DEVELOPMENT OF STRENGTH PREDICTION MODELS FOR IN-SITU CONCRETE IN EASTERN SAUDI ARABIA

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الخلاصـــة :

لقد تم تطوير طريقة لتقدير قوة الخرسانة في الموقع اعتمادا على فحوص لاإتلافية كسرعة الذبذبات فوق الصوتية ومقياس مطرقة شميدت (قياس رجع صدى المطرقة) ، وذلك للمنطقة الشرقية في المملكة العربية السعودية .

وتم ذلك بتطوير نموذج لقياس قوة خلطة خرسانية قياسية عن طريق تثبيت أحسن منحنى لمجموعة نتائج الفحوص اللاإتلافية . وبالنسبة للخلطة الخرسانية المراد قياس قوتها فقد تم تطوير معامل لتقدير قوة هذه الخلطة بالقياس للخلطة القياسية . وهذا المعامل يمثل دالة لعدد من المتغيرات الأساسية والتي تحدد مدى اختلاف الخلطة المراد قياس قوتها عن الخلطة القياسية .

ABSTRACT

A combined method has been developed for estimation of in-situ concrete strength nondestructively in the Eastern region of Saudi Arabia by incorporating measurements of ultrasonic pulse velocity and surface hardness method (hammer rebound number). The strength prediction equations are first developed for a reference concrete by a multilevel regression analysis of test data. For a concrete whose mix design is different from that of reference concrete, a total correction factor is proposed. This correction factor is expressed as a function of individual correction factors corresponding to each dominant variable of the mix design.

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INTRODUCTION

The increasing need for in-situ estimation of concrete strength by nondestructive means has led to the development and application of numerous methods, among which mention can be made of surface hardness, ultrasonic pulse, pullout, and penetration methods. References [1–4] provide an excellent appraisal of a wide range of test methods, listing useful references to the past work. An annotated bibliography [5] covering research from 1975 to 1983 is one of over forty informative papers collectively published in the ACI special publication SP-82 [1].

The generally accepted notion that the accuracy and reliability of a strength prediction can be improved by a mathematical model based on the results of at least two independent measurements has led to the development of what is commonly referred to as the combined method. First proposed in reference [6], the most fundamental work in the advancement of the combined method was presented by Facaoaru [7]. The ensued global interest has culminated in numerous investigations in many countries, for which reference [8–11] can be cited as representative samples only. Most researchers have attempted to combine ultrasonic pulse velocity and the surface hardness methods in proposing combined methods, recognizing their simplicity.

In this paper, the developmental work of a strength prediction model for in-situ concrete in the Eastern Region of Saudi Arabia is presented. The need for such work dictated by the increasing activity in diagnostic evaluation of concrete problems either as part of a repair or restoration program or as check or monitoring of compliance with specifications. Using laboratory generated test results of ultrasonic pulse velocity and surface hardness method, a combined nondestructive technique for estimation of in-situ concrete strength is proposed. Jebel Dhahran coarse aggregate, which is a typical representative of marginal limestone type coarse aggregates frequently used in the Eastern Province, has been used in this study.

STRENGTH CALIBRATION BY COMBINED METHOD

Approach

Development of a reliable strength prediction model for in-situ concrete based on simple in-situ measurements faces difficulty due primarily to the interactive influences of the parameters of concrete mix design and the factors influencing the concrete strength. Inevitably, some simplifications must be postulated to accommodate the influence of various parameters and consequently various approaches have emerged in the development of strength equations.

In this approach, first the concrete strength is formulated for a reference or standard concrete by using regression analysis of test data generated by both pulse velocity and the rebound hammer. Isostrength curves are then developed from a combined calibration of the two methods, using a multilevel regression. Appropriate correction factors are developed for concrete whose composition is not identical to that of the reference concrete. These correction factors take into account the effect of significant variables such as cement content, coarse aggregate size, and coarse aggregate volume fraction. By applying these correction factors, the reference concrete strength corresponding to a given value of pulse velocity and rebound number measured on an in-situ concrete is converted to a value which becomes the estimated strength of the in-situ concrete.

CALIBRATION FOR REFERENCE CONCRETE

Test Program

An elaborate test program was engineered to generate sufficient test data for the purpose of modelling. While the details of the work have been covered in reference [12], the work is described briefly here. Two types of test specimens, namely concrete panels of dimensions 500 × 300 × 150 mm and 75 × 150 mm cylinders, were used in testing. Slabs were used in measuring rebound numbers (R) and indirect pulse velocity (V_i) and the cylinders were used to determine compressive strength (f'_c) and direct pulse velocity (V_d).

Materials used consisted of ordinary Portland cement Type I, beach sand and crushed limestone aggregate which is used widely in and around Dhahran city. Such a typical coarse aggregate, known as Jebel Dhahran, has absorption of about 5%, bulk specific gravity about 2.25, and shows loss of soundness of 4.5% and abrasion loss exceeding

35%. For standard concrete, the mix design corresponded to a cement content of 360 kg m^{-3}, a coarse-to-fine aggregate ratio of 2.0, a maximum coarse aggregate size of 20 mm and a wide range of water cement (w/c) ratios varying from 0.85 to 0.45. It should be noted that by varying w/c ratios and keeping the composition otherwise unchanged, different strengths were generated, and in the way w/c ratio was eliminated as a variable for the mix design. Superplasticizer was used for mixes having w/c ratios of 0.60 or less to enhance workability. For nonreference concrete, different cement contents, coarse aggregate volume fractions, and maximum sizes of coarse aggregate were used to examine parametric variation.

Two types of curing were employed: moist curing and air curing. For moist curing, the specimens, after demolding, were moist cured in water for a full 7 days followed by self curing in air for 21 days inside the laboratory. For the case of air curing, specimens were moist cured after demolding for 1 day only followed by self curing in air for the remaining 28 days. A total of six different mixes were used for the reference concrete, whereas a total of twenty-four different mixes were introduced for nonreference concrete. Tables 1 and 2 show the designations and mix designs for moist cured and air cured concrete, respectively.

Table 1. Mix Design and Test Data for Moist Cured Concrete

Designation	Cement Content kg m^{-3}	CA/FA	Max. Size of Coarse Aggregates (mm)	W/C	V_d km s^{-1}	R	V_i km s^{-1}	Composition Strength f_c' MPa
MS1/2	360	2.0	20	0.85	4.04	30.3	3.72	19.90
MS2/2	360	2.0	20	0.80	4.06	32.7	3.94	24.80
MS3/2	360	2.0	20	0.75	4.31	33.3	3.95	28.10
MS4/2	360	2.0	20	0.70	4.33	38.0	3.98	32.10
MS5/2	360	2.0	20	0.60	4.43	41.3	4.04	37.90
MS6/2	360	2.0	20	0.50	4.50	42.0	4.11	40.60
MS7/2	360	2.0	20	0.45	4.56	43.0	4.14	41.90
MD1/2	400	2.0	20	0.75	4.33	38.0	3.99	31.42
MD1/4	400	2.0	20	0.70	4.35	39.7	4.04	33.74
MD1/6	400	2.0	20	0.50	4.52	43.0	4.10	41.85
MD1/8	400	2.0	20	0.45	4.58	45.0	4.15	42.23
MD2/2	330	2.0	20	0.80	4.03	32.0	3.85	22.55
MD2/4	330	2.0	20	0.75	4.18	33.7	3.89	24.33
MD2/6	330	2.0	20	0.70	4.26	37.0	3.95	28.76
MD2/8	330	2.0	20	0.50	4.50	41.0	4.04	38.92
MD3/2	280	2.0	20	0.85	3.98	30.7	3.68	18.84
MD3/4	280	2.0	20	0.80	4.00	31.7	3.81	19.70
MD3/6	280	2.0	20	0.75	4.15	32.3	3.90	26.70
MD3/8	280	2.0	20	0.70	4.39	36.0	3.93	32.00
MD4/2	360	2.5	20	0.75	4.36	34.3	4.03	24.30
MD4/4	360	2.5	20	0.70	4.38	38.7	4.08	28.47
MD4/6	360	2.5	20	0.60	4.44	42.3	4.13	35.21
MD5/2	360	1.5	20	0.75	4.24	33.3	4.03	29.36
MD5/4	360	1.5	20	0.70	4.29	36.0	4.07	34.52
MD5/6	360	1.5	20	0.60	4.37	38.0	4.10	38.18
MD6/2	360	2.0	12.5	0.80	4.02	32.5	3.69	23.64
MD6/4	360	2.0	12.5	0.70	4.22	36.3	3.90	32.02
MD6/6	360	2.0	12.5	0.60	4.37	37.0	3.96	35.68
MD7/2	360	2.0	25	0.80	4.27	34.0	3.89	27.76
MD7/4	360	2.0	25	0.70	4.35	40.3	3.97	36.40
MD7/6	360	2.0	25	0.60	4.51	42.7	4.10	39.27

Table 2. Mix Design and Test Data for Air Cured Concrete

Designation	Cement Content kg m^{-3}	CA/FA	Max. Size of Coarse Aggregates (mm)	W/C	V_d km s^{-1}	R	V_i km s^{-1}	Composition Strength f'_c MPa
MS1/1	360	2.0	20	0.85	3.82	29.7	3.82	17.80
MS2/1	360	2.0	20	0.80	3.90	30.7	3.86	19.60
MS3/1	360	2.0	20	0.75	4.08	32.0	4.08	23.10
MS4/1	360	2.0	20	0.70	4.10	35.0	4.10	25.90
MS5/1	360	2.0	20	0.60	4.30	38.3	4.30	32.20
MS6/1	360	2.0	20	0.50	4.45	39.3	4.45	35.20
MS7/1	360	2.0	20	0.45	4.52	40.3	4.52	38.0
MD1/1	400	2.0	20	0.75	4.10	35.0	3.97	26.0
MD1/3	400	2.0	20	0.70	4.12	38.3	4.01	26.63
MD1/5	400	2.0	20	0.50	4.46	41.0	4.08	36.33
MD1/7	400	2.0	20	0.45	4.53	45.3	4.12	38.86
MD2/1	330	2.0	20	0.80	3.82	31.7	3.81	18.58
MD2/3	330	2.0	20	0.75	4.07	32.0	3.87	20.24
MD2/5	330	2.0	20	0.70	4.10	34.0	3.93	27.65
MD2/7	330	2.0	20	0.50	4.29	39.0	4.01	33.38
MD3/1	280	2.0	20	0.85	3.80	29.0	3.66	17.83
MD3/3	280	2.0	20	0.80	3.82	30.0	3.78	18.04
MD3/5	280	2.0	20	0.75	4.08	31.3	3.86	22.54
MD3/7	280	2.0	20	0.70	4.10	34.0	3.91	25.77
MD4/1	360	2.5	20	0.75	4.10	33.3	3.98	21.38
MD4/3	360	2.5	20	0.70	4.12	35.7	4.05	23.72
MD4/5	360	2.5	20	0.60	4.32	39.0	4.10	29.23
MD5/1	360	1.5	20	0.75	4.07	31.7	4.01	24.81
MD5/3	360	1.5	20	0.70	4.09	35.7	4.05	29.13
MD5/5	360	1.5	20	0.60	4.17	36.0	4.09	33.42
MD6/1	360	2.0	12.5	0.80	3.84	30.7	3.67	18.82
MD6/3	360	2.0	12.5	0.70	4.07	33.7	3.85	25.48
MD6/5	360	2.0	12.5	0.60	4.18	34.0	3.93	30.07
MD7/1	360	2.0	25	0.80	4.13	32.3	3.85	22.72
MD7/3	360	2.0	25	0.70	4.24	37.0	3.94	29.23
MD7/5	360	2.0	25	0.60	4.36	40.3	4.06	32.66

All test data were generated in the age range of 30–35 days. The rebound number (R) was determined by a NR type Schmidt Hammer equipped with an automatic recorder from test panels and the ultrasonic pulse velocity was measured with a PUNDIT apparatus. Standard procedure were followed in taking measurements and the final value of each measurement corresponded to an average value of a large number of readings. The cylinder strength was determined from compression tests of 75 × 150 mm cylinder and the final compressive strength of a concrete type corresponds to an average of six cylinders strengths. Test data for R, V_d, V_i, and f'_c are tabulated in Tables 1 and 2 for all mixes of moist cured concrete and air cured concrete, respectively.

Strength Curve

A combined strength calibration curve was developed first for the reference concrete by using a regression analysis of data for f'_c, V_d, and R. In order to ascertain the best form of the formula by which f'_c can be related to R and V_d, first the relationship between f'_c and R and f'_c and V_d were examined separately. Among various forms of equations attempted, it was observed that the most appropriate calibration of R for f'_c was linear, $f'_c = a_1 R + b_1$ and that for V_d was a second order polynomial of the form $f'_c = a_2 V_d^2 + b_2 V_d + C_2$. In view of this observation, in the combined calibration, f'_c was modelled as a linear function of R and a nonlinear function of V_d:

$$f'_c = a_3 + b_3R + C_3V_d^n\,, \qquad (1)$$

where a_3, b_3, c_3, and n are constants to be determined from a multilevel regression on all test data for f'_c, and R, and V_d.

The best fitting equation takes the form:

for moist cured concrete

$$f'_c = 0.24V_d^3 + 1.1R - 27.81\,, \qquad (2)$$

and for air cured concrete

$$f'_c = 0.288V_d^3 + 0.872R - 24.13\,. \qquad (3)$$

In Equations 2 and 3, f'_c is expressed in N mm^{-2} and V_d in km s^{-1}. For all regressed equations, the correlation coefficient was over 0.96 and the value of standard error of estimate was no more than 4%. The calibration equations (Equations 2 and 3) can be used to generate isostrength curves in $R-V_d$. Figures 1 and 2 show respectively the isostrength curves for the moist cured and air cured reference concrete.

CORRECTION FACTORS

Individual Correction Factors

In order to determine the strength of a concrete whose composition varies from that of the reference concrete in terms of a single variable, individual correction factor has been developed for each of the three dominant variables of mix design considered in this study. Individual correction factors for variation in cement content, coarse aggregate volume fraction, and maximum coarse aggregate size have been proposed to account for the variability of concrete strength due to each of these variables.

To study the effect of cement content alone, test specimens were cast using variable cement content, keeping all other parameters of the mix design same as the reference concrete. For each cement content (400 kg m^{-3}, 330 kg m^{-3}, and 280 kg m^{-3}), four mixes were used with varying w/c ratio. In Tables 1 and 2, these samples are marked as MD1 to MD3. It should be recognized that the w/c ratio was excluded as a variable by making use of different w/c ratios to generate a wide range of compressive strength for a fixed mix proportions of raw materials.

The correction factor for cement content alone, designated as C_c, is defined as the ratio of the actual to the estimated strength of the reference concrete. For evaluation of C_c, first the equation for f'_c was developed exclusively for each cement content using experimental data for f'_c, R, and V_d (Tables 1 and 2) in a regression analysis. For example, the concrete strength equation for cement content of 400 kg m^{-3} for moist cured concrete is:

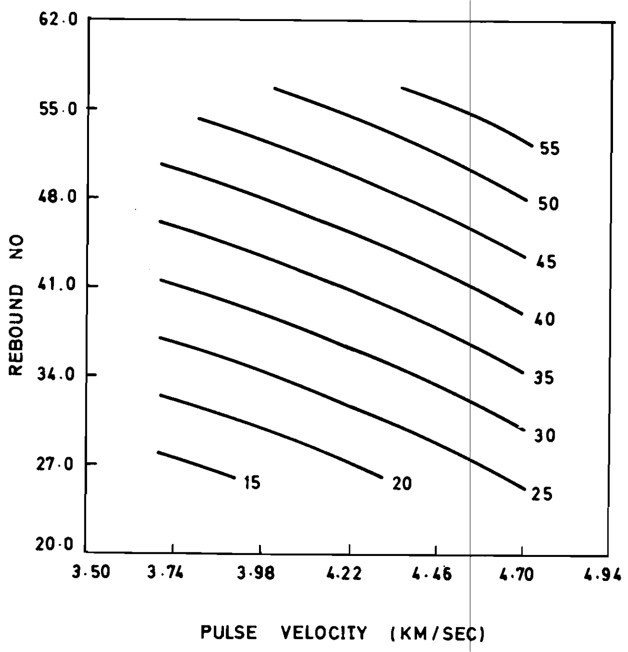

Figure 1. Isostrength Curve for Reference Concrete (Moist Cured).

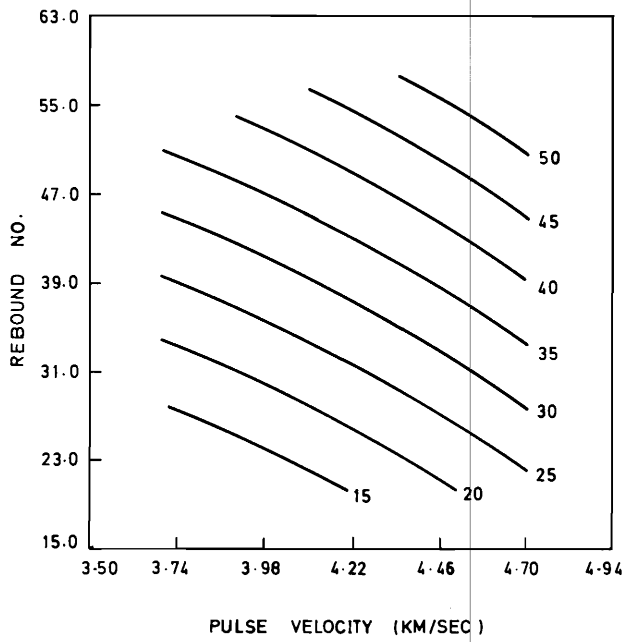

Figure 2. Isostrength Curve for Reference Concrete (Air Cured).

$$f'_c = 1.26R + 0.191V_d^3 - 27.59\,. \qquad (4)$$

The value of C_c for cement content of 400 kg m^{-3} is then given as the ratio of Equation 4 to Equation 2 for moist cured concrete. Thus for this cement content,

$$C_c = \frac{1.26R + 0.191V_d^3 - 27.59}{1.1R + 0.24V_d^3 - 27.81} \,. \tag{5}$$

For specifying an average value of C_c for each cement content which can be used for a wide range of f'_c values, the following procedure was followed. Using the cement content of 400 kg m^{-3} as an example, Equation 5 was used to generate values of C_c for arbitrary values of R and V_d within the range recorded in test measurements. From these computed values of C_c shown in Table 3, which varied from 1.04 to 1.07, an average value of C_c was established as 1.06 for cement content of 400 kg m^{-3}.

Similar procedure was followed for other two cement contents, 280 kg m^{-3} and 300 kg m^{-3}. Using an average values of C_c established for each cement content, a regression analysis was performed to derive a relationship between C_c and the cement content. For this purpose, cement content was normalized with respect to reference concrete's cement content and is expressed as a variable α defined as

$$\alpha = \frac{\text{cement content in kg m}^{-3}}{360\ \text{kg m}^{-3}} \,. \tag{6}$$

The best fitting equations relating C_c to α are as follows:

for moist cured concrete

$$C_c = 0.817 + 0.183\alpha^3 \,, \tag{7}$$

and for air cured concrete

$$C_c = 0.490 + 0.510\alpha^3 \,. \tag{8}$$

Figures 3 and 4 show plots of Equations 7 and 8, respectively. A value of $\alpha = 1.0$ represents the reference concrete for which C_c is 1.0. As seen from Figures 3 and 4, the proposed equations for C_c closely fit with the data and have correlation coefficients exceeding 0.96.

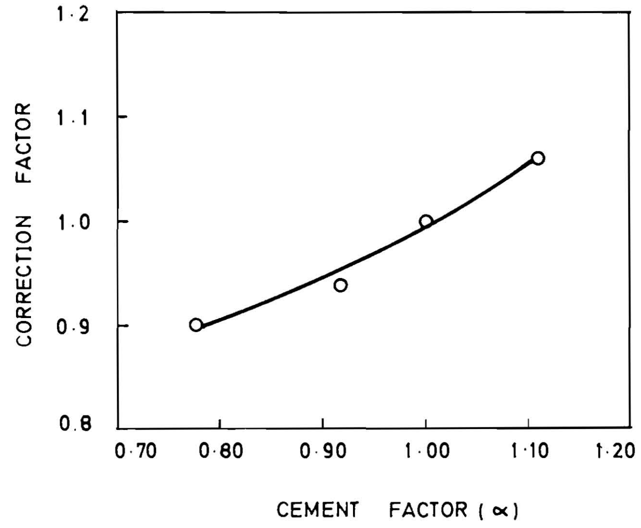

Figure 3. Correction Factor for Cement Content (Moist Cured Concrete).

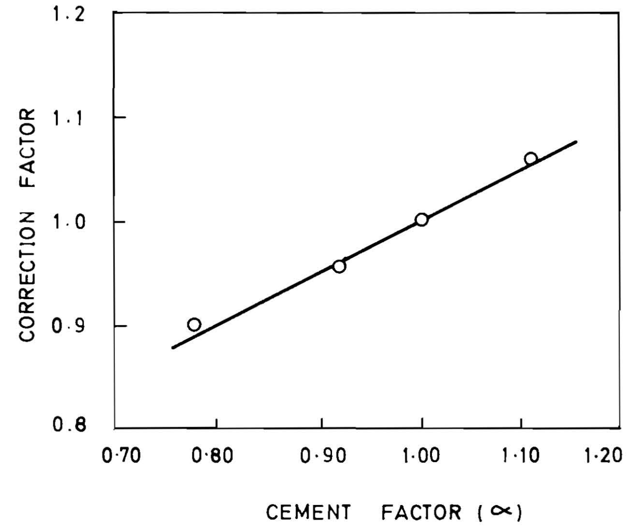

Figure 4. Correction Factor for Cement Content (Air Cured Concrete).

Table 3. Value of C_c for Cement Content of 400 kg m^{-3}

Value of C_c	V_d	R	C_c	Average C_c
$C_c = \frac{1.26R + 0.19V_d^3 - 27.59}{1.1R + 0.24V_d^3 - 27.81}$	4.0	30	1.09	1.06
	4.15	34	1.08	
	4.30	38	1.07	
	4.45	40	1.06	
	4.60	45	1.06	
	4.80	50	1.05	
	5.0	55	1.04	

Following exactly the same procedure prescribed for evaluation of C_c, the correction factors for coarse aggregate volume fraction and the maximum aggregate size were determined. For coarse aggregate volume fraction, V_F, the correction factor, C_v, is

for moist cured concrete,

$$C_v = 2.667 - 2.763\,V_F\,, \tag{9}$$

and for air cured concrete,

$$C_v = 2.615 - 2.671\,V_F\,. \tag{10}$$

In the development of correction factor, C_s, for the maximum coarse aggregate size, only two other aggregate sizes different from the 20 mm size used in reference concrete, namely 25 mm and 12.5 mm, were used. The values of C_s determined were as follows: $C_s = 0.90$ for 12.5 mm, $C_s = 1.00$ for 20.0 mm, and $C_s = 1.09$ for 25.0 mm aggregate size. These values are applicable for both moist cured and air cured concrete.

Total Corrector Factor

For a concrete whose mix design is totally different from that of the reference concrete, a total correction factor C_t in terms of the three variables must be applied to the strength of reference concrete. For such a concrete whose R and V_d readings are available, the strength of the reference concrete corresponding to these values of R and V_d (Equations 2 and 3 as applicable) is multiplied by the total correction factor C_t to obtain the strength of the concrete in question.

In the past work [8, 9], C_t has been modelled as a product of individual correction factors. The validity of this formulation is questionable, as it ignores the possible interactive influences of each variable on the other with regard to strength. In this study, a new approach has been followed to relate C_t with three variables C_c, C_v, and C_s considered in this work.

For the purpose of a better correlation, the data from 8 different mixes shown in Table 4 as MC series were used in a multilevel regression analysis. For each of these mixes, individual correction factors were determined considering each variable (Table 4) and then using the actual strength and the strength of the reference concrete, a relationship between C_t and the individual correction factor was derived. The best form of the resultant equation is

$$C_t = C_c^{1.15}\,C_v^{0.10}\,C_s^{0.20}\,. \tag{11}$$

Equation 11 is valid for Jebel Dhahran aggregate which has been used in this study. It is apparent that the most dominant factor for the correction factor is the cement content. For a given cement content and w/c ratio, the relatively small fluctuations in strength due to variation in the coarse aggregate volume fraction and the maximum aggregate size are taken care of by the C_v and C_s factors. For an aggregate other than the Jebel Dhahran type, this equation may have to be modified to include the effect of aggregate types. In a limited study undertaken in reference [12], the total correction factor C_t^* has been suggested in the following form:

$$C_t^* = C_A\,C_t\,. \tag{12}$$

Where C_A is the correction factor for aggregate type other than Jebel Dhahran (For Jebel Dhahran aggregate $C_A = 1.0$).

Correction Between Direct and Indirect Pulse Velocity

Due to the difficulty encountered in getting direct pulse velocity measurements in the field, pulse

Table 4. Experimental Data for Modeling Total Correction Factor

Designation	V_d km s^{-1}	R	Actual Strength MPa	Estimated Strength MPa	C_t	C_c	C_v	C_s
MC1	4.36	37.8	28.2	33.65	0.838	0.916	1.009	1.0
MC2	4.44	41.5	42.2	38.86	1.086	0.964	0.899	0.90
MC3	4.49	42.5	37.66	40.67	0.926	1.017	1.064	1.09
MC4	4.25	37.3	26.35	31.63	0.833	1.025	1.193	1.0
MC5	4.14	37.0	27.30	29.93	0.912	1.061	1.062	1.0
MC6	4.53	40.3	32.76	35.95	0.911	1.061	1.24	1.0
MC7	4.79	40.7	44.68	40.13	1.11	1.10	1.01	0.9
MC8	4.60	41.0	36.90	37.64	0.98	1.025	1.11	1.0

velocity is often measured indirectly. Thus, it is necessary to correlate direct and indirect pulse velocities. From a large number of test data for V_d and V_i for different concrete mixes, it was observed that relationship of V_d to V_i can be taken in the form

$$V_\mathrm{d} = KV_\mathrm{i}\,, \tag{13}$$

K being a constant. Although the value of K varies from one mix to the other, the narrow fluctuations allow to suggest a mean value of $K = 1.07$ for all concrete made of Jebel Dhahran aggregate.

VERIFICATION OF MODEL

The strength equations were developed on the basis of 28-day cylinder strength of concrete. Due to aging, the in-situ strength of a physically perfect concrete is likely to be slightly higher than the 28-day strength. The strength prediction model would thus produce results which are expected to be slightly conservative.

For the purpose of verification of the reliability of the proposed model, attempt made to collect field data from concrete made with Jebel Dhahran or similar coarse aggregate in the Eastern Province did not meet with success. As an alternative, in-situ data for concrete collected in a project on the cracking of bridge decks [13] was used. Reference 13 provides in-situ measurements of R, V_i, and core strengths of concrete in a number of concrete bridges in Saudi Arabia.

Six bridges decks were selected for which data appeared to be flawless. It should be noted that coarse aggregates used in these decks were of superior quality compared to the Jebel Dhahran aggregate. Table 5 shows the in-situ measurements of R, V_i and f'_c for cores along with the computed values of correction factors. The core strength was converted to equivalent cylinder strength by dividing by 0.91, a value which was established as an appropriate conversion factor [12]. The ratio of the actual to predicted strength of concrete are shown in Table 5. As expected, the predicted strength underestimates the actual strength in all cases. The discrepancy is attributable to the quality of coarse aggregate used for which the factor C_A in Equation 12 would be greater than 1.0.

An Example

To demonstrate the use of the suggested approach for estimation of the in-situ concrete strength, an example is given.

Suppose that from in-situ measurements, R is 40; V_i is 3.80 km s^{-1}. From chemical analysis of a broken piece of in-situ concrete, the cement content is 340 kg m^{-3}; CA/FA ratio is 1.80, the maximum size of coarse aggregate = 25 mm, concrete density is 2380 kg m^{-3} and the bulk specific gravity of coarse aggregate is 2.25.

$V_\mathrm{d} = 1.07 \times 3.80 = 4.07$ km s^{-1}; thus f'_c from Equation 2 equals 32.4 MPa. For the correction factor C_c, $\alpha = 340/360 = 0.944$; hence $C_\mathrm{c} = 0.97$ from Equation 7. The coarse aggregate volume fraction, $V_\mathrm{F} = 1.8(2380-340)/(2.8 \times 2250) = 0.583$; thus, from Equation 9, C_v is 1.06 and for 25 mm aggregate size C_s equals 1.09. Thus total correction factor C_t is 0.99 from Equation 11. Assuming Jebel Dhahran or similar aggregate, $f'_\mathrm{c} = 0.99 \times 32.4 = 32.1$ MPa.

CONCLUSIONS

For estimation of in-situ concrete strength in the Eastern region of Saudi Arabia, a prediction model has been proposed by combining in-situ measurements of two nondestructive test methods, namely

Table 5. Verification of the Proposed Model

Designation	V_d km s^{-1}	R	C_c	C_v	C_s	C_t	Actual Core Strength MPa	Cylinder Strength f'_c MPa	Estimated Strength by Equation (2) MPa	Estimated Strength f'_ce with Correction MPa	Ratio $f'_\mathrm{c}/f'_\mathrm{ce}$
HAIL	3.42	41.37	0.89	1.00	0.90	0.842	26.25	28.85	27.29	23.00	1.25
ABHA-1	3.90	37.73	0.92	1.34	1.00	0.960	29.29	32.19	27.93	26.81	1.20
ABHA-2	4.12	31.00	0.88	1.34	1.09	0.933	20.29	22.30	23.10	21.55	1.04
ABHA-3	3.88	30.80	0.94	1.53	1.09	1.040	22.33	24.54	20.10	20.90	1.17
JED-1	3.67	34.74	0.86	1.45	1.00	0.900	24.97	27.44	22.27	20.04	1.38
JED-2	3.73	37.00	0.86	1.14	1.09	0.880	29.54	32.46	25.34	22.30	1.45

ultrasonic pulse velocity and hammer rebound number (surface hardness). The strength equations are developed by a regression analysis of test data generated from a reference concrete of a specified mix proportions. From a study of the variability of concrete strength due to significant mix parameters, appropriate correction factors are proposed for evaluation of concrete strength whose composition is different from that of the reference concrete.

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