Green environmental sustainability development in construction industry using response surface methodology

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Abstract: The purpose of this study was to investigate an effective method for the partial replacement of cement using waste materials to create green environmental sustainability in the construction industry. The tests were performed to predict the strengths of concrete by replacing the cement with waste materials, such as GSA (*X*1: 6%–10%), GGBS (*X*2: 20%–50%) and PPF (*X*3: 0.1%–0.5%) using RSM. The experimental variables were optimised using Design-Expert 8.0.7.1 software package. The optimum replacement of cement was observed at 7.5%–8% (GSA), 35% (GGBS) and 0.3% (PPF). Under this situation, the optimum cube compressive strengths at 7 and 28 days were 18.76–18.83 N/mm^2 and 30.91–31.06 N/mm^2; the cylinder splitting tensile strengths at 7 and 28 days were 2.32–2.39 N/mm^2 and 4.32–4.41 N/mm^2 respectively and the prism flexural strengths at 7 and 28 days were 3.37–3.49 N/mm^2 and 5.24–5.32 N/mm^2 respectively.

Keywords: compressive strength; flexural strength; groundnut shell ash; ground granulated blast furnace slag; polypropylene fibre; response surface methodology; splitting tensile strength.

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1 Introduction

In modern construction trends, the utilisation of cement plays a vital role in concrete production; hence, cement is essential in the construction of civil engineering structures, such as buildings, bridges, dams, sidewalks, runways and roads. Therefore, the cement industry produces a great deal of cement; as a result, usually in the dry process, large amounts of CO_2 are released into the environment. Cement manufacturing is the third largest CO_2 producer compared with other manufacturing industries (Saunois et al., 2016), with 1.25 tonnes of CO_2 emissions per tonne of cement manufacturing (Habeeb and Fayyadh, 2009), accounting for approximately 5% of the world's anthropogenic CO_2 emission (Mikulčić et al., 2013). CO_2 emissions may increase the Earth's temperature and lead to global warming (Patel and Balakrishna, 2014). In addition, the cost of cement is enormous; therefore, it is difficult for the construction industry to operate in poor areas (Alabadan et al., 2005). The environmental problems and cost associated with cement manufacturing have induced many researchers to seek the most suitable supplementary cementing materials to overcome these issues. Therefore, our present work was carried out for identifying the most efficient way to partially replace cement with waste materials.

Presently, large amounts of waste materials, such as groundnut shells, ground granulated blast-furnace slag (GGBS), sawdust, rice husks, millet husks, coconut shells and fly ash, are deposited on the land, and they are creating environmental problems. Some of these waste materials are effectively recycled, but they are not fully used, and this poses a threat to humans, animals and the environment (Raheem et al., 2013). Various agricultural waste ashes have been used as pozzolanic material or supplementary cementing materials. The partial replacement of cement with ashes plays a major role in making concrete, and it reduces the concrete's permeability due to the altered pore structure of the concrete. Hence, the concrete structure is protected from corrosion due to an increased resistance against the penetration of water and other chemicals (Olutoge et al., 2013). Recent research has demonstrated that high levels (40%–60%) of pozzolanic materials replacing cement can be used in structural applications. Moreover, the pozzolanic materials blended with cement increases the durability of concrete with age up to 1.5 years (Marceau et al., 2002).

Among the materials mentioned above, groundnut shell ash (GSA) is an excellent pozzolanic material; it consists of $Ca(OH)_2$, $Mg(OH)_2$, KOH and so on, and it reacts with cement and water to form Ca and Mg silicate hydrate. Its pozzolanic activity increases along with the age of curing (Buari et al., 2013). As a result, it has been suggested that GSA should be used for the partial replacement of cement in the manufacturing of concrete to protect the people, land and environment from serious environmental hazards and make the construction industry more economical.

Another supplementary material, GGBS, also has good pozzolanic properties. It is an excellent replacement for cement in concrete preparations, since it has remarkable advantages compared with the performance and behaviour of usual OPC concrete, in addition to the environmental and ecological gains (Escalante et al., 2001; Guettala et al., 2012). It is a by-product of the iron industries. The ore obtained from the iron, coke and limestone are fed into the furnace, and the resulting molten slag floats above the molten iron at a temperature of about 1,500ºC–1,600ºC. This is a good replacement for OPC, as the molten slag consists of approximately 40% calcium oxide (CaO) and 30–40% silicon dioxide (SiO_2), which is comparable to the chemical composition of OPC (Arivalagan, 2014). When reacted with water and calcium hydroxide in concrete, GGBS forms a calcium silicate hydrate (CSH) paste and produces a concrete matrix with a denser microstructure. It helps in enhancingthe strength and durability of concrete and increase the performance of concrete structures beyond the estimated service life (Shi and Qian, 2000; Binici et al., 2007).

The tensile strength of concrete is usually much poorer than its compressive strength, where the former is only about 10% of the latter. Therefore, the concrete will mainly crack because of its low tensile strength. This can be improved in an efficient and economical way by adding fibres. Different types of fibres, such as steel, glass and synthetic have been used in concrete, in addition to various natural, organic and mineral fibres (Wang et al., 1987). These fibres are used to enhance the tensile strength (Zollo, 1997; Bindiganavile and Banthia, 2001; Banthia and Nandakumar, 2003), flexural strength, toughness and impact strength (Gopalaratnam et al., 1991). They are also used for increasing the post-cracking ductility, which will help to change the failure mode. The formability and bending strength of concrete have been improved by adding fibres (Naaman et al., 2005). Polypropylene fibres (PPFs) have several advantages that make them a good fit for insertion into concrete; specifically, they are inexpensive, easily spreadable and highly ductile and also have good anchoring capacity. In addition, PPFs exhibit good resistance against corrosion, thermal stability and chemical inertness, while they are characterised by extreme stability in the alkaline environment (Banthia and Gupta, 2006; Kakooei et al., 2012).

The present study was performed to determine the best possible mix proportions of concrete by effectively replacing the cement with three different waste materials, namely GSA, GGBS and PPF. The discussed parameters and their effects may not be independent of each other. For this reason, it is necessary to study the interaction effects of mixing these parameters on concrete's strength properties. Under this condition, a numerical optimisation technique is expected to be helpful in reducing the cost and time of the project by limiting the number of specimens via fixing the optimum ranges of the replacement level to achieve adequate concrete strength. The response surface methodology (RSM) is one numerical tool used to measure the quantitative data from suitable experiments to establish and simultaneously solve multivariant equations. In this optimisation, five levels (–1.683,–1, 0, +1 and +1.683) with a seven-factor central composite rotatable design (CCRD) was utilised to study the optimum conditions regarding the cube compressive strength (CCS), cylinder splitting tensile strength (CSTS) and prism flexural strength (PFS) of concrete. The RSM is regularly employed in various engineering fields, such as material and mechanical engineering technologies (Nekahi and Dehghani, 2010;Younesi and Bahrololoom, 2010; Khan et al., 2012), transportation engineering in asphalt research (Chávez-Valencia, 2007; Haghshenas et al., 2013; Hamzah et al., 2013; Nassar et al., 2016) and so on. Recently, there have been remarkable endeavours related to the utilisation of the RSM in concrete technology to predict the mix proportions of concrete (Bayramov et al., 2004; Aldahdooh et al., 2013; Bektas and Bektas, 2014).

2 Materials and methods

2.1 Materials

2.1.1 Cement

Ordinary Portland cement (43 grade) conforming to IS 8112-1989 was used in this research. The physical properties of the cement were as follows: standard consistency = 26.2, setting time (initial and final) = 112 min and 213 min and specific gravity = 3.13.

2.1.2 Fine aggregate

River sand of a size varying from 300µ to 4.75 mm was used as the fine aggregate. The grading of the fine aggregate conformed to zone II, as per IS 383-970. The fine aggregates were tested in accordance with IS 2386 (Part-I): 1983. The different physical properties of the fine aggregate were as follows: specific gravity = 2.55, bulk density = 1,674kg/m^3, fineness modulus = 2.8, absorption of water = 1.75% and surface moisture = 2.0%.

2.1.3 Coarse aggregate

Crushed granite of a size varying from 4.75mm to 20mm, conforming to IS 383-1970, was used in this work. The coarse aggregate was tested in accordance with IS 2386 (Part I)-1983. The physical properties of coarse aggregate were as follows: specific gravity = 2.72, fineness modulus = 8.74, bulk density = 1,723 kg/m^3 and absorption of water = 0.75%.

2.1.4 GSA

The groundnut shell obtained from the groundnut oil manufacturing industry was thoroughly cleaned and dried. It was heated for 4h in the incinerator at a temperature of 600ºC to obtain the ash. The maximum size of the GSA used in the concrete preparation was 75µ. The properties of the GSA were as follows: specific gravity = 1.93, fineness modulus = 4.96, bulk density = 845kg/m^3 and moisture content = 0.55%.

2.1.5 GGBS

The GGBS of JSW Cement Limited, conforming to IS 4031-1988, was used in the research. The maximum size of GGBS used in this work was 45µ. The physical properties of the GGBS were as follows: standard consistency = 33.7, setting time (initial and final) = 210 min and 357 min, bulk density = 1,172kg/m^3 and specific gravity = 2.75.

2.1.6 PPF

Randomly distributed fine polypropylene monofilament fibres of a small size were used. The PPF was obtained from Reliance Industry under the name of RECRON 3s. The various properties of the PPF were as follows: diameter of the fibre = 0.05 mm, length of the fibre = 12mm, tensile strength of the fibre = 4,000–6,000kg/cm^2 and melting point = 250ºC.

2.1.7 Superplasticiser

The superplasticiser conplast SP 430, procured from FOSROC Chemicals, was used in the study. The dosage of superplasticiser used was 1%of the weight of the cement. The properties of the superplasticiser were as follows: appearance = brown liquid, active solids (% by wt.) = 40, specific gravity = 1.20, chloride content (%) = nil and pH value = 7.0–8.0.

2.1.8 Water

Clean, fresh, potable water with a pH of 7.8 was used for casting and curing of the concrete specimens, conforming to the requirements of IS 456-2000. The water was free from any organic matter, silt, oil, chloride or acidic material.

2.2 Casting and testing of specimens

2.2.1 Mix ratios

To calculate the mix ratios of plain concrete, a mix design was carried out. The mix ratios of design mix M20 as per IS 10262-2009 are listed in Table 1.

Table 1 Mix ratio of plain cement concrete

Sl. no.	*Materials*	*Mix proportions*	
		In weight	*In parts*
1	Cement	351.75kg	1
2	Fine aggregate	664.15kg	1.89
3	Coarse aggregate	1132.45kg	3.22
4	Water	191lit	0.55

2.2.2 Casting of specimens

The design mix of M20 (1:1.89:3.22) with the water-cement ratio of 0.55 was adopted for the preparation of the concrete. The concrete batching was carried out by weight. The materials required for preparing the concrete were placed on the watertight platform, and the concrete materials were mixed thoroughly by hand with the appropriate w/c ratio to ensure the concrete was homogeneous and obtain a uniform mass. The superplasticiser at 1% volume on the weight of cement was mixed with the concrete materials to achieve better workability. Before filling the concrete, the moulds were cleaned with engine oil for easy stripping of the concrete. This helped in avoiding the concrete sticking to the mould. Then, the fresh concrete was filled into the mould in three layers, each approximately one-third of the mould's height; each layer of concrete was rammed with 25 blows using a tamping rod. It was left to dry in contact with open air for 24 h. The specimens were casted without waste materials were called control specimens, and the test specimens were casted by replacing the cement with GSA (6%–10%), GGBS (20%–50%) and PPF (0.1%–0.5%). Three specimens were casted for each proportion, and the specimens were as follows: cube (150 × 150 × 150 mm), cylinder (150 mm in diameter and 300 mm in height) and prism (150 × 150 × 700 mm). These specimens were carefully removed from the mould after 24 h and kept in water for curing for a specified period.

2.2.3 Testing of specimens

Physical and mechanical tests of concrete specimens were carried out at the civil engineering laboratory of PAC Ramasamy Raja Polytechnic College, Rajapalayam, Tamilnadu, India. Three specimens were casted and tested for each proportion, and the average value was considered for each test.

2.2.3.1 CCS test

A CCS test at seven and 28 days of curing was conducted on the concrete cube of 150 × 150 × 150 mm, as per the IS 516-1959 standard test method. A standardised compression testing machine (CTM) with a capacity of 200 tonnes was engaged to determine the cube compression of the concrete. The load was applied on the specimen at a rate of 140 kg/cm^2/min. The cube specimen was subjected to a concentrated compressive force until failure occurred. The maximum compression load at failure was observed. Figure 1 shows the test setup of the cube compression test.

The compressive strength of the concrete cube was determined using the following formula (1),

$$Compression\ strength,\ F_c = \frac{P_c}{A} \tag{1}$$

where P_c = maximum compression load at failure in N and A = loaded cross-section area of the cube specimen in mm^2.

Figure 1 Test setup of cube compression test (see online version for colours)

2.2.3.2 CSTS test

A CSTS test at seven and 28 days of curing was carried out on a concrete cylinder of 150mm in diameter and 300mm in length, as per the IS 5816-1999 standard test method. A calibrated CTM with a capacity of 200 tonnes was used for examining the cylinder splitting tension. A plywood strip of 30 cm in length, 12 mm in width and 4 mm in thickness was kept on the lower plate of the CTM, and then the cylinder specimen was placed above it, and another plywood strip was kept above the cylinder specimen. The load was applied on the specimen at a rate of 1.4 N/(mm^2/min). The specimen was subjected to concentrated compressive force until failure occurred, and the breaking load at failure was noted. Figure 2 shows the test setup of the cylinder splitting tension test.

Figure 2 Test setup of cylinder splitting tension test (see online version for colours)

The splitting tensile strength of the concrete cylinder was determined using the following formula (2):

$$Splitting\ tensile\ strength,\ S_c = \frac{2P}{\pi DL} \tag{2}$$

where P = maximum load at failure in N, D = diameter of specimen in mm and L = length of specimen in mm.

2.2.3.3 PFS test

A PFS test at seven and 28 days of curing was performed on the concrete prism of 150 × 150 × 700 mm, following the IS: 9399-1979 standard test method. A calibrated universal testing machine (UTM) with a capacity of 60 tonnes was engaged to find the PFS of the concrete. The prism was placed on the supports symmetrically for the span of 600 mm and subjected to a two-point loading system. The load was applied on the specimen at a rate of 4 kN/min until failure occurred. The maximum flexural load at failure was recorded. Figure 3 shows the loading arrangement and test setup of the prism flexure test.

Figure 3 Test setup of prism flexural test (see online version for colours)

The flexural strength of the concrete prism was calculated using the following formula (3a) and (3b):

$$Flexural\ strength\ of\ prism,\ F_c = \frac{3Pa}{bd^2} \tag{3a}$$

when ‘a’ is lies between 17cm to 20cm.

$$F_c = \frac{PL}{bd^2} \tag{3b}$$

when ‘a’ is lies between 20cm to 30cm.

Where P = maximum flexural load at failure in N, a = distance between the line of fracture in mm, b = breadth of prism in mm and d = length of prism in mm.

2.3 Selection of significant variables and experimental design using RSM

In this optimisation technique, the most reliable method of the RSM with CCRD was employed to optimise the parameters, namely the compressive, splitting tensile and flexural strength of concrete at seven and 28 days of curing. The CCRD was applied to examine the optimum proportions of strength of the concrete samples, with five levels and seven factors. The independent variables, namely GSA (6%–10%), GGBS (20%–50%) and PPF (0.1%–0.5%), and the dependent variables, namely the CCS, CSTS and PFS of concrete at 7 and 28 days were selected. The fixed coded levels of each independent variable were –1.682, –1, 0, +1, and +1.682, as shown in Table 2. The CCRD comprised 20 experimental runs with eight factorial points, six axial points at a distance of ±1.682 from the centre point and six replicates, as shown in Table 4. The experimental data were fitted by a second-order polynomial model to connect the dependent variable to the independent variable.

Table 2 Experimental parameters and range of coded and actual parameters of CCRD

Parameters [independent variables (x_j)]	*Units*	*Factor levels*				
		–1.682	*–1*	*0*	*1*	*1.682*
GSA (X_1)	%	4.636	6	8	10	11.36
GGBS (X_2)	%	9.77	20	35	50	60.23
PPF (X_3)	%	0	0.1	0.3	0.5	0.636

The generalised equation in second-order polynomial form employed in the RSM was as follows:

$$Y = \beta_0 + \sum_{i=1}^{3} \beta_i X_i + \sum_{i=1}^{3} \beta_{ii} X_i^2 + \sum_{i=1}^{2} \sum_{j=i+1}^{3} \beta_{ij} X_i X_j + \varepsilon \tag{4}$$

In this research work, equation (4) can be transformed into the following equation, relating to the value of the independent variables:

$$\begin{aligned} Y = {} & \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \\ & + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 \end{aligned} \tag{5}$$

where Y represents the dependent variables, namely CCS, CSTS and PFS, at 7 and 28 days of curing. Moreover, β_0 is the model constant; X_i and X_j are coded values of the independent variables, such as GSA content (%), GGBS content (%) and PPF content (%); β_i, β_{ii} and β_{ij} are the model coefficients; and ε is the error. Further verification experiments were conducted to confirm the numerical experimental analysis.

2.4 Statistical data analysis

The results obtained by conducting the experiments on various strength characteristics, namely the compressive strength, splitting tensile strength and flexural strength of concrete at seven and 28 days, were examined using the Design Expert (version 8.0.7.1, Stat-Ease, Inc., Minneapolis, MN, USA) software. The strength of the analysis was processed by one-way analysis of variance (ANOVA) and student's *t*-test. The optimal strength characteristics of concrete were investigated using three-dimensional (3D) response surfaces and contour plots.

3 Results and discussions

The preliminary tests were carried out to predict the compressive strength, splitting tensile strength and flexural strength of concrete after aging for seven and 28 days of curing, and the results are shown in Table 3. The results indicated that when the GSA (from 0% to 10%) alone was added for the partial replacement of cement, the compressive strength of concrete was close to that of the control specimen with a replacement level of 8% GSA, while it decreased for the other percentages of replacement of GSA (2%, 4%, 6% and 10%).

Table 3 Mechanical strength results for preliminary experiments

Sl. no.	*Cement (%)*	*GSA (%)*	*GGBS (%)*	*PPF (%)*	*Compressive strength in N/mm²*		*Splitting tensile strength in N/mm²*		*Flexural strength in N/mm²*	
					CCS 7 days	*CCS 28 days*	*CSTS 7 days*	*CSTS 28 days*	*PFS 7 days*	*PFS 28 days*
1	100	0	0	0	14.72	25.62	1.67	2.99	2.34	4.15
2	98	2	0	0	12.17	22.73	1.09	2.27	1.73	2.97
3	96	4	0	0	11.32	20.23	0.87	1.62	1.12	1.88
4	94	6	0	0	11.52	21.62	0.99	1.79	1.34	2.41
5	92	8	0	0	12.97	24.93	1.12	2.43	1.84	3.12
6	90	10	0	0	10.92	18.47	0.73	1.37	0.92	1.64
7	74	6	20	0	13.89	24.59	0.99	1.75	1.09	2.21
8	57	8	35	0	16.19	26.57	1.62	2.93	2.03	3.56
9	40	10	50	0	12.74	20.61	0.74	1.13	0.83	1.72

However, the splitting tensile strength and flexural strength of concrete decreased compared with the control specimens for all the mixes. Hence, it was planned to add GGBS (20%–50%) along with GSA (6%–10%) for the replacement of cement to improve the strength of the concrete. While replacing the cement with 35% GGBS and 8% GSA, there was an increase in the compressive strength compared with the control mixture. At the same time, the splitting tensile strength and flexural strength of the concrete decreased compared with those of the control concrete specimen for all the mixes.

Consequently, it was suggested that a small (0.05 mm in diameter and 12 mm in length), randomly distributed PPF (0.1%–0.5%) could be incorporated along with the GSA (6%–10%) and GGBS (20%–50%) for enhancing the splitting tensile and flexural strength of the concrete. In this connection, it was proposed to utilise the statistical technique of optimisation with the RSM to avoid the preparation of many concrete specimens, such as cubes, cylinders, and prisms, by replacing the cement with three different materials for investigating the strength properties of hardened concrete. Further, it was observed that the workability of concrete was decreased when replacing the cement with GSA, GGBS and PPF, while it was improved by adding a superplasticiser.

Table 4a CCRD with experimental responses

Sl. no.	*Cement (%)*	*Independent variables (X_j) in (%)*			*Experimental (Y_1) in N/mm^2*					
					Compressive strength		*Splitting tensile strength*		*Flexural strength*	
		GSA	*GGBS*	*PPF*	*CCS*	*CCS*	*CSTS*	*CSTS*	*PFS*	*PFS*
					Seven days	*28 days*	*Seven days*	*28 days*	*Seven days*	*28 days*
1	56.70	8.00	35.00	0.30	18.75	30.88	2.31	4.31	3.35	5.23
2	39.50	10.00	50.00	0.50	13.41	21.37	1.20	2.09	1.46	2.79
3	57.00	8.00	35.00	0.00	16.15	26.48	1.59	2.89	1.97	3.51
4	81.93	8.00	9.77	0.30	12.33	19.27	1.07	1.82	1.25	2.46
5	56.70	8.00	35.00	0.30	18.75	30.89	2.31	4.32	3.36	5.24
6	56.70	8.00	35.00	0.30	18.76	30.91	2.32	4.32	3.37	5.24
7	56.70	8.00	35.00	0.30	18.75	30.89	2.31	4.31	3.34	5.21
8	56.70	8.00	35.00	0.30	18.75	30.88	2.31	4.31	3.35	5.23
9	73.50	6.00	20.00	0.50	14.39	23.45	1.30	2.35	1.68	3.01
10	69.90	10.00	20.00	0.10	13.75	22.21	1.19	2.14	1.43	2.74
11	56.70	8.00	35.00	0.30	18.76	30.90	2.32	4.31	3.35	5.24
12	31.47	8.00	60.23	0.30	12.68	20.93	1.12	1.94	1.35	2.60
13	60.06	4.64	35.00	0.30	16.17	26.92	1.69	3.20	2.55	3.92
14	43.90	6.00	50.00	0.10	14.57	24.22	1.37	2.47	1.75	3.07
15	56.36	8.00	35.00	0.64	14.92	24.26	1.48	2.69	1.75	3.28
16	73.90	6.00	20.00	0.10	14.40	23.15	1.33	2.44	1.71	3.05
17	53.34	11.36	35.00	0.30	14.50	23.26	1.30	2.35	1.75	3.11
18	39.90	10.00	50.00	0.10	14.09	22.78	1.12	1.89	1.34	2.63
19	43.50	6.00	50.00	0.50	14.65	24.27	1.42	2.64	1.84	3.25
20	69.50	10.00	20.00	0.50	13.17	20.88	1.11	1.91	1.31	2.54

Table 4b CCRD with predicted responses

Sl. no.	Cement (%)	Independent variables (X_j) in (%)			Predicted value (Y_2) in N/mm^2					
					Compressive strength		Splitting tensile strength		Flexural strength	
		GSA	GGBS	PPF	CCS	CCS	CSTS	CSTS	PFS	PFS
					Seven days	28 days	Seven days	28 days	Seven days	28 days
1	56.70	8.00	35.00	0.30	18.75	30.90	2.31	4.32	3.35	5.23
2	39.50	10.00	50.00	0.50	13.41	21.38	1.20	2.11	1.45	2.80
3	57.00	8.00	35.00	0.00	16.13	26.43	1.59	2.89	1.97	3.53
4	81.93	8.00	9.77	0.30	12.30	19.35	1.04	1.79	1.22	2.42
5	56.70	8.00	35.00	0.30	18.75	30.90	2.31	4.32	3.35	5.23
6	56.70	8.00	35.00	0.30	18.75	30.90	2.31	4.32	3.35	5.23
7	56.70	8.00	35.00	0.30	18.75	30.90	2.31	4.32	3.35	5.23
8	56.70	8.00	35.00	0.30	18.75	30.90	2.31	4.32	3.35	5.23
9	73.50	6.00	20.00	0.50	14.45	23.45	1.32	2.38	1.72	3.05
10	69.90	10.00	20.00	0.10	13.77	22.12	1.18	2.12	1.40	2.72
11	56.70	8.00	35.00	0.30	18.75	30.90	2.31	4.32	3.35	5.23
12	31.47	8.00	60.23	0.30	12.69	20.77	1.11	1.90	1.33	2.57
13	60.06	4.64	35.00	0.30	16.12	26.79	1.66	3.15	2.47	3.86
14	43.90	6.00	50.00	0.10	14.61	24.32	1.37	2.47	1.76	3.07
15	56.36	8.00	35.00	0.64	14.83	24.08	1.42	2.57	1.66	3.16
16	73.90	6.00	20.00	0.10	14.42	23.19	1.35	2.48	1.76	3.09
17	53.34	11.36	35.00	0.30	14.54	23.34	1.30	2.34	1.78	3.11
18	39.90	10.00	50.00	0.10	14.05	22.84	1.12	1.91	1.34	2.64
19	43.50	6.00	50.00	0.50	14.64	24.41	1.45	2.71	1.91	3.32
20	69.50	10.00	20.00	0.50	13.14	20.83	1.14	1.96	1.33	2.59

3.1 Fitting the models

Based on the preliminary experimental results, small numbers of concrete specimens were casted with respect to the experimental design. The various mix proportions of the concrete are shown in Tables 4(a) and 4(b).The prepared concrete specimens were investigated to determine the CCS, CSTS and PFS of the concrete, as well as the most effective way of replacing cement with waste materials. The experiments were performed for the parameters and ranges shown in Table 2. From the RSM with CCRD, the optimised results were obtained with 8% GSA, 35% GGBS and 0.3% PPF. Under these circumstances, the observed results indicated significant effects, with compressive strengths of concrete at seven and 28 days of 18.75 N/mm^2 and 30.90 N/mm^2, splitting tensile strengths at 2.31 N/mm^2 and 4.32 N/mm^2 respectively and flexural strengths at 3.35 N/mm^2 and 5.23 N/mm^2 respectively.

The responses were fitted to second-order polynomial equations (6)–(11), and Tables 5–7 illustrate the quadratic models fitted with the data. The experimental models were validated by ANOVA, and the coefficients of the individual responses and regression coefficients of the obtained equations were found. The significance of the responses was monitored using the F-test and p-value at the 95% confidence level.

The experimental variables will likely be significant and more suitable if the F-value becomes higher and p-value becomes lower (Selvaraj et al., 2014). The p-values were used as a main tool to check the significance and adequacy between the interactions of the variables. A p-value less than 0.05 specified that the coefficient was statistically significant. In addition, the lack-of-fit F-values (F = 113.02, 157.94, 45.57, 182.27, 43.52 and 35.70) and lack-of-fit p-values (p = 0.0001, 0.0001, 0.0004, 0.0001, 0.0004 and 0.0006) implied that the quadratic models for all the dependent variables were highly significant. The fitting of the quadratic models was confirmed by finding the R^2 value (multiple regression coefficients) and the significance of lack-of-fit. The second-order polynomial equations for the fitted quadratic models, such as the CCS, CSTS and PFS, of concrete at seven and 28 days in the coded variables are given in the following equations:

$$\begin{aligned} CCS\ seven\ days = {} & 18.755 - 0.469X_1 + 0.117X_2 - 0.151X_3 \\ & +0.0188X_1X_2 - 0.166X_1X_3 - 0.00125X_2X_3 \\ & -0.1213X_1^2 - 2.2133X_2^2 - 1.267X_3^2 \end{aligned} \tag{6}$$

$$\begin{aligned} CCS\ 28\ days = {} & 30.90 - 1.026X_1 + 0.4204X_2 - 0.299X_3 - 0.1038X_1X_2 \\ & -0.3863X_1X_3 - 0.0413X_2X_3 - 2.066X_1^2 - 3.83X_2^2 - 2.182X_3^2 \end{aligned} \tag{7}$$

$$\begin{aligned} CSTS\ seven\ days = {} & 2.314 - 0.1066X_1 + 0.01934X_2 + 0.0105X_3 \\ & -0.0175X_1X_2 - 0.0025X_1X_3 + 0.03X_2X_3 \\ & -0.2958X_1^2 - 0.4372X_2^2 - 0.314X_3^2 \end{aligned} \tag{8}$$

$$\begin{aligned} CSTS\ 28\ days = {} & 4.315 - 0.242X_1 + 0.033X_2 + 0.0234X_3 - 0.0488X_1X_2 \\ & -0.0138X_1X_3 + 0.0863X_2X_3 - 0.558X_1^2 - 0.874X_2^2 - 0.616X_3^2 \end{aligned} \tag{9}$$

$$\begin{aligned} PFS\ seven\ days = {} & 3.355 - 0.204X_1 + 0.0314X_2 + 0.0204X_3 \\ & -0.0175X_1X_2 - 0.0075X_1X_3 + 0.045X_2X_3 \\ & -0.435X_1^2 - 0.736X_2^2 - 0.5997X_3^2 \end{aligned} \tag{10}$$

$$\begin{aligned} PFS\ 28\ days = {} & 5.2331 - 0.2228X_1 + 0.0465X_2 + 0.03205X_3 \\ & -0.015X_1X_2 - 0.0225X_1X_3 + 0.0725X_2X_3 \\ & -0.6193X_1^2 - 0.968X_2^2 - 0.738X_3^2 \end{aligned} \tag{11}$$

3.2 Analysis of the model

3.2.1 Effect of the concrete cube's compressive strength at seven and 28 days of curing on the partial replacement of cement

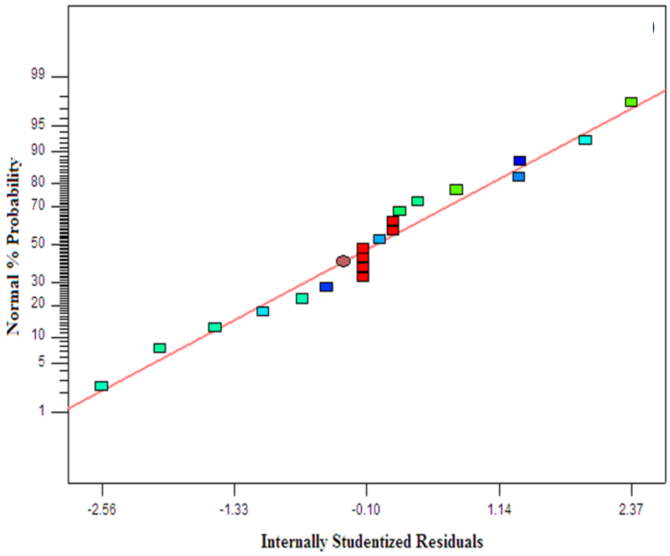
The model equations (6)–(7) and ANOVA in Table 5 shows that the quadratic terms of (X_1^2), (X_2^2) and (X_3^2), followed by the linear terms of (X_1), (X_2) and (X_3) and interaction term of (X_1X_3) had significant effects ($p \ll 0.05$) for CCS at seven days' curing of concrete for the partial replacement of cement using waste materials, namely GSA (X_1), GGBS (X_2) and PPF (X_3), in an effective way. The interaction term (X_1X_2) also had a significant effect ($p << 0.05$) on the 28-daycompressive strength of the concrete, in addition to the above terms. It is strongly evident that the compressive strength of concrete at the early stage was due to the combined action of GSA and PPF, and the development of compressive strength at the later age was because of the interaction of GSA and GGBS; this occurred because GSA and GGBS reacted slowly together and facilitated the development of compressive strength at the later age.

Table 5 ANOVA for the quadratic polynomial mode of CCS of concrete at seven and 28 days of curing

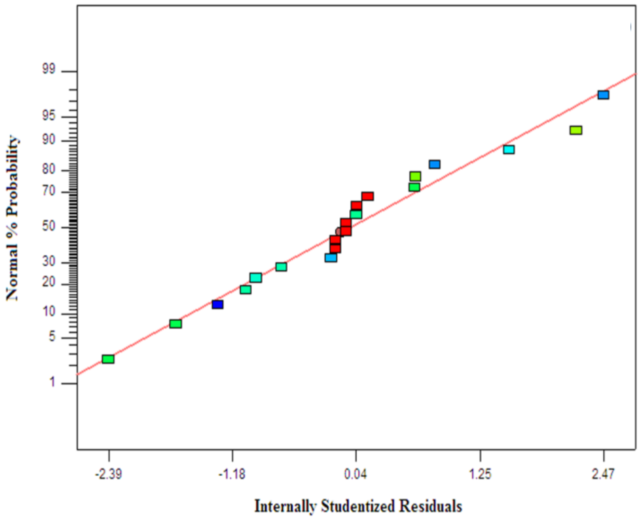
Source of data	*Sum of squares*	*DF*	*Mean square*	*F value*	*p-value*
CCS seven days					
Model	102.4316972	9	11.38129969	7,486.307626	< 0.0001
X_1	2.997908945	1	2.997908945	1,971.942504	< 0.0001
X_2	0.187130199	1	0.187130199	123.0891264	< 0.0001
X_3	0.297002786	1	0.297002786	195.3603092	< 0.0001
X_1X_3	0.2211125	1	0.2211125	145.4417545	< 0.0001
X_1^2	21.28383362	1	21.28383362	13,999.92359	< 0.0001
X_2^2	70.89251503	1	70.89251503	46,631.15729	< 0.0001
X_3^2	19.69827518	1	19.69827518	12,956.98661	< 0.0001
Residual	0.015202821	10	0.001520282		
Lack of fit	0.015069488	5	0.003013898	113.0211596	< 0.0001
Pure error	0.000133333	5	2.66667E-05		
Cor total	102.4469	19			
CCS 28 days					
Model	312.970391	9	34.77448788	3,201.804058	< 0.0001
X_1	14.36276279	1	14.36276279	1,322.427877	< 0.0001
X_2	2.41402538	1	2.41402538	222.2674359	< 0.0001
X_3	1.158152867	1	1.158152867	106.6350297	< 0.0001
X_1X_2	0.0861125	1	0.0861125	7.928667501	0.0183
X_1X_3	1.1935125	1	1.1935125	109.8907101	< 0.0001
X_1^2	61.7567657	1	61.7567657	5,686.153127	< 0.0001
X_2^2	212.2866439	1	212.2866439	19,545.9453	< 0.0001
X_3^2	58.37384143	1	58.37384143	5,374.675912	< 0.0001
Residual	0.108609044	10	0.010860904		
Lack of fit	0.107925711	5	0.021585142	157.9400649	< 0.0001
Pure error	0.000683333	5	0.000136667		
Cor total	313.079	19			

Figures 4(a) and 4(b) shows a normal percentage probability plot for the involvement of (X_1), (X_2) and (X_3); these variants are normally distributed and show no deviation.

Figure 4 Normal percentage probability plot for the studentised residuals for CCS after (a) seven and (b) 28 days of curing (see online version for colours)



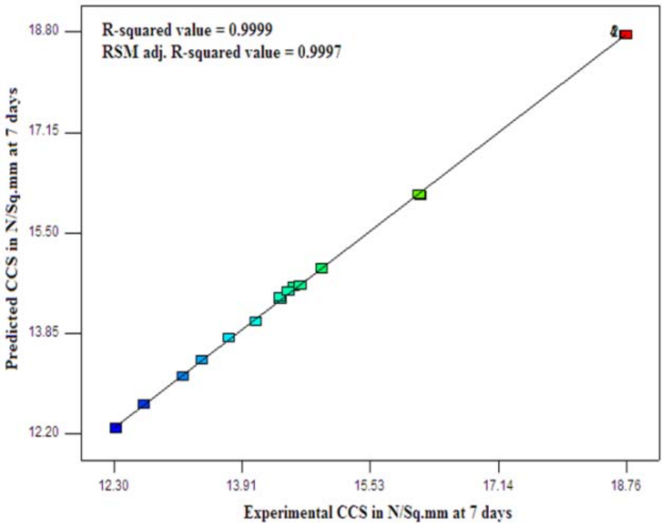
(a)



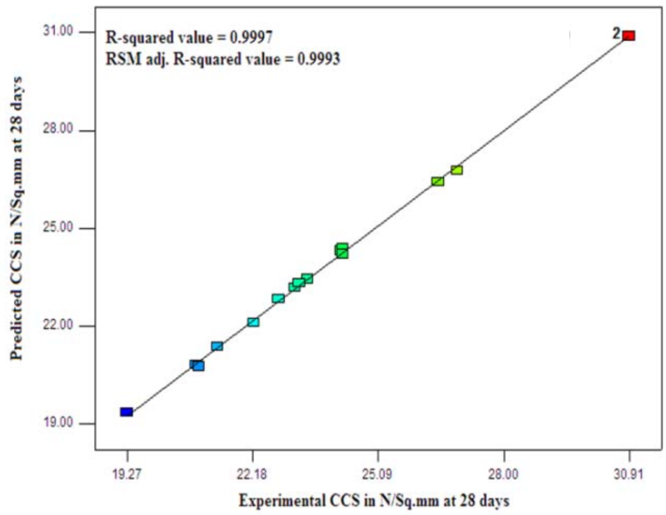
(b)

The regression coefficient values (R^2) of the models for compressive strength at seven and 28 days were 0.9999 and 0.9997, respectively; the *p*-values for lack of fit were 0.0001 and 0.0001, respectively. A high value of the regression coefficient ($R^2 >> 0.8$) is a good fit. This signifies that the model had considerably high fit. In addition, the predicted data against the experimental data, which had higher R^2 values of compressive strength at seven and 28 days, were0.9999 and 0.9997, respectively, compared with the RSM's adjusted R^2 values (0.9997 and 0.9993). Figures 5(a) and 5(b) shows the relationship between the experimental and predicted values for compressive strength at seven and 28 days' curing of concrete, respectively.

Figure 5 Relationship between the experimental and predicted values for CCS after (a) 7 and (b) 28 days of curing (see online version for colours)



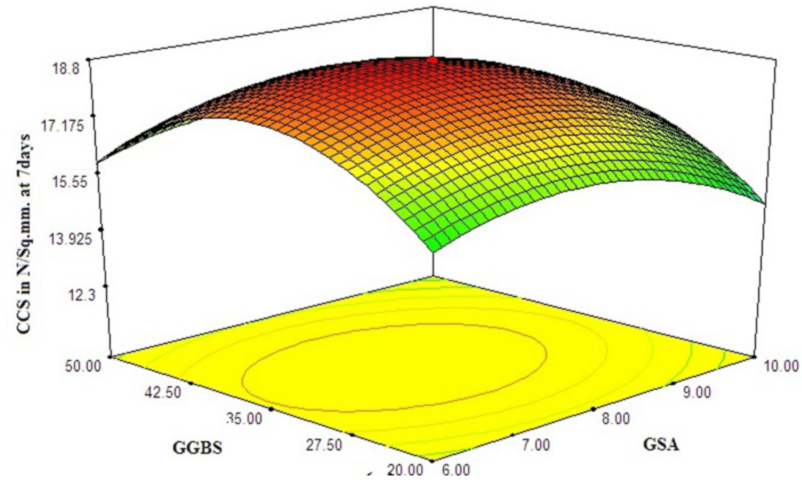
(a)



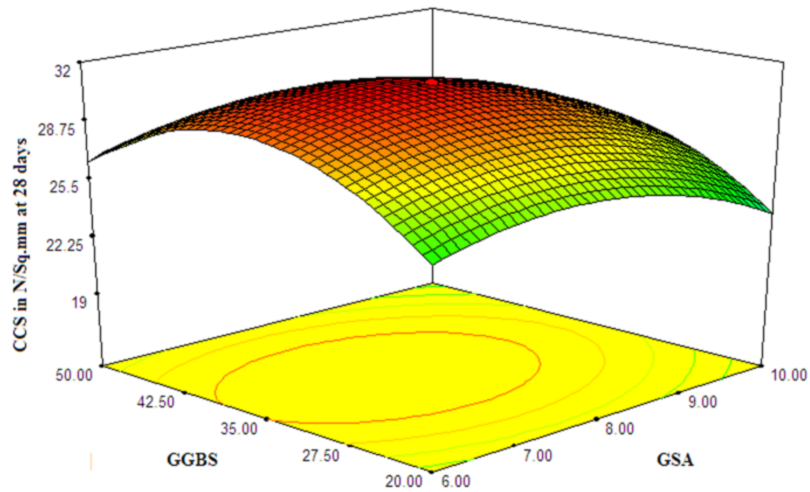
(b)

The 3D response surfaces [Figures 6(a) and 6(b)] and contour plots [Figures 6(c) and 6(d)] showed significant effects on compressive strength at seven and 28 days for the partial replacement of cement with accountable of the functional variables of GSA, GGBS and PPF. The figures show that partial replacement of cement with GSA at 8% and GGBS at 35% corresponded to the highest compressive strengths of the concrete cube at seven and 28 days, at 18.75 N/mm^2 and 30.90 N/mm^2 respectively, when PPF was kept at a fixed level (zero level = 0.30%).

Figure 6 (a)–(b) 3D response surfaces and (c)–(d) contour plots showing the combined effects of GSA and GGBS for the CCS at seven and 28 days of curing, when PPF was held at a fixed level (zero level = 0.30%) (see online version for colours)



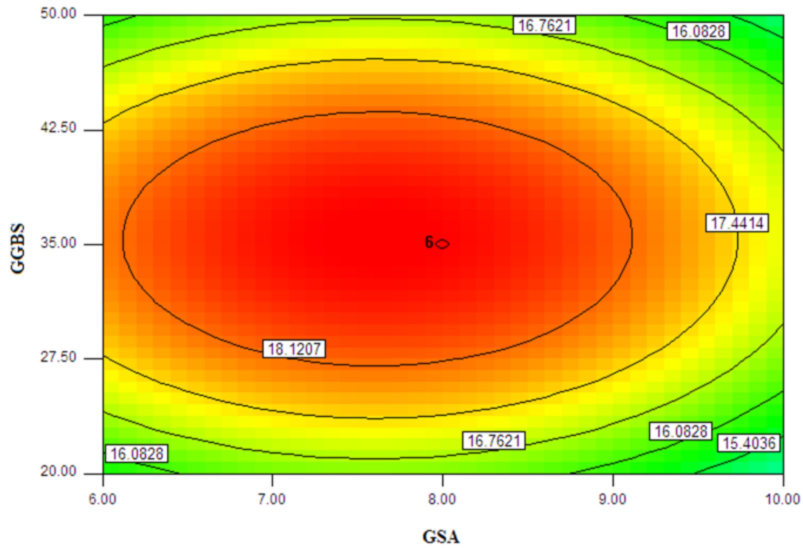
(a)



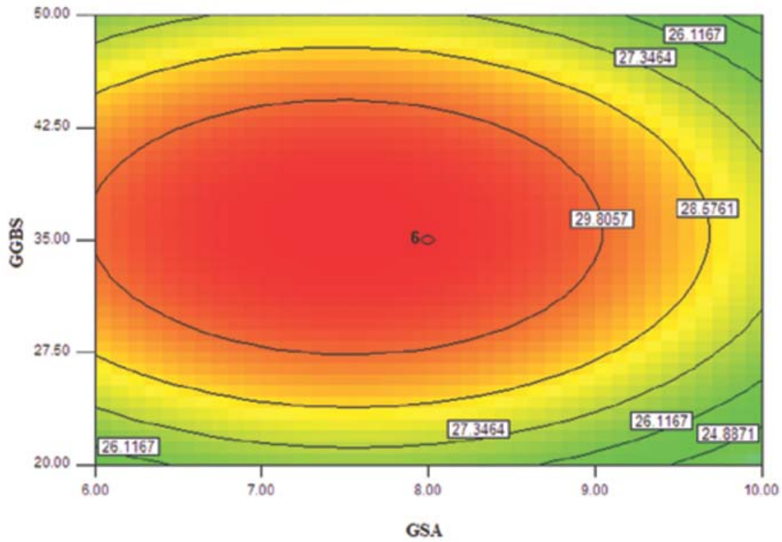
(b)

Note: Zero level = 0.30%.

Figure 6 (a)–(b) 3D response surfaces and (c)–(d) contour plots showing the combined effects of GSA and GGBS for the CCS at seven and 28 days of curing, when PPF was held at a fixed level (continued) (see online version for colours)



(c)



(d)

Note: Zero level = 0.30%.

3.2.2 *Effects of the splitting tensile strength of the concrete cylinder at seven and 28 days of curing with the partial replacement of cement*

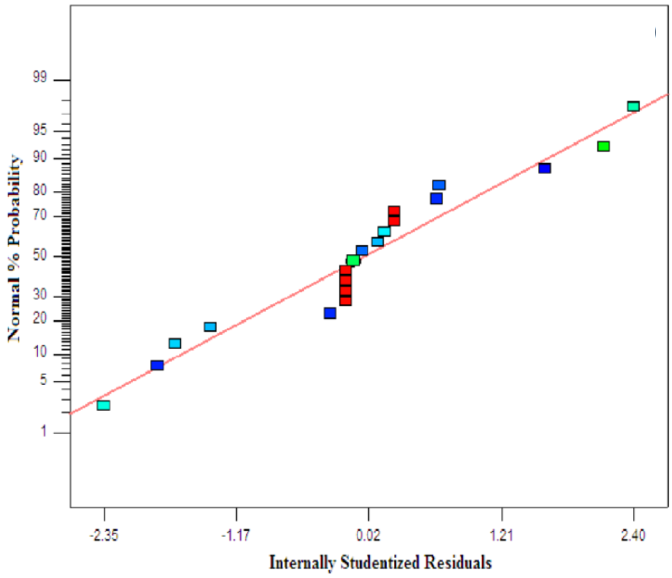
The model equations (8)–(9) and ANOVA results in Table 6 confirmed that the quadratic terms of (X_1^2), (X_2^2) and (X_3^2), followed by the linear terms of (X_1), (X_2) and interaction term of (X_2X_3),had significant effects ($p << 0.05$) on the splitting tensile strength after seven days of curing of concrete; the interaction term (X_1X_2) also had a significant effect ($p << 0.05$) on the splitting tensile strength of concrete after 28 days with the partial replacement of cement with three different waste materials, namely GSA (X_1), GGBS (X_2) and PPF (X_3). It is overwhelmingly clear that the splitting tensile strength of concrete in the early stage stemmed from the integrated action of GGBS and PPF, and this strength improved at the later age due to the slow reaction between the pozzolanic materials, namely GSA and GGBS. Further, the regression coefficient values (R^2) of the models for the splitting tensile strength at seven and 28 days were 0.9987 and 0.9987, respectively; the *p*-values for lack of fit were 0.0004 and 0.0001 respectively.

Table 6 ANOVA for the quadratic polynomial mode of CSTS of concrete at seven and 28 days curing

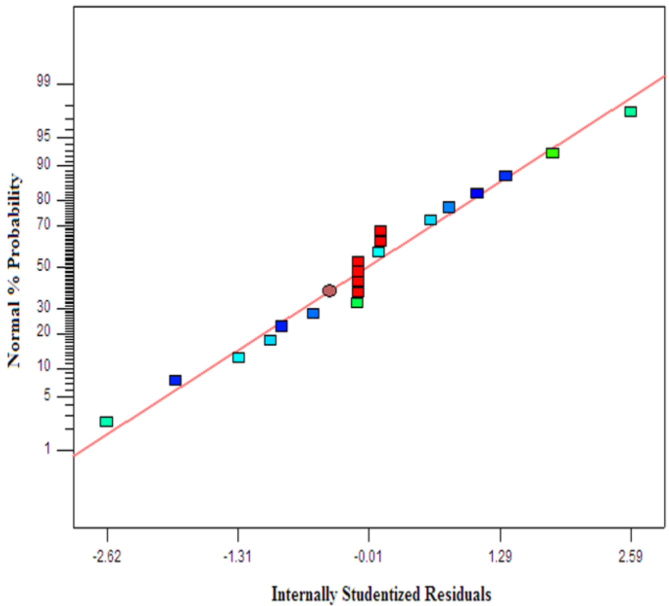
Source of data	*Sum of squares*	*DF*	*Mean square*	*F value*	*p-value*
CSTS seven days					
Model	4.71624584	9	0.524027316	843.9585195	< 0.0001
X_1	0.155207228	1	0.155207228	249.9649512	< 0.0001
X_2	0.005106838	1	0.005106838	8.224684275	0.0167
X_2X_3	0.0072	1	0.0072	11.59577213	0.0067
X_1^2	1.266108788	1	1.266108788	2039.098471	< 0.0001
X_2^2	2.766274136	1	2.766274136	4455.150628	< 0.0001
X_3^2	1.209069717	1	1.209069717	1947.235684	< 0.0001
Residual	0.00620916	10	0.000620916		
Lack of fit	0.006075826	5	0.001215165	45.56869711	0.0004
Pure error	0.000133333	5	2.66667E-05		
Cor total	4.722455	19			
CSTS 28 days					
Model	18.4614645	9	2.051273833	839.4645852	< 0.0001
X_1	0.797171721	1	0.797171721	326.2350532	< 0.0001
X_2	0.01494758	1	0.01494758	6.117156948	0.0329
X_1X_2	0.0190125	1	0.0190125	7.780687379	0.0191
X_2X_3	0.0595125	1	0.0595125	24.35493268	0.0006
X_1^2	4.501274016	1	4.501274016	1842.104191	< 0.0001
X_2^2	11.05821129	1	11.05821129	4525.469296	< 0.0001
X_3^2	4.652544985	1	4.652544985	1904.010417	< 0.0001
Residual	0.024435502	10	0.00244355		
Lack of fit	0.024302168	5	0.004860434	182.2662631	< 0.0001
Pure error	0.000133333	5	2.66667E-05		
Cor total	18.4859	19			

Figures 7(a) and 7(b) shows a normal percentage probability plot for the involvement of (X_1), (X_2) and (X_3); these variants are normally distributed and show no deviation. In addition, the predicted data against the experimental data, which has higher R^2 values of the splitting tensile strength at seven and 28 days, were 0.9987 and 0.9987, respectively, compared with the RSM's adjusted R^2 values (0.9975 and 0.9975).

Figure 7 Normal percentage probability plot for the studentised residuals for CSTS after (a) seven and (b) 28 days of curing (see online version for colours)

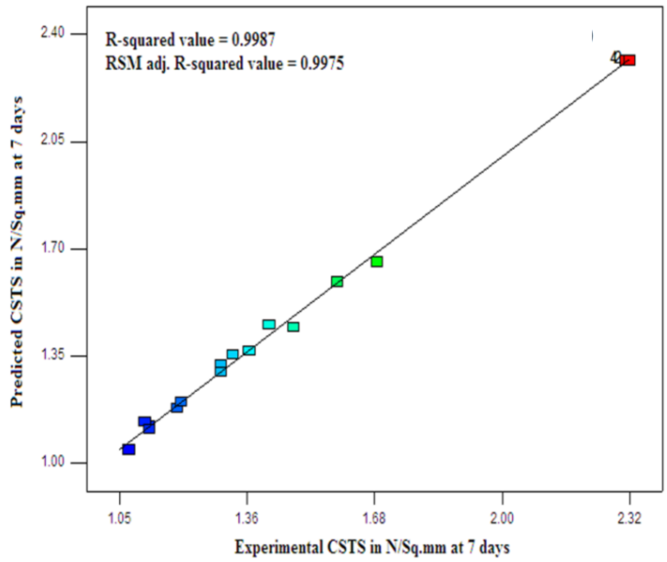


(a)

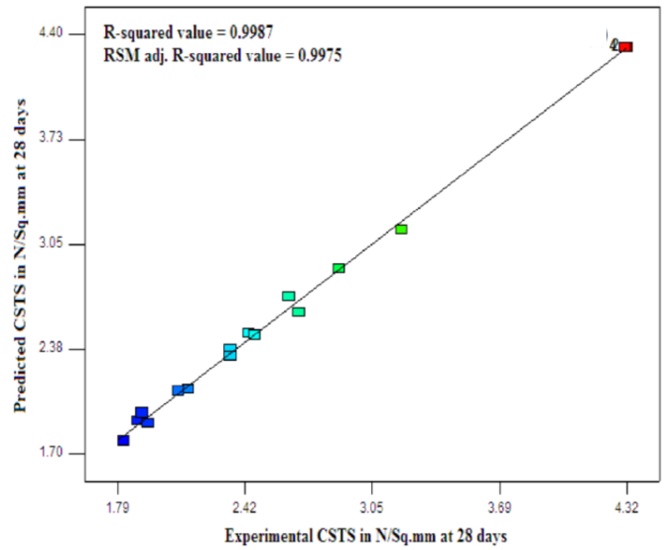


(b)

Figure 8 Relationship between the experimental and predicted values for CSTS after (a) seven and (b) 28 days of curing (see online version for colours)



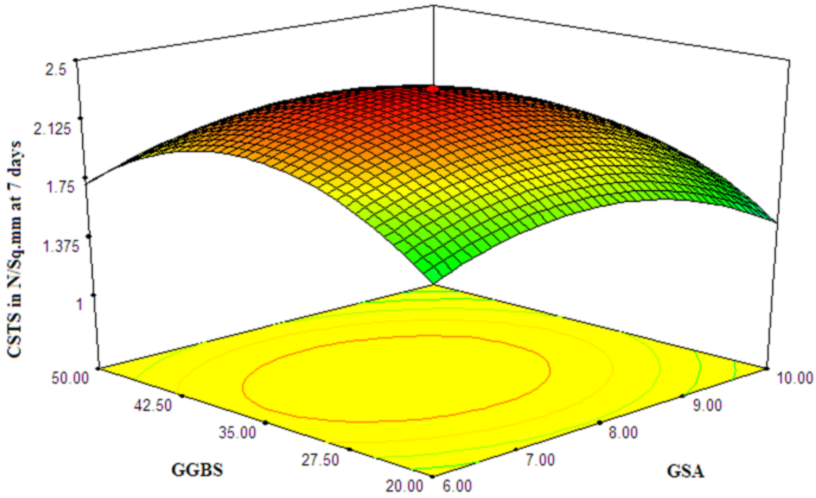
(a)



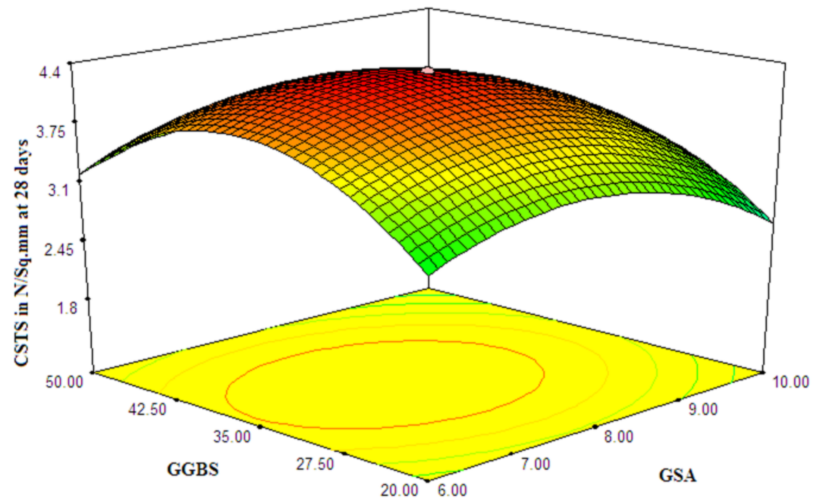
(b)

Figures 8(a) and 8(b) shows the relationship between the experimental and predicted values for splitting tensile strength at seven and 28 days' curing of concrete, respectively. The 3D response surfaces [Figures 9(a) and 9(b)] and contour plots [Figures 9(c) and 9(d)] show significant effects on the splitting tensile strength at seven and 28 days of curing for partial replacement cement with the functional variables of GSA, GGBS and PPF. The figures show that the partial replacement of cement with 8% GSA and 35% GGBS corresponded to the highest splitting tensile strengths of the concrete cylinder at seven and 28 days of 2.31 N/mm^2 and 4.32 N/mm^2, respectively, when PPF was held at a fixed level (zero level = 0.30%).

Figure 9 (a)–(b) 3D response surfaces and (c)–(d) contour plots showing the combined effects of GSA and GGBS for CSTS at seven and 28 days of curing, when PPF was held at fixed level (see online version for colours)



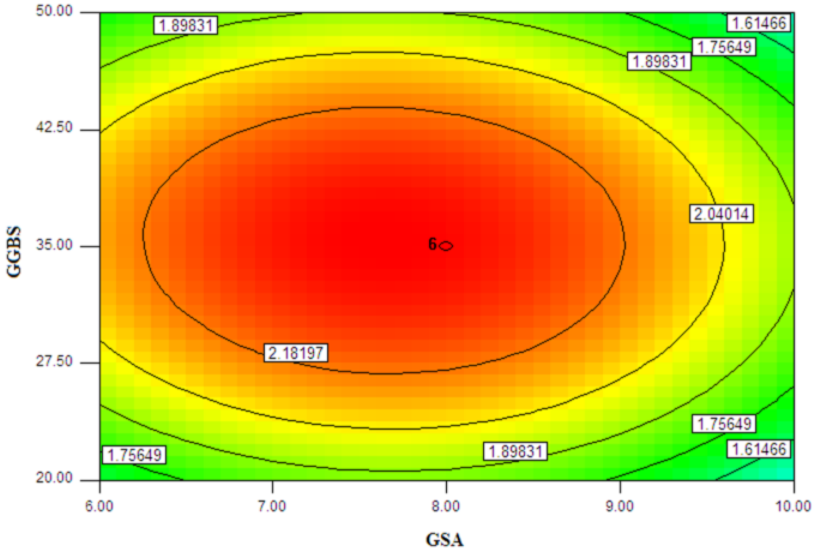
(a)



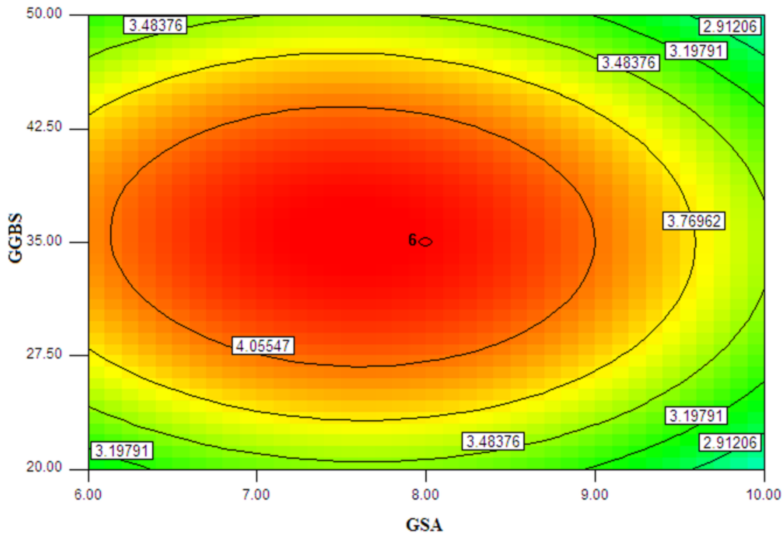
(b)

Note: Zero level = 0.30%.

Figure 9 (a)–(b) 3D response surfaces and (c)–(d) contour plots showing the combined effects of GSA and GGBS for CSTS at seven and 28 days of curing, when PPF was held at fixed level (continued) (see online version for colours)



(c)



(d)

Note: Zero level = 0.30%.

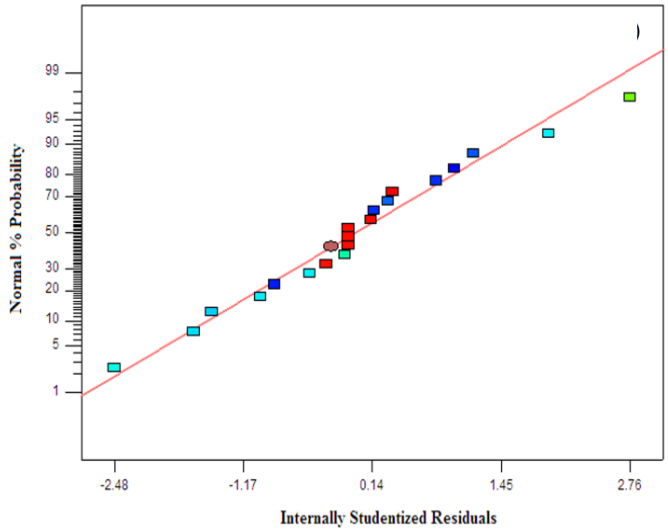
3.2.3 *Effects of flexural strength of the concrete prism at seven and 28 days of curing on the partial replacement of cement*

The results of ANOVA in Table 7 and polynomial equations (10)–(11) show that the independent parameters GSA, GGBS and PPF had significant effects on the flexural strength at seven and 28 days of concrete curing for the effective replacement of cement. The observed results and polynomial equations further confirmed that the linear terms (X_1) and (X_2), interaction term (X_2X_3) and quadratic terms (X_1^2), (X_2^2) and (X_3^2) were significant (p << 0.05) for the flexural strength at seven days of curing; in addition to these terms, the linear term (X_3) also had a significant effect (p << 0.05) on the 28-day flexural strength of the concrete in terms of the partial replacement of cement with GSA (X_1), GGBS(X_2) and PPF (X_3). It is evident that the flexural strength of concrete in the early stage emerged because of the integrated action of GGBS and PPF; PPF played an important, independent role for the improvement of the concrete's flexural strength at the later stage. The observed flexural strength at seven and 28 days had high regression coefficient values (R^2) of 0.9983 (seven days) and 0.9989 (28 days); the p-values for lack of fit were 0.0004 and 0.0006, respectively (p << 0.05), signifying that the model had considerable fitting one.

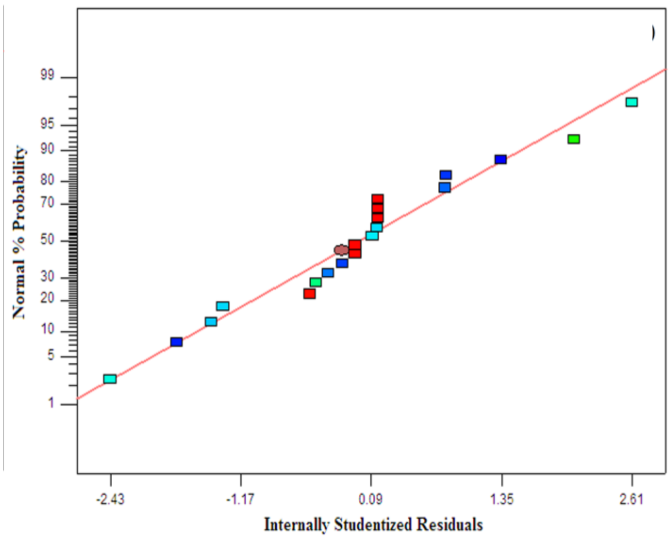
Table 7 ANOVA for the quadratic polynomial mode of PFS of concrete at seven and 28 days curing

Source of data	*Sum of squares*	*DF*	*Mean square*	*F value*	*p-value*
PFS seven days					
Model	13.6506743	9	1.516741589	638.7435969	< 0.0001
X_1	0.568113557	1	0.568113557	239.2489923	< 0.0001
X_2	0.013424578	1	0.013424578	5.6534765	0.0388
X_2X_3	0.0162	1	0.0162	6.8222869	0.0260
X_1^2	2.742723209	1	2.742723209	1155.039791	< 0.0001
X_2^2	7.836419356	1	7.836419356	3300.142044	< 0.0001
X_3^2	4.40935903	1	4.40935903	1856.90817	< 0.0001
Residual	0.023745703	10	0.00237457		
Lack of fit	0.02321237	5	0.004642474	43.52319353	0.0004
Pure error	0.000533333	5	0.000106667		
Cor total	13.67442	19			
PFS 28 days					
Model	23.12529919	9	2.569477688	1024.684028	< 0.0001
X_1	0.677703535	1	0.677703535	270.2619258	< 0.0001
X_2	0.029567422	1	0.029567422	11.79121535	0.0064
X_3	0.01330158	1	0.01330158	5.30454757	0.0440
X_2X_3	0.04205	1	0.04205	16.76915257	0.0022
X_1^2	5.549914218	1	5.549914218	2213.254656	< 0.0001
X_2^2	13.54713435	1	13.54713435	5402.472361	< 0.0001
X_3^2	6.670859258	1	6.670859258	2660.27721	< 0.0001
Residual	0.025075805	10	0.002507581		
Lack of fit	0.024392472	5	0.004878494	35.69630001	0.0006
Pure error	0.000683333	5	0.000136667		
Cor total	23.150375	19			

Figure 10 Normal percentage probability plots for the studentised residuals for the PFS after (a) seven and (b) 28 days of curing (see online version for colours)



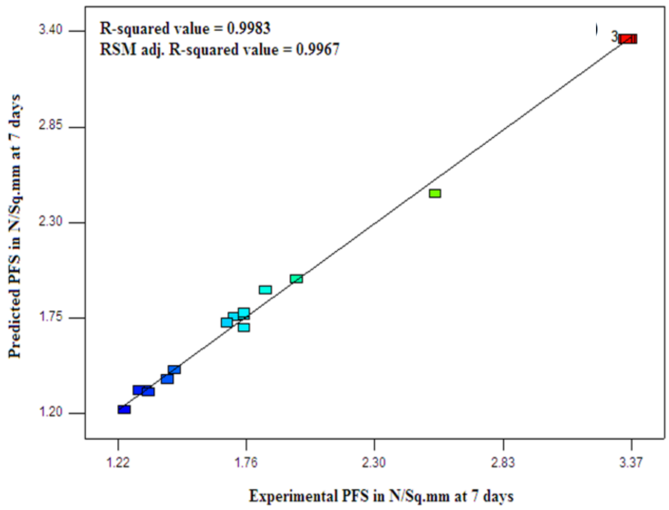
(a)



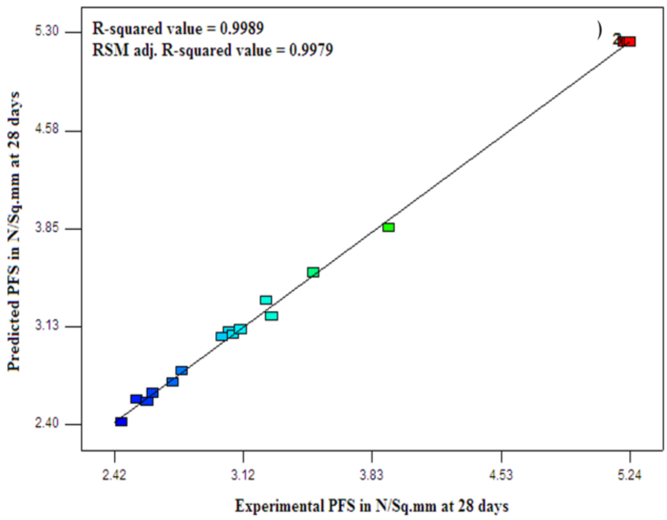
(b)

Figures 10(a) and 10(b) shows a normal percentage probability plot for the involvement of (X_1), (X_2) and (X_3), and these variants are normally distributed and show no deviation. Further, the predicted data and the experimental data have a higher R^2 value of 0.9983 and 0.9989 compared with the RSM's adjusted R^2 value of 0.9967 and 0.9979 at seven and 28 days of curing, respectively [Figure11(a) and 11(b)].The high obtained values of the regression coefficient (R^2 >> 0.8) are an indication of good fit. The 3D response surfaces [Figures 12(a) and 12(b)] and contour plots [Figures 12(c) and 12(d)] illustrate that the maximum flexural strengths of the concrete prism at seven and 28 days were 3.35 N/mm^2 and 5.23 N/mm^2, respectively, of the effective replacement of cement at GSA (X_1 = 8), GGBS (X_2 = 35) and PPF (X_3 = 0.30).

Figure 11 Relationship between experimental and predicted values for the PFS after (a) seven and (b) 28 days of curing (see online version for colours)

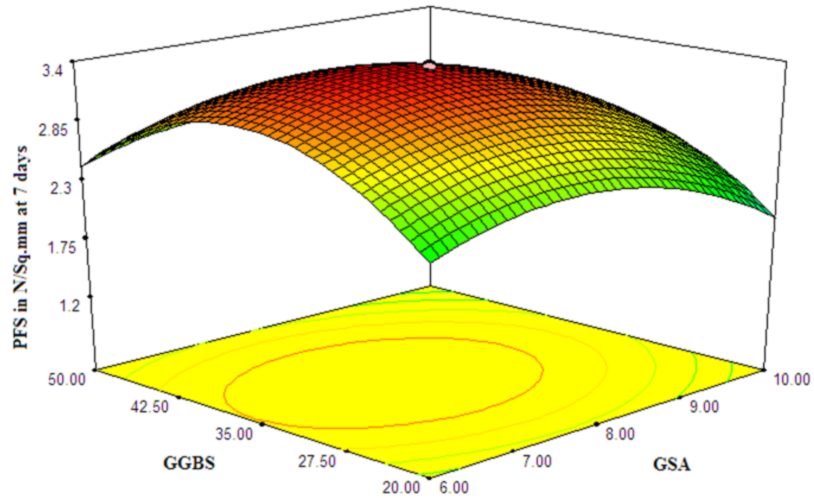


(a)

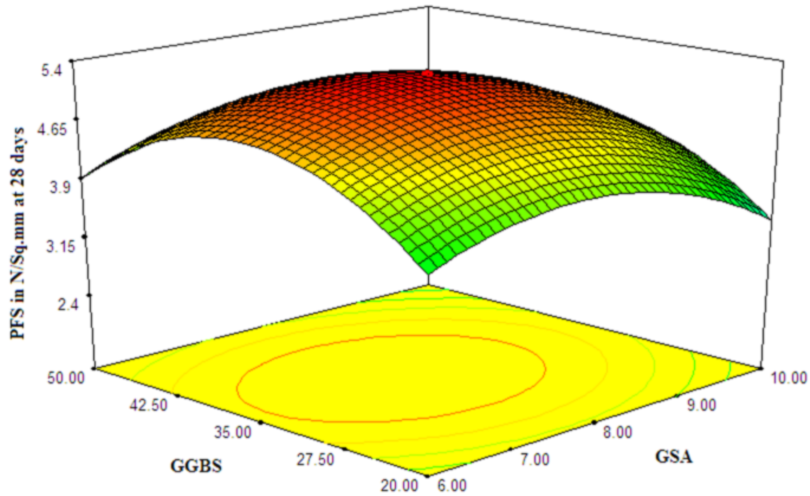


(b)

Figure 12 (a)–(b) 3D response surfaces and (c)–(d) contour plots showing the combined effects of GSA and GGBS for the PFS at seven and 28 days of curing, when PPF was held at a fixed level (see online version for colours)



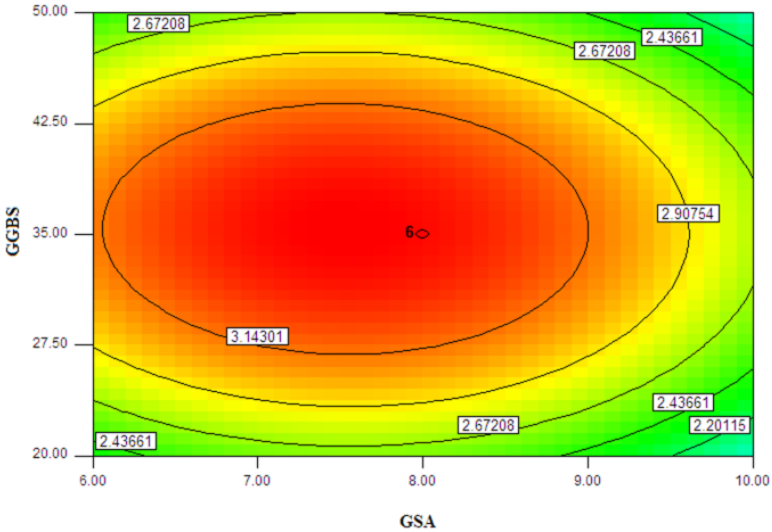
(a)



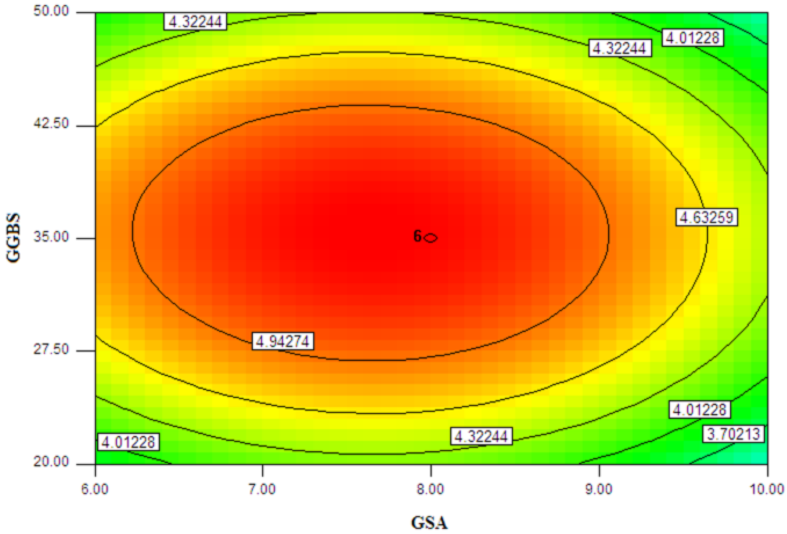
(b)

Note: Zero level = 0.30%.

Figure 12 (a)–(b) 3D response surfaces and (c)–(d) contour plots showing the combined effects of GSA and GGBS for the PFS at seven and 28 days of curing, when PPF was held at a fixed level (continued) (see online version for colours)



(c)



(d)

Note: Zero level = 0.30%.

3.3 Verification of the model

Verification of the suitability of the experiments was carried out to check the reliability of the optimisation of the partial cement replacement. In this vein, Tables 8a and 8b shows the verification of experiment under optimum conditions based on each individual response with the predicted and experimental values.

The experimental results showed that the replacement of cement with GSA (X_1), GGBS (X_2) and PPF (X_3) had significant effects on the maximum compressive strength, splitting tensile strength and flexural strength of concrete at seven and 28 days of curing. The verification experiment was conducted under optimum conditions based on the combination of responses, and small deviations were observed compared with the predicted values. The optimal conditions based on the combination of responses were GSA (X_1): 7.2%–8.4%, GGBS (X_2): 35% and PPF (X_3): 0.3%. Under these conditions, the obtained experimental results (compressive strength at seven and 28 days of 18.83 N/mm^2 and 31.06 N/mm^2 splitting tensile strengths of 2.39 N/mm^2 and 4.41 N/mm^2 and flexural strengths of 3.49 N/mm^2 and 5.32 N/mm^2, respectively) and predicted results (compressive strength at seven and 28 days of 18.80 N/mm^2 and 31.02 N/mm^2, splitting tensile strengths of 2.32 N/mm^2 and 4.34 N/mm^2 and flexural strengths of 3.38 N/mm^2 and 5.25 N/mm^2) were well matched. This experimental design implied that there was a good fit between the experimental values and those predicted by the regression model.

Table 8a Verification of experimental values under optimum conditions based on combination of responses

Sl. no.	*Cement (%)*	*Independent variables (X_j) in (%)*			*Experimental (Y_1) in N/mm^2*					
					Compressive strength		*Splitting tensile strength*		*Flexural strength*	
		GSA	*GGBS*	*PPF*	*CCS*	*CCS*	*CSTS*	*CSTS*	*PFS*	*PFS*
					Seven days	*28 days*	*Seven days*	*28 days*	*Seven days*	*28 days*
1	57.5	7.2	35	0.3	18.79	30.96	2.34	4.37	3.42	5.27
2	57.2	7.5	35	0.3	18.83	31.06	2.39	4.41	3.49	5.32
3	56.9	7.8	35	0.3	18.82	30.94	2.29	4.31	3.36	5.24
4	56.6	8.1	35	0.3	18.77	30.81	2.27	4.25	3.29	5.15
5	56.3	8.4	35	0.3	18.57	30.54	2.19	4.15	3.24	5.11

Table 8b Verification of predicted values under optimum conditions based on combination of responses

Sl. no.	*Cement (%)*	*Independent variables (X_j) in (%)*			*Predicted value (Y_2) in N/mm^2*					
					Compressive strength		*Splitting tensile strength*		*Flexural strength*	
		GSA	*GGBS*	*PPF*	*CCS*	*CCS*	*CSTS*	*CSTS*	*PFS*	*PFS*
					Seven days	*28 days*	*Seven days*	*28 days*	*Seven days*	*28 days*
1	57.5	7.2	35	0.3	18.75	30.98	2.31	4.32	3.37	5.22
2	57.2	7.5	35	0.3	18.80	31.02	2.32	4.34	3.38	5.25
3	56.9	7.8	35	0.3	18.79	30.98	2.32	4.33	3.37	5.25
4	56.6	8.1	35	0.3	18.73	30.84	2.31	4.30	3.34	5.22
5	56.3	8.4	35	0.3	18.61	30.61	2.28	4.24	3.30	5.16

4 Conclusions

Our initial evaluation demonstrated that the compressive strength of concrete was near that of the control specimen when the cement was replaced with 8% GSA. At the same time, when 8% GSA and 35% GGBS were substituted for the replacement of cement, the compressive strength of the concrete increased compared with that of the control specimen. Further, PPF (0.1%–0.5%) was incorporated into the cement mixture to enhance the splitting tensile strength and flexural strength of the concrete. The workability of the concrete was decreased when replacing the cement with GSA, GGBS and PPF, and it was enhanced by including superplasticiser.

In this research work, a statistical method of optimisation (RSM) based on CCRD was successfully applied to optimise the possible waste materials for the replacement of cement without changing its characteristics. The three waste materials – GSA, GGBS and PPF – had noteworthy effect and contributed to the improvement of the different types of concrete strength, namely compressive, splitting tensile and flexural strength, at seven and 28 days of curing. The optimum conditions ensuring the maximum compressive strength at seven and 28 days were 18.76–18.83 N/mm^2 and 30.91–31.06 N/mm^2 respectively, those for splitting tensile strength were 2.32–2.39 N/mm^2 and 4.32–4.41 N/mm^2 and those for flexural strength were 3.37–3.49 N/mm^2 and 5.24–5.32 N/mm^2, respectively. These results were observed with 7.5%–8% GSA, 35% GGBS and 0.3% PPF.

From the ANOVA for the second-order polynomial equation of the fitted model, it was concluded that the compressive strength of the concrete in the early stage was due to the combined action of GSA and PPF, while the splitting tensile strength of concrete at this stage was due to the integrated action of GGBS and PPF. It is overwhelmingly evident that the compressive and splitting tensile strengths of concrete improved in the later stage caused due to the slow reaction between the pozzolanic materials (GSA and GGBS). Furthermore, it is concluded that the flexural strength of the concrete in the early stage was due to integrated action of GGBS and PPF, while PPF alone played a major role for the development of the flexural strength in the later stage. The validity of the model was proven by fitting the observed experimental values and carrying out experiments using the predicted values.

The optimisation technique will be helpful for designing an effective method for replacing cement with waste materials. Moreover, the results showed that GSA, GGBS and PPF are good alternative materials, as they do not change the properties of cement and minimise the cost of construction, as well as environmental pollution.

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