Challenge Journal of Concrete Research Letters

Research Article

Efficacies of suggested strength-based prediction models for estimation of compressive and tensile properties of normal concrete

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ABSTRACT

One of the most crucial challenges faced by today's construction industry for a speedy delivery is undeniably the 'time-factor' accompanied by promised quality within the framework of distinct budget. Strength based - Prediction models helps in estimating the early strengths as well as later-stage strength or strength at any age of concrete. Such models assist the structural and execution engineers in arriving at a fair judgement of compressive strength of concrete. A normal practice usually followed by the material testing laboratories and quality assurance cell at site is to assess the cube compressive strength of concrete which is an intrinsic engineering property governing the design and performance phase of structures. It is found from the literature that most of the prediction models that are formulated to estimate the compressive strength of concrete at any age are actually based on cylinder compressive strength of concrete. Therefore, this paper attempts to use some of the suggested prediction models with two sets of data, that is, one by considering experimental results of cube compressive strength found at the age of 7, 14 and 28-days and two by utilizing a conversion value, suitable cylinder compressive strength is obtained. These datasets are thoroughly used in the prediction models to accurately estimate the compressive strength of concrete. Similarly, appropriate prediction models are sought to determine the split tensile strength of normal concretes based on cubic compressive strength and cylinder compressive strength. Particularly, results of the present study showcase that although the prediction models are developed based on cylinder compressive strength, they can agreeably be used on cube strength data as the ratio of (Pi/Ai) obtained is the higher range of 0.85-1.00 and with only an early cube strength result, it is possible to predict an accurate value of split tensile strength of concrete at an age of 28-days. The effectiveness of suggested prediction models through statistical parameters are determined and their efficiencies are found to be in the higher range of 94% to 98%.

ARTICLE INFO

Article history:
Received 1 February 2023
Revised 3 March 2023
Accepted 13 March 2023

Keywords:
Concrete
Cube
Cylinder
Compressive strength
Prediction model
Split tensile strength

1. Introduction

Concrete is one of the most dynamic and versatile construction material. The performance and durability aspects of concrete largely depends on its compressive strength and is attributed to play a pivotal role in design and construction of any structure. The strength-based prediction models help in obtaining the early age strength or gain of strength at any age without having to wait for the stipulated time period of 28 days (Masood and Murtaza 2015). The later-stage strength characteristics such as durability, permeability, volume firmness are also dependent on compressive strength of concrete. In case of assessing such parameters, it is always desirable to use the strength-based prediction models so that accurate and precise designs are carried out. The evidently known and most common practice is to determine the compressive strength of concrete by casting cubes

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ISSN: 2548-0928 / DOI: https://doi.org/10.20528/cjcrl.2023.02.003

and testing it at the age of 28 days. Some of the recent research articles have documented that the cylinder strength test is the acclaimed process to ensure the precise values of concrete compressive strength and hence the prediction models are actually based on cylinder compressive strength (Monjurul Hasan and Kabir 2011).

The split tensile strength is another distinguished design property which is used in the ductility based designs of concrete structural elements subjected to transverse shear, torsion, differential shrinkage, and thermal strains (Ashwini and Srinivasa Rao 2021). The tensile strength determines the load-bearing behaviour of concrete structures by taking the compressive strength as a design parameter (Reinhardt 2013). This essentially proves that both compressive strength and the tensile strength supremely affects one another and dictates the performance and response of structures.

The assessment of these strength-related parameters are usually carried out in material testing laboratories and are studied as specimens cast into cubes or cylinders. Hence, the estimation of these governing properties becomes the premise of the present study wherein a few suggested prediction models are sought to predict the cube compressive strength on the basis of cylinder-based prediction models.

2. Review of the Recent Research

In the recent past, several researchers have attempted to predict the compressive and tensile strength of concrete based on mathematical and computation models considering the basic constituents of concrete such as cement, fine aggregates, coarse aggregates, water content, water-cement ratio and in some cases, the physical properties such as fineness modulus of sand and size ratio of components of coarse aggregates are also accounted. Some of the noteworthy research investigations are documented in the paragraphs below.

2.1. Prediction models for compressive strength

Chopra et al. (2014) carried out statistics based mathematical analysis by developing multiple non-linear regression models for predicting the compressive strength of concrete based on experimental work on concrete mixes proportioned for medium and high workability at different curing ages of 28, 56 and 91 days. The multivariable power equations were developed and the study suggested two models for medium and high workable concrete mixes. Co-efficient of determination (COD) and Root Mean Square Error (RMSE) were chosen as the statistical parameters to evaluate the effectiveness of the predicted models and they were found to 95% accurate with experimental data. Masood and Murtaza (2014) presented analytical models that were developed by using the data of concrete strengths obtained from the experimental results of testing cylinders. Two models were proposed to predict the compressive strength of concrete up to 28-days using the 7-day compressive strength. The research work suggested that of the four cement compounds, as C_3S and C_2S largely contribute to the early and long-term strengths of cement, hence they were included in the prediction models as 'logical variables' along with the fineness of cement. Also, for the sake of simplicity and owing to the fact that strength properties are majorly influenced by the composition of C_3S and fineness of cement up to 7-days, the 7-days compressive strength was included as one of the leading parameters in both the prediction model. Regression analysis using the least square method were used to predict the important two-defining parameters α and β correlating the effects of chemical composition of cement, specifically, C_3S and C_2S and fineness of cement. The proposed models provided a good correlation with experimental data and were validated with results of several types of cement brands reported in literature. Chopra et al. (2015) made efforts to develop prediction models to estimate the concrete compressive strength using the two data mining techniques, such as, Artificial Neural Networks (ANN) and Genetic Programming (GP). The study reported a comparison of predicted results from these two models and inferred that the model developed by using ANN with a training function Levenberg-Marquardt (LM) yielded better results and lesser value of RMSE, meaning that the predicted values are mostly precise with the experimental results. Ahsanul et al. (2012) suggested a simple mathematical equation comprising of two constants and a variable, age of concrete in days, based on rational polynomial to predict the compressive strength of concrete at 28-days from 7-days early strength. The constants '*p*' associated with stress unit and 'q' as unit in days. The model proposed is a simple equation where the compressive strength of any data can be determined from only one test result input data. It was observed that the constants *p*, *q* and strength at a particular day, $f'_{c,D}$ maintained a correlation of polynomial surface (especially fitted well as a second degree polynomial surface equation) and facilitated to express constant *p* in-terms of *q*. The general form of correlation equation was found as : $p = m(f'_{cD})^r$, with '*m*' equal to 3.0 and 2.5 respectively for 7 and 14 days and '*r*' equal to 0.80.

The effectiveness of the predicted models were determined using RMSE, Mean absolute error (MAE) and the efficiency up to 92% were reported. The suggested model predicted similar results when compared with the experimental data and mentioned that the predicted tool could be used to estimate the strength of concrete at any age. Metwally (2013) carried out similar studies on predicting the compressive strength of concrete at any age based on statistical analysis. The prediction model put forth two constants, A and B in the equation which were considered as a characteristic property for a concrete mix. The constants A and B were introduced as a components of a rate of strength gain constant and grade strength constant respectively. The research work emphasized on development of these constants based on thorough understanding of strength developments of pure clinker compounds, the C_3S, C_2S, C_3A and C_4AF. The research study implied that for a given degree of hydration, the strength increases in the order of $C_3A < C_4AF < C_2S < C_3S$, signifying the prevailing differences in the intrinsic strengths of hydrates formed in the hydration of clinker compounds. Hence, the study specified that based on cement composition, the strength development of pure clinker minerals is found to be in the form of $f_t = A \ln(t) + B$ with correlation coefficient approaching unity. The analysis revealed that the proposed predicted model gave highly accurate results following the concrete mixes with no additives and mixes with additives such as silica fume and nano silica when cured at normal temperature and in water.

2.2. Prediction models for split tensile strength

Mehrdad and Ramezan (2021) examined the behaviour of normal and steel fiber reinforced concrete to predict the tensile strength when exposed to high temperatures as it greatly influences on the performance characteristics of concrete structures especially when the members are subjected to high temperatures. The main objective of this work was to aid a broader application of steel fibers specifically with fire resistant structures and the proposed prediction model would help in estimating the tensile strength under high-temperature exposure conditions as high as 28°C to 800°C. The study aimed at predicting tensile strength based on regression analysis for both normal concrete and steel fiber reinforced concrete separately and these formed the basis for developing tensile strength expressions when normal concrete and steel FRC exposed to high elevated temperatures. Further, it showed that the compressive strength has a great impact on the tensile strength of concrete, where an increase of compressive strength from 20.1 MPa to 84.45 MPa improves the tensile strength by 169.4% at ambient temperature and an average deviation of experimental results with the predicted model showed about 7.53% indicating high accuracy and validating the predicted tensile strength model. Açıkgenç et al. (2015) conducted experimental investigations to develop relation between splitting tensile strength and flexural strengths of plain concrete and steel fiber-reinforced concrete. The study focused on estimating the flexural strength by using a relation with splitting tensile strength as the former requires testing heavy beams while the latter needs standard cubes or cylinders as specimens. In this study, the functions of compressive strength, split tensile strength and flexural strengths for varying volume fraction of steel fibers are defined in terms of Abram's law comprising of water-cement ratio and two empirical constants. The relations of compressive-splitting tensile strength and compressive-flexural strengths yielded a strong correlation of 95% and 96% respectively. Ashwini and Srinivasa Rao (2021) carried out research investigations on determination of correlation between compressive and splitting tensile strength of concrete using alccofine and nano silica based on prediction model – power type regression equation and validating them with the experimental results with an age of 28-days curing time. Three concrete grades of M40, M60 and M80 were selected with mixes having no additives, with alccofines and with both alccofines and nano silica. It was observed that split tensile strength for all grades of concrete increased with an increase in compressive strength. The proposed model gave a good correlation of R^2 of 95.45% and the results of error analysis on the model showed lowest error results of the model proving its accuracy. Mane et al. (2019) conducted experimental investigations on use of pozzolanic materials such as fly ash, GGBS, silica fume and metakaolin as a partial replacement to cement along with replacement of natural sand by manufactured sand to determine the tensile strength of concrete. The experimental results obtained were checked with a prediction model developed based on artificial neural networks (ANN) at an age of 28 days. In all the cases of incremental replacement studies, the predicted model showed almost similar results as that of the experiments with high R^2 value in the range of 0.94 – 0.96. Jinping et al. (2019) conducted rigorous experiments to evaluate the concrete cube splitting tensile strength based on the curing age and aging degree of concrete. The study related to the significance of maturity concept of concrete wherein along with time, temperature of curing also plays an important role and that the age degree has a direct influence on splitting tensile strength of concrete indicating that a larger difference of age degree results in larger difference in split tensile strength of concrete. A predictor model was developed based on the experimental results of cubic split tensile strength of 150x150x150 mm and a comparison with experimental data showed that the intensity of increase in split tensile strength of concrete is rapid for the first 7-days and the intensity of 70% is reached up to an age of 28-days.

It is clear from this extensive study on literature, that there is a need to find out whether the available prediction models (which are based on cylinders) are capable enough in accurately predicting the compressive strength of concrete when the type of specimens cast are cubes and its implications on predictions of cubic and cylinder split tensile strength of concrete. Therefore, these pointers essentially forms the motivation of the present investigation which is discussed in detail in the following section.

3. Present Investigation

3.1. Scope of the study

It has already been well-highlighted that use of strength based - prediction models will help in saving time in order to obtain nearly accurate estimation of probable development of strength after a certain curing time. As a normal practice, it is seen that usually compressive strength of concrete is determined by casting them into cubical moulds of either 150 mm or 100 mm in size. On the other hand, it is finely indicated in several research articles that the prediction models are based on cylinder compressive strength as they are found to be far more accurate and precise. Hence, there is need to have clear understanding of these aspects before using the prediction models. Therefore, the objectives of the present investigation are summarized as follows –

- Prediction of cube compressive strength using prediction models (1 to 4) at 14 and 28-days using 7-days test results and validating them with experimental results.

- Prediction of cylinder compressive strength by using an appropriate conversion factor to cube strength and then using the prediction models to estimate the strength of 14 and 28-days.
- Prediction of cubic and cylinder split tensile strength by various prediction models suggested in literature.
- Estimation of effectiveness of prediction models using simple statistical error analysis.

3.2. Methodology

The present investigation is aligned with use of suggested prediction models mentioned in Table 1 and are based on literature studies (covered in previous section) to predict the compressive and split tensile strength of normal concrete. In this context, around 16 experimental results of cube compressive strength of normal concrete of M25 grade, cured and tested for compressive strength in accordance with IS: 516–1959 (reaffirmed in 2004) at an age of 7, 14 and 28-days in concrete material testing laboratory of Dept. of Civil Engineering, B.M.S College of Engineering, Bengaluru, Karnataka are considered.

It is to be noted here that the developed prediction models of referred literature are based on cylinder compressive strength of concrete. Based on several literature studies, a conversion factor suggested by relevant research studies of João et al. (2019) and David and Gongkang (1995) of 0.81 is adopted to convert the cube compressive strength to appropriate cylinder compressive strength of concrete. This value of conversion factor is based on computations of model accounting as both deterministic (considering practical conversions of test data) and probabilistic (considering normal distributions) in nature for normal concretes with natural aggregates. These estimated values along with experimental data considered for the present study are shown in Table 2. The use of suggested prediction models for compressive strength and split tensile strength are abbreviated in the series of C_p – 1, 2, 3, 4 and T_p – 1, 2 respectively. For each case of use of suggested prediction model (P_i), cube compressive strength at 28-days is obtained and verified with experimental data (A_i) and correspondingly cylinder compressive strength is estimated and again verified with the predicted data.

Table 1. Summary of prediction models based on literature.

Prediction models for compressive strength		
Model Code	Prediction model	Notations
Cp-1 (Ahsanul et al. 2012)	$f'_{C,D} = \frac{D}{D+q} \cdot p$ $p = 3.0\left(f'_{C,7}\right)^{0.8}$	$f'_{C,D}$ = strength of concrete at D^{th} day, D = No. of days, p and q are constants determined by using regression analysis.
Cp-2 (Metwally 2014)	$f_t = A\ln(t) + B$ $B = 0.005(f_c)^{2.20}$ $A = 1.4035\ln(B) + 2.9956$	f_t = compressive strength at age (t) days, f_c = 28-day compressive strength, B = is the grade constant (R^2 = 0.91), A = is the rate constant (R^2 = 0.98).
Cp-3 (Masood and Murtaza 2015)	$f_c = 0.56 \times f_{c,7} \times t_n^{0.29}$ where $\{7 < t_n \le 28\}$	f_c = compressive strength of concrete beyond 7-day strength, $f_{c,7}$ = 7- day compressive strength of concrete, t_n = age of concrete at which strength of concrete is to be predicted (n = 8,…,28), $f_{c,t}$ = strength of concrete at time (t) beyond 28 days.
Cp-4 (Masood and Murtaza 2015)	$f_{c,t} = f_{c,7} \times \frac{t_n}{(3.2 + 0.58t)}$ where $\{7 < t_n \le 28\}$	
Prediction models for split tensile strength		
Using cube compressive strength		
Tp-1 (Jinping et al. 2019)	$f_{cp} = 0.25 \times f_{cu}(t,T)^{0.7}$ $f_{cu}(t,T) = [0.2134 \times \ln(T) + 0.3122] \times \left[1 + 0.05968 \times \left(1 - \frac{20t}{T}\right)\right] f_{cu}$	f_{cp} = concrete cubic split tensile strength of different curing and age degree, t = curing age of the specimen (in days), T = age degree of the specimens (°C.d), f_{cu} = 28-days cube compressive strength, f_{cu} (t,T) = is the cubic strength prediction based on age and age degree
Using cylinder compressive strength		
Tp-2$_i$ (Mehrdad and Ramezan 2021)	$f_t = 0.167 f_c^{0.821}$	f_t = split tensile strength of concrete, f_c = cylinder compressive strength, MPa
Tp-2$_{ii}$ (Mehrdad and Ramezan 2021)	$f_t = 0.188 f_c^{0.84}$	
Tp-2$_{iii}$ (Mehrdad and Ramezan 2021)	$f_t = 0.21 f_c^{0.83}$	
Tp-2$_{iv}$ (Ramadoss 2014)	$f_t = 0.12 f_c^{0.95}$	
Tp-2$_v$ (Mehrdad and Ramezan 2021)	$f_t = 0.56 f_c^{0.5}$	

3.2.1. Use of prediction models for estimating compressive strength of concrete

The experimental data of cube compressive strength obtained at 7, 14 and 28 days considered for the present study are presented in Table 2. In addition, the cylinder strength is estimated as 0.81 times cube strength value obtained at 7, 14 and 28 days.

Cp-1. In the present study, using the experimental data of cube strength and estimated cylinder strength at 7-days (Table 2), constants are calculated and then 14th and 28-days compressive strengths are predicted using the expressions mentioned in Table 1. The results of use of Cp-1 in the present study are shown in Table 3.

Cp-2. The prediction model requires 28-days strength as an input value to determine the constants A (rate of strength gain constant and B (grade constant). Hence, in the present study, the experimental data of cube strength and estimated cylinder strength at 28-days are considered. From this, constants B and A are calculated and then 7th and 14-days strength are computed along with corresponding ratios of predicted to actual values. The results are shown in Table 4.

Table 2. Experimental data of cube strength and estimated cylinder strength considered for present study.

	Experimental cube strength in days (MPa)			Estimated cylinder strength in days (MPa) by using conversion value of 0.81				Experimental cube strength in days (MPa)			Estimated cylinder strength in days (MPa) by using conversion value of 0.81		
Sp. No	7	14	28	7	14	28	Sp. No	7	14	28	7	14	28
1	22.40	28.40	35.50	18.14	23.00	28.76	9	28.91	32.84	41.05	23.42	26.60	33.25
2	23.74	27.76	34.70	19.23	22.49	28.11	10	29.83	32.54	40.68	24.16	26.36	32.95
3	22.01	29.52	36.90	17.83	23.91	29.89	11	19.12	21.80	27.25	15.49	17.66	22.07
4	24.23	30.96	38.70	19.63	25.08	31.35	12	19.05	22.26	27.82	15.43	18.03	22.53
5	24.30	30.00	37.50	19.68	24.30	30.38	13	19.16	22.62	28.27	15.52	18.32	22.90
6	21.68	28.56	35.70	17.56	23.13	28.92	14	19.59	23.33	29.16	15.87	18.90	23.62
7	26.40	30.52	38.15	21.38	24.72	30.90	15	19.52	23.82	29.78	15.81	19.30	24.12
8	25.60	31.68	39.60	20.74	25.66	32.08	16	19.63	23.08	28.85	15.90	18.69	23.37

Mean = 34.35/27.82 MPa (28-days strength of cube/cylinder), COV = 14.53

Table 3. Results of the prediction model: Cp-1.

Sp. No	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
	p	q	14		28		p	q	14		28	
1	36.08	4.28	27.64	0.97	31.30	0.88	30.49	4.76	22.75	0.99	26.06	0.91
2	37.80	4.15	29.16	1.05	32.93	0.95	31.94	4.63	24.01	1.07	27.41	0.98
3	35.58	4.32	27.20	0.92	30.83	0.84	30.06	4.80	22.38	0.94	25.66	0.86
4	38.42	4.10	29.72	0.96	33.52	0.87	32.46	4.58	24.46	0.98	27.90	0.89
5	38.51	4.09	29.80	0.99	33.60	0.90	32.54	4.57	24.53	1.01	27.97	0.92
6	35.15	4.35	26.82	0.94	30.43	0.85	29.70	4.84	22.07	0.95	25.32	0.88
7	41.15	3.91	32.17	1.05	36.11	0.95	34.77	4.38	26.48	1.07	30.06	0.97
8	40.15	3.98	31.27	0.99	35.16	0.89	33.92	4.45	25.74	1.00	29.27	0.91
9	44.25	3.72	34.97	1.06	39.07	0.95	37.39	4.18	28.80	1.08	32.54	0.98
10	45.38	3.65	36.00	1.11	40.15	0.99	38.34	4.11	29.64	1.12	33.43	1.01
11	31.79	4.64	23.88	1.10	27.27	1.00	26.86	5.14	19.65	1.11	22.69	1.03
12	31.70	4.65	23.80	1.07	27.19	0.98	26.78	5.15	19.58	1.09	22.62	1.00
13	31.84	4.63	23.93	1.06	27.32	0.97	26.90	5.14	19.68	1.07	22.74	0.99
14	32.42	4.58	24.42	1.05	27.86	0.96	27.39	5.08	20.09	1.06	23.18	0.98
15	32.32	4.59	24.34	1.02	27.77	0.93	27.31	5.09	20.03	1.04	23.11	0.96
16	32.47	4.58	24.47	1.06	27.91	0.97	27.43	5.08	20.13	1.08	23.22	0.99

Mean = 31.6/26.4 MPa (28-days strength of P_i - cube/cylinder), COV = 13.4

Table 4. Results of the prediction model: Cp-2.

Sp. No	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
	B	A	7		14		B	A	7		14	
1	12.87	6.58	25.67	1.15	28.70	1.01	8.09	5.93	19.63	1.08	22.49	0.98
2	12.24	6.51	24.91	1.05	27.68	1.00	7.70	5.86	19.10	0.99	21.72	0.97
3	14.01	6.70	27.05	1.23	30.29	1.03	8.81	6.05	20.58	1.15	23.63	0.99
4	15.56	6.85	28.88	1.19	32.03	1.03	9.79	6.20	21.84	1.11	24.78	0.99
5	14.52	6.75	27.65	1.14	30.65	1.02	9.13	6.10	21.00	1.07	23.82	0.98
6	13.03	6.60	25.87	1.19	29.02	1.02	8.19	5.95	19.77	1.13	22.74	0.98
7	15.08	6.80	28.31	1.07	31.14	1.02	9.48	6.15	21.46	1.00	24.10	0.97
8	16.36	6.92	29.83	1.17	32.90	1.04	10.29	6.27	22.49	1.08	25.35	0.99
9	17.71	7.03	31.39	1.09	34.26	1.04	11.14	6.38	23.55	1.01	26.21	0.99
10	17.36	7.00	30.99	1.04	33.73	1.04	10.92	6.35	23.28	0.96	25.82	0.98
11	7.19	5.76	18.41	0.96	20.95	0.96	4.52	5.11	14.47	0.93	16.94	0.96
12	7.53	5.83	18.87	0.99	21.48	0.97	4.73	5.18	14.81	0.96	17.34	0.96
13	7.80	5.88	19.23	1.00	21.88	0.97	4.90	5.23	15.08	0.97	17.64	0.96
14	8.35	5.97	19.97	1.02	22.66	0.97	5.25	5.32	15.61	0.98	18.20	0.96
15	8.74	6.04	20.49	1.05	23.26	0.98	5.50	5.39	15.98	1.01	18.65	0.97
16	8.15	5.94	19.71	1.00	22.36	0.97	5.13	5.29	15.42	0.97	17.98	0.96

Mean = 35.19/26.87 MPa (28-days strength of P_i - cube/cylinder), COV = 17.69/17.16

Cp-3. The prediction model requires 7-days compressive strength and any age/day strength beyond 7-days can be calculated by the respective relation mentioned in Table 1. It is reported that the coefficients of the regression equation, α = 0.56 and β = 0.29 are determined as function of cement type which in turn is represented by the chemical and compound composition and fineness.

Cp-4. The equation represented in this prediction model is slated to be a modification to ACI 209R- 92 code which is used to predict the strength at any time, t beyond the age of 28-days where α and β range from 0.05 - 9.25 and 0.67 - 0.98 respectively. It is documented that the average values of α and β complying with the (fineness + C_3S content) and total silicate content (C_3S+ C_2S) of cement composition is equal to 3.2 and 0.58 respectively.

Table 5. Results of the prediction model: Cp-3.

Sp. No	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
	α	β	14		28		α	β	14		28	
1	0.56	0.29	26.97	0.95	32.97	0.93	0.56	0.29	21.84	0.95	26.71	0.93
2			28.58	1.03	34.94	1.01			23.15	1.03	28.30	1.01
3			26.50	0.90	32.40	0.88			21.46	0.90	26.24	0.88
4			29.17	0.94	35.66	0.92			23.63	0.94	28.89	0.92
5			29.25	0.98	35.77	0.95			23.69	0.98	28.97	0.95
6			26.10	0.91	31.91	0.89			21.14	0.91	25.85	0.89
7			31.78	1.04	38.86	1.02			25.74	1.04	31.47	1.02
8			30.82	0.97	37.68	0.95			24.96	0.97	30.52	0.95
9			34.80	1.06	42.55	1.04			28.19	1.06	34.47	1.04
10			35.91	1.10	43.91	1.08			29.09	1.10	35.56	1.08
11			23.02	1.06	28.14	1.03			18.64	1.06	22.79	1.03
12			22.93	1.03	28.04	1.01			18.58	1.03	22.71	1.01
13			23.07	1.02	28.20	1.00			18.68	1.02	22.84	1.00
14			23.58	1.01	28.83	0.99			19.10	1.01	23.36	0.99
15			23.50	0.99	28.73	0.96			19.03	0.99	23.27	0.96
16			23.63	1.02	28.89	1.00			19.14	1.02	23.40	1.00

Mean = 33.6/27.2 MPa (28-days strength of P_i - cube/cylinder), COV = 15.5

Table 6. Results of the prediction model: Cp-4.

Sp. No	Using experimental cube strength in days (MPa)						Using estimated cylinder strength in days (MPa)					
	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)	Constants		P_i	Ratio (P_i/A_i)	P_i	Ratio (P_i/A_i)
	α	β	14		28		α	β	14		28	
1	3.20	0.58	27.70	0.98	32.26	0.91	3.20	0.58	22.44	0.98	28.45	0.99
2			29.36	1.06	34.19	0.99			23.78	1.06	27.81	0.99
3			27.22	0.92	31.70	0.86			22.05	0.92	29.57	0.99
4			29.97	0.97	34.90	0.90			24.27	0.97	31.01	0.99
5			30.05	1.00	35.00	0.93			24.34	1.00	30.05	0.99
6			26.81	0.94	31.23	0.87			21.72	0.94	28.61	0.99
7			32.65	1.07	38.02	1.00			26.45	1.07	30.57	0.99
8			31.66	1.00	36.87	0.93			25.65	1.00	31.74	0.99
9			35.75	1.09	41.64	1.01			28.96	1.09	32.90	0.99
10			36.89	1.13	42.97	1.06			29.88	1.13	32.60	0.99
11			23.65	1.08	27.54	1.01			19.15	1.08	21.84	0.99
12			23.56	1.06	27.44	0.99			19.08	1.06	22.30	0.99
13			23.70	1.05	27.60	0.98			19.19	1.05	22.66	0.99
14			24.23	1.04	28.22	0.97			19.62	1.04	23.37	0.99
15			24.14	1.01	28.12	0.94			19.55	1.01	23.87	0.99
16			24.28	1.05	28.27	0.98			19.66	1.05	23.12	0.99

Mean = 32.87/27.53 MPa (28-days strength of P_i - cube/cylinder), COV = 15.46/14.53

In the present investigation, the experimental cube and estimated cylinder 7-days strength are utilized and strength at 14th and 28-days are predicted and corresponding (P_i/A_i) ratio are determined separately by using Cp-3 and Cp-4. The results are shown in tables 5 and 6 respectively. The mean and co-efficient of variation (COV) of predicted results (28-days) are computed for each predicted model and the results are mentioned below each of them

The experimental data of cube and estimated cylinder compressive strengths of all the specimens with the results obtained from the above four considered prediction models are plotted graphically presented below as Fig. 1(a-b), respectively. It can be seen from these graphs that the nearly almost all the results obtained through the predicted models match with the experimental cube and estimated cylinder compressive strength data implying the effectiveness of the prediction models.

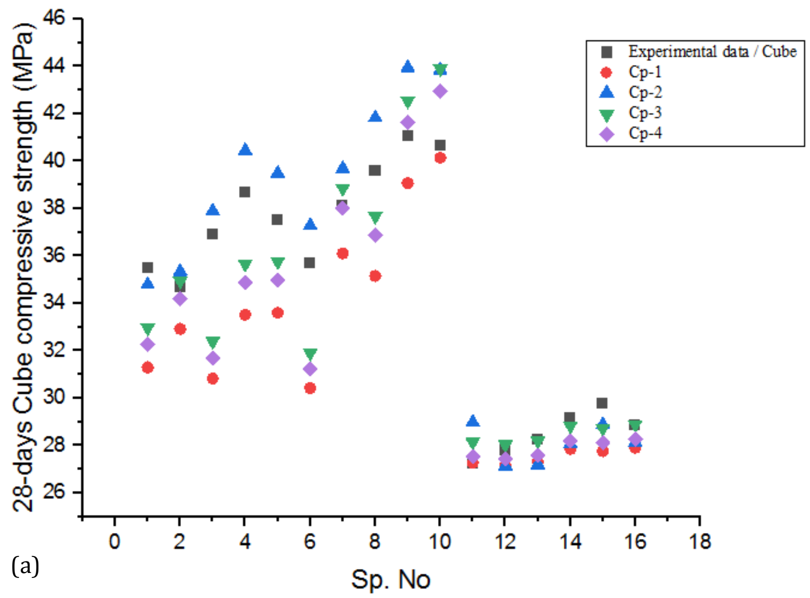
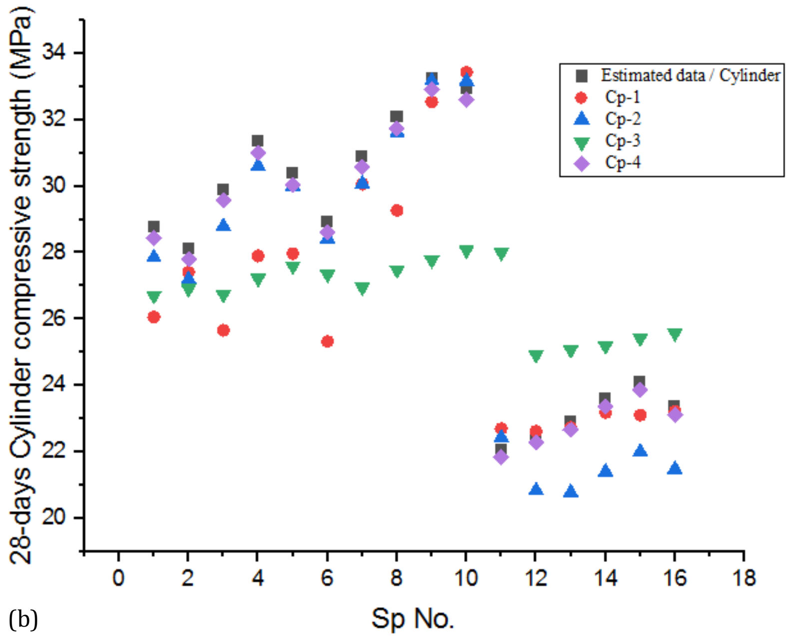


Fig. 1. (continued)



(b)

Fig. 1. (a) Experimental cube strength data with results of prediction models at 28-days; (b) Cylinder strength data with results of prediction models at 28-days.

The statistical error analysis are performed to understand the efficacies of considered predicted model in obtaining the cube and cylinder compressive strengths by using the following expressions.

- Mean absolute error = $MAE = \frac{1}{n}\sum_{i=1}^{n}|P_i - A_i|$
- Root mean square error = $RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i - A_i)^2}$
- Efficiency = $EF = (1 - (\frac{1}{n}\sum_{i=1}^{n}\frac{|P_i - A_i|}{A_i})) \times 100\%$

The results of these statistical parameters obtained from each of the predicted model are shown in Table 7.

Table 7. Statistical error analysis on predicted cube and cylinder compressive strength results.

Statistical parameters	Predicted results of cube compressive strength							
	Cp-1		Cp-2		Cp-3		Cp-4	
	14	28	7	14	14	28	14	28
RMSE	1.65	3.20	2.72	0.83	1.62	2.13	1.82	2.45
MAE	1.45	2.58	2.12	0.76	1.33	1.61	1.47	1.87
EF (%)	94.67	92.82	91.04	97.25	95.39	95.59	94.73	94.78
Avg (*Pi*/*Ai*)	1.03	0.93	1.08	1.00	1.00	0.98	1.03	0.96
(Min - Max)	0.92-1.11	0.84 -1.00	0.96-1.23	0.96-1.04	0.90-1.10	0.88-1.08	0.92-1.13	0.86-1.06

Statistical parameters	Predicted results of cylinder compressive strength							
	Cp-1		Cp-2		Cp-3		Cp-4	
	14	28	7	14	14	28	14	28
RMSE	1.53	2.05	1.30	0.57	1.31	1.72	1.47	0.30
MAE	1.30	1.52	1.00	0.55	1.07	1.31	1.19	0.29
EF (%)	94.03	94.81	94.56	94.72	95.39	95.59	94.73	98.95
Avg (*Pi*/*Ai*)	1.04	0.95	1.03	0.97	1.00	0.98	1.03	0.99
(Min - Max)	0.94-1.12	0.86-1.03	0.93-1.15	0.96-0.99	0.90-1.10	0.88-1.08	0.92-1.13	0.99-0.99

3.2.2. Use of prediction model for estimating splitting tensile strength of concrete

In the section based on literature studies, two distinct type of models are chosen. The first one, Tp-1 presents cubic split tensile strength which is centered on cubic compressive strength and the second type of models, that is, Tp-2$_{i \text{ to } v}$ represents a group of similar equations developed on the basis of regression analysis and relies on cylinder compressive strength.

Tp-1. This model requires 28-days cube compressive strength of concrete as an input value. It is reported that along with curing age in days, age degree (°C.d) is another crucial parameter that is involved which accounts to the maturity concept of concrete. Hence in the present study, in order to calculate curing age and age degree, 28-days and 25°C of prevalent temperature are considered. Experimental data of 28-days cube compressive strength and median (as the obtained results appear to be skewed) of 28-days results of predicted models from Cp-1 to Cp-4 are considered separately to predict cubic split tensile strength of concrete and the outcomes are compared as shown in Table 8.

Tp-2$_{i, ii, iii, iv, v}$. In this model, prediction of split tensile strength based on regression equations which are developed by several researchers in recent times for normal (plain) concretes based on cylinder compressive strength are considered. The estimated cylinder strength and median of predicted results from Cp-1 to Cp-4 at 28-days are considered and used as an input value f_c in the above mentioned regression equations to predict the split tensile strength of concrete and the obtained results are compared.

It can be seen from both tables 8 and 9 that the results of predicted split tensile strength, both cubic and cylinder have yielded almost similar results when compared with the experimental/estimated data. The lower value of co-efficient of variation (COV) highlights the advantage and efficiency of prediction models. A comparison of predicted cubic and cylindrical splitting tensile strength of concrete results is shown graphically in Fig. 2.

4. Summary of Findings

The present study focuses on effective use of the predicted models for estimating the compressive strength and split tensile strength of concrete which are suggested in several literatures. The predicted results of each model comprising of cube and cylinder strength when compared with the experimental data are found to be close to each other. The effectiveness of these prediction models are summarized in Table 7 and it can be seen from this table that the statistical parameters, viz., RMSE and MAE are mostly found to be on the lower side, that is, between 1.3-3.20, indicating high efficiencies in the order of 94% to 98% of the prediction models. This proves that although the prediction models are developed based on cylinder compressive strength, they can still be effectively and efficiently adopted to predict the cube compressive strength.

Table 8. Results of Tp-1.

Sp. No	Experimental data, f_c (MPa)	Predicted cubic split tensile strength, f_{cp} (MPa)	Median of predicted results, f_c (MPa)	Predicted cubic split tensile strength, f_{cp} (MPa)
1	35.50	3.13	32.62	2.95
2	34.70	3.08	34.57	3.07
3	36.90	3.21	32.05	2.92
4	38.70	3.32	35.28	3.11
5	37.50	3.25	35.38	3.12
6	35.70	3.14	31.57	2.89
7	38.15	3.29	38.44	3.30
8	39.60	3.37	37.28	3.23
9	41.05	3.45	42.10	3.51
10	40.68	3.43	43.41	3.59
11	27.25	2.61	27.84	2.65
12	27.82	2.65	27.31	2.62
13	28.27	2.68	27.46	2.63
14	29.16	2.74	28.15	2.67
15	29.78	2.78	28.42	2.69
16	28.85	2.72	28.20	2.68
Mean		3.05		2.98
COV		10.0		10.7

Table 9. Results of Tp-2$_{i, ii, iii, iv, v}$.

Sp. No	Estimated cylinder 28-days strength, f_c (MPa)	Tp-2$_i$	Tp-2$_{ii}$	Tp-2$_{iii}$	Tp-2$_{iv}$	Tp-2$_v$	Predicted median cylinder 28-days strength, f_c (MPa)	Tp-2$_i$	Tp-2$_{ii}$	Tp-2$_{iii}$	Tp-2$_{iv}$	Tp-2$_v$
1	28.76	2.63	3.16	3.41	2.92	3.00	27.28	2.52	3.02	3.27	2.77	2.92
2	28.11	2.58	3.10	3.35	2.85	2.97	27.61	2.55	3.05	3.30	2.81	2.94
3	29.89	2.72	3.26	3.52	3.03	3.06	27.52	2.54	3.04	3.29	2.80	2.94
4	31.35	2.83	3.40	3.66	3.17	3.14	29.75	2.71	3.25	3.51	3.01	3.05
5	30.38	2.75	3.31	3.57	3.07	3.09	29.48	2.69	3.23	3.48	2.99	3.04
6	28.92	2.64	3.17	3.43	2.93	3.01	27.14	2.51	3.01	3.25	2.76	2.92
7	30.90	2.79	3.36	3.62	3.12	3.11	30.33	2.75	3.30	3.57	3.07	3.08
8	32.08	2.88	3.46	3.74	3.24	3.17	31.07	2.81	3.37	3.64	3.14	3.12
9	33.25	2.97	3.57	3.85	3.35	3.23	33.04	2.95	3.55	3.83	3.33	3.22
10	32.95	2.94	3.54	3.82	3.32	3.21	33.30	2.97	3.57	3.85	3.35	3.23
11	22.07	2.12	2.53	2.74	2.27	2.63	22.56	2.16	2.58	2.79	2.32	2.66
12	22.53	2.15	2.57	2.79	2.31	2.66	22.46	2.15	2.57	2.78	2.31	2.65
13	22.90	2.18	2.61	2.82	2.35	2.68	22.70	2.17	2.59	2.80	2.33	2.67
14	23.62	2.24	2.68	2.90	2.42	2.72	23.27	2.21	2.64	2.86	2.39	2.70
15	24.12	2.28	2.73	2.95	2.47	2.75	23.19	2.21	2.64	2.85	2.38	2.70
16	23.37	2.22	2.65	2.87	2.40	2.71	23.17	2.20	2.63	2.85	2.38	2.70
Mean	27.82	2.56	3.07	3.31	2.83	2.95	27.12	2.50	3.00	3.25	2.76	2.91
COV	14.53	11.99	12.26	12.12	13.82	7.37	14.12	11.60	11.87	11.73	13.42	7.08

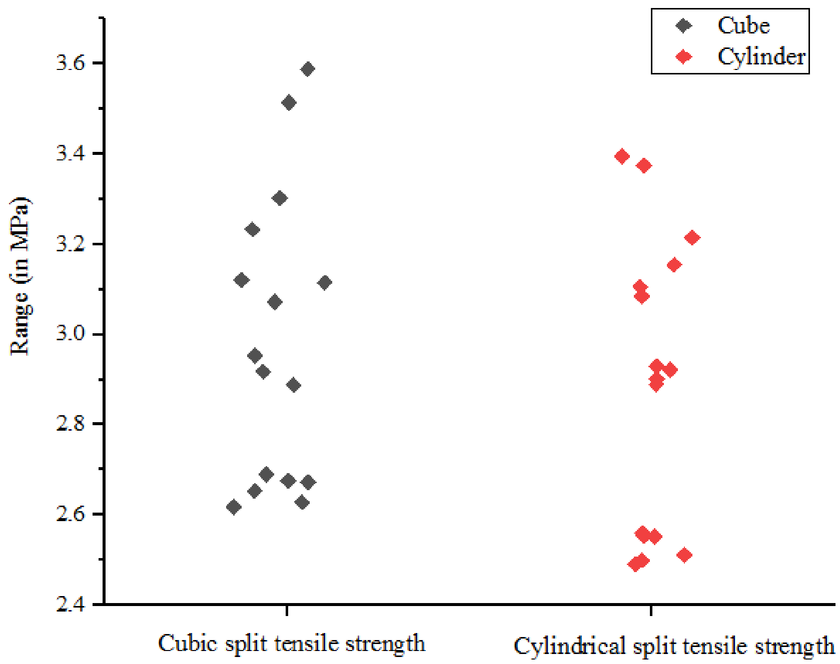


Fig. 2. Comparison of predicted cubic and cylinder split tensile strength.

Of the four prediction models considered in the present study for estimating the compressive strength, model Cp-2 (Metwally 2014) requires 28-days strength as an input value while the other three models rely on 7-days strength to predict strength beyond that age. The development of models Cp-3, Cp-4 (Masood and Murtaza 2015) gives weightage to the chemical compounds of cement by incorporating dimensionless factors such as α and β as they are the ones which are primarily responsible for rate of gain of strength by concrete. The model Cp-1 (Ahsanul et al. 2012) presents a mathematical expression with only one input strength value and using which two constants p and q are calculated. It is also reported that any day strength as high as strength at 365-days can also be calculated using this model. Hence, this prediction model can be conveniently used to assess the durability aspects of concrete structures where later-age strength development is of prime importance. Models Cp-3and Cp-4 mentions a certain limitation with respect to use of the models beyond the age of 28-days and informs the readers to carefully examine the constants α and β before using them for other types of cements.

Normally, splitting tensile strength of concrete is determined by testing cylindrical concrete specimens in the laboratories and hence most of the regression based models utilize the same component, f_c in their expressions. The reported model Tp-1 highlights the use of 28-days cubic compressive strength of concrete. It can be seen from Fig. 2 when predicted cubic of Tp-1 and predicted cylindrical split tensile strength of Tp-$2_{i,ii,iii,v}$ (Mehrdad and Ramezan 2021) and Tp-2_{iv} (Ramadoss 2014) are plotted on the same scale, the range of values obtained are similar. Hence, this model proves as an advantage in cases where only cube compressive strength data is available.

5. Conclusions

In recent times, it is observed that numerous types of prediction models are available in literature and some of them appear to be too complex to use it in any other circumstance because of involvement of complex variables and various constraints. In the present study, attempts are made to collate a few of the simple statistical based prediction models developed on normal concrete, with an objective to investigate the efficacies of these models as they are of great help to determine the two most important and governing design properties of structural elements, that is, compressive strength and tensile strength of concrete. Four types of prediction models for estimating compressive strength and two kinds of prediction models for assessing the tensile strength are dealt in this research article. Computations using the prediction models and subsequent comparison with experimental data shows that cube compressive strength is almost nearly equal to cylinder compressive strength wherein the latter is pronounced as more accurate type of measure in literature. The use of these non-expensive prediction models with an efficiency of 94% to 98% as obtained from the present study suggest a way to arrive at early and later-age compressive strength and split tensile strength of normal concretes without having to wait for long time to obtain results in the laboratory and can positively proceed to incorporate them in the design phase of structural members. In addition, this research work showcases that any age data, say 7-day strength data can be easily used on the cylinder-based suggested prediction models to predict the concrete compressive strength at any age and can also be used to obtain the split tensile strength of concrete. As the present study considers the use of suggested models for estimating the compressive and split tensile strength of normal concretes, efforts could be made to account the relation of flexural strength of concrete with these two leading parameters for an insightful and comprehensive understanding.

Acknowledgements

The author wishes to thank undergraduate students, Ajay HP and Himaraju of BMSECE, for assisting in carrying out experiments in the laboratory.

Funding

The author received no financial support for the research, authorship, and/or publication of this manuscript.

Conflict of Interest

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

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