ESTIMATION OF COMPRESSIVE STRENGTH TO IDENTIFY LOW-STRENGTH CONCRETE WITH NON-DESTRUCTIVE TEST METHODS

非破壊検査手法を用いた低強度コンクリートの強度推定

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This study involves non-destructive test (NDT) methods for concrete compressive strength estimation to identify very low-strength concrete (≤ 9 MPa) in existing buildings in developing countries. Surface hardness and pin penetration resistance methods are focused. The influence on calibration equations of surface hardness procedures due to differences in aggregate and surface roughness of the tested concrete are observed with experimental methods. The influence of the two parameters is found negligible when estimating the compressive strength of very low-strength concrete. A new pin penetration resistance method, with a wood tester is verified on concrete. The method is found to be applicable to identify low-strength concrete and is useful in the local condition of Bangladesh. Finally, an application method of screening the low-strength concrete buildings is proposed including concrete classification chart for conservative estimation of compressive strength.

Keywords: *Non-destructive test (NDT), Compressive strength, Surface hardness, Penetration resistance.*
非破壊検査手法, 圧縮強度, 表面硬度, 貫入抵抗

1. Introduction

Compressive strength of concrete is one of the most important input parameters while investigating concrete structure during its service life. Evaluation of compressive strength with non-destructive tests (NDTs) has gained popularity due to its rapidity and simplicity. NDTs can evaluate concrete directly in the structure which is not possible by the compression test of molded cylindrical specimen. Also, NDTs are easier and more economical than core tests. A known relationship with compressive strength and an NDT parameter is necessary. These relationships may get affected by various factors such as a difference in aggregate, surface conditions, moisture conditions, cement type, etc. [1]. Basically, the relationships established between an NDT method and compressive strength by past researchers are empirical, and no universal method is yet available.

Considering the case of Bangladesh, a developing country in southeast Asia, uses brick chips as coarse aggregate for producing concrete which is weaker than stone aggregate. Brick chip aggregate might influence the NDT results to be different from that of stone aggregate concrete. Recent studies have also found the existence of very low-strength concrete in existing buildings [2]. The country is exposed to the threat of future major earthquakes as it is in a tectonically active region between the Indian and Eurasian plate boundary. Incidents of collapse of readymade garment factory buildings without an earthquake due to substandard concrete material is also a known fact. Therefore, finding an appropriate NDT method to identify the low-strength concrete buildings in Bangladesh is necessary.

The presence of large number of buildings renders a detailed seismic investigation impossible. The existing guidelines of seismic evaluation designate concrete with compressive strength no more than 13.5 MPa as low-strength concrete. Concrete having compressive strength less than 9 MPa is regarded as unfit for seismic evaluation with the existing formulas [3]. Therefore, as a first step, it is necessary to identify the concrete buildings having a compressive strength ≤ 9 MPa. This concrete can be termed as very low-strength concrete. Identifying or screening these vulnerable buildings having very low-strength concrete with easy NDTs is necessary.

The study aims at selecting easy, economical, and effective NDTs for screening the low-strength concrete buildings in developing countries with appropriate calibration equations by considering the effects of influential parameters. Rebound hammer (Type L) and a scratching test device is used as surface hardness methods. A pin penetration tester, Pilodyn is used for penetration resistance test. Effect of aggregate type and the surface roughness are studied as influential parameters. Finally, a step by step screening method is developed for application in developing countries.

2. Experimental outline

In this study, experiments are performed to obtain calibration equations of the selected NDTs. Specimens are prepared to observe the effect of type of aggregate and the effect of surface roughness on the surface hardness methods. Field tests are performed in Bangladesh and Sri Lanka. Laboratory tests are performed in Japan. Applicability of the pin penetration device is assessed by performing a series of trial tests.

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2.1. Surface hardness test methods

The most popular method for surface hardness testing of concrete is the rebound hammer,. which was developed by Ernst Schmidt in 1948. Older versions measure a rebound number *R*. Rebound number is the mechanical travel of the mallet on rebound of a spring-loaded piston. The newer versions record rebound quotient *Q,* which is measured from the velocity of impact and the rebound immediately before and after the impact. The formula of *Q* is, $Q = (v_r^2/v_0^2) * 100$, where v_0 indicates the velocity reached by hammer before impact and v_r is the velocity of hammer mass after impact. The determined rebound quotient is independent of the hitting direction unlike the original rebound number. Rebound hammer test was performed on the test specimens following JIS A 1155 (based on ISO 1920-7). The device is shown in Fig. 1a.

Scratching test is another surface hardness testing method in this study. The device is developed by Japan Society for Finishing's Technology and certified by Japan Floor Coating Industry [4]. It is a simple tester that can scratch the concrete surface at a constant angle with loads of 1 kgf and 0.5 kgf with two carbide tungsten alloy pins. The pins are inserted in a rectangular prism made of plastic material. Spring coils inside the device performs the load adjustment. The width of the grooves made by scratching is measured to relate the compressive strength of concrete. In this study, the groove widths made with 1kgf load is considered. The device is shown in Fig. 1b.

a. Rebound hammer

b. scratching test

c. pin penetration tester "Pilodyn"

Fig. 1 Non-destructive test devices

2.2. Penetration resistance test methods

For penetration resistance test, a pin penetration device "Pilodyn" is used which is basically a wood tester. Testing with the device involves injecting a spring-loaded pin into the target surface of concrete by shooting and reading the depth of needle penetration from a digital recorder. Three types of pins were used, sharp pin with 2.5 mm and 3.5 mm diameters, and flat pin with 2.5 mm diameter. The measurement capacity of the device is 40 mm, like the length of the pin, with an accuracy of 0.1 resolution. The device can be handheld, with a body of 345 mm length and 50 mm diameter, weighing 900 grams. The pins are not damaged easily when the concrete strength is lower. Therefore, applicable on low-strength concrete. The device is shown in Fig. 1c.

2.3. Test specimens

At first, the effect of different types of aggregates are observed on the surface hardness methods. Thus, different aggregates are used for making concrete specimens of rectangular prism with high water cement ratio (0.6 – 2) for making low-strength concrete. The aggregates are, low strength brick chips (LB), normal strength brick chips (NB), crushed stone (CS), lightweight aggregate (LW), and Recycled aggregate (RA). Field surveys were performed in Bangladesh and Sri Lanka on stone aggregate and brick aggregate concrete buildings. The data contains minimum compressive strength 1.02 MPa from a laboratory specimen and a maximum compressive strength of 39.25 MPa of core sample from the field survey in Bangladesh.

To observe the effect of surface roughness 8 stone aggregate concrete rectangular prism specimens are made. Three different surface conditions are made on each specimen manually by chipping. The specimens are tested on different ages to obtain data for different ranges of compressive strength. Roughness is quantified using 3D scanning. The arithmetic mean height S_a of three surfaces is calculated to quantify the surface roughness.

The aim of performing the penetration resistance test with "Pilodyn" was to check the applicability of the device on concrete because the device is basically a wood tester. A series of trial tests have been performed with various test specimens, such as, brick aggregate concrete cylinders, stone aggregate concrete rectangular prisms, and cubes. Another usefulness of the device is that it can be used through a plaster mortar layer by drilling holes. The plaster mortar layer is a finishing layer on the concrete surface, mostly common in Bangladesh. While performing a field test to identify the low-strength concrete, this finishing layer needs to be removed. However, if the owner is reluctant to permit the removal of the layer, penetration resistance test by drilling holes can be performed, as shown in Fig. 2. Several tests are performed through the plaster mortar layer.

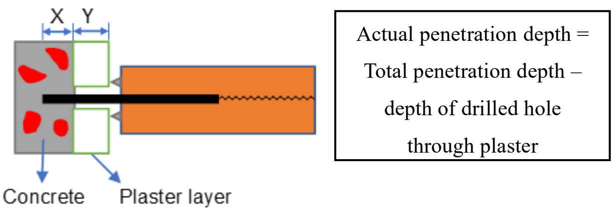

Fig. 2 "Pilodyn" pin penetration resistance test through plaster.

3. Results and discussions

3.1. Effect of aggregate type on surface hardness test

In Fig. 3a, the results of rebound hammer with compressive strengths. The compressive strength in this study is not more than 40 MPa because the aim of the study is to identify low-strength concrete in developing countries. An example equation, different from the derived regression equation, is also shown. Triangular legends represent laboratory test data in Japan, whereas round and square legends represent field test data in Bangladesh and Sri Lanka, respectively. The data is heteroscedastic meaning that the scattering increases with increase in *Q*. Also, result of scratching test in Fig. 4a shows the increase of variation with decreasing groove width. The variation can be well understood with a standard deviation of compressive strengths in certain ranges of rebound quotient and groove width in Fig. 3b and Fig. 4b. The standard deviation (σ) value is the smallest when Q ≤ 30 and GW ≥ 1. In addition, the compressive strength is not greater than 9 MPa in the range. Therefore, these two boundary values can be considered the NDT value for very low-strength concrete. Moreover, the normal distribution curves indicate that the aggregates have negligible influence as the distribution along the X-axis is very narrow when Q ≤ 30 and GW ≥ 1. Therefore, the effect of difference in aggregate can be neglected while estimating the compressive strength of low-strength concrete.

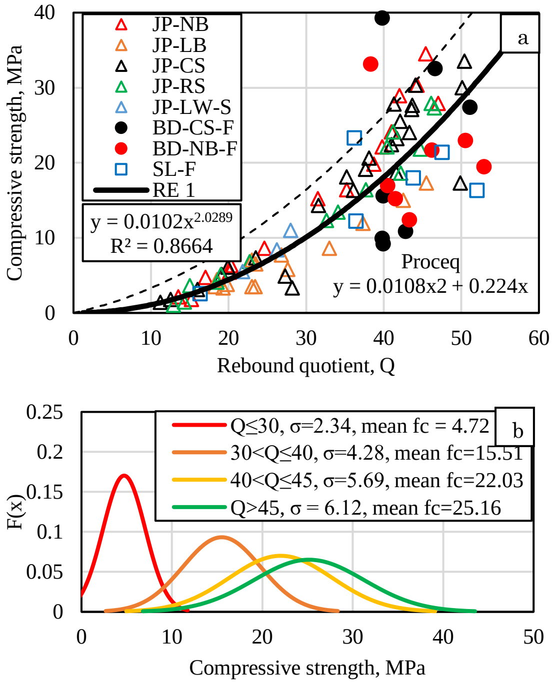

Fig. 3 Result of rebound hammer test. (a) Calibration equation, (b) Normal distribution of compressive strength with boundary *Q* values

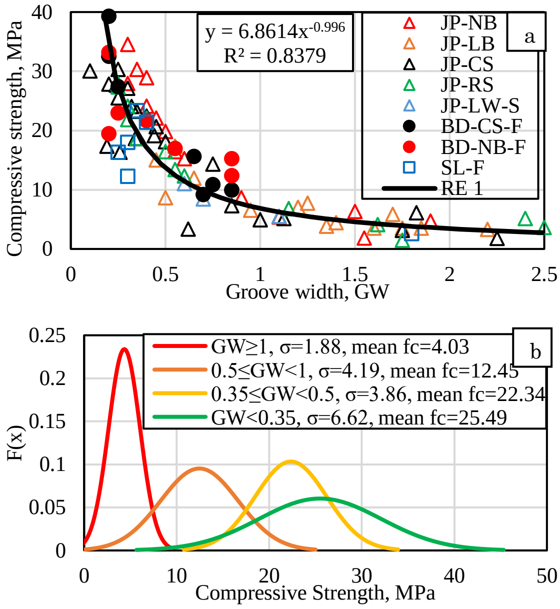

Fig. 4 Result of scratching test. (a) Calibration equation, (b) Normal distribution of compressive strength with boundary *GW* values

3.2. Effect of surface roughness

The result for the effect of surface roughness is shown in Fig. 5. The blank, hatched and filled histograms show the frequency of Q values on low, medium and high roughness of the surfaces. In the figure, two results of different compressive strengths are shown, high strength concrete and very low strength concrete. In the case of high strength concrete, the peak of mean Q from the smooth surface is higher than the peak from rough surface. The rougher surface shows the frequency of Q over a wide range indicating a greater variation of data in case of high strength concrete specimen. On the contrary, the low strength concrete specimen shows a narrower spread of Q values indicating that the surface roughness can be neglected for estimating the strength of low strength concrete. The scratching test does not show any significant changes on 3 types of surfaces, however, a surface having a very rough surface (arithmetic mean height S_a, >1 mm) may make scratching and reading the groove widths difficult. The effect of surface roughness on pin penetration test is also found negligible.

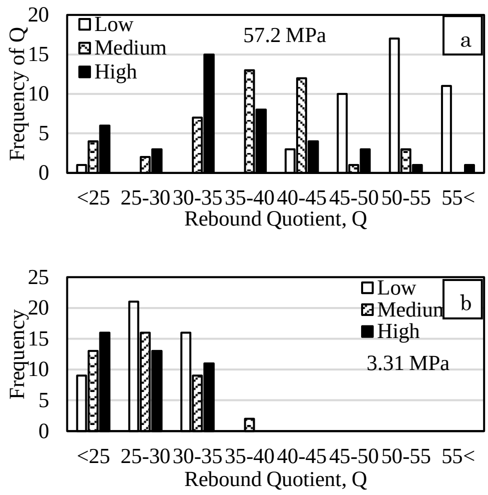

Fig. 5 Effect of surface roughness, (a)High strength concrete, (b) Very low strength concrete

3.3. Penetration resistance test

The penetration test results are shown in Fig. 6. The calibration equation, shown as a solid black line, is derived with tests on cube specimens of two concrete mixes, thus presented as Cube 1 and Cube 2. The blank legends represent the results through the hole on the plaster layer. The dashed lines show 95% confidence intervals. Some of the plaster results are found outside of the confidence interval boundary. Also, in most cases, the plaster showed lower penetration depth than directly hit measurements. The R^2 value is found greater for sharp pins, and the slope is flatter. The maximum strength that can be measured with the sharp pin is almost 32 MPa.

3.4. Combination of NDT methods

Three types of NDTs are studied. Here, the method of using these NDTs to identify the low-strength concrete during actual field tests is proposed. First, the two surface hardness methods are combined because using any one of the devices may give an overestimation of compressive strength. A relationship between the two surface hardness methods is developed in Fig. 7, and concrete classes are defined according to the boundary values of Q and GW in Fig. 3b and Fig. 4b. This graph includes total 92 data points. This classification chart can determine the quality of concrete based on two NDT values Q and GW. For each class, more than 75% of the data lies above the compressive strength of the lower boundary. For example, if Q and GW are found to be 42 and 0.65 respectively, the concrete will be classified as “Bad” and there are 75% chances that the compressive strength will be above 9 MPa. However, to determine the specific compressive strength, the calibration equations of each test should be followed, and the lower compressive strength determined should be considered representative. With this method, a lower value of compressive strength will be calculated, thus it is a “conservative” estimation process.

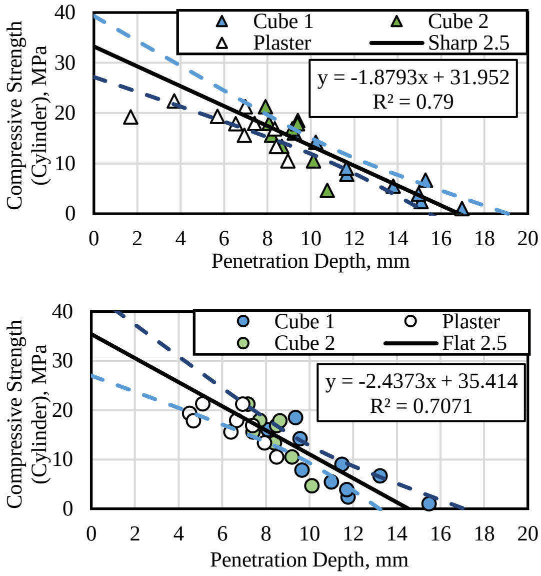

Fig. 6 Pin penetration test results. (a) Sharp 2.5 mm diameter pin. (b) Flat 2.5 mm diameter pin

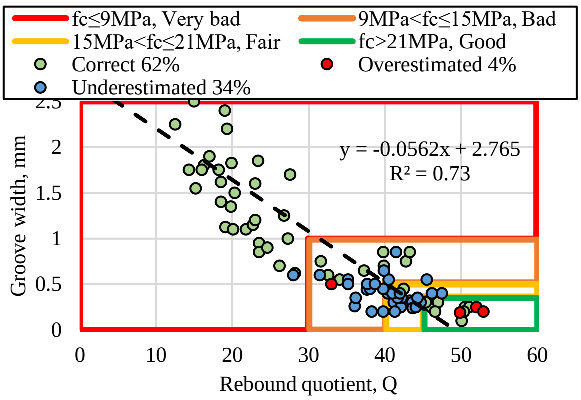

Fig. 7 Concrete classfication chart based surface hardness methods

3.5. Proposal of a practical procedure to find low-strength concrete

As mentioned earlier, reluctancy of the owner to remove the upper plaster mortar layer in certain cases may lead to the inability to perform the two surface hardness methods. Therefore, in such cases, the penetration resistance test can be performed through the plaster. The flow of performing the tests is shown in Fig. 8. The case of using only the rebound hammer, specifically in Bangladesh, is also focused and a new regression equation (RE 2) is derived using -σ (standard deviation) data points. This equation is proposed considering the case of obtaining higher Q values, although the core compressive strengths were lower as observed during field surveys in Bangladesh. The equation is as follows.

(RE2) $$\mathbf{y = 0.0052x^{2.1283}}$$ 1

4. Conclusion

Three NDT methods are explored, and calibration equations are developed. Regarding the surface hardness tests, the effect of type of aggregate and the effect of surface roughness decreases as the compressive strength decreases. When Q≤30 and GW≥1mm, indicates very low strength concrete and effect of the two parameters can be neglected while estimating the compressive strength. A concrete classification chart is proposed combining the surface hardness NDTs with a conservative strength estimation approach. A new method to perform penetration resistance test considering the case of Bangladesh is also proposed. Finally, a new conservative calibration equation for rebound hammer is derived in case of using only the hammer while performing field investigation in Bangladesh.

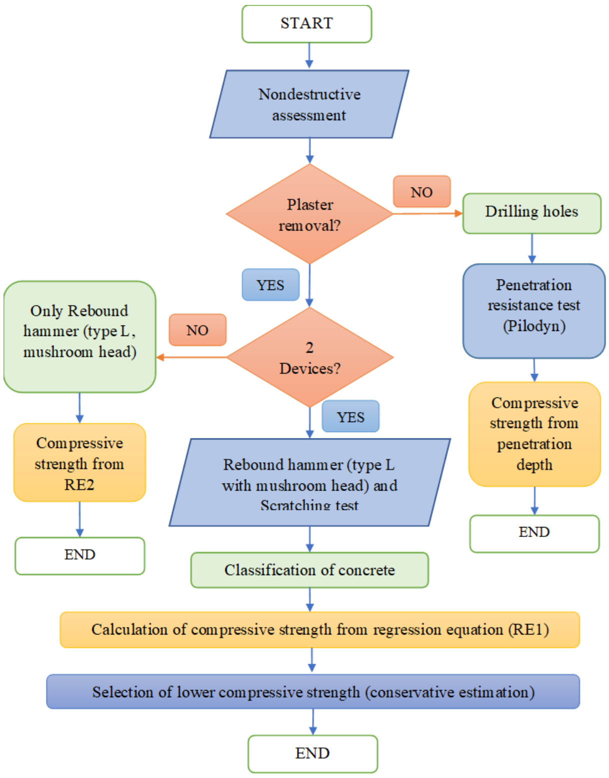

Fig. 8 Method of screening low-strength concrete

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