Experimental and Statistical Evaluations of Strength Properties of Concrete with Iron Ore Tailings as Fine Aggregate

Gayana Bangalore Chinnappa[1] and Ram Chandar Karra, Ph.D.[2]

Abstract: Iron ore tailings (IOT) are the by-products of iron ore beneficiation, and these tailings are disposed of in several tons annually in quarries, landfills, and tailings dams, causing environmental issues. Various researchers have attempted to study the properties of IOT and the use of them in concrete as a building material. The present research aims to investigate the potential use of alccofine, a microfine particle of slag, as a cement replacement and IOT as fine aggregates in concrete. Experimental results indicated that the concrete workability decreased with an increase in the IOT-alccofine content and the maximum compressive strength (CS) obtained was 70.00, 68.67, and 65 MPa respectively at 40%, 30%, and 20% IOT-alccofine dosage for varying water-to-cement (w/c) ratios of 0.35, 0.40, and 0.45 respectively. Similarly, the flexural strength (FS) and splitting tensile strength (STS) increased with an increase in IOT-alccofine content. A statistically fitted multiple regression analysis was performed for all the mechanical properties to evaluate the significant level of concrete containing alccofine and IOT in concrete. These prediction models have high accuracy and low bias and the validation process represented that the equations can perform excellently in predicting the IOT-alccofine concrete properties. **DOI:** 10.1061/(ASCE)HZ.2153-5515.0000480. © *2019 American Society of Civil Engineers.*

Author keywords: Water-to-cement ratio; Mechanical properties; Regression analysis; Iron ore tailings (IOT); Alccofine.

Introduction

The increasing trend of solid waste generation has made its ecological disposal an important issue due to concerns about its hazardous social and environmental impact. One of the methods to minimize these issues is recycling of industry wastes. The construction industry has a great potential to absorb various industrial residues provided the recycled materials are properly characterized before its application as a construction material. Iron is the world's most commonly used metal—steel, in which iron ore is the raw material, represents almost 95% of all metals used annually. World production averages 2 billion metric tons of raw ore annually. The total recoverable reserves of iron ore in India are about 9,602 million tons of hematite and 3,408 million tons of magnetite. World consumption of iron ore grows at 10% (Government of India 2018). Fig. 1 depicts the statistics of iron ore production from 2000 to 2018. Steel production has increased in recent years to meet industry demands.

A brief literature study based on the utilization of alccofine and iron ore tailings is discussed in this section.

Research on green concrete is being done, and efforts are being made to find suitable marginal materials to replace cement and natural aggregates in concrete. Generally, the marginal materials used for replacement of cement are granulated blast furnace slag (GGBS), fly ash, silica, metakaoline, alccofine, etc. Alccofine is a by-product of slag and a microfine material, with particle size finer than other hydraulic materials like cement, fly ash, silica, etc. Because of the optimized particle size distribution of alccofine, it enhances the performance of fresh and hardened concrete. Singhal et al. (2018) developed a geopolymer concrete at the laboratory scale using alccofine and fly ash as cementitious material. Based on the results obtained, the mechanical properties of geopolymer concrete increased due to the addition of alccofine as it increases the densification process and enhances the mechanical properties of concrete. The optimal percentage at which the maximum compressive strength of 42 MPa was obtained was at 10% replacement of cement with alccofine without elevated heat curing. Reddy and Meena (2015) investigated the use of GGBS (0%, 10%, 20%, 30%, and 40%) as a cementitious material in Grade M30 concrete and then considered the optimum GGBS content. By varying alccofine (8%, 10%, 12%, and 14%) as a cementitious material to study the performance of alccofine, they found that the addition of alccofine resulted in a reduction of strength. Saxena et al. (2017) conducted an experimental study using pond fly ash with alccofine in a geopolymer mortar. Based on the results obtained, the strength increased along with durability properties with the addition of alccofine as a cement replacement.

The need for an aggregate replacement is urgent for the present scenario of the construction industry as the mining of sand has been banned in various parts of India. The rapid development of infrastructure increased the need for sand mining, leading to the river beds becoming overexploited, so recycled materials are currently in demand. Iron ore tailings (IOT) are the processed waste from steel processing that are disposed in tailing ponds. A few studies by previous researchers have suggested that IOT can be considered as a construction material. The various environmental issues of sand mining are the depletion of virgin deposits, water table lowering, collapsing of river banks, and water pollution (Kang et al. 2011).

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An increase in the production of iron ore for economic development worldwide has been generating a massive amount of iron ore tailings, which are frequently discarded as wastes. This has led to serious environmental deterioration. A statistical survey has shown that 4.54×10^9–6.35×10^9 metric tons (5–7 billion tons) of iron ore tailings are produced yearly worldwide (Edraki et al. 2014). In spite of such a huge amount of iron ore tailings stockpiled as waste, its safe disposal or utilization has remained a major unsolved and challenging task for iron ore industries (Yu et al. 2011). There are various other mine wastes that need to be explored as marginal materials in construction industry. Ram Chandar et al. (2016a, b) investigated the use of laterite and sandstone as a partial replacement for sand. They observed that sandstone enhanced the strength properties of concrete and laterite did not show much improvement in the strength properties of concrete. Filho et al. (2017) evaluated the use of IOT as fine aggregates in interlocking concrete blocks. The physical and mechanical properties were superior to the conventional interlocking paver blocks. Bastos et al. (2016) evaluated the feasibility of IOT as a road material. IOT were chemically stabilized using cement, lime, and steel making slag as binder consisting of 1%, 2%, 5%, and 10% binder content, respectively. X-ray fluorescence (XRF), X-ray diffraction (XRD), leaching, compaction, and California bearing ratio (CBR) tests were conducted and the results suggested that IOT with chemical stabilization are feasible to be considered as a road paving material. Gorakhki and Bareither (2017) evaluated the binder amendment of unconfined compressive strength (UCS) of mine tailings in the application of earthworks. A review was done on the use of iron ore mine waste and tailings and other industrial waste materials as a replacement for aggregates with various admixtures to enhance the properties of concrete (Gayana and Chandar 2018).

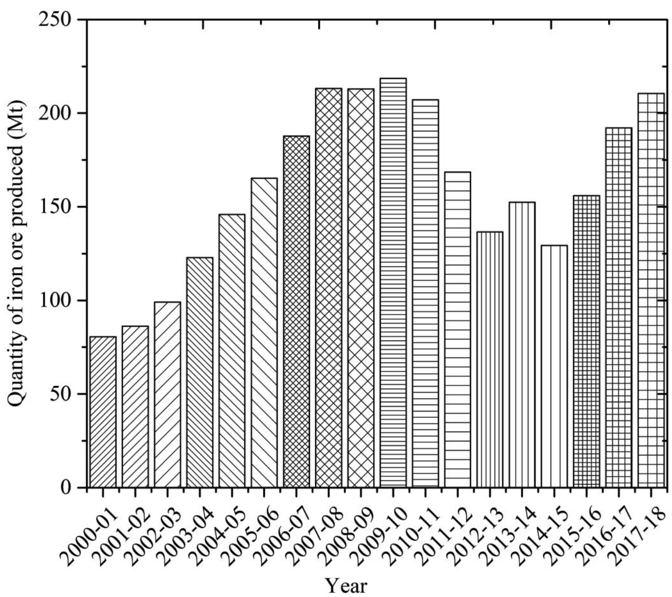

Fig. 1. Statistics of iron ore production in India. (Data from OGD PMU Team 2018.)

Various researchers have experimented with the use of IOT as a replacement for fine aggregates in concrete by partially replacing cement with fly ash, GGBS, silica fumes, pond ash, alccofine, etc. The present study aims to enhance the properties of IOT concrete with the addition of alccofine as a partial replacement for cement. Based on the literature review discussed, 10% alccofine is considered as a cement replacement. The optimization of the concrete mixes was observed for varying IOT replacement (0%, 10%, 20%, 30%, 40%, and 50%) as fine aggregates for different numbers of curing days (3, 7, 28, and 56 days) and water-to-cement (w/c) ratios (0.35, 0.40, and 0.45). Based on the experimental data obtained for the mechanical properties of concrete, statistical studies were conducted to compare the laboratory values to the predicted values and the same have been validated.

Materials and Methods

Cement and Virgin Aggregates

This studied used ordinary portland cement (OPC) of Grade 53 with specific gravity 3.14 and initial and final setting times of 60 and 450 min respectively. The properties of the cement are listed in Table 1. Compared with IS:12269 (BIS 2013), they are found to be within the limits.

The coarse and fine aggregates used are natural and locally available materials in the southwestern part of India. Table 2 shows the physical properties of the aggregates as per IS:383 (BIS 1970).

Water and Superplasticizer

The amount of water in a concrete mix has a direct effect on the strength development of the mixture. Water must be added as per the mix design to lubricate the solids in the mixture. Tap water was used for mixing concrete. Sulfonated naphthalene formaldehyde polymer admixture (Conplast SP 430) was used in the present study to improve the workability of concrete. The properties of Conplast SP 430 are as follows: its specific gravity is 1.20, chloride content is nil, solid content is 40%, 10°C–40°C is the operating temperature, and the color of the admixture is a dark brown liquid.

Alccofine 1203

Alccofine 1203 is a microfine material. Alccofine is used as a supplementary cementitious material. The specific gravity of alccofine is 2.86 and its bulk density is 600 kg/m^3.

Iron Ore Tailings

IOT were obtained from the tailings pond of an iron ore mine located in the southern part of India (Fig. 2). The samples were

Table 1. Physical properties of OPC and alccofine

S. No.	Property	Value	Requirement per IS (BIS 2013)
1	Specific gravity	3.14	—
2	Standard consistency (%)	29	—
3	Fineness (m^2/kg)	300	Should not be less than 225 m^2/kg
4	Initial setting time (min)	60	Should not be less than 30 min
5	Final setting time (min)	450	Should not be more than 600 min
6	Soundness (mm) (by Le Chatelier mold)	2	Should not exceed 10 mm

Note: The cement satisfies the requirement for Grade 53 OPC stipulated by IS:12269. Tests are conducted as per guidelines of IS:4031.

Table 2. Physical properties of natural and marginal aggregates

S. No.	Property	Coarse aggregates	Fine aggregates	IOT
1	Specific gravity	2.8	2.7	3.31
2	Bulk density, loose (kg/m^3)	1,370	1,440	1,684
3	Bulk density, compacted (kg/m^3)	1,670	1,770	1,816
4	Moisture content	Nil	Nil	3.9
5	Water absorption (%)	0.50	0.10	2.29

Fig. 2. Overview of iron ore tailing pond.

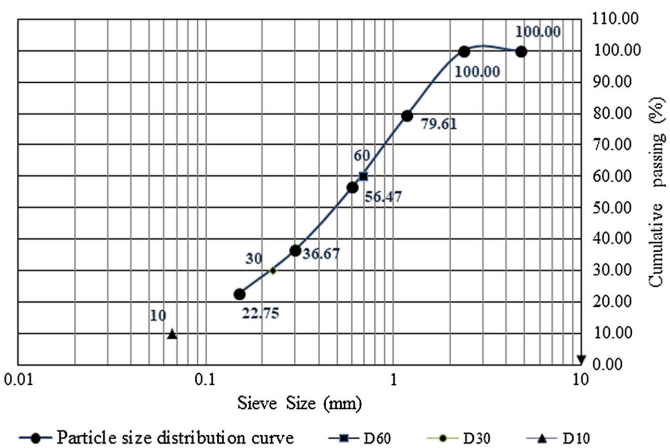

Fig. 3. Particle size distribution of natural and marginal aggregates.

collected by random sampling at various locations from the tailing pond as per IS:1199. The basic physical properties were determined to assess the suitability of IOT as an aggregate in concrete as shown in Table 2. The grain size distribution from Fig. 3 indicated that IOT are fine particles and are medium grade quality. D60, D30, and D10 show the percentage of particles passing in that particular sieve size.

Table 3 shows the chemical composition of IOT using the XRF method. Figs. 4(a and b) give the results of the electron dispersive spectroscopy (EDS) and scanning electron microscopy (SEM). SEM analysis shows that the IOT particles are irregularly shaped and porous, due to which they have a high surface area.

Table 3. Chemical composition by XRF of IOT

Chemical composition	IOT (%)	Alccofine (%)
SiO_2	49.750	34.4
Al_2O_3	9.742	21.6
Fe_2O_3	27.030	1.1
CaO	4.057	34
MnO	0.171	—
K_2O	0.500	—
ZnO	0.100	—
CuO	0.200	—
PbO	0.400	—
MgO	3.109	6.6
pH	8.030	—
Electrical conductivity (mS)	0.329	—

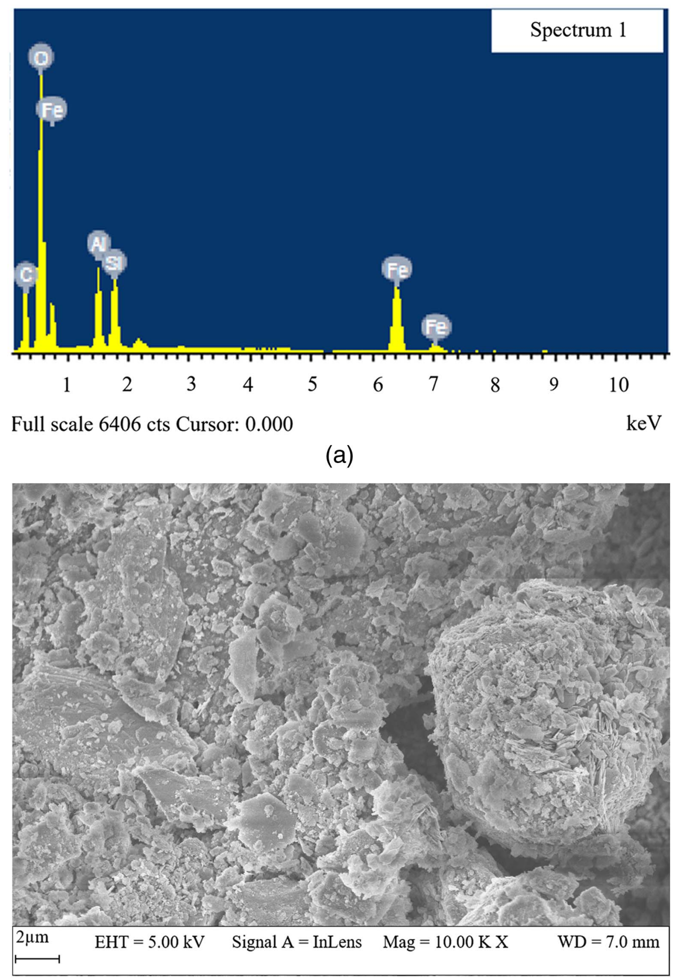

Fig. 4. (a) EDS; and (b) SEM for IOT.

The heavy metal concentration in IOT was made up of As, Ba, Cd, Cr, Pb, Se, Ag, Zn, and Cu, which confirms that the materials were nonhazardous. The toxicity characteristic leaching procedure (TCLP) established by the US EPA was used in estimating the heavy metal concentration from IOT material. The experimental procedure was carried out per US EPA guidelines. The IOT materials were mixed with deionized water at a liquid-to-solid (L/S) ratio of 20:1 and 30 rpm agitation for 24 h. Later, leachates were extracted and filtered, thereby determining the heavy metal concentration by

Table 4. Heavy metal concentration in IOT

Element	Regulatory limits (mg/L)	IOT concentration (mg/L)	
		Present study	Shettima et al. (2016)
As	0.05	0.005	0.002
Ba	1.00	0.0006	0.0008
Cd	0.01	0.004	0.002
Cr	0.05	0.0003	0.0002
Pb	0.05	0.0010	0.0008
Se	0.01	0.002	0.001
Ag	0.05	0.01	0.01
Zn	0.50	0.0009	0.0005

inductively coupled plasma mass spectrometry (ICP-MS). The heavy metal concentration in IOT is tabulated in Table 4 and was compared to the regulatory limits. Based on the results, the IOT material used in the present study can be considered as nonhazardous mine waste and can be utilized as a construction material.

Mix Design and Proportioning

The nominal mix ratio was designed for the marginal materials as a replacement for cement and fine aggregates as discussed in this section.

Mix design was carried out in accordance with the IS:10262 (BIS 2009) specification for Grade M40 concrete. Cement was partially replaced with alccofine by 10% and fine aggregates were replaced by IOT at 0%, 10%, 20%, 30%, 40%, and 50% by volume. The designated w/c for all the mixtures was varied as 0.35, 0.40, and 0.45. The concrete was designed for a workability test with slump between 25 and 50 mm. Conplast SP 430 was used as a water reducing admixture between 0.5% and 1.0% by weight of cement for all the mixes.

Six batches of mix proportions were prepared for each type of w/c; therefore a total of 18 batches were prepared for three w/c ratios considered for varying mix proportions in the present study (Table 5).

Experimental Program

Specimen Preparation and Curing Conditions

The test blocks were prepared with concrete samples casted in different molds depending on the test requirements. Cubes of dimensions $100 \times 100 \times 100$ mm accounting for 72 cubes per mix proportion were casted for compressive strength (CS). In all, 36 cylinders with a 150-mm diameter and 300-mm length were casted for splitting tensile strength (STS) and 36 beams of dimensions $500 \times 100 \times 100$ mm were prepared for testing flexural strength (FS) for varying w/c. Fresh concrete was used for the slump tests. It should be noted that among the 72 cubes prepared for compression tests, three replicate cubes each were cured for four different numbers of curing days (3, 7, 28, and 56 days) prior to testing compressive strength and three cylinders and three beams for each mix proportion were considered at 28 and 56 days of curing prior to testing the splitting tensile strength and flexural strength for three different w/c.

The concrete mix was carried out using a drum mixer with 150-kg capacity. The mixer was hand loaded and the duration of mixing was about 2.5–3.0 min after the addition of all the materials, i.e., cement, alccofine, sand, coarse aggregates, IOT, superplasticizer, and water as per the mix design, until a homogenous concrete mix was attained. After the mixing operation, the materials were immediately transferred to the tray and the workability of fresh concrete was determined. The concrete was placed in a slump cone in three layers and each layer was given 25 strokes using a tamping rod to compact the concrete and to reduce the air voids.

Workability and Density of Concrete

The fresh and hardened state of IOT-alccofine concrete mixes was assessed. The workability of concrete was characterized using the slump cone test. Later, the fresh concrete was placed in desired molds and dried for 24 h. Then it was demolded and water cured for the desired curing ages. The samples were weighed and the dimensions were recorded to determine the density as per IS:1199 (BIS 1959b). The results of workability are plotted in Fig. 5 and the results of density are plotted in Figs. 6(a–c).

Compressive Strength

The compressive strength was determined using a compressive testing machine with a loading capacity of 2,000 kN as per IS:516. The loading rate applied in the compressive machine was 140 $kg/cm^2/min$. The compressive strength results are plotted in Figs. 7(a–c) for 3, 7, 28, and 56 curing days and for varying w/c.

Table 5. Mix proportion for IOT-alccofine concrete mixtures

Mix	Cement (kg)	Alccofine (kg)	Coarse aggregates (kg)	Fine aggregates (kg)	Water-to-cement ratio	Superplasticizer (% by weight of cement)	IOT (kg)
IOT1-0	445	50	1,066	789	0.35	0.5	—
IOT1-10				711		1	97
IOT1-20				660		1	165
IOT1-30				590.1		1	252.9
IOT1-40				516.6		1	344.4
IOT1-50				439.5		1	439.5
IOT2-0	386	43	1,120	796	0.4	0.5	—
IOT2-10				716		1	97.5
IOT2-20				636.85		1	195.18
IOT2-30				557.25		1	292.76
IOT2-40				477.64		1	390.36
IOT2-50				398.03		1	487.96
IOT3-0	346	39	1,116.5	861.3	0.45	0.5	—
IOT3-10				775		1	105.58
IOT3-20				720.16		1	180.04
IOT3-30				641.69		1	275.01
IOT3-40				563.48		1	375.65
IOT3-50				479.3		1	479.3

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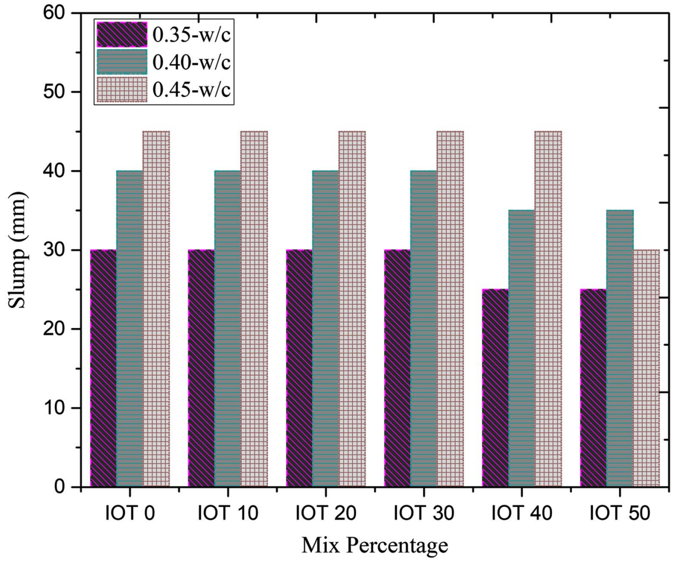

Fig. 5. Workability of fresh concrete with IOT-alccofine and varying w/c.

Compressive strength was calculated using Eq. (1), given as

$$f_r = \frac{P}{A} \tag{1}$$

where f_r = compressive strength; P = load at failure; and A = area of cross section.

Splitting Tensile Strength

The splitting tensile strength was determined using a compressive machine with a loading capacity of 2,000 kN. The test was conducted as per IS:5816 (BIS 1999). The loading rates applied in the splitting tensile strength were 1.2–2.4 MPa/min. The splitting tensile strength of IOT-alccofine concrete was tested and the results are plotted in Figs. 7(a–c) for 28 and 56 curing days at varying w/c.

Splitting tensile strength was calculated using Eq. (2), given as

$$f_r = \frac{2P}{\pi LD} \tag{2}$$

where f_r = splitting tensile strength; P = load at failure; L = length of cylinder; and D = diameter of cylinder.

Flexural Strength

The IOT-alccofine concrete beams were tested under a three-point loading method for flexural strength. The load capacity of the flexural testing machine was 230 kN. The loads were positioned within the middle third 150 mm of the specimen, thus maintaining a loading span of 450 mm during the test. The modulus of rupture (MOR) of the beams was determined for the 28- and 56-day cured samples after the test, depending on the place of occurrence of the failure fracture.

Under three-point loading, two scenarios are possible:

1. For a fracture occurring within the middle third, the MOR was calculated as

$$f_b = \frac{Pl}{bd^2} \quad \text{for } a > 133.3 \text{ mm} \tag{3}$$

2. For a fracture outside the middle third

$$f_b = \frac{3\text{ Pa}}{bd^2} \quad \text{for } 110 \text{ mm} < a < 133.3 \text{ mm} \tag{4}$$

where f_b = flexural strength; a = distance between the line of fracture and the nearer support; P = maximum load; l = span of the beam; and b and d are the cross-sectional dimensions.

Statistical Analysis

Statistical analysis was carried out for density, compressive strength, splitting tensile strength, and flexural strength for varying mix percentages (0%, 10%, 20%, 30%, 40%, and 50%); number of curing days (3, 7, 28, and 56 days); and w/c (0.35, 0.40, and 0.45). In the present study, the response variables are density, compressive strength, splitting tensile strength, and flexural strength, while w/c, mix percentage, and curing days are the independent variables. To obtain reliable estimates of the model parameters, stepwise regression analysis (forward selection and backward elimination) was used to assess the individual predictive contributions of the independent variables, their powers, and their interaction to remove the redundancy caused by the multicollinearity. P-values below 0.05 were considered the significance level for identifying the variables with a significant impact on the response and the estimated coefficient of each factor refers to the contribution of that factor to the response.

Multiple Regression Analysis

To propose the backward elimination method using empirical equations, statistical methods are used. Multiple regression analysis is one of the methods widely used for modeling and analyzing the experimental results obtained from laboratory studies. The analysis is conducted to derive a relationship between the predator variables and response variables. The performance of the model depends on various factors that act in a complex manner. Analysis of variance (ANOVA) was used to find the input parameter significantly affecting the desired response. In the present paper, MINITAB version 17 software was used for the analysis.

Performance Prediction of the Models

The values of variance accounted for (VAF) [Eq. (5)] and root-mean-square error (RMSE) [Eq. (6)] indices were calculated to compare the performance of the prediction capacity of predictive models developed in the study. Mean absolute percentage error (MAPE) [Eq. (7)], which is a measure of accuracy in a fitted series value in statistics, was also used to check the prediction performances of the models. MAPE usually expresses accuracy as a percentage (Kumar et al. 2013)

$$VAF = \left[1 - \frac{var(OCS - PCS)}{var(OCS)}\right] \tag{5}$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(OCS - PCS)^2} \tag{6}$$

$$MAPE = \frac{1}{N}\sum_{i=0}^{N}\left|\frac{OCS - PCS}{PCS}\right| \times 100 \tag{7}$$

where OCS = observed compressive strength; and PCS = predicted compressive strength.

Results and Discussion

Effect of IOT-Alccofine on Workability of Concrete

The workability of concrete was designed for a 25–50 mm slump. The effect of alccofine and IOT on the workability of concrete was

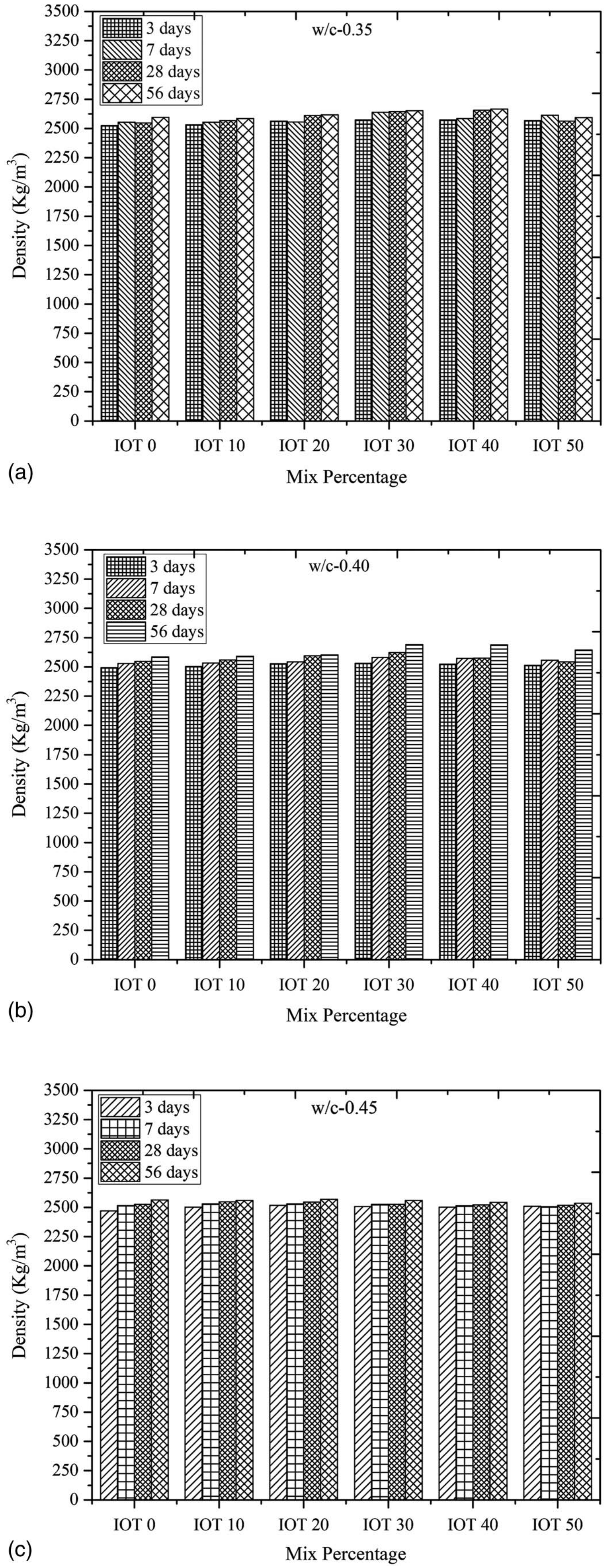

Fig. 6. Density of IOT-alccofine concrete for (a) 0.35 w/c; (b) 0.40 w/c; and (c) 0.45 w/c.

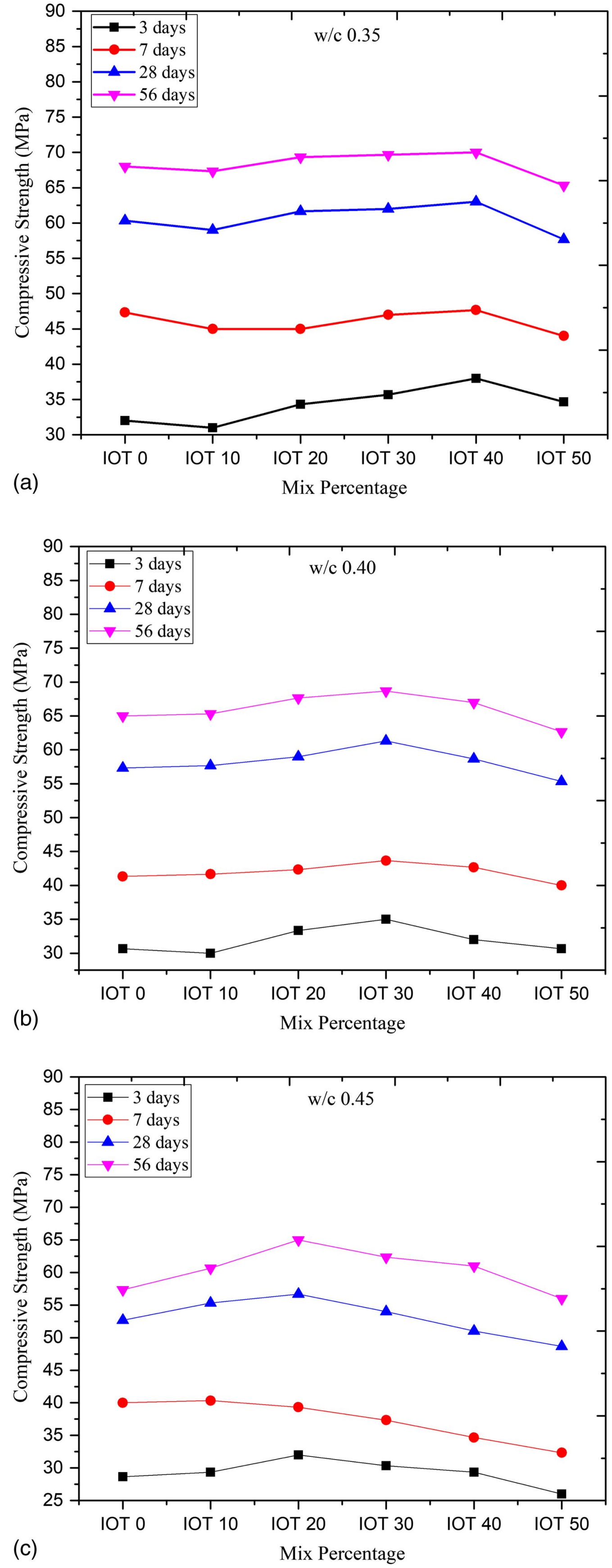

Fig. 7. Compressive strength of IOT-alccofine concrete for (a) 0.35 w/c; (b) 0.40 w/c; and (c) 0.45 w/c.

measured using a slump cone. With reference to the results obtained, by increasing the dosage of IOT in replacement of river sand, the workability of concrete decreased, and with an increase in the w/c ratio, the workability increased. With an increase in IOT up to 50% and with 10% alccofine as cementitious material, a decrease in 38%, 27%, and 26% was observed for mixes compared to control concrete for 0.35, 0.40, and 0.45 w/c respectively. This might be due to the high water absorption, angular surface area, and fineness of IOT materials. The fineness modulus of IOT is 3.05 due to which the water demand increases, thus resulting in decrease in workability.

Effect of IOT-Alccofine on Density of Concrete

The density of IOT-alccofine concrete mixed with different mix proportions at varying w/c was determined. The density of concrete was determined on hardened concrete cubes of dimensions $100 \times 100 \times 100$ mm at 3, 7, 28, and 56 curing days at varying w/c of 0.35, 0.40, and 0.45. The density observed was almost equal to or slightly varied with the increase in IOT replacement with reference to the control concrete. The density ranged between 2,535 and 2,690 kg/m^3 for all the mix proportions. This increase in density might be due to the high specific gravity of IOT. The densities of different mix proportions are plotted in Figs. 6(a–c).

Effect of IOT-Alccofine in Compressive Strength

The compressive strengths of different mix proportions of IOT-alccofine concrete with reference to the control concrete were tested and the results observed are plotted in Figs. 7(a–c). An increase in strength was observed for each w/c. The maximum compressive strength obtained for a w/c of 0.35, 0.40, and 0.45 was 75, 68.67, and 65 MPa at IOT replacement of 40%, 30%, and 20% respectively for samples with 56 curing days. There was a decreasing trend of compressive strength with the increase in the water-to-cement ratio. But the overall strength of concrete was higher compared to the concrete mixes with IOT-alccofine replacement in experiments by previous researchers.

Effect of IOT-Alccofine in Splitting Tensile Strength

The splitting tensile strengths of different mix proportions of IOT-alccofine concrete with reference to the control concrete were tested and the results observed are plotted in Figs. 8(a–c). An increase in strength was observed for each w/c. The maximum splitting tensile strength obtained for w/c 0.35, 0.40, and 0.45 were 4.86, 4.76, and 4.36 MPa for IOT replacement of 40%, 30%, and 20% respectively for 56 days cured samples. With reference to the splitting tensile strength, a decreasing trend was observed with the increase in w/c as shown in Figs. 8(a–c).

Effect of IOT-Alccofine in Flexural Strength of Concrete

The flexural strength of IOT-alccofine concrete was tested on concrete beams at 28 and 56 curing days. The flexural strength at 28 and 56 days for 0.35 w/c increased by 9% and 15%, respectively, with reference to the control concrete for an IOT replacement of 40%. At 0.40 w/c, an increase by 13% and 11% was observed at 30% IOT replacement and for 0.45 w/c, an increase by 5% and 6% was observed at 20% IOT replacement. With reference to the over flexural strength, a decreasing trend was observed with an increase in w/c as shown in Figs. 9(a–c).

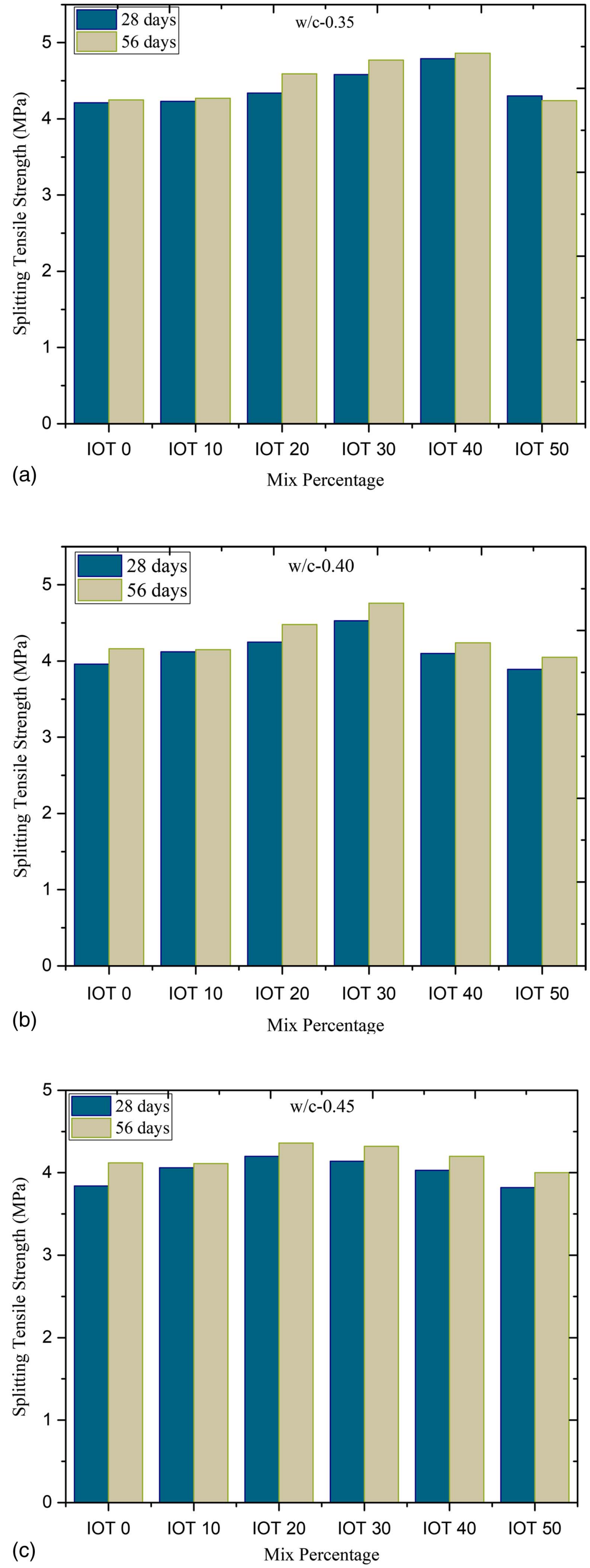

Fig. 8. Splitting tensile strength of IOT-alccofine concrete for (a) 0.35 w/c; (b) 0.40 w/c; and (c) 0.45 w/c.

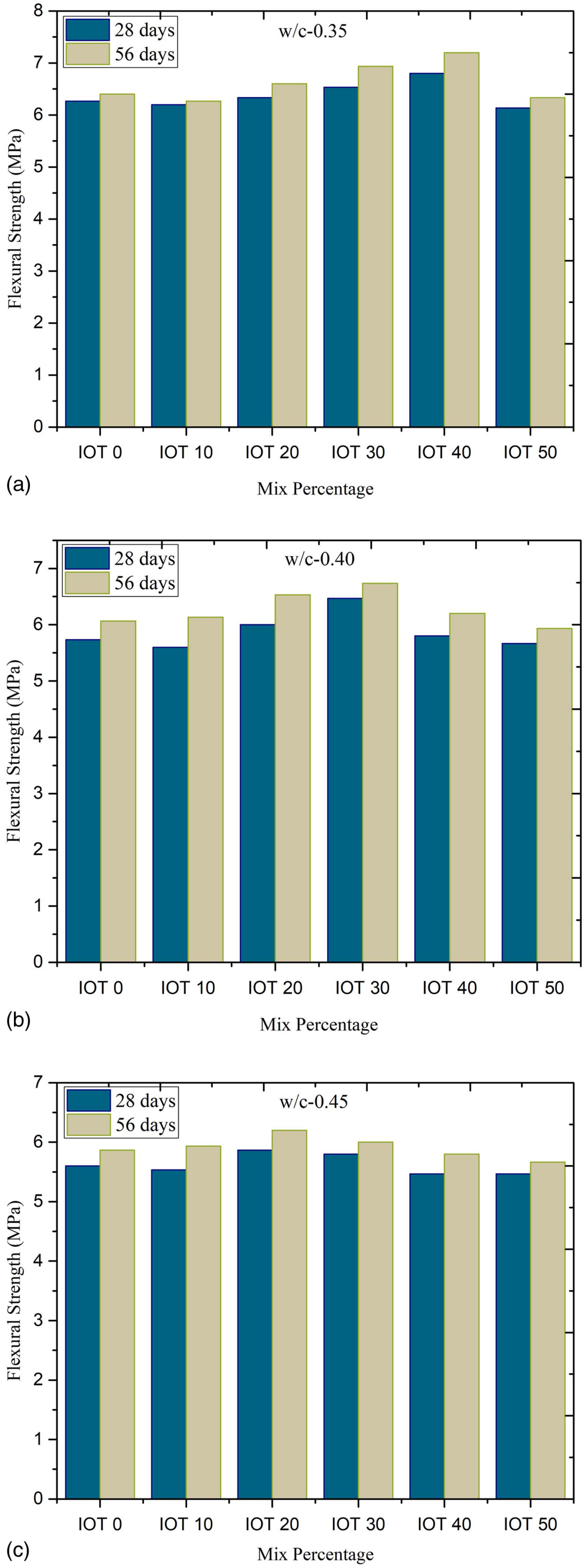

Fig. 9. Flexural strength of IOT-alccofine concrete for (a) 0.35 w/c; (b) 0.40 w/c; and (c) 0.45 w/c.

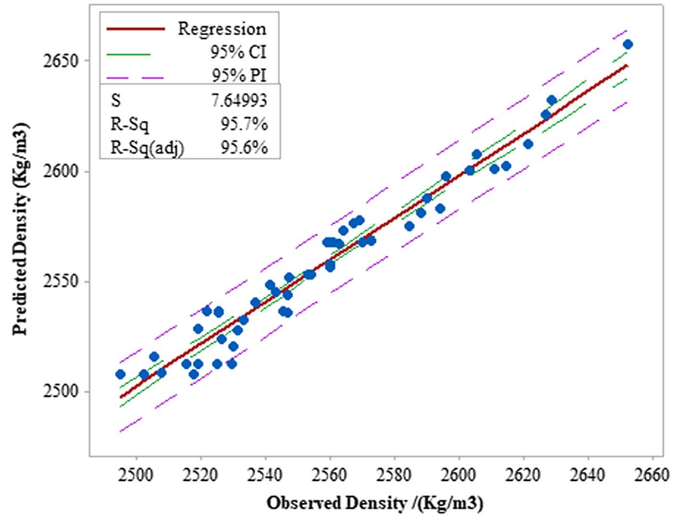

Fig. 10. Predicted versus observed density of IOT-alccofine concrete.

Prediction Model for Density of Concrete

A regression model was developed to predict the density of IOT-alccofine concrete as shown in Eq. (8), by considering the water-to-cement ratio (w/c), mix percentage (Mp), and curing days (Cd) of IOT-alccofine concrete. In the present study, regression models were developed using the backward elimination method to eliminate the independent variables that do not influence the dependent variable. If the *P*-value is greater than 0.05, then that parameter is insignificant. The observed versus predicted density values shown in Fig. 10 were obtained using 70% of the data set that was considered to develop this model (Table 6) (Chandrappa and Biligiri 2018). The majority of observed density values were within the predicted ranges. Hence, from these data, it is apparent that the model predicts the density accurately based on the percent error, which is within the limit of 10% as shown in Fig. 11.

To validate the model, 30% of the data were considered and a comparison between the experimentally measured values and predicted density values was done as shown in Table 7. The percent error ranges between 0.03 and 3.17, which is within the range of 10%, and hence the model developed can certainly help in the mix design optimization.

The ANOVA test summary and parametric estimates are given in Tables 8 and 9 respectively. Table 8 indicates that the model is robust and Table 9 shows that all the independent variables were significant at a 95% confidence level. The R^2 value obtained is 95.66%, RMSE is 7.664, MAPE is 0.2538, and VAF is 95.66%.

The regression model for the density of concrete is given as

$$\begin{aligned}\text{Density (kg/m}^3) &= 2575.2 - 156.3\ \text{w/c} + 1.1200\ \text{Cd} + 11.120\ \text{Mp}\\ &\quad - 24.70\ \text{w/c} \times \text{Mp} \quad R^2 = 95.66\%\end{aligned} \tag{8}$$

Prediction Model for Compressive Strength of IOT-Alccofine Concrete

A regression model was developed to predict the compressive strength of IOT-alccofine concrete as shown in Eq. (9), by considering the w/c, Mp, and Cd of IOT-alccofine concrete. As discussed

Table 6. Data used for model development for density of IOT-alccofine concrete

w/c	Cd	Mp	Observed density	Predicted density	Percent error
0.35	3	0	2,526.33	2,523.84	0.099
0.35	3	10	2,541.33	2,548.59	−0.286
0.35	3	20	2,564.00	2,573.35	−0.365
0.35	3	30	2,596.00	2,598.11	−0.081
0.35	7	0	2,531.33	2,528.32	0.119
0.35	7	10	2,553.33	2,553.07	0.010
0.35	7	20	2,569.33	2,577.83	−0.331
0.35	7	30	2,614.33	2,602.58	0.449
0.35	28	0	2,547.33	2,551.84	−0.177
0.35	28	10	2,567.33	2,576.59	−0.361
0.35	28	20	2,611.00	2,601.35	0.370
0.35	28	30	2,626.67	2,626.10	0.022
0.35	56	0	2,594.33	2,583.20	0.429
0.35	56	10	2,605.33	2,607.95	−0.101
0.35	56	20	2,628.67	2,632.71	−0.154
0.35	56	30	2,652.33	2,657.46	−0.194
0.4	3	0	2,505.33	2,516.02	−0.427
0.4	3	10	2,519.33	2,528.43	−0.361
0.4	3	20	2,536.67	2,540.84	−0.164
0.4	3	30	2,554.33	2,553.24	0.043
0.4	7	0	2,530.00	2,520.50	0.375
0.4	7	10	2,533.33	2,532.91	0.017
0.4	7	20	2,543.33	2,545.32	−0.078
0.4	7	30	2,560.00	2,557.72	0.089
0.4	28	0	2,546.67	2,544.02	0.104
0.4	28	10	2,560.00	2,556.43	0.140
0.4	28	20	2,572.67	2,568.84	0.149
0.4	28	30	2,588.33	2,581.24	0.274
0.4	56	0	2,584.67	2,575.38	0.359
0.4	56	10	2,590.00	2,587.79	0.085
0.4	56	20	2,603.33	2,600.19	0.120
0.4	56	30	2,621.33	2,612.60	0.333
0.45	3	0	2,495.00	2,508.21	−0.529
0.45	3	10	2,502.37	2,508.27	−0.236
0.45	3	20	2,518.00	2,508.32	0.384
0.45	3	30	2,508.00	2,508.38	−0.015
0.45	7	0	2,515.33	2,512.69	0.105
0.45	7	10	2,519.00	2,512.75	0.248
0.45	7	20	2,529.67	2,512.80	0.667
0.45	7	30	2,525.00	2,512.86	0.481
0.45	28	0	2,525.33	2,536.21	−0.431
0.45	28	10	2,546.67	2,536.26	0.409
0.45	28	20	2,545.33	2,536.32	0.354
0.45	28	30	2,525.67	2,536.38	−0.424
0.45	28	40	2,522.00	2,536.44	−0.572
0.45	56	0	2,562.67	2,567.57	−0.191
0.45	56	10	2,560.00	2,567.62	−0.298
0.45	56	20	2,570.00	2,567.68	0.090
0.45	56	30	2,559.33	2,567.74	−0.329
0.45	56	40	2,561.00	2,567.80	−0.265

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

in the previous section, all the regression models in the present study were developed using the backward elimination method. The observed versus predicted compressive strengths are shown in Fig. 12, which were obtained using the 70% of the compressive strength data set for model development (Table 10). The majority of observed compressive strength was within the predicted ranges. Hence, from these data it is apparent that the model predicts the compressive strength accurately based on the percent error, which is within the limit of 10% as shown in Fig. 13.

To validate the model, 30% of the data set was considered and a comparison between the experimentally measured values and predicted density values was done as shown in Table 11. The percent error ranges within the limit for maximum values of compressive strength; hence the model developed can certainly help in the mix design optimization.

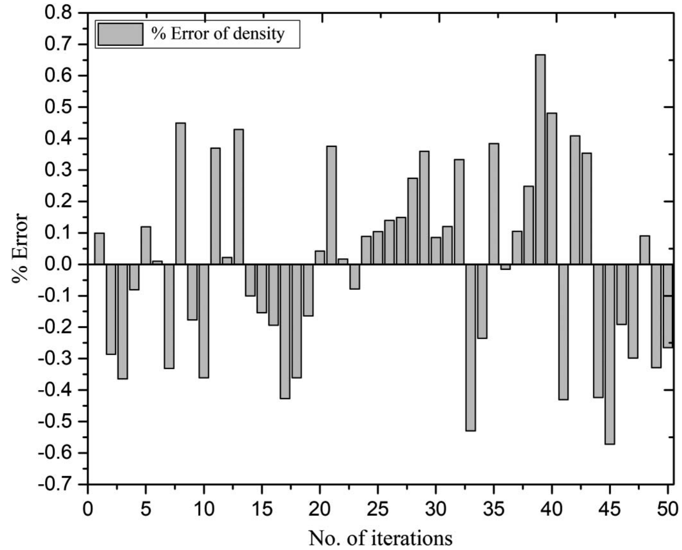

Fig. 11. Error plot for density of IOT-alccofine concrete.

Table 7. Data used for model validation for density of IOT-alccofine concrete

w/c	Cd	Mp	Observed density	Predicted density	Percent error
0.35	3	40	2,573.00	2,622.86	−1.94
	3	50	2,566.33	2,647.61	−3.17
	7	40	2,584.67	2,627.34	−1.65
	7	50	2,612.00	2,652.09	−1.53
	28	40	2,656.00	2,650.86	0.19
	28	50	2,563.67	2,675.61	−4.37
	56	40	2,665.67	2,682.22	−0.62
	56	50	2,592.00	2,706.97	−4.44
0.4	3	40	2,522.67	2,565.64	−1.70
	3	50	2,514.33	2,578.04	−2.53
	7	40	2,573.00	2,570.12	0.11
	7	50	2,558.00	2,582.52	−0.96
	28	40	2,574.67	2,593.64	−0.74
	28	50	2,543.33	2,606.04	−2.47
	56	40	2,688.33	2,625.00	2.36
	56	50	2,644.00	2,637.40	0.25
0.45	3	40	2,501.67	2,508.43	−0.27
	3	50	2,510.67	2,508.48	0.09
	7	40	2,513.67	2,512.91	0.03
	7	50	2,505.00	2,512.96	−0.32
	28	50	2,517.33	2,536.48	−0.76
	56	50	2,536.00	2,567.84	−1.26

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

Table 8. ANOVA summary for density of IOT-alccofine concrete

Source	DF	Adj. MS	F-value	F-tabulated	P-value
Regression	4	16,177.6	247.91	2.56	0.000
Residual	45	65.3	—		—
Total	49	—	—		—

Note: DF = degree of freedom; and F = standard statistical test.

Table 9. Parametric estimates for density model for IOT-alccofine concrete

Term	Coefficient	SE coefficient	T-value	T-tabulated	P-value
Constant	2,575.2	18.9	136.53	2.776	0.000
w/c	−156.3	46.5	−3.36		0.002
Cd	1.12	0.0544	20.58		0.000
Mp	11.12	0.943	11.79		0.000
w/c × Mp	−24.7	2.3	−10.73		0.000

Note: w/c = water-to-cement ratio; Cd = curing days; Mp = mix percentage; SE = standard error; and T = standard statistical test.

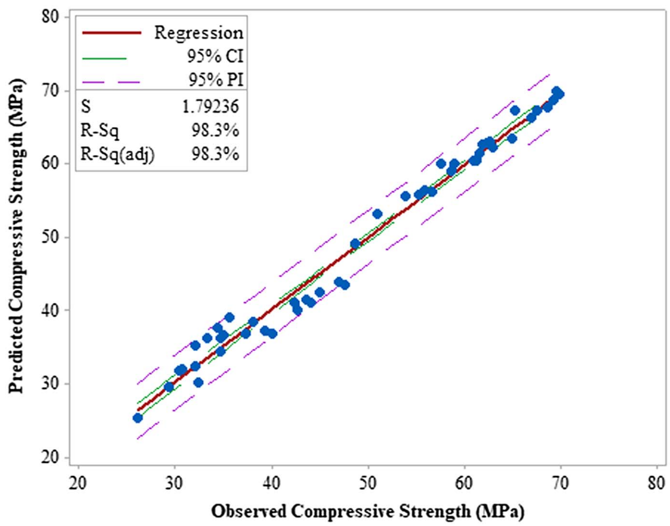

Fig. 12. Predicted versus observed plot for compressive strength of IOT-alccofine concrete.

The ANOVA test summary and parametric estimates are shown in Tables 12 and 13 respectively. Table 12 indicates that the model is robust and Table 13 shows that all the independent variables were significant at a 95% confidence level. The R^2 value obtained is 98.29%, RMSE is 1.770, MAPE is 3.326, and VAF is 99.37.

The regression model for compressive strength is given as

$$\begin{aligned}\text{Compressive strength (MPa)} &= -46.3 + 376\ \text{w/c} + 1.3534\ \text{Cd} + 1.250\ \text{Mp} - 488\ \text{w/c} * \text{w/c} \\ &\quad - 0.013031\ \text{Cd} * \text{Cd} - 0.00896\ \text{Mp} * \text{Mp} \\ &\quad - 1.909\ \text{w/c} * \text{Mp} \qquad R^2 = 98.29\% \end{aligned} \tag{9}$$

Prediction Model for Splitting Tensile Strength of IOT-Alccofine Concrete

A regression model was developed as given in Eq. (10) to predict the splitting tensile strength of IOT-alccofine concrete considering the w/c, Mp, and Cd. The observed versus predicted splitting tensile strengths are shown in Fig. 14, which were obtained using the 70% of the data set considered for model development (Table 14). The majority of observed splitting tensile strength was within the predicted ranges. Hence, from these data it is apparent that the model predicts the results accurately based on the percent error, which is within the limit of 10% as shown in Fig. 15.

Table 10. Data used for model development for compressive strength of IOT-alccofine concrete

w/c	Cd	Mp	Observed compressive strength	Predicted compressive strength	Percent error
0.35	3	20	34.33	37.69	−9.80
	3	30	35.67	39.03	−9.42
	3	40	38.00	38.58	−1.52
	3	50	34.67	36.33	−4.79
	7	20	45.00	42.59	5.36
	7	30	47.00	43.93	6.54
	7	40	47.67	43.47	8.80
	7	50	44.00	41.23	6.30
	28	20	61.67	61.43	0.38
	28	30	62.00	62.77	−1.24
	28	40	63.00	62.32	1.08
	28	50	57.67	60.07	−4.16
	56	20	69.33	68.68	0.94
	56	30	69.67	70.02	−0.49
	56	40	70.00	69.56	0.62
	56	50	65.33	67.32	−3.03
0.4	3	20	33.33	36.31	−8.95
	3	30	35.00	36.70	−4.85
	3	40	32.00	35.29	−10.28
	3	50	30.67	32.09	−4.63
	7	20	42.33	41.21	2.65
	7	30	43.67	41.59	4.76
	7	40	42.67	40.18	5.82
	7	50	40.00	36.98	7.54
	28	20	59.00	60.05	−1.77
	28	30	61.33	60.43	1.46
	28	40	58.67	59.03	−0.60
	28	50	55.33	55.83	−0.89
	56	20	67.67	67.30	0.55
	56	30	68.67	67.68	1.44
	56	40	67.00	66.27	1.08
	56	50	62.67	63.07	−0.64
0.45	3	20	32.00	32.49	−1.54
	3	30	30.33	31.92	−5.25
	3	40	29.33	29.56	−0.78
	3	50	26.00	25.41	2.27
	7	20	39.33	37.39	4.94
	7	30	37.33	36.82	1.37
	7	40	34.67	34.45	0.62
	7	50	32.33	30.30	6.27
	28	20	56.67	56.23	0.77
	28	30	54.00	55.66	−3.07
	28	40	51.00	53.30	−4.50
	28	50	48.67	49.14	−0.97
	56	20	65.00	63.48	2.34
	56	30	62.33	62.91	−0.92
	56	40	61.00	60.54	0.74
	56	50	56.00	56.39	−0.69

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

For validating the model, a comparison between the measured values with the predicted values is given in Table 15. The percent error ranges within the limit of 10%; hence the model developed can certainly help in the mix design optimization.

The ANOVA test summary and parametric estimates are shown in Tables 16 and 17 respectively. Table 16 indicates that the model is robust and Table 17 shows that all the independent variables were significant at a 95% confidence level. The R^2 value obtained is 73.00%, RMSE is 0.118, MAPE is 2.059, and VAF is 73.00.

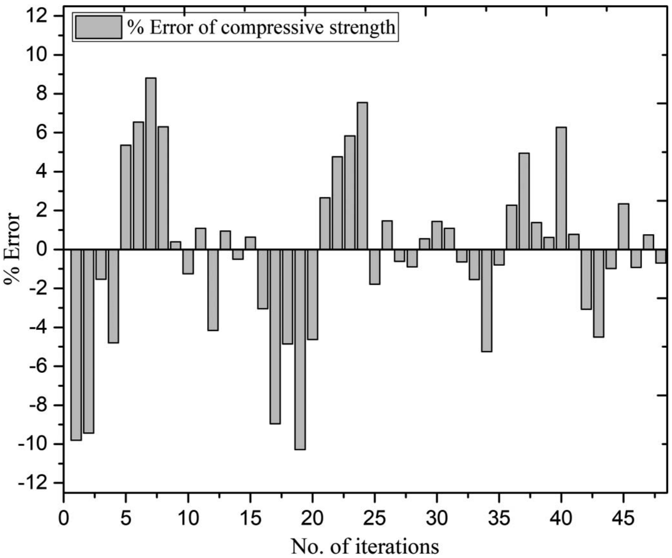

Fig. 13. Error plot for compressive strength of IOT-alccofine concrete.

Table 11. Data used for model validation for compressive strength of IOT-alccofine concrete

w/c	Cd	Mp	Observed compressive strength	Predicted compressive strength	Percent error
0.35	3	0	32.00	29.46	7.92
	3	10	31.00	34.39	−10.92
	7	0	47.33	34.36	17.41
	7	10	45.00	39.28	12.71
	28	0	60.33	53.20	11.82
	28	10	59.00	58.12	1.48
	56	0	68.00	60.45	11.11
	56	10	67.33	65.37	2.91
0.4	3	0	30.67	29.96	2.30
	3	10	30.00	33.93	−13.10
	7	0	41.33	34.86	15.66
	7	10	41.67	38.82	6.83
	28	0	57.33	53.70	6.33
	28	10	57.67	57.67	0.01
	56	0	65.00	60.95	6.23
	56	10	65.33	64.91	0.63
0.45	3	0	28.67	28.02	2.25
	3	10	29.33	31.04	−5.81
	7	0	40.00	32.92	17.71
	7	10	40.33	35.93	10.91
	28	0	52.67	51.76	1.73
	28	10	55.33	54.77	1.00
	56	0	57.33	59.01	−2.92
	56	10	60.67	62.02	−2.22

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

Table 12. ANOVA summary for compressive strength model of IOT-alccofine concrete

Source	DF	Adj. MS	F-value	F-tabulated	P-value	R2
Regression	7	1233.77	328.24	2.20	0.000	98.29
Residual	40	3.76	—		—	—
Total	47	—	—		—	—

Note: DF = degree of freedom; and F = standard statistical test.

Table 13. Parametric estimates for compressive strength model of IOT-alccofine concrete

Term	Coefficient	SE coefficient	T-value	T-tabulated	P-value
Constant	−46.3	38.8	−1.19	2.365	0.240
w/c	376	191	1.97		0.050
Cd	1.3534	0.0592	22.85		0.000
Mp	1.25	0.315	3.97		0.000
w/c × w/c	−488	237	−2.05		0.047
Cd × Cd	−0.013031	0.000978	−13.33		0.000
Mp × Mp	−0.00896	0.0028	−3.2		0.003
w/c × Mp	−1.909	0.613	−3.11		0.003

Note: SE = standard error; and T = standard statistical test.

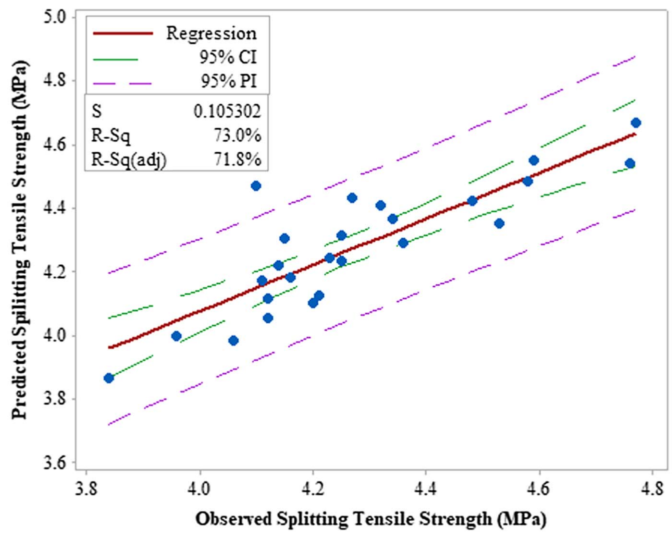

Fig. 14. Predicted versus observed splitting tensile of IOT-alccofine concrete.

The regression model for splitting tensile strength is given as

$$\begin{aligned}\text{Splitting tensile strength (MPa)} &= 4.854 - 2.612\ \text{w/c} + 0.00670\ \text{Cd} \\ &+ 0.01185\ \text{Mp} \qquad R^2 = 73.00\%\end{aligned} \tag{10}$$

Prediction Model for Flexural Strength of IOT-Alccofine Concrete

A regression model was developed to predict the flexural strength of IOT-alccofine concrete. Eq. (11) was developed considering the w/c, Mp, and Cd. The observed versus predicted flexural strengths along with the prediction intervals indicating the range of prediction for individual values are shown in Fig. 16, which were obtained using the data set considered for model development as shown in Table 18. The majority of observed splitting tensile strength was within the predicted ranges. Hence, from these data it is apparent that the model predicts the results accurately based on the percent error, which is within the limit of 10% as shown in Fig. 17. For validating the model, a comparison between the measured values with the predicted values is given in Table 19. The percent error ranges within the limit of 10%; hence the model developed can certainly help in the mix design optimization.

Table 14. Data used for model development for splitting tensile strength of IOT-alccofine concrete

w/c	Cd	Mp	Observed splitting tensile strength	Predicted splitting tensile strength	Percent error
0.35	28	0	4.21	4.13	1.97
	28	10	4.23	4.25	−0.36
	28	20	4.34	4.36	−0.55
	28	30	4.58	4.48	2.12
	56	0	4.25	4.31	−1.52
	56	10	4.27	4.43	−3.81
	56	20	4.59	4.55	0.83
	56	30	4.77	4.67	2.09
0.4	28	0	3.96	4.00	−0.92
	28	10	4.12	4.11	0.12
	28	20	4.25	4.23	0.39
	28	30	4.53	4.35	3.93
	28	40	4.10	4.47	−9.03
	56	0	4.16	4.18	−0.57
	56	10	4.15	4.30	−3.67
	56	20	4.48	4.42	1.31
	56	30	4.76	4.54	4.63
0.45	28	0	3.84	3.87	−0.67
	28	10	4.06	3.98	1.86
	28	20	4.20	4.10	2.31
	28	30	4.14	4.22	−1.96
	56	0	4.12	4.05	1.61
	56	10	4.11	4.17	−1.50
	56	20	4.36	4.29	1.59
	56	30	4.32	4.41	−2.05

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

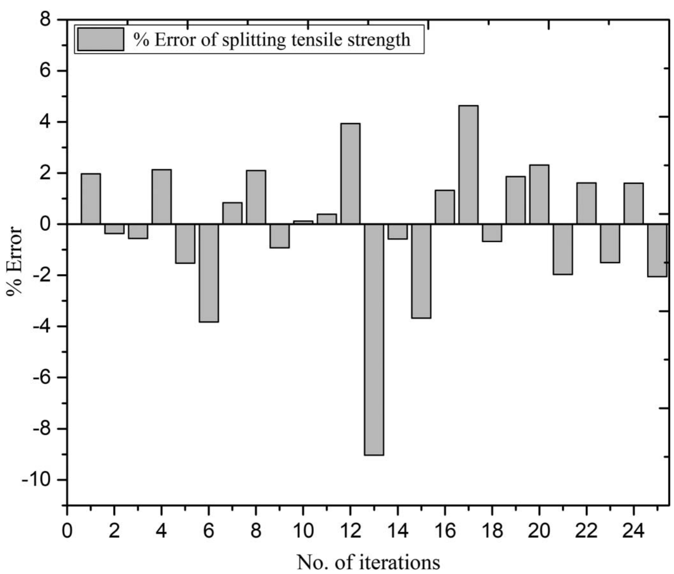

Fig. 15. Error plot for splitting tensile of IOT-alccofine concrete.

The ANOVA test summary and parametric estimates are shown in Tables 20 and 21 respectively. Table 20 indicates that the model is robust and Table 21 shows that all the independent variables were significant at a 95% confidence level. The R^2 value obtained is 77.21%, RMSE is 0.17, MAPE is 2.160, and VAF is 77.21.

Table 15. Data used for model validation for splitting tensile strength of IOT-alccofine concrete

w/c	Cd	Mp	Observed	Predicted	Percent error
0.35	28	40	4.79	4.601	−0.03
	28	50	4.30	4.720	0.09
	56	40	4.86	4.789	−0.01
	56	50	4.24	4.908	0.15
0.4	28	50	3.89	4.589	0.18
	56	40	4.24	4.658	0.09
	56	50	4.05	4.777	0.17
0.45	28	40	4.03	4.340	0.07
	28	50	3.82	4.459	0.16
	56	40	4.20	4.528	0.07
	56	50	4.00	4.646	0.16

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

Table 16. ANOVA summary for splitting tensile strength model of IOT-alccofine concrete

Source	DF	Adj. MS	F-value	F-tabulated	P-value
Regression	3	0.31481	18.92	3.01	0.000
Residual	21	0.01664	—		—
Total	24	—	—		—

Note: DF = degree of freedom; and F = standard statistical test.

Table 17. Parametric estimates for splitting tensile strength model of IOT-alccofine concrete

Term	Coefficient	SE coefficient	T-value	T-tabulated	P-value
Constant	4.854	0.273	17.76	3.182	0.000
w/c	−2.612	0.645	−4.05		0.001
Cd	0.0067	0.00185	3.62		0.002
Mp	0.01185	0.00216	5.49		0.000

Note: SE = standard error; and T = standard statistical test.

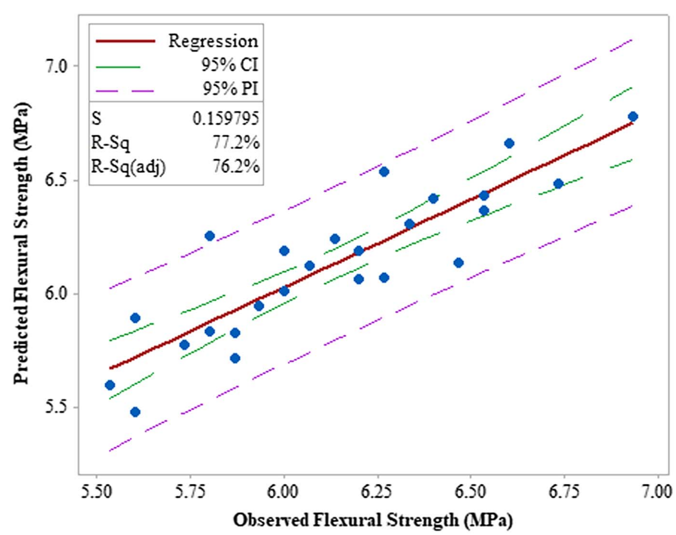

Fig. 16. Predicted versus observed flexural strength of IOT-alccofine concrete.

Table 18. Data used for model validation for flexural strength of IOT-alccofine concrete

w/c	Cd	Mp	Observed	Predicted	Percent error
0.35	28	0	6.27	6.07	0.031
	28	10	6.20	6.19	0.001
	28	20	6.33	6.31	0.003
	28	30	6.53	6.43	0.016
	56	0	6.40	6.42	−0.003
	56	10	6.27	6.54	−0.044
	56	20	6.60	6.66	−0.009
	56	30	6.93	6.78	0.022
0.4	28	0	5.73	5.78	−0.008
	28	10	5.60	5.90	−0.053
	28	20	6.00	6.02	−0.003
	28	30	6.47	6.14	0.051
	28	40	5.80	6.26	−0.079
	56	0	6.07	6.13	−0.010
	56	10	6.13	6.25	−0.018
	56	20	6.53	6.37	0.026
	56	30	6.73	6.49	0.037
0.45	28	0	5.60	5.48	0.021
	28	10	5.53	5.60	−0.012
	28	20	5.87	5.72	0.025
	28	30	5.80	5.84	−0.007
	56	0	5.87	5.83	0.006
	56	10	5.93	5.95	−0.003
	56	20	6.20	6.07	0.021
	56	30	6.00	6.19	−0.032

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

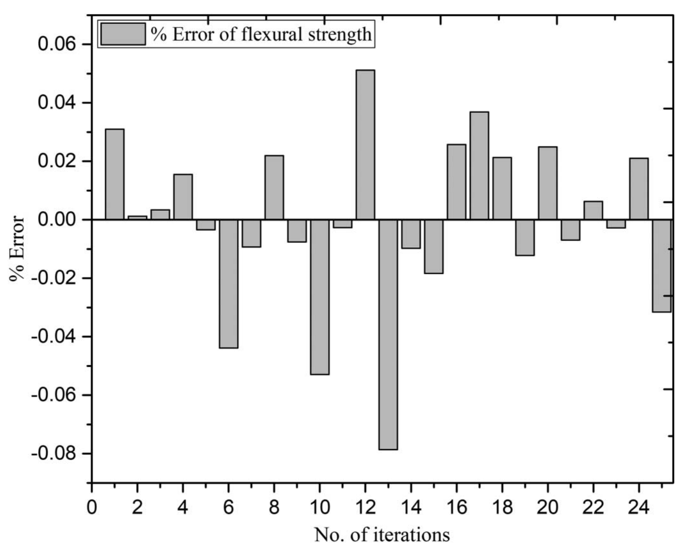

Fig. 17. Error plot for flexural strength of IOT-alccofine concrete.

The regression model for flexural strength is given as

$$\text{Flexural strength (MPa)} = 7.794 - 5.917\ \text{w/c} + 0.01247\ \text{Cd} + 0.01198\ \text{Mp} \qquad R^2 = 77.21\% \tag{11}$$

Conclusions

Based on the results obtained from the experimental study on IOT-alccofine concrete, the following conclusions can be drawn:

Table 19. Data used for model validation for flexural strength of IOT-alccofine concrete

w/c	Cd	Mp	Observed	Predicted	Percent error
0.35	28	40	6.80	6.55	3.66
	28	50	6.13	6.67	−8.77
	56	40	7.20	6.90	4.16
	56	50	6.33	7.02	−10.85
0.4	28	50	5.67	6.38	−12.51
	56	40	6.20	6.60	−6.53
	56	50	5.93	6.72	−13.33
0.45	28	40	5.47	5.96	−9.02
	28	50	5.47	6.08	−11.21
	56	40	5.80	6.31	−8.77
	56	50	5.67	6.43	−13.45

Note: w/c = water-to-cement ratio; Cd = curing days; and Mp = mix percentage.

Table 20. ANOVA summary for flexural strength model of IOT-alccofine concrete

Source	DF	Adj. MS	F-value	F-tabulated	P-value
Regression	3	0.85898	23.71	3.01	0.000
Residual	21	0.03622	—		—
Total	24	—	—		—

Note: DF = degree of freedom; and F = standard statistical test.

Table 21. Parametric estimates for flexural strength model of IOT-alccofine concrete

Term	Coefficient	SE coefficient	T-value	T-tabulated	P-value
Constant	7.794	0.403	19.33	3.182	0.000
w/c	−5.917	0.952	−6.22		0.000
Cd	0.01247	0.00273	4.57		0.000
Mp	0.01198	0.00318	3.76		0.001

Note: SE = standard error; and T = standard statistical test.

1. Based on the properties of alccofine and IOT, they are suitable as a replacement material for cement and sand respectively in concrete as per Indian Standards 12269 (BIS 2013) and 383 (BIS 1970). Leaching test results show that IOT do not have hazardous materials and the metals present are within the limits. The SEM images resulted in high density IOT materials with high surface area and rough texture.
2. Alccofine was used as a partial replacement for cement by 10% consistently for all concrete mixes with a partial replacement of fine aggregates with IOT. The workability of concrete decreased with an increase in IOT-alccofine replacement. This might be due to the high surface area of IOT aggregates, therefore increasing the demand of water content. With reference to the varying water-to-cement ratio, the workability of concrete increased with reference to the control concrete mix.
3. The density and compressive strength increased up to the optimum percentage for each w/c mix of concrete samples. For 0.35 w/c, the compressive strength increased by 70 MPa, i.e., 3% with reference to the control concrete at 40% IOT replacement. Similarly, for 0.40 and 0.45 w/c, a 3% and 13% increase resulted in 30% and 20% IOT replacement respectively at 56 curing days.
4. The splitting tensile strength and flexural strength of IOT-alccofine concrete depicted an increase in strength similar to the compressive strength at the same IOT replacement levels with reference to the w/c.

5. The regression models were developed for each of the properties tested at a laboratory scale. The equations developed were found to be robust and statistically fit for prediction of the properties. The R^2 obtained for density, compressive strength, splitting tensile strength, and flexural strength was 95.66%, 98.29%, 73.00%, and 77.21% respectively with RMSE and MAPE values within the range.

From the present study, it can be concluded that iron ore tailings with alccofine can be used as a marginal material in the construction industry. Based on the mix design for Grade M40, the strength obtained for the varying mix proportions increased gradually compared to the control mix. A comparison study was made using multiple regression analysis and prediction models were developed for each parameter i.e., density, compressive strength, splitting tensile strength, and flexural strength. By using these models, validation was made for the respective parameters. It was observed that the models developed were robust and statistically significant and these models can be considered to optimize the mixes.

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