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Assessment of concrete compressive strength using the Lok test

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This paper reports the results of a comprehensive investigation to assess the accuracy and predictability of the Lok test for estimation of the *in situ* compressive strength of concrete made with: (i) three water-to-cement ratios, (ii) two cement contents, and (iii) two types of local carbonate aggregates from eastern Saudi Arabia. The compressive strength of both cast and cored cylindrical specimens was statistically correlated with the Lok force. Based on a regression analysis of the generated data, the influence of the above mixture design variables on the compressive strength–Lok force correlation was assessed. The results of the statistical analyses compared well with those reported in the international literature. Among the linear, bi-linear, quadratic and cubic models used, the results indicated that the linear relationship between the compressive strength and the Lok force was very significant and totally independent of all the mixture design variables. Hence, the Lok test can be used in estimating the *in situ* compressive strength with a high degree of reliability.

Keywords: concrete; correlation; compressive strength

It is now well recognized that compressive strength is an excellent indicator of concrete quality and it invariably forms the most important basis of specifications and quality control, as many other properties of concrete are directly or indirectly related to it. However, the conventional methods of determining compressive strength of a concrete structure have some limitations typified by the inherent errors in sampling and the fact that concrete to be cast in structures is transported, placed, compacted and cured differently from that cast in typical laboratory cylinders or cubes. Further, determining the compressive strength of a concrete structure is considered at best a semi-destructive test and at worst a destructive one. To overcome such limitations, considerable efforts have been made in the past to develop other testing methods, particularly those of a nondestructive nature, that would permit an assessment of the quality of concrete and its behaviour in the structure.

Over the past few decades, nondestructive testing of concrete has received increasing acceptance for an evaluation of the strength, properties and uniformity of *in situ* concrete; such testing has been necessary either as part of a quality assurance programme or as part of a diagnostic evaluation of the causes of concrete problems with regard to durability, cracking and compliance to prescribed specifications. Hence, an increased demand for more precise and practical methods to assess concrete quality has led to the development of a large variety of techniques for evaluating concrete properties, such as strength, durability and quality control.

These techniques attempt to measure some of the properties of concrete from which an estimate of strength, durability and its elastic parameters are obtained. Based on some inherent properties, such as hardness, resistance to penetration and the propagation of an ultrasonic pulse, various nondestructive methods of testing concrete have evolved, such as the rebound method, penetration techniques, pulse velocity methods, and pullout tests.

Of the nondestructive tests available, the pullout tests appear to have the greatest potential for acceptance as a measure of the compressive strength of structural concrete. Pullout testing is not a recent development; it has been in use in what was previously the USSR since the 1930s[1]. However, much of its recognition and advances occurred during the 1960s and 1970s[2,3], and it has been standardized under the ASTM C 900 specification for determining the pullout strength of concrete[2]. These techniques are specially designed for *in situ* testing of concrete and, unlike most other nondestructive methods, offer the advantage of a direct determination of some strength parameters. In addition, the techniques show a relatively good degree of correlation with the 'standard' strength. Furthermore, another potential usage of pullout testing is to determine the safe removal time for forms or the earliest time at which

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post-tensioning of prestressed tendons may safely take place. Pullout tests are also known to meet general field-use requirements[4] in that they are relatively inexpensive, fast and easily performed with a minimal amount of training.

Studies[5–8] show that some correlations exist between the compressive strength of standard cylinders or cubes cured under standard conditions or of cores drilled from structures and the pullout strength of concrete, indicating the possible usefulness of these tests for comparative studies. Further, a review of the literature indicates that the pullout tests actually measure the direct shear strength of concrete[5,6,8,9], and the failure of concrete is caused by crushing of the concrete[10], and not by cracking, which means that the pullout strength depends primarily on the compressive strength of concrete.

The mechanisms of pullout tests are very simple; they measure the force required to pull out test bolts embedded in the structure. Thereafter, an empirically-established relationship is used for conversion of these measurements to the cylinder or cube compressive strength of concrete[11]. Principally, there are two types of pullout tests: the Lok and the Capo tests; both are conducted when a solid part is extracted from the concrete by means of an embedded disc which is pulled out under the application of a counter-pressure. In the former test, however, the insert is placed in the specimens to be tested during the casting stage of concrete, as will be explained in the experimental programme. For the Capo test, the insert is placed after the concrete has been hardened[8].

This investigation was conducted to generate a sufficient amount of test data on the Lok test for the purpose of modelling. In particular, the isolated effect of aggregate type, cement content, water-to-cement ratio and curing period was assessed to verify the accuracy and reliability of Lok-test methodology for estimation of the *in situ* compressive strength of concrete and to develop the necessary predictive models between the pullout force and compressive strength using both cast and cored 'standard' cylinders. Because of the increasing usage of the Lok test in quality assurance/quality control and in determining removal time for forms, the information presented in this paper can enhance the predictability of the Lok test as an *in situ* tool for the evaluation of concrete strength.

Experimental programme

Materials

ASTM 150 Type V cement and a coarse-to-fine aggregate ratio of 1.63 by weight were kept invariant in all concrete mixtures. Two cement contents of 300 and 400 kg m^{-3} were used. Two types of indigenous crushed limestone coarse aggregate from the Eastern Province of Saudi Arabia, namely the Jabel Dhahran and Abu-Hadriyah, were used with a maximum size of 19 mm. The fine aggregate was dune sand. The specific gravity and absorption of fine and coarse aggregates are presented in *Table 1*. Three water-to-cement ratios of 0.45, 0.55 and 0.65 were used. A naphthalene formaldehyde sulphonate-based superplasticizer was used, when necessary, to maintain a slump in the range of 75 to 100 mm for all concrete mixtures. Potable water was used in the mixing and curing of all concrete specimens.

Techniques

Casting of specimens. For each concrete mixture, 21 cylinders, 75 mm in diameter and 150 mm in height, and two slab panels, 750 × 500 × 150 mm, were cast by filling the moulds in approximately three equal layers and compacting them on a vibrating table. Each panel had seven standard 25 mm diameter inserts (i.e., a total of 14 Lok inserts for each mix) that were distributed at equal distances of 12.5 mm centre-to-centre to achieve adequate edge distances and spacings between the test points. Furthermore, the inserts were placed in the mid-height region of two side faces of the panels in order to: (i) avoid the effects of bleeding and levelling of top layers, and (ii) ensure uniformity of tests. Such an arrangement is expected to minimize the effects of within-specimen variability[12]. After casting, the specimens were covered with wet burlap for 24 h prior to demoulding. It is noteworthy to mention that the Lok-test inserts had been placed in the panel mould before casting; the distance between the disc and mould surface was 25 mm, as recommended by the manufacturer[13]. One day after casting, the screws were removed and the specimens demoulded. Thereafter, both types of specimens were cured by spraying with water twice a day for seven days followed by curing at the exposure site until testing. Typical environmental conditions of the exposure site are shown in *Table 2*[14]. It is to be noted that casting and exposure of all test specimens were conducted during the months of September and October.

Table 1 Absorption and specific gravity of fine and coarse aggregates

Aggregate type	Bulk specific gravity[a]	Apparent specific gravity[a]	Absorption (%)[b]
Fine aggregate (sand)	2.70	–	0.23
Jabel Dhahran aggregate	2.25	2.54	2.86
Abu-Hadriyah aggregate	2.48	2.63	1.40

[a] ASTM C 127
[b] ASTM C 128

Table 2 Environmental data typical of the eastern Saudi exposure site[14]

Parameter	January	April	July	October
Temperature (°C)				
Average mean	16.8	24.3	34.9	27.0
Average maximum	20.5	28.9	36.6	31.2
Average minimum	12.6	20.8	33.5	22.7
Relative humidity (%)				
Average maximum	87.3	70.5	60.6	77.6
Average minimum	52.0	40.5	26.8	39.0
Rainfall (mm)				
Total/month	15.6	4.0	0.0	0.2
Average wind speed (mps)	4.3	4.6	5.2	3.9
Average mean H_2S (ppb)	1.0	1.0	1.0	1.0
Average mean SO_2 (ppb)	1.0	1.0	1.0	1.0

Compressive strength and Lok tests. Following the prescribed period of curing, three cylindrical specimens were retrieved and tested in accordance with ASTM C 39. All the tested specimens were capped before testing.

At each testing interval, i.e., after 3, 7, 14 and 28 days, at least three Lok tests were conducted according to the following procedure[15] (reference is made to *Figure 1*):

1. Lok-test inserts were placed in the form before casting of the concrete (*Figure 1(a)*).
2. Just before testing, the disc stem is removed. A special pull-out bolt is threaded into the discs and attached to the testing machine (*Figure 1(b)*).
3. Pulling force is applied by turning the instrument handle. At the moment of concrete failure, the pointer of the gauge will stop moving and fall back, and the maximum pulling force is recorded (*Figure 1(c)*).
4. The Lok instrument and the pull-bolt are removed and, in this case, the surface of the concrete will be relatively undamaged. If, however, turning the instrument handle (i.e., loading) continues until failure, a small conical pit will be formed on the concrete surface (*Figure 1(d)*).

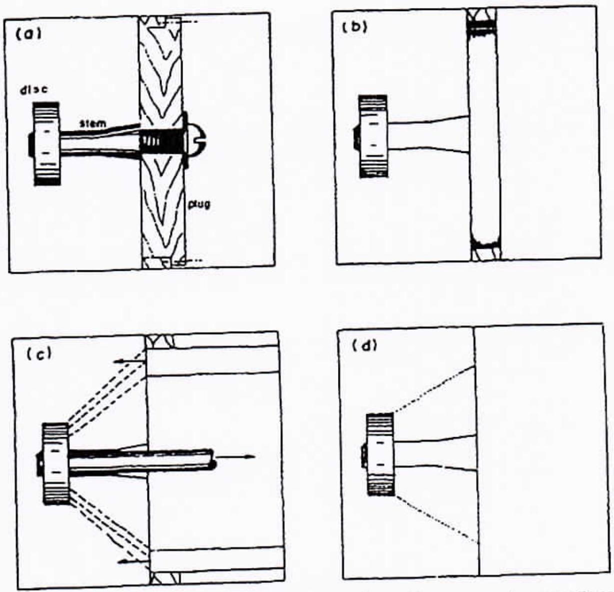

Figure 1 Schematic diagrams showing the general procedure followed in the Lok test[15]

Results and discussion

Results of this investigation are presented numerically in *Tables 3* and *4* and schematically in *Figures 2* to *9*. These typical figures represent only part of the data in the tables to identify the role of the different mixture design variables, that included curing period, water-to-cement ratio, cement content and aggregate type, on the compressive strength of the concrete cylinders as well as on the Lok strength. Thereafter, this laboratory-generated data was statistically analysed in conjunction with the other data developed from the compressive strength of cylindrical cores from similar mixtures[16], to arrive at the best predictive models that could be used to predict the compressive strength of *in situ* concrete structures if and when Lok tests are to be used. Finally, these models were compared with those reported in the literature.

Effect of curing period

The compressive strength data of the concrete cylinders using Jabel Dhahran aggregate (hereafter denoted as J-D aggregate) is presented in *Figure 2* for the various water-to-cement ratios and made with a cement content of 300 kg m^{-3}. This data follows the conventional behaviour of an increase in compressive strength with an extension in the curing period. The rate of increase in strength, however, decreased marginally beyond the initial 14 day period of curing. The increase in strength with extended curing is also shown in *Figure 3* when the Lok test was used. Similar trends can also be observed for all the other mixtures using the 400 kg m^{-3} cement content and Abu-Hadriyah aggregate (hereafter abbreviated as A-H aggregate) (see *Tables 3* and *4*).

Table 3 Summary of cylinder strength test results (MPa)

Curing period, days ↓	Jabel Dhahran aggregate								Abu-Hadriyah aggregate					
Cement content →	300		kg m^{-3}		400				300		kg m^{-3}	400		
W/C →	0.45	0.55	0.65	0.70	0.45	0.55	0.65	0.70	0.45	0.55	0.65	0.45	0.55	0.65
3	15.93	12.19	10.92	9.22	26.33	18.90	15.09	10.54	24.41	17.03	14.89	25.24	17.92	15.20
7	22.86	19.06	13.77	12.04	28.28	24.67	18.79	14.21	28.70	24.25	19.80	29.58	24.40	22.49
14	25.91	24.09	16.58	15.32	31.17	28.15	21.82	16.66	31.87	28.47	24.02	32.38	29.64	25.62
28	29.35	26.82	20.09	18.81	35.11	30.40	24.15	19.80	35.43	28.83	25.94	36.75	34.00	30.30

Table 4 Summary of the Lok force test results (kN)

Curing period, days ↓	Jabel Dhahran aggregate								Abu-Hadriyah aggregate					
Cement content →	300		kg m^{-3}		400				300		kg m^{-3}	400		
W/C →	0.45	0.55	0.65	0.70	0.45	0.55	0.65	0.70	0.45	0.55	0.65	0.45	0.55	0.65
3	16.67	15.00	12.33	9.00	23.67	16.67	14.00	13.33	20.00	17.67	16.00	21.33	16.67	15.00
7	22.00	18.33	15.33	12.33	26.00	18.67	16.33	15.00	26.67	19.67	17.33	24.00	21.67	18.00
14	24.33	19.67	17.00	15.00	30.33	23.33	19.00	15.67	28.00	23.67	20.67	29.00	24.00	21.67
28	27.33	22.00	18.67	17.33	31.00	25.00	20.00	16.67	31.67	26.00	23.33	32.67	28.00	25.00

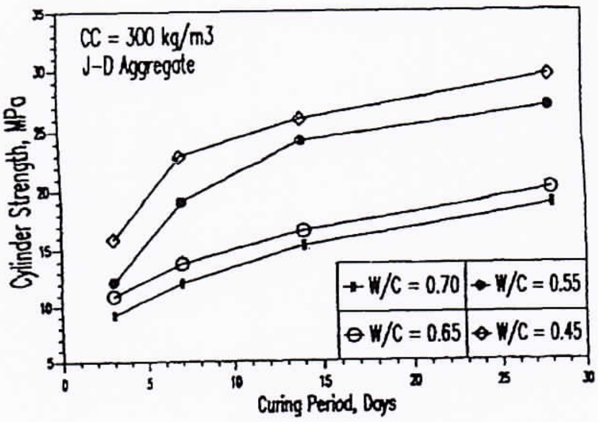

Figure 2 Typical presentation showing the effect of curing period on cylinder strength

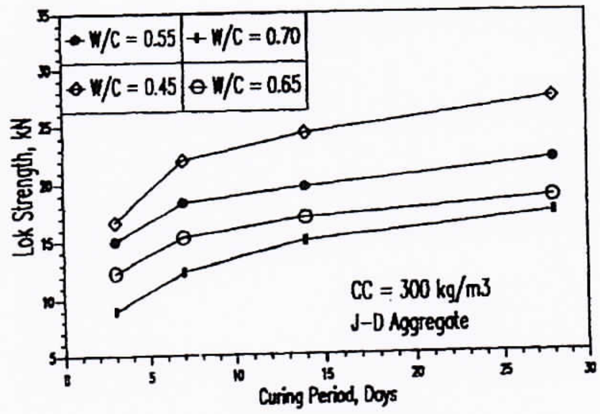

Figure 3 Typical presentation showing the effect of curing period on Lok strength

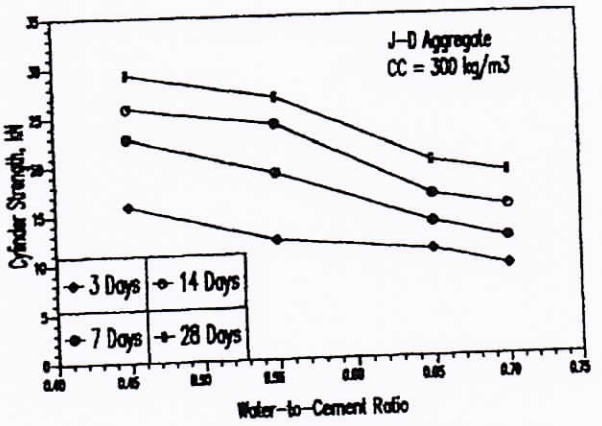

Figure 4 Typical presentation showing the effect of water-to-cement ratio on cylinder strength

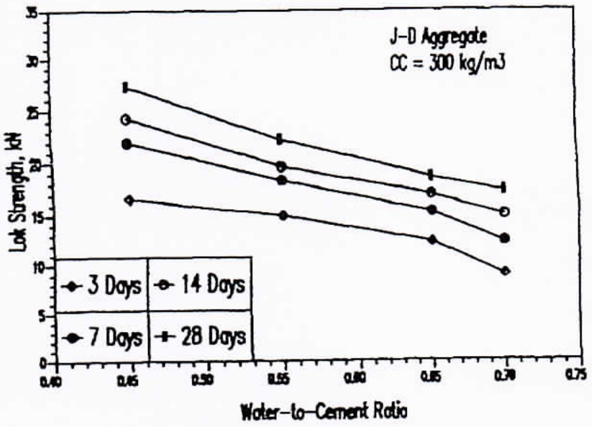

Figure 5 Typical presentation showing the effect of water-to-cement ratio on Lok strength

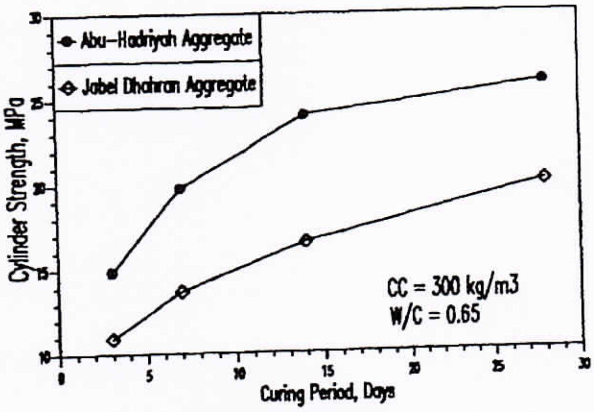

Figure 6 Typical presentation showing the effect of aggregate type on cylinder strength

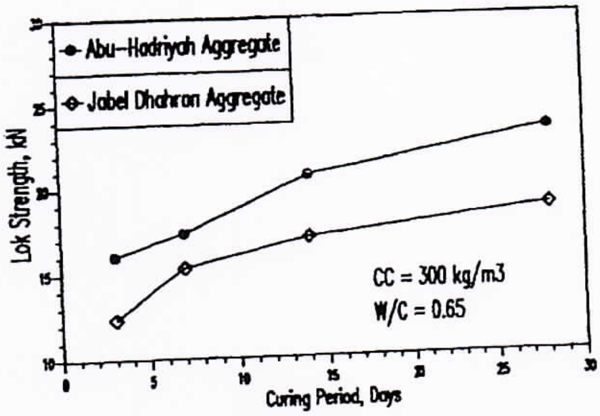

Figure 7 Typical presentation showing the effect of aggregate type on Lok strength

Effect of w/c ratio

Figure 4 depicts the change in cylinder strength with water-to-cement (w/c) ratio at various curing periods for J-D aggregate and a cement content of 300 kg m^{-3}. As expected, the strength decreases with an increase in the w/c ratio; the decrease is more significant when the w/c ratio is more than 0.55. The other data in *Table 3* follows, more or less, the same trend. Similar observations can also be depicted in *Figure 5* and *Table 4* for the Lok test data.

Effect of aggregate type

The effect of aggregate type on the cylinder and Lok strength is presented in *Figures 6* and *7*, respectively, for

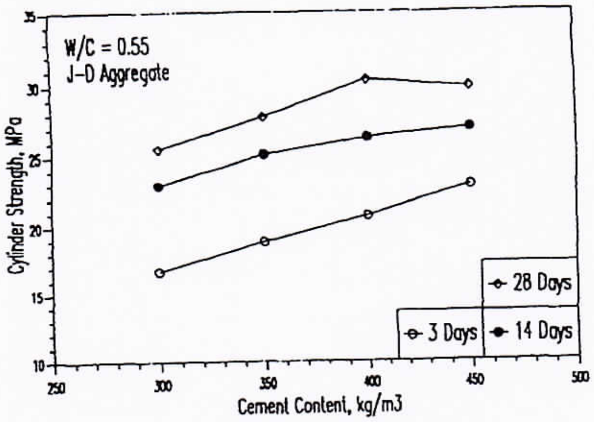

Figure 8 Typical presentation showing the effect of cement content on cylinder strength

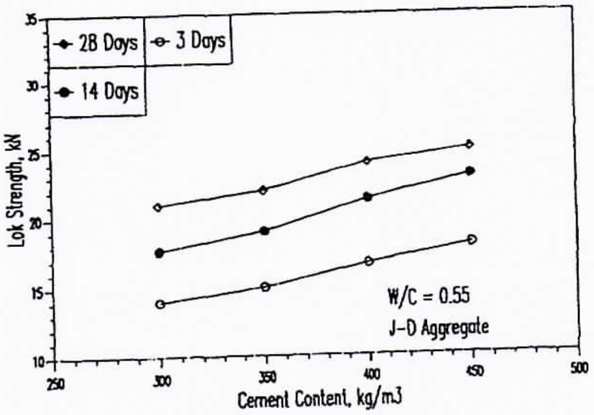

Figure 9 Typical presentation showing the effect of cement content on Lok strength

a w/c ratio of 0.65 and a cement content of 300 kg m^{-3}. This data indicates that the strength of both the cylinder and the Lok is significantly increased when the J-D aggregate is replaced by the A-H aggregate. For example, an increase of 29% and 20% in the 28-day cylinder and Lok strengths, respectively, was attained when A-H aggregate was used.

A similar improvement can be observed for the other mixtures presented in *Tables 3* and *4*. These significant improvements in concrete strength negate the general belief that aggregates, particularly the coarser ones, are inert materials which are used only to increase the volume of concrete[17]. It should be noted that although both types of aggregate are composed of crushed limestone rocks, the superior performance of concrete mixtures made with A-H aggregate is attributed to its denser structure and characterized by its higher specific gravity and lower absorption compared with J-D aggregate, as shown in *Table 1*.

Effect of cement content

The data in *Tables 3* and *4* indicates that increasing the cement content from 300 to 400 kg m^{-3} is associated with an increase in the concrete strength of both the cylinder and Lok test specimens, almost totally irrespective of the w/c ratio, type of aggregate or period of curing. However, the quantum of increase in strength could not be assessed because only two cement contents were used in the initial stages of this investigation. Therefore, two more cement content mixtures of 350 and 450 kg m^{-3} were cast using a w/c ratio of 0.55 and J-D aggregates. Both cylinder and Lok strength tests were conducted after 3, 14 and 28 days of curing. *Figures 8* and *9* show the results of these tests whereby the strength, both the cylinder and the Lok, increased relatively marginally with an increase in the cement content. This increase in strength was, however, observed to diminish beyond a cement content of 400 kg m^{-3}. Furthermore, it can be observed that the increase in strength during the early period of curing (i.e., from 3 to 14 days) was more than that during the later period (i.e., from 14 to 28 days). This is attributed to the fact that the rate of hydration during the early period, when the cement is not yet fully hydrated, is accentuated with curing compared with the rate of hydration at later periods.

Predictive models

The main objective of this experimental research programme was to develop the best possible correlative model capable of evaluating the strength of concrete structures with a high degree of predictability and accuracy using the nondestructive Lok strength data. Hence, both the cylinder and Lok strength results presented in *Tables 3* and *4*, within the 28 days of curing, were analysed statistically based on a regression analysis using the SAS computer package[18]. To enhance the degree of predictability, the compressive strength of cylindrical cores of 75 × 150 mm was also included in the statistical analyses[16]. These cores were obtained from the same panels which were used in the Lok strength determination. They were tested in a similar manner to the cylindrical specimens, as explained previously. Each test result represents an average of triplicate specimens of the same concrete mixture.

The results of the statistical analyses are presented quantitatively in *Table 5* and schematically in *Figures 10* to *13*. These figures show, respectively, the influence of curing period, w/c ratio, cement content and aggregate type on the compressive strength (MPa) and Lok force (kN) correlations. Furthermore, *Figure 14* presents the relationship between the strength of the cored cylinders and the Lok strength for similar mixtures to those presented in this investigation. These results reveal the following observations:

(i) From the statistical test results (*Table 5*), it seems that the best relationship between the cylinder strength and the Lok force is linear and of the general form:

$$F_c = a + b\,P_L \tag{1}$$

where:

Table 5 Summary of statistical analyses of test results

Variable parameter	Best predictive model	√MSE	Coefficient of variation (%)	Coefficient of multiple determination (R^2)	Coefficient of correlation
Time					
3 days	$F_c = -5.74 + 1.38\ P_L$	1.82	10.9	0.90	0.95
7 days	$F_c = -2.48 + 1.29\ P_L$	2.96	13.7	0.75	0.86
14 days	$F_c = -0.31 + 1.14\ P_L$	1.84	7.34	0.91	0.95
28 days	$F_c = 0.90 + 1.11\ P_L$	1.39	4.92	0.95	0.97
W/C Ratio					
0.65	$F_c = -7.15 + 1.50\ P_L$	1.44	7.23	0.93	0.96
0.55	$F_c = -6.66 + 1.47\ P_L$	1.92	7.90	0.90	0.95
0.45	$F_c = -0.33 + 1.12\ P_L$	1.60	5.58	0.92	0.96
Cement Content					
300 kg m^{-3}	$F_c = -3.14 + 1.26\ P_L$	2.40	11.3	0.88	0.94
400 kg m^{-3}	$F_c = -1.37 + 1.21\ P_L$	1.87	7.63	0.93	0.96
Aggregate Type					
Jabel Dhahran	$F_c = -2.93 + 1.24\ P_L$	1.97	9.59	0.92	0.96
Abu-Hadriyah	$F_c = 0.44 + 1.15\ P_L$	2.15	8.24	0.88	0.94
Overall	$F_c = -2.878 + 1.252\ P_L$	1.858	8.100	0.932	0.965
Cored cylinders	$F_c = 0.48 + 0.934\ P_L$	1.97	8.91	0.86	0.93

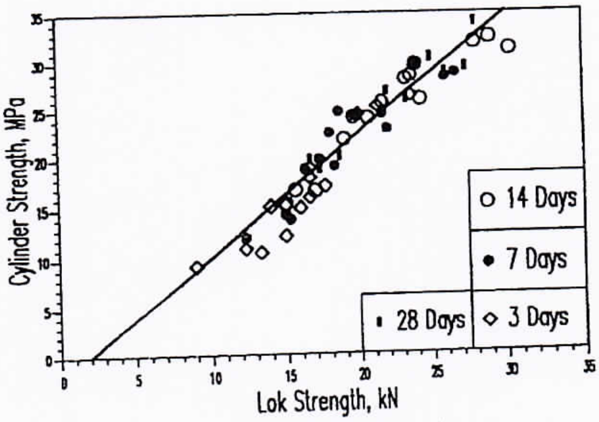

Figure 10 Effect of curing period on the cylinder–Lok strength relation

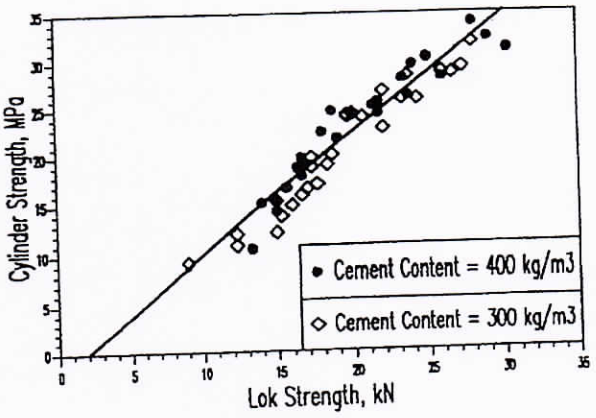

Figure 12 Effect of cement content on the cylinder–Lok strength relation

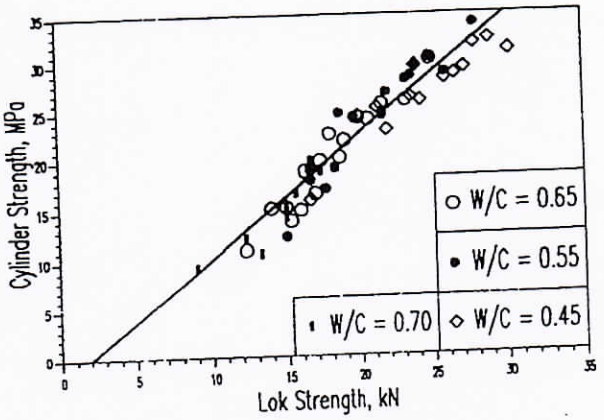

Figure 11 Effect of w/c ratio on the cylinder–Lok strength relation

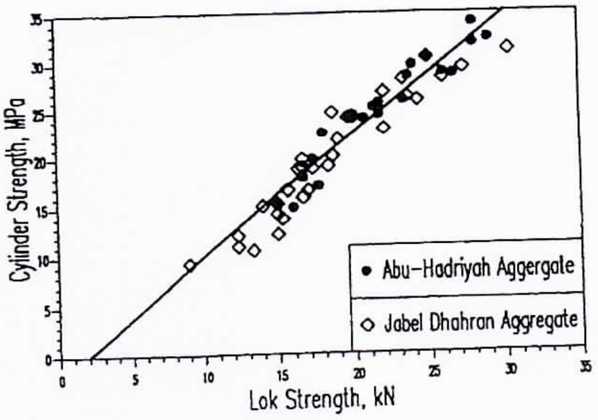

Figure 13 Effect of aggregate type on the cylinder–Lok strength relation

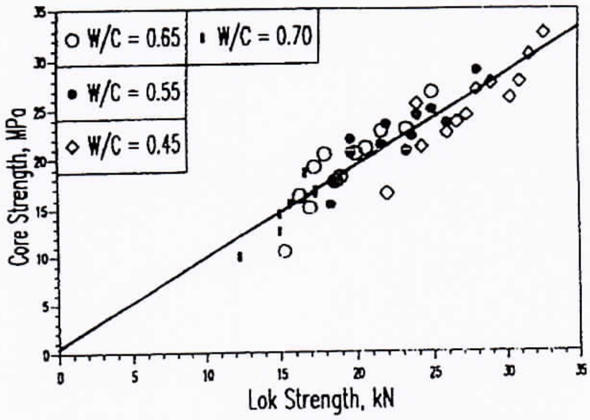

Figure 14 Relationship between the cored cylinder strength and Lok strength

F_c = compressive strength of the cylinders in MPa;
P_L = Lok pullout force in kN; and
a,b = constants (i.e., intercept and slope, respectively).

This linear relationship holds true, irrespective of the mixture design parameters. This is the first indication that the Lok test truly measures the compressive strength of concrete because, apart from the mixture design variables, any change in concrete strength will be associated with a similar change in the Lok force.

(ii) The degree of correlation between the compressive strength and the Lok force is excellent, irrespective of the mixture design parameters. This is evidenced by the coefficient of multiple determination (R^2) which is invariably above 0.85, the coefficient of variation which is in the range of 4.9 to 11.3%, and the coefficient of correlation which varies from 0.93 to 0.96 (*Table 5*). Based on correlation data for 16 calibration models relating the pullout force to standard cylinder compressive strength, Krenchel and Petersen[19] reported similar findings where the coefficient of variation and the coefficient of correlation varied in the range of 4.1 to 16.4% and 0.91 to 0.99, respectively. This is the second indication of the precision of the linear relationships between F_c and P_L.

(iii) The relationship between the compressive strength of the concrete cores and the Lok force is presented in *Figure 14*, and their statistical analysis is also included in *Table 5* (the coefficient of multiple determination was 0.86 and the coefficient of variation was 8.91). Again, the relationship is linear and the statistical coefficients are within those reported elsewhere[19], indicating the significance of the linear correlation.

(iv) A comparison of the coefficients of multiple determination, of variation and of correlation in *Table 5* indicates that the degree of precision for the compressive strength–Lok force correlation is higher when cast cylinders were used rather than cored cylinders. This could be attributed to the coring process whereby some damage may inevitably be introduced to the core cylinders[16,20]. It should be mentioned, however, that both the cast and cored cylindrical strengths did correlate well with the Lok force (i.e., R^2 was more than 0.85).

(v) Despite the very good correlations between the compressive strength and the Lok force for different mixture design parameters and curing periods, it appears that the constants a and b (refer to Equation (1)) vary remarkedly with each model, as shown in *Table 5*. Therefore, the significance of these constants and their variation has to be tested.

Hypothesis testing in simple linear regression

Equation (1) indicates that the fitted simple linear regression model should be of the form[21]:

$$y' = \beta'_0 + \beta'_1 x \qquad (2)$$

Therefore, it is imperative to test the hypothesis that the slope of each model (β'_1) for each of the mixture design variables in *Table 5* equals the slope of the overall model (β'_{10}) (i.e., the slope when all mixture design parameters are incorporated in the statistical analysis and indicated in *Table 5* as: $F_c = -2.878 + 1.252\ P_L$). The appropriate hypotheses are:

$$H_0\colon \beta'_1 = \beta'_{10}$$

$$H_1\colon \beta'_1 \neq \beta'_{10}$$

The statement H_0 is called a null hypothesis while that of H_1 is called the alternative hypothesis, and the test statistic for the slope is (see the definition of these terms in Montgomery[21]):

$$t_0 = \frac{\beta'_1 - \beta'_{10}}{\sqrt{\dfrac{MSE}{S_{xx}}}}$$

To determine whether to reject the hypothesis H_0: $\beta'_1 = \beta'_{10}$, t_0 should be compared with the 't' distribution with $(n-2)$ degrees of freedom. If $|t_0| > t_{\alpha/2,\,(n-2)}$ we would reject H_0 and conclude that the two slopes differ significantly.

Similarly, for the case of the straight line intercepts, the hypotheses will be[21]:

$$H_0 : \beta'_0 = \beta'_{00}$$

$$H_1 : \beta'_0 \neq \beta'_{00}$$

and the test statistic for the intercept is:

$$t_0 = \frac{\beta_0 - \beta_{00}}{\sqrt{MSE\left(\dfrac{1}{n} + \dfrac{\overline{x}}{S_{xx}}\right)}}$$

Table 6 Typical statistic test results for slopes

Mixture design parameter	S_{xx}	MSE	β'_1	β'_{10}	$\lvert t_0\rvert$	$t_{0.25,(n-2)}$	Decision[a]
Age[a] = 3 days	182.17	3.323	1.382	1.252	0.977	2.179	Accept H_0
W/C[a] = 0.55	213.70	3.681	1.474	1.252	1.707	2.145	Accept H_0
Cement content[a] = 300 kg m^{-3}	755.06	5.750	1.261	1.252	0.115	2.056	Accept H_0
Abu-Hadriyah aggregate[a]	553.42	4.637	1.147	1.252	1.125	2.074	Accept H_0

[a] Similar decisions for all other mixture design parameters

Table 7 Typical statistic test results for intercepts

Mixture design parameter	n	$\bar{x}$	β'_0	β'_{-}	$\lvert t_0\rvert$	$t_{0.25,(n-2)}$	Decision[a]
Age[a] = 3 days	14	16.24	–5.744	–2.878	1.275	2.179	Accept H_0
W/C[a] = 0.55	16	18.10	–6.658	–2.878	1.559	2.145	Accept H_0
Cement content[a] = 300 kg m^{-3}	28	19.75	–3.143	–2.878	0.148	1.706	Accept H_0
Abu-Hadriyah aggregate[a]	24	22.82	0.441	–2.878	1.556	1.717	Accept H_0

[a] Similar decisions for all other mixture design parameters

whereby the null hypothesis is rejected if $|t_0| < t_{\alpha/2,(n-2)}$. If the level of significance (α) is selected as 5% (i.e., the risk we take of rejecting the null hypothesis when it is in fact true), then the results of the slope and intercept verifications are presented in *Tables 6* and *7*, respectively. These results indicate that all the slopes and intercepts should be accepted. This indirectly means that the variation of these constants (i.e., *a* and *b*) in the models presented in *Table 5* reflects the differences in the concrete mixture design parameters investigated. It is therefore rational to work with the overall model ($F_c = -2.878 + 1.252\ P_L$), irrespective of the mixture design variables, rather than working with the many individual models. This is especially important for actual structures in quality control and quality assurance programmes, when the concrete mixture design parameters may not be well documented.

Comparison of linear and polynomial models

Although the above analysis indicates the significance of the linear correlation between the compressive strength of both cast and cored standard cylinders and the Lok force (i.e., Equation (1)), a review of the literature reveals that such a relationship can also be modelled in terms of bi-linear or non-linear equations[19,22]. Therefore, the data in *Tables 3* and *4* was statistically analysed to explore these hypotheses.

The statistical analysis of the linear and polynomial models is presented in *Table 8*, whereby the best three bi-linear models were included. The data of the root mean square, of the coefficient of variation, and of R^2 indicates that the third model is relatively the best bi-linear model, and therefore this model will only be considered in the following discussion.

Comparison of the data in *Table 8* indicates that all the models are statistically reliable (R^2 is greater than 0.85). However, the linear model is better than the bi-linear model, particularly in the range of Lok strength values of more than 25 kN; the R^2 for the bi-linear model is only 0.799 compared with 0.932 for the linear one. Both polynomial models (i.e., the quadratic and cubic) appear to be statistically relatively more reliable than the linear model within the range of the data in *Tables 3* and *4*, as verified by the root mean square, coefficient of variation and R^2 (*Table 8*). The difference between the quadratic and cubic models is negligible. The enhanced reliability of these two models is truly ascribable to the generally linear relationship between the Lok force and cylinder strength within the experimental data. This is evident in *Figures 15* and *16*, whereby these two models will not be capable of predicting the cylinder strength for Lok strength values greater than 40 and 35 kN for the quadratic and cubic models, respectively. Further research is required to

Table 8 Statistical comparison of linear and polynomial models

Model	Best predictive equation	$\sqrt{MSE}$	Coefficient of variation (%)	Coefficient of multiple determination (R^2)	Coefficient of correlation (R)
Linear	$F_c = -2.878 + 1.252\ P_L$	1.858	8.100	0.932	0.965
Bi-linear	1) $F_c = -8.103 + 1.563\ P_L$ (P <20 kN)	1.811	10.562	0.821	0.906
	$= 4.520 + 0.965\ P_L$ (≥ 20 kN)	1.453	5.061	0.854	0.924
	2) $F_c = -7.375 + 1.517\ P_L$ (P<23kN)	1.723	9.153	0.880	0.938
	$= 5.916 + 0.916\ P_L$ (P≥23kN)	1.547	5.101	0.767	0.876
	3) $F_c = -6.461 + 1.459\ P_L$ (P<25kN)	1.675	8.087	0.920	0.959
	$= -1.325 + 1.157\ P_L$ (P≥25 kN)	1.423	4.447	0.799	0.894
Quadratic	$F_c = -12.338 + 2.193\ P_L - 0.0219\ P_L^2$	1.718	7.491	0.943	0.971
Cubic	$F_c = -1.086 + 0.420\ P_L + 0.0662\ P_L^2 - 0.00139\ P_L^3$	1.702	7.420	0.945	0.972

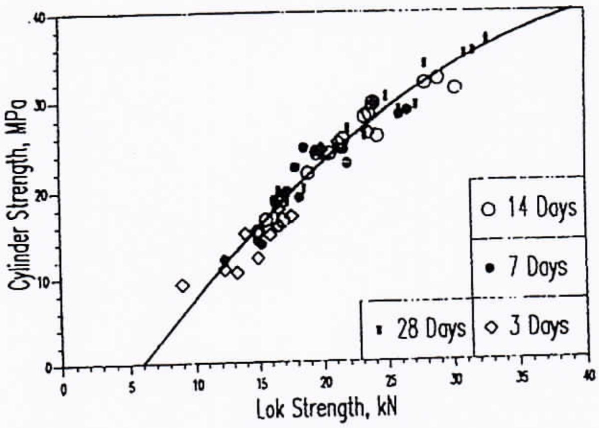

Figure 15 Quadratic model for the cylinder–Lok strength data

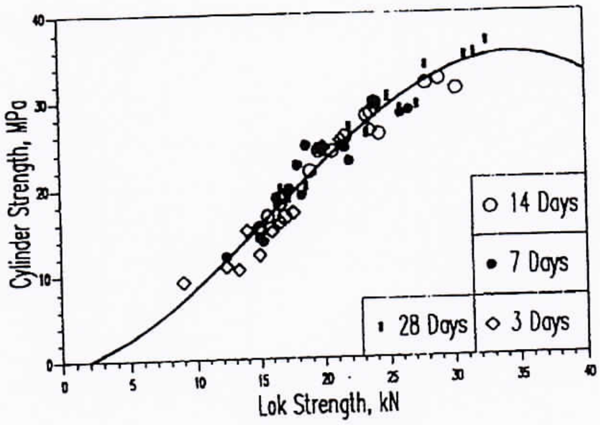

Figure 16 Cubic model for the cylinder–Lok strength data

explore these polynomial models for high strength and high performance concretes.

The above discussion entails that the linear model is the best predictive tool to assess the compressive strength of concrete. This model is the simplest and its reliability does not vary significantly from that of the quadratic and cubic models. It is also more reliable for Lok strength values greater than 35 kN.

Conclusions

The influence of water-to-cement ratio, cement content, aggregate type and curing period on compressive strength and Lok force of concrete has been investigated. Based on the findings of this investigation, the following main conclusions can be drawn:

1. An increase of 29 and 20% in the 28-day compressive strength and Lok force, respectively, was attained when the Jabel Dhahran aggregate was exchanged for the Abu-Hadriyah aggregate in the concrete mixtures.
2. The relationship between the compressive strength of concrete and its Lok force was linear and of the general form presented in Equation (1). This linear relationship was almost independent of all mixture design parameters.
3. The linear correlation between the compressive strength of concrete, as measured by both cast and cored cylindrical specimens, and the Lok force was excellent and evidenced by R^2 values well above 0.85. However, the correlation between the strength of cast cylinders and the Lok force was more precise than the correlation between the strength of the cored cylinders and the Lok force.
4. The results of this investigation indicate that a rational approach would be to work with the best overall predictive model (i.e., $F_c = -2.878 + 1.252\ P_L$) to assess the *in situ* concrete compressive strength if and when the Lok force data points are available. This is particularly important when the concrete mixture design parameters are not documented.
5. Comparison of the linear model with the bi-linear, quadratic and cubic models indicates that the linear model is the most viable one to predict the compressive strength of concrete.

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