Geomechanics and Engineering, *Vol. 23, No. 2 (2020) 115-125*
DOI: https://doi.org/10.12989/gae.2020.23.2.115

Prediction of concrete strength from rock properties at the preliminary design stage

Kadir Karaman* and Aknur Bakhytzhan

Department of Mining Engineering, Karadeniz Technical University, 61080 Trabzon, Turkey

(Received January 21, 2020, Revised September 7, 2020, Accepted September 25, 2020)

Abstract. This study aims to explore practical and useful equations for rapid evaluation of uniaxial compressive strength of concrete (UCS-C) during the preliminary design stage of aggregate selection. For this purpose, aggregates which were produced from eight different intact rocks were used in the production of concretes. Laboratory experiments involved the tests for uniaxial compressive strength (UCS-R), point load index (PLI-R), P wave velocity (UPV-R), apparent porosity (n-R), unit weight (UW-R) and aggregate impact value (AIV-R) of the rock samples. UCS-C, point load index (PLI-C) and P wave velocity (UPV-C) of concrete samples were also determined. Relationships between UCS-R–rock parameters and UCS-C–concrete parameters were developed by regression analyses. In the simple regression analyses, PLI-C, UPV-C, UCS-R, PLI-R, and UPV-R were found to be statistically significant independent variables to estimate the UCS-C. However, higher coefficients of determination (R^2=0.97-1.0) were obtained by multiple regression analyses. The results of simple regression analysis were also compared to the limited number of previous studies. The strength conversion factor (k) values were found to be 14.3 and 14.7 for concrete and rock samples, respectively. It is concluded that the UCS-C can roughly be estimated from derived equations only for the specified rock types.

Keywords: rock and concrete strength; aggregate selection; strength conversion factor

1. Introduction

Understanding of engineering properties of an intact rock is crucial for dams, tunnels, foundations on rock and rock slopes (Fereidooni 2016). Uniaxial compressive strength (UCS-R) of rocks is the most important parameter among the engineering characteristics of intact rock (Abdelhedi *et al*. 2017, Asheghi *et al*. 2019). UCS-R parameter could be found experimentally through either indirect or direct methods (ISRM 2007, Singh *et al*. 2012). The procedure for measuring this parameter has been standardized by the International Society for Rock Mechanics (ISRM). UCS-R is the main parameter for instability analysis, rock classification, excavation works, determination of bearing capacity for foundations, and aggregates utilized in concrete production (Tsiambaos and Sabatakakis 2004, Karaman *et al*. 2013). However, high-quality core samples may not be mostly taken for the UCS-R test due to the weak rock conditions. Besides, since representative rock blocks could not be taken, the UCS-R test cannot commonly be carried out at an early stage of underground projects (Yagiz 2009). Therefore, developing empirical equations have become essential to estimate the UCS-R of rocks using indirect tests such as ultrasonic P wave velocity (UPV-R), point load index (PLI-R), porosity (n-R), unit weight (UW-R), etc (Madhubabu *et al*. 2016, Diamantis 2019). PLI test method can also be applied to other brittle materials, such as concrete (Robins 1980). These tests are relatively cheap and simple and have also less strict requirements than the UCS-R test for the preparation of the sample (Kainthola *et al*. 2015).

Concrete is one of the most commonly used construction materials in the world (Karaman and Bakhytzhan 2020). Concrete structures are expected to be resistant to various environmental effects along with improved uniaxial compressive strength (UCS-C). UCS-C is considered as one of the key parameters in concrete characterization for all kind of engineering practice. Since it requires standard samples for testing, indirect tests are often preferred to estimate the strength (Zacoeb and Ishibashi 2009). Evaluating the UCS-C of concrete is crucial for assessing the deterioration of concrete structures and ensuring their safety (Steenbergen and Vervuurt 2012). On the other hand, UCS-C of concrete is affected by a lot of factors, such as type of aggregate and cement, casting process, water/cement ratio, coarse/fine aggregate ratio, age of concrete and chemical reactions. The evaluation of UCS-C is generally based on empirical relationships between strength and nondestructive parameters. Manufacturers generally give such relationships for their testing systems, which are not appropriate for every kind of concrete (Trtnik *et al*. 2009). However, the use of manufactured sand (M-Sand) represents a higher strength than the corresponding natural sand concrete at all test ages (Donza *et al*. 2002, Balasubramaniam and Thirugnanam 2015).

Robins (1980) who first investigated the relationship between PLI-C and UCS-C of concrete found a linear relationship between the data pairs. He indicated the use of small portable equipment on site reduces unit cost since

*Corresponding author, Ph.D.
E-mail: kadirkaraman@ktu.edu.tr

ISSN: 2005-307X (Print), 2092-6219 (Online)

trimming and capping are not necessary. Richardson (1989) performed PLI-C tests of cast samples with different diameters (50.8, 76.2 and 101.6 mm). He stated that compared to the UCS-C, the PLI-C test is cheaper and faster. A good relationship was obtained by the author between the PLI-C of cast cylindrical samples and UCS-C of standard cylinders. PLI-C is a simple and easy test commonly performed in rock mechanics, but a relatively new method to predict the concrete strength (Zacoeb and Ishibashi 2009; Selçuk and Gökçe 2015). Zacoeb *et al*. (2006) found a strong relationship between PLI (core drilled samples) and UCS-C using coarse aggregate (Gmax= 20 mm). Similarly, Zacoeb and Ishibashi (2009) obtained a strong correlation between PLI-C of core drilled samples and UCS-C and proposed a new geometric correction factor. Selçuk and Gökçe (2015) developed the relationship between the ratio of PLI-C/UCS-C and UCS-C, using regression analysis. The reliability and accuracy of their proposed equation were verified by the authors using a database collected from previous studies. Kılıç *et al*. (2019) estimated the UCS-C using physico-mechanical properties (UCS-R, Young's modulus, n-R, UW-R, and UPV) of aggregates. Selçuk and Gökçe (2015) articulated that proposed equations in the literature have good relationships with experimental findings. On the other hand, they also stated that more case studies should be implemented to evaluate many uncertainties (i.e., type of aggregate and strength in the concrete mixture). All empirical relations also have some limitations because of the some factors such as different type of aggregate and cement, casting process, water/cement ratio and range of dataset used. Therefore, there is no single equation applicable to the full range of strengths in rock/concrete materials.

The testing of concrete samples has the most similarities with the testing of rock samples. Concrete samples exhibit the same failure modes as the coal and rock when the uniaxial and triaxial compression tests were carried out (Wang *et al*. 2019). Concrete sample homogeneity is mostly better than in rock samples. Since it affects the repeatability of measurement, homogeneity is significant in experimental studies (Kuhinek 2011). Aggregate characteristics play an important role in concrete properties since it is the main component (75-80%) of concrete (Kılıç *et al*. 2019). Various strength characteristics of concrete can be obtained using different aggregate types when cement quality is the same (Neville 1981). To produce a good structural concrete, good quality of aggregate is essential (Hudson 1999).

According to the literature, there are a lot of studies related to UCS-R estimation from indirect simple tests (Kahraman 2001). Furthermore, the relationships between concrete strength (UCS-C) and curing time, grain size of aggregates, water/cement ratio, length to diameter ratio have been studied by many authors (Majeed 2011, Hamad 2017, Tugrul-Tunc 2018, Wedatalla *et al*. 2019). However, there are few studies on the estimation of concrete strength based on engineering parameters of rocks and concretes. Therefore, the current study aims to explore practical and useful equations for rapid evaluation of UCS-C at an early design stage of aggregate selection. The relationships between UCS-R–rock parameters and UCS-C–concrete parameters have also been investigated. Furthermore, strength conversion factor (k) between the UCS-C and PLI-C was firstly obtained for concrete samples.

2. Experimental studies

2.1 Sampling and characterization of rocks

Rocks used for aggregate are taken from the Black Sea Region of Turkey (Trabzon, Rize, Ordu and Samsun vicinities) (Fig. 1). Eight types of rocks namely basalt (Bt), diabase-1 (D-1), diabase-2 (D-2), granodiorite (Gd), andesite (And), limestone (Ls), lapilli tuff (Lt) and clay stone (Cs) were selected having different engineering properties.

Each rock block was examined for macroscopic defects so that it may provide standard testing samples clear of fractures, cracks, and fissures. Mineralogical and textural properties of rocks were determined using a trinocular polarizing research microscope. XRD (Rietveld) analysis was carried out on clay stone sample (Karaman and Bakhytzhan 2020). Petrographic thin section analyses for the other samples are given in Fig. 2.

UCS-R, UPV-R, UW-R, n-R, and PLI-R tests were performed under the ISRM suggested method (ISRM 2007). Unit volume weight and effective porosity tests were carried out using the caliper and saturation techniques. UW-R parameter was calculated for this study whereas n-R value was obtained from the study of Karaman and Bakhytzhan (2020). Furthermore, only UCS-R and UCS-C values for four rock samples (basalt, diabase-1, diabase-2 and granodiorite) were obtained from Karaman *et al*. (2019). The digital PLI test apparatus was utilized for testing. The axial point load test method was performed on NX–size core samples. Ten samples were used in the test

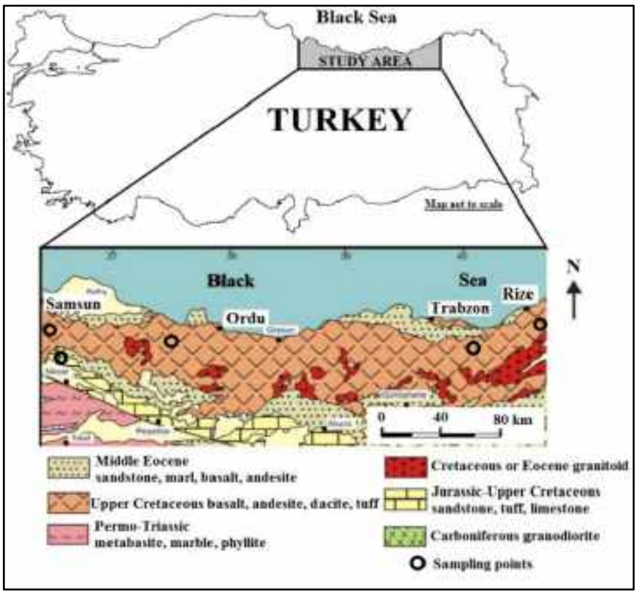


Fig. 1 Major geological features of the study area (modified from Okay and Sahinturk (1997) and Parlak *et al*. (2013))

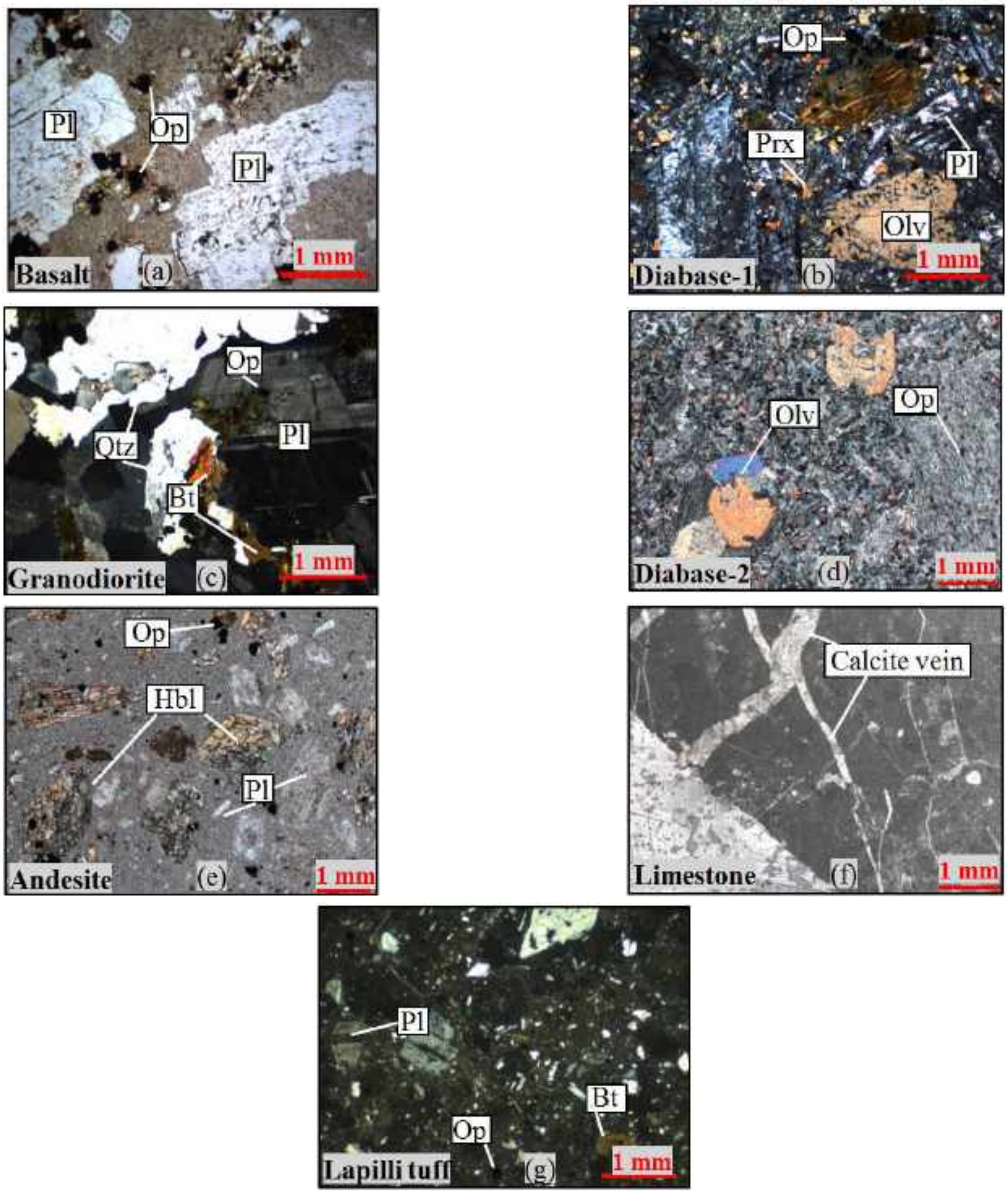


Fig. 2 Microscopic images of rock samples studied: basalt (a), diabase-1 (b), granodiorite (c), diabase-2 (d), andesite (e), limestone (f), and lapilli tuff and (g) Pl: plagioclase, Hbl: hornblende, Qtz: quartz, Prx: Pyroxene, Op: opaque mineral, Bt: Biotite, Olv: olivine

and the mean value was determined by the remaining six values, discarding the lowest and highest two ones. PLI-R value was corrected to the standard equivalent diameter (De) of 50 mm for each test. To prepare the core samples, laboratory core drill and sawing machines were used. All rock blocks were cored using 54.7-mm-diameter diamond coring bits. At least 10 cores (five for the UCS-R/UPV-R and five for the UW-R) were obtained from each rock sample. Core samples that have a length-to-diameter ratio of 2.5 were used for UPV-R and UCS-R tests. The press machine having 200 tons capacity servo–control system was used for the UCS-R tests. The stress rate was selected within the limits of 0.5–1.0 MPa/s. Before testing the UCS-R of each core sample, UPV-R tests were carried out for these samples with direct transmission using a Portable Ultrasonic Nondestructive Digital Indicating Tester (PUNDIT). The end surfaces of the samples were polished to produce a sufficiently smooth and flat plane for good coupling before the measurements. A thin film of Vaseline was applied to the surface of the transmitter and receiver. The time of ultrasonic pulses was read with an accuracy of 0.1 µs. The UPV-R was determined from the measured travel time and the distance between the transmitter and receiver. The mean values obtained along with the standard deviation are presented in Table 1.

Aggregate impact value (AIV-R) was performed

Table 1 The average test results of rock sample

Rock name	UCS-R (MPa)	UPV-R(m/s)	PLI-R (MPa)	n-R (%)	UW-R(kN/m^3)	AIV-R (%)
Basalt	163±19.8	5231±234	10.2±0.8	4.48±0.3	25.1±0.9	10
Diabase-1	116±17.0	5247±207	8.6±0.8	4.64±0.13	27.4±0.5	7.94
Granodiorite	170±20.1	5104±111	10.5±1.4	1.29±0.02	26.0±0.2	11
Diabase-2	183±3.8	5899±43	13.7±0.6	2.33±0.08	27.8±1.8	5.13
Andesite	86±22.5	4115±241	4.7±0.6	5.01±0.15	25.1±0.3	12.2
Limestone	81±11.7	6226±363	5.7±2.1	0.74±0.16	26.2±0.1	15.8
Lapilli tuff	12±2.2	2810±94	1.3±0.1	27.2±0.98	17.0±0.4	24.6
Clay stone	25±9.5	4253±376	2.3±1.2	7.96±0.88	23.5±0.4	19.2

UCS-R: Uniaxial compressive strength of rocks, UPV-R: Ultrasonic P wave velocity of rocks, PLI-R: Point load index of rocks, n-R: Apparent porosity of rocks, UW-R: Unit weight of rocks, AIV-R: Aggregate impact value of rocks

Table 2 The average test results of concrete samples

Bedrock of aggregates	UCS-C (MPa)	UPV-C (m/s)	PLI-C (MPa)
Basalt	26.4±5.2	3818±28.4	1.77±0.4
Diabase-1	22.3±1.3	3743±58.6	1.60±0.8
Granodiorite	24.2±3.8	3988±52.0	1.74±0.9
Diabase-2	26.5±0.6	4015±46.3	1.68±0.9
Andesite	18.7±2.2	3722±93.4	1.56±0.7
Limestone	25.6±1.7	4135±54.7	1.63±0.9
Lapilli tuff	4.5±0.9	2572±122	0.58±0.3
Clay stone	17.8±3.0	3435±153	1.39±0.7

UCS-C: Uniaxial compressive strength of concrete, UPV-C: Ultrasonic P wave velocity of concrete, PLI-C: Point load index of concrete samples

Fig. 3 A view from some experimental studies in the laboratory: some concrete samples (a), UPV test (b), aggregate impact test (c), before PLI test (d), after PLI test (e) and UCS tests (f) and (g)

following BSI (1990). The test sample consisted of aggregates that passed through the 12.5 mm and was retained on the 10.0 mm International standard sieve. The AIV-R was determined by dropping a 14 kg weight through 381 mm onto an aggregate sample contained in a steel cup. The crushed dry aggregate after 15 blows was removed and sieved through 2.36 mm.

2.2 Mixture design and characterization of concrete

Rocks having different strengths from very low to very high were selected to show the different concrete strengths. Cementitious concrete was produced with the same dimension with rock core samples in order to compare the results. Ordinary Portland cement (OPC, CEM-I 42.5-R) was used in this study. It is widely known that the properties of aggregates are associated to a great extent with the mineral composition and the properties of individual rock when crushed aggregates are obtained directly from rock material breaking. Crushed stone aggregate was used as the type of aggregate. Aggregate particles were mostly evaluated cubical and angular shapes since laboratory crushers (jaw crusher, etc.) were used to obtain desired size of aggregates. Therefore, particles were free from flat and elongated particles for each sample used. The quantities of aggregates for every sieve size (0.25, 0.50, 1, 2, 4 and 8 mm) were kept in the same and amounts of cement were kept constant in all concrete mixtures. TS-706 (2003) recommends that proper sieves defined can be used for special use of aggregates. For sample preparation, well-graded aggregates of maximum size 8 mm were obtained according to TS-706 (2003). Yılmaz *et al*. (2017) studied the effects of compaction pressure, cement/sand (C/S) ratio, and water/cement (W/C) ratio on UCS of cement treated sand soils. Two types of sieves No. 16 (1.18 mm) and No. 30 (0.595 mm) were used in their study.

Aggregate-cement paste interface enlarges with the increase of the maximum grain size and caused micro-fractures (TS-3530 2007). According to the petrographic examinations, all of the average mineral grains in the studied rocks are also less than 8 mm in size except for lapilli tuff that has different shape and size of rock fragments. Therefore, relatively small grain sizes were used to provide homogenous cementitious material. Cementitious mixes included 345.5 kg/m^3 cement, 1720 kg/ m^3 aggregate, 190 kg/m^3 water. To see the effect of aggregate type on strength, other factors that affect concrete strength were kept in the same for all concrete mixtures (cement, water/cement ratio, coarse/fine aggregate ratio, etc.). All samples were removed from the mold after 24 h and continually cured in a water basin at a temperature of approximately 20°C until the testing date.

In this study, representative samples (three for UCS-C and eight for PLI-C (50 x 30 mm)) for each concrete mixture were poured into plastic cylindrical cast 50 mm in diameter and 100 mm in length with a perforated bottom for UPV-C and UCS-C testing. Furthermore, cubic concrete samples with dimensions of 150 × 150 × 150 mm and cylindrical samples with 100 mm in diameter and 200 mm in length were prepared for some rock samples. The mixing of concrete was manually done at the cement water ratio of 0.55 for each sample. Potable water was used for preparing of mixtures. Slump values of fresh concrete were ranged between 16 and 20 cm for all mixtures depending on the aggregate properties. Vibrator was used to improve workability.

Table 3 Results of statistical evaluation of rocks

Data pairs	Equations	R.Type	R^2	ANOVA		Coeff. S. Le.
				(F)	S.Le.	
UCS-R and PLI-R	UCS-R=9.81 PLI-R$^{1.192}$	Power	0.97	229.69	0.000	<0.05
UCS-R and UPV-R	UCS-R=(1.181x10^{-10})x UPV-R$^{3.214}$	Power	0.68	44.47	0.001	<0.05
UCS-R and UW-R	UCS-R=0.14e$^{0.26\text{UW-R}}$	Expo.	0.78	12.97	0.011	<0.05
UCS-R and AIV-R	UCS-R=533.58e$^{-0.15\text{AIV-R}}$	Expo.	0.88	21.07	0.004	<0.05

R. Type: Relation type, S. Le: Significance level, Coeff.: Coefficients, Expo: Exponential

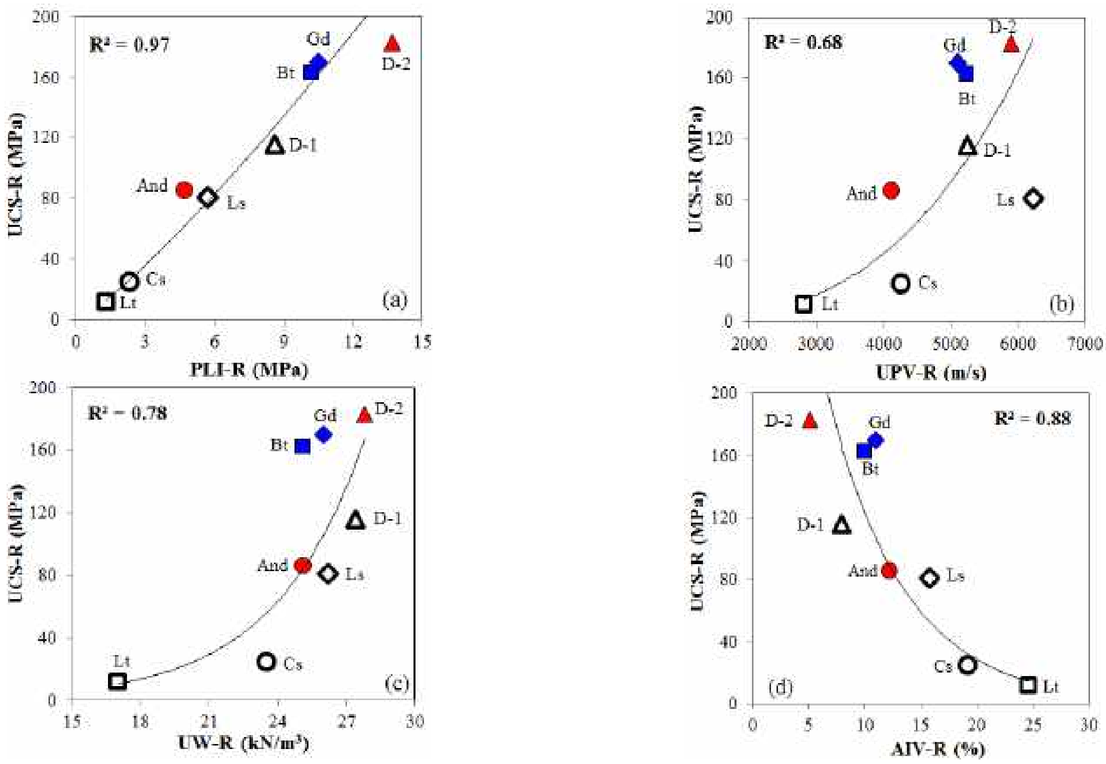


Fig. 4 Relationships between UCS-R and PLI-R (a), UCS-R and UPV-R (b), UCS-R and UW-R (c) UCS-R and AIV-R (d) for rocks; Lt: Lapilli tuff, Cs: Clay stone, And: Andesite, Ls: Limestone, D-1: Diabase-1, D-2: Diabase-2, Gd: Granodiorite and Bt: Basalt

UPV-C tests of cylindrical samples (50x100 mm) were carried out by PUNDIT that measures the time of propagation of ultrasound pulses with a precision of 0.1 μs and its transducers were 42 mm in diameter with 54 kHz according to ASTM (2009). UPV-C tests of concrete samples were carried out in the same experimental conditions with those of rock. After UPV-C tests, the UCS-C tests were conducted on the same samples using a computer-controlled mechanical press having 30 tons capacity according to ASTM (2002). Cylindrical samples were subjected to the UPV-C and UCS-C tests at 7 days of curing periods. Furthermore, UCS-C tests were also carried out at 28 days of curing time in core and cubic samples for some aggregates (basalt, limestone etc.). Special cast specimen was prepared for PLI-C test using the cylindrical moulds. The axial testing method was preferred as in the rock samples. Eight samples were used in the PLI-C tests and the mean value was determined by the remaining six values, discarding the lowest and highest one value (Table 2). A view from experimental studies for rock and concrete was depicted in Fig. 3.

2.3 Statistical analysis of rock and concrete data

Predictive analytics software (PASW Statistics 18) was used to confirm statistically derived equations. All variables i.e., UCS-R, UCS-C, UPV-R, UPV-C, PLI-R, PLI-C, UW-R, AIV-R of the rocks and concrete were found to be normally distributed according to the Kolmogorov-Smirnov Z test and were then subjected to parametric statistical tests. Linear, power, exponential, logarithmic and quadratic relationships were examined between the variables to obtain the most reliable equations. ANOVA tables were checked whether regression models are significant or not. Similarly, the significance of coefficients in equations was examined, as well.

3. Result and discussion

Selçuk and Gökçe (2015) mentioned that the evaluation

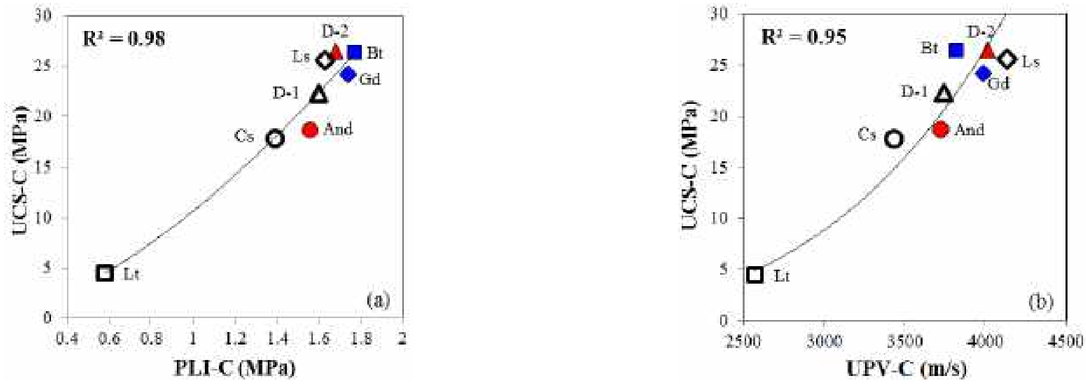


Fig. 5 Relationships between UCS-C and PLI-C (a), UCS-C and UPV-C for concrete (b)

Table 4 Results of statistical evaluation of concrete

Data pairs	Equations	R.Type	R^2	ANOVA		Coeff. S. Le.
				(F)	S. Le.	
UCS-C and PLI-C	UCS-C = 10.62 PLI-C $^{1.6}$	Power	0.98	346.82	0.000	<0.05
UCS-C and UPV-C	UCS-C = 4.87x10^{-13} UPV-C$^{3.814}$	Power	0.95	121.74	0.000	<0.05

R. Type: Relation type, S. Le: Significance level, Coeff.: Coefficients

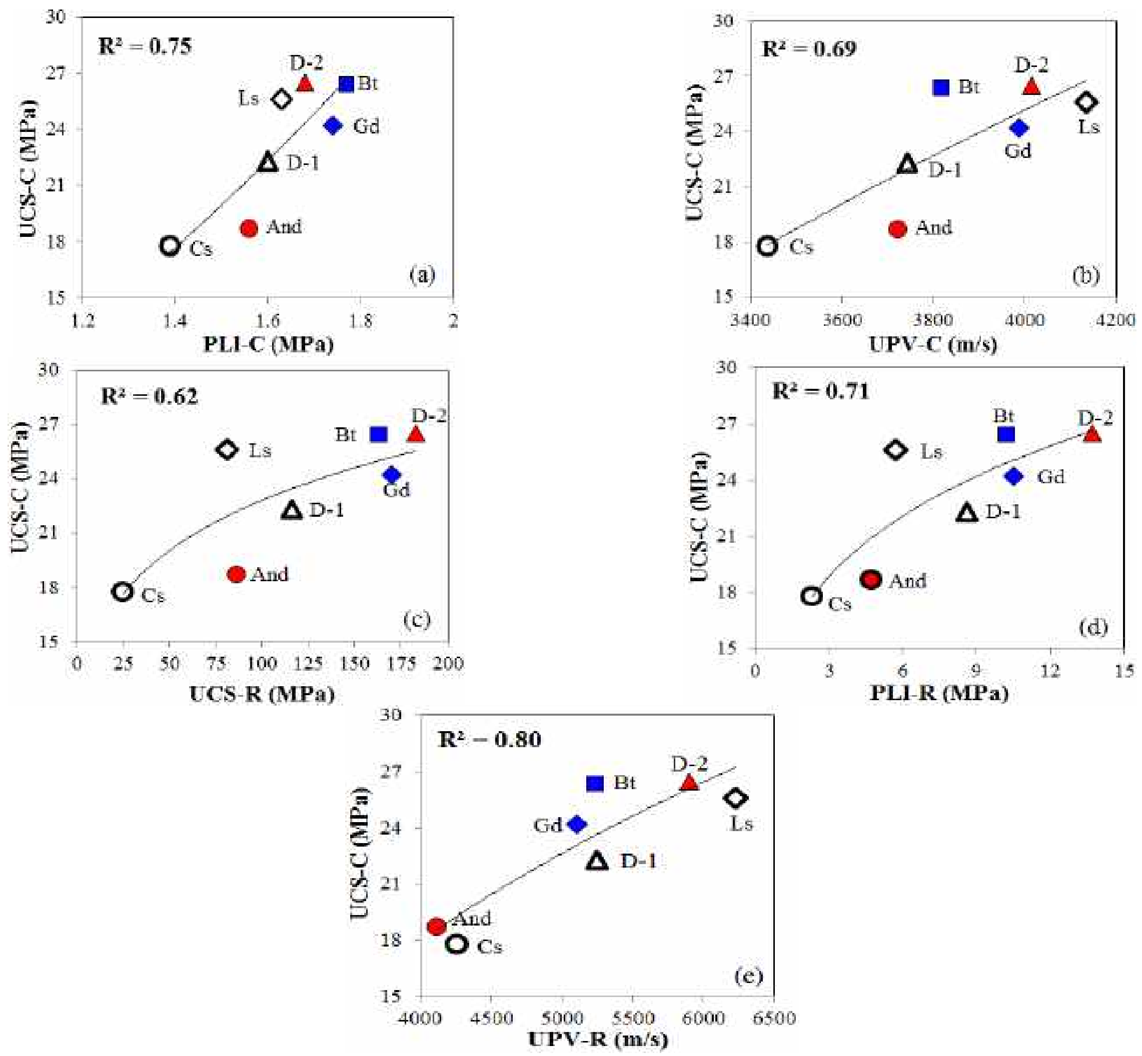


Fig. 6 Relationships between UCS-C and PLI-C (a), UCS-C and UPV-C (b), UCS-C and UCS-R (c) UCS-C and PLI-R (d), UCS-C and UPV-R and (e) for rock and concrete

Table 5 Regression equations of rock-concrete and coefficients of determination and significance values

Relationships	Relation type	Equations	ANOVA		Significance		
			F	Sig. Le.	C1	C2	R^2
UCS-C and PLI-C	Power	UCS-C = 9.78 PLI-C $^{1.76}$	14.87	0.012	0.012	0.006	0.75
UCS-C and UPV-C	Logarithmic	UCS-C=48.28ln(UPV-C)-375.3	10.89	0.021	0.021	0.027	0.69
UCS-C and UCS-R	Power	UCS-C = 9.67 UCS-R $^{0.19}$	8.15	0.036	0.036	0.022	0.62
UCS-C and PLI-R	Power	UCS-C = 14.72 PLI-R $^{0.23}$	12.05	0.018	0.018	0.001	0.71
UCS-C and UPV-R	Logarithmic	UCS-C =20.94ln(UPV-R)-156	19.43	0.007	0.007	0.012	0.80

of concrete strength requires the length/diameter ratio of core concrete samples and the minimum diameter of core sample is three times the maximum aggregate diameter according to Japanese Industrial Standard (1993). Thus, suggestions were taken into account in the current study.

All strength values of cylindrical (5x10, 10x20 cm) and cubic samples (15x15x15 cm) were evaluated for specific curing times (7 and 28 days). For example, concrete made from basalt aggregate was 26.4 MPa at 7-day curing time; it rose to 40.6 MPa at the end of 28 days. Furthermore, the strength of the concrete made with limestone aggregate increased up to 38.3 MPa from 25.6 MPa at the same curing condition. The increase in UCS-C value has generally changed between 30 % and 45 % depending on the curing times (7-28 days). The increase in the UCS-C related to the curing times was shown both for cubic and core samples. However, detailed experimental studies (UPV-C and PLI-C) were conducted on only small core concrete samples (5x10 mm) at 7-day curing time due to rapid evaluation of aggregate for the suitability of concrete. Ruijie (1996) stated that small cores are generally used as substitutes for large cores to test UCS-C of concrete.

In the current study, in order to be able to show the relationships between UCS-R–rock parameters and UCS-C-concrete parameters, regression curves were drawn regardless of the rock type (Sections 3.1 and 3.2). However, since the lapilli tuff is the weak rock which contains high porosity (Table 1), it is not used in normal concrete except for special purposes. The lapilli tuff was hence omitted from the regression analyses and the analyses were performed again for the remaining samples (Section 3.3).

3.1 Relationships between UCS-R and rock parameters

UCS-R values of rocks ranged from 12 MPa for lapilli tuff to 183 MPa for diabase-2. The relationships between UCS-R and other parameters were given in Fig. 4. A strong power relationship was obtained between the UCS-R and PLI-R with a high coefficient of determination (R^2=0.97). This result is not so surprising since the relationship between these parameters is generally high (cf. Mishra and Basu 2012, Kahraman 2014, Kaya and Karaman 2016). A similar relationship (power) between UCS-R and UPV-R was found. However, the UPV-R values produced more scattered the data points (R^2=0.68) compared with the PLI-R values (Fig. 4(b)). Similarly, moderate relations (R^2=0.64–0.69) between UCS-R and UPV-R were found by some researchers (Tugrul and Zarif 1999, Kahraman 2001) whereas some obtained strong relations (Azimian *et al*. 2014). There are exponential relations between the UCS-R–UW-R and UCS-R–AIV-R data pairs with a high coefficient of determination (R^2=0.78–0.88) (Figs. 4(c) and 4(d)). Tugrul and Zarif (1999) found a relatively good relationship (r=0.81) between UCS-R and UW-R data pairs. Statistically significant relationships between UCS-R and other parameters were determined with 95% safety according to the statistical analyses (Table 3).

3.2 Relationships between UCS-C and some concrete parameters

The relationships between UCS-C and other engineering parameters of concrete samples were determined by simple regression analyses (Fig. 5(a) and 5(b)). Statistically significant relations (power) were obtained between UCS-C and PLI-C, UCS-C and UPV-C (Table 4). Higher coefficient of determination was obtained for the more homogenous cementitious samples than those of rock samples because of the same mortar mixture (w/c ratio, curing, grain sizes, etc.).

3.3 Estimation of concrete strength from rock and some concrete parameters

It is widely known that rock characteristics substantially affect concrete strength. Therefore, simple regression analyses were performed to estimate concrete strength from some rock and concrete parameters including UPV-R, PLI-R, UW-R, AIV-R, PLI-C and UPV-C (Figs. 6(a)-6(e)). Various relation types (quadratic, logarithmic, power and linear) were obtained between the UCS-C and rock/concrete parameters. For the estimation of UCS-C; PLI-C, UPV-C, UCS-R, PLI-R, and UPV-R were found to be significant independent variables according to the statistical analyses (R^2=0.62–0.80) (Table 5). UPV-R was the best independent variable to estimate the UCS-C with R^2= 0.80. However, UPV-C is thought not to be practical parameter since sample preparation for the test is needed like UCS-C test.

The AIV-R and UW-R were not reliable (R^2=0.46–0.48) according to statistical analyses (sig. level >0.05) for the prediction of UCS-C. The weak relation may have originated from some factors affecting the AIV-R value (i.e., grain shape of the aggregate and direction of the minerals within the aggregate). It is hard to find strong relationships between data pairs in rocks/concrete having close values.

Rocks that differ in mineral composition, porosity, cementation, consolidation, texture and structural anisotropy can be expected to have different strength and deformation properties. Solid constituents are mainly taken into account for geological nomenclature of rocks, whereas from the engineer's point of view, pores, defects and anisotropy are of greater mechanical significance (Franklin 1970). Therefore, for each type of rock the mechanical properties can vary even if the rock name is the same. In the current study, porosity values of diabase-1 have nearly two times higher than diabase-2 (Table 1). Furthermore, the UCS-R and PLI-R (strength properties) of limestone are very less than basalt, diabase (1 and 2) and granodiorite. However the UCS-C and PLI-C values of limestone are equal or more than these rocks. UCS-C increases with the decrease in porosity of aggregate because porosity is one of the main parameters which affect the strength properties of concrete based on the hydration. Furthermore, both UPV-R and UPV-C values of the limestone are higher than those obtained from other rocks. Since the limestone has very low porosity value (0.74%), this result is not so surprising, because porosity directly affects the UPV-R and UPV-C. Karaman and Kesimal (2015) stated that unit weight and porosity are some of the important parameters that affect both UCS-R and UPV-R values of rocks.

3.4 Evaluation of strength conversion factor (k)

Point load index test is widely performed on strong (i.e., granite, basalt and diorite) and weak rocks (i.e., pyroclastic rocks). Pyroclastic rocks can be thought to be similar with concrete in terms of the PLI tests. Concrete includes cement mortar and different size and shape of aggregates which have specific ranges. Similarly, pyroclastic rocks contain paste materials/natural cement and different shape and size of minerals and rock fragment which have random sizes. However, in the current study, the diameter and height of special cast specimen used in PLI-C test (50x30 mm) is more than three times the maximum aggregate diameter (8 mm) and largest grain diameters of the rock samples.

Zacoeb and Ishibashi (2009) stated that the PLI may also be widely used to predict other material strength parameters because of its simplicity of sample preparation and portability. Kahraman (2014) tested pyroclastic rocks (dry and saturated), with UCS-R mainly below 25 MPa (between 1.4-46.7 MPa) and PLI-R values vary from 0.12 to 3.25 MPa for saturated and dry conditions. He suggested a non-linear correlation between the UCS-R and PLI-R. Heidari *et al*. (2012) carried out the UCS-R tests on gypsum rocks, ranging from 17.44 to 33.69 MPa which may be consisted with concrete strength. They also obtained PLI-R values lower than 1 MPa for 18 samples.

In the current study, k values were determined both for concrete and rock samples based on the zero-intercept regression analysis (Fig. 7). k value was firstly determined in the current study for concrete samples. To see the difference between concrete and rock samples in terms of the regression curves, two graphs were combined. It was shown that there was a strong similarity between the two trends. Furthermore, k value (14.3) of concrete samples was

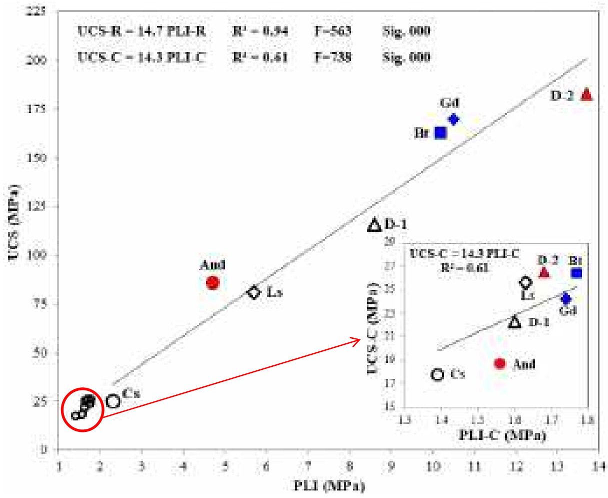


Fig. 7 Zero-intercept linear relations between UCS and PLI for both rock and concrete, points inside the circle line indicate concrete samples

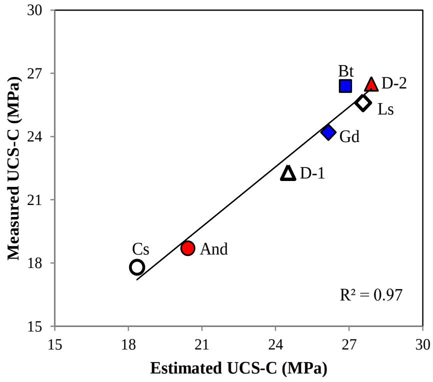
Table 6 Results of multiple linear regression analyses

Relationships	Equations	ANOVA		
		F	Sig.	R^2
UCS-C and PLI-C, UCS-R, UPV-R	UCS-C=12.1PLI-C+0.007UCS-R+0.003UPV-R–11.4	27.92	0.011	0.97
UCS-C and PLI-C, PLI-R, UPV-R	UCS-C=13PLI-C+0.096PLI-R+0.003UPV-R–12.2	28.75	0.010	0.97
UCS-C and PLI-C, PLI-R, n, UPV-R, UW-R, AIV-R	UCS-C=9*PLI-C+0.15*PLI-R+0.03*n+0.004*UPV-R-1.28*UW-R-0.24*AIV-R+22.3	-	-	1.00

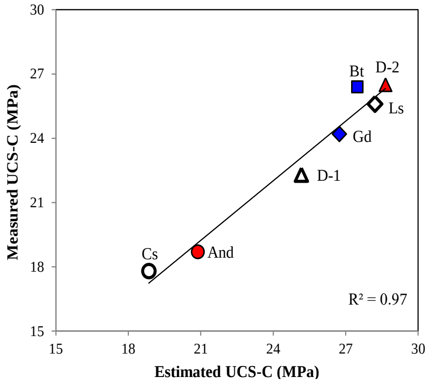
in very close agreement with the k value (14.7) of rock samples. This indicates that concrete strength can be approximately 14.3 times the PLI-C values for the samples studied.

3.5 Multiple regression analyses

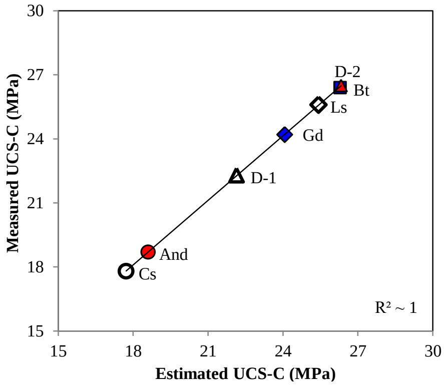
To establish an empirical equation with a higher coefficient of determination (R^2), multiple regressions were performed for seven rock types. Various models were applied using possible independent variables for the prediction of the dependent variable (UCS-C). The measured values of UCS-C were then plotted against the estimated values of UCS-C which derived from the multiple regression equations (Figs. 8(a)-8(c)). In the simple regression analysis, UPV-R was better independent variable than others to predict the UCS-C with R^2=0.80. However, in the multiple regression analysis, R^2 value increased 0.97 when PLI-C, UCS-R, and UPV-R were used as independent variables (Fig. 8(a)). Similarly for the prediction of UCS-C; PLI-R was used instead of UCS-R. According to the ANOVA table, a relatively more reliable result was obtained although R^2 value was the same (0.97) (Fig. 8(a) and 8(b), Table 6). This study indicated that R^2 value can be 1.00 if more variables (PLI-C, PLI-R, n-R, UPV-R, UW-R, and AIV-R) are included in multiple regression analysis



(a) Measured UCS-C versus estimated UCS-C (PLI-C, UCS-R and UPV-R)



(b) Measured UCS-C versus estimated UCS-C (PLI-C, PLI-R and UPV-R)



(c) Measured UCS-C versus estimated UCS-C (PLI-C, PLI-R, n-R, UPV-R, UW-R and AIV-R)

Fig. 8 Multiple regression analyses; measured UCS-C versus estimated UCS-C (PLI-C, UCS-R and UPV-R) (a), measured UCS-C versus estimated UCS-C (PLI-C, PLI-R and UPV-R) (b), measured UCS-C versus estimated UCS-C (PLI-C, PLI-R, n-R, UPV-R, UW-R and AIV-R) (c)

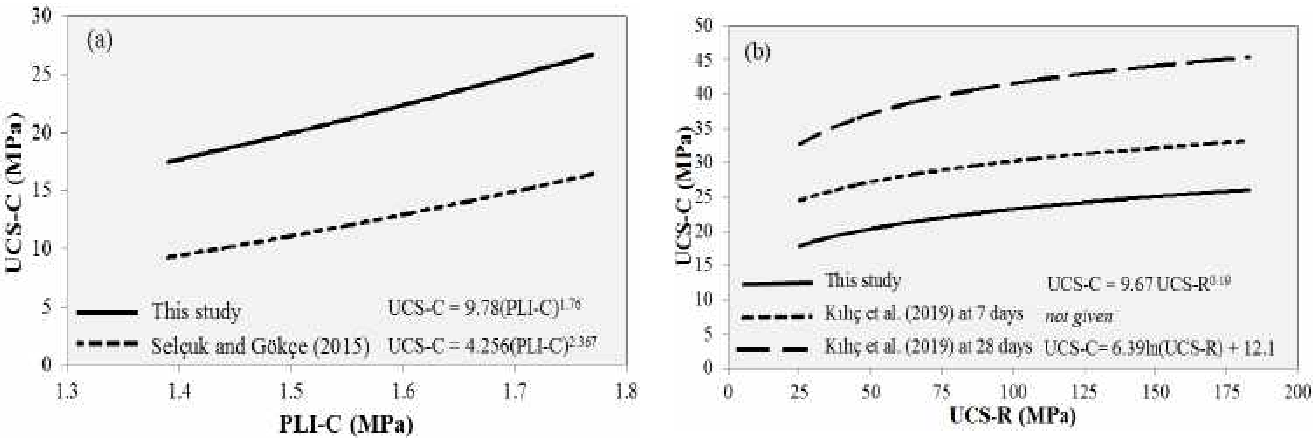


Fig. 9 The comparison between the equations derived in this study and the previous equations for UCS-C and PLI-C (a) and UCS-C and UCS-R (b) data pairs

although they aren't practical to use for initial studies (Fig. 8(c)). Furthermore, some independent variables (PLI-C, PLI-R, and UPV-R) were found to be significant in the estimation of concrete strength (UCS-C) for practical purposes.

3.6 Comparison with other studies

The UCS-C values were calculated and compared with the limited number of empirical equations suggested by different researchers (Selçuk and Gökçe 2015, Kılıç *et al.* 2019) and some suggestions for further work were made. As shown in Figs. 9(a) and 9(b), different researchers have found different equations. This result is not so surprising since the current study was performed on seven rock types (UCS-R varied between 25 and 183 MPa except for lapilli tuff). On the other hand, Selçuk and Gökçe (2015) performed experiments on limestone aggregate (UCS-R varied between 61.1 and 71.9 MPa) at 28 days of curing time.

Kılıç *et al.* (2019) used nine different rocks (basalt, dolerites, andesite, andesitic tuff, dacitic tuffs, ignimbrite and rhyolitic tuff) (UCS-R varied between 7.8 and 123.3 MPa) in the production of nine different concretes at 3, 7, 14 and 28 days of curing time. They established correlations between the UCS-C and UCS-R at 28 days curing time. However, the relation proposed by Kılıç *et al.* (2019) is different from the relation proposed in this study mainly due to the effect of the curing time and different rock types (Fig. 9(b)). Therefore, a relationship was developed between UCS-C and UCS-R values using the data of Kılıç *et al.* (2019) for a curing period of 7 days. The relation derived in the current study showed the similar trend with the relation derived in the study of Kılıç *et al.* (2019) when the aggregate type, mortar mixture and curing time is the same (7 days).

Equations proposed in the current study, are thought to be useful, particularly for the rapid estimation of UCS-C in the preliminary evaluation of rock-aggregates. The long-term behavior of concrete may be different. However, these approaches can help rapid evaluation of the initial stage of aggregate selection. Furthermore, aggregates that have completed the first stage should be undergone detailed experimental studies (i.e., test of chemical reaction) in the laboratory. Aggregates to be used in the concrete are generally evaluated according to national threshold limits of different countries and suggested methods whether they are used in concrete or not. However, equations also predict at which intervals the strength value may vary.

4. Conclusions

Strong relationships (R^2=0.62–0.98) were generally obtained between UCS-C and concrete and rock parameters after data evaluation. All relationships mentioned above were significant at a 95% confidence level. The strength conversion factor (k) values were found to be 14.3 and 14.7 for concrete and rock samples, respectively. The relation derived in the concrete sample showed nearly the same trend with the relation derived in rock samples. Also, multiple regression analyses showed that the coefficient of determination values increased when proper parameters of concrete and rock were selected. No agreement was found between the equations derived from this study and proposed by different researchers because of the use of different rock type and mortar mixture.

This study revealed that the UCS-C can be estimated by the engineering properties of rocks for specific curing times. Manufactures can develop empirical relationships to estimate the UCS-C for their testing system. Therefore, variations of the concrete strength can be evaluated roughly based on the equations derived from the specific quarry or plant when selecting the new aggregate. Proposed equations are also very important especially at the preliminary studies of the geotechnical works since UCS-C can be roughly forecasted with caution for different rocks having similar properties.

Acknowledgments

The study was financially supported by Karadeniz Technical University through the project (No: 7828). The authors would like to express their sincere thanks and appreciation to Dr. Asghar Ali (University of Peshawar) for improving the quality of the paper.

References

Abdelhedi, M., Aloui, M., Mnif, T. and Abbes, C. (2017), "Ultrasonic velocity as a tool for mechanical and physical parameters prediction within carbonate rocks", *Geomech. Eng.*, **13**(3), 371-384. https://doi.org/10.12989/gae.2017.13.3.371.

Asheghi, R., Shahri, A.A. and Zak, M.K. (2019), "Prediction of uniaxial compressive strength of different quarried rocks using metaheuristic algorithm" *Arab. J. Sci. Eng.*, **44,** 8645. https://doi.org/10.1007/s13369-019-04046-8.

ASTM C 39 (2002), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, Annual Book of ASTM Standards, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

ASTM C 597-09 (2009), Standard Test Method for Pulse Velocity through Concrete, Annual Book of ASTM Standards, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Azimian, A., Ajalloeian, R. and Fatehi, L. (2014), "An empirical correlation of uniaxial compressive strength with p-wave velocity and point load strength index on marly rocks using statistical method", *Geotech. Geol. Eng.*, **32**(1), 205-214. https://doi.org/10.1007/s10706-013-9703-x.

Balasubramaniam, T. and Thirugnanam, G.S. (2015), "Durability studies on bottom ash concrete with manufactured sand as fine aggregate", *J. Ind. Poll. Cont.*, **31**(1), 69-72.

BSI (1990), Testing Aggregates: Methods for Determination of Aggregate Impact Value, Part 112, Code no. BS812, British Standards Institution, London, U.K.

Diamantis, K. (2019), "Estimation of tensile strength of ultramafic rocks using indirect approaches", *Geomech. Eng.*, **17**(3), 261-270. https://doi.org/10.12989/gae.2019.17.3.261.

Donza, H., Cabrera, O. and Irassar, E.F. (2002), "High strength concrete with different fine aggregate", *Cement Concrete Res.*, **32**(11), 1755-1761. https://doi.org/10.1016/S0008-8846(02)00860-8.

Fereidooni, D. (2016), "Determination of the geotechnical characteristics of hornfelsic rocks with a particular emphasis on the correlation between physical and mechanical properties", *Rock Mech. Rock Eng.*, **49**(7), 2595-2608. https://doi.org/10.1007/s00603-016-0930-3.

Franklin, J.A. (1970), "Classification of rock according to its mechanical properties", Ph.D. Dissertation, University of London Imperial College, London, U.K.

Hamad, A.J. (2017), "Size and shape effect of specimen on the compressive strength of HPLWFC reinforced with glass fibres", *J. King Saud Univ. Eng. Sci.*, **29**, 373-380. http://doi.org/10.1016/j.jksues.2015.09.003.

Heidari, M., Khanlari, G.R., Torabi Kaveh, M. and Kargarian, S. (2012), "Predicting the uniaxial compressive and tensile strengths of gypsum rock by point load testing", *Rock Mech. Rock Eng.*, **45**(2), 265-273. http://doi.org/10.1007/s00603-011-0196-8.

Hudson, B. (1999), "Modification to the fine aggregate angularity test", *Proceedings of the 7th Annual International Center for Aggregates Research Symposium*, Austin, Texas, U.S.A., April.

ISRM (2007), *The Complete ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 1974-2006*, in *Suggested Methods Prepared by the Commission on Testing Methods, International Society for Rock Mechanics*, ISRM Turkish National Group, Ankara, Turkey, 628.

Japanese Industrial Standard (1993), Method of Sampling and

Testing for Compressive Strength of Drilled Cores of Concrete, Japanese Industrial Standard, (JIS), A1107.

Kahraman, S. (2001), "Evaluation of simple methods for assessing the uniaxial compressive strength of rock", *Int. J. Rock Mech. Min. Sci.*, **38**, 981-994. https://doi.org/10.1016/S1365-1609(01)00039-9.

Kahraman, S. (2014), "The determination of uniaxial compressive strength from point load strength for pyroclastic rocks", *Eng. Geol.*, **170**, 33-42. https://doi.org/10.1016/j.enggeo.2013.12.009.

Kainthola, A., Singh, P.K., Verma, D., Singh, R., Sarkar, K. and Singh, T.N. (2015), "Prediction of strength parameters of himalayan rocks: A statistical and ANFIS approach", *Geotech. Geol. Eng.*, **33**(5), 1255-1278. https://doi.org/10.1007/s10706-015-9899-z.

Karaman, K. and Bakhytzhan, A. (2020), "Effect of rock mineralogy on mortar expansion", *Geomech. Eng.*, **20**(3), 233-241. https://doi.org/10.12989/gae.2020.20.3.233.

Karaman, K. and Kesimal, A. (2015), "Evaluation of the influence of porosity on the engineering properties of volcanic rocks from the Eastern Black Sea Region: NE Turkey", *Arab. J. Geosci.*, **8**(1), 557-564. https://doi.org/10.1007/s12517-013-1217-6.

Karaman, K., Erçıkdı, B. and Kesimal, A. (2013), "The assessment of slope stability and rock excavatability in a limestone quarry", *Earth Sci. Res. J.*, **17**, 169-181.

Karaman, K., Öztemir, M., Akan, E., Gültekin, E., Bakhytzhan, A. and Avci, E. (2019), "Estimating the uniaxial compressive strength of rocks from concrete", *Proceedings of the International Conference on Civil Environmental, Geology and Mining Engineering*, Trabzon, Turkey, April.

Kaya, A. and Karaman, K. (2016), "Utilizing the strength conversion factor in estimation of the uniaxial compressive strength from the point load index", *B. Eng. Geol. Environ.*, **75**(1), 341-357. https://doi.org/10.1016/j.jafrearsci.2015.03.006.

Kılıç, A., Teymen, A. Özdemir, O. and Atiş, C.D. (2019), "Estimation of compressive strength of concrete using physico-mechanical properties of aggregate rock", *Iran J. Sci. Technol. Trans. Civ. Eng.*, **43**(1), 171-178. https://doi.org/10.1007/s40996-018-0156-6.

Kuhinek, D., Zorić, I. and Hrženjak, P. (2011), "Measurement uncertainty in testing of uniaxial compressive strength and deformability of rock samples", *Meas. Sci. Rev.*, **11**(4), 112-117. https://doi.org/10.2478/v10048-011-0021-2.

Madhubabu, N., Singh, P.K., Kainthola, A., Mahanta, B., Tripathy, A. and Singh, T.N. (2016), "Prediction of compressive strength and elastic modulus of carbonate rocks", *Measurement*, **88**, 202-213. https://doi.org/10.1016/j.measurement.2016.03.050.

Majeed, S.A. (2011), "Effect of specimen size on compressive, modulus of rupture and splitting strength of cement mortar", *J. Appl. Sci.*, **11**(3), 584-588. https://doi.org/10.3923/jas.2011.584.588.

Mishra, D.A. and Basu, A. (2012), "Use of the block punch test to predict the compressive and tensile strengths of rocks", *Int. J. Rock Mech. Min. Sci.*, **51**, 119-127. https://doi.org/10.1016/j.ijrmms.2012.01.016.

Neville, A.M. (1981), *Properties of Concrete*, 3rd Edition, Longman Scientific, London, U.K., 287.

Okay, A.I. and Sahinturk, O. (1997), *Geology of the Eastern Pontides*, in *Regional and Petroleum Geology of the Black Sea and Surrounding Region*, American Association of Petroleum Geologists, Tulsa, Oklahoma, U.S.A., 291-311.

Parlak, O., Çolakoğlu, A., Dönmez, C., Sayak, H., Türkel, A., Yıldırım, N. and Odabaşı, I. (2013), *Geochemistry and Tectonic Significance of Ophiolites along the İzmir-Ankara-Erzincan Suture Zone in Northeastern Anatolia*, in *Geological Development of Anatolia and the Easternmost Mediterranean Region*, Geological Society of London, Special Publication, 75-105.

Richardson, D.N. (1989), "Point-load test for estimating concrete compressive strength", *ACI Mater. J.*, **86**(4), 409-416.

Robins, P.J. (1980), "Point-load strength test for concrete cores", *Mag. Concrete Res.*, **32**(111), 101-111. https://doi.org/10.1680/macr.1980.32.111.101.

Ruijie, L.K. (1996), "The diameter-compression test for small diameter cores", *J. Mater. Struct.*, **29**(1), 56-59. https://doi.org/10.1007/BF02486007.

Selçuk, L. and Gökçe, H.S. (2015), "Estimation of the compressive strength of concrete under point load and its approach to strength criterions", *KSCE J. Civ. Eng.*, **19**(6), 1767-1774. https://doi.org/10.1007/s12205-015-1303-2.

Singh, T.N., Kainthola, A. and Venkatesh, A. (2012), "Correlation between point load index and uniaxial compressive strength for different rock types", *Rock Mech. Rock Eng.*, **45**(2), 259-264. https://doi.org/10.1007/s00603-011-0192-z.

Steenbergen, R.D.J.M. and Vervuurt, A.H.J.M. (2012), "Determining the in situ concrete strength of existing structures for assessing their structural safety", *Struct. Concrete*, **13**(1), 27-31. https://doi.org/10.1002/suco.201100031.

Trtnik, G., Kavcic, F. and Turk, G. (2009), "Prediction of concrete strength using ultrasonic pulse velocity and artificial neural networks", *Ultrasonics*, **49**(1), 53-60. https://doi.org/10.1016/j.ultras.2008.05.001.

TS 3530 EN 933-1/A1. (2007), *Agregaların geometrik özellikleri için deneyler bölüm 1: Tane büyüklüğü dağılımı tayini-eleme metodu*, Türk Standartları Enstitüsü, Ankara, Turkey (in Turkish).

TS 706 EN 12620, Türk Standartları, (2003), *Beton Agregalari*, TSE, Ankara (in Turkish).

Tsiambaos, G. and Sabatakakis, N. (2004), "Considerations on strength of intact sedimentary rocks", *Eng. Geol.*, **72**, 261-273. https://doi.org/10.1016/j.enggeo.2003.10.001.

Tugrul-Tunc, E. (2018), "Strength properties of hardened concrete produced with natural aggregates for different water/cement ratios", *Eur. J. Sci. Technol.*, **14**, 280-287. http://doi.org/10.31590/ejosat.486093.

Tugrul, A. and Zarif, I.H. (1999), "Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey", *Eng. Geol.*, **51**(4), 303-317. https://doi.org/10.1016/S0013-7952(98)00071-4.

Wang, C., Yang, S., Li, X., Jiang, C. and Li, M. (2019), "Study on the failure characteristics of concrete specimen under confining pressure", *Arab. J. Sci. Eng.*, **44**, 4119-4129. https://doi.org/10.1007/s13369-018-3335-7.

Wedatalla, A. M., Jia, Y. and Ahmed, A.A. (2019), "Curing effects on high-strength concrete properties", *Adv. Civ. Eng.*, 1683292. https://doi.org/10.1155/2019/1683292.

Yagiz, S. (2009), "Predicting uniaxial compressive strength, modulus of elasticity and index properties of rocks using the Schmidt hammer", *B. Eng. Geol. Environ.*, **68**(1), 55-63. https://doi.org/10.1007/s10064-008-0172-z.

Yılmaz, Y., Çetin, B. and Kahnemouei, V.B. (2017), "Compressive strength characteristics of cement treated sand prepared by static compaction method", *Geomech. Eng.*, **12**(6), 935-948. https://doi.org/10.12989/gae.2017.12.6.93.

Zacoeb A., Ishibashi, K. and Ito, Y. (2006), "Estimating the compressive strength of drilled concrete cores by point load testing", *Proceeding of the 29th JCI Annual Meeting*, Sendai, Japan.

Zacoeb, A. and Ishibashi, K. (2009), "Point load test application for estimating compressive strength of concrete structures from small core", *ARPN J. Eng. Appl. Sci.*, **4**(7), 46-57.

GC