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Laboratory and in situ investigation of the compressive strength of CFRD concrete

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HIGHLIGHTS

- Destructive test not only expensive but also it make weakness in concrete face of dam.
- Cube and cylinder concrete specimens prepared in laboratory are not represented in situ concrete.
- Nondestructive testing (Ultrasonic pulse velocity and rebound hardness) can be used to assessment of strength of concrete and integration of strength CFRD confidently.
- For durability and designing a structural member such as concrete face rockfill dam (CFRD), concrete compressive strength is the most important property.
- The relation between the results of the laboratory concrete compressive strength, Schmitt hammer, and ultrasonic test, using analysis of variance (ANOVA).

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ABSTRACT

One of the most essential and costly stages in Concrete Face Rockfill Dams (CFRD) construction is to implement the concrete at the upstream face of the dam without joints. As the face concrete is considered as the most integral part to prevent water penetration in CFRDs, it's quality control is of paramount importance. One of the conventional approaches for quality control of the concrete which is used in CFRD is the compressive strength of laboratory samples. The comparison of laboratory and in situ measurements provides information about the accuracy of the obtained results. This research investigates the correlation of concrete compressive strength determined by using different methods in the dam face. In general, it is not possible to establish a connection between the compressive strength of experimental samples and in situ concrete. In this regard, this study aims to find out the relation between destructive (experimental samples) and nondestructive (Schmidt hammer, Ultrasonic Pulse Velocity Method) tests of the concrete implemented in the dam face. Moreover, statistical and probability study is conducted to investigate the importance of input variables as well as develop the predictive model for concrete compressive strength. The results indicate satisfactory agreement between the data obtained with the in situ methods and laboratory tests. Further, the results of analysis of variance show that the concrete temperature is the most important factor in the concrete compressive strength.

1. Introduction

In fact, dams are one of the essential infrastructures of societies, and it is inevitable to have comprehensive understanding of their performance and safety. Although many researchers have researched in the field of dam engineering, most of these studies have only focused on numerical assessment of dams' behavior [1–5]. Over the past few decades, economically, adaptively and using local material cause to constructed CFRD widely all over the world [6–10]. The extensive use of CFRDs is because of its low cost and prompt construction. One of the most important techniques to use NDT is to reduce the cost of periodic inspections of a structure. By nonetheless, there is a severe shortage in the experimental data of in situ concrete strength of the dams [35], particularly concrete face rockfill dam (CFRD) [36]. The main dam's concrete face slabs play to prevent the flowing of water from the reservoir to the main dam [37]. By increasing the height of dams, the strain of the concrete face became more and more complicated.

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A concrete slab is one of the most critical elements of the CFRD which the impermeability of system is based on this element [9]. In addition, CFRD is advantageous because of the cost-effective use of local materials, adaptability, simple construction methods, and a short construction period [11,12]. The compressive strength of concrete is the most common factor considered in both construction and design stages of concrete structures. Considering cracks propagation in the CRFD is significantly important in the design stage, and it is highly vital to prevent crack propagation. Besides, it is always a controversy amongst the researchers that the implemented concrete structures have different compressive strength to the one tested based on standard samples i.e., the design characteristic strength [13].

Consequently, the evaluation of the compressive strength of the face concrete for the accurate performance of CRFD during the lifetime is necessary. As the implemented concrete at dam face has a vital role in sealing these dams, the sample extraction from implemented concrete in these dams is costly and even time-consuming, and practically core making of concrete is not possible [14,15]. For this reason, other methods are developed which measure some unique properties of concrete and then a proper relationship will be established among these characteristics with compressive strength and additional required quantities of concrete.

The aim of this study is to control concrete production and determine the concrete face of dam. Because the destructive methods not only expensive but also it make weakness in concrete face of dam, and sometimes it destroyed integrity of concrete. Cube and cylinder concrete specimens prepared in laboratory are not represented in situ concrete. Schmitt hammer and ultrasonic pulse velocity method in concrete are very simple, economical and have many advantages for this reason these methods were most common non-destructive tests [16,31,33]. To use of obtained tests resulted from this method, the existence of a proper correcting curve (calibrating the apparatus) would be trustable for any considered concrete. In this article, the relation between destructive and non-destructive tests of concrete of the dam's face was given by using linear regression. For confidence of nondestructive test result, before a compressive strength test of laboratory cylinder specimen calibration of nondestructive test (Schmitt hammer and ultrasonic) was used.

2. Methodology

The compressive strength of concrete specimens can represent the trend of cement activities and matrix quality of concrete and its continuity with aggregates. For designing a structural member such as concrete face rockfill dam (CFRD), concrete compressive strength is the most important property. The crucial points in the compressive strength test can be the assurance from appropriate loading speed for the tests and also their accurate setting in the jaw center of applying load [17]. The most common and usual apparatus to measure surface stiffness is the concrete rebound of Schmitt elastic hammer [18,34]. Ultrasonic wave velocity in solid materials is a function of the elasticity module to its specific weight ratio square root. There is also an appropriate relation among compressive strength and elasticity module of concrete. Therefore a relationship between ultrasonic wave velocity in concrete and its compressive strength can be expected. In this research, PUNDIT apparatus is utilized which is one of two conventional devices to determine ultrasonic wave velocity in concrete [18].

3. Specimens preparation

A large number of 333 field samples implemented in the place of face concrete of a reservoir dam in Bijar (Gilan province) are used. The field concrete mix design of the samples taken at the implementation place is shown in Table 1. The number of materials used in field samples was given in Table 2. Concerning the aim of this research that is investigating the relation of concrete compressive strength (destructive) by comparing other nondestructive tests.

The dimension of the concrete samples was 150 × 150 × 150 mm. After accomplishing the specimens, they were transferred to the laboratory site and finally were cured in the saturated lime-water pond until the intended age (7, 28, and 90 days). All of the laboratory samples are constructed at the implementation place of the concrete face and in the laboratory of Bijar's reservoir dam project and were tested in the intended age. To make all laboratory samples, Abiek cement factory's type-2 cement, fine and coarse grain sand with the maximum diameter of 37 mm (grain grading test according to ASTM C136-84a standard), natural washed sand 0–5 mm and broken sand 0–6 mm (in the range of ASTM 33 standard) were used. Target slump for this sample was between 12 and 16 cm which almost 23% of samples were under 10 cm and 73%, between 10 and 15 cm and 4% above 15%.

4. The geometry of Bijar CFRD

The width of dam concrete face blocks is constructed from 34 blocks with a width of 12.20 m (Figs. 1 and 2). To evaluate the mechanical properties of laboratory samples and in situ concrete, concerning the access to the intended range in the concrete face, the dam face was selected, and then non-destructive tests including ultrasonic and Schmitt hammer at mentioned levels (Fig. 3) were performed [19].

5. Test result and discussion

Although, compressive strength is one of the most critical parameters in evaluating concrete, it has to be considered that the tested samples in a laboratory can't be the representative of applied concrete in the dam face [38]. For the prediction of dam face concrete strength many parameters were affected because each type of concrete placed in dams has different maximum sizes of aggregates; different sizes of specimens were needed to determine the properties of concrete [39,50]. The reason is that the compressive strength of implementing concrete in the dam site and the condition of the concrete laboratory is not same since the laboratory condition is not reflected site condition [20]. In this research, to investigate dam's real conditions with test samples and to present concrete quality control curves concerning administrative and test data they are performed in field and laboratory and performing non-destructive tests applicable on face concrete is investigated.

The primary goals of this research are to investigate the properties and evaluation (comparison) of laboratory samples mechanical properties and specifications and in situ concrete in concrete faced rockfill dam (CFRD). In order to better comparison of properties and mechanical characteristics of specimens, the implementation of compressive strength, ultrasonic wave velocity and Schmitt hammer, and the results from concrete mix design by performing above experiments and also presenting the factors related to the changes over concrete face slabs (it is worth mentioning that the slabs under research are selected in terms of access to the range of dam concrete face to perform non-destructive tests including Schmitt hammer and ultrasonic) and the presentation of comparison charts between different levels, the difference percent diagrams of compressive strength, coefficient of variations, and investigating obtained results with existing data and controlling effective factors on concrete quality with separate study of each

Table 1
Field concrete mix design of the samples taken at the implementation place (kilograms per cubic meter).

Concrete Flow	Air Entrainment (%)	Air (%)	Percentage of micro-silica EDM-250	Cement	Natural washed sand	Sand 37–19	Sand 25–5	Water-cement ratio
(5 min = 16) (15 min = 12)	02/0	5/5	3	360	880	366	586	0/38

Table 2
The number of concrete samples taken in concrete implementation place.

Percent of samples compressive strength growth, day-28 to 7 (kg/cm^2)	Temperatures °C	Air (%)	Concrete temperature °C	Slump (cm)	90-day compressive strength (kg/cm^2)	28-day compressive strength (kg/cm^2)	7-day Compressive Strength (kg/cm^2)	Statistical Committee
60/38	32/22	03/4	50/11	50/11	17/339	34/374	64/272	Average
26/89	35	6	50/16	50/16	381	50/517	433	Maximum
69/13	11	4/2	4	4	309	239	153	Minimum
09/11	44/4	56/0	33/2	33/2	99/1	52/5	02/5	Standard Deviation

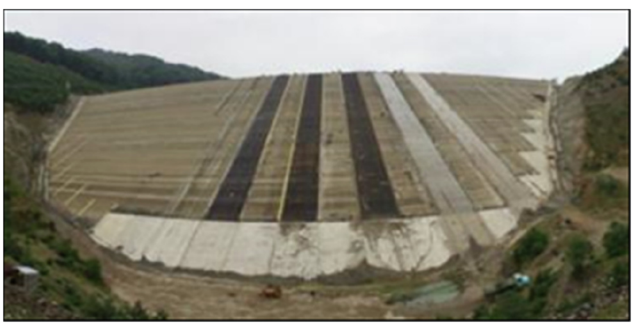

Fig. 1. View of pouring-concrete at concrete face of dam body [18].

concrete components and compressive strength is examined that the following findings and comparisons are obtained.

As is clear from Figs. 4 and 5, at concrete compressive strength in age 7-days, 93% of strength is between 250 and 350 kg/cm^2 (25–35 MPa), and 7% is in the strength range of 350–450 kg/cm^2 (35–45 MPa), and the remarkable percentage of examinees were higher than the predicted characteristic strength level and the results are acceptable. It is clear from Figs. 6 and 7 that at concrete compressive strength in age 28-days, almost 35% of the strength is between 250 and 350 kg/cm2 (25–35 MPa), and 56% is in the strength range of 350–450 kg/cm2(35–45 MPa). It is clear from Fig. 8 that the slump number range of 9–14 cm is an appropriate range to access target compressive strengths which using. By increasing this amount, compressive strengths are decreased both in the age's day-7 and day-28. The slump of fresh concrete between 30 mm and 70 mm. Plasticizing agents can be introduced to improve the workability of the concrete, if necessary [48]. In this study using superplasticizer (used 0.1% of weight of cement) and air to increase workability for this purpose increasing slump amount. As was clear from Fig. 9, by increasing air percentage more than 5%, compressive strength decreases remarkably. One of the methods of improving the workability without increasing the water content, air-entraining agents can be used. Jiang and Zhao [48] suggested that entrained air should be between 4 and 6 percent in warmer climates, and 5–7 percent in colder climates. But generally preserving air percentage in the range of 3.50–4.50%, which depends on maximum size of coarse aggregate [40] that affect durability and freezing and thawing properties of dam. Mean, minimum and maximum numbers of concrete temperatures are equal to 27.60, 32, 15 °C, respectively. Concrete temperature is a function of environmental conditions and the temperature of each concrete component, especially cement. By increasing the

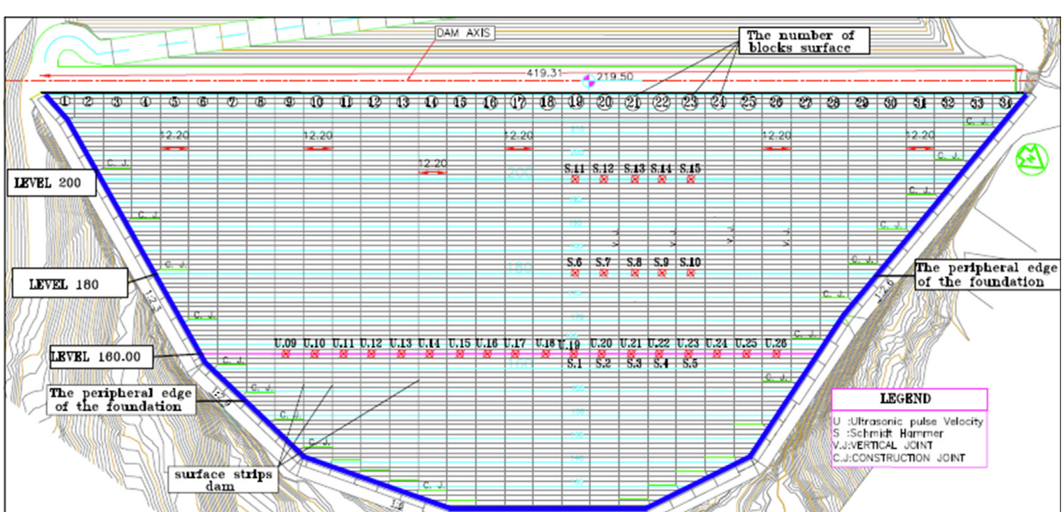

Fig. 2. Concrete face plan of Bigar's reservoir dam [18].

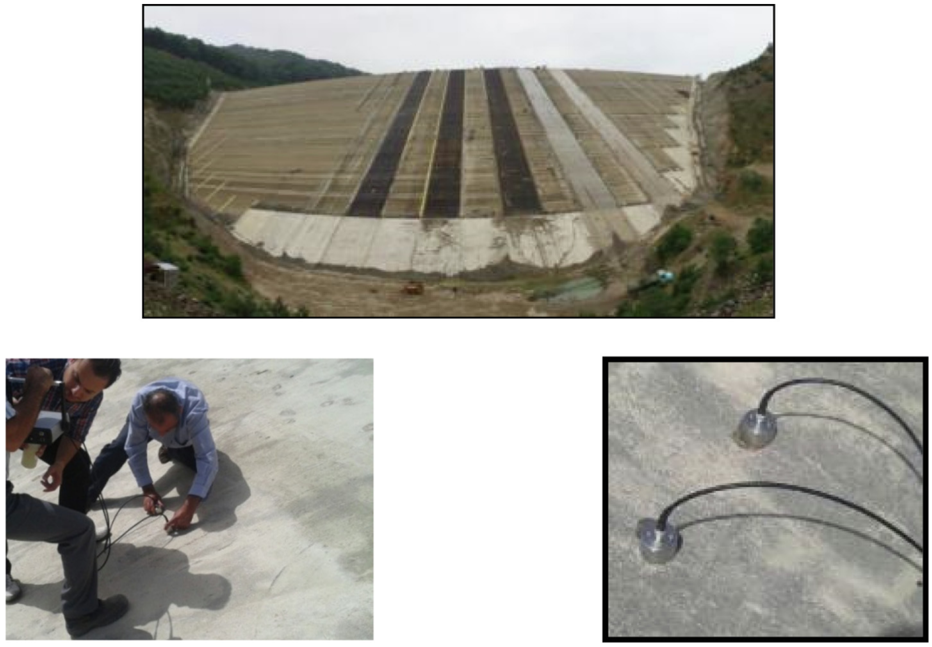

Fig. 3. Determination test of the passing pulse time from dam face concrete.

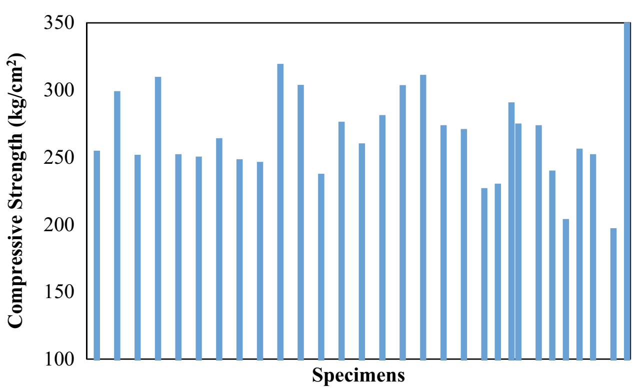

Fig. 4. Compressive strength of concrete (7 days).

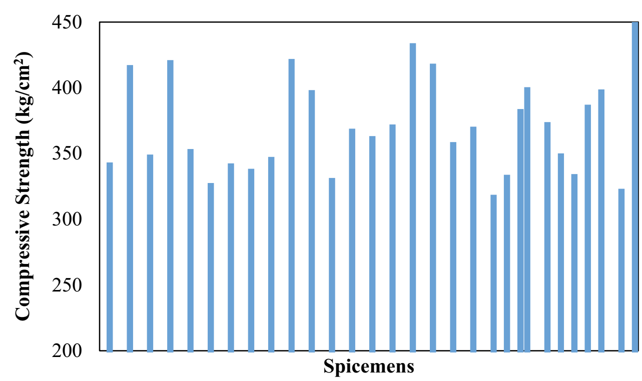

Fig. 6. Compressive strength of concrete (28 days).

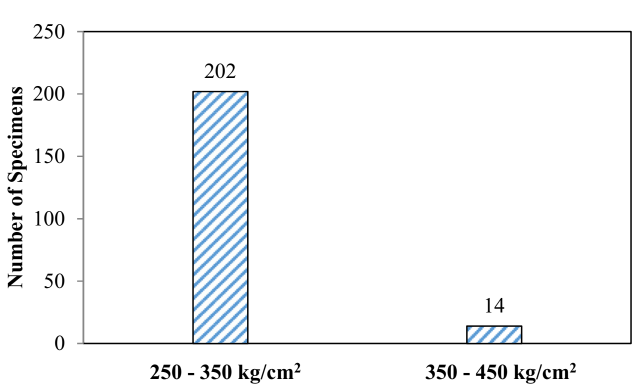

Fig. 5. Fluctuations in the results of the compressive strength of samples taken at the age of 7 days.

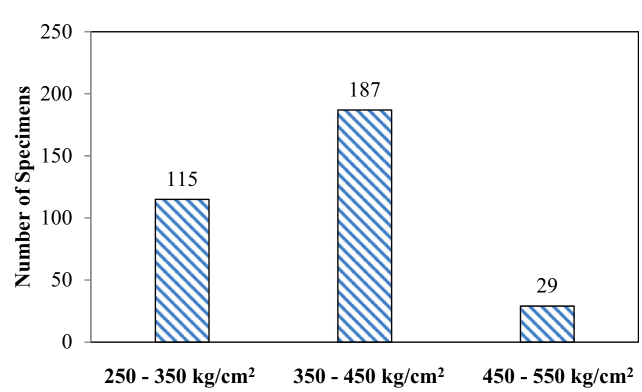

Fig. 7. Fluctuations in the results of the compressive strength of samples taken at the age of 28 days.

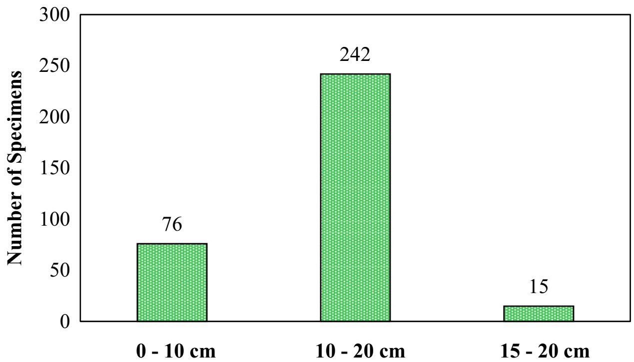

Fig. 8. Slump fluctuations of concrete samples.

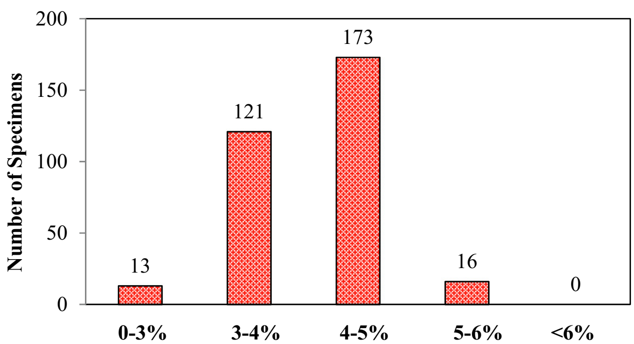

Fig. 9. Fluctuations of concrete air percentage.

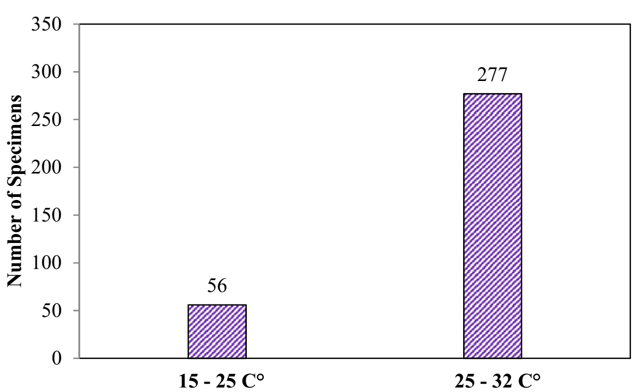

Fig. 10. The air temperature variations.

temperature cracking maybe occurred in face concrete of dam. Fig. 10 shows that the concrete temperature of the sample is between 25 and 32 °C in almost 84%.

6. Nondestructive tests

Many non-destructive testing techniques were used for the evaluation of civil engineering structures [43]. In this study, NDT methods such as ultrasonic pulse velocity, rebound hardness which can be applied to the assessment of strength of concrete and integration of strength whole CFRD more confident.

6.1. Ultrasonic testing (ultrasonic pulse velocity method)

The evaluation of concrete using the ultrasonic pulse velocity method concerning testing nature is a function of various factors that their most important ones are a cement–water ratio, cement type, concrete age, curing temperature, and maintenance conditions (humidity) [32]. The most important applications of this method include concrete strength estimation (both in situ and prefab), concrete uniformity control, quality control and destruction rate analysis, concrete durability study, surface crack depth measurement [21]. This method is normally based on the use of portable equipment, composed by the source/detector unit and the surface transducers. The ultrasonic pulses depend on the density and elastic properties of the material especially cement type and water/ cement ratio. Lorenze et al. [41] was shown standard concrete cylinders with W/C of 0.35 result as ages of 3 days no more difference between the ages of 7 and 28 days. According to Fig. 11, first, the non-destructive test of determining the transmission time of ultrasonic pulse by non-direct transmission method about the access at approximation level 162 on concrete face surface was performed by the testing machine of pulse velocity determination that the test procedure is shown in Figs. 12 and 13.

Nineteen points of face concrete surface at regular intervals for each point (total number of points 76) was performed, and after the test accomplishment, the obtained results were registered as pulse transmission duration, and its compressive strength was measured. The compressive strength results obtained from the pulse velocity determination test and the compressive strength of the taken samples are shown in the charts of Fig. 14 [22]. Increasing emptiness decreasing velocity in this method and low velocity result low strength of concrete. The pulse velocity in saturated concrete may be up to 5% higher than in dry concrete [42]. In this study the velocity of the ultrasonic wave that travels through the concrete was an average speed of 4 to 4.4 km/sec, and it showed the quality of concrete was suitable.

6.2. Schmidt (Rebound) hammer test

This test is very straightforward, less expensive and has many advantages [45]. In the performance of Schmitt hammer test on a laboratory cubic sample with dimensions 15 × 15 × 15 cm, strength determination was performed to obtain calibration coefficient on cubic samples (control sample). Without any calibration coefficient, this test method is not suitable as the basis for acceptance or rejection of concrete [44]. In addition, the strength determination was performed with compressive strength obtained from the samples with the method of smashing samples in laboratory (Jack pressure) and then Schmitt hammer test in three levels 180, 160, 200 was performed on concrete in dam face that in each level with the number of 80 readings and the total number of 240 readings. It is worth noting that in each stage of reading, 16 readings were performed on a surface with dimensions of 30 cm. Then the performed readings on the correlation curve between concrete

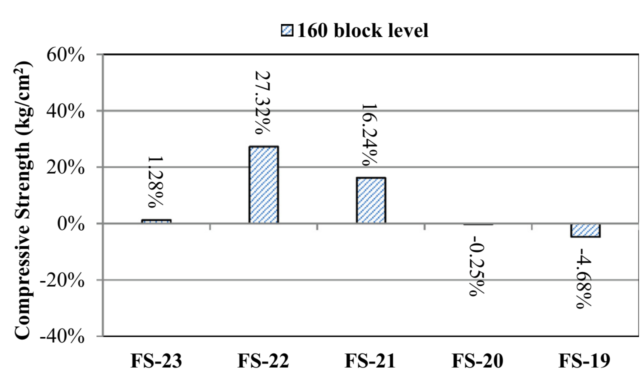

Fig. 11. Comparing the ratio of laboratory samples compressive strength to the samples with ultrasonic test.

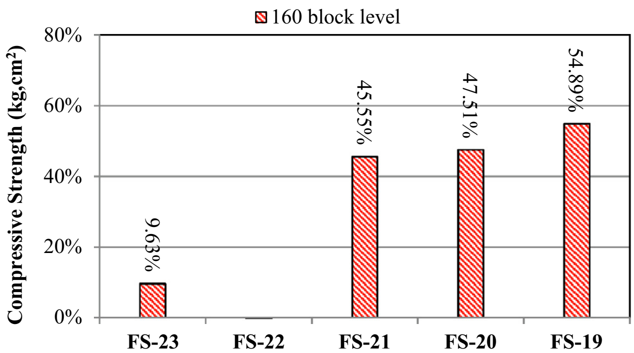

Fig. 12. Comparison of laboratory samples compressive strength to the samples with Schmitt test at level 160.

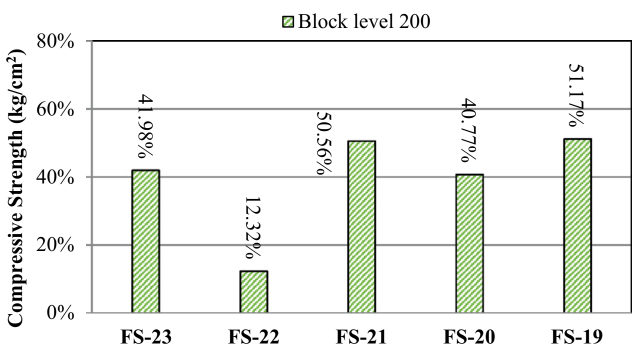

Fig. 13. Comparison of compressive strength laboratory samples to samples with Schmidt test at level 200.

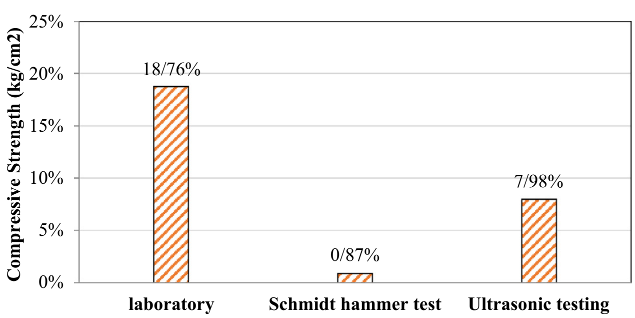

Fig. 14. Comparison of compressive strength (laboratory samples, ultrasonic and Schmitt hammer tests).

strength and compressive strength return number in concrete in situ were performed which Schmitt hammer results are shown in Fig. 14.

Regarding Fig. 15, comparing the ratio of laboratory samples compressive strength to the samples with ultrasonic experiment indicates that the compressive strength of laboratory samples by ultrasonic test at level 160 of dam concrete face is about 13% more than the compressive strength obtained by ultrasonic. Concerning Fig. 15, comparing the ratio of laboratory samples compressive strength to the samples by Schmitt hammer test indicates that the compressive strength of laboratory samples by ultrasonic test at level 160 is about 36% more than compressive strength obtained by Schmitt hammer. Concerning Fig. 15, comparing the ratio of laboratory samples compressive strength to the samples with Schmitt hammer test indicates that the compressive samples of laboratory samples with ultrasonic at level 200 is about 39% more than compressive strength obtained by Schmitt hammer. Schmidt Hammer

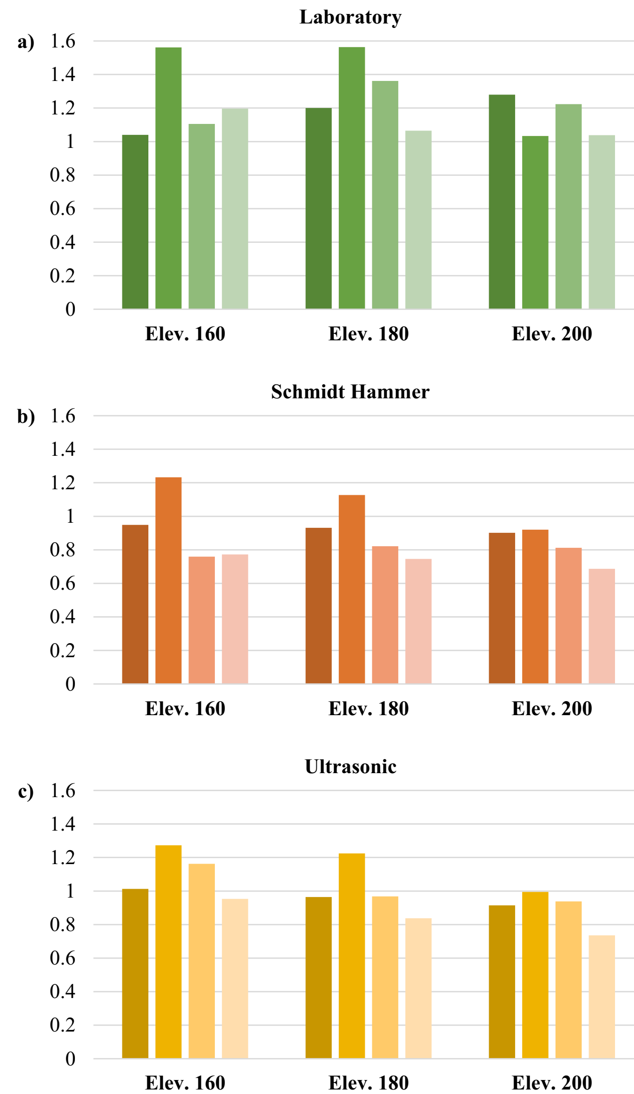

Fig. 15. Normalized concrete compressive strength to the design value for different elevations; a) laboratory, b) Schmidt Hammer, and c) ultrasonic.

test results can be influenced by many factors, such as the characteristics of the mixture, moisture condition, age of concrete. The use of Schmitt (rebound) hammer test method not suitable for estimate the strength of old concrete because of high variations [45].

Moreover, a comparison of concrete strength with after 7 and 28 days for different elevations is presented in Fig. 16. The normalized compressive strength obtained with different methods to the target value is illustrated in Fig. 17. It is concluded from this figure

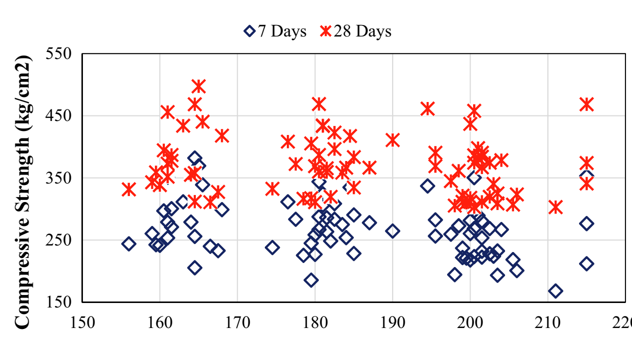

Fig. 16. Comparison of comprehensive strength of 28 and 7 days samples in different elevation.

that the results indicate good agreement with each other. The obtained compressive strength at different elevations and for all the experiments are presented in Fig. 18. As it is clear from this figure, the laboratory test and Schmitt hammer results overestimate and underestimate the concrete compressive strength, respectively. The results obtained through ultrasonic tests better represent the target value of the concrete compressive strength.

6.3. Combined method (SONREB method)

The reduction of the influence of several factors affecting the Schmitt (rebound) hammer test and UPV method could be partially achieved by using both methods together. The poor reliability of these non-destructive technique due to different aspects could be partially contrasted by using both methods together. A classic example of this application is the SONREB method [46,47,49], developed mostly by the effort of RILEM Technical Committees 7 NDT and TC-43 CND [46,47]. This combination technique has some advantageous because the Schmitt hammer result (RN) obtained by the concrete strength near the surface, whereas the results obtained from the UPV test reflects the interior concrete properties.

7. Probabilistic and statistical investigation

7.1. Bayesian predictive model

In order to develop a model predicting the concrete compressive strength, Bayesian regression is utilized [23–25]. After considering several candidate models, it is shown that the following model is more suitable than the others.

$$\frac{\sigma_c}{\sigma_d} = \theta_1 + \theta_2 \cdot \ln\left(\frac{S}{20}\right) + \theta_3 \cdot \ln\left(\frac{T_c}{273}\right) + \theta_4 \cdot \ln\left(\frac{1}{A}\right) + \theta_5 \cdot \ln\left(\frac{T_a}{273}\right) + \varepsilon \quad (1)$$

where σc and σd are the compressive strength of the laboratory test and design value, respectively. θ1 to θ5 are the regression coefficients, S is the slump, and A is the air percentage of the concrete. Tc and Ta are the concrete and ambient temperatures, respectively.

After performing the model diagnostics, the model (1) led to the following equation:

$$\frac{\sigma_c}{\sigma_d} = \theta_4\left(\ln\left(\frac{1}{A}\right) + \beta + +\beta' \cdot \ln\left(\frac{T_c}{273}\right) + \beta'' \cdot \ln\left(\frac{S}{20}\right) + \beta''' \cdot \ln\left(\frac{T_a}{273}\right)\right) + \alpha + \alpha' \cdot \ln\left(\frac{T_c}{273}\right) + \alpha'' \cdot \ln\left(\frac{S}{20}\right) + \alpha''' \cdot \ln\left(\frac{T_a}{273}\right) + \varepsilon \quad (2)$$

The coefficient of the above equation is presented in Table. 5. To investigate the model accuracy, the model prediction versus observation, model error normality, model predication to observation ratio, and residual versus regressor plots are produced (Figs. 24–27). According to these plots, the developed model is considered appropriate.

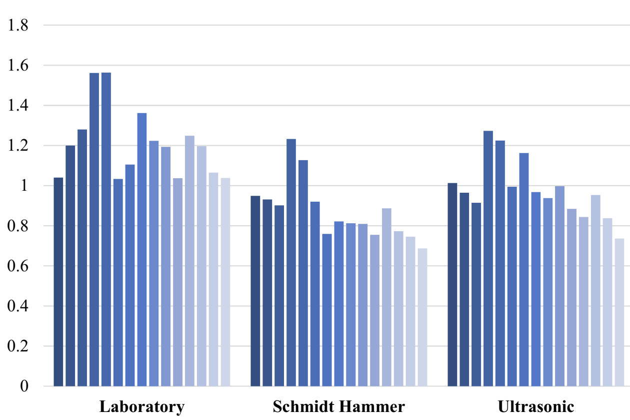

Fig. 17. Normalized laboratory, Schmidt Hammer, and ultrasonic results to the design compressive strength of concrete.

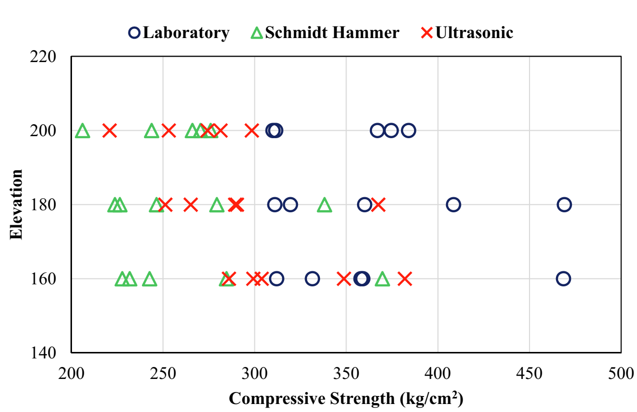

Fig. 18. Comparison of comprehensive strength determined using different methods.

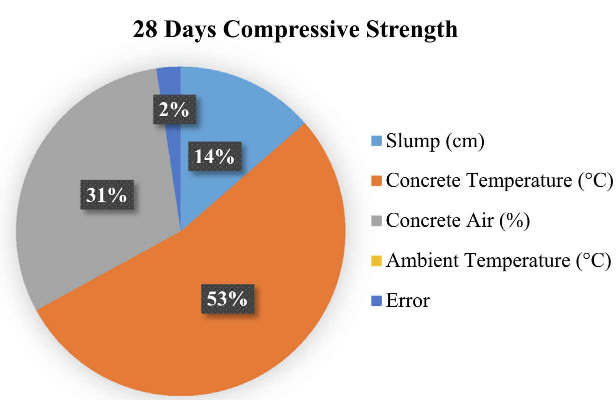

Fig. 19. Contribution of each factor to the compressive strength of 28 days samples.

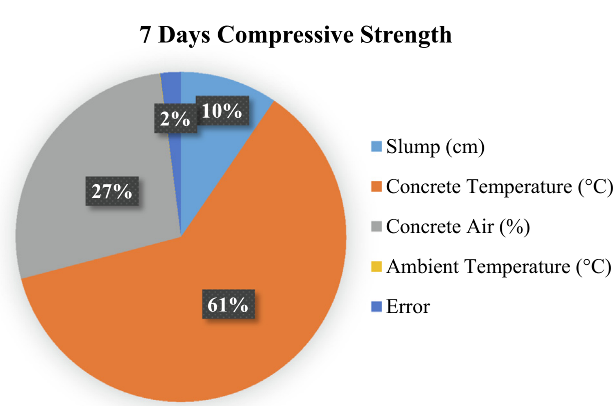

Fig. 20. Contribution of each factor to the compressive strength of 7 days samples.

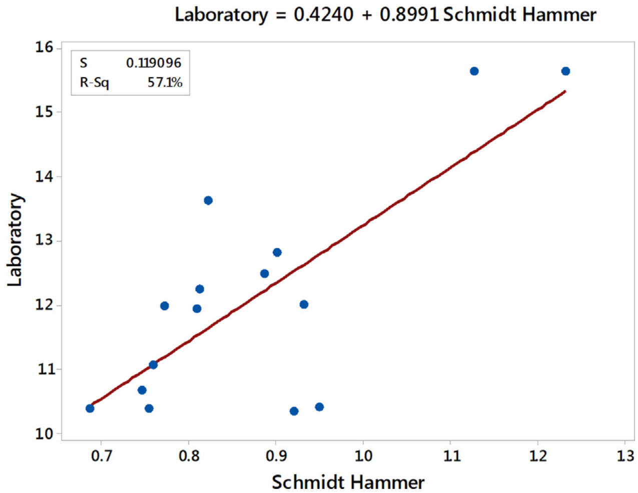

Fig. 21. Correlation of the results of laboratory and Schmidt Hammer tests.

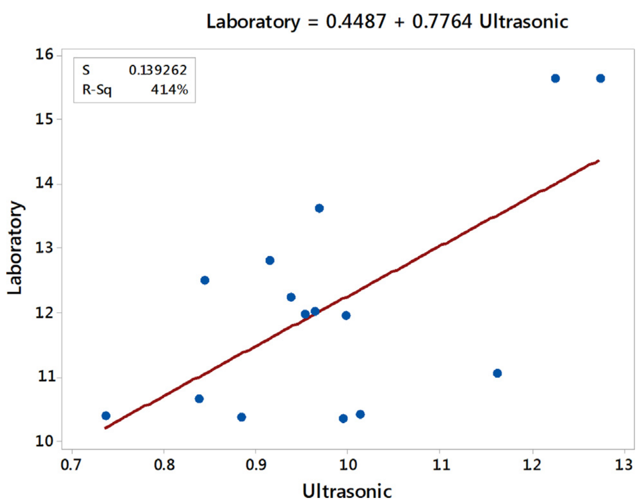

Fig. 22. Correlation of the results of laboratory and ultrasonic tests.

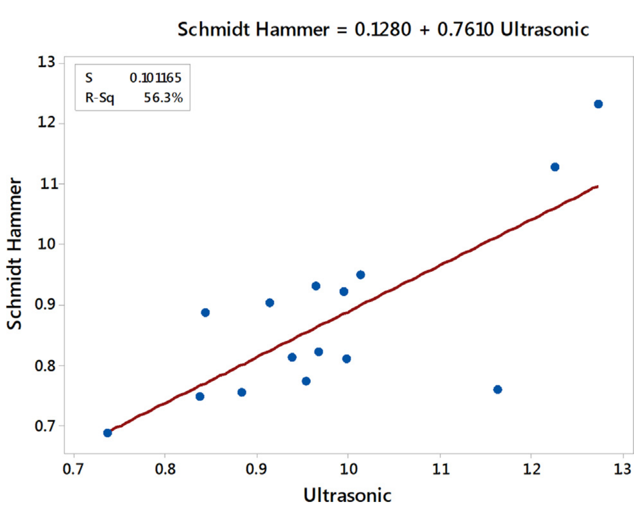

Fig. 23. Correlation of the results of ultrasonic and Schmidt Hammer tests.

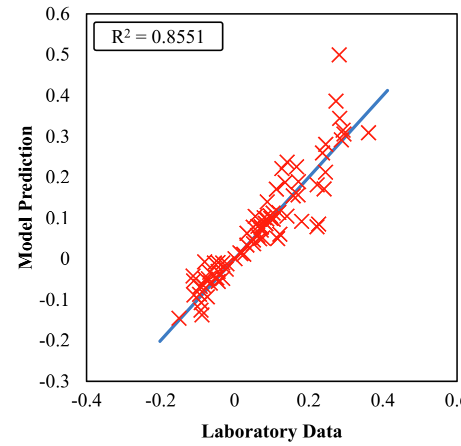

Fig. 24. Model diagnosis – model prediction versus observation.

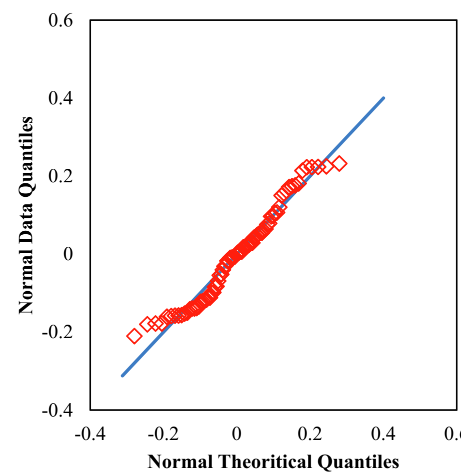

Fig. 25. Model diagnosis – model error normality.

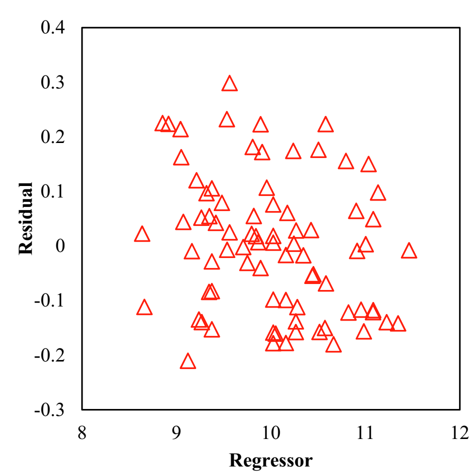

Fig. 26. Model diagnosis – model predication to observation ratio.

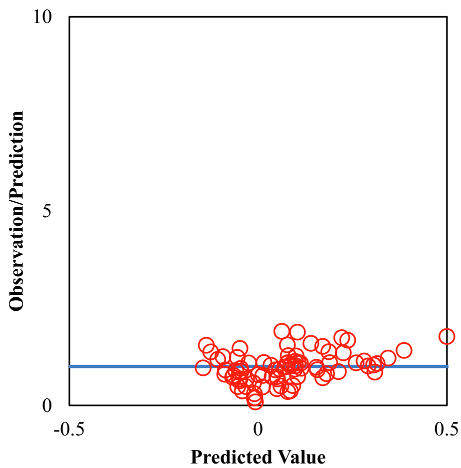

Fig. 27. Model diagnosis – residual versus regressor.

Table 3
Output of ANOVA for 28 days comressive strength specimens.

28 Days Compressive Strength				
Source	DF	SS	MS	Contribution (%)
Slump (cm)	15	24912.82	1660.855	13.59
Concrete Temperature (°C)	39	97955.23	2511.673	53.44
Concrete Air (%)	22	56064.98	2548.408	30.59
Ambient Temperature (°C)	1	0	0	0
Error	1	4371.125	4371.125	2.38
Total	78	183304.2		100

Table 4
Output of ANOVA for 7 days comressive strength specimens.

7 Days Compressive Strength				
Source	DF	SS	MS	Contribution (%)
Slump (cm)	15	14714.41	980.9604	9.53
Concrete Temperature (°C)	39	94707.78	2428.405	61.37
Concrete Air (%)	22	41706.79	1895.763	27.02
Ambient Temperature (°C)	1	84.5	84.5	0.05
Error	1	3120.5	3120.5	2.02
Total	78	154,334		99.99

Table 5
Coefficient of the developed Bayesian model.

θ4	A	B	A′	B′	A″	B″	A‴	B‴
0.0065	0.2062	3.59	2.29	70.42	−0.050	5.86	−0.911	39.69

7.2. Analysis of variance (ANOVA)

The contribution of input variables in the concrete compressive strength is studied using analysis of variance (ANOVA) [26–30]. The input variables are concrete and ambient temperature, concrete air percentage, and concrete slump. ANOVA has been performed separately for 7 and 28 days samples. The results of the ANOVA are presented in Figs. 19 and 20. The results indicate that the most influential parameter on the concrete compressive strength is concrete temperature. Further, it is shown that slump is the least important variable in determining the compressive strength of concrete. The detailed results of ANOVA are shown in DF Tables 3 and 4.

Moreover, to indicate the relation between the results of the laboratory, Schmitt hammer, and ultrasonic test, linear regression is applied to the results (Figs. 21–23). As it is obvious from the mentioned figures, the equation for each pair of the results is presented as well. It is concluded that the results of nondestructive tests, i.e., Schmitt hammer and ultrasonic, are in higher agreement than the others.

8. Conclusions

A real case-study (Bijar CFRD) was used as a basis for the assessment of the in-situ concrete strength by NDT tests. Relationships between the concrete strength (lab specimens) and NDT measurements (Ultrasonic testing and Schmidt hammer test) have been identified according to the traditional engineer approach. Based on the results obtained, the following conclusions could be drawn:

- The average of compressive strength of laboratory samples to the samples with Schmitt test at levels 160, 180, 200 ratio, the compressive strength of taken samples was about 36–43% more than ultrasonic test results.
- Ultrasonic wave velocity is increased by increasing concrete age, and also about due to the low coefficient of variation of 10%, it shows the uniformity of the concrete implemented in the dam design.
- The average of laboratory samples compressive strength is obtained 16–25% more than design characteristic compressive strength.
- The average of samples compressive strength is 13% more than compressive strength with the ultrasonic test.
- The average laboratory samples' compressive strength is 36% more than the compressive strength obtained by the Schmitt hammer test.
- The relation between compressive strength of concrete samples in laboratory and ultrasonic cleared that the compressive strength of obtained samples in laboratory in age 7-days is by direct method 17.60% and by indirect method 8.40% more than the results of compressive strength obtained by ultrasonic test method.
- The mean growth ratio of compressive strength for 28–7 days obtained about 37.30% and the standard deviation of 9.96%.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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