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Estimation of the Compressive Strength of Concrete under Point Load and its Approach to Strength Criterions

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Abstract

The point load strength ($I_{s(50)}$) is an alternative mechanical parameter to predict the compressive strength of concrete. The scope of this investigation is to develop an empirical equation relating the point load strength and compressive strength of concrete. In this context, crushed limestone aggregates at two different strength levels were used in concrete mixture. Point load strength and compressive strength tests on concrete specimens which had 6 different compressive strengths were performed for each limestone aggregate. A series of regression analyses was applied using any general statistical package to evaluate the ratio of point load strength test to cube compressive strength of concrete, ($I_{s(50)}/f_{cu}$). The accuracy and reliability of the equation in this investigation was assessed by means of the Mean Absolute Percent Error (MAPE). The relative error can be considered reasonably well for the empirical relationship. The ratio of $I_{s(50)}/f_{cu}$ was also verified by a large database collected from previous studies. The proposed equation is quite compatible with the database. Furthermore, the ratio of $I_{s(50)}/f_{cu}$ indicates significant material property of concrete and defines the material constant in strength criterions. It can be used to estimate the axial compressive strength of concrete under confining stress without performing triaxial tests, considered Hoek-Brown and Johnson empirical failure criterions.

Keywords: *point load strength test, compressive strength, concrete, strength criterion*

1. Introduction

The Point Load strength Test (PLT) is simple test and widely used in rock mechanics, but relatively new method to predict the compressive strength of concrete. The main advantages of PLT are a portable, simple, lightweight and cost-effective device. In addition to these advantages, it provides simplicity of sample preparation, testing on site in a simple and easily portable apparatus. The test measures the point load strength ($I_{s(50)}$) of concrete. The relationship between $I_{s(50)}$ and compressive strength of concrete was first investigated by Robins (1980). The results showed a linear relationship between $I_{s(50)}$ and compressive strength of concrete. He also claimed that the testing variability is comparable to that expected for conventional core testing. Using this approach, trimming and capping are not required, and the testing forces are lower, thus permitting the use of small portable equipment on site at a reduced unit cost. Similar relationship was also derived by Richardson (1989), considering three specimen diameters (50.8, 76.2 and 101.6 mm) and two directions of loading (diametral and axial). In recent years, Zacoeb *et al.* (2006) showed a strong correlation between the $I_{s(50)}$ of core drilled specimen and core concrete strength for small diameters of 35 and 50 mm. Zacoeb and Ishibashi (2009) obtained $I_{s(50)}$ results using two height to diameter ratios of core specimen, h/d of 1.5 and 2.0, and two portland cement types. Their study also evaluates the reliability of test results for each core specimen and proposes a new geometric correction factor. These investigations indicated that proposed equations have good correlations with experimental results. However, more case studies should be performed to consider many uncertainties such as aggregate type and strength in concrete mixture.

The PLT is intended to be used as index test for strength classification of earth materials. It may also be used to predict uniaxial tensile strength and compressive strength of intact rock (Broch and Franklin, 1972). In rock mechanics application, $I_{s(50)}$ is usually converted to compressive strength of rock by multiplying with a certain Coefficient (C). This coefficient has a wide range for different rock materials (Vallejo *et al.*, 1989; Bieniawski, 1989; Singh and Singh, 1993; Sönmez and Osman, 2008; Kayabalı and Selcuk, 2010). Therefore, rock material properties (texture, strength etc.) must be considered in order to estimate the compressive strength. According to Hoek-Brown and Johnston strength criterions for intact rock under triaxial compression, the material constants depending on material type/ properties define the failure envelope. They are related to the ratio of compressive strength to tensile strength. Reported results of Setunge *et al.* (1993) and Xie *et al.* (1995) for high strength concrete in triaxial compression are good agreement with the

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strength criterions proposed by researches (Arıoğlu *et al.*, 2002; Girgin *et al.*, 2007).

The main objective of this study is to evaluate the ratio of point load strength ($I_{s(50)}/f_{cu}$) to compressive strength as a function of compressive strength of concrete, by means of regression analysis. Regression analyses reveal that an acceptable relationship exists between the ratio of ($I_{s(50)}/f_{cu}$) and the compressive strength of concrete. The reliability and accuracy of proposed equation were verified by a database collected from limited number of previous studies. The database includes a total of 56 data which were mostly obtained from the studies of Robins (1980) and Zacoeb *et al.* (2006). The applications of proposed equation in strength criterion were also sought to estimate axial compressive strength of concrete under confining stress without performing triaxial tests.

2. Experimental Study

Two different crushed limestone aggregates were used in this study, since this type of sedimentary rock is most common for the production of concrete in Turkey. The limestone aggregates which were obtained from Kutludüğün (Ankara-Turkey) and Kaymaz (Eskişehir-Turkey) regions have different compressive strength value. The mechanical and physical properties of the limestone aggregates were determined by a variety of laboratory tests in accordance with the procedures given by the American Society for Testing and Materials (ASTM, 2003; 2006; 2008b). The values of compressive strength, Schmidt rebound number, ultrasonic velocity and point load strength for the aggregate rocks are presented in Table 1.

Table 1. Mechanical and Physical Properties of Limestone Aggregates

Properties		I. Group limestone	II. Group limestone
Compressive strength, MPa		71.9	61.1
Schmidt rebound test, R_{ort}		56.3	49.4
Ultrasonic velocity test, km/sec		6.6	5.8
Point load strength test, MPa		4.1	3.2
Density, g/cm^3	0-4	2.69	2.68
	4-11.2	2.69	2.69
	11.2-22.4	2.67	2.70
Water absorption, %	0-4	0.76	0.65
	4-11.2	0.40	0.64
	11.2-22.4	0.28	0.58

In the study, CEM I 42.5 R type ordinary Portland cement was used. To produce the concrete with a low water-cement ratio, a F type super-plasticizer additive (Polycar 100) was used, which is consistent with ASTM C 494. The D_{max} value of the aggregate used in the concrete mixtures was selected as 22.4 mm, which consists of three groups of 0-4, 4-11.2 and 11.2-22.4 mm. A total of 12 concrete mixtures were prepared from two different limestone aggregates, with constant cement content and six different w/c ratios (0.69, 0.60, 0.54, 0.42, 0.37, 0.32) as shown in Table 2. Eight cubic concrete samples with dimensions of 150 × 150 × 150 mm were moulded from each concrete mixture. Slump values of fresh concretes which were ranging from 4 to 20 cm were decreased with reducing w/c ratio. Thus, fresh concretes were moulded into two layers by means of a vibration table to minimize and eliminate the entrapped air in concrete. The samples were de-moulded after 24 hours and were cured in lime-saturated water at 20°C up to 28 days. Additionally, ten cubic concrete samples (from 50 mm to 75 mm in dimensions) for each concrete grade were prepared for the point load strength test described in ISRM (1985). Two testing techniques were employed in this investigation. They include the uniaxial compression test and the point load test. The details of each testing method are explained in the following subsections.

2.1 Point Load Strength Test

The Point Load strength Test (PLT) is based on the principle that rock or concrete sample was compressed between two points. The sample fails as a result of a tensile fracture across its breaking surface and this tensile nature of failure is an advantage since axial cleavage is the principal mode of rock failure in

Table 2. Mixing Ratios of Concrete

Group	Grade	Cement kg/m^3	Water kg/m^3	Water-cement ratio	Super-plasticizer kg/m^3	Compressive strength, f_{cu} (MPa)	Point load strenght $I_{s(50)}$ (MPa)	Aggregates, kg/m^3			Total kg/m^3
								0-4	4-11	11-22	
I	C20	318.8	220	0.69	-	23.5	2.18	702.6	526.6	527.0	2295.0
	C25	366.7	220	0.60	-	28.0	2.32	686.1	514.2	514.6	2301.6
	C30	407.4	220	0.54	-	30.4	2.47	672.1	503.7	504.1	2307.2
	C40	523.8	220	0.42	-	39.9	2.65	631.9	473.6	473.9	2323.3
	C50	594.6	220	0.37	5.9	44.0	2.85	607.5	455.3	455.6	2333.0
	C60	687.5	220	0.32	10.3	59.4	3.02	575.5	431.3	431.6	2349.3
II	C20	318.8	220	0.69	-	23.9	1.98	710.5	524.8	520.7	2294.8
	C25	366.7	220	0.60	-	27.0	2.10	693.8	512.5	508.4	2301.4
	C30	407.4	220	0.54	-	33.9	2.35	679.6	502.0	498.0	2307.0
	C40	523.8	220	0.42	-	39.0	2.46	639.0	472.0	468.3	2323.1
	C50	594.6	220	0.37	5.9	49.2	2.70	614.3	453.8	450.2	2332.9
	C60	687.5	220	0.32	10.3	64.7	2.92	581.9	429.8	426.4	2349.0

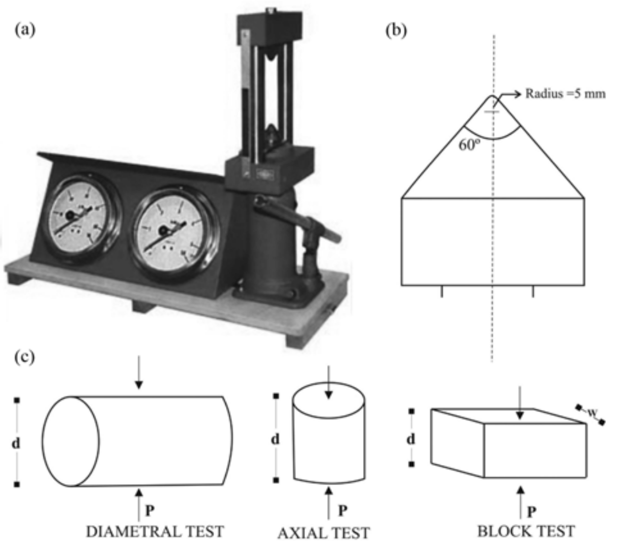

Fig. 1. (a) Portable Point Load Test Machine, (b) Standart Conical Loading Platen, (c) Configuration of Possible Specimens for Point-Load

compression (Bienieviski, 1974). The point-load strength is calculated as the ratio of the applied load to the square of the core diameter for core sample (diametral test) or cross sectional area for block or irregular sample (axial, block and irregular lump tests) (Fig. 1). The uncorrected point load strength (I_s) is determined by following equation (Broch and Franklin, 1972; ISRM, 1985):

$$I_S = \frac{P}{d_e^2} \tag{1}$$

where, d_e^2 is equal to d^2 for diametric tests and $d_e^2 = 4A/\pi$ for axial, block and irregular lump tests, P is failure load in kN and d_e is equivalent core diameter in mm, d is core diameter, mm and A is a minimum cross sectional area of a plane through the platen contact points, mm^2. I_s varies as a function of d in diametral test and as a function of d_e in axial, block and irregular lump tests, so that a size correction must be applied to obtain a unique point load strength value for the sample. The point load strength ($I_{s(50)}$) value for concrete is determined by using the following equation (Zacoeb and Ishibashi, 2009):

$$\begin{aligned} I_{S(50)} &= FI_S \\ F &= (d_e/50)^{0.53} \end{aligned} \tag{2}$$

In the study, the block test was used on concrete samples. The block samples were compressed between two points so that the height was between 0.3 w and w, where w is the dimension representing the width and length and is equal to or >50 mm. Ten block-test samples were prepared for each concrete grade. The block samples were loaded by the hand pump (8.0-17.5 kN) until failure and their maximum load, P was determined from its gauge. The point load strength, $I_{s(50)}$ for concrete was calculated by Eq. (2), modified from Broch and Franklin (1972) and ISRM (1985). Finally, the mean value of $I_{s(50)}$ for each concrete grade was calculated as mean of remaining values after discarding the two highest and lowest value.

2.2 Uniaxial Compression Test

Standard concrete cube samples with dimensions of 150 × 150 × 150 mm were preferred to determine the strength of the concrete sample, because of simplicity of sample preparation. Concrete cube samples of different strength for each aggregate type were measured with a loading speed of 2.4 kN/s and the average cube compressive strengths of concrete (f_{cu}) samples were obtained. These test explained above were carried out in the laboratory to establish an empirical relationship between the ratio of ($I_{s(50)}/f_{cu}$) and compressive strength of concrete for cube samples.

3. Results of Regression Analysis and Discussion

3.1 General

The strength evaluation of concrete structure requires the length/diameter ratio of core concrete specimen. The minimum diameter of core sample is 100 mm or three times the maximum aggregate diameter according to Japanese Industrial Standard (1993). However, simple conversion factor dependent upon the length/diameter (h/d) ratio are widely used to estimate the compressive strength of concrete in practice. In this regard, the experimental investigations to derive the empirical relations between point load strength and compressive strength of concrete are generally focused on the effect of aggregate and core size of concrete sample (e.g., Robins, 1980; Richardson, 1989; Zacoeb *et al*., 2006; Zacoeb and Ishibashi, 2009). Here in, a single strength conversion factor for point load strength of concrete is unlikely to prove adequate because of the tensile nature of the point load test. The two main factors influence the conversion of point load strength are the core diameter or cross sectional area of concrete sample and its aggregate properties (type, strength etc.). Previous studies have considered a variations of Is with specimen size and shape. Size correction chart for concrete proposed by Zacoeb and Ishibashi (2009) is considered to overcome the effect of core size. In addition to core size effect, the influence of some of the aggregate characteristics on the strength of concrete has been previously reported by various researchers (e.g., Aitcin and Mehta, 1990; Özturan and Çeçen, 1997; Şengül *et al*., 2002; Zou *et al*., 1995; Kılıç *et al*., 2008). The compressive strength of concrete increases with increasing aggregate rock strength. The results obtained are valid for point load strength, $I_{s(50)}$. Fig. 2(a) indicates that an acceptable relationship exists between compressive strength and $I_{s(50)}$ of concrete for limestone aggregates used in the current study. The $I_{s(50)}$ increases with increasing compressive strength of concrete. This finding is in agreement with various researchers (e.g., Robins, 1980; Richardson, 1989; Zacoeb *et al*., 2006; Zacoeb and Ishibashi, 2009). Robins (1980) reported that the empirical relations between the $I_{s(50)}$ and compressive strength of concrete were affected by different aggregate properties. Therefore, regression analyses for each aggregate group were evaluated

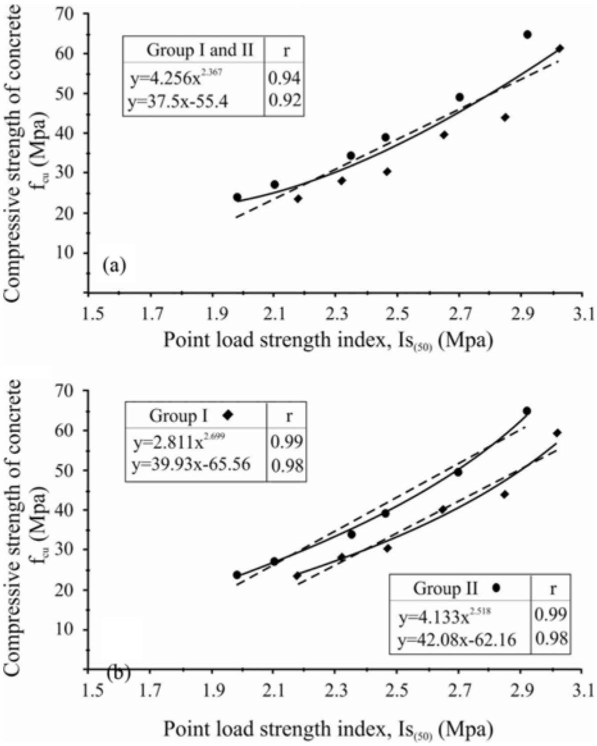

Fig. 2. Effect of Aggregate Groups on Compressive Strength of Concrete: (a) Evaluation of Regression Analysis for all Aggregate Group, (b) For each Aggregate Group

separately as shown in Fig. 2(b). The regression coefficients obtained from each aggregate group are higher than those of all aggregate groups. The regression coefficients for Group I and Group II of aggregates were 0.99 and 0.98, respectively. In brief, the empirical relations between $I_{s(50)}$ and the compressive strength of concrete vary depending upon the aggregate rock properties in the concrete mixture as indicated in Fig. 2.

In consideration of the experimental observations, the failure plane of PLT specimens showed that the crack passed though the aggregate and paste. As can be seen in Fig. 3, the failures of aggregates are observed by examination of the failure plane developed in broken concrete specimens. The changing values of $I_{s(50)}$ in same grade are related to the aggregate rock type and theirs strength values. Thus, the relationships between the strength ratio ($I_{s(50)}/f_{cu}$) and the compressive strength were derived by following subsection. These equations consider the effects of material properties on the strength of concrete.

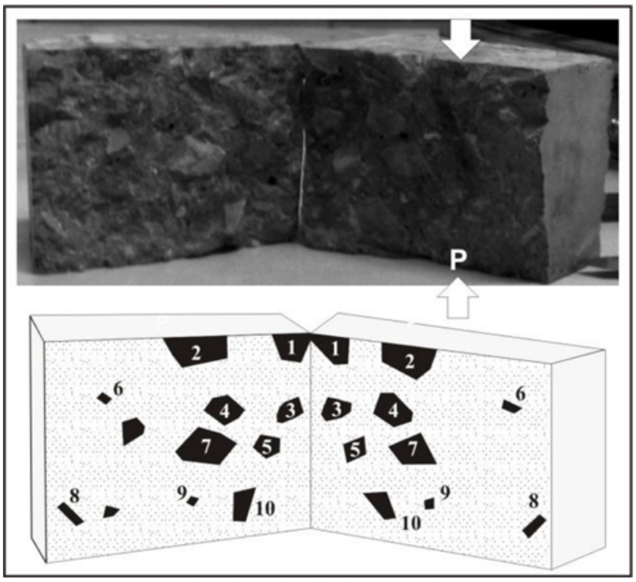

Fig. 3. View of the Concrete Samples after Point Load Strength Test

Table 3. Results of Statistical Models used in Regression Analyses

Equations	Statistical model	Constants of regression equation		Correlation coefficient (r)
		A	B	
(3)	$\frac{I_{S50}}{f_{cu}} = \frac{f_{cu}}{(Af_{cu}+B)}$	19.38	-158.58	0.89
(4)	$\frac{I_{S50}}{f_{cu}} = Af_{cu}+B$	-1.04×10^{-3}	0.11	0.90
(5)	$\frac{I_{S50}}{f_{cu}} = Af_{cu}^{\left(\frac{B}{f_{cu}}\right)}$	3.66×10^{-2}	6.03	0.93
(6)	$\frac{I_{S50}}{f_{cu}} = \frac{1}{(A+Bf_{cu})}$	6.52	0.22	0.94
(7)	$\frac{I_{S50}}{f_{cu}} = Af_{cu}^{B}$	0.41	-0.50	0.95

3.2 Result of Regression Analysis

In order to determine the best empirical correlations between the ratio of ($I_{s(50)}/f_{cu}$) and compressive strength of concrete, a series of regression curves was drawn and the results of these regression analyses are summarized in Table 3. In this study, the reliability of the empirical equations was evaluated on the basis of the mean absolute percent error (MAPE, %). when MAPE values approaching to zero, the estimated values from regression equation are closer to measured values. MAPE, (%) is computed by following equation:

$$MAPE,(\%) = \frac{1}{n}\sum\frac{|Q_i - P_i|}{Q_i}\cdot 100 \tag{8}$$

where, Q_i is the measured value and P_i is the estimated value from regression equation, n is the number of data set points. The values of MAPE between the measured and the estimated compressive strength data were found to be smaller than 10% for all equations as given in Table 4. Thus, the range of relative error can be considered reasonably well for the given empirical relationships. Based on the coefficient of correlation (r), Eqs. (6) and (7) in Table 3 provide strong relationships between the ratio of ($I_{s(50)}/f_{cu}$) and compressive strength of concrete. These

Table 4. Calculated Values of MAPE for Derived Equations given in Table 3

Equations	Mean absolute percent error (MAPE, %)	
	I	II
(3)	10.93	6.58
(4)	4.66	7.07
(5)	8.35	5.37
(6)	4.33	5.74
(7)	5.61	5.36

Note: MAPE calculated for: (I) the data obtained from this study, (n=12), (II) I and a database collected from literature (n=56).

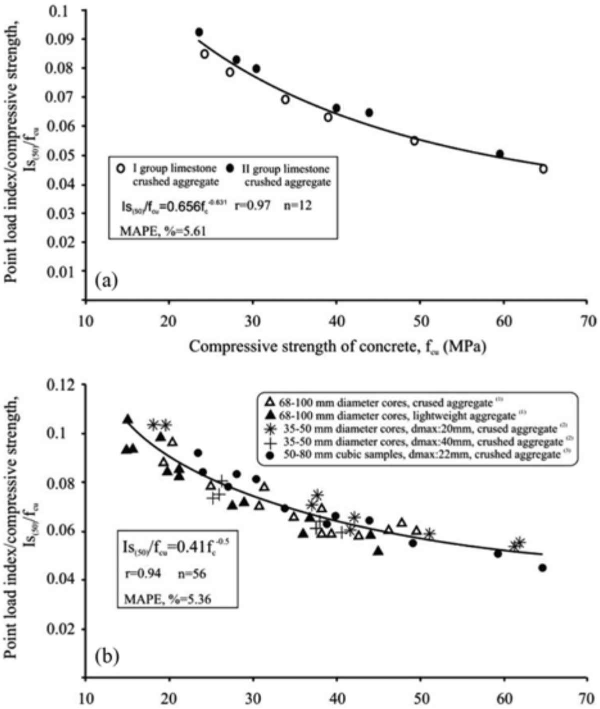

Fig. 4. Ratio of Point Load Strength to Compressive Strength vs. Compressive Strength of Concrete: (a) One Group Data Obtained from this study, (b) Other Group Data Obtained from various Sources (Robins, 1980, Zacoeb *et al.* (2006) and this study)

equations also provide the smallest MAPE values as shown in Table 4. Herein, Eq. (7) can be selected for its simplicity without loss of accuracy.

The reliability and accuracy of derived equations were also verified a database collected from literature. The literature review indicates that the compressive strength values of cubic and core concrete samples were compared with the uncorrected point load strength (I_s) values. While this database was established, the values of I_s were converted to $I_{s(50)}$ by using Eq. (2). Furthermore, in order to ensure data integrity, the cylinder (f_c) and cube (f_{cu}) strength values in previously studies were converted each other by given equation (Popovics, 1998).

$$f_c/f_{cu} = 0.85 - 0.21 f_{cu}/1000 \tag{9}$$

When the database (number of data, n = 56) are assessed with the test results obtained from this study, the percentage value of MAPE for Eq. (7) in Table 4 have found to be smaller (% 5.36). It can be asserted that the proposed equation is quite compatible with the database obtained from previous studies.

3.3 Experimental Results and Discussion

As can be seen from Fig. 4, the alternative proposed relationship between the ratio of ($f_{cu}/I_{s(50)}$) and compressive strength of concrete is:

$$\frac{I_{S(50)}}{f_{cu}} = 0.41 f_{cu}^{-0.5} \tag{10}$$

Figure 4 indicates that the ratio of the ($I_{s(50)}/f_{cu}$) is decreasing with the increasing level of compressive strength. Similar relation is exists between the ratio of tensile strength (f_t/f_{cu}) or splitting tensile strength (f_{ts}/f_{cu}) to compressive strength and compressive strength of concrete. As the compressive strength of concrete increases, the ratio of two strengths (f_t/f_{cu}) decreases (e.g., Zain *et al.*, 2002; Arıoğlu *et al.*, 2002; Li and Ansari, 2000; Komlos, 1970; Arıoğlu *et al.*, 2006). This finding can be explained by the behavior of tensile failure, because the point load test is essentially a tensile test. The tensile failure in concrete occurs with a relatively small rate, compared to the concrete compressive strength. Besides, the compressive strength of concrete approaches approximately 100 MPa and higher, there is no further increase in the tensile strength (Komlos, 1970; König, 1991). The significant decrease in the ratio of two strentgh more clearly observed in high strength concretes (Komlos, 1970; Arıoğlu *et al.*, 2006).

As mentioned previously, there is little information in the literature concerning the estimation of compressive strength of concrete from point load strength. Furthermore, the accuracy of other statistical models have not provided in terms of relative error. In this respect, the following findings can be obtained from Table 4.

According to derived equations, the minimum and maximum values of the MAPE are 4.33 and 10.93, respectively. It can be asserted that the form of the relationship has significant effect on the estimated compressive strength. The proposed equation in this study provides a minimum MAPE of 5.36, while the linear relationship does not agree accurately with the same test data. It underestimates the ratio of two strength with compressive strength f_{cu} > 45 MPa as can also be seen from Fig. 4.

The derived equations in this study consider the concrete which have different strength and type of aggregate. In other words, the type and strength of aggregate have no significant effect on the normalized strengths ($I_{s(50)}/f_{cu}$). The same findings in tension behavior of concrete were mentioned previously by other investigators (Setunge *et al.*, 1993; Xie *et al.*, 1995; Arıoǧlu *et al.*, 2006).

The data obtained from literature were shown to be in a close agreement with proposed equation in this study. The reliability of the equation increases with previously test results as shown in Figs. 4(a) and 4(b). Further research will be important to increase the accuracy of this relationship for high strength concrete (80 MPa to 120 MPa).

4. Application of the Ratio of $I_{s(50)}/f_{cu}$ in Strength Criterions

The application to concrete of Hoek and Brown (1980) and Johnston (1985) strength criteria has been verified by using 71 tiaxial test data (e.g., Setunge *et al.*, 1993; Xie *et al.*, 1995) on high strength concrete. Both criteria seem to be in good agreement with the triaxial data under consideration (Girgin *et al.*, 2007). These following subsections will underline the ratio of $I_{s(50)}/f_{cu}$ for concrete on the Hoek-Brown and Johnson failure criterions.

4.1 Hoek-Brown Failure Criterion

The Hoek-Brown empirical failure criterion was developed in the early 1980s for intact rock and rock masses (Hoek and Brown, 1980). The failure criterion is given by the following equation:

$$f_1 = f_r + \sqrt{m f_r f_c + s f_c^2} \tag{11}$$

where, f_1 is the major principal stress at failure (ultimate strength), f_r is the minor principal stress (confining pressure), and f_c is the uniaxial compressive strength of core rock sample. Here in, m and s are material constants which depend on the properties of rock. The values of m have been presented by researchers. For instance, the representative value of limestone is 8.4. The other material constant describes the rock joints and ranges from 0 for heavily jointed rocks to 1 for intact rocks.

Rearrangement of Eq. (11) gives:

$$\left(\frac{f_1 - f_r}{f_c}\right)^2 = \frac{m f_r}{f_c} + s \rightarrow Y = AX + B \tag{12}$$

where, $Y = (f_1 - f_r/f_c)^2$, $X = f_r$, $A = m/f_c$ and $B = s$. This results in a linear graph with the slope m and an intercept s. if the results of f_1 and f_r obtained from a series of triaxial test, Y and X values are determined. Then, the sample linear regression can be applied to estimate m and s for the uniaxial compressive strength level.

In Eq. (11), substituting $f_1 = 0$ $f_r = -f_t$ where f_t is uniaxial tensile strength and solving the equation give the ratio of two strengths (f_t/f_c) of the rock as:

$$\frac{f_t}{f_c} = \frac{1}{2}\left(m - \sqrt{m^2 + 4s^2}\right) = \lambda \frac{I_{S(50)}}{f_c} \tag{13}$$

Application of Hoek-Brown strength criterion for concrete can be explained in the following.

The concrete has no joints or macro-discontinuities. Therefore, the material constant s can be taken as s = 1 (that is, intact rock). After a series of triaxial test were carried out for the uniaxial compressive strength level, unknown material constant m is calculated by given Eq. (12) between Y and X. Thus, the failure envelope (Eq. (11)) between the pairs of f_1 and f_r values can be constructed simply. In the absence of experimental triaxial test data, the material constant *m* can be estimated by proposed Eq. (10) for uniaxial compressive strength level. If the relationship between the uniaxial tensile strength and point load strength or between the calculated m values from triaxial tests and estimated m values from point load test are established as shown in Eq. (13) where λ is converting factor, the failure envelope is also determined by using m assigned through aforementioned regression analysis.

4.2 Johnston Failure Criterion

Johnston (1985) proposed a criterion for different earth materials of the form:

$$f_{1n} = \left(\frac{M}{B} f_{rn} + 1\right)^B \tag{14}$$

where, $f_{1n} = (f_1/f_c)$ and $f_{rn} = (f_r/f_c)$ are the normalized principal stresses at failure. f_1 is ultimate compressive strength, f_r is confining pressure and f_c is uniaxial compressive strength of core sample (Fig. 5). M and B are two different material constants.

In the tension case, that is, $f_1 = 0$ and $f_r = -f_t$. The ratio of uniaxial compressive strength to uniaxial tensile strength is equal to the value of M/B:

$$\frac{f_c}{f_t} = \frac{M}{B} \tag{15}$$

This ratio is not a constant. The rock strength and rock type change the value of this ratio (Johnston, 1985). The material constant is obtained from a regression analysis taking into account a series of triaxial test on samples of rock or concrete (Arıoğlu *et al.*, 2006). If there are no laboratory triaxial compression test data, the values of constants can be estimated by the following two equations:

$$B = 1 - 0.0172(log1000 f_c)^2$$

$$M = B\frac{f_c}{f_t} = \frac{f_c}{\lambda I_{s50}} \tag{16}$$

where, f_c is expressed in kilopascals. The general trends are

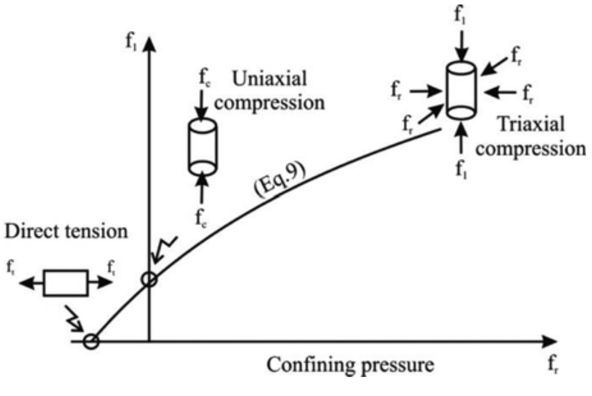

Fig. 5. Johnston's Strength Criterion to Estimate Ultimate Axial Compressive Strength for Intact Rock under Triaxial Compression (Arıoğlu *et al.* 2006)

decreasing B with increasing f_c and increasing M with increasing f_c. The parameter B compared to M is dependent strongly on the type of material and material strength. The value of $f_{cu}/I_{s(50)}$ can be estimated from proposed equation (Eq. (10)). The value l is the factor for converting point load strength to direct tensile strength. If the relationship between the uniaxial tensile strength and point load is established as shown in Eq. (16), the failure envelope under triaxial compression can be estimated by using Eq. (14). The strength criterion may be rewritten in the following form:

$$f_{1n} = \left(\frac{f_c}{\lambda I_{s50}} f_{rn} + 1\right)^B \tag{17}$$

Thus, the ratio of ($I_{s(50)}/f_c$) can be used to estimate the axial compressive strength of concrete under confining stress without performing triaxial tests, considered Hoek-Brown and Johnson empirical failure criterions.

Regarding the validity of the proposed method, actual triaxial data were obtained from a previously study (Richart *et al*., 1928).

Cylinder compressive strength, f_c: 25 MPa (cube compressive strength, f_{cu}: 29.7 MPa from Eq. (9).

Applied confining pressure: f_r = 7.5 MPa

Estimate the point load strength to cube compressive strength ratio, from Eq. (10):

$$\frac{I_{s(50)}}{f_{cu}} = 0.41 f_{cu}^{-0.5} = \frac{I_{s(50)}}{29.7} = 0.41(29.7)^{-0.5} = 2.23 \text{ MPa} \tag{18}$$

The ultimate triaxial compressive strength f_1 is estimated from following steps:

$$\frac{f_1}{f_c} = \left(\frac{f_c}{\lambda I_{s50}}\frac{f_r}{f_c} + 1\right)^B = \left(\frac{25}{1.36\times 2.23}\frac{7.5}{25} + 1\right)^{0.66} = 2.27$$
$$f_1 = 2.27 f_c = 2.27\times 25 = 56.75 \text{ MPa} \tag{19}$$

where, the material constant, B is calculated from Eq. (16) and converting factor, l can be obtained from following equations:

$f_t = 0.9 f_{ts}$ (Attard and Setunge, 1996)

$$f_{ts} = 0.84 e^{0.6256 I_{s(50)}}$$

According to Richart *et al.* (1928), the axial compressive strength f_1 was found to be 55.0 MPa. The ultimate strength values estimated from proposed method is in very close agreement with the experimental ultimate strength value.

5. Conclusions

The point load strength test is alternative method to determine the compressive strength of concrete. These investigations indicated that proposed equations have good correlations with experimental results, but more case studies are required to consider many uncertainties such as aggregate type and strength in concrete mixture. A simple empirical relationship is proposed in order to estimate the compressive strength of concrete. The relationship conforms well to the concretes made with different aggregate properties. The reliability and accuracy of proposed relationship to assess the compressive strength of concrete seem to be very high. It is also in close agreement with the test data obtained from previously studies.

The test results are valid for normal strength concrete ($f_{cu} < 60$ MPa). The ratio of ($I_{s(50)}/f_{cu}$) decreases with increasing compressive strength. In the case of high strength concrete ($f_{cu} > 100$ Mpa), the ratio of two strength ($I_{s(50)}/f_{cu}$) may be significantly decrease with the increasing compressive strength level, because the increase in tensile strengths occurs at much smaller rate, compared to the increase of compressive strength. Therefore, the proposed equation given above should be reevaluated by using high strength concrete made different types and strength of aggregate.

The application of the ratio of ($I_{s(50)}/f_{cu}$) in strength criterions demonstrated that proposed equation provide the opportunity to indirectly estimate the failure envelope of confined concrete strength, knowing only the compressive strength of concrete. This is a highly significant finding, if the triaxial test data are not available anyway.

The derived equation in this study was established to estimate indirectly the compressive strength of normal strength concrete ($f_{cu} < 60$ MPa). In many applications requiring the determination of concrete strength (e.g., tension, splitting tension and compressive strength of concrete), the proposed equation could be more helpful, these major applications may include investigating *in-situ* compressive strengths in terms of uniformity on concrete, especially at damaged buildings during an earthquake or other natural disasters, determining decreasing strength due to chemical and environmental impacts on building and/or possible long-term changes in concrete strength.

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