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TECHNICAL PAPER

Optimization of sustainable high-strength–high-volume fly ash concrete with and without steel fiber using Taguchi method and multi-regression analysis

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Abstract
The progression of high-strength–high-volume fly ash concrete addresses fly ash as a resource productive material with the sustainability of the construction industry. This paper presents the evaluation and optimization of the sustainable mechanical properties of concrete with and without crimped steel fibers. In the first phase, the experimental tests are conducted to know the compressive strength, split tensile strength, and flexural strength obtained from the optimal mixes of concrete. Taguchi L_{16} orthogonal array experimental design is applied to optimize the performance of mechanical properties of concrete by using the design of experiments. The level of influence of fly ash percentage on mechanical properties of a concrete mixture is determined by multiple regression analysis. However, after multiple regression analysis, it is found that the error related to the correlation between experimental and analytical value strength is about 5%. Hence, it can be strongly recommended that the developed regression model is sufficient and has a competent approach to optimize the experimental as well as analytical value simultaneously. However, it is concluded that the Taguchi technique is an effective methodical model to reduce the overall investigational work. It is also an efficient approach to optimize designs for performance and quality. The present research confirms that with the mechanical properties of the high-strength–high-volume fly ash steel fiber concrete, it is a more suitable alternative sustainable solution to the concrete industry.

Keywords High-volume fly ash concrete · Fly ash · Steel fibers · Taguchi approach · Optimization

Introduction

According to the Central Electricity Authority of India, fly ash production in India is 93.26 million tons, whereas consumption is 64.08 million tons, i.e., 68.72% till June 2019 [1]. The unused fly ash affects directly or indirectly the surrounding ecosystem due to various harmful reasons. Thus, consumption of fly ash should be increased to minimize the environmental impact. However, the utilization of Fly ash, especially in concrete, has significant environmental benefits. The consumption of large contents of fly ash in concrete shows a significant impact on the production of cement [2]. The effect of blast furnace slag and high-volume C class fly ash was studied by Demirbog et al. [3] to know the compressive strength of lightweight aggregate concrete. Hardjito et al. [4] investigated geopolymer concrete using ASTM class F fly ash and its effect on compressive strength. From the study, the authors stated that the research progress of the material integrates with the idea of sustainable development and has begun gradually in the world. Hilal and Najif [5]

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studied various parameters of ground-granulated blast furnace slag and fly ash analytically and experimentally. Gupta et al. [6] evaluated the shrinkage of high-strength concrete by partial replacement of cement with fly ash and silica fume. From the study, the authors concluded that the shrinkage strain of high-strength concrete was less than that of normal strength concrete. According to the American Concrete Institute (ACI) report [7], concrete with a compressive strength over 41 MPa was considered as a high-strength concrete. The alkali-activated slag-fly ash-cementitious material system was studied by Xin et al. [8]. From the study, it has been shown that the rheological characterization and mechanical properties are sensitive to the change of alkali-activator temperature. Mehta and Monteiro [9] reported that fly ash concrete mixtures contain greater strength than normal concrete in humid atmospheres. Garg and Wang [10] estimated the efficiency of fly ashes collected from different sources. A simplified 'k*' value was proposed to express the reactivity of fly ashes by the authors. Suryawanshi and Thakare [11] investigated the flexural strength of concrete using a combination of high reactive metakaolin and self-curing agents. According to Master Builders Solutions [12], the size, shape of the concrete member, and the quantity of reinforcement are the most affecting factors for drying shrinkage in design parameters. Several factors affecting the definitive sustainable properties of high-volume fly ash-based high-strength concrete specimens were reported by Joshaghani et al. [13]. In high-volume fly ash concrete, water-to-binder ratio is not more than 0.4, and substitution of cement level by fly ash is 50% or more as investigated by Basu and Saraswati, [14]. Afroz et al. [15] evaluated a suitable fiber combination for high-strength–high-volume fly ash concrete. Chakravarthy et al. [16] analyzed mechanical properties for concrete specimens by substituting them with 50% of fly ash. The effect of fly ash, bottom ash, and a combination of both on age-dependent strength of hooked-end steel fiber-reinforced concrete was studied by Pal et al. [17]. Recently, Nayak [18–21] have studied the use of fiber for concrete structures to improve the load-carrying capacity. Farhan et al. [22] investigated the engineering properties of ambient cured alkali-activated slag-fly ash concrete using different types of steel fibers. The effect of fly ash on tensile properties of ultra-high performance cementitious composites using steel fibers was studied by Shaikh et al. [23]. Prakash et al. [24] reported the effect of the addition of steel fiber on the mechanical properties of the concrete. A significant improvement in compressive strength, split tensile strength and flexural strength was observed. Olivia and Nikraz [25] investigated the mechanical properties of the fly ash geopolymer concrete by the Taguchi method. The Taguchi method was implemented by Dung et al. [26] for evaluating the influence factor on bond strength of cladding plaster and concrete substrate at an early age. For concrete strength estimation, a prediction model based on response surface methodology and robust optimization was developed by Kostic et al. [27] using historical laboratory experimental data. Koksal et al. [28] proposed an optimum mix design for steel fiber-reinforced concrete plates using a multi-objective simultaneous optimization technique. Bagheri and Nazari [29] studied the compressive strength of geopolymeric specimens using class C fly ash and granulated blast furnace slag aggregates. In this study, four factors each at three levels were studied through the method of Taguchi design. The effect in the multi-response optimization for deciding the best possible mixture proportions of concretes was studied by Simsek et al. [30] using response surface methodology. The mixed proportion parameters of high-strength self-compacting concrete were studied. For optimal design, six parameters and three levels were analyzed through Taguchi's experiment design method [31].

The goal of this research work is to optimize the sustainable mechanical properties of high-volume fly ash-based steel fiber concrete using Taguchi and multi-regression analysis. In the present research work, four factors and four levels are considered for the determination and optimization of the mechanical properties of the specimens. These factors are fly ash class F, cement paste, super-plasticizer, and steel fibers. For the concrete mixture, fly ash is used 30%, 45%, 60%, and 70% by weight of cement for levels 1, 2, 3, and 4, respectively. The cement paste is used 70%, 55%, 40%, and 30% for level 1, 2, 3, and 4, respectively. The super-plasticizer is used 1% for levels 1 and 2 and 1.5% for levels 3 and 4 by weight of cement. The steel fiber is used 0% for levels 1 and 2 and 0.5% for level 3 and 4 of total concrete. An overall number of 16 series of experiments with each replicates by three times are conducted at 7, 28, 56, and 90 days of water curing regimes. However, the effects of each factor on strength properties of the high-strength–high-volume fly ash steel fiber concrete specimens are considered.

Taguchi approach

The Taguchi technique has been usually selected to make the design criterion better as this methodical progress can considerably reduce the overall investigational expenditure [32, 33]. In the Taguchi approach, an authoritative tool provides an efficient approach to optimize designs for performance and quality. The response surface method has been developed and optimized in both the research and the industrial field [34]. The signal-to-noise (S/N) ratio was determined by using Eq. (1). The 'larger-the-better' performance characteristics are adopted for evaluating the optimal mixture of factor levels which correspond to the highest calculated S/N ratio.

Table 1 Chemical properties of OPC and fly ash

Oxide composition	CaO	SiO_2	Fe_2O_3	Al_2O_3	MgO	SO_3	Na_2O	Chlorides, % by mass	Loss of ignition
OPC %	63.28	20.46	4.05	5.64	3.14	2.50	0.69	0.01	2.72
Fly ash,%	10.2	45.5	16.4	25.8	0.9	1.94	0.71	0.05	3.85

Table 2 Physical properties of coarse and fine aggregate

Property	Coarse aggregate	Fine aggregate (river sand)
Fineness modulus	6.2	2.65
Water absorption %	0.76	2.21
Specific gravity	2.71	2.67
Size, mm	9.5- 12.5	4.75

$$\text{Larger} - \text{the} - \text{better} S/N = -10 \log_{10} \left[\frac{1}{n} \sum_{1}^{n} \frac{1}{Y_i^2} \right] \quad (1)$$

where S/N is performance data, 'n' is the number of repetitions for an investigational mixture, and Y_i is a performance value of the ith experimentation.

Methodology

Materials and compositions

The experimental work is carried out on concrete specimens, consisting of fly ash and ordinary Portland cement (OPC) as binder material as confirmed with Bureau of Indian Standard (BIS) 12,269 [35]. High-performance retarding superplasticizer and crimped steel fibers are used to achieve good workability of concrete mix. The chemical compositions of fly ash and OPC are shown in Table 1 confirmed with BIS 3812 [36].

In the laboratory, a pan mixer is used for preparing the concrete mixtures. The properties of fine aggregate and crushed coarse aggregate are found out and shown in Table 2. The physical properties of coarse and fine aggregate are checked as per the guidelines given by BIS 383 [37]. The potable water is used as recommended by BIS 456 [38].

Design of Experiment (DOE)

The choice of controlled factors is a significant stage in the DOE. The compressive and splitting tensile strength investigation parameters are mostly dependent on fabricating conditions employed in the casting of concrete. DOE is preferred for the most excellent mixture of control parameters so that the product will get most of the response in terms of S/N ratios. Taguchi design method was used to reach the maximum numeral of experiments except for repeating the procedure [39]. Robust design, i.e., Taguchi parameter design, can be employed to achieve robust reliability, specifically to make a product's reliability insensitive to factors that are hard or impossible to control [40]. In this study, Taguchi L_{16} experimental design applied to optimize the mechanical properties of concrete using four factors and four levels is given in Table 3.

According to Murumi and Gupta [41], 45% and above fly ash concrete denotes high-volume fly ash concrete. Therefore, the percentage of fly ash selected for this research work is 30%, 45%, 60%, and 70%. The proposed standard L_{16}

Table 3 Input parameters with their levels used to proposed sixteen experiments

Controlled factors	Unit	Level 1	Level 2	Level 3	Level 4
A: Fly ash	%	30	45	60	70
B: Cement paste	Kg/m^3	335	263	191	143
C: Super-plasticizer	Kg/m^3	3.35	2.63	2.865	2.145
D: Steel fibers	Kg/m^3	0	0	11.76	11.76

Table 4 Proposed L_{16} (OA) series of mixtures by Taguchi approach for the present study

Series of experiment	Level 1 (fly ash)	Level 2 (cement)	Level 3 (super-plasticizer)	Level 4 (crimped steel fibers)
A1	1	1	1	1
A2	1	2	2	2
A3	1	3	3	3
A4	1	4	4	4
A5	2	1	2	3
A6	2	2	1	4
A7	2	3	4	1
A8	2	4	3	2
A9	3	1	3	4
A10	3	2	4	3
A11	3	3	1	2
A12	3	4	2	1
A13	4	1	4	2
A14	4	2	3	1
A15	4	3	2	4
A16	4	4	1	3

Table 5 Actual DOE of mixture proportions for L_{16} OA

Series of experiment	Factors			
	Fly ash %	Cement Kg/m^3	Super-plasticizer Kg/m^3	Steel fibers Kg/m^3
A1	30	335	3.35	0
A2	30	263	2.63	0
A3	30	191	2.86	11.76
A4	30	143	2.15	11.76
A5	45	335	2.63	11.76
A6	45	263	3.35	11.76
A7	45	191	2.15	0
A8	45	143	2.86	0
A9	60	335	2.86	11.76
A10	60	263	2.15	11.76
A11	60	191	3.35	0
A12	60	143	2.63	0
A13	70	335	2.15	0
A14	70	263	2.86	0
A15	70	191	2.63	11.76
A16	70	143	3.35	11.76

Table 7 Fresh properties of high-strength–high-volume fly ash-based with and without steel fiber concrete

Series of experiment	Air temp. (ºC)	Concrete temp. (ºC)	Slump (mm)	Unit weight (Kg/m^3)
A1	26.1	18.9	105	2462
A2	25.8	20.2	95	2456
A3	25.7	19.5	115	2391
A4	25.8	21.5	125	2399
A5	24.9	20.5	105	2448
A6	24.2	22.5	115	2398
A7	24.8	23.2	127	2489
A8	25.1	18.7	114	2468
A9	24.9	19.2	105	2387
A10	23.2	20.3	122	2368
A11	22.8	21.6	128	2477
A12	21.9	20.1	122	2485
A13	22.4	18.7	110	2475
A14	23.5	19.6	129	2428
A15	23.6	18.8	120	2481
A16	24.5	20.1	115	2471

OA is shown in Table 4 for experimentation and optimization. Based on the L_{16} (4 × 4) OA, the required 16 concrete mixtures are illustrated in Table 5. The seventeenth mixture (A17) is prepared with 100% OPC, 0% fly ash, and 0% steel fiber as a control mix to know the target compressive strength.

Experimentation

For experimentation, class F fly ash is used to prepare concrete mixtures with advanced low viscosity retarding superplasticizer for a low water–binder ratio. The dosage of superplasticizer is taken 1.0% by mass of cement for levels 1 and 2. Further for achieving a specific slump, the dosage superplasticizer is increased to 1.5% for level 3 and 4. The various properties of the super-plasticizer are given in Table 6.

For one cubic meter batch of concrete, obtained mixture proportions from design are 30% to 70% of fly ash, 478 kg/m^3 of cement, 694 kg/m^3 of fine aggregate, and 1181 kg/m^3 of coarse aggregate, and W/C ratio is 0.33. The various fresh properties of high-strength–high-volume fly ash-based with and without steel fiber concrete are calculated from experimentation and are given in Table 7.

Table 6 Properties of super-plasticizer [42]

Properties	Super-plasticizer
Color appearance	Light yellow-colored liquid
pH	Minimum 6.0
Specific gravity (kg/*l*)	1.085
Chemical description	Based on a polycarboxylic ether polymer
Alkali substance	< 1.5 g Na_2O equivalent / liter of admixture
Recommended dosage	0.5 to 3.0 L/100 kg of cementitious material

All concrete mixing is done as per the standard procedure using a 1 m^3 pan mixer. The slump cone test is performed on fresh concrete according to the BIS 1199 [43]. After the slump cone test, three specimens are casted for each test as per the required dimensions. For the compressive test, the cubes are cast with dimensions of 150 × 150 × 150 mm; for the split tensile test, cylinders are cast with dimensions of 150 mm diameter and 300 mm height. For flexure, test beams are cast with dimensions of 100 × 100 × 500 mm. After 24 h ± 1 h of air curing, specimens are removed from the molds and placed for curing in potable water. After getting sufficient curing, the test specimens are removed from the curing tank and dried at room temperature. The standard test is performed on the specimens by the procedures given by the BIS 516 [44] at the age of 7, 28, 56, and 90 days.

The sixteen combinations are taken using four variables and four levels for the analysis. The four parameters are the percentage of fly ash (weight percentage), cement paste (percentage, kg/m^3), super-plasticizer (kg/m^3), and crimped steel fiber (kg/m^3) that all can be easily constrained. The influence of every parameter involving the compressive, flexural, and split tensile strength at 7, 28, 56, and 90 days is determined by using multiple regression analyses. By using Taguchi experimental design, the statistical investigation is carried out on the experimental data achieved through Minitab 18.0.

Thus, through the Taguchi approach, sixteen combinations with three replicates by each run are utilized for further analysis to determine the optimal parameters for mechanical properties of high-volume fly ash with a steel fiber mixture.

Results and discussion

The strength properties continuously cured concrete specimens at the age 7, 28, 56, and 90 days and are presented in Table 8. The mechanical properties at different curing days are presented in terms of the effect of S/N ratios in the following subsections.

S/N ratios of mechanical properties, i.e., compressive, splitting tensile and flexural strengths, are calculated by using Eq. 1. The results of the response table in terms of S/N ratios obtained with L_{16} OA are shown in Tables 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 , 21, 22, 23, 24. The response table shows the results of compressive, split tensile, and flexural strengths for each mixture. The regression analysis is also done to form a linear model of the obtained results and found the optimum combination for high-strength–high-volume fly ash steel fiber concrete. The rank of each factor is also calculated by the response of each level. To maximize the strengths, 'larger-the-better' category of control characteristic is studied of fly ash-based steel fiber concrete.

Compressive strength

The importance of compressive strength input parameters response of S/N ratios at 7 days is shown in Table 9. Fly ash, cement paste, super-plasticizer, and steel fibers were considered as control factors for optimizing the compressive, splitting tensile, and flexure strengths of concrete. Superplasticizer shows a significant role and its rank is one continued by the rank of cement paste, fly ash, and steel fibers.

Figure 1a demonstrates the response results of input parameters at 7 days. From the response results, the optimal combination for 7 days is A1; 30% fly ash, B1; 70% cement paste, C2; 1% super-plasticizer, and D1; 0.5% steel fibers maximum compressive strength.

The effect of each parameter on the development of compressive strength for 7 days is presented in Fig. 1a, which has been based on the exploitation of the data of Table 1. For example, the compressive strength of 7 days of factor A, level 1 is (49.13 + 49.94 + 39.69 + 36.96) /4. The parameter seems to have a significant impact on the development of the compressive strength due to the percentage variation of mix proportions of control factors. It must be noted that the effect of each parameter on the development of various strength for the age of 7, 28, 56, and 90 days can be found out within the specified range with their chosen levels and for the specific mix proportions. The multi-regression equation for 7 days on optimized combination is calculated and is given in Eq. 2.

$$
\begin{aligned}
7\text{ days} = 54.94 &- 0.0898\text{ fly ash (kg)} \\
&- 0.220\text{ cement paste (kg)} \\
&+ 1.395\text{ super-plasticzer(kg)} \\
&- 1.146\text{ fibers (kg)}
\end{aligned} \tag{2}
$$

The optimal combination conditions for achieving the highest compressive strength for 7 days are: fly ash 143 kg/m^3, cement paste 263 kg/m^3, super-plasticizer 2.63 kg/m^3, and no fibers. The optimized value of the compressive strength for a 95% confidence interval was predicted to be 48.64 MPa ± 3.1 MPa. To confirm the model prediction, concrete specimens with fly ash 143 kg/m^3, cement paste 335 kg/m^3, super-plasticizer 3.35 kg/m^3, and no fibers were prepared, appropriately cured for 7 days, and subjected to a compression test. The compressive strength was found to be 51.43 MPa, which falls within the predicted range.

Table 10 shows the response results input parameters at 28 days for compressive strength. Fly ash plays a vital role and its rank is one, followed by the position of steel fibers, super-plasticizer, and cement paste.

The effects of key parameters at 28 days on compressive strength are shown in Fig. 1b. At 28 days, maximum compressive strength is given by combination of A1; 30% fly ash, B1; 70% cement paste, C2; 1% super-plasticizer, and D1; 0.5% steel fibers. The multi-regression equation for 28 days on an optimized combination is calculated and given in Eq. 3.

$$
\begin{aligned}
28\text{ days} = 62.57 &- 0.298\text{ fly ash (kg)} \\
&- 0.715\text{ cement paste(kg)} \\
&+ 0.396\text{ super-plasticzer(kg)} \\
&+ 0.675\text{ fibers (kg)}
\end{aligned} \tag{3}
$$

Table 11 shows the response factors of input parameters showing maximum S/N ratios results on compressive strength, at 56 days. The above results show fly ash, cement paste, steel fibers, and super-plasticizer ranked 1, 2, 3, and 4, respectively.

At 56 days, the main effect of key parameters on compressive strength is shown in Fig. 1c. For maximum compressive strength, the combinations are by A_1; 30% fly ash, B_1; 70% cement paste, C_4; 2% super-plasticizer, and D_4; 0.5% steel fibers. Equation 4 shows maximum compressive strength at 56 days with corresponding input parameters by using multi-regression analysis as given below:

Table 8 Strength properties of high-strength–high-volume fly ash-based with and without steel fiber concrete at 7, 28, 56, and 90 days

Expt. series	Fly ash Kg/m^3	Cement Kg/m^3	Super-plasticizer Kg/m^3	Steel fibers Kg/m^3	Compressive strength (N/mm^2)				Split tensile strength (N/mm^2)				Flexural strength (N/mm^2)			
					7 days	28 days	56 days	90 days	7 days	28 days	56 days	90 days	7 days	28 days	56 days	90 days
A1	143	335	3.35	0	49.13	60.48	69.09	73.16	3.96	4.38	4.88	4.95	4.48	4.77	5.08	6.15
A2	143	263	2.63	0	49.94	54.41	62.87	67.86	3.86	5.17	5.51	5.97	4.13	5.81	6.76	5.92
A3	143	191	2.86	11.76	39.69	56.45	66.58	71.85	1.78	2.98	3.05	4.32	3.84	4.84	6.21	6.53
A4	143	143	2.15	11.76	36.96	55.73	67.59	72.86	1.24	1.53	1.85	2.02	3.41	4.25	5.57	6.01
A5	215	335	2.63	11.76	48.06	51.55	62.93	68.16	3.22	3.82	4.65	5.19	3.68	4.67	6.64	6.98
A6	215	263	3.35	11.76	37.51	48.53	58.98	66.35	3.19	3.72	4.73	5.23	3.51	4.09	5.87	5.84
A7	215	191	2.15	0	38.08	45.18	53.68	61.86	1.45	1.94	2.41	3.32	2.92	3.56	5.97	6.26
A8	215	143	2.86	0	35.88	46.59	54.46	62.57	2.83	3.89	5.12	6.01	3.41	4.25	5.21	6.95
A9	287	335	2.86	11.76	42.42	43.9	62.31	69.25	3.01	3.58	4.72	5.01	4.29	5.03	5.86	6.48
A10	287	263	2.15	11.76	35.63	44.75	54.41	65.49	3.35	4.28	4.88	5.51	3.61	4.71	5.58	7.29
A11	287	191	3.35	0	39.65	46.8	55.45	58.81	3.46	4.11	4.83	5.68	3.19	3.82	5.4	6.96
A12	287	143	2.63	0	44.46	52.57	55.23	62.17	3.59	4.47	5.16	5.97	2.89	3.24	5.97	6.51
A13	335	335	2.15	0	41.65	49.38	64.35	70.41	2.64	3.42	3.87	4.87	3.16	4.25	5.49	5.57
A14	335	263	2.86	0	40.78	50.25	55.65	62.58	3.38	4.05	4.53	5.45	3.94	4.27	5.61	6.31
A15	335	191	2.63	11.76	45.55	47.32	53.69	58.65	1.71	2.11	2.35	3.21	3.56	3.26	5.28	7.61
A16	335	143	3.35	11.76	34.89	41.62	54.75	59.77	1.55	1.88	2.05	2.32	3.09	3.79	5.98	6.84

Table 9 Response table of S/N ratios for compressive strength at 7 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	32.78	33.10	32.03	32.65
2	31.96	32.17	33.43	32.36
3	32.13	32.18	31.96	31.87
4	32.16	31.57	31.60	32.14
Delta	0.82	1.54	1.83	0.78
Rank	3	2	1	4

$$\begin{aligned}56\text{ days } = {} & 69.52 - 0.289\text{ fly ash (kg)} \\ & - 2.062\text{ cement paste (kg)} \\ & + 1.803\text{ super-plasticzer(kg)} \\ & + 0.707\text{ fibers(kg)}\end{aligned} \quad (4)$$

The significance of key parameters and their response on compressive strength at 90 days is illustrated in Table 12 along with present rank one for fly ash, subsequent by the rank of cement paste, super-plasticizer, and steel fibers.

The effect of each parameter on compressive strength is shown in Fig. 1d. The response of S/N ratios on compressive strength maximizing response at 90 days is observed. For maximizing response, i.e., compressive strength and its corresponding input parameters are given as: A_1; 30% fly ash, B1; 70% cement paste, C4; 2% super-plasticizer, and D4; 0.5% steel fibers. For 90 days, the obtained Eq. 5 with multi-regression is given below:

$$\begin{aligned}90\text{ days} = {} & 72.83 - 0.265\text{ fly ash (kg)} \\ & - 2.048\text{ cement paste (kg)} \\ & + 1.769\text{ super-plasticzer (kg)} \\ & + 0.691\text{ fibers (kg)}\end{aligned} \quad (5)$$

The quantitative impact of each control factor on the development of compressive strength at 7, 28, 56, and 90 days was estimated independently through multi-regression models. Figure 1b, c, d shows the compressive strength increase for 28, 56, and 90 days when fly ash content increases. Table 13 presents the studied parameters and their resultant ranks contribution to the compressive strength.

The multi-regression equations were obtained from Minitab 18.0 software using all given input parameters. From the multi-regression analysis, the highest percentage of fly ash and cement paste is found from level 2. Table 13 shows the four parameters and the importance of testing ages for compressive strength. The S/N ratio gives the modified input parameters on the basis of the influence of output variables on input parameters. The rank is assigned to all parameters based on the contribution and significance of individuals in output variables. Different testing ages like 7, 28, 56, and 90 days are taken into account to find the resultant rank of parameters, where fly ash is a major influence parameter having rank one subsequent with the order of cement paste, super-plasticizer as well as steel fibers for compressive strength. The most influencing parameter is binder content (both fly ash and cement). The mix A3, A4, and A9 showed better results at 56 and 90 days age of testing. The inclusion of higher fly ash content significantly improves the strength of the concrete. It also found that the analytical results are fairly agreed with experimental results. The investigation of resultant rank for input parameters on compressive strength at testing ages 7, 28, 56, and 90 days are listed in Tables 9, 10, 11, and 12, respectively. However, for analyzing and optimizing the compressive strength of concrete, Fig. 1 shows the mean values in terms of the S/N ratio for all the four control factors. When amount of fly ash is increased in the concrete, the normal compressive strength of the 28 days (except A8) is reduced for mixtures of investigational series, viz. A4, A6, A8, and A16. It is marked that in 28 and 56 days, cement paste 55% in level 2 has a drastic effect on compressive strength properties. Compressive strength improved for mixes A3, A4, and A9 with concrete age at 56 and 90 days, while mixture A16 is shown at 7 days achieved low compressive strength, but improved on 56 and 90 days. The large compressive strength of mixture A15 can follow the large content of fly ash through its subsequent percentage of super-plasticizer, steel fiber content of this mix at 7, 28 curing days and slowly developed at 56 and 90 days. From Fig. 1a, b and c, the response index for levels 3 and 4, i.e., 45 and 60% fly ash content mixtures for 7, 28, and 56 days after curing, the resultant is maximum compressive strength for mixtures A3, A4, and A9. Factor B, i.e., cement paste shows the superior response effect on compressive strength than factors C and D at the age of 7 and 28 days. Figure 1 presents that the compressive strengths for mixtures of concrete are steadily developed from 28; 56 to 90 days because of fly ash amount vary from 45 to 70% of OPC mix.

Split tensile strength

The effectiveness of the Taguchi method for optimizing the splitting tensile strength properties was estimated independently through multi-regression analysis. The response factor for split tensile strength at 7 days is shown in Table 14. The main effect of key parameters on split tensile strength shows that cement paste plays a significant role and its rank is one followed by the rank of fly ash, steel fibers, and super-plasticizer. The optimal combination conditions for achieving the highest split tensile strength for 7 days are fly ash 143 kg/m^3, cement paste 191 kg/m^3, super-plasticizer 2.86 kg/m^3, and the fiber content of 11.76 kg/m^3. The fly ash

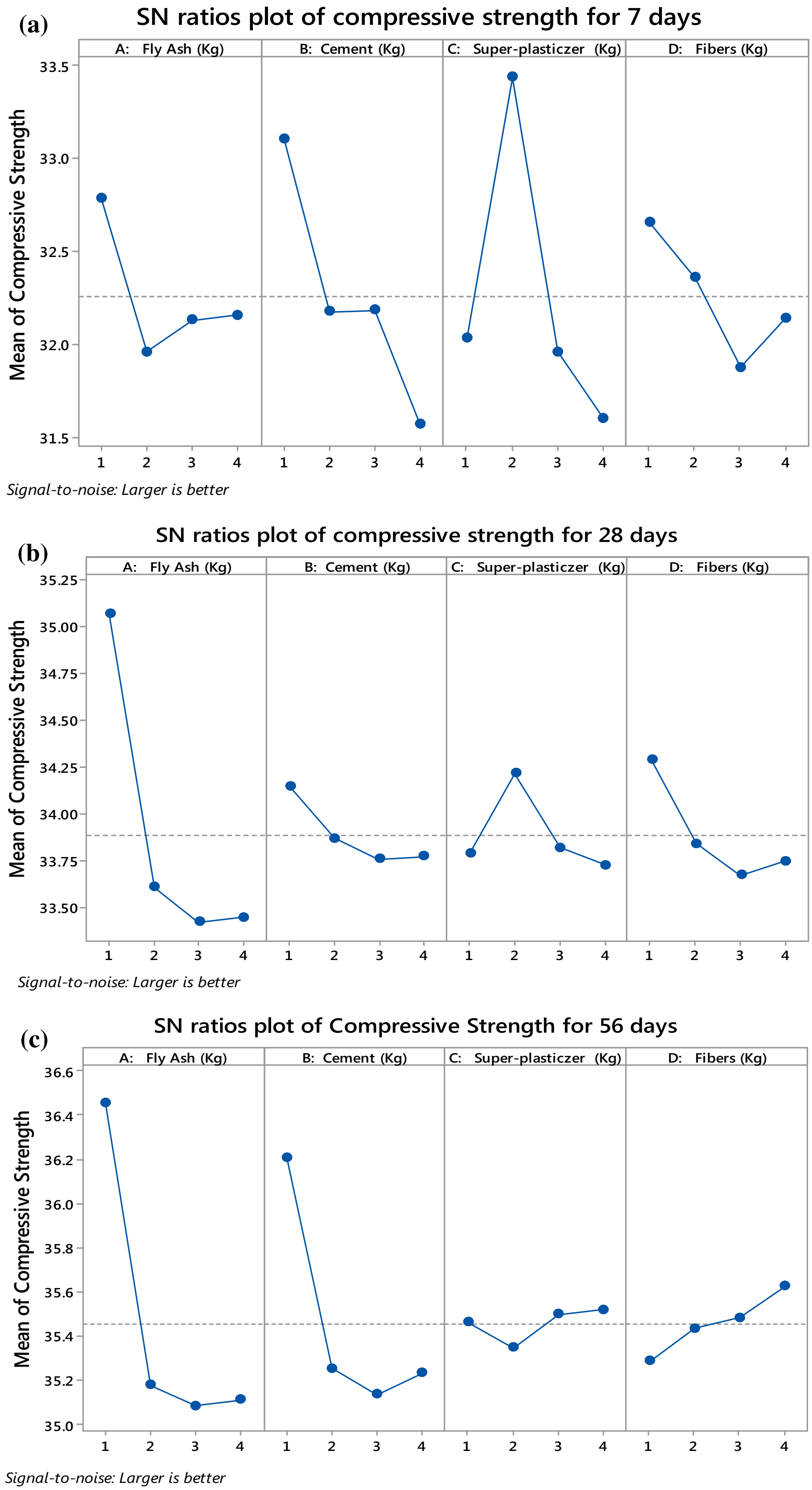

Fig. 1 Effects of parameters on mean S/N ratio for compressive strength

Fig. 1 (continued)

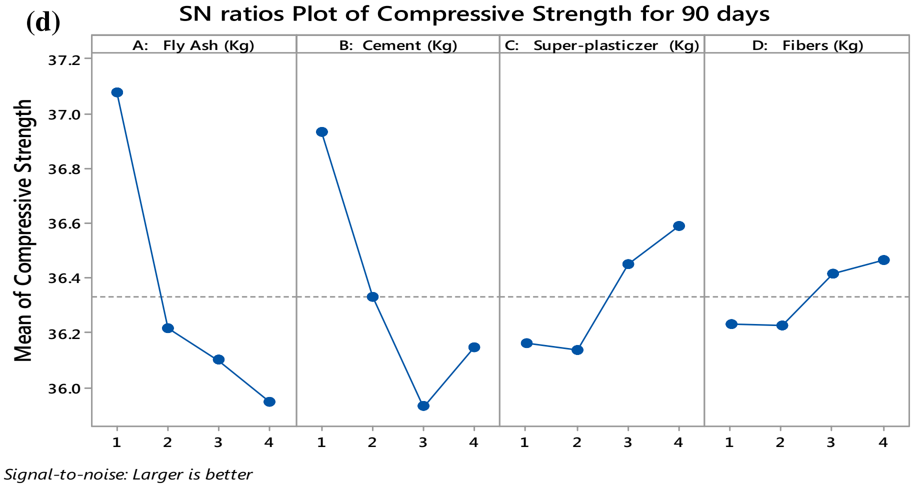

Table 10 Response table of S/N ratios for compressive strength at 28 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	35.08	34.15	33.79	34.29
2	33.61	33.87	34.22	33.84
3	33.42	33.76	33.82	33.67
4	33.45	33.77	33.73	33.75
Delta	1.65	0.39	0.49	0.62
Rank	1	4	3	2

Table 11 Response table of S/N ratios for compressive strength at 56 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	36.46	36.21	35.46	35.28
2	35.18	35.25	35.35	35.43
3	35.08	35.13	35.50	35.48
4	35.11	35.23	35.52	35.63
Delta	1.37	1.07	0.17	0.34
Rank	1	2	4	3

and cement paste is the most influencing factors for strength development.

The performance of input key parameters on split tensile strength at 7 days is shown in Fig. 2a. It is observed that A3; 60% fly ash, B2; 55% cement paste, C2; 2% superplasticizer, and D2; 0.5% steel fibers have a maximum split tensile strength.

Table 12 Response table of S/N ratios for compressive strength at 90 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	37.07	36.93	36.16	36.23
2	36.22	36.33	36.13	36.23
3	36.10	35.93	36.45	36.41
4	35.94	36.14	36.59	36.47
Delta	1.13	1.00	0.45	0.24
Rank	1	2	3	4

Table 13 Resultant ranks of testing ages for compressive strength

Parameters	A: Fly ash	B: Cement paste	C: Super-plasticizer	D: Fibers
7 days	3	2	1	4
28 days	1	4	3	2
56 days	1	2	4	3
90 days	1	2	3	4
Resultant rank	1	2	3	4

Table 14 Response table of S/N ratios for split tensile strength at 7 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	7.641	10.029	9.154	9.215
2	8.124	10.722	9.413	9.995
3	10.489	5.919	8.548	7.368
4	6.869	6.453	6.007	6.544
Delta	3.620	4.802	3.405	3.451
Rank	2	1	4	3

Fig. 2 Effects of parameters on mean S/N ratio for split tensile strength

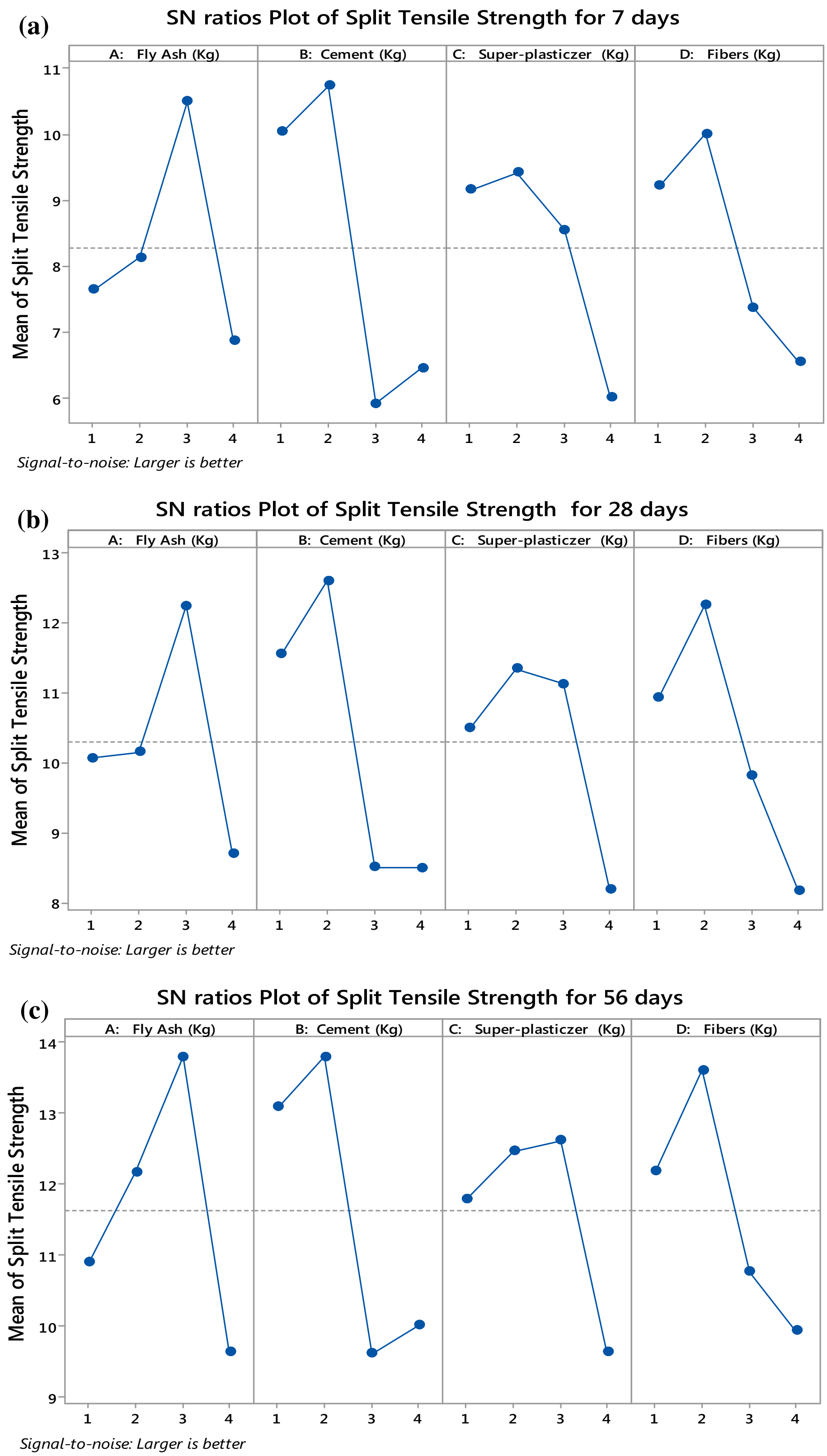

Fig. 2 (continued)

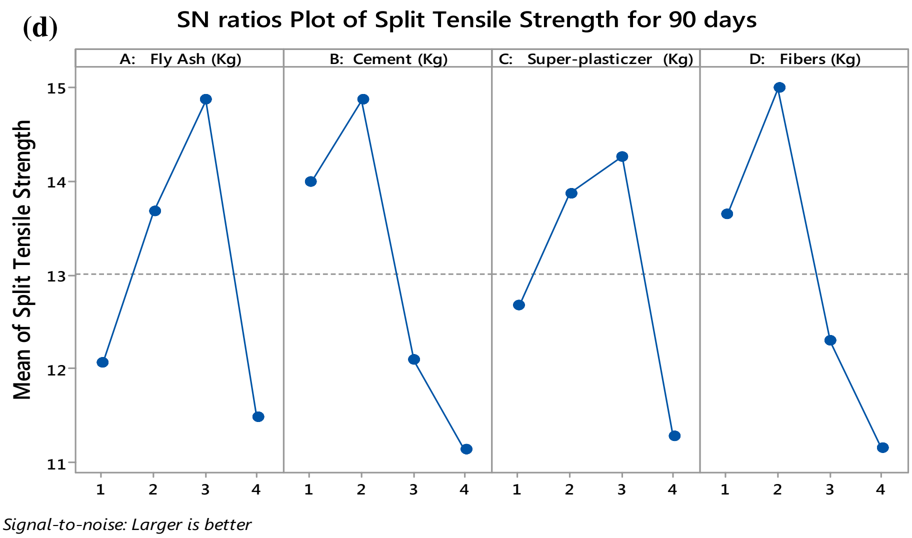

Table 15 Response table of S/N ratios for split tensile strength at 28 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	10.069	11.557	10.500	10.935
2	10.152	12.615	11.351	12.257
3	12.247	8.501	11.128	9.809
4	8.700	8.496	8.190	8.167
Delta	3.548	4.119	3.161	4.090
Rank	3	1	4	2

Table 16 Response table of S/N ratios for split tensile strength at 56 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	10.905	13.088	11.795	12.196
2	12.168	13.803	12.462	13.610
3	13.795	9.607	12.618	10.760
4	9.633	10.004	9.627	9.935
Delta	4.162	4.196	2.991	3.675
Rank	2	1	4	3

At 7 days, the obtained multi-regression Eq. 6 of split tensile strength is calculated as given below:

$$\begin{aligned} 7\text{ days} = {} & 5.426 - 0.016\text{ fly ash (kg)} \\ & - 0.0406\text{ cement paste (kg)} \\ & - 0.0120\text{ super-plasticzer(kg)} \\ & - 0.0295\text{ fibers (kg)} \end{aligned} \tag{6}$$

Table 15 shows the response results obtained from all factors at each level at 28 days on split tensile strength.

Table 17 Response table of S/N ratios for split tensile strength at 90 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	12.06	13.99	12.66	13.64
2	13.67	14.86	13.87	14.98
3	14.86	12.09	14.25	12.29
4	11.48	11.13	11.28	11.15
Delta	3.38	3.73	2.98	3.83
Rank	3	2	4	1

For split tensile, cement paste performs a vital role and its rank is one followed by the rank of steel fibers, fly ash, and super-plasticizer.

The main attainment of key parameters on split tensile strength at duration of 28 days is demonstrated in Fig. 2b. It is observed that A3; 60% fly ash, B2; 55% cement paste, C2; 1% super-plasticizer, and D2; 0.5% steel fibers maximize the response for split tensile strength. For 28 days, on optimized multi-regression Eq. 7 is calculated and given as below.

$$\begin{aligned} 28\text{ days} = {} & 6.35 - 0.0134\text{ fly ash (kg)} \\ & - 0.0409\text{ cement paste (kg)} \\ & - 0.0246\text{ super-plasticzer (kg)} \\ & - 0.0383\text{ fibers (kg)} \end{aligned} \tag{7}$$

Table 16 presents the performance effect of input parameters on split tensile strength demonstrating maximum S/N ratios achieved from all factors at each level for 56 days. Similar patterns of compressive strength are observed at 56 days curing period. Cement paste plays a significant role and its rank is one followed by the rank of fly ash, steel fibers, and super-plasticizer. As per the response parameter

Table 18 Resultant ranks of testing ages for split tensile strength

Parameters	A: Fly ash	B:Cement	C: Super-plasticizer	D: Fibers
7 days	2	1	4	3
28 days	3	1	4	2
56 days	2	1	4	3
90 days	3	2	4	1
Resultant rank	2	1	4	3

Table 19 Response tables of S/N ratios for flexural strength at 7 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	11.93	11.66	10.95	10.87
2	10.35	11.57	10.97	10.76
3	10.77	10.52	11.82	10.99
4	10.68	10.09	10.22	11.31
Delta	1.58	1.57	1.60	0.55
Rank	2	3	1	4

from Tables 14, 15, and 16, the maximum split tensile strength is found due to cement paste.

Figure 2c presents the effect of input parameters on the mean S/N ratio for split tensile strength at 28 days is established. A3; 60% fly ash, B2; 55% cement paste, C3; 1% super-plasticizer, and D2; 0.5% steel fibers give response maximum split tensile strength. The resultant Eq. 8 is obtained with multi-regression for 56 days and is calculated as given below.

$$\begin{aligned}56\text{ days} = 7.10 &- 0.0120\text{ fly ash (kg)}\\ &- 0.0105\text{ cement paste (kg)}\\ &- 0.0267\text{ super-plasticzer (kg)}\\ &- 0.0367\text{ fibers (kg)}\end{aligned} \tag{8}$$

The best combination for achieving the maximum split tensile strength for 56 days are: fly ash 143 kg/m^3 cement paste 191 kg/m^3, super-plasticizer 2.86 kg/m^3, and steel fibers 11.76 kg/m^3. The optimized value of the split tensile strength for a 95% confidence interval was predicted to be 3.89 MPa ± 0.5 MPa. For the validation of the predicted model, cylinder specimens are casted with fly ash 143 kg/m^3, cement paste 191 kg/m^3, super-plasticizer 2.86 kg/m^3, and steel fibers 11.76 kg/m^3. After 56 days of curing split tension, the test was performed and found 4.07 MPa, which falls within the predicted range.

Table 17 illustrates the importance of key parameters on split tensile strength for maximizing the response at 90 days and also demonstrates rank one as steel fiber, subsequent by the rank of cement paste, fly ash, and super-plasticizer.

The effect of each response parameter is shown in Fig. 2d. The result of S/N ratios on split tensile strength maximizing response at 90 days is observed. For maximizing response, i.e., compressive strength given by A3; 60% fly ash, B2; 55% cement paste, C3; 2% super-plasticizer, and D2; 0.5% steel fibers. For 90 days, the resultant of the optimized combination is shown by Eq. 9 using a multi-regression analysis as given below.

$$\begin{aligned}90\text{ days} = 8.36 &- 0.0450\text{ fly ash (kg)}\\ &- 0.0418\text{ cement paste (kg)}\\ &- 0.0173\text{ super-plasticzer(kg)}\\ &- 0.0246\text{ fibers (kg)}\end{aligned} \tag{9}$$

Table 18 shows the four parameters and their importance for different testing ages of split tensile strength. The effect of parameters on mean S/N ratios on split tensile strength in terms of rank is assigned to all parameters based on the contribution of individuals in output results. Testing ages 7, 28, 56, and 90 days are taken into consideration to find the resultant rank of parameters. The cement is a major influence, having rank one followed by the rank of fly ash, steel fibers, and super-plasticizer for split tensile strength. Figure 2 shows that the effect of parameters on mean S/N ratios on split tensile strength at the age of 7, 28, and 56 days trends is similar even though values of character testing are different. Similar trends are found in the mix designs A5, A6, A8, A11, and A12, which have the maximum split tensile strength values, but mixture A8 has the least significant split tensile strength at 7 days than mixes A5, A6, A11, and A12. Split tensile strength value is in the range of 1.24 to 6.01 for corresponding input parameters. Tables 14 15, 16 and 17 show that at 28 days, 60% fly ash and 55% cement paste give a better result than 7 days. Figure 2 shows that increasing the fly ash content for 45% cement paste the split tensile strength is increasing. Table 8 shows that the gradual increase in splitting tensile strength is up to the age of 90 days for all concrete mixtures. At 7, 28, and 56 days, fly ash and cement paste is the most influencing due to pozzolanic action while eliminating calcium hydrate crystals which reduces voids and refining both grains and pores. It is observed that the second most influencing factor is superplasticizer with 2% weight of cement paste.

Flexural strength

The importance of key parameters on flexural strength response for 7 days is demonstrated in Table 19. The main effect of input parameters on flexural strength shows that super-plasticizer performs a significant role and rank is one, continued by the rank of fly ash, cement paste, and steel fibers.

Figure 3a presents the main effect of S/N ratios on flexural strength for 7 days duration. The response of flexural

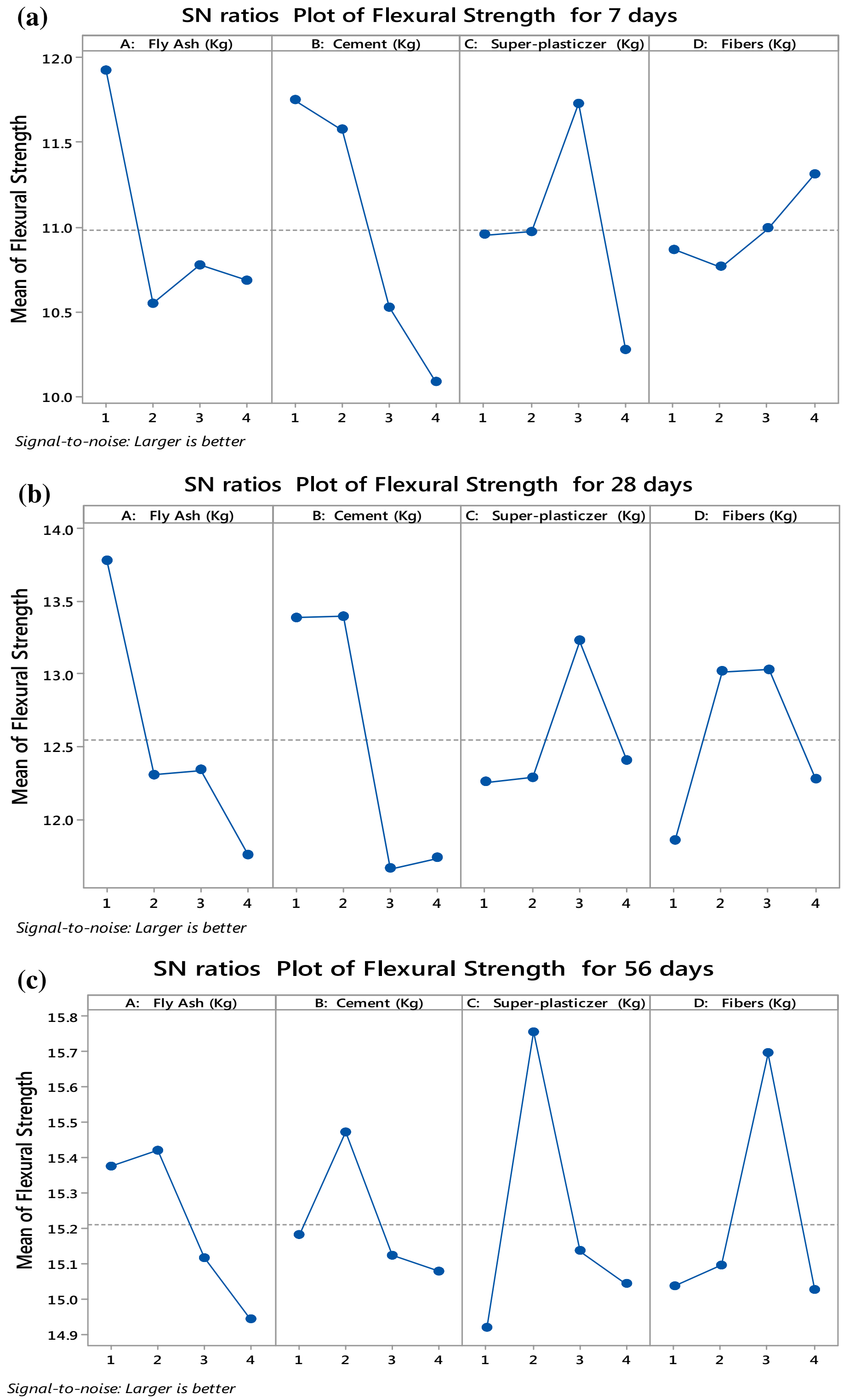

Fig. 3 Effects of parameters on mean S/N ratio for flexural strength

strength is given by A1; 30% fly ash, B1; 70% cement paste, C3; 1% super-plasticizer, and D4; 0.5% steel fibers.

For 7 days flexural strength, the multi-regression Eq. 10 on optimized combination is calculated and given as below.

Fig. 3 (continued)

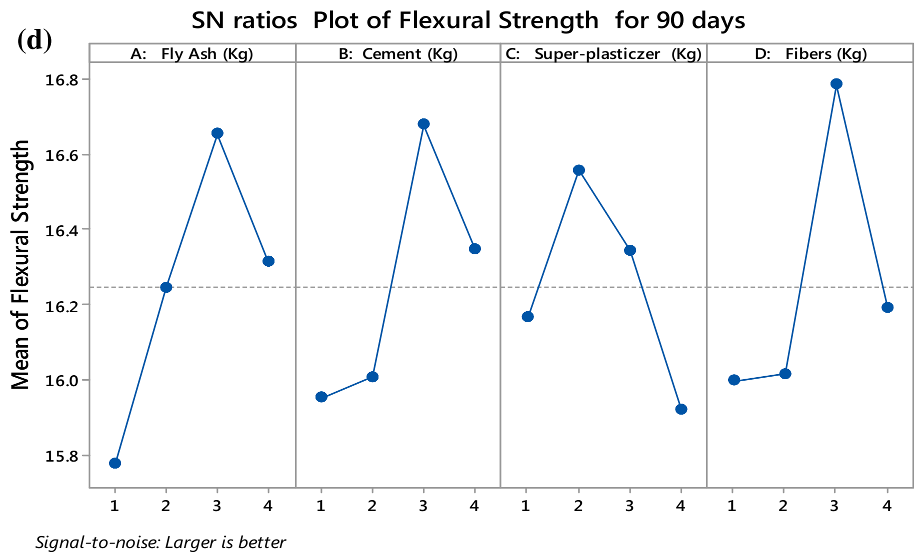

Table 20 Response table of S/N ratios for flexural strength at 28 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	13.78	13.39	12.25	11.85
2	12.30	13.40	12.29	13.02
3	12.34	11.66	13.23	13.03
4	11.75	11.73	12.41	12.27
Delta	2.03	1.74	0.97	1.17
Rank	1	2	4	3

Table 21 Response table of S/N ratios for flexural strength at 56 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	15.37	15.18	14.92	15.03
2	15.42	15.49	15.77	15.09
3	15.11	15.12	15.13	15.69
4	14.92	15.01	15.01	15.03
Delta	0.50	0.48	0.85	0.67
Rank	3	4	1	2

$$\begin{aligned}\text{7 days} = &4.589 - 0.0146 \text{ fly ash (kg)} \\ &- 0.0252 \text{ cement paste (kg)} \\ &+ 0.0226 \text{ super-plasticzer (kg)} \\ &+ 0.0488 \text{ fibers (kg)}\end{aligned} \tag{10}$$

Table 20 shows that the fly ash and cement paste are the most significant factor that affects the flexural strength. Fly ash plays very significant role and it stands at rank one followed by the rank of cement paste, steel fibers and super-plasticizer improves response on flexural strength.

Table 22 Response table of S/N ratios for flexural strength at 90 days

Level	A: Fly ash (Kg)	B: Cement (Kg)	C: Super-plasticizer (Kg)	D: Fibers (Kg)
1	15.77	15.95	16.16	16.00
2	16.24	16.01	16.56	16.01
3	16.65	16.68	16.34	16.78
4	16.31	16.35	15.92	16.19
Delta	0.88	0.73	0.64	0.79
Rank	1	3	4	2

The effect of each parameter on the development of flexural strength for 28 days is presented in Fig. 3b. For example, the flexural strength of 28 days of factor A, level 1 is (4.48 + 4.13 + 3.84 + 3.41) /4. The response of all parameters in terms of S/N ratios is shown in Fig. 3b. It is observed that the effect of S/N ratios on maximizing response of flexural strength is at 28 days. The optimal combination of input parameters for flexural strength is observed as; A1; 30% fly ash, B2; 70% cement paste, C3; 2% super-plasticizer, and D3; 0.5% steel fibers. For 28 days, the optimized combination is calculated by multi-regression analysis and it is given in Eq. 11 as below.

$$\begin{aligned}\text{28 days} = &5.568 - 0.0602 \text{ fly ash (kg)} \\ &- 0.0556 \text{ cement paste (kg)} \\ &+ 0.0580 \text{ super-plasticzer(kg)} \\ &+ 0.0560 \text{ fibers (kg)}\end{aligned} \tag{11}$$

The best possible combination for 28 days maximum flexural strength is fly ash 143 kg/m^3, cement paste 191 kg/m^3, super-plasticizer 2.86 kg/m^3, and steel fibers 11.76 kg/m^3. The optimized value of the flexural strength for a 95%

Table 23 Resultant ranks of testing ages for flexural strength

Parameters	A: Fly ash	B: Cement	C: Super-plasticizer	D: Fibers
7 days	2	3	1	4
28 days	1	2	4	3
56 days	3	4	1	2
90 days	1	3	4	2
Resultant Ranks	1	3	4	2

confidence interval was predicted to be 4.96 MPa ± 0.5 MPa. In order to confirm the model prediction, concrete specimens with fly ash 143 kg/m^3, cement paste 191 kg/m^3, super-plasticizer 2.86 kg/m^3, and steel fibers 11.76 kg/m^3 were prepared, appropriately cured for 28 days, and subjected to flexural test. The flexural strength was found to be 5.18 MPa, which falls within the predicted range.

Table 21 presents the significance of key parameters on flexural strength for maximizing response at the age of 56 days. The main effect of input parameters on the flexural strength of super-plasticizer shows the rank one and is followed by the rank of steel fibers, fly ash, and cement paste.

Figure 3c shows the main effect of each parameter in terms of S/N ratios. At 56 days, the effect of S/N ratios maximizes the response of flexural strength. For maximizing response, flexural strength is given by A2; 45% fly ash, B2; 55% cement paste, C2; 1% super-plasticizer, and D3; 0.5% steel fibers. The resultant multi-regression Eq. 12 at 56 days is calculated and is given as below.

$$\begin{aligned} 56\text{ days } &= 6.165 - 0.0116\text{ fly ash (kg)} \\ &- 0.010\text{ cement paste (kg)} \\ &+ 0.052\text{ super-plasticzer(kg)} \\ &+ 0.035\text{ fibers (kg)} \end{aligned} \tag{12}$$

The importance of key parameters on flexural strength at 90 days is shown in Table 22. The main input parameter on the performance result of flexural strength maximizing the flexural strength of concrete is studied. The first rank of fly ash plays a vital role and is continued by the rank of steel fibers, cement paste, and super-plasticizer. The performance of each parameter on flexural strength is shown in Fig. 3d. It is observed that the response of S/N ratios on flexural strength is highest at the age of 90 days for all concrete mixtures. For maximizing the response, i.e., flexural strength is given by A3; 60% fly ash, B3; 40% cement paste, C2; 1% super-plasticizer, and D3; 0.5% steel fibers.

In flexural strength, at 90 days response result, steel fibers are more important than cement paste and fly ash. In other words, the mean S/N ratio of steel fibers is 16.78 which is higher than other ratios. For 90 days, the optimized combination of input parameters is calculated by multi-regression analysis and is given in Eq. 13 as below.

$$\begin{aligned} 90\text{ days } &= 5.676 + 0.052\text{ fly ash (kg)} \\ &+ 0.051\text{ cement paste (kg)} \\ &- 0.068\text{ super-plasticizer(kg)} \\ &+ 0.109\text{ fibers (kg)} \end{aligned} \tag{13}$$

From Table 23, the fly ash and steel fibers are positively affecting on development of flexural strength. For maximizing the flexural strength, fly ash plays a vital role and is continued by the rank of steel fibers, cement paste, and super-plasticizer. The response effect of parameters on flexural strength in terms of rank is assigned to all parameters based on the contribution of individual parameters on the output result. The S/N ratio related to the evaluated flexural strength shows the deviation of the performance on different days. The response ranks with parameters are given in Tables 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 , 21, 22, 23. At 90 days, for 60% fly ash, 40% cement paste, 0.5% steel fibers, and 2% super-plasticizer. At 28 and 90 days, the flexural strength of the steel fiber-based high-strength–high-volume fly ash concrete is comparable to OPC concrete. Both split tensile strengths and flexural strength of high-strength high-volume fly ash are based on with and without steel fiber concrete developed with increasing concrete age and is given in Table 8. Compared to the control mixture, the steel fiber-based concrete mixes with large content of fly ash had a lower rate of initial compressive strength achieved, equivalent tensile strength, and lower flexural strength. In compressive strength, cement paste content is more important than fly ash and steel fibers. In other words, the mean S/N ratio of cement paste content is 36.21 and 36.93 for 56 and 90 days, respectively, which are higher than other ratios.

Table 24 Confirmation of test result

	Compressive strength (N/mm^2)			Split tensile strength (N/mm^2)			Flexural strength (N/mm^2)		
Days	Experimental	Analytical	% Error	Experimental	Analytical	% Error	Experimental	Analytical	% Error
7	51.68	53.79	3.86	4.19	4.41	4.98	4.71	4.94	4.65
28	62.82	64.38	2.42	4.70	4.92	4.47	5.26	5.49	4.18
56	71.24	73.44	2.99	5.74	5.96	3.69	6.98	7.2	3.05
90	75.84	77.29	1.87	6.26	6.49	3.54	7.83	8.09	3.21

On the other hand, in splitting tensile strength and flexural strength cement paste and fly ash are playing, respectively, the most significant role. Therefore, Minitab 18.0 suggests a mixture design with 30% fly ash, 70% cement paste content, 2% super-plasticizer, and 0.5% steel fibers for all mechanical properties as the optimum design.

Confirmation tests

To validate the experimental and analytical results, the confirmation test is conducted. The confirmation results of the optimized compressive, split tensile, and flexural strength are accomplished from multi-regression analysis using Eqs. 2 to 13.

Table 24 presents the results of values of confirmation for compressive, split tensile, and flexural strength of experimental value and analytical value. The error related to the relationship along with the experimental value and analytical value of the regression model for strength is very less and is about 5%. Therefore, the developed regression model demonstrates a sufficient and competent approach to the compressive, split tensile, and flexural strength.

Conclusion

In this research, Taguchi L_{16} OA is employed for the design of experiments for substituting the OPC with fly ash material to reduce the experimental attempts. Using Taguchi and multi-regression analysis, the performance of sustainable high-strength high-volume fly ash-based with and without steel fiber concrete mixtures is optimized. Based on the present study, major conclusions are summarized below:

- The optimal combination of the input parameters for compressive strength is 30% fly ash, 70% cement paste, 2% super-plasticizer, and 0.5% crimped steel fibers.
- It is observed that the optimal combination of the input parameters for split tensile strength is 60% fly ash, 30% cement paste, 2% super-plasticizer, and without crimped steel fibers.
- The optimal combination for flexural strength is 30% fly ash, 60% cement paste, 2% super-plasticizer, and 0.5% crimped steel fibers. The mean strength of replicates between the ages of 28 and 56 days, and declares a strong relationship between compressive strength, split tensile strength as well as flexural strength.
- Fly ash content is the most leading control factor in compressive and flexural strength, while cement paste is the major control factor for split tensile strength according to the outcomes resultant from Taguchi and multi-regression analysis.
- Moreover, the optimal water curing of steel fiber concrete with high-strength–high-volume fly ash is in between 28 and 56 days for compressive strength, flexural, and splitting tensile strength.
- The optimized control factors for the mixtures of sustainable high-strength high-volume fly ash-based steel fiber concrete are 30% fly ash, 70% cement content, 2% super-plasticizer, and 0.5% steel fibers for all mechanical properties like compressive strength, flexural, and splitting tensile strength.
- The experimental confirmation test shows that the multi-regression technique is suitable for mechanical properties of high-strength–high-volume fly ash concrete-based mixtures as the deviation in predicted values is within 5% of experimental values. Hence, the developed regression model is a sufficient and competent approach to optimize the experimental as well as analytical value simultaneously.
- From the statistical investigation using Taguchi experimental design, the authors recommend that Taguchi methodical model is a better technique to optimize performance, quality, and investigational work.
- On the whole, it was concluded that the present study confirmed with the mechanical properties of the high-strength high-volume fly ash steel fiber concrete, it is a more suitable alternative sustainable solution to the ordinary concrete as it gives better performance.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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