

Multiple Regression Analysis of Compressive, Flexural, and Split Tensile Strength in M40 Grade Concrete

M.M. Chokhawala^{1*}, Jaydeep J. Chavda², J.R. Pitroda³, Indrajit N. Patel⁴, Chirag Patel⁵

Abstract

Concrete plays a key role as a construction material across the globe. The strength parameters of the concrete are the primary reason for which it is designed. The design mixed concrete has multiple strength parameters like compressive strength, split tensile strength, flexural (bending) strength, etc. For each newly designed mixed concrete, the mentioned strength parameters are tested for various time durations, like 3 days, 7 days, 14 days, 28 days, etc., before using the prepared concrete for actual work. This process may consume additional project duration along with additional materials. One can adopt the prediction modeling concept to overcome the issue, as in prediction modeling, multiple results can be predicted based on one obtained result. By doing so, one can reduce project duration along with material wastage. In this paper, statistical regression analysis is used for the strength prediction purpose using Microsoft Excel 2013 and the accuracy was obtained using the deviation factor. Experimental tests were conducted on M40 concrete specimens to determine their mechanical properties. The collected data were statistically analyzed, and regression models were formulated using five different equations, namely (i) linear, (ii) exponential, (iii) logarithmic, (iv) polynomial, and (v) power equations incorporating time duration as the key influencing factor in strength properties of concrete. The emphasis is on the relation between flexural strength, split tensile strength, and compressive strength of M40 grade concrete. Multiple regression models were obtained using multiple regression equations, and the most precise regression model was identified based on its deviation factor value.

Keywords: Compressive strength, flexural strength, split tensile strength, M40 concrete, multiple regression analysis, predictive modeling

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INTRODUCTION

Concrete stands as the most widely used and preferred construction material globally, owing to its durability, ease of production on-site, and manageable handling. With increasing globalization and rapid infrastructure development, the demand for high-strength concrete has grown significantly. The mechanical properties of concrete, including compressive strength, flexural strength, and split tensile strength, are critical determinants of its structural performance. Among these, compressive strength is the most evaluated property, as it serves as a primary indicator of concrete quality. However, flexural and tensile strengths are equally important, particularly in structural elements subjected to bending and shear forces, such as beams, slabs, and pavements.

Strength is the main aspect in the construction sector when selecting concrete for a specific

application. Concrete construction gains strength over a long period after curing. According to Indian Standards codal provisions, the strength obtained after 28 days of curing age is taken into consideration. In some special construction projects, waiting for tests may affect the speed of construction, which ultimately increases the construction project cost. But it is also not viable to neglect the test; therefore, the need for rapid and reliable prediction for the concrete strength, or in other words, the need to establish a relationship between different types of concrete strength, has arrived. It offers the chance to make the required adjustments to the mix proportions used to avoid situations where the concrete does not reach the required design strength, and to make more cost-effective use of raw materials and to reduce construction costs. Therefore, establishing a relationship between the concrete strength is an active area of research, and a substantial number of studies have been carried out. Several studies have been performed to obtain an effective mathematical model that is able to predict concrete strength with greater precision at various ages and can establish the accurate relationship between various types of concrete strength. The prime objectives of this investigation are to determine the possibility of using a bacterial approach in high-strength concrete in enhancing the strength characteristics of the concrete and to develop multiple regression models to obtain empirical expressions for establishing the relationship between flexural strength and compressive strength based on the obtained test results (Tables 1–4). Also, to recognize the most precise regression model among them [1–3].

EXPERIMENTAL MATERIALS

Experimental Materials

The materials used during the present research are cement, fine aggregate, coarse aggregate, and water.

1. *Cement*: The ordinary Portland cement of 53 grade meeting the requirements of IS 12269-2013 has been used for all concrete mixes in this research for making M40 grade concrete. The specific gravity of cement is 3.15.
2. *Fine Aggregates*: These are fractions from 4.75 mm to 150 microns are called fine aggregates. In this research for making M40 grade concrete fine aggregates meeting the requirements of IS 383-2016 were used. The specific gravity of fine aggregates is 2.65, and the fineness modulus is 3.16.
3. *Coarse Aggregates*: For making M40 grade concrete, the proper gradation is very important. 10-mm and 20-mm size coarse aggregates are used, meeting the requirements of IS 383-2016 for making M40 grade concrete. The specific gravity of 10-mm aggregates is 2.87, and the fineness modulus is 6.08; for specific gravity is 2.81 and fineness modulus is 6.94.
4. *Water*: Ordinary portable water available locally was used for casting and curing all specimens of this research.

Design Mix

The mix design for conventional M40 grade was prepared as per IS 10262:2019 code for concrete mix design.

Step 1: Target Strength Determination

Target strength is calculated as:

$$F'_{ck} = f_{ck} + (1.65 \times s) \quad \text{where } s = 5 \text{ (from Table 2 of IS 10262:2019)}$$

$$F'_{ck} = 40 + (1.65 \times 5) = 48.25 \text{ N/mm}^2$$

Where:

- f'_{ck} = Target Average Compressive Strength at 28 Days
- f_{ck} = Characteristic Compressive Strength at 28 Days
- s = Standard Deviation, taken from Table 2 of IS 10262:2019 (for M40, $s = 5$).

Step 2: Water–Cement Ratio Selection

As per IS 456:2000 Table 5 (page 20), the maximum permissible w/c ratio for moderate exposure is 0.40.

Step 3: Water Content Calculation

From Table 2 of IS 10262:2019, for 20-mm aggregate, the maximum water content is 186 liters. Thus, the Estimated Water Content is:

$$186 + (3\% \text{ of } 186) = 191.6 \text{ liters.}$$

Step 4: Cement Content Verification

Using the water–cement ratio of 0.40,

$$\text{Cement Content} = \frac{191.6}{0.40} = 479 \text{ kg/m}^3$$

As per Table 5 of IS 456:2000, the stipulated minimum cement content for moderate exposure conditions is 300 kg/m³. Given that the adopted cement content of 479 kg/m³ exceeds this requirement, the mix design complies with the standard specifications [4–7].

Step 5: Aggregate Proportioning

Table 5 of IS 10262:2019 prescribes a 0.60 volume fraction for the blend of 20-mm coarse aggregate and Zone I fine aggregate when the water–cement ratio is maintained at 0.50. The volume proportion for coarse aggregate is adjusted by ± 0.02 for each ± 0.05 change in the water–cement ratio.

For a water–cement ratio of 0.40

$$\text{Volume of Coarse Aggregate} = 0.60 + 0.02 = 0.62 \quad (62\%)$$

$$\text{Volume of Fine Aggregate} = 1 - 0.62 = 0.38 \quad (38\%)$$

Absolute Volume Calculation (1m³)

1. Volume of cement

$$\text{Volume of Cement} = \left(\frac{\text{Mass of Cement}}{\text{Specific Gravity of Cement}} \right) \times \left(\frac{1}{1000} \right) = \frac{479}{3.15} / 1000 = 0.152 \text{ m}^3$$

2. Volume of water

$$\text{Volume of Water} = \left(\frac{\text{Mass of Water}}{\text{Specific Gravity of Water}} \right) \times \left(\frac{1}{1000} \right) = \frac{191.6}{1} / 1000 = 0.1916 \text{ m}^3$$

3. Volume of all in aggregate

$$\text{Volume of All-in Aggregate} = 1 - (0.152 + 0.1916) = 0.6564 \text{ m}^3$$

4. Mass of coarse aggregate

$$\text{Mass of Coarse Aggregate} = 0.6564 \times 0.62 \times 2.84 \times 1000 = 1155.78 \text{ kg/m}^3$$

5. Mass of fine aggregate

$$\text{Mass of Fine Aggregate} = 0.6564 \times 0.38 \times 2.65 \times 1000 = 660.99 \text{ kg/m}^3$$

Compressive Strength Test

Compressive strength represents the most critical engineering property of concrete. To evaluate this parameter, three cube specimens (150 × 150 × 150 mm) were cast for each concrete mix composition. The compressive strength testing was conducted in accordance with IS: 516-1959 at both 7-day and 28-day curing intervals. All testing procedures were performed at the BVM Engineering College, V. V. Nagar, Gujarat. Experimental observations revealed that the average strength for seven days was

obtained as 31.98 N/mm² and the average strength for 28 days was obtained as 49.73 N/mm². Table 2 and Figure 1 show the compressive strength test results for control mix concrete at 7 and 28 days for M40 grade concrete [8–11].

Table 1. Design mixed proportions in 1 m³ of concrete.

For 1 m ³ of Concrete	
Cement	479 kg
Coarse aggregate	1155.78 kg
Fine aggregate	660.99 kg
Water	191.6 liters

Table 2. Compressive strength test results for control mix concrete at 7 and 28 days for M40 grade concrete.

Days	Number of Cubes	Compressive Strength (N/mm ²)	Average Compressive Strength (N/mm ²)
7	1	32.44	31.98
	2	31.50	
	3	32.00	
28	1	49.00	49.73
	2	50.5	
	3	49.70	

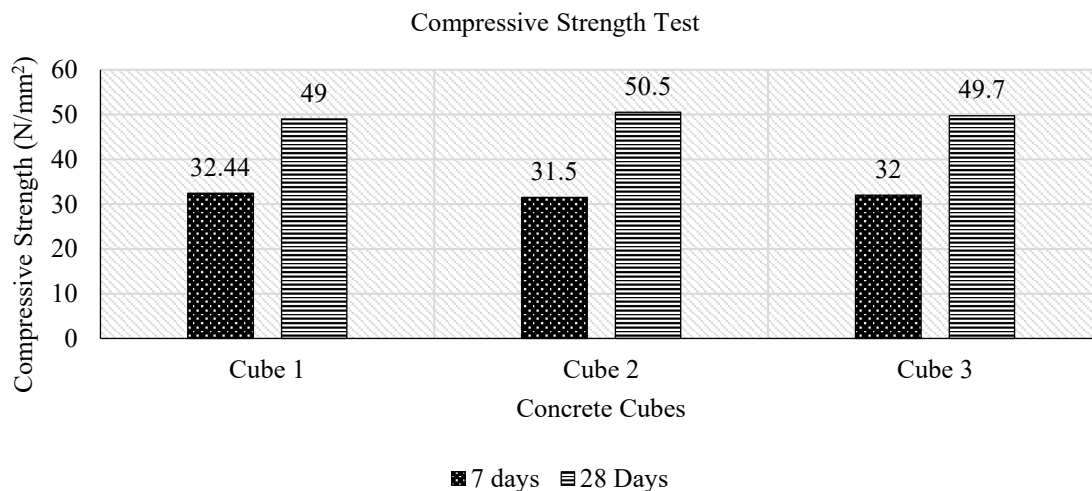


Figure 1. Compressive strength test.

Flexural Strength Test

Flexural strength is one of the important strengths of concrete. It provides resistance against the bending of concrete. The flexural strength assessment was conducted by preparing three beam specimens (500 × 100 × 100 mm) for each concrete mix. Testing was performed in compliance with IS: 516–1959 at curing ages of 7 and 28 days. The experiments were carried out at the BVM Engineering College, V. V. Nagar, Gujarat. The average flexural strength values obtained were 3.03 N/mm² at 7 days and 9.16 N/mm² at 28 days. Table 3 and Figure 2 present the flexural strength test results for the control mix of M40 grade concrete at both curing intervals.

Split Tensile Strength Test

The split tensile strength assessment was conducted as per IS 516:2021 guidelines on M40 grade control concrete specimens. For each testing interval (7-day and 28-day curing periods), three

cylindrical specimens (150 mm diameter × 300 mm height) were prepared and tested. Figure 3 and Table 4 summarize the split tensile strength test outcomes for the reference concrete mixture at both specified curing durations.

Table 3. Flexural strength test results for control mix concrete at 7 and 28 days for M40 grade concrete.

Days	Number of Beams	Flexural Strength (N/mm ²)	Average Flexural Strength (N/mm ²)
7	1	3.08	3.03
	2	2.99	
	3	3.04	
28	1	8.5	9.16
	2	10.5	
	3	8.5	

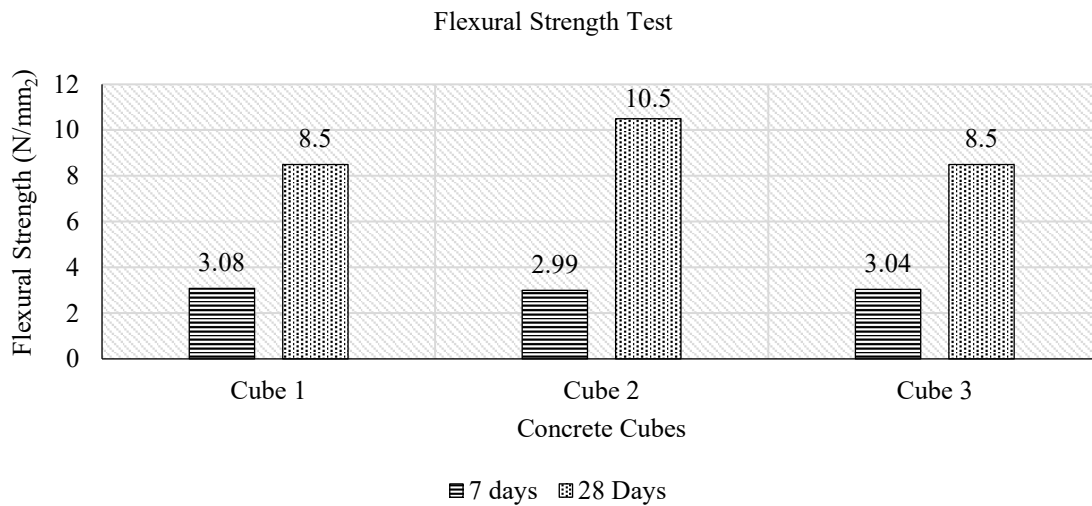


Figure 2. Flexural strength test.

Table 4. Split tensile strength test outcomes for the reference concrete mixture at both specified curing durations.

Days	Number of Cylinders	Split Tensile Strength (N/mm ²)	Average Split Tensile Strength (N/mm ²)
7	1	3.73	3.67
	2	3.62	
	3	3.68	
28	1	14	14.66
	2	16	
	3	14	

REGRESSION MODELING

Regression modeling is a form of prediction modeling technique that establishes the relationship between dependent and independent variables. This analytical approach is employed for time series forecasting and quantifying relationships between variables. In statistical modeling, the coefficient of determination (R^2) serves as a critical metric in regression analysis. R^2 represents a statistical measure that quantifies the proportion of variance in the dependent variable accounted for by the independent variable(s) within the regression model. While correlation analysis evaluates the strength of association between independent and dependent variables, R^2 specifically measures the degree to which the variance in one variable explains the variance in another. For example, if a model's R^2 is 0.50, then

about 50% of the observed variance can be explained by inputs from the experiment. It shows that in the case of a comparative study of multiple regression models, the value of R^2 plays an important role in determining the accuracy of the model. In case the value of R^2 is close to 0, it indicates that the variance is very large between the variables and the relationship between the variables is very inaccurate. Alternatively, in case the value of R^2 is close to 1, it indicates that the variance is very small and the relationship between the variables is very highly accurate, and the obtained model describes the most precise relationship between the variables [11].

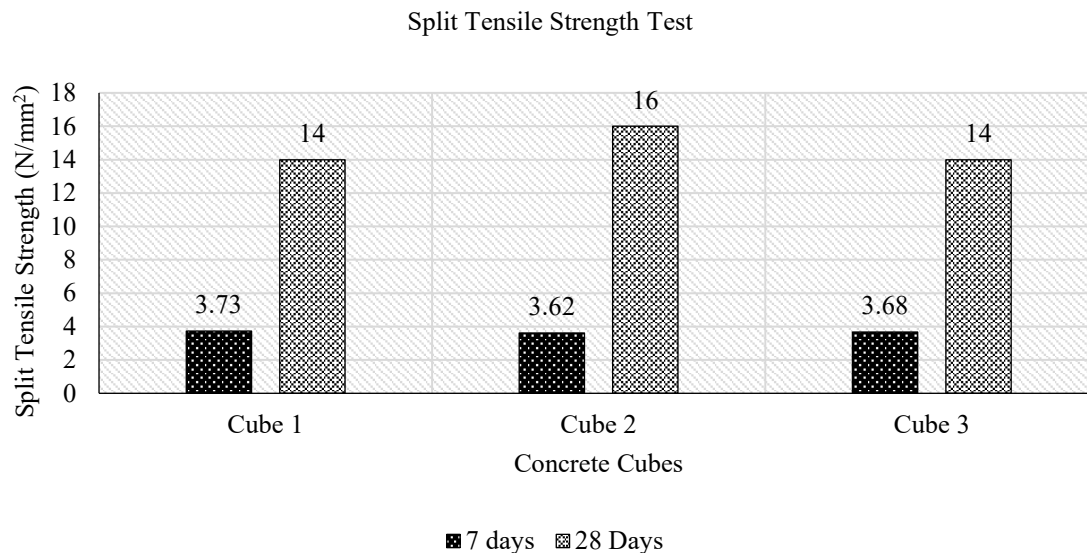


Figure 3. Split tensile strength test.

In this investigation, the relationship between compressive strength, flexural strength, and split tensile strength is obtained based on the observed strength at 28 days of curing age for M40 concrete grade. Multiple regression models are developed using various regression equations, namely (i) linear, (ii) exponential, (iii) logarithmic, (iv) polynomial, and (v) power equation. After developing multiple regression models with the use of various equations, a comparative analysis has been carried out between observed experimental values and calculated values, which are obtained from multiple regression models. Based on the obtained values of R^2 for each of the regression models, the most precise regression model is identified, which shows the most accurate relationship between compressive strength, flexural strength, and split tensile strength based on their strength values obtained after 28 days of curing age for M40 grade concrete. For this investigation, multiple regression models were developed based on curve fitting. The graphs are prepared by using Microsoft Excel of MS Office 2013 software. Figures 4–8 show the multiple regression models that are developed by using various regression equations.

Regression Model Developed for Comparison of Compressive Strength and Flexural Strength for 28 Days

Table 5 shows the comparison between observed values from the experiment and calculated values of flexural strength for different concrete mixes by using the obtained polynomial regression equation for M40 concrete, by using the compressive strength values as an independent variable (Figures 9–13).

Regression Model Developed for Comparison of Compressive Strength and Split Tensile Strength for 28 Days

Table 6 shows the comparison between observed values from the experiment and calculated values of split tensile strength for different concrete mixes by using the obtained polynomial regression equation for M40 concrete by using the compressive strength values as an independent variable.

Table 5. The comparison between observed values from the experiment and calculated values of flexural strength.

S.N.	Concrete Mixes	Polynomial Equation	Value of R^2	Observed Values (N/mm ²)	Calculated Values (N/mm ²)
		$x =$ compressive strength of M40 grade concrete at 28 days $y =$ flexural strength of M40 grade concrete at 28 days			
1.	A0	$y = 1.518x^2 - 149.8x + 3705$	0.8774	8.50	9.04
2.	B1	$y = 1.518x^2 - 149.8x + 3705$	0.8774	10.50	9.98
3.	B2	$y = 1.518x^2 - 149.8x + 3705$	0.8774	8.50	9.04

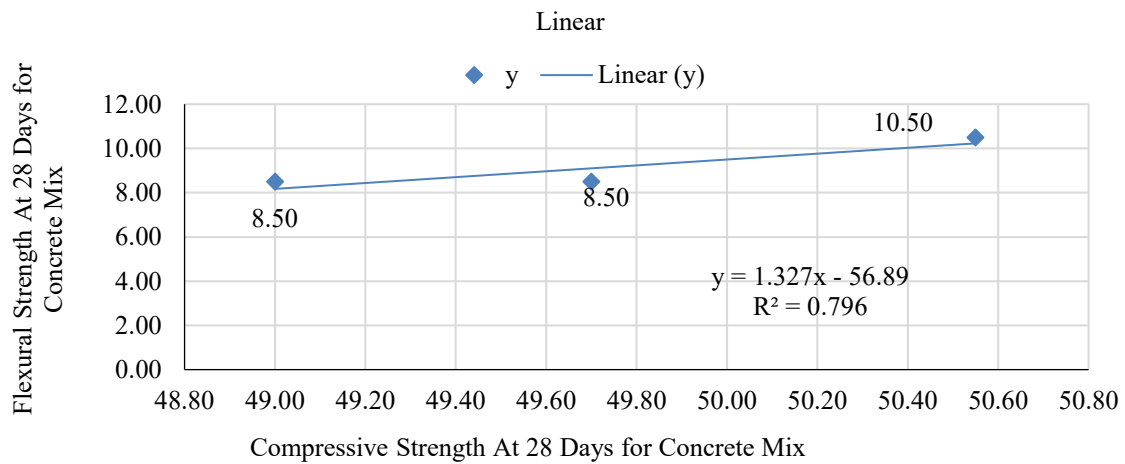


Figure 4. Linear regression model.

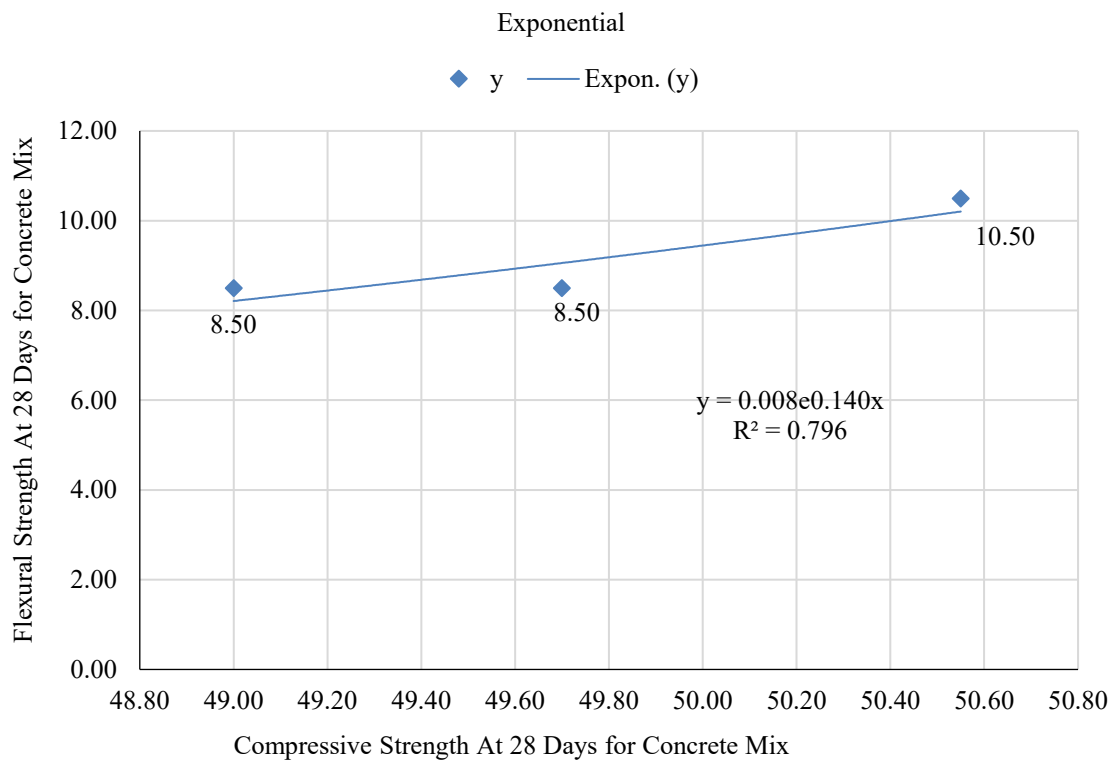


Figure 5. Exponential regression model.

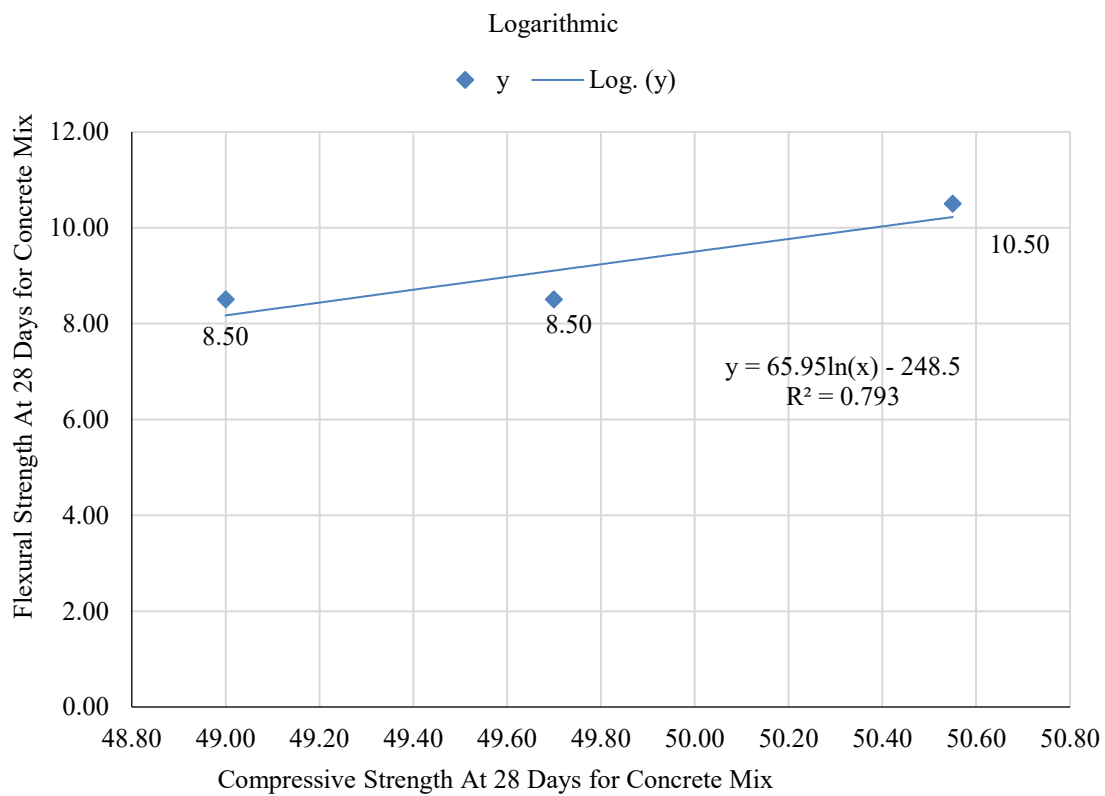


Figure 6. Logarithmic regression model.

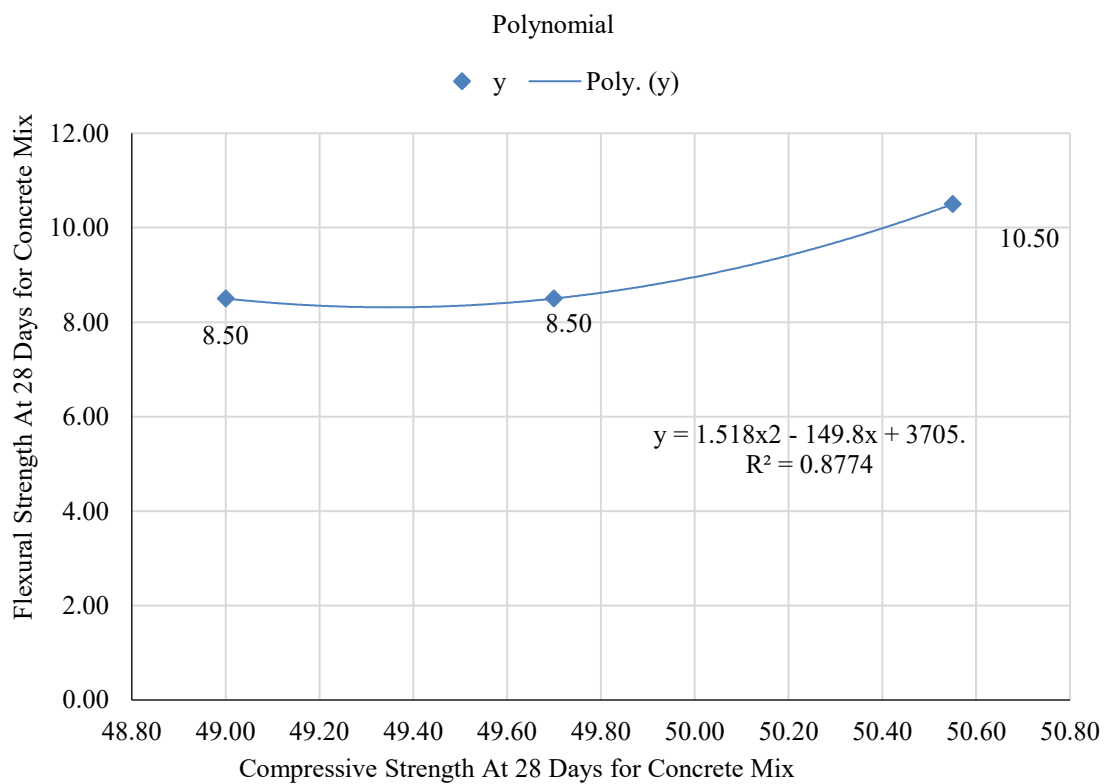


Figure 7. Polynomial regression model.

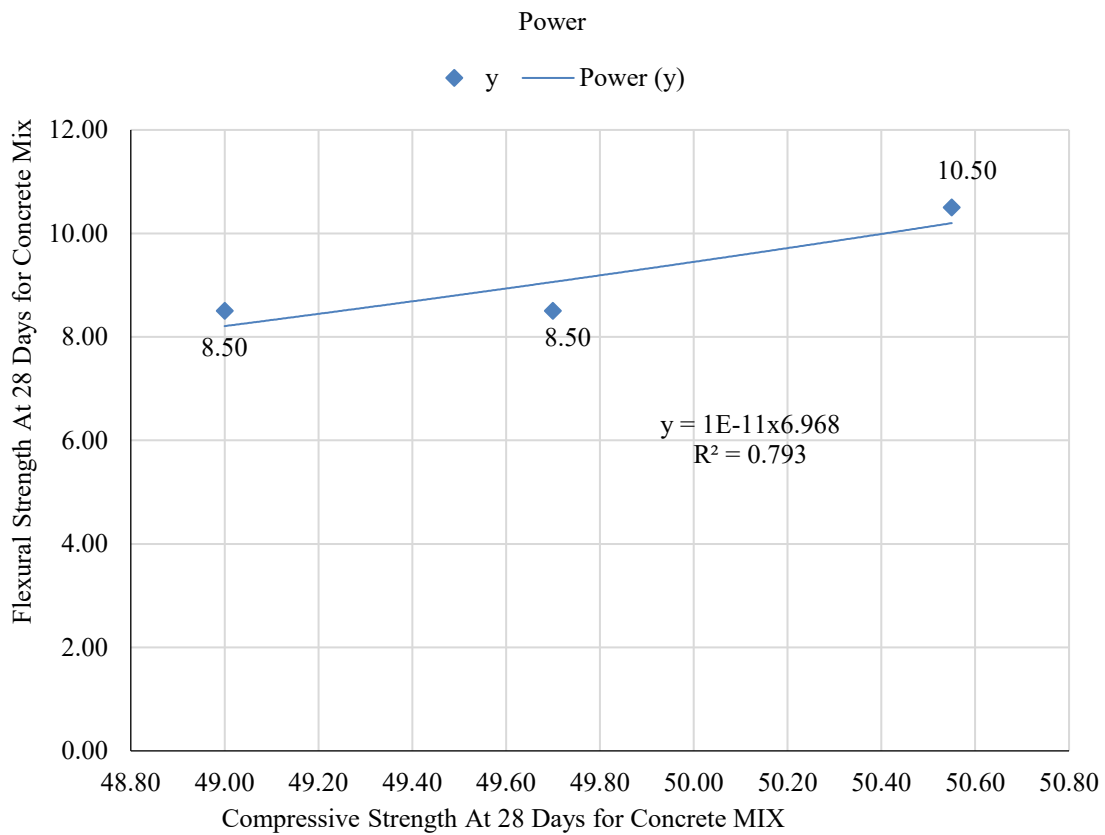


Figure 8. Power regression model.

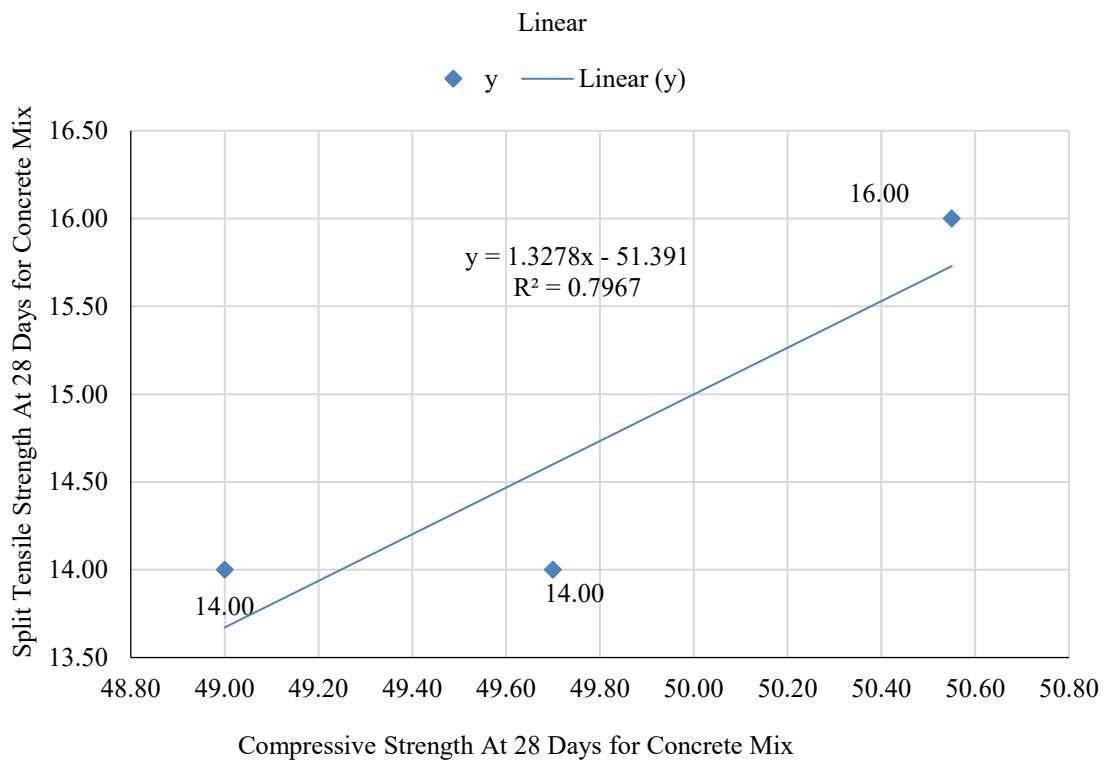


Figure 9. Linear regression model.

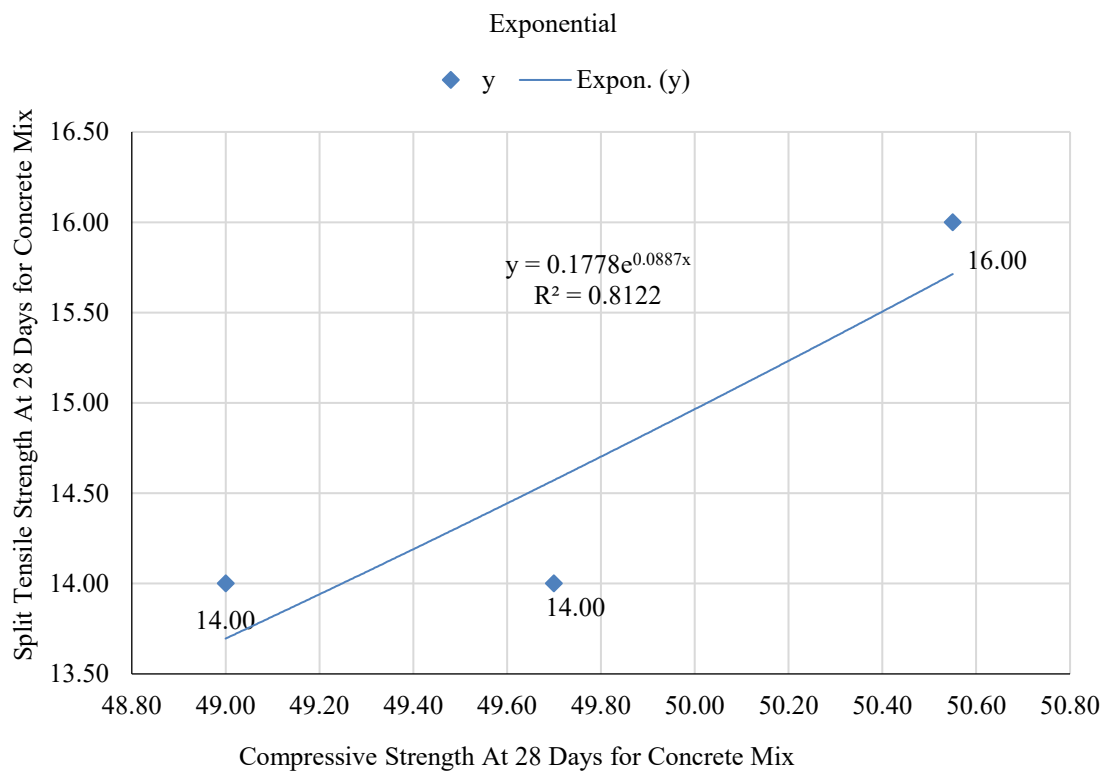


Figure 10. Exponential regression model.

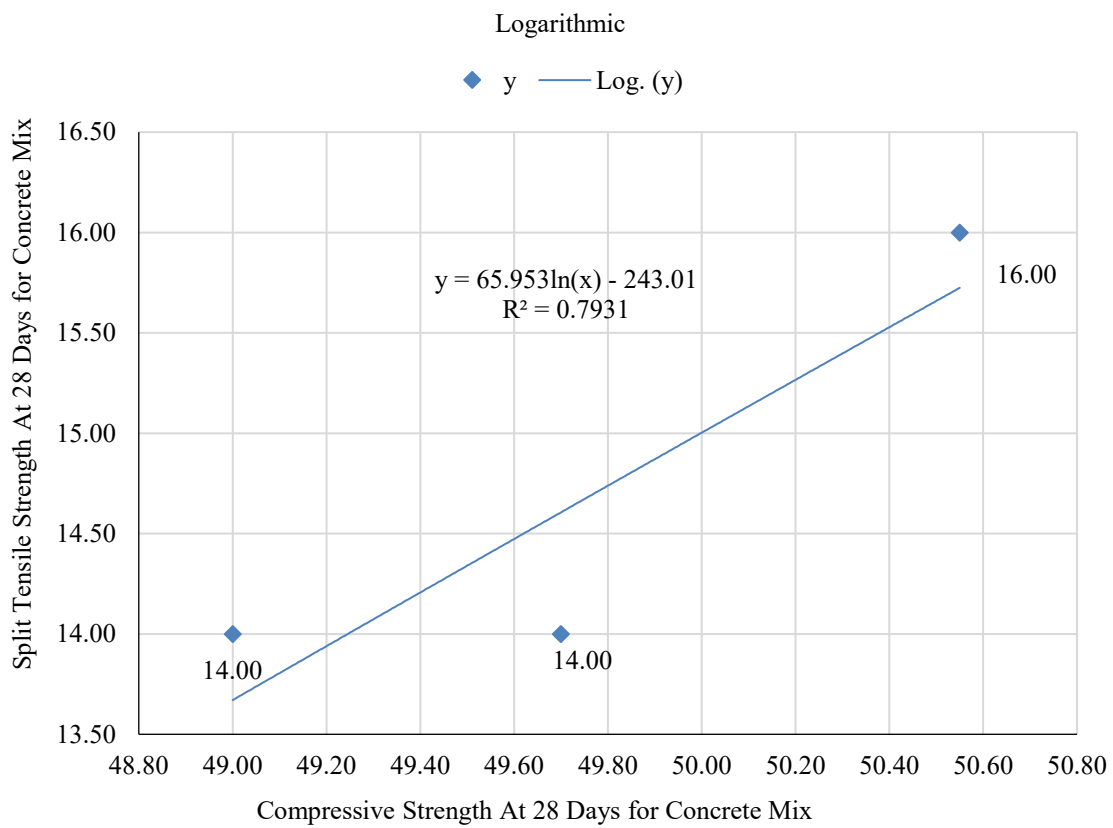


Figure 11. Logarithmic regression model.

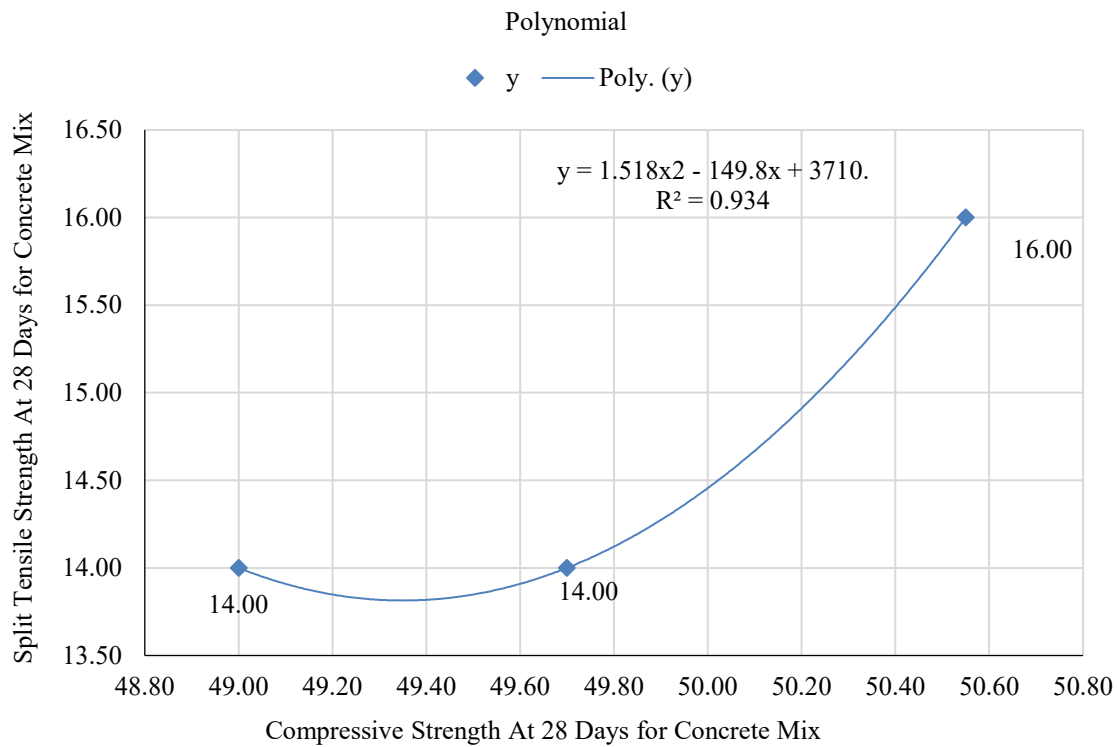


Figure 12. Polynomial regression model.

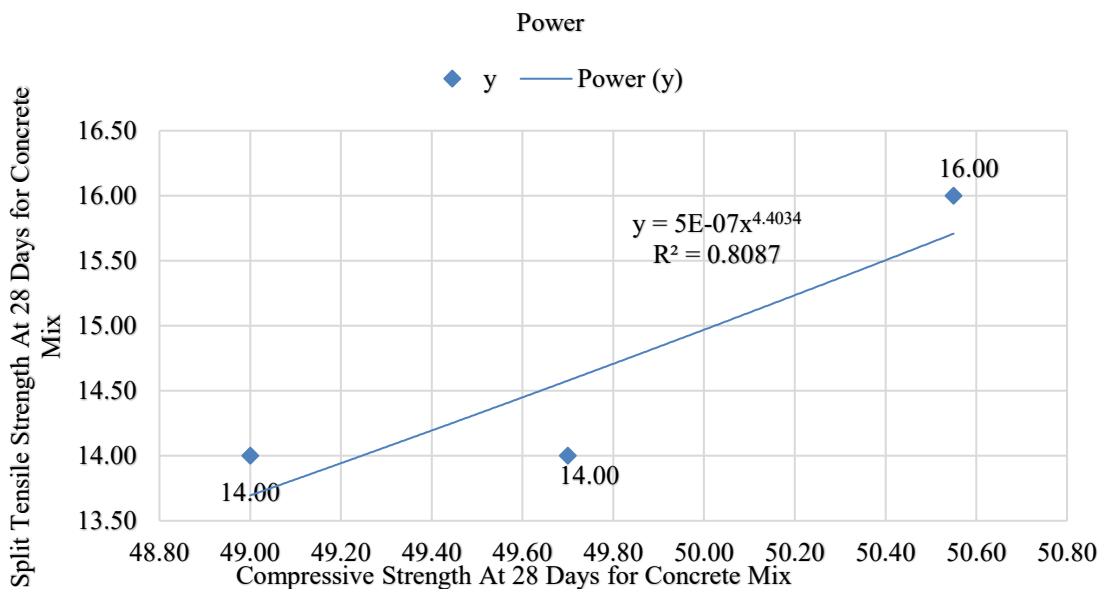


Figure 13. Power regression model.

Regression Model Developed for Comparison of Flexural Strength and Split Tensile Strength for 28 Days

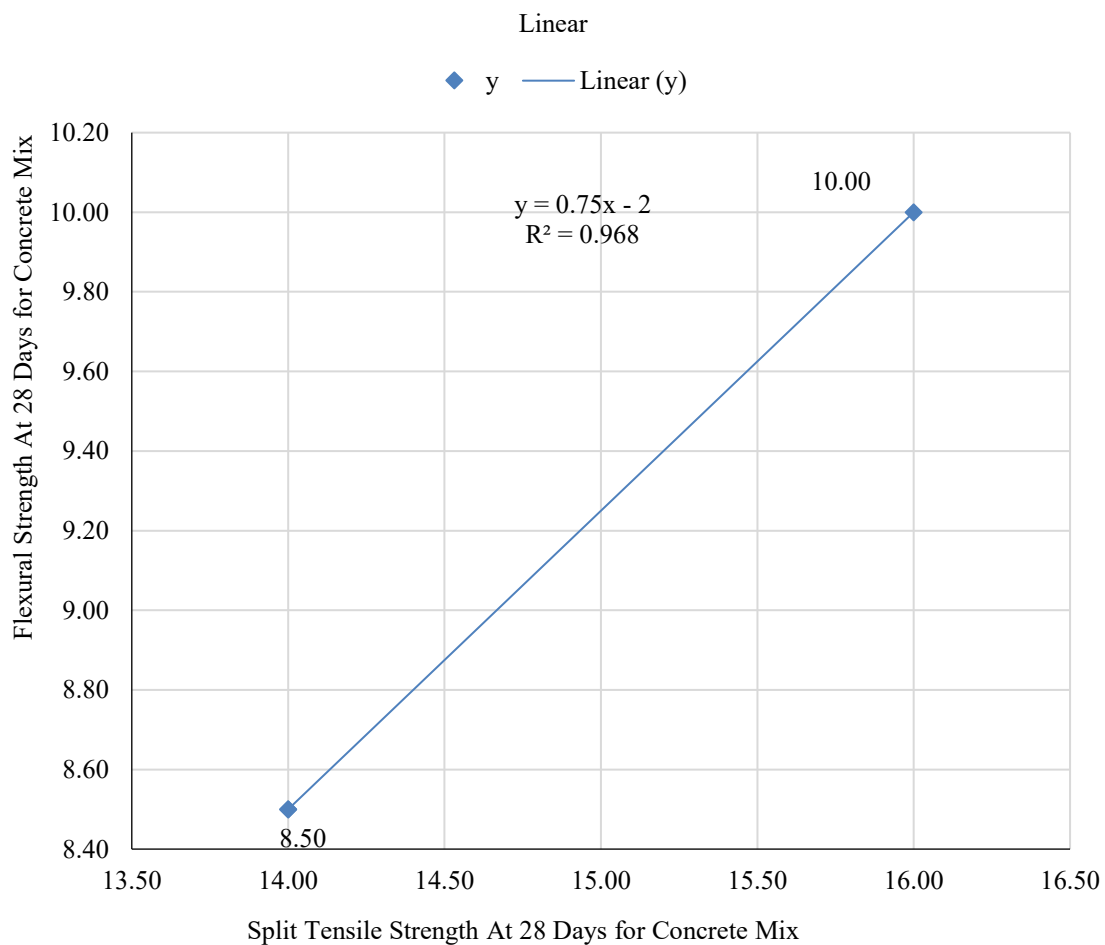
Table 7 shows the comparison between observed values from the experiment and calculated values of split tensile strength for different concrete mixes by using the obtained polynomial regression equation for M40 concrete by using the compressive strength values as an independent variable (Figures 14–18).

Table 6. The comparison between observed values from the experiment and calculated values of split tensile strength.

S.N.	Concrete Mixes	Polynomial Equation	Value of R^2	Observed Values (N/mm ²)	Calculated Values (N/mm ²)
		x = compressive strength of M40 grade concrete at 28 days y = split tensile strength of M40 grade concrete at 28 days			
1.	A0	$y = 1.518x^2 - 149.8x + 3710$	0.934	14.00	14.4
2.	B1	$y = 1.518x^2 - 149.8x + 3710$	0.934	16.00	15.47
3.	B2	$y = 1.518x^2 - 149.8x + 3710$	0.934	14.00	14.46

Table 7. The comparison between observed values from the experiment and calculated values of split tensile strength and flexural strength.

S.N.	Concrete Mixes	Polynomial Equation	Value of R^2	Observed Values (N/mm ²)	Calculated Values (N/mm ²)
		x = compressive strength of M40 grade concrete at 28 days y = split tensile strength of M40 grade concrete at 28 days			
1.	A0	$y = 0.75x - 2$	0.934	8.50	8.45
2.	B1	$y = 0.75x - 2$	0.934	10.0	9.94
3.	B2	$y = 0.75x - 2$	0.934	8.50	8.45

**Figure 14.** Linear regression model.

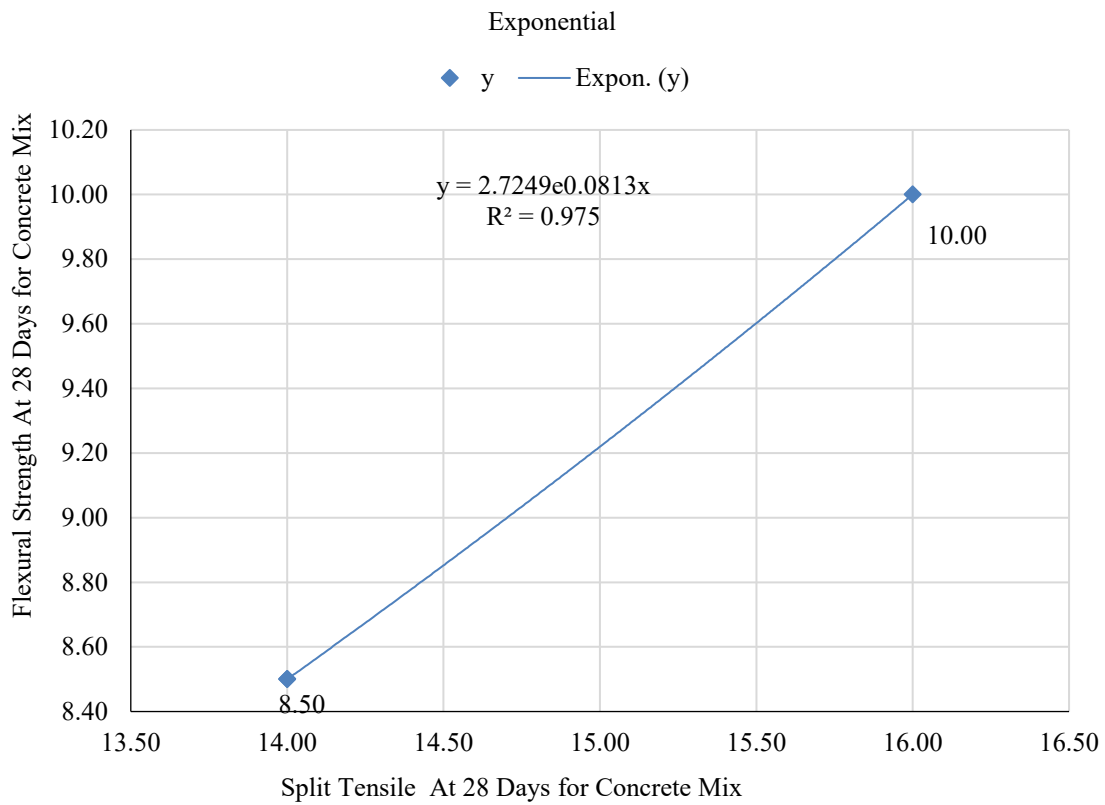


Figure 15. Exponential regression model.

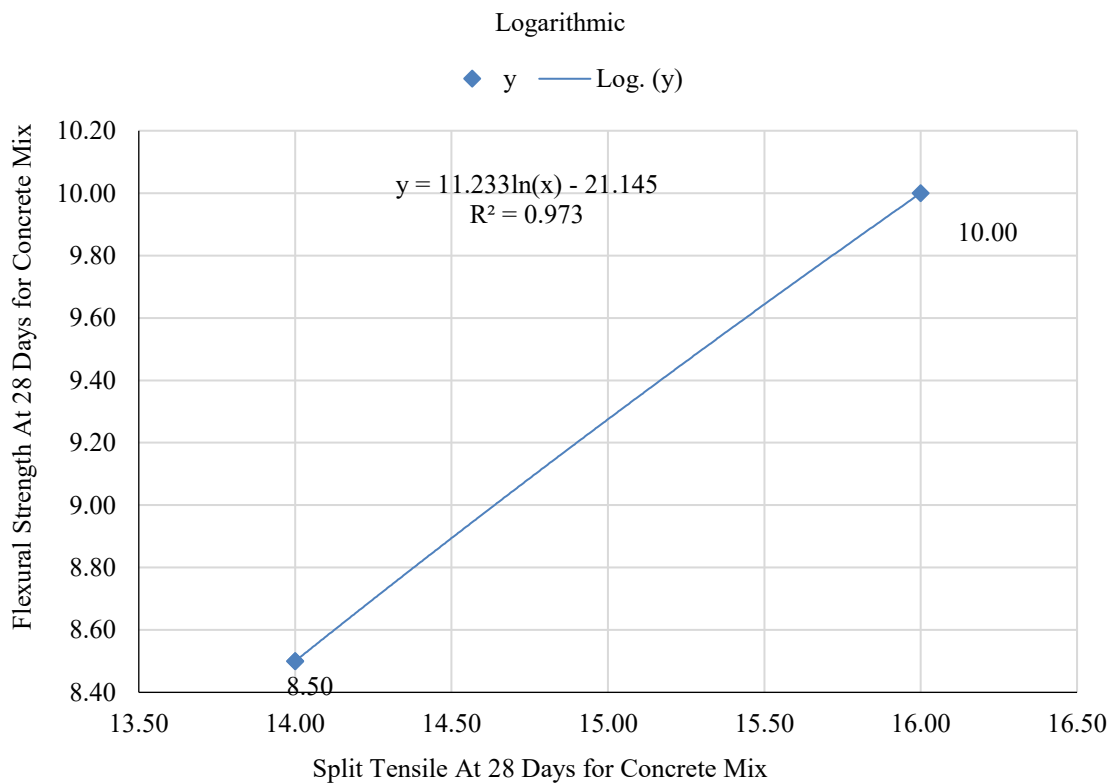


Figure 16. Logarithmic regression model.

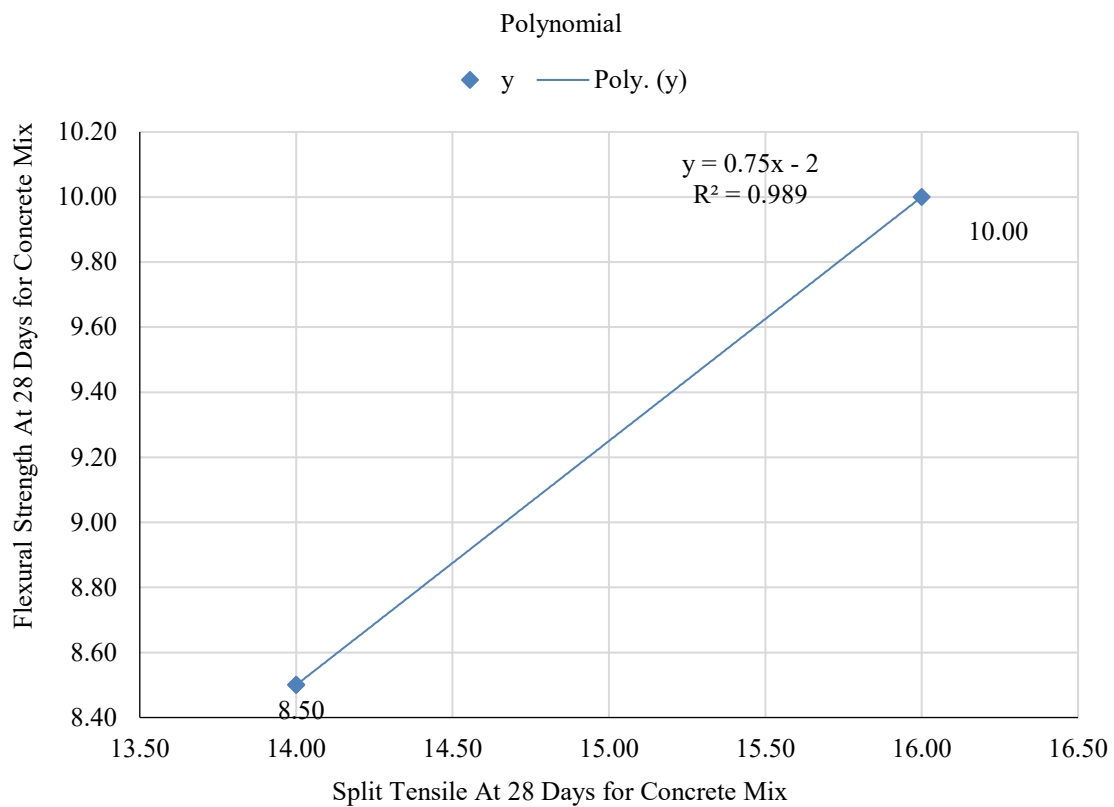


Figure 17. Polynomial regression model.

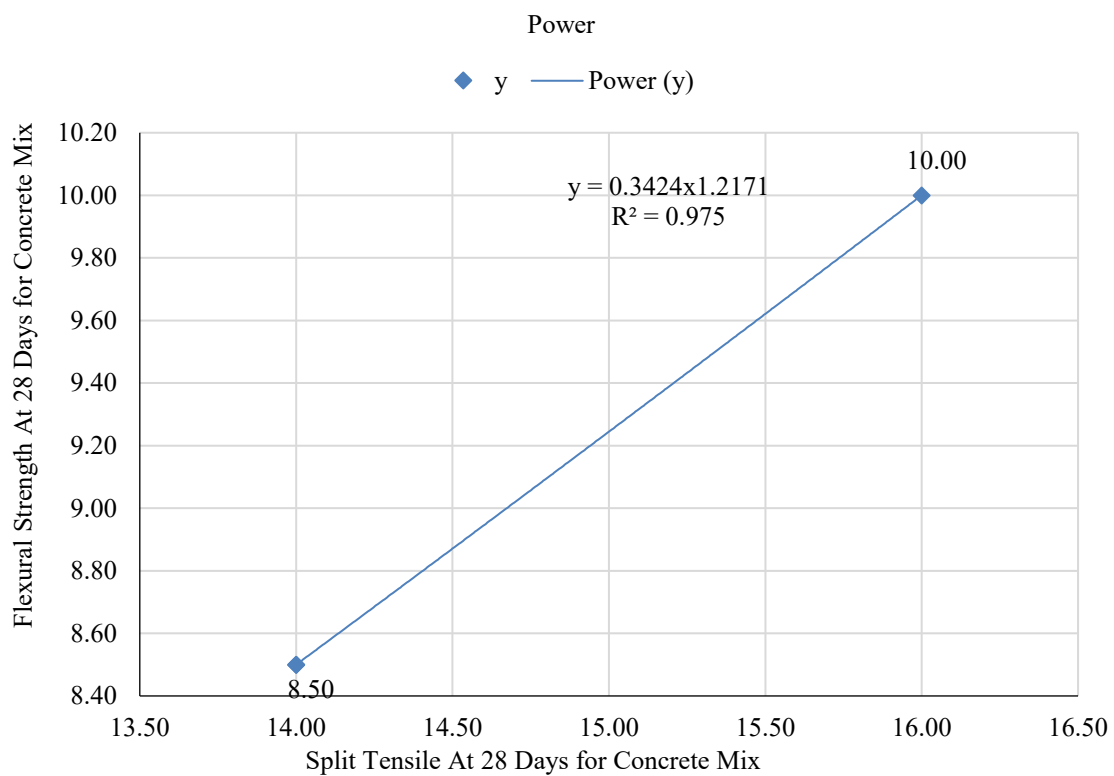


Figure 18. Power regression model.

CONCLUSIONS

1. The mix design of M40 grade has been prepared based on IS 102629:2019 by trial-and-error method. After performing three mechanical tests on prepared concrete all results are observed satisfactory.
2. The regression modeling was done in Microsoft Excel 2013 in which the values for the modeling were taken from the observed values as input parameters, which were originally obtained by the actual physical testing of the concrete specimen.
3. This study explored the relationship between compressive strength, flexural strength, and split tensile strength in M40 grade concrete using multiple regression models. The experimental results demonstrated a strong interdependence among these mechanical properties, allowing for the reliable prediction of flexural and split tensile strengths based on compressive strength data.
4. Establishing the relationship between various types of concrete strength can become very useful for predicting strength at an early stage, which can be helpful in adopting essential changes required in the concrete mix design and that can save the construction time and material cost, which will ultimately reduce the cost overrun and time overrun in major infrastructure projects.
5. In the present research, multiple regression models have been developed for establishing the accurate relationship between compressive strength, flexural strength, and split tensile strength of the M40 grade concrete for 28 days of curing age by utilizing five different types of regression equations, namely (i) linear, (ii) exponential, (iii) logarithmic, (iv) polynomial, and (v) power equation.
6. By comparing all the obtained regression models based on the values of coefficient of determination R^2 and by comparing the observed values with the values calculated by each of the equations, it has been determined that the regression model developed using polynomial equation is more accurate and precise compared to others as it has highest value for R^2 . This may have occurred because of the higher-order characteristics of a polynomial equation, which are not found in other regression equations developed in this research.

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