} \cdot V_P^{\,2/b} = k\,V_P^{\,\alpha} \qquad (3)$$

Where k and α are coefficient. This relationship indicates that the compressive strength is a exponent function of the velocity of elastic wave, and it is conceivable that if the velocity of elastic wave is measured in concrete structure, the compressive strength of concrete structure will be able to estimated by the relational expression shown in Eq.(3).

3. Relation between compressive strength of concrete and velocity of elastic wave

3.1. Experiment description

To investigate the relation between the velocity and the compressive strength in case of different mix proportions, the velocity and the compressive strength of cylinder specimen were measured in 32 kinds concretes with different mix proportions. Table 1 shows the number of sets of measured specimens in each nominal strength and types of cement. It explains the types of cement as follows.

N: ordinary portland cement
BB: portland blast-furnace slag cement typeB
H: high-early-strength portland cement
L: low-heat cement

Table 1 Numbers of sets of specimens

types of cement / nominal strength	N	BB	H	L
24	2	3	2	2
27	1	3	1	1
30	3	2	1	0
36	2	1	3	1
40	2	2	0	0

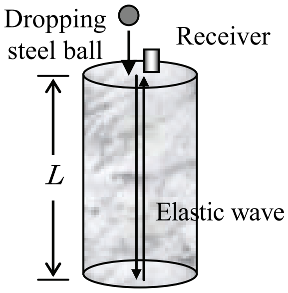

Fig.1 Measurement situation of velocity in cylinder specimen

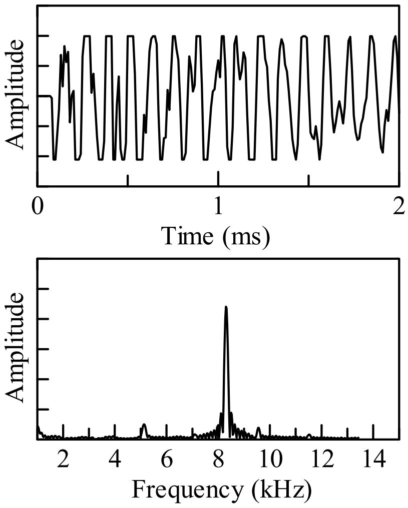

Fig.2 Example of recorded waveform and spectrum

Twelve specimens per a set were manufactured. The velocity and the compressive strength of the cylinder specimen were measured four times in different material ages. The material ages when the measurement was performed were 3day, 7day, 28day, 91day in cement type H, and 7day, 14day, 28day, 91day in another cement types. The measurement situation of the velocity of elastic wave in the cylinder specimen is shown in Fig.1. The elastic wave is introduced into the concrete by impact at the surface of concrete from dropping steel ball. The elastic wave propagates into the concrete, and undergoes reflection and reflection at an interface. The elastic wave was recorded by the receiver which was positioned at a distance less than 30mm away from the impact, the frequency with which elastic wave was reflected, f_0, was measured by the frequency analysis. The example of recorded waveform and spectrum are shown in Fig.2. The velocity of elastic wave was calculated from the measured frequency, f_0, and length of the specimen, L, as shown in Eq.(4).

$$V_P=2\cdot f_0\cdot L \qquad (4)$$

3.2. Result and Discussion

The relations between measured compressive strength and measured velocity at each nominal strength are shown in Fig.3. As the velocity increases, the compressive strength increases. However, such as the compressive strength is distributed from 30 to 70 N/mm^2 in

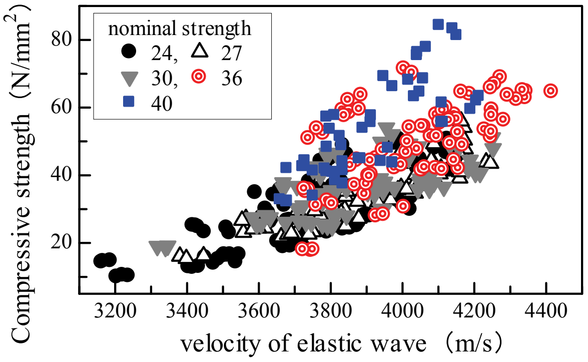

Fig.3 Relations between compressive strength and velocity at each nominal strength

Table 2 Relations between compressive strength and velocity at each mix proportion

Structure Name	A	B	C	D	E
Mix proportion	24-8-25BB	27-8-20BB	30-8-20N	36-15-20H	40-12-25N
Correlation coefficient	0.992	0.963	0.955	0.984	0.990
Coefficient: α	4.851	5.048	4.772	6.056	4.815
Coefficient:k	1.525×10^{-16}	2.648×10^{-17}	2.369×10^{-16}	7.120×10^{-21}	2.803×10^{-16}

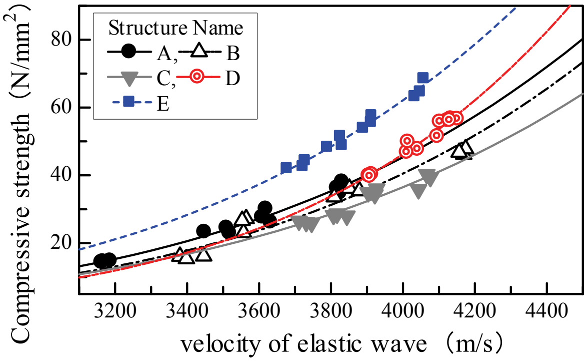

Fig.4 Relations between compressive strength and velocity at each mix proportion

4000m/s of the velocity of nominal strength 36, there are poor correlations between the compressive strength and the velocity. Then, one mix proportion was selected at each nominal strength, the relations between measured compressive strength and measured velocity at each mix proportion were investigated. The results are shown in Table 2 and Fig.4. The results show strong correlations between the compressive strength and the velocity, the relational expression which is shown in Eq.(3) are obtained by the least-square method. As shown in above, the relations between compressive strength of concrete and velocity are changed by difference of mix proportions. It is presumed that the cause of this change is due to coefficient which are shown in Eq.(2) are changed by difference of mix proportions. To estimate compressive strength of concrete structures in narrow range of the error, it is essential that the relational expression is calculated by the measured velocity and the compressive strength of cylinder specimen with which mix proportion is equal to tested concrete structures.

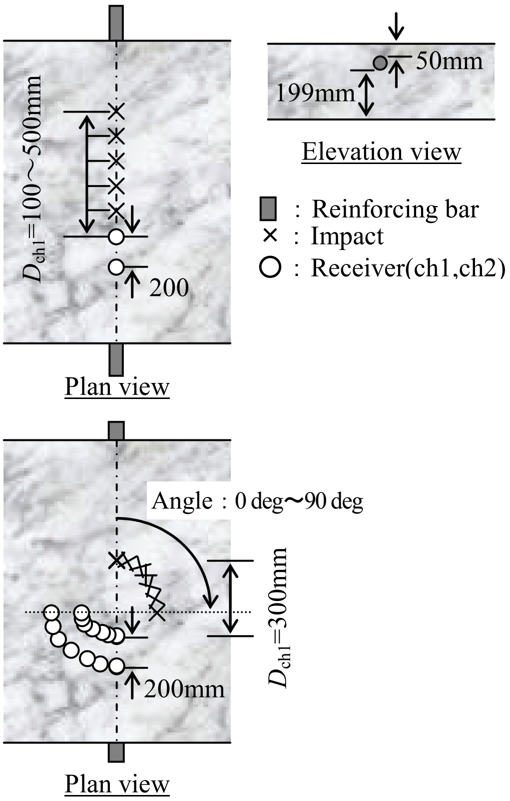

Fig.5 Measurement configuration for study on influence by reinforcing bar

4. Study on influence by reinforcing bar

4.1. Experiment description

To investigate the influence by the reinforcing bar when the velocity of elastic wave is measured in reinforced concrete structures, various measurements were performed in the concrete plate specimen. The measurement configuration is shown in Fig.5. First, the impact point source and 2 points receiver were located immediately above the reinforcing bar, the velocities were measured in several distances, D_{ch1}, between impact point and point of the receiver ch.1. The velocities were measured on the upper side and downside of the concrete, so the covering depths are 50mm and 199mm. Secondly, the measuring lines which is connected impact point source and 2 points receive were located on the upper side of the concrete, and the velocities were measured in several angles formed by the meeting of the measuring lines with the reinforcing bar. The measurement situation of the velocity of elastic wave in concrete plate specimen is shown in Fig.6. The elastic wave generate by dropping steel ball propagates at the surface of concrete plate.

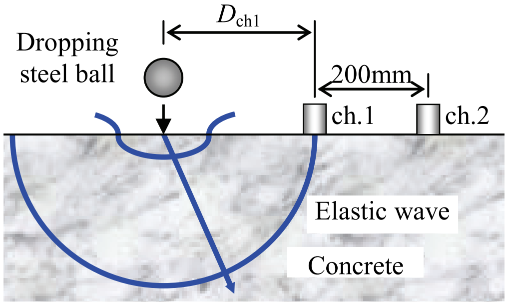

Fig.6 Measurement situation of velocity in concrete plate specimen

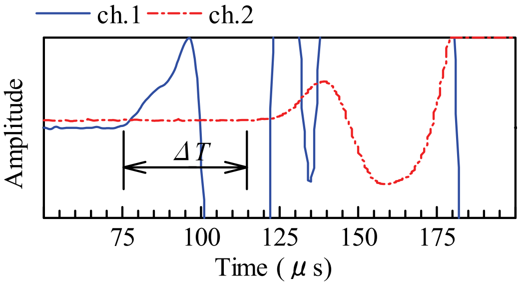

Fig.7 Example of recorded waveforms

The elastic wave was recorded by the receivers which were positioned at the surface of concrete plate. From the recorded wave forms , the difference of time to propagate the distance from ch.1 to ch.2, $\varDelta T$, was measured. The example of recorded waveform are shown in Fig.7. The velocity of elastic wave was calculated from the measured $\varDelta T$, and distance from ch.1 to ch.2.

4.2. Result and Discussion

In several distances between impact point and receive point, example of the waveforms of ch.2 are shown in Fig.8, the results of the velocities are shown in Fig.9. When the covering depth is 199mm the measured velocity was not change by D_{ch1}. On the other hand, when the covering depth is 50mm the measured velocity was change by D_{ch1}, the measured velocity was about 4000m/s when the D_{ch1} was 100mm, and when the D_{ch1} were 300mm or more, the measured velocity were about 5500m/s. Then, the results of the velocities are shown in Fig.10 in several angles formed by the meeting of the measuring lines with reinforcing bar. The measured velocity was change by the angle, the measured velocity was about 5500m/s when the angle was 10 deg or less, and when the angle was 45 deg or more, the measured velocities were about 4000m/s. From the above-mentioned results, when the covering depth is 50mm, D_{ch1} were 300mm or more, and the angle was 10 deg or less, it is confirmed that the reinforcing bar affects the measured velocity. The discussion about the cause of this influence is shown below.

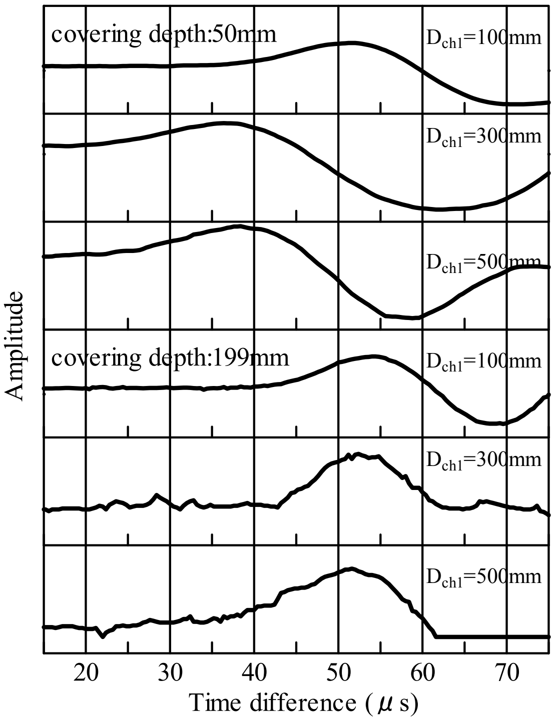

Fig.8 Example of waveforms of ch.2 for measurement velocity in several distances

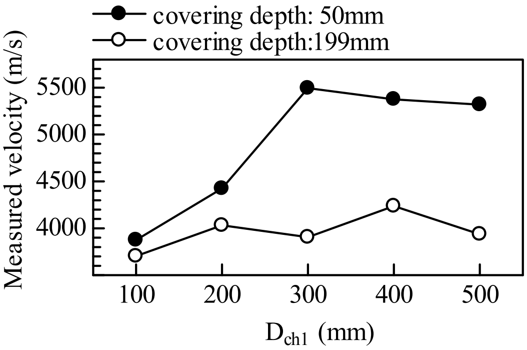

Fig.9 Measured velocity in several distances

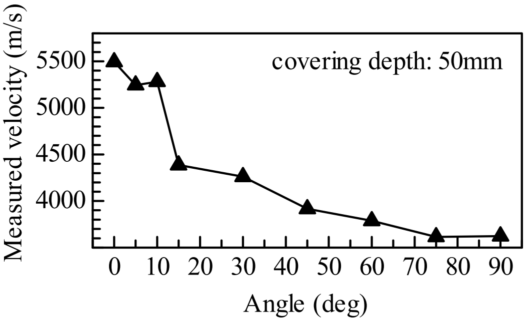

Fig.10 Measured velocity in case of angle changes

The pattern diagram of the propagation situation of elastic wave in reinforced concrete based on Snell's law is showed Fig.11. The travel time of elastic wave which propagate surface of concrete, T_{PC} , and the travel time of elastic wave which go by way of reinforcing bar, T_{PS} ,are given by the following equation:

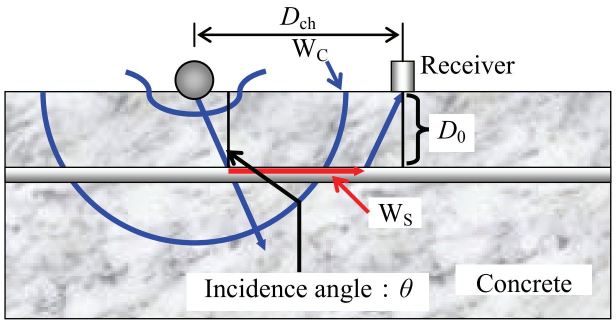

Fig.11 Pattern diagram of propagation situation of elastic wave in reinforced concrete

$$T_{PC} = \frac{D_{ch}}{V_{PC}} \qquad (5)$$

$$T_{PS} = \frac{2D_0}{V_{PC} \cdot \cos\theta} + \frac{D_{ch} - 2D_0 \tan\theta}{V_{PS}} \qquad (6)$$

where
D_{ch} : distance from impact to receiver
W_C : elastic wave which propagate surface of concrete
V_{PC} : velocity of W_C
W_S : elastic wave which go by way of reinforcing bar
V_{PS} : velocity of W_S
D_0 : shortest distance from impact/ receiver to reinforcing bar
$\theta = \sin^{-1}(V_{PC}/V_{PS})$

From the relationship between Eqs.(5) and (6), in case that the condition is shown in Eq.(7), T_{PC} and velocity of W_C are measured without influence of reinforcing bar.

$$D_{ch} < \frac{2D_0\sqrt{V_{PS}^{\ 2} - V_{PC}^{\ 2}}}{V_{PS} - V_{PC}} \qquad (7)$$

On the other hand, in case that the D_0 which is calculated by the covering depth and the angles formed by the meeting of the measuring lines with reinforcing bar is short as compared to the D_{ch}, the reinforcing bar affects the measured velocity. From the above-mentioned results, to measure the velocity of concrete without influence of reinforcing bar, if the case where covering depth is not measured is assumed, it is effective that the measuring line is set up at high angle to reinforcing bar.

5. Measurement of velocity and estimation of compressive strength in concrete structure

5.1. Measurement of velocity in concrete structure

In newly - established structure A, B, C, D shown in Table 2, and in structure F of which material age is around 30 years, the velocities of concrete were measured. The measurement situation of the velocities is shown in Fig 12. Impulse hammer was used as the impact source. From the recorded wave forms by the impulse hammer and the receiver, the difference of time to propagate the distance from impulse hammer to receiver , $\varDelta T$, were measured. The velocity of elastic wave was calculated from the measured $\varDelta T$ and the distance from the impulse hammer to the receiver, D_{ch}. D_{ch} were changed from 200mm to 1000mm. And, in consideration of influence by reinforcing bar showed in §4.2, the measuring line which is connected the impact point and the receiver was set up at around 45deg angle to the vertical reinforcement and the horizontal reinforcement.

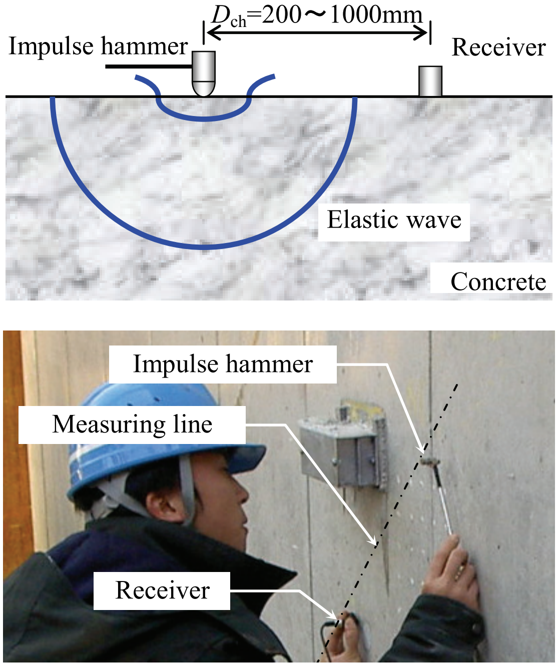

Fig.12 Measurement situation of the velocity of elastic wave in concrete structure

The examples of measured velocities at each distance are shown in Fig.13. In newly-established structure A, B, C, and D , the measured velocities were not changed by D_{ch}. On the other hand, in structure F of which material age is around 30 years, the measured velocities were changed by D_{ch}. It is presumed that the cause of this change is due to difference between the velocity of surface of concrete and the velocity of internal of concrete. In newly-established structures, there is little difference between the velocity of surface of concrete and the velocity of internal of concrete. In this case, the elastic wave which propagate surface of concrete arrives at receiver fastest in any D_{ch}, so ΔT is measured from the elastic wave which propagate surface of concrete at all D_{ch}. On the other hand, in structure F, the surface of concrete was deterioration as shown in Fig.14. In this case, it is predicted that the velocity of surface of concrete is slower than the velocity of internal of concrete, and the passage of the elastic wave from which ΔT is measured is different depending on D_{ch}. As is the case in Fig.11, in case that D_{ch} is short, the elastic wave which arrives at receiver fastest is the elastic wave which propagate surface of concrete. On the other hand, in case that D_{ch} is long, the elastic wave which arrives at receiver fastest is the elastic wave which go by way of internal of concrete, and ΔT is measured from this elastic wave. From the above-mentioned results, it is expected that the deterioration in surface of concrete is detected by the measuring velocities in several distances from impact to receiver and the

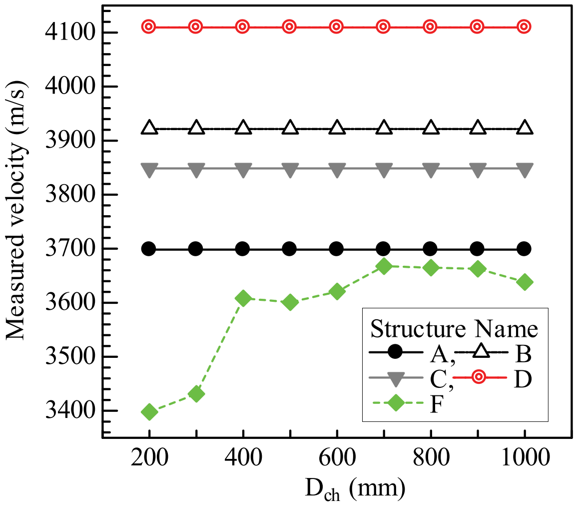

Fig.13 Examples of measured velocities at each distance

Fig.14 Core sample of Structure F

comparison of measured velocities at each distance.

5.2. Estimation of compressive strength in concrete structure

In newly - established structure A, B, C, and D, the compressive strengths were estimated from the measured velocities and the relational expressions which were obtained by measured velocity and compressive strength shown in §3.2. The obtained coefficients α and k of relational expressions are shown in Table 2. Figure 15 shows the comparison of the estimated compressive strengths with the compressive strengths by coring test. It appears that the compressive strengths are estimated by this method within around 15 percent range of error.

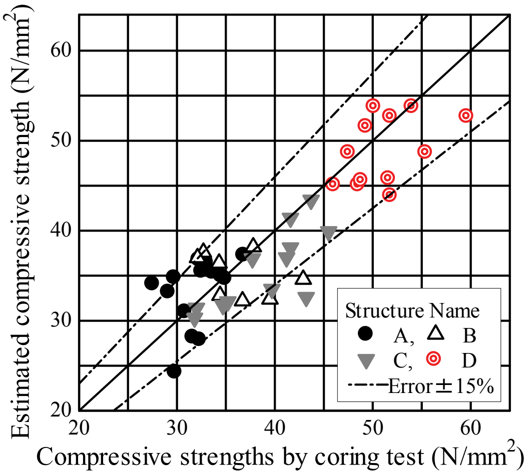

Fig.15 Confirming the error in the test

6. Conclusions

In this paper, the relation between the velocity and the compressive strength of concrete, the influence by reinforcing bar in measuring velocity of elastic wave of reinforced concrete, and, the measuring method for velocity of elastic wave in established concrete structures were discussed. Results are concluded as follows:

1) The relation between the compressive strength of concrete and the velocity of elastic wave are changed by difference of mix proportions. Therefore, it is essential that the relational expression is calculated by the measured velocity and the compressive strength of cylinder specimen with which mix proportion is equal to tested concrete structures.

2) The influence by reinforcing bar is generated by the shortest distance from measuring points to reinforcing bar. The shortest distance is calculated by the covering depth and the angles formed by the meeting of the measuring lines with reinforcing bar. To measure the velocity of concrete without influence of reinforcing bar, it is effective that the measuring line is set up at high angle to reinforcing bar.

3) In concrete structure with which surface is deterioration, the measured velocity is changed by distance from impact to receiver. Therefore, it is expected that the deterioration in surface of concrete is detected by the measuring velocities in several distances from impact to receiver and the comparison of measured velocities at each distance.

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