DESIGN AND OPTIMIZATION OF MECHANICAL PROPERTIES OF GEOPOLYMER CONCRETE COMPOSITES USING RESPONSE SURFACE METHODOLOGY

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This paper shows the study of a statistical approach for finding the optimum values of the dependent and independent factors in Geopolymer concrete (GPC) composites using 75:25 of fly ash and Ground Granulated Blast Furnace Slag (GGBS). The input parameters considered in this study were alkali/binder, binder content and water/solids ratio. These factors affect the fresh and hardened properties of Geopolymer concrete such as slump value, compressive strength and split tensile strength for 28 days ambient curing. Response Surface Methodology (RSM) technique was used to optimize the trial mixes using Box-Behnken Design (BBD) by considering three factors. Results show that the optimum compressive strength of 57.05 MPa, optimum tensile strength of 4.52 MPa and optimum slump value of 135.034 mm was achieved by using optimum alkali/binder ratio, binder content and water/solids ratio of 0.386,420 kg/m^3 and 0.17 respectively. The desirability achieved for the optimum value is 0.9212 and the mean error was less than 5%. ANOVA results of the regression studies showed that each factor contribute significantly to the strength development of GPC.

Keywords: *Response Surface Methodology, ANOVA, regression, Box-Behnken, Geopolymer concrete, optimum value.*

1. Introduction

Geopolymer concrete shows superior void distribution than OPC concrete and hence better performance in bleeding behavior. The microstructural studies confirm the dense GPC microstructure and 6 % of the total green house gases comes from the construction industry[1]. Non destructive test like ultrasonic pulse velocity test can be used in response surface methodology technique for predicting compressive strength[2]. Increase in paste content affects the consistency; water to solids ratio affects the setting property and compressive strength of GPC. Liquid to binder ratio effect was less pronounced in GPC than OPC [3]. The reduced voids and discontinuous capillaries caused by proper curing leads to the increase in compressive strength of GPC[4]. The compressive strength of GPC attains maximum value with the increase in age and depends on the type of curing[5].Addition of OPC in GPC results in reduction of water absorption, sorptivity and chloride permeability[6]. Indian standard method can be used to design geopolymer concrete mix [7]. Box-Behnken Design can also be used in self-compacting concrete using bentonite and the response of the model is validated by using mean absolute error and root mean square error [8].

A model to find the compressive strength using ultrasonic pulse velocity and microstructural phase volume fractions shows good performance of geopolymer concrete[9].The shape of the specimen influences the strength of concrete. Cube specimens perform well when compared to cylindrical specimen [10].Regression analysis of mechanical properties of GPC shows similar performance in OPC concrete [11]. The compressive strength increases with longer curing time. Super plasticizers can be utilized to improve the workability of fresh geopolymer concrete. Geopolymer concrete uses no cement and includes the alumino silicate rich materials like fly ash [12].In Ultra High Performance Concrete (UHPC), using 1.75% of the volume of hybrid steel fibers gives the optimum values in RSM [13]. As the molarity of GPC increases,density of GPC increases and the microstructure shows that GPC structure is homogeneous[14]. RSM can be used to find the optimum compressive strength and workability values in UHPC using cement and silica fume [15]. Central Composite Design (CCD) was done in finding the relation between curing and compressive strength of 3, 7 and 28 days.S/N,H/Al,Na/Al ratios were considered in CCD of alkali activated phosphorous slag. Results conclude that Na/Al is an important factor for compressive strength of 7 and

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28 days[16]. When the coefficient of variance is less than 10% the predicted model is good. Multi objective optimization is a robust technique of finding compatibility of all the factors at the same time [17].Treated bamboo reinforced epoxy composites offered treated core structures [18]. The strength of GPC increases followed by the increase in binder content, curing temperature and curing period [19]. With the increase in cement production the amount of CO_2 emitted into the atmosphere is also increased leading to global warming.It is estimated that one ton of cement produces one ton of CO_2 [20]. The addition of sisal fibers improved the mechanical properties with optimum activator/metakaolin ratio of 0.59 [21]. Various efforts have been taken to reduce the CO_2 emission caused by the production of cement. Low alkaline/binder ratio reduces the consistency of mix leading to low compressive strength. If the alkaline /binder ratio is increased to 0.6, segregation of the mixture starts. Oven curing gains more strength when compared to ambient curing. [22]. If the GPC is coated with rice husk ash, the voids are filled and adhesion strength increases [23].When the sodium silicate/sodium hydroxide ratio lies between 0.5 to 1 the compressive strength increases .GGBS, rice husk ash, metakaolin etc., which can be used as binders [24].Fine aggregate/fly ash ratio and water to geopolymer solids are optimized using response surface methodology.The results show that the difference between experimental and predicted values are less than 5 % [25]. Gap graded aggregate design seems to be fit since all the voids are filled completely by fine aggregate leading to increase in strength [26].Fly ash blended with GGBS can be used to produce medium strength concrete and reduces the setting time [27].Geopolymers belong to inorganic polymers family and its microstructure is an amorphous one.Silicon and Aluminium can be made to react with an alkaline liquid and industrial by-product materials such as fly ash, GGBS etc to make a polymerization reaction [28].Compared to artificial neural network and other optimization methods, response surface methodology technique is used to find the optimization of compressive strength in geopolymer concrete[29].When the coefficient of variance is less than 10% the predicted model is good. In ANOVA analysis if the probability is greater than 0.001 it indicates that the selected values for the responses are insignificant [30].Fineness properties of GGBS, fly ash, alkali activated solution, molarity and curing temperature affects the GPC properties [31]. RSM model helps to reduce the number of trials when compared to conventional method [32]. Alkaline activator influences the workability and end products [33]. RSM technique can be used when more individual factors have influence on one factor [34]. Statistical approach produces cost effective and reliable results [35].RSM technique gives accurate result when compared to taguchi method [36]. Combined grading of aggregates and including specific gravity of all materials of GPC eradicates the errors in mix design [37].If the silica alumina ratio increases the alkali activator content also increases resulting in higher cost [38].The quadratic model shows higher prediction accuracy in BBD when compared to all other design [39]. The alkali activated solution increases the mechanical properties of GPC [40].Curing temperature, activator/fly ash ratio and molarity are significant for the early responsible of compressive strength when compared to sodium hydroxide/sodium silicate ratio [41]. If the total aggregate content is increased to 78% there is a reduction in workability by 37.5 %. Hence 76% of the total aggregates in GPC contribute to good workability [42]. Davidovits proposed the term 'geopolymer' concrete as an alternative material to Ordinary Portland Cement (OPC) concrete.Geopolymers belong to inorganic polymers family and its microstructure is an amorphous one. The ring structure in geopolymer is made of Si-O and Al-O bonds [43]. An average of 112 million tons of fly ash is produced as waste material in the world. Hence there is a need for using alternative material for cement. [44].

2 .Materials and Mix Proportions of GPC

2.1 Materials

Low calcium fly ash of class F (ASTM C 618) used in the study was obtained from Tuticorin. GGBS was purchased from Madurai. The properties of fly ash and GGBS are given in the table. Locally available coarse aggregate having (10mm and 20mm) size was used. Fine aggregate was obtained as conforming to grading zone II as per IS: 383:1970.Sodium silicate solution and sodium hydroxide solids were obtained commercially from Salem. The sodium hydroxide solids obtained was of pellet form and is of 99 percent pure. The sodium hydroxide solution of 10 Mol was prepared by dissolving (10 x 40 = 400) grams of NaOH in distilled water to form 1 litre solution. The sodium silicate and sodium hydroxide mixture will be acting as an activator in forming the geo polymerization reaction in GPC. The mixture of sodium silicate solution and sodium hydroxide solution forms the alkaline liquid and it was prepared 24 hours prior to mixing. To start with, fine aggregate and coarse aggregate of the desired proportion as given in the table was mixed in a mixer. After 30 seconds, fly ash and GGBS were mixed and alkaline solution was mixed continuously. Then extra water and super plasticizer (as calculated) was added to the mixture to achieve the desired workability of placing GPC. In this present investigation, naphthalene based super plasticizer called as Conplast SP 30 has been used for obtaining workable concrete. Three cubes were casted for each mix proportions of fly ash and

Table 1

Properties of materials used

(i) Chemical properties (%)

Compounds	fly ash	GGBS
SiO_2	60.21	31.24
Al_2O_3	24.30	13.65
Fe_2O_3	4.98	1.25
CaO	3.24	42.62
MgO	1.10	4.53
SO_3	0.85	3.12
Loss of Ignition	1.15	0.75

(ii) Physical properties

Property	fly ash	GGBS
Specific surface area (m^2/kg)	358	510
Specific gravity	2.32	2.76

GGBS in the ratios of 75:25 respectively by replacing cement as per the design mix proportions.

2.2 Mix proportions of GPC

In this study low calcium (class F) fly ash and GGBS were used instead of cement in making GPC. The physical and chemical properties of all materials used in GPC are shown in Table 1. Coarse aggregate and fine aggregate contributes 75% to 80% by mass of GPC. By taking 77% by mass of coarse and fine aggregate in this design, fine aggregate contributes 30% of total aggregate. The ratio of (Na_2SiO_3 / NaOH) is 2.5. The coarse aggregates were taken as 776.4 kg/m^3 and 517.6 kg/m^3 for 20 mm and 10 mm size respectively. The fine aggregate taken was 554 kg/m^3, GGBS and fly ash were taken as 98.5 kg/m^3 and 295.5 kg/m^3.Sodium silicate, sodium hydroxide, water and super plasticizer used was 113 kg/m^3, 45 kg/m^3, 90 kg/m^3 and 11.82 kg/m^3 respectively.

In this work several trials were done to study the behavior of alkali activation using the binder comprising of fly ash and GGBS. If the percentage of GGBS is greater than 40% it will leads to shrinkage cracks and if GGBS is less than 30 % it will not support ambient curing [28]. To balance this fly ash and GGBS were taken in the ratio of 75:25 for binder. The main constituents of fly ash were silica and alumina. It will react with alkali activated solution and forms alumino silicate hydrate gel. GGBS mainly compromises of silica and calcium and it forms calcium silicate hydrate gel. According to Mallikarjuna Rao et.al (2018) for achieving higher strength, fly ash is combined with GGBS and it holds better here [22].The ratio of sodium silicate and sodium hydroxide was taken between 2-2.5.The binder quantities were taken between 360-420 kg/m^3.The ratio of water to solids ratio was maintained between 0.16-0.24.All these values were taken by referring to the past literatures [25, 28, 31].

3. Experimental Programme

3.1 Workability Test

The workability of GPC was measured by slump cone test as per IS 1199-1959. Workability depends on the binder materials, amount of fluid present in the mix including alkali activated solution, water, super plasticizer and the aggregates present. Unless cement based concrete, GPC provides sustainability by reducing the emission of carbon-di-oxide because cement is replaced by fly ash and slag [20]. The slump test should be done immediately after the GPC is prepared. The workability gets reduced with the addition of GGBS, but it improves the initial workability of the mix [28].

3.2 Compressive strength Test

In this study the compressive strength test is done as per IS 516-1959 in a compression testing machine under the standard loading requirement. For each binder content and alkali/binder (al/bi) ratio three cubes were casted, tested and the average values of three cubes were taken as the average compressive strength. Totally 45 cubes were tested. The compressive strength test in GPC was determined in cubes 150 mm x 150 mm x 150 mm size. The cubes were de-moulded after 24 hours and cured in room temperature (temperature is 28 $\pm$ 5 ^{0}C and relative humidity is 75%) for 28 days. After 28 days the cubes were tested and the results were tabulated. The compressive strength value depends upon the binder content, activated solution and the amount of aggregates present.

3.3 Split Tensile Test

Cylinders of size 150 mm x 300 mm were casted for doing split tensile test as per IS 516-1959.Within 20 minutes, the GPC was prepared ,mixed ,vibrated and placed in moulds ,to avoid initial setting of the mixture. Totally 45 cylinders were tested. The cylinders were casted and left for one day and it was de moulded. The specimens were cured at ambient temperature which means out door temperature (temperature is 28 $\pm$ 5 ^{0}C) for 28 days. After the curing period was completed the cylinder specimens were tested in a compression testing machine.

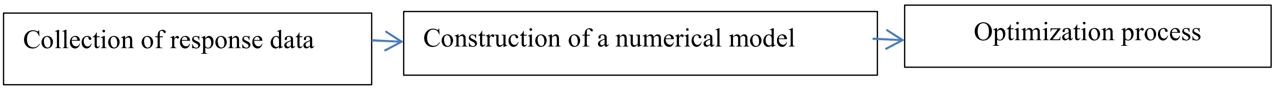
3.3 Response Surface Methodology (RSM):

Conventional method of trial and error basis is a time consuming method if the number of

Table 2

Coded factor levels for Box-Behnken Design (BBD)

Parameter	Levels			
	Levels of code	-1	0	1
Alkali/binder (ratio)	A	0.300	0.375	0.45
Binder (kg/m^3)	B	360	390	420
Water/solids (ratio)	C	0.16	0.20	0.24



variables are more. Hence a robust method of optimizing multi variables was done using response surface model. RSM is an optimization technique for finding the optimum parametric values under some controlled factors. It is a statistical cum mathematical modelling to find out the effect and response. Three main steps are included above.

The basic equation for single order RSM is represented by Yo = f ($X1 + X2 \ldots\ldots\ldots X_n$)

Where Yo is the expected response of all independent variables $X1, X2 \ldots\ldots Xn$

For second order RSM, the polynomial equation is given by

$$Yo = \beta o + \sum_{i=1}^{n} \beta iXi + \sum_{i=1}^{n} \beta iiXii + \sum_{i=1}^{n} \beta ijXij$$

Where Yo is the expected response (slump value, compressive strength, split tensile strength) Xij represents the independent variable (alkali/binder ratio (al/bi), binder, water/solids (w/s) ratio) βo is the constant, βi, βii and βij are the linear coefficient, square coefficient and interactive coefficient respectively.

3.4 Design of Experiments (DOE)-Box Behnken Design

In this study Response Surface Methodology (RSM) was done by Box-Behnken Design (BBD) in minitab 19 software. BBD gives the compatibility between the selected three factor levels and their responses. In BBD design the number of experiments (N) is given by the equation N = 2k (k-1) + C, where K is called the number of factors and C is the number of central points. Here three factors taken were alkali/binder ratio, binder, water/solids ratio and the base runs were 15. In this design the low level, central point and high level was encoded as -1, 0 and +1 respectively. Table 2 shows the coded factor levels and Table 3 indicates the coded values, actual values and response values. Mix number 13 to 15 is the experimental mix to find the stability of the design.

4. Results and Discussion

The results for workability, compressive strength and split tensile test were tabulated. The results obtained were analyzed for the effect of alkali/binder ratio (al/bi), binder (bind) and.

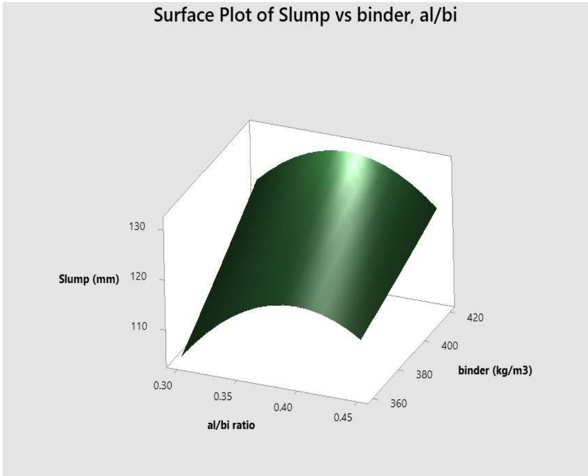


Fig 1(a) Surface plot of slump vs binder, al/bi ratio

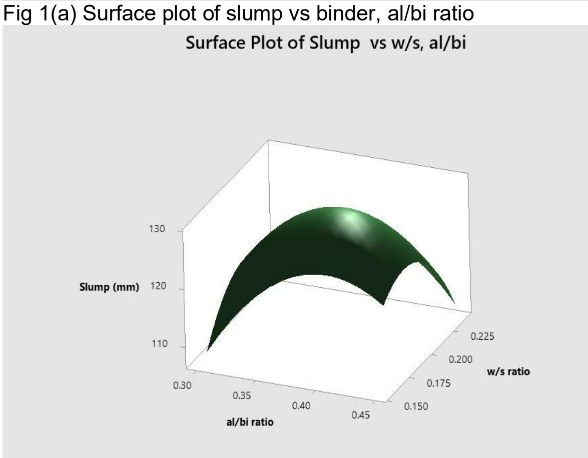


Fig 1(b) Surface plot of slump vs w/s ratio,al/bi ratio

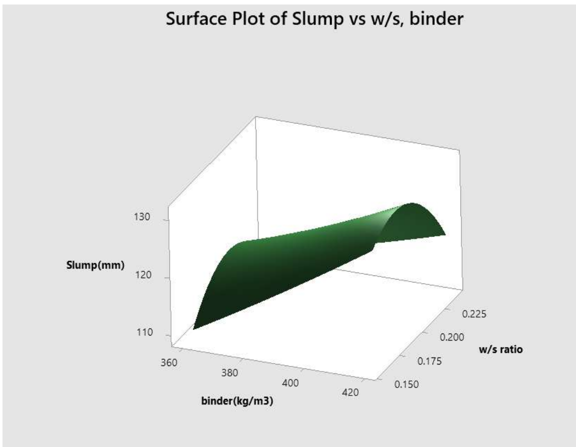


Fig 1(c) Surface plot of slump vs w/s ratio,binder

Table 3

Design of Experiments (DOE) matrix for Box-Behnken Design

Mix	**Coded values**			**Actual values**			**Response values**		
	A	B	C	al/bi ratio (A)	Binder (kg/m^3) (B)	w/s ratio (C)	Slump (mm)	Compressive strength (MPa)	Split tensile strength (MPa)
G1	-1	-1	0	0.375	420	0.16	135	57.84	4.52
G2	1	-1	0	0.375	390	0.20	132	57.56	4.38
G3	-1	1	0	0.375	390	0.20	130	56.94	4.26
G4	1	1	0	0.300	420	0.20	125	54.88	4.09
G5	-1	0	-1	0.450	360	0.20	118	55.49	3.98
G6	1	0	-1	0.375	360	0.16	115	55.75	3.85
G7	-1	0	1	0.450	390	0.24	110	56.41	3.81
G8	1	0	1	0.375	360	0.24	112	55.64	3.97
G9	0	-1	-1	0.450	390	0.16	119	54.78	4.14
G10	0	1	-1	0.300	360	0.20	108	54.43	4.12
G11	0	-1	1	0.300	390	0.16	106	54.22	4.06
G12	0	1	1	0.300	390	0.24	113	55.21	4.32
G13	0	0	0	0.375	420	0.24	121	55.35	4.38
G14	0	0	0	0.375	390	0.20	124	55.62	4.46
G15	0	0	0	0.450	420	0.20	126	55.81	4.48

Note: al/bi represents alkali/binder; w/s represents water/solids

water/solids (w/s) ratio from surface diagram, contour diagram of BBD and p values from ANOVA using minitab 19 software. Finally multi objective optimization and validation of the results were done.

4.1. Effect of workability (slump) on GPC

Workability refers to the ease with which concrete can be easily handled, mixed, transported and placed. Figure 1a, 1b, 1c and 2a, 2b, 2c shows the surface plot and contour plot of slump values against binder, w/s and al/bi ratio. From the contour plot there is an increase in slump value with the increase in binder content. According to Muhammad Zahid et.al (2020), the spherical shape of fly ash combined with the lubricating effect of the sodium hydroxide and sodium silicate solutions are responsible for the roller effects and easy flow of the GPC [25]. It can also be noted that the alkaline to binder ratio has an impact in the slump value and the central area of the figure shows slump value greater than 125 mm. The workability increases up-to al/bi ratio of 0.375 and after that it decreases with the increase in binder ratio. The maximum slump of 132 mm reaches after various trials at al/bi ratio of 0.375 and w/s ratio of 0.20 at the central region. The slump value is least of 110 mm when the alkaline binder ratio is 0.450 and water to solids ratio is 0.24 as seen in the contour diagram. When the w/s ratio decreases there will be an increase in workability due to increase in geo polymerization [27].The workability gets reduced due to the increase in GGBS and reduced sodium hydroxide to sodium silicate ratio [28]. The regression equation in uncoded unit for slump is given by:

Slump = -858 + 1903 (al/bi) + 1.35 binder +3230 (w/s) -1615 (al/bi x al/bi) - 0.00037 binder x binder – 4740 (w/s x x w/s) -1.000 ((al/bi) x binder) -1333 ((al/bi) x x (w/s)) -2.29 (binder x (w/s))

Where (al/bi) and (w/s) represents alkali/binder and water/solids ratio respectively.

4.2 Effect of compressive strength on GPC

The primary mechanical property to be understood in concrete is the compressive strength. According to Partha Sarathi Deb et.al (2014), the compressive strength of concrete acts as an indicator for other mechanical properties since all other properties correlates with it correctly [28]. The surface plot and contour plot shown in figure 3a, 3b, 3c and 4a, 4b, 4c indicates that the compressive

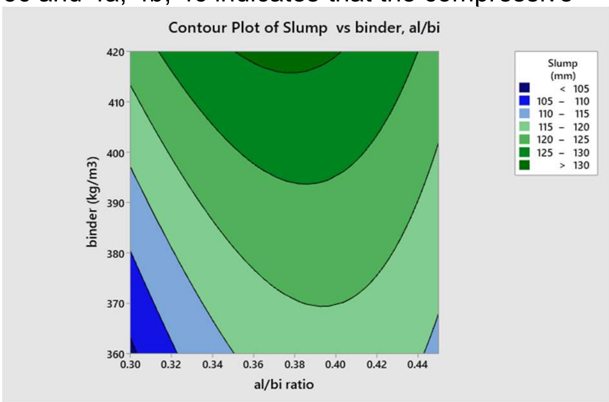


Fig 2(a) Contour plot of slump vs binder,al/bi ratio

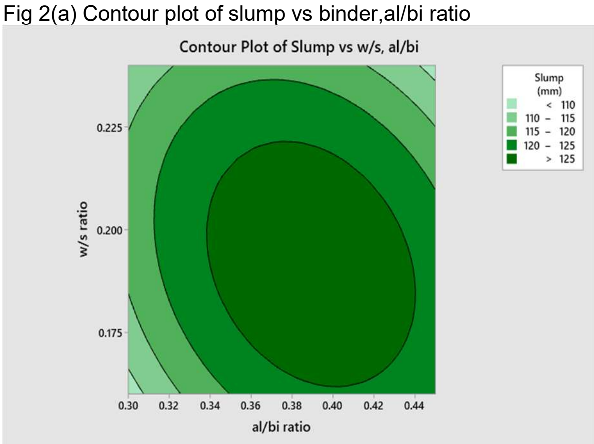


Fig 2(b) Contour plot of slump vs w/s ratio ,al/bi ratio

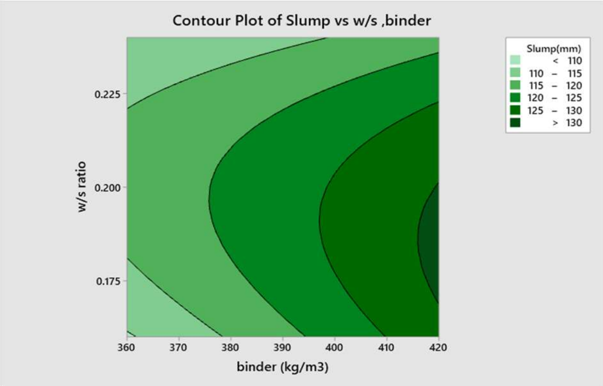


Fig 2(c) Contour plot of slump vs w/s ratio,binder

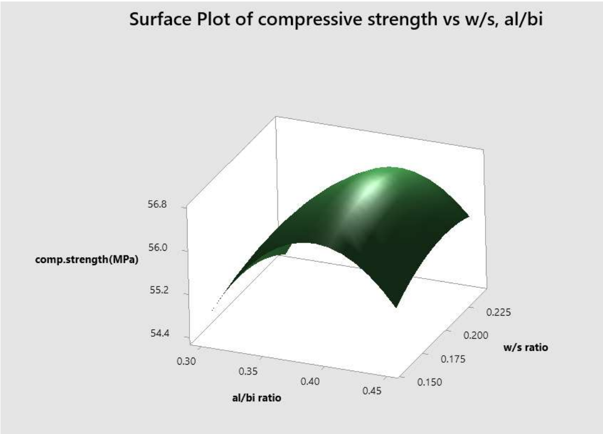


Fig 3(a) Surface plot of compressive strength vs w/s ratio,al/bi ratio

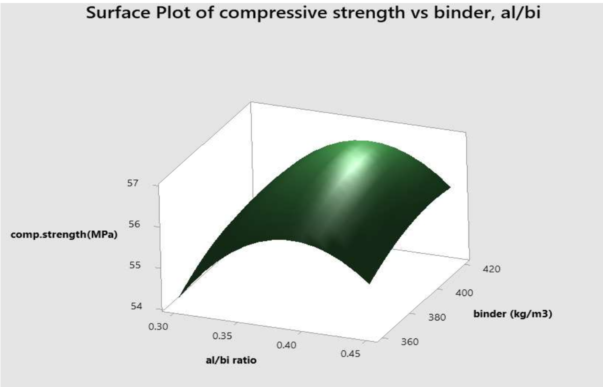


Fig 3(b) Surface plot of compressive strength vs binder,al/bi ratio

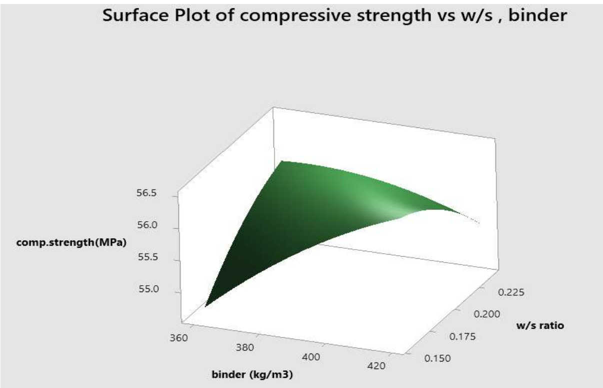


Fig 3(c) Surface plot of compressive strength vs w/s ratio,binder

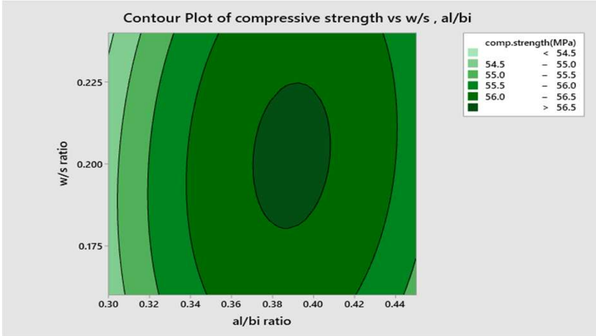


Fig 4(a) - Contour plot of compressive strength vs w/s ratio,al/bi ratio.

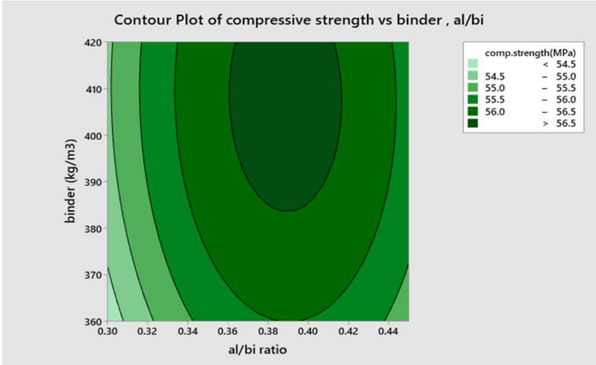


Fig 4(b) - Contour plot of compressive strength vs binder,al/bi ratio

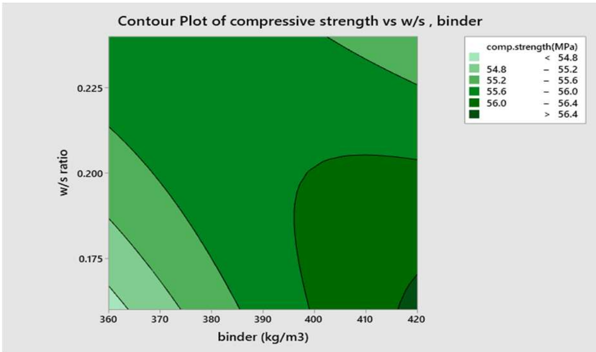


Fig 4(c) - Contour plot of compressive strength vs w/s ratio,binder

strength increases with the increase of binder content and decreases with the increase of w/s ratio from 0.175 to 0.20. If the water to solids ratio further decreases the workability decreases leading to poor strength [10]. When the water content is reduced the alkali content increases the polymerization reaction resulting in good strength. Furthermore the al/bi ratio increases, the compressive strength also increases. The maximum compressive strength was found as 57.56 MPa for al/bi ratio of 0.375. When the ratio of sodium silicate/sodium hydroxide is increased beyond 3 the compressive strength decreases due to increase in alkali content which reduces the polymerization reaction [40].The compressive strength is decreased to 54.88 MPa for w/s ratio of 0.20. The regression equation is derived as given below:

Compressive strength = -73+171(al/bi) +0.360 binder +243 (w/s) -226.1 (al/bi x al/bi)
- 0.000313 binder x binder – 175 (w/s x w/s) -0.014 ((al/bi) x binder)
+53 ((al/bi) x (w/s))-0.496 (binder x (w/s))

Where (al/bi) and (w/s) represents alkali/binder and water/solids ratio respectively.

4.3 Effect of split tensile strength on GPC

It is an indirect method used to find the tensile strength of concrete. The variation of results using many trial mixes in GPC is shown below.

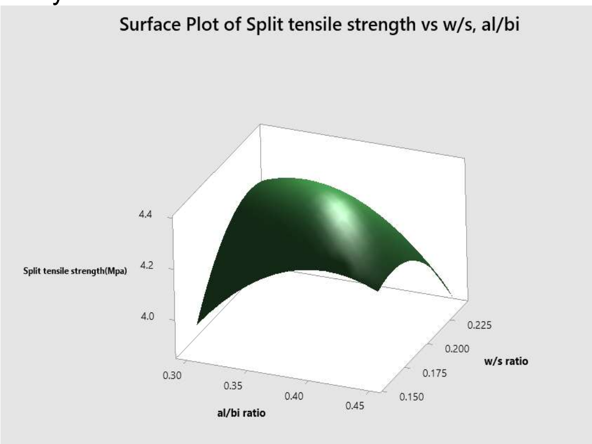


Fig 5(a) - Surface plot of split tensile strength vs w/s ratio,al/bi ratio

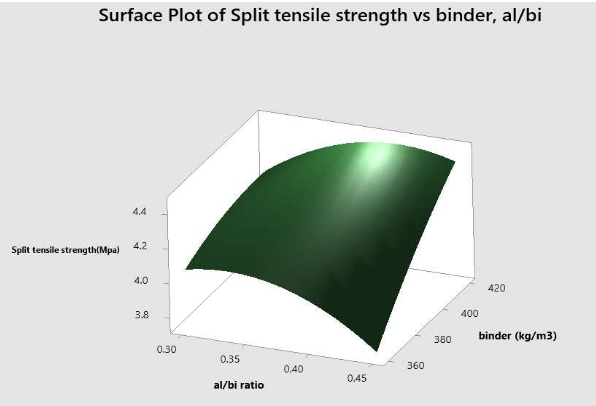


Fig 5(b) - Surface plot of split tensile strength vs binder,al/bi ratio

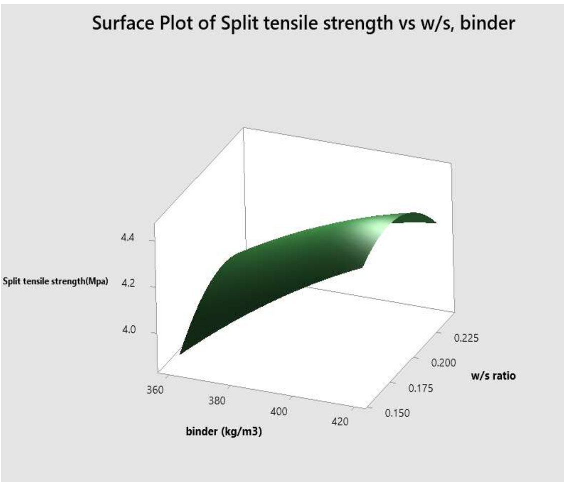


Fig 5(c) - Surface plot of split tensile strength vs w/s ratio,binder

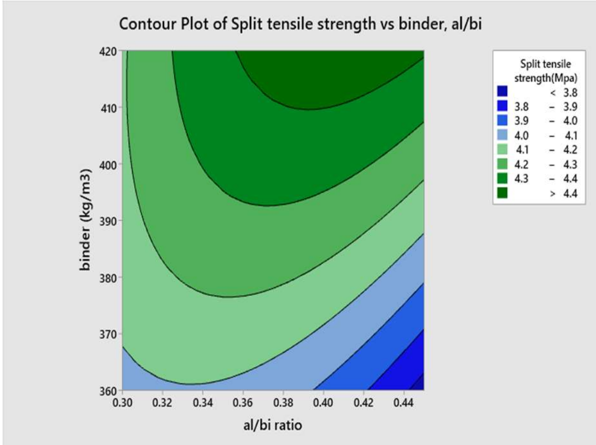


Fig 6(a) - Contour plot of split tensile.strength vs binder,al/bi ratio

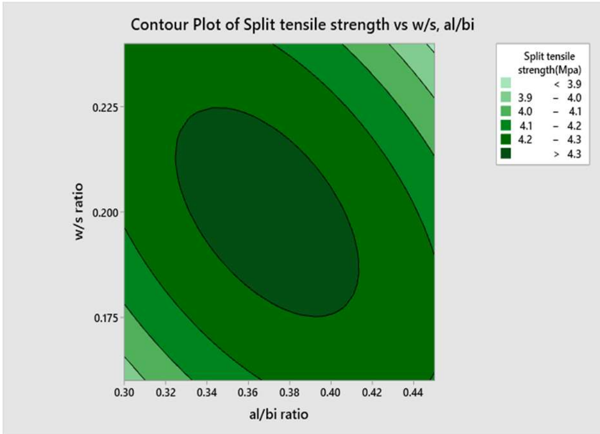


Fig 6(b) - Contour plot of split tensile strength vs w/s ratio,al/bi ratio

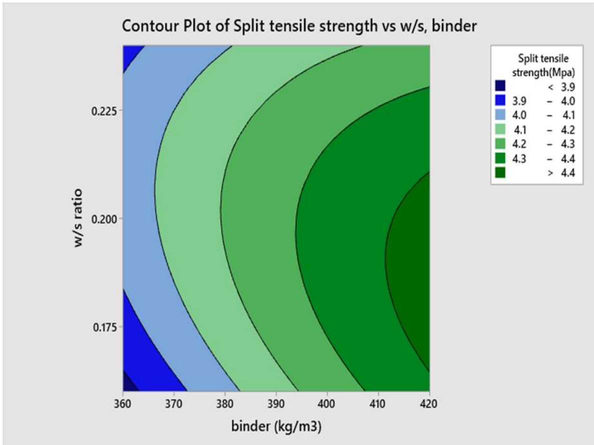


Fig 6(c) - Contour plot of split tensile strength vs w/s ratio,binder

The surface plot and contour plots are drawn for the behavior of split tensile strength test in figure 5a, 5b 5c and 6a, 6b, 6c. From the contour surface plot it is known that the maximum split tensile strength is 4.38 MPa at the central region for al/bi ratio 0.375 and w/s ratio 0.20.As the alkali/ binder ratio increases the split tensile strength starts decreasing but the binder content increases the split tensile test results. The maximum split tensile value is experimentally found as 4.52 N/mm^2 for a binder

Table 4

ANOVA results for regression analysis

Response	Mean	Standard deviation	R^2 (%)	R^2 predicted (%)	R^2 adjusted (%)	Sum of square	Mean square	F value	P value
Slump	119.60	8.97	99.46	99.37	99.43	1520021	506674	3407.17	0.000
Compressive strength	55.729	1.063	99.55	99.48	99.52	1581137	527046	4090.22	0.000
Split tensile strength	4.188	0.2309	99.58	99.52	99.55	1697374	565791	4400.11	0.000

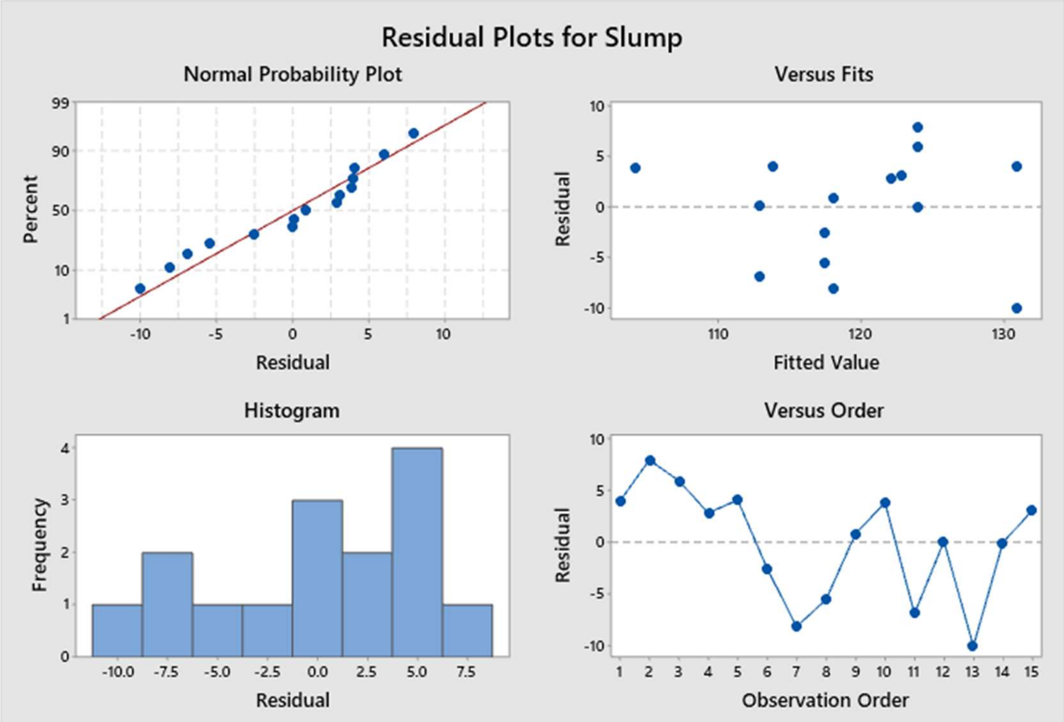


Fig 7 (a) - Residual plots for workability (slump)

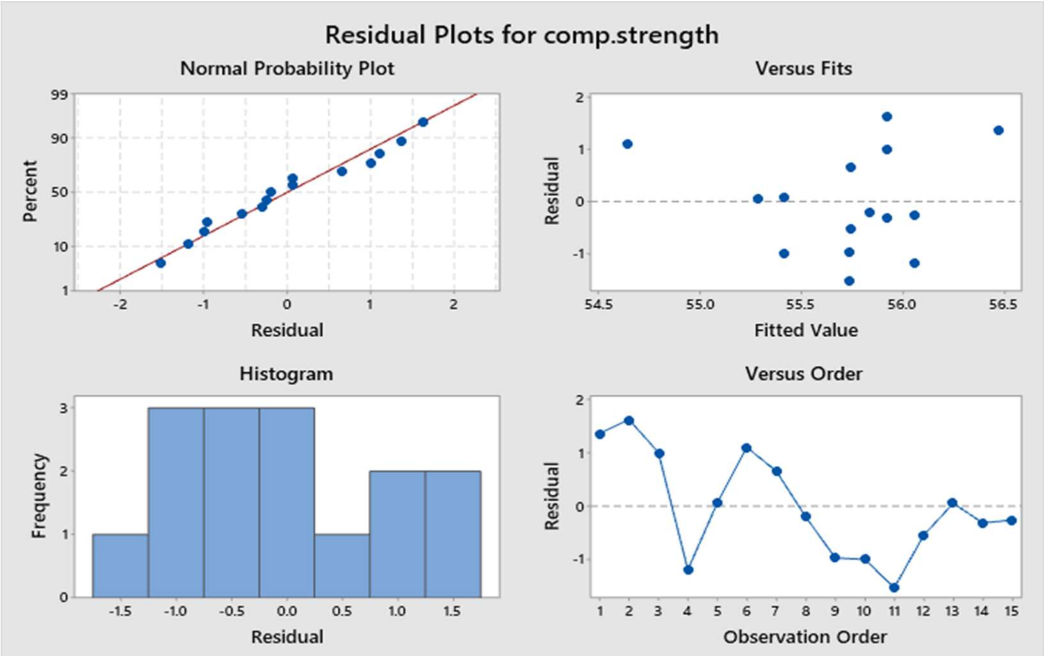


Fig 7 (b) - Residual plots for compressive strength

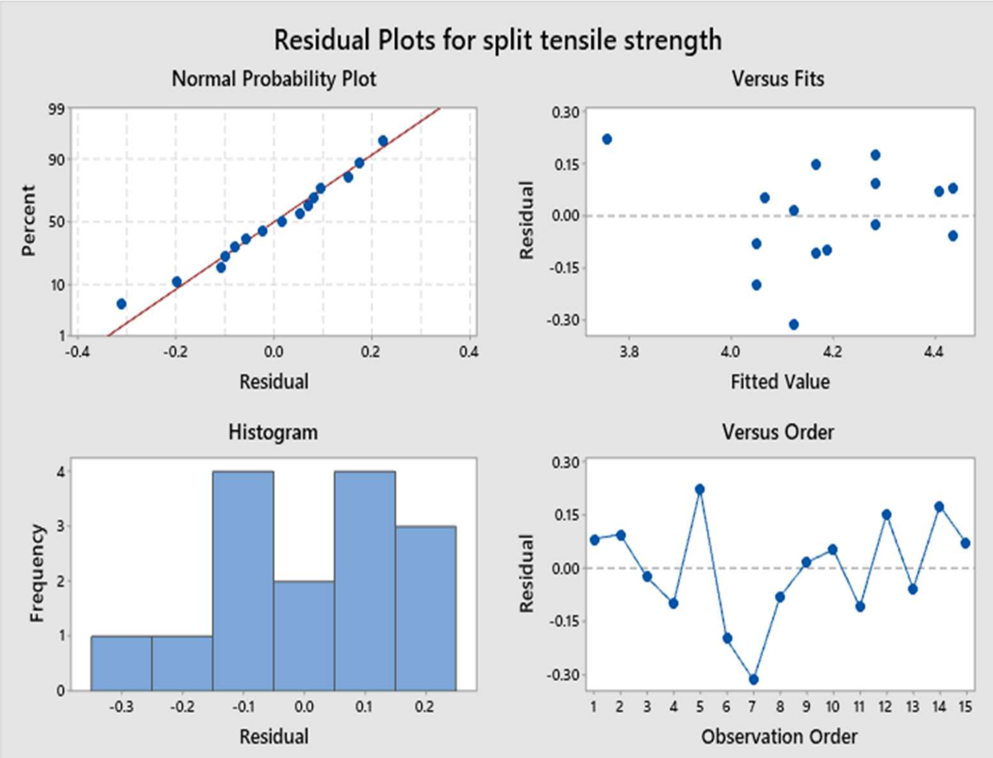


Fig 7 (c) - Residual plots for split tensile strength

content of 135 kg/m^3. The water/solids ratio has minimum effect on tensile strength since there is a lower bond between the binder and water content. From the regression analysis, the equation was derived as given below.

Split tensile strength = -13+6.3 (al/bi) +0.0.93 binder +73.2 (w/s) -26.4 (al/bi x al/bi)
-0.000056 binder x binder –
-84.9 (w/s x w/s) +0.0589 ((al/bi) x binder) -
-49.2 ((al/bi) x (w/s)) -
-0.0542(binder x (w/s))

Where (al/bi) and (w/s) represents alkali/binder and water/solids ratio respectively.

4.4 ANOVA results

Extra experiments were carried out to check whether the analytical results are correct so that it can be referred for future use. The experimental results are verified using ANOVA analysis to find the optimum value of alkali/binder, binder content and water/solids ratio. Since the two order interaction shows some values greater than 0.05 (significant level) these values are taken unimportant and the equation was rewritten using first order terms only. All the input and output response were taken at 95% significant level. The value of p in this regression analysis taken for the response values is 0.000 as shown in Table 4 and is of significant .The difference between R^2 adjusted and predicted having less than 0.2 and low standard deviation are considered as the model accepted values[25].

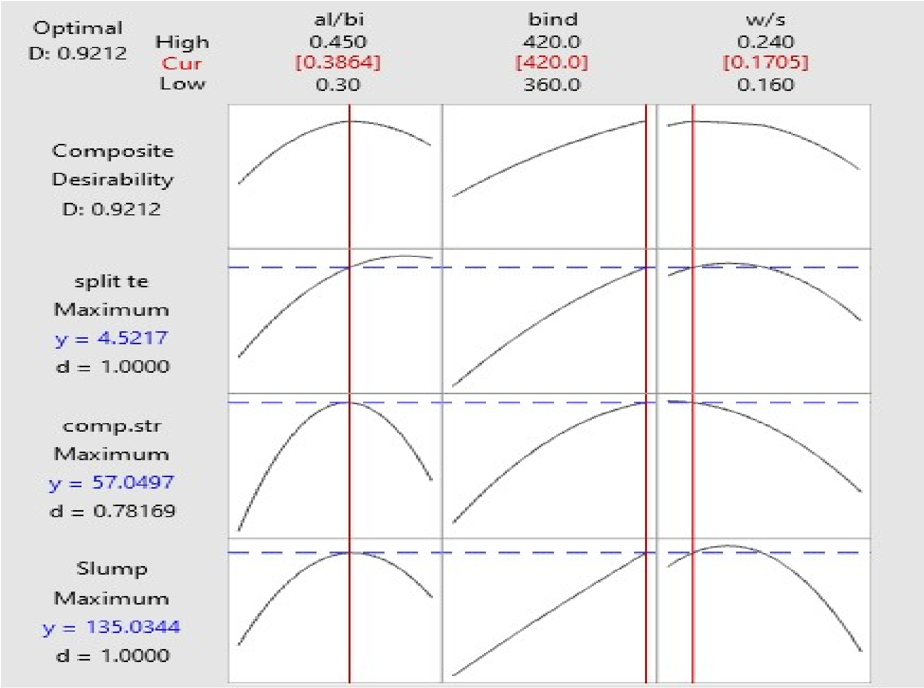
4.5 Residual plot

Residual plot helps to identify the deviations in regression analysis. Figure 7 a, 7 b and 7 c shows the four in one residual plots for all the three responses namely slump, compressive strength and split tensile strength. The first plot and third plot in the entire figure is the normal probability plot in which all points are clustered near the red line for all the base runs of 15 and it is quite normal. In the second graph and fourth graph for the fitted value all the data points are randomly distributed and there is no cyclic pattern or trend line pattern observed.

4.6 Optimization and Validation

In order to verify the experimental values of this GPC mix design an additional experiment was carried out to find the minimum input factors for getting maximum response. Response optimization plots helps to find the optimal response of all the factors individually. In multi objective optimization all the three inputs of alkaline/binder ratio, binder content and water/solids ratio are taken simultaneously and analyzed to achieve the desired goals. The input values given are assessed for getting the optimum values using minitab software. Figure 8 shows the optimized response values for three input parameters and three responses. The vertical red lines in the graph shows the best values for the input factors.

Desirability is defined as the average desirability of independent and non-independent factors. The desirability value is 0.9212 which is nearer to 1 is a good one in the case of three factor optimization. The optimization was done by considering the desirability values. The experimental values and the predicted values show little difference with a mean error less than 5 %.



Note: al/bi-alkali/binder ratio; bind-binder (kg/m^3); w/s-water/solid ratio; slump in mm; compressive strength in MPa; split tensile strength in MPa

Fig 8 - Optimization and desirability result

Table 5

Responses and goals in multi response optimization

Response	Lower value	Upper value	Goal
Slump (mm)	106	135	Maximum
Compressive strength (MPa)	54.22	57.84	Maximum
Split tensile strength (MPa)	3.81	4.52	Maximum

Table 6

Validation of optimal design

Parameters	Optimized values	Experimental values	Error (%)
Slump (mm)	135.034	135	0.025
Compressive strength (MPa)	57.0497	57.84	1.37
Split tensile strength (MPa)	4.52169	4.52	0.037
Mean Error			0.477

The mean error for the optimization is 0.477 % which shows that there is a good significance between the factors considered and the response values. Table 5 and 6 shows the goals and validation results respectively.

5. Conclusion

The geopolymer concrete was studied by considering three main factors that affect the mechanical properties namely alkali/binder, binder content and water/solids. The orthogonal study was performed using BBD of response surface methodology. The following conclusions were drawn from the experimental results:

1. The experimental work shows that the increase in workability is followed by the increase in compressive strength and split tensile strength as the alkali/binder ratio increases to 0.450. An increase in alkali/binder ratio made the mix segregated thus increasing the slump and compressive strength. This is similar to ordinary concrete where in the slump value increases as the water/cement ratio increases. If the al/bi ratio is reduced to 0.300 the mix became stiffer leading to reduction in compressive strength.
2. The specimens with high binder content and low water/solids ratio exhibited higher compressive strength and tensile strength. The workability is decreased with the increase in water /solids ratio. The lesser the water content, lesser will be the unreacted fly ash and GGBS present in the mix leading to denser structure and higher strength. The addition of GGBS in GPC tends to form a compacted microstructure leading to the increase in compressive strength. Split tensile strength also follows the same trend of compressive strength.

3. In ANOVA results the R^2 value is above 99% for all the responses and hence p value is also significant. The RSM models derived by using BBD can be used to predict the responses value very nearer to the experimental values within 95% confidence level. The predicted R^2 values from the derived RSM models shows that the predicted results fit with the experimental values and the error was very small. Small deviations are seen in residual vs fitted value plots for slump, compressive strength and split tensile strength. This may be due to distribution of various aggregate sizes and inadequate curing.

4. Multi objective optimization helps to know the optimum values of each dependent variable and independent variables. The optimum responses for slump, compressive strength and split tensile strength were 135.034 mm, 57.0497 MPa and 4.52169 MPa respectively. The desirability was 0.9212 and the mean error was found to be 0.477 %.

5. The optimum mixtures for Geo Polymer Concrete were suggested as alkali/binder ratio of 0.386, binder content of 420 kg/m^3 and water/solids ratio of 0.17. This mix design shows that high compressive strength can be achieved by ambient curing of GPC.

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