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Screening Method for Very-Low-Strength Concrete

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A screening method is developed by predicting the strength of very-low-strength (<9 MPa) concrete by the use of the rebound quotient and groove width from two low-energy, direction-independent nondestructive test methods (NDTs)—that is, a Type L rebound hammer and a scratching test—for brick and stone aggregate concrete. It is statistically demonstrated that low-strength concrete (LSC) exhibits a smaller standard deviation because of the low strength of the mortar phase, which ensures reliable LSC screening with any of the aforementioned methods. However, for higher-strength (>9 MPa) concrete classes, due to the increase in standard deviation, the simultaneous use of the two methods is proposed with a conservative approach to estimate the in-place concrete strength during "rapid visual screening" of buildings. Normal distribution curves classify the concrete compressive strength considering NDT boundary values with information on occurrence probability. Field test results are verified with laboratory-based correlations within acceptable statistical significance.

Keywords: brick aggregates; groove width (*GW*); low-strength concrete (LSC); nondestructive test (NDT); rebound hammer (RH); rebound quotient (*Q*); scratching test (ST).

INTRODUCTION

Major advances have been made to confidently produce high-strength concrete with strengths higher than 100 MPa.[1,2] Meanwhile, because concrete is the most basic construction and building material worldwide, there are construction sites in non-engineered conditions that are not adequately controlled. In such cases, low-strength concrete (LSC) that is structurally unsafe may be included. During construction, the occurrence of lower-strength concrete than the intended design strengths is inevitable,[3-5] which should be identified. A suitable screening methodology can reliably identify LSC, which accounts for up to 10% of the total production.[6,7] Moreover, the use of low-grade materials, bricks, and recycled aggregates in inappropriate methods and nonengineered, undocumented construction practices ultimately lead to less-durable constructions.[7-9] Unfortunately, over the last two decades, several catastrophic building collapses under gravity loading have occurred due to the inadequate performance of load-bearing structural members constructed with LSC.[10] Structures with LSC near seismically active faults in many areas of developing countries, including Bangladesh, India, and Myanmar, are at higher risk of earthquake-induced damage.[11] It is impractical to quickly collect concrete strength information from a large number of weak constructions by core drilling and other detailed test methods to arrive at remedial decisions for a large building stock. A reliable screening method is required to assess these low-performing infrastructures and develop a cost-effective strengthening scheme to transform them into safe, code-compliant facilities. The outcomes of the rapid visual screening method[12] for buildings largely rely on compressive strength information, which is preferably determined through the nondestructive testing (NDT) method. Nevertheless, any NDT method applicable to LSC should preferably be not only a low-energy method with minimal destructive impact on existing structures, but also should obtain sufficient statistically significant information on the general strength characteristics for concrete characterization purposes.

Providing appropriate attention to the scatter in the NDT data that originate from heterogeneity in reinforced concrete is of utmost importance to arrive at a reasonable decision on concrete strength. Heterogeneity in concrete due to variations in density, moisture condition, surface hardness properties for coarse aggregates, and mortars with the presence of reinforcement bars are considered major potential sources to induce scatters in the NDT data. However, in a methodology for LSC screening, appropriate testing devices are required to reduce uncertainties. The use of low-energy, direction-independent devices, where measurements are not interfered by the reinforcement bars, is preferred. This motivates researchers to focus on the applicability of the rebound quotient *Q* from a low-energy L-type rebound hammer (RH)[13] with a mushroom head and groove width *GW* measurement from the scratching test (ST) method[14] (Fig. 1), which is an extension of surface hardness testing with scratching dating back to 1640 after Mohs.[15] These two methods have the mentioned novelties and escape from difficulties associated with the original Schmidt hammer[16,17] and ultrasonic pulse velocity (UPV) tests.[18] The measured *Q*, which has a mushroom head, and *GW* over a wider area and a longer stretch, has a representative measurement and can avoid local interferences. Mineral testing is one of the oldest methods to estimate the concrete strength when reliable correlations are developed considering heterogeneity in concrete due to cement mortar and coarse aggregates.[14,19] The RH determines the rebound quotient *Q*, which is independent of the striking direction[13] and contains a mushroom head to consider responses from a wide zone by eliminating the influence of a local area (Fig. 1). The scratching test method involves measuring *GW* created through a low-energy application and correlating with the compressive strength. Although UPV is a well-known NDT method, concrete strength estimations from this method widely vary because there is reinforcement in the path of sonic wave transmission.[18] In this regard, this study takes the RH and ST methods in combination to

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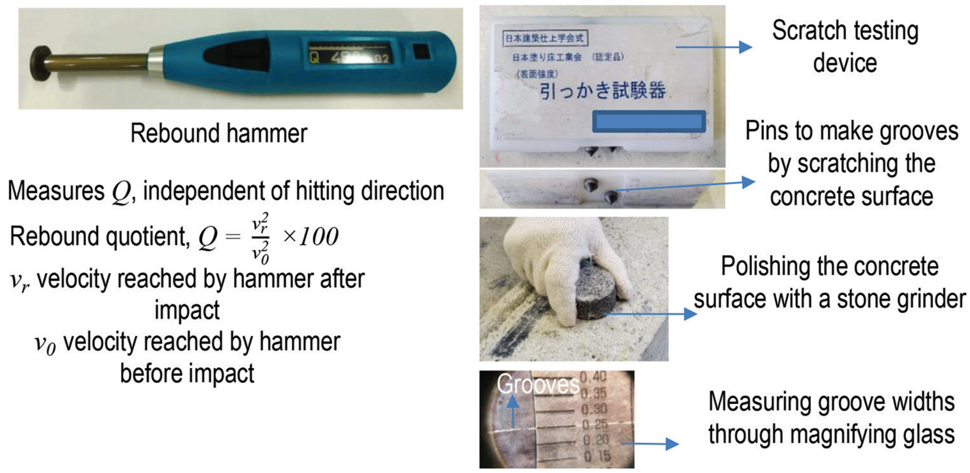


Fig. 1—Low-energy nondestructive test devices.

Table 1—Existing models for rebound surface hardness method

Name of test and measured quantity	Authors	Proposed model	Compressive strength of test data
Rebound number N	Grieb[20]	Effect of surface smoothness, moisture, and aggregate difference are discussed. No specific model is given.	13 to 48 MPa
	EN 13791[21]	$f_c = 1.25N - 23, 20 \leq N \leq 24$ $f_c = 1.73N - 34.5, 24 \leq N \leq 50$	7 to 85 MPa
	Kazemi et al.[22]	$f_c = 6.813e^{0.05N}$; recycled aggregate wet condition $f_c = 5.958e^{0.05N}$; recycled aggregate dry condition	Cube compressive strength 10 to 40 MPa
	Saha and Amanat[23]	$f_c = 2.20N - 45.67$, stone $f_c = 5.40e^{0.051N}$, crushed brick $f_c = 0.0098N^{2.21}$, recycled brick $f_c = 0.0253N^{2.09}$, recycled stone	18.2 to 47.2 MPa
Rebound number N and ultrasonic pulse velocity test *USPV*	Ravindrajah et al.[24]	Recycled aggregate concrete $f_c = 7.25e^{0.08N}$ $f_c = 0.008e^{2.06V}$	10 to 75 MPa
	Qasrawi[25]	$f_c = -1.353N + 17.393$ $f_c = 36.72USPV + 129.077$	Cube strength 5 to 42 MPa
	Hobbs and Kebir[26]	$f_c = 2.168N - 27.747$ $f_c = 11.228V^2 - 39.075V + 1.4658$	20 to 50 MPa
Rebound number N and rebound quotient Q	Ayding and Basu[27]	$f_c = 1.4459e^{0.0706Q}$ $f_c = 0.9165e^{0.0669N}$	22.66 to 196.45 MPa
	Brozovsky[28]	$f_c = 0.0076Q^{2.4229}$	47.1 to 134.6 MPa
	Cikrle et al.[29]	$f_c = -4.762 + 0.82917Q$; recycled aggregate concrete	5 to 30 MPa
Scratch testing device, groove width *GW*	Kasai et al.[30]	$f_c = 3.4GW^{-2.24}$	—
	Nishikawa et al.[31]	$f_c = -9.76GW - 20.1$	4 to 38 MPa

overcome the well-cited shortcomings. To obtain workable correlations within their own limitations, efforts have been made to combine more than a single method with their own methodology of synthesizing the data. Table 1 shows the existing models for characteristic strength derivation through the surface hardness method; however, there is no universal correlation[25,32] for LSC screening. In addition, most of the studied correlations are for the Type-N RH, which is of higher energy (2.207 Nm) than the L-type RH (0.735 Nm) and not suitable for low-strength concrete. Figures 2 and 3 compare the available correlations for L-type hammers and scratchers, but these widely vary among themselves and are inconclusive. Moreover, earlier studies mainly discuss the influential factors instead of the construction of a model for characteristic strength derivation. These results motivated the current study to develop a model for characteristic strength estimation to identify very-low-strength concrete using low-energy devices. Extensive experimental data points in the very-low-strength range (<9 MPa) are gathered in this study, but very thinly reported data in the available literature[22-24,26,28] provide the vital foundation for deriving a statistically significant empirical correlation through regressions to screen LSC in developing countries.

The goodness of fit for an established hardness testing model is typically defined with the coefficient of determination R^2, which is the proportion of the variance in the dependent variable predicted with the independent variables.[33] A high R^2 value can be obtained with correlations developed through single-laboratory experiments, which sometimes do not represent the actual scenario of concrete onsite. A lower

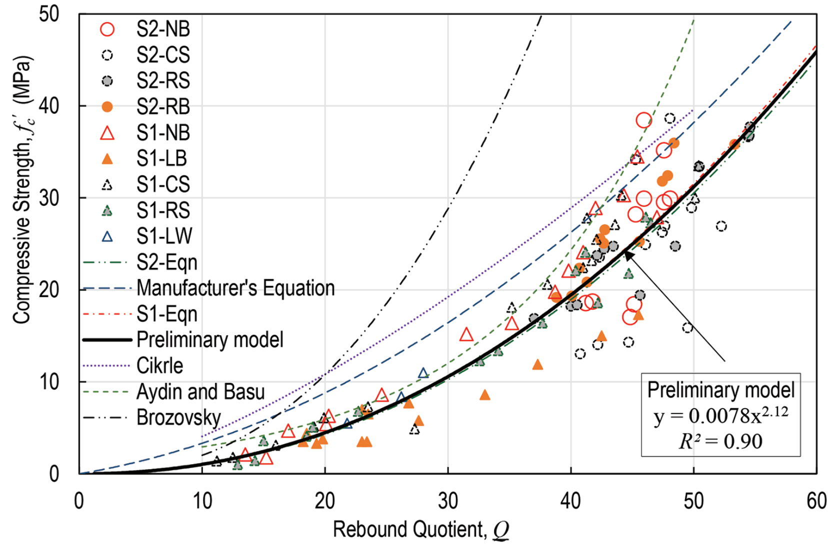


Fig. 2—Comparison of different correlations in Type L hammer.

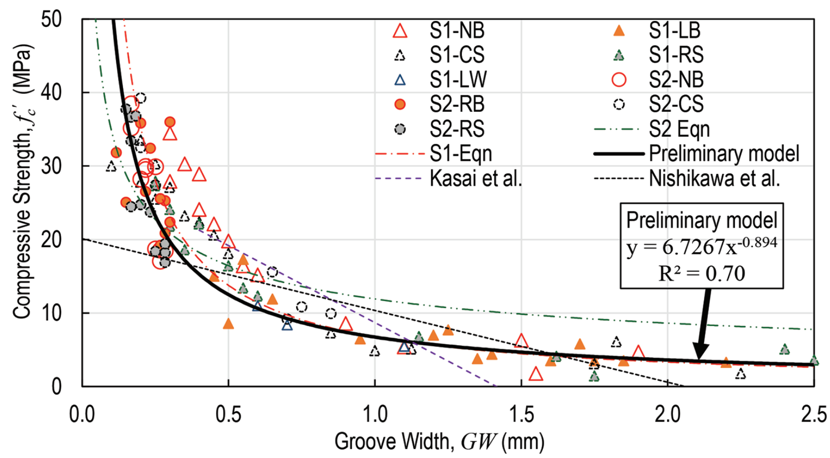


Fig. 3—Comparison of different correlations for scratching test.

value is possible when specimens are retrieved from different building locations. At present, the most popular hardness testing NDT device, which is the RH, produces an increasing standard deviation with increasing rebound value.[17,34-36] Moreover, to reduce the uncertainty in the results, the combination of two NDT methods is considered more reliable than a single test.[31,37,38] In contrast to past studies, the statistical variability is considered here to create a classification chart for concrete considering the boundary values of the hardness measurements collected through two low-energy NDT methods and the compressive strength measurements. Many test specimens of various strength ranges, including concrete with a very low strength (≤9 MPa) and different aggregates, were prepared under two independent laboratory conditions and material sets (Set 1 and Set 2, Fig. 2 and 3).

RESEARCH SIGNIFICANCE

A statistically significant concrete classification chart is developed for two low-energy hardness testing techniques for rapid onsite screening of very-low-strength concrete (< 9 MPa). The statistical analysis considers the effect of variability for stone aggregate, brick, and recycled aggregates in concretes between 0 and 40 MPa in laboratory samples and existing buildings. The data set to develop the method with statistical analysis is independent from the one used for the validation study. The proposed screening method can produce a reliable occurrence probability of low-strength concrete in a conservative approach and can be followed to formulate a similar model with different NDT devices. The method is rapid, easy, and cost-effective for application in developing countries.

METHODOLOGY FOR STRENGTH ASSESSMENT

The step to formulate the assessment is briefly shown in Fig. 4. A regression model to assess the compressive strength is considered first, which relates the compressive strength with NDT measurements: rebound quotient Q and groove width GW, which are obtained from the RH and ST, respectively. The NDT value is the independent variable related to the compressive strength of the corresponding cylinders or drilled core specimens. The compressive strength f_c' is the dependent variable. To establish the model, the compressive strengths must be calculated from cylinders or cores of the same concrete tested with NDT. The most widely applied models are second-order polynomial, power, and exponential models.[19] Among the models that yield the highest

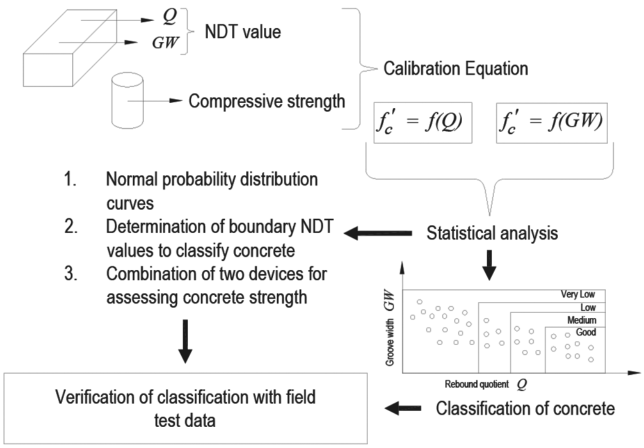


Fig. 4—Development of concrete strength assessment method with combination of NDTs.

coefficients of determination, the R^2 value is adopted as the preliminary fitting model measure for each device. The following two equations are examples of two power models for these two testing techniques

$$F\left(f_c'\right) = \alpha_1 Q^{\beta_1} \quad (1)$$

$$F\left(f_c'\right) = \alpha_2 GW^{\beta_2} \quad (2)$$

In these equations, f_c' is the compressive strength of concrete; Q is the rebound quotient; GW is the groove width; and α_1, β_1, α_2, and β_2 are constants estimated from the analyzed data.

A population (the data points) originating from a given observation has a mean and a standard deviation. With the standard probability density function based on the mean and standard deviation of the population, a bell-shaped curve or normal distribution curve is obtained. A narrower bell-shaped curve or a higher peak indicates a higher probability of an observation approaching the population mean and vice versa. When the standard deviation is high, the bell-shaped curve exhibits a wider distribution. The bell-shaped curve also depicts the percentage of data within certain standard deviation boundaries. If the population data consist of the compressive strength f_c' within given ranges of the NDT values, either Q or GW, the standard deviation of the compressive strength and mean compressive strength within each range may be applied to develop multiple bell-shaped curves. The significance of the bell-shaped curve predicts the maximum data percentage falling within two standard deviations, which gives the probability of a trial test. The following probability density function can be used to develop the bell-shaped curve

$$F\left(f_c'\right) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\left(\frac{f_c'-\mu}{\sigma}\right)^2} \quad (3)$$

The bell-shaped curve developed from each range of NDT values specifies the lower and upper bounds of the compressive strength corresponding to ±1σ, ±2σ, or ±3σ. When an NDT value is obtained from a test, the compressive strength determined with any of these models may be fitted with a bell-shaped curve to predict the probability of occurring above the lower boundary or below the upper boundary of the compressive strength.

EXPERIMENTAL PROGRAM

Materials and mixture proportions

Table 2 summarizes all test specimens for the NDT experiments. Laboratory specimens were prepared in two independent laboratories: the Life Cycle Engineering Laboratory, Tohoku University, Sendai, Japan (S1)[39]; and the Concrete Laboratory, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh (S2). In Set 1, five different types of aggregates were adopted to prepare the laboratory specimens. Low-strength brick chips (LB, 23 MPa, density of 2.2 g/cm^3), high-strength brick chips (NB, 40 MPa, density of 1.9 g/cm^3), crushed stone (CS, density of 2.7 g/cm^3), lightweight aggregates (LW, density of 0.3 g/cm^3), and recycled stone aggregates (RS, density of 2.5 g/cm^3) were used. Ordinary portland cement was employed as the binder. Limestone powder (LSP) (density of 2.71 g/cm^3) was applied as the filler powder to prevent segregation because of the high water-cement ratio (*w/c*). The fine aggregates were composed of a combination of sand (density of 2.61 g/cm^3) and crushed sand (density of 2.65 g/cm^3). Very high *w/c* ratios were used for the low-strength brick aggregates to obtain LSC. Compressive strength measurements were performed on the cylindrical specimens (100 mm in diameter and 200 mm in height), while NDT observations were conducted on the prism-shaped specimens (150 x 150 x 600 mm). After casting and demolding, the specimens were stored in a climate-controlled room (20°C, 95% relative humidity). In Set 2, 48 concrete cube specimens consisting of four different types of coarse aggregates were subjected to NDT experiments: normal brick aggregates (NB), recycled brick aggregates (RB), crushed stone aggregates (CS), and recycled stone aggregates (RS). Three different *w/c* of 0.73, 0.60, and 0.48 were maintained while producing 48 concrete cube specimens with design strengths of 10, 20, and 35 MPa. Sylhet sand (a bulk unit weight of 1.52 g/cm^3) was used as the fine aggregate. The specimens were cured for up to 28 days in a water bath (20°C). After curing, the specimens were left open to the environment for more than 1 year. The total number of specimens for NDT testing is shown at the bottom of Table 2.

NDT and compressive strength experiments in laboratory

NDT experiments were conducted at 3, 7, 14, and 56 days on Set 1 of the prismatic specimens, which contained brick chip, stone, and recycled aggregates. The specimens consisting of low-strength brick chips (LB) were tested on days 7, 28, and 56. The compressive strength of the cylinders was measured on the same days. The L-type hammer test was performed in accordance with JIS A 1155,[40] which also conformed to ISO 1920-7.[41] According to the standard, nine or more points were measured at 50 mm or farther away from the specimen edge and at 30 mm or farther away from each other. The average value of these nine points excluding those values differing 20% or more from the average value was calculated as the rebound quotient

Table 2—Mixture proportion of concrete specimens in laboratory experiments for different types of aggregates

	Aggregate type	*w/c*	Water, kg/m³	Cement, kg/m³	Limestone powder (LSP), kg/m³	Fine aggregate, kg/m³	Coarse aggregate, kg/m³
Set 1	NB	2.0	200	100	218	880	467
		1.2	181	150	168	880	467
		1.0	181	181	137	880	467
		0.8	181	226	92	880	467
		0.6	181	318	0	880	467
	LB	2.1	354	169	68	584	662
		2.0	235	118	160	716	807
		1.5	225	150	150	730	825
		1.0	210	210	110	730	825
		0.6	210	350	0	730	825
	CS	2.0	200	100	218	880	995
		1.2	181	150	168	880	995
		1.0	181	181	137	880	995
		0.8	181	226	92	880	995
		0.6	181	318	0	880	995
	RS	2.0	200	100	218	880	995
		1.2	181	150	168	880	995
		1.0	181	181	137	880	995
		0.8	181	226	92	880	995
		0.6	181	318	0	880	995
	LW	1.2	286	237	237	481	98
		1.0	286	284	190	481	98
		0.8	286	356	119	481	98
Set 2	F-NB*	0.8	112	139	0	363	555
	NB	0.73	145	199	0	419	545
		0.60	122	204	0	430	559
		0.48	100	209	0	441	574
	RB	0.73	133	182	0	412	498
		0.60	112	186	0	422	510
		0.48	91	190	0	432	522
	CS	0.73	153	210	0	477	636
		0.60	130	216	0	490	654
		0.48	106	222	0	503	671
	RS	0.73	138	189	0	428	570
		0.60	116	193	0	439	585
		0.48	95	198	0	449	599

*Full-scale laboratory column specimen was tested during field survey in Bangladesh. Mixture proportions were added because of its availability. Other locations of testing were in existing buildings; thus, no mixture proportions were available.

Note: Each *w/c* from Set 1 corresponds to one rectangular prism specimen for NDT testing, total 23 prismatic samples; each *w/c* from Set 2 corresponds to four rectangular prism specimens for NDT testing, total 48 prismatic samples.

Q. The standard clearly eliminated any abnormal measured value that deviated from more than 20% of the average value. The ST was carried out on the same side of the test surface subjected to the L-type hammer test. The ST device is a simple tester that scratches the concrete surface at a constant angle. The two pins of the device applied constant loads of 9.8 and 4.9 N (1 and 0.5 kg) when pressed against the surface. The pins consist of carbide tungsten alloy, which has high hardness and wear resistance. They were inserted with spring coils at the center of a rectangular prism constructed of plastic material at a 90-degree angle. Load adjustment was performed through the spring coils of the device installed along the body of the pins. Approximately 10 cm long grooves were made on the concrete surface by scratching at a speed of 2 cm/s, and the *GW* value was measured with various scales available with the surface hardness measurement device, as shown in Fig. 2. The obtained *GW* value of 9.8 N (1 kg) was considered for the calibration curves in this study. The test was carried out on a painted surface to clearly visualize the grooves.

The NDT test method for Set 2 specimens was similar. When the narrow groove widths were difficult to determine, more than three lines maintaining sufficient distance from each other were recommended. The average width of all grooves was used to determine the compressive strength. When the aggregate surface was exposed, the direct contact of the pin with the aggregate should be avoided, because directly scratching on the aggregate will always yield narrow grooves. The curing age of the specimen was 28 days. After the end of the curing time, the samples were removed from the bath and kept in an open environment. These samples were tested after 1 year. A compressive strength test was performed on drilled cores collected from the same location as the NDT test on the same day. Each specimen corresponds to one data point.

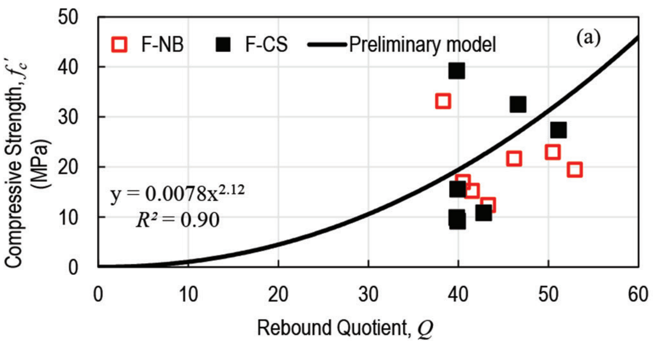
Field survey: case study of developing country, Bangladesh

Bangladesh is a developing country in Southeast Asia that is vulnerable to earthquakes.[42,43] Moreover, several incidents involving reinforced concrete (RC) building collapse without the influence of earthquakes have occurred in recent years due to the use of substandard concrete materials. Bangladeshi concrete is mainly composed of brick aggregates from baked clay bricks after crushing due to the aggregate scarcity in local markets and limited access to international imports in the past.[44] Three existing RC buildings built in the 1970s and 1980s were surveyed in Dhaka, Bangladesh, and a laboratory column specimen consisting of normal brick (NB) aggregate concrete was tested (mixture proportions in Table 2). The finishing layers on columns in existing buildings were removed and polished with a stone grinder to conduct the NDT measurements. The inside concrete surface was uneven due to the exposed aggregate.

RESULTS

Preliminary model

Figure 2 shows the results of *Q*. The manufacturer of the RH provided the relationship (Eq. (4)) indicated with the dashed line (Fig. 2), which plots above the calibration equations derived from the experimental data points.



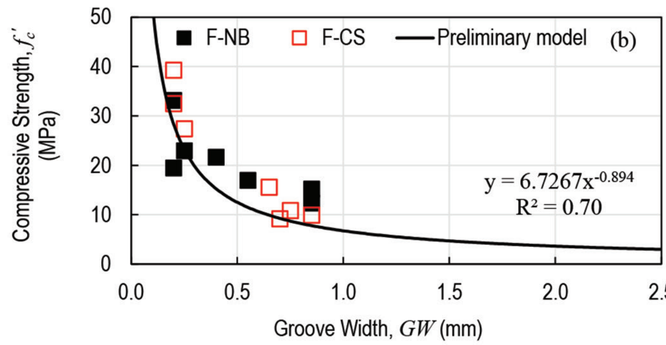


Fig. 5—Comparison of field test results to preliminary model of: (a) RH; and (b) ST.

$$f_c' = 0.0108Q^2 + 0.224Q; R^2 = 0.8962 \quad (4)$$

The red dashed line was derived from the Set 1 data points, which relates the compressive strength of the cylindrical specimens to the NDT measurements of the prismatic specimens, as indicated by Eq. (5).

$$f_c' = 0.0072Q^{2.1432}; R^2 = 0.91 \quad (5)$$

The green double dot dashed line derived from the Set 2 data points indicates the relationship of the core compressive strength and NDT measurements.

$$f_c' = 0.0071Q^{2.1406}; R^2 = 0.50 \quad (6)$$

However, the two regression lines are notably similar. These two data sets were employed to derive a "preliminary model" of the RH, as indicated by the black solid line. Other models previously proposed by Brozovsky[28] (Eq. (7)), Cikrle et al.[29] (Eq. (8)), and Aydin and Basu[27] (Eq. (9)) are also shown in the graph. The position of the models in Fig. 2 clearly shows that these models overestimate the compressive strength. The three models are as follows.

$$f_c' = 0.0076Q^{2.4229} \quad (7)$$

$$f_c' = 0.1559Q^{1.4157} \quad (8)$$

$$f_c' = 1.4459Q^{0.0706} \quad (9)$$

The ST regression equations based on these two data sets are shown in Fig. 3. Similar to the RH test, the compressive strength of the cylindrical specimens was included in the Set 1 data, and the core compressive strength was included in the Set 2 data to develop the ST-based equations. *GW*s are small, and the compressive strength is higher in the Set 2 data. No data indicating a low compressive strength were obtained from this data set. However, low-compressive strength data were acquired for the specimens of Set 1. The data points from Sets 1 and 2 were used to obtain a preliminary model for the scratching test. Here, the R^2 values are 0.85 and 0.70 for the RH and ST experiments, respectively. The previously established models of Nishikawa et al.[31] and Kasai et al.[30] for comparison are as follows.

$$f_c' = -9.76GW + 20.1 \quad (10)$$

$$f_c' = -20.854GW + 29.639 \quad (11)$$

The preliminary models for compressive strength determination are proposed as follows.

$$f_c' = 0.0078Q^{2.12} \quad (12)$$

$$f_c' = 6.7267GW^{-0.894} \quad (13)$$

Verification against field data and normal distribution

The field test results are shown in Fig. 5(a) and (b) to verify the proposed preliminary model. The derived preliminary models appear to overestimate the compressive strength in certain cases of the field survey in Bangladesh. Here, overestimation indicates that the calculated compressive strength from Q is higher than the compressive strength determined from the cores. Overestimation of the compressive strength with the NDT method is an issue that must be avoided due to safety concerns. However, an estimated compressive strength approaching the actual value or an underestimated compressive strength value may be beneficial as input information for a second screening that involves detailed seismic calculations.

The samples in this study comprise concrete specimens with low to high compressive strengths. The lowest compressive strength of the laboratory specimens is 1.5 MPa, and the highest is 39.5 MPa. Figures 5(a) and (b) show that the field data are heteroscedastic. The data with high Q and low GW values exhibit much scatter, which is revealed by dividing Sets 1 and 2 data into four zones according to selected boundary values of Q and GW. The boundary values of Q and GW divide the data into four classes of compressive strengths. Table 3 lists the mean and standard deviation of the concrete compressive strength within the corresponding boundaries of each class. Normal distribution curves for the four different zones based on the boundary values of Q and GW are shown in Fig. 6(a) and (b), respectively. As shown in Fig. 6(a), at $Q > 30$, the curves flatten, whereas at $Q \leq 30$, the peaks are high. The data points in this range are within 9 MPa of the mean compressive strength, and a high peak indicates a high probability of LSC occurrence. For the normality check of these data in the four zones, p values are calculated. All four zones for the rebound hammer show a higher value than 0.05, which proves that the null hypothesis cannot be

Table 3—Division of sample data into four zones based on *Q* and *GW* boundary values

RH Q	Mean compressive strength, MPa	Standard deviation of compressive strength, MPa	p-value	Scratching test GW, mm	Mean compressive strength, MPa	Standard deviation of compressive strength, MPa	p-value
$Q \leq 30$	4.76	2.37	0.11	$1 \leq GW$	4.12	1.84	0.80
$30 < Q \leq 35$	12.38	2.79	0.26	$0.5 \leq GW < 1$	12.45	4.20	0.80
$35 < Q \leq 40$	19.13	7.67	0.45	$0.4 < GW \leq 0.5$	21.74	3.52	0.65
$40 < Q$	25.45	6.92	0.38	$GW < 0.35$	25.60	6.91	0.006

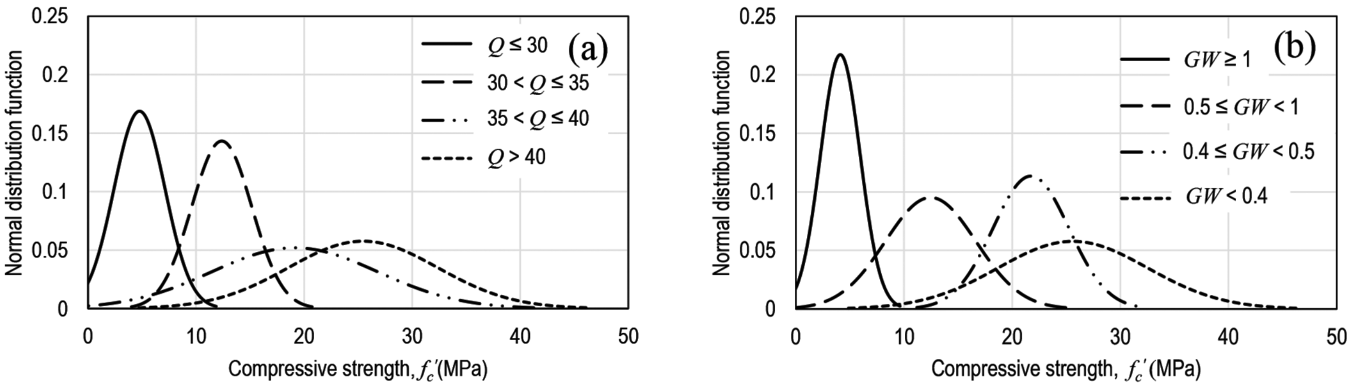


Fig. 6—Normal probability density curves for four zones of: (a) RH; and (b) ST.

rejected. Thus, the data are normal for all four zones. Similarly, regarding the ST at $GW \geq 1$ mm, the probability density curves exhibit high peaks, which indicates a high probability of LSC occurrence. Each zone is individually considered to determine the standard deviation. The standard deviation increases with increasing rebound quotient and decreasing GW. At $Q \leq 30$, the standard deviation is low. In the ST case, the highest standard deviation is also found at small GW values—that is, at $GW \leq 0.35$. The data set in this zone also indicates a lower p value (below 0.05), as shown in Table 3. However, the lowest standard deviation is obtained at large GW values—that is, at $GW \geq 1$ mm. According to this result, the ST method is very suitable for LSC screening. Therefore, $Q \leq 30$ and $GW \geq 1$ are selected as criteria to reflect concrete with a very low strength—that is, less than or equal to 9 MPa. Because the standard deviations are low for both RH and ST methods despite the occurrence of different types of aggregates within this sample data range, the effect of aggregate variation may be neglected during LSC screening.

Conservative classification of concrete strength based on combination of NDTs

Depending on the boundary NDT values of the normal distribution curves, as shown in Fig. 6(a) and (b), a concrete classification is developed for a specific range of compressive strength. As shown in Fig. 7, the normal distribution curves of the RH and ST methods are combined for low to high compressive strengths. The area above or below this specific compressive strength value indicates a certain probability. For example, at $Q \leq 30$ and $GW \geq 1$ mm, these graphs indicate that the probability of a compressive strength below 9 MPa is higher than 95%. Similarly, at $30 < Q \leq 35$ and $0.5 \leq GW < 0.4$, the probability of a compressive strength above 9 MPa is higher than 75%. The other ranges indicate that the probabilities of a compressive strength above 13.5 and 21 MPa are higher than 75%. The predicted compressive strength values with NDT methods are approximate, and a probabilistic prediction provides the examiner with a level of certainty. While expressing the probability, in the range with $Q \leq 30$ and $GW \geq 1$ and the other three ranges, values higher than 90% and 75%, respectively, can be considered while reporting an examined value.

A combination of these two devices was developed, as shown in Fig. 8. A simple linear relationship between the two devices was considered. The linear relationship considering these two devices is as follows

$$GW = -0.0565Q + 2.779 \tag{14}$$

Here, the x-axis represents the rebound quotient axis, and the y-axis represents the GW axis. As shown in Fig. 8, Q decreases along the x-axis, and GW increases along the y-axis, which indicates a low compressive strength. With rebound quotient and GW values determined in concrete tests, a single data point can be identified on this chart. According to the aim of this study, to identify vulnerable buildings containing LSC, it is necessary to consider a conservative relationship, which indicates that a low compressive strength must be identified by any of these devices. If a point lies on the line between two zones, the lower class is recommended for selection.

Figure 8 also shows the four regions of concrete classification based on the boundaries depicted in the figure, where the concrete compressive strength is denoted as high when both Q and GW values fall within the green region. The red region represents the very low strength, where Q is lower than 30 or GW is higher than 1 mm. In this case, the estimated concrete compressive strength is lower than 9 MPa. The concrete classification based on the upper and lower limits of the compressive strength corresponding to Q and GW is summarized in Table 3. The other classes are denoted "Low"

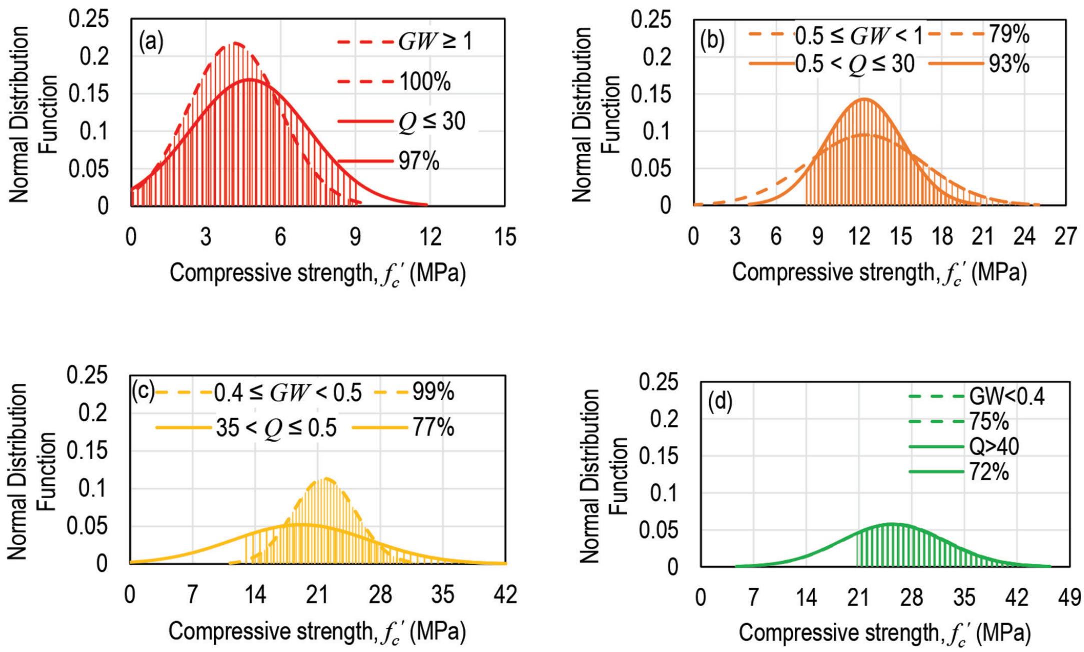


Fig. 7—Normal distribution of compressive strengths within upper and lower boundary values for RH and ST: (a) very low; (b) low; (c) medium; and (d) good.

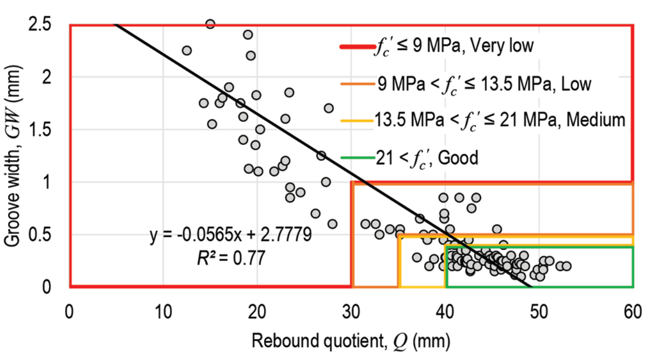


Fig. 8—Classification of concrete according to boundary values of NDT and concrete compressive strength.

and "Medium" strength. A compressive strength of 21 MPa is considered the upper limit of the fair class because this value is the most common design compressive strength employed in Japan. Each class is designated a color code. The data in this study are classified according to this proposed conservative method, and 6% of the data are classified in a higher compressive strength range (overestimated), while 30% of the data are classified in a lower compressive strength range (conservatively estimated). Moreover, 64% of the data are classified in the correct compressive strength range. When the Q and GW values assign a tested concrete on the boundary between the two classes, the lower class is recommended to select, because the approach is said to be conservative.

Reliability of proposed conservative method

To assess the reliability of the conservative estimation method, the ratio of the predicted strength to the actual strength is calculated. Figure 9 shows the distribution of this ratio when the predicted strength is calculated using the proposed model. A ratio of the predicted strength to the actual strength below 1.0 indicates a conservative estimation. Figure 9(a) shows that 63% of the compressive strength data are conservatively estimated, whereas 37% are overestimated. Similarly, Fig. 9(b) shows that 54% of the compressive strength data are conservatively estimated, whereas 46% are overestimated. With the combination of these two devices, Fig. 9(c) shows the most conservative estimation of the compressive strength, which includes 77% of the data. The skewness of the distribution describes the characteristics of the data. If the skewness is zero, the data are normally distributed. A negative skewness indicates that the data distribution exhibits a long tail on the left side, and a positive skewness indicates that the distribution exhibits a long tail on the right side. As shown in Fig. 9(a), (b), and (c), the skewness values are 1.39, 2.14, and 1.44, respectively. All the values are positive, which indicates that the tail is long on the right side. Most of the data are accumulated on the left side of these graphs. The skewness value indicates that a high percentage of the compressive strength is conservatively predicted. In summary, the classification chart provides a range of compressive strengths, and a specific compressive strength may be conservatively estimated from the combination of these two devices with the developed calibration equations with 77% reliability.

CONCLUSIONS

A systematic series of laboratory and field surveys are performed to establish a simple low-strength concrete (LSC) (≤9 MPa) screening method by combining two low-energy nondestructive testing (NDT) devices. The outcomes of the study are as follows:

1. A concrete classification chart (Fig. 8) is proposed based on the boundary values of the two NDT methods. This chart is applied to classify concrete into four classes: "very low" ($f_c' \leq 9$), "low" ($9 < f_c' \leq 13.5$), "medium" ($13.5 < f_c' \leq 21$) and "good" ($21 < f_c'$). The "very low" and "low" strength concrete classes are of major concern and thus require immediate attention to retrofit or discard. The compressive

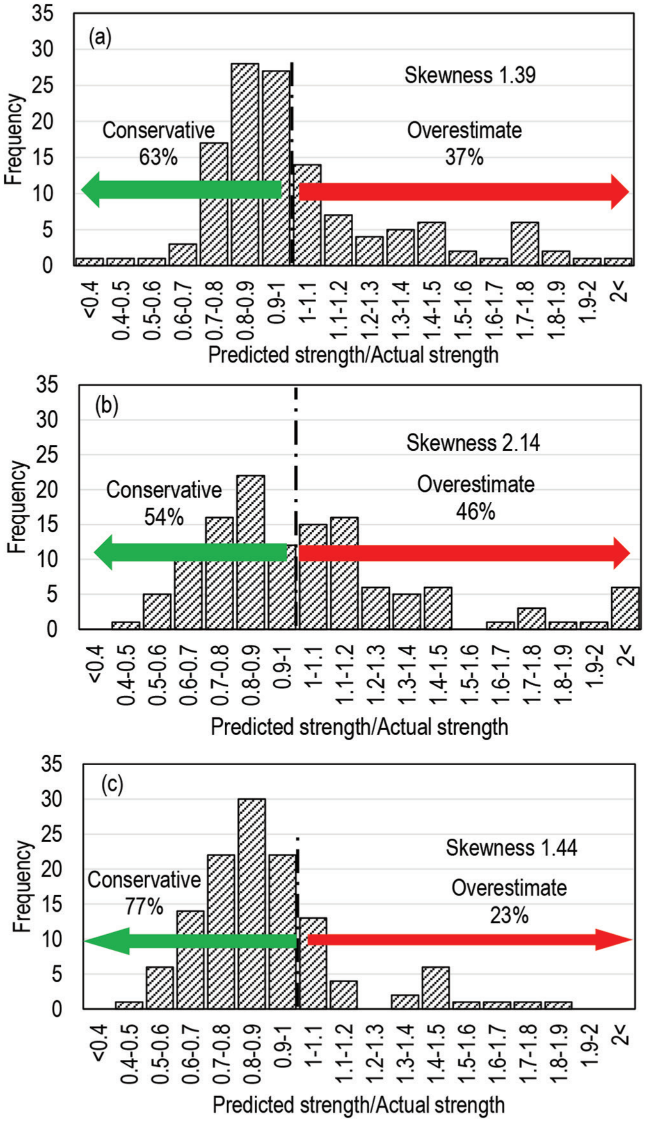


Fig. 9—Comparison of ratio of predicted strength to actual strength: (a) RH; (b) ST; and (c) combination of RH and ST.

strength of the tested concrete is determined with a conservative approach in whichever class the combined value of *Q* and *GW* lies. The representative compressive strength in all four classes is proposed to be the lower compressive strength between the rebound hammer and scratching test.

2. To determine the compressive strength, the proposed calibration curves are provided in Eq. (12) and (13). Previously determined calibration equations cannot be used to determine the compressive strength of the tested concrete, and Fig. 2 and 3 show that they overestimate or do not appropriately estimate the compressive strength.

3. The standard deviation of the compressive strengths in the very LSC range is found to be lower; thus, the effect of the aggregate type, either brick or stone aggregates, on the nondestructive devices can be neglected when estimating the compressive strength in this range. Despite the difference in aggregates, the compressive strength in this very LSC is represented by the lower strength of the mortar in the concrete.

4. The evaluation of the compressive strength is also aided by the information of occurrence probability. The data in this study show that the occurrence probabilities are more than 70% when both NDT values assign a tested concrete in the orange and green zones. The occurrence probability is more than 90% when the NDT values assign a tested concrete in the red or yellow zone.

5. The reliability of the proposed conservative compressive strength estimation procedure that combines these two devices is verified based on the ratio of the predicted strength with the NDTs to the actual strength. This procedure of conservative estimation greatly reduces the possibility of overestimating compressive strength by only 23%. A good compressive strength of 77% is conservatively determined.

A universal model to evaluate the compressive strength has not been developed. The method established in this study provides a concrete strength range via a classification chart and a conservative estimate of the compressive strength. The established correlations comprise a reasonable LSC screening procedure in Bangladesh. For concrete other than LSC, various parameters that influence the NDT methods should be considered in future research.

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