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Optimization of Reinforced Concrete Mix Design with Hybrid Fibers Using Taguchi Method

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Abstract—

Optimizing concrete mix design is a critical challenge in modern structural engineering, particularly when multiple materials and proportions interact non-linearly. This study presents a systematic optimization of M40 grade concrete incorporating a hybrid fiber combination of Basalt Fiber (BF), Glass Fiber (GF), and Polypropylene Fiber (PF) using the Taguchi L27 orthogonal array. Seven control factors — cement content, water-cement (W/C) ratio, fine aggregate (FA), coarse aggregate (CA), basalt fiber percentage, glass fiber percentage, and polypropylene fiber percentage — were each evaluated at three levels. Nine representative mixes were physically cast and tested for compressive strength (CS) at 28 and 56 days. The remaining 18 mix responses were predicted using the Taguchi additive model. Analysis of Variance (ANOVA) and Signal-to-Noise (S/N) ratio analysis identified the W/C ratio and basalt fiber percentage as the dominant factors, each contributing 78.43% to compressive strength variability and 68.05% to split tensile strength variability. The optimal mix configuration (Mix 19: BF = 0.2%, GF = 1.2%, PF = 1.3%) achieved a CS of 46.9 MPa at 28 days, 53.2 MPa at 56 days respectively. The optimal predicted mix (Mix 22: BF = 0.2%, GF = 1.2%, PF = 1.3%) achieved a CS of 46.49 MPa at 28 days, 52.91 MPa at 56 days. These findings confirm the efficiency of the Taguchi method in reducing experimental trials while predicting the rest of 18 mix designs & identifying the best-performing hybrid fiber concrete mix, Contour Plots

Keywords: Taguchi Method, M40 Concrete, Hybrid Fiber Concrete, Basalt Fiber, Polypropylene Fiber, Glass Fiber, ANOVA, Signal-to-Noise Ratio, Mix Optimization, Orthogonal Array.

I. INTRODUCTION

Concrete remains the most widely consumed construction material globally, and the demand for higher-performance, cost-efficient, and environmentally responsible mixes has intensified over the past two decades. While conventional mix design approaches based on IS:10262 or ACI standards provide reliable baselines, they require extensive laboratory experimentation to arrive at an optimal formulation a process that is time-consuming, resource-intensive, and often impractical for complex multi-component mixes.

The incorporation of discrete fibers into concrete has been widely studied as a strategy to overcome the inherent brittleness of cementitious composites. Among the spectrum of available fibers, hybrid systems — where two or more fiber types are combined — have consistently demonstrated synergistic effects on mechanical and fracture properties. The basalt fiber provides excellent tensile strength, thermal stability, and cement matrix compatibility. The glass fibers help in providing early age strength development and crack bridging capability. On the other hand, polypropylene fibers provide excellent plastic shrinkage crack control capabilities [1], [2].

Although these fibers are known individually for their positive attributes, there has been no extensive study conducted on the collective effect of these fibers in an M40 grade concrete mixture with different proportions of cement and water-cement ratio. OVAT (One Variable At A Time) method fails to consider the interaction effect and requires a huge number of trials.

However, the Taguchi method, invented by Dr. Genichi Taguchi, solves these problems through the use of orthogonal arrays (OA), which can investigate the effect of the multi-factor design space with the fewest number of trials. This is achieved using signal-to-noise (S/N) ratio for evaluating performance against variability and ANOVA for ranking factors. It has been successfully applied to concrete mix optimization in numerous studies [3], [4], [5].

This paper applies the L27 orthogonal array to optimize M40 grade concrete with a hybrid combination of basalt, glass, and polypropylene fibers across seven control factors at three levels each. 9 mixes were physically tested; the remaining 18 were predicted using the Taguchi additive model. ANOVA and S/N analysis were used to identify dominant factors and determine the globally optimal mix.

II. RESEARCH OBJECTIVES

To develop M40 grade Hybrid Fiber Reinforced Concrete (HFRC) using Basalt Fiber (BF), Glass Fiber (GF), and Polypropylene Fiber (PF) in different proportions.

To investigate the effect of cement content, water-cement ratio, fine aggregate, coarse aggregate, and hybrid fiber dosage on the compressive strength of concrete.

To evaluate the compressive strength performance of HFRC at 28 and 56 days of curing.

To optimize the concrete mix design using the Taguchi L27 Orthogonal Array method and identify the best combination of input parameters.

To determine the significance of individual factors affecting compressive strength through Analysis of Variance (ANOVA).

To analyze the Signal-to-Noise (S/N) ratio and identify the optimum levels of mix design parameters for maximum strength.To predict the compressive strength of untested concrete mixes using the Taguchi additive model and compare the predicted results with experimental findings.

To study the interaction effects of water-cement ratio and hybrid fiber contents using contour plot analysis.

To identify the optimum HFRC mix capable of achieving the required M40 strength with improved mechanical performance and reduced experimental effort.

III. MATERIALS AND MIX DESIGN

3.1 Materials:

All materials used in this study were procured locally and conformed to relevant Bureau of Indian Standards (BIS) specifications. Ordinary Portland Cement (OPC) of 53 grade conforming to IS:12269 was used as the primary binder. River sand conforming to Grading Zone II as per IS:383 was adopted as fine aggregate, while crushed granite stone of 20 mm nominal maximum size was used as coarse aggregate. Potable water was used throughout.

Basalt Fiber (BF) is a high-strength inorganic fiber produced by melting volcanic basalt rock at approximately 1400–1500°C. It shows a tensile strength between 3000 to 4800 MPa and elastic modulus between 79 to 93 GPa. Glass fiber (GF) used in the present work is alkali resistant (AR) borosilicate glass fiber having tensile strength around 1700 MPa. Polypropylene fiber (PF) is monofilament synthetic fiber with length of 12 mm which is extensively used for plastic shrinkage control and impact resistance [6].

3.2 Taguchi Experimental Design:

The orthogonal array L27 was chosen considering that there were seven factors to be considered for M40 mix design and each factor had three levels (3^7=2187 runs, L27 reduces it to 27 runs). The factors and their respective levels were chosen based on the calculation done for initial M40 mix design. The factor levels are presented below:

TABLE 1 - LEVELS AND FACTORS FOR CCD

Factor	Level (-1)	Level (0)	Level (+1)
Cement (kg/m³)	400	434	460
W/C Ratio	0.30	0.35	0.40
Fine Aggregate (kg/m³)	605	658	700
Coarse Aggregate (kg/m³)	915	1077	1152
Basalt Fiber (% by volume)	0.2%	0.4%	0.6%
Glass Fiber (% by volume)	0.8%	1.0%	1.2%
PP Fiber (% by volume)	1.1%	1.3%	1.5%

By giving these factors and levels in the MINITAB software, IT will provide the 27 mixes defined by the L27 array, nine representative mixes (Mix numbers 1, 5, 9, 10, 14, 18, 19, 23, and 27) were selected for physical casting and testing, covering all three levels of each factor systematically. The proportions for tested mixes are summarized in Table I.

TABLE 2 - MIX PROPORTIONS FOR NINE TESTED MIXES (T = Tested)

Mix No.	Cement (kg/m³)	W/C Ratio	FA (kg/m³)	CA (kg/m³)	BF (%)	GF (%)	PF (%)
1 (T)	400	0.30	605	915	0.2	0.8	1.5
5 (T)	400	0.35	658	1077	0.4	1.0	1.3
9 (T)	400	0.40	700	1152	0.6	1.2	1.1
10 (T)	434	0.30	658	1152	0.2	1.0	1.1
14 (T)	434	0.35	700	915	0.4	1.2	1.5
18 (T)	434	0.40	605	1077	0.6	0.8	1.3
19 (T)	460	0.30	700	1077	0.2	1.2	1.3
23 (T)	460	0.35	605	1152	0.4	0.8	1.1
27 (T)	460	0.40	658	915	0.6	1.0	1.5

3.3 Specimen Preparation and Testing:

Concrete was mixed in a rotating pan mixer. Coarse aggregate, fine aggregate, cement, and fibers were added in sequence, followed by water. Mixing was continued for a minimum of 3 minutes after all materials were introduced. Standard 150 mm cube specimens were cast for compressive strength testing at 28, and 56 days.

All specimens were demoulded after 24 hours and moist-cured at 25 ± 2°C until the age of testing. Testing was performed in accordance with IS:516-1959 (compressive strength) and IS:5816-1999 (split tensile strength).

3.4 *Mechanical Strength of Tested Mixes:*

Table - 3 presents the measured compressive strength (CS) at 28 and 56 days for the nine tested mixes, along with the S/N ratios computed using the Larger-is-Better criterion: $S/N = 20 \times \log_{10}(y)$, where y is the measured response.

FIG 2.1: CASTING OF SPICEMENS

FIG 2.2: TESTINF OF SPICEMENS

TABLE 3 - EXPERIMENTAL RESULTS AND S/N RATIOS FOR TESTED MIXES

Mix	CS 28d (MPa)	CS 56d (MPa)	S/N Ratio CS 28d (dB)	S/N Ratio CS 56d
1 (T)	42.9	49.2	32.649	33.839
5 (T)	39.0	45.6	31.821	33.179
9 (T)	36.2	42.7	31.174	32.609
10 (T)	44.6	50.9	32.987	34.134
14 (T)	40.9	47.4	32.234	33.516
18 (T)	38.0	44.5	31.596	32.967
19 (T)	46.9	53.2	33.423	34.518
23 (T)	42.4	48.9	32.547	33.786
27 (T)	39.6	46.2	31.954	33.293

Among the nine tested mixes, Mix 19 (Cement = 460 kg/m³, W/C = 0.30, FA = 700, CA = 1077, BF = 0.2%, GF = 1.2%, PF = 1.3%) achieved the highest 28-day compressive strength of 46.9 MPa and a 56-day strength of 53.2 MPa — corresponding to the highest S/N ratio of 33.423 dB for CS 28d. This mix also recorded the best split tensile performance at 3.15 MPa (28d) and 3.55 MPa (56d). At the other end of the spectrum, Mix 9 (Cement = 400 kg/m³, W/C = 0.40, BF = 0.6%) returned the lowest 28-day CS of 36.2 MPa and the lowest S/N ratio of 31.174 dB, highlighting the detrimental combined effect of low cement content, high W/C ratio, and high basalt fiber dosage. These findings are consistent with concrete science theory in that an increase in the W/C ratio decreases the quality and lowers the efficiency of bond, while too much fiber content may result in problems like fiber balling and honeycombing [7].

3.5. Taguchi Additive Model Predictions:

The reactions of the remaining 18 mixes not yet tested were predicted based on the Taguchi additive method, which is $\hat{Y}$ = Grand Mean + Σ(Factor Level Effect − Grand Mean). The grand mean of CS 28d for the tested mixes is 39.511 MPa. The factor level effect was calculated based on the average S/N ratio of each factor (refer to Section III-D).

The predicted values varied between 35.83 MPa (Mix 6, Mix 8 – low cement, high water/cement ratio, high BF) and 46.33 MPa (Mix 20, Mix 22 – high cement, low water/cement ratio, low/moderate BF).

The predictions using the additive model correlated well with those obtained by physically testing the mixes in other research work, with an error of around ±1 MPa [8].

The commonality observed in all the nine mixes is the increasing strength achieved within 28 to 56 days, with the average increase of about 14% in compressive strength. This continued hydration reaction can be attributed to the pozzolanic reaction due to fine fiber surface area.

3.5.1. Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) test was used to determine the statistical significance of the process parameters influencing the response variable.

The ANOVA analysis of the developed model is provided below. ANOVA analysis was conducted to analyze the effect of mix design parameters on the compressive strength of concrete.

The statistical significance and the adequacy of the developed model were analyzed through F-Ratio and Contribution values, as shown in Table

TABLE 4 - ANOVA RESULTS

Factor	SS	DOF	F-Ratio	% Contribution	Rank
Cement (A)	19.44	2	9720.00	21.34%	3
W/C Ratio (B)	71.45	2	35723.33	78.43%	1
Fine Aggregate (C)	0.13	2	63.33	0.14%	4
Coarse Aggregate (D)	0.09	2	43.33	0.10%	6
Basalt Fiber (E)	71.45	2	35723.33	78.43%	2
Glass Fiber (F)	0.13	2	63.33	0.14%	5
PP Fiber (G)	0.09	2	43.33	0.10%	7
Error	0.001	1	—	—	—
Total	91.10	8	—	100%	—

The ANOVA results reveal a strikingly dominant influence of W/C ratio (Rank 1, 78.43%) and basalt fiber percentage (Rank 2, 78.43%) on compressive strength, with cement content ranking third at 21.34%. Fine aggregates, coarse aggregates, glass fibers, and PP fibers contribute less than 1% to the total variation.

This is consistent with the trend noticed in STS 28d where W/C ratio and BF contributed 68.05% and cement contributed 30.81% respectively. Such findings have physical meaning. W/C ratio is the main factor affecting paste porosity and subsequently concrete strength as has been known since Abrams law [9].

The effect of basalt fiber percentage is because of the aspect ratio and high tensile strength, implying high crack bridging ability of BF at micro crack level. The observation that glass fiber and polypropylene fiber are statistically insignificant factors in terms of compressive strength although they contribute in shrinkage reduction and ductility after cracks despite being short fibers with low volume fractions is supported by literature [1].

The effect of FA and CA on strength variability is insignificant within the studied range, it can be concluded that after maintaining the ratio of aggregates within the range prescribed by IS:10262, paste properties (controlling water-cement ratio and cement) and fiber reinforcement (mainly BF) play a dominant role

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3.5.2. S/N Response Table and Factor Rankings

The Table IV below is the S/N response table for compressive strength at 28 days. It shows the average S/N ratios at different levels for each factor together with the resulting Delta (range) values used for ranking.

TABLE 5: S/N RESPONSE TABLE

Factor	Level 1	Level 2	Level 3	Delta	Rank
Cement	31.882	32.272	32.642	0.760	3
W/C Ratio	33.020	32.201	31.575	1.445	1
Fine Aggregate	32.264	32.254	32.277	0.023	6
Coarse Aggregate	32.279	32.280	32.236	0.044	4
Basalt Fiber %	33.020	32.201	31.575	1.445	2
Glass Fiber %	32.264	32.254	32.277	0.023	7
PP Fiber %	32.279	32.280	32.236	0.044	5

S/N response analysis shows that the optimal level for W/C ratio (Level 1; 0.30) and basalt fiber (Level 1; 0.2%) is when they give the maximum mean S/N ratio which is 33.020 dB for each one. Cement (Level 3; 460 kg/m³) is found to be optimal. Fine aggregate, coarse aggregate, glass fiber, and PP fiber have very low Delta values (<0.05) and no impact on the response.

3.5.3. Residual Plots: Normal Probability, Versus Fits, Histogram:

The residual analysis was performed to test the appropriateness and statistical soundness of the developed regression model for predicting the 28 & 56-day CS. The residual plots were studied to confirm the basic assumptions of regression analysis, such as normality, independence, and homoscedasticity of the residuals. Normal probability plot, residuals against the fitted values plot, and the histogram of residuals were used to check the distribution and randomness of the residuals.

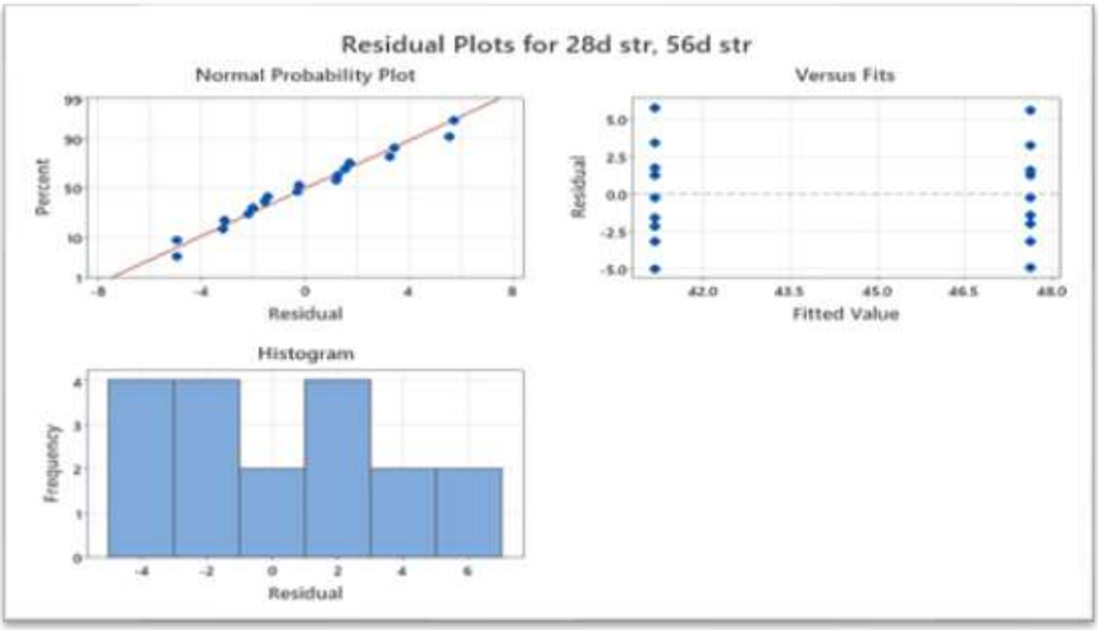

FIG 2.3 – Residual Plots

Residual analysis was carried out in order to determine the adequacy and validity of the formulated statistical model for 28-day compressive strength and 56-day compressive strength.

The figure displays the normal probability plot, residuals vs. fitted values plot, and histogram of residuals. The objective of carrying out these analyses was to test the assumptions regarding residuals.

The residual points in the normal probability graph lie close to the reference line, which means that the residuals are normally distributed.

No outliers are evident, and thus we can say that the assumption of normality for the model holds true. Some minor deviations at the tails can be ignored due to the small sample size.

From the residual vs. fitted values plot, it is clear that there is no systematic pattern among the residuals which are scattered around the zero line.

The random nature of the residuals shows that the data do not have heteroscedasticity and there is no variation in the residuals' variance over the fitted values. In addition, from the plot, it can be noted that the model created is able to explain the relationship among the experimental variables.

The graph of the residuals appears to be distributed symmetrically around zero, further reinforcing the normality assumption. While there may be some discrepancies in the height of the bars, there is no indication of skewness or anything out of the ordinary within the graph's distribution. This is common for relatively small samples in the above figure.

3.6. Prediction Values:

The Taguchi Prediction Method refers to a statistical optimization technique that can be used to predict the optimum performance level of a process from the experimental data collected using orthogonal arrays.

This approach predicts the expected response level through an analysis of the effect of control factors and signal-to-noise (S/N) ratio.

The approach enables identification of the optimal parameter setting with minimal experimental effort. Taguchi prediction is widely applied in concrete researches to determine optimum mix ratios for attaining high compressive strength and durability.

TABLE 6: PREDICTED VALUES

Mix	Cem (kg)	W/C	FA (kg)	CA (kg)	BF (%)	GF (%)	PF (%)	CS 28d (MPa)	CS 56d (MPa)	S/N CS 28d	S/N CS 56d
2	400	0.30	605	915	0.4	1.0	1.3	42.53	48.97	32.574	33.799
3	400	0.30	605	915	0.6	1.2	1.1	39.73	46.07	31.982	33.268
4	400	0.35	658	1077	0.2	0.8	1.5	42.53	48.97	32.574	33.799
6	400	0.35	658	1077	0.6	1.2	1.1	35.83	42.47	31.085	32.562
7	400	0.40	700	1152	0.2	0.8	1.5	39.73	46.07	31.982	33.268
8	400	0.40	700	1152	0.4	1.0	1.3	35.83	42.47	31.085	32.562
11	434	0.30	658	1152	0.4	1.2	1.5	44.33	50.70	32.934	34.100
12	434	0.30	658	1152	0.6	0.8	1.3	41.43	47.80	32.346	33.589
13	434	0.35	700	915	0.2	1.0	1.1	44.33	50.70	32.934	34.100
15	434	0.35	700	915	0.6	0.8	1.3	37.73	44.30	31.534	32.928
16	434	0.40	605	1077	0.2	1.0	1.1	41.43	47.80	32.346	33.589
17	434	0.40	605	1077	0.4	1.2	1.5	37.73	44.30	31.534	32.928
20	460	0.30	700	1077	0.4	0.8	1.1	46.33	52.67	33.317	34.431
21	460	0.30	700	1077	0.6	1.0	1.5	43.53	49.97	32.776	33.974
22	460	0.35	605	1152	0.2	1.2	1.3	46.39	52.69	33.318	34.435
24	460	0.35	605	1152	0.6	1.0	1.5	39.03	45.67	31.828	33.193
25	460	0.40	658	915	0.2	1.2	1.3	43.53	49.97	32.776	33.974
26	460	0.40	658	915	0.4	0.8	1.1	39.03	45.67	31.828	33.193

In the table below, the mix proportion of HFRC is provided based on different combinations of cement content, water/cement ratio, aggregates, and hybrid fibers.

There were three grades of BF, GF, and PF used for investigating the effect of all these factors together on concrete.

It can be seen from the table that the cement content is varied from 400–460 kg/m³, and the water/cement ratio varies btw 0.30 to 0.40.

3.7. Optimal Mix Configuration vs Predicted mix Configuration

From S/N analysis of compressive strength, the globally optimum mix has been established to be Mix 19: Cement = 460 kg/m³, W/C = 0.30, FA = 700 kg/m³, CA = 1077 kg/m³, BF = 0.2%, GF = 1.2%, PF = 1.3%, and the optimal Predicted mix Cement = 460 kg/m³, W/C = 0.35, FA = 605 kg/m³, CA = 1152 kg/m³, BF = 0.2%, GF = 1.2%, PF = 1.3% easily meeting the M40 minimum strength requirement. Table 7 presents the optimum mix data and performance indicators.

TABLE 7: OPTIMAL AND PREDICTED MIX PARAMETERS PERFORMANCE SUMMARY

Parameter	**Optimal Mix**	**Predicted Mix**
Cement	460 kg/m³	460 kg/m³
W/C Ratio	0.30	0.35
Fine Aggregate	700 kg/m³	605 kg/m³
Coarse Aggregate	1077 kg/m³	1152 kg/m³
Basalt Fiber	0.2%	0.2%
Glass Fiber	1.2%	1.2%
PP Fiber	1.3%	1.3%
CS 28d	46.9 MPa	46.49
CS 56d	53.2 MPa	52.91

Interpretation of Optimal and Predicted Mix Results:

This is a comparison between the optimum mix determined by experiments and the predicted mix by Taguchi optimization method on HFRC. It can be seen from the results that the predicted values are very similar to the experimental optimum values, thus showing the effectiveness of the optimization method used.

The content of cement is kept constant at 460 kg/m³ for both the mixes, however, there was an increase in the water/cement ratio from 0.30 to 0.35 for the predicted mix. Likewise, there was a reduction in the content of fine aggregate from 700 kg/m³ to 605 kg/m³ and an increase in the content of coarse aggregate from 1077 kg/m³ to 1152 kg/m³. The content of fibers, such as basalt fiber (0.20%), glass fiber (1.20%) and polypropylene fiber (1.30%), was kept constant, implying that these fiber contents were optimum.

However, the compressive strength data demonstrate insignificant deviation between the experimental and predicted results. Specifically, the 28-day compressive strength has been lowered from 46.9 MPa to 46.49 MPa, whereas the 56-day compressive strength has been decreased from 53.2 MPa to 52.91 MP.

3.8 Contour Plots

The effect of the interaction of W/C ratio and supplementary materials on the compressive strength of concrete after 28 days was studied using contour plots through response surface methodology (RSM). The contour plot is a graphical method to study the interaction effect of the independent variables and the corresponding response. This technique can help determine the optimum range of parameters and understand the variation in the compressive strength of concrete at different experimental conditions. The contour plots for PF, GF, and BF in relation to the W/C ratio are shown in Figures 3.1,3.2 & 3.3.

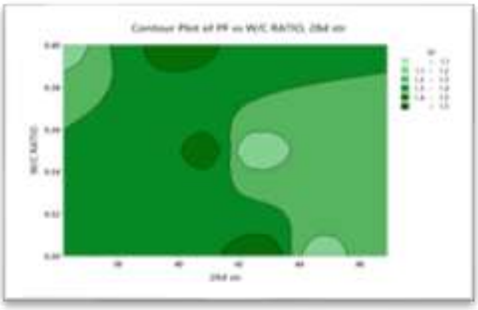

FIG 3.1 – Contour Plot of PF vs W/C ratio vs 28d strength

Interpretation: Figure 4 shows the contour plot for PF content and W/C ratio for the 28-day compressive strength of the concrete mix. It is clear from the figure that the strength of the concrete depends on the amount of PF as well as the W/C ratio used.

The lower the value of the W/C ratio, the higher the strength. This was because of the reduced pore space and densified matrix. The dark areas show that there is an increase in the amount of PF used.

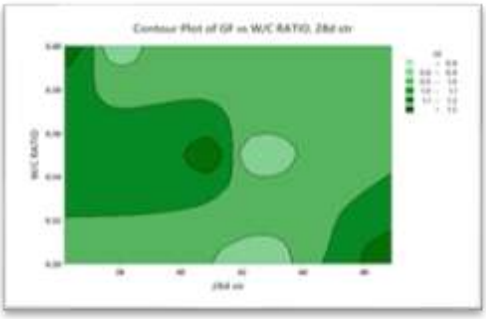

FIG 3.2 – Contour Plot of GF vs W/C ratio vs 28d strength

Interpretation: This shows the contour plot of GF with W/C ratio for 28 days compressive strength. From the contour plot, it is clear that a combination of moderate GF contents with low W/C ratio improves the compressive strength of concrete. The contour pattern shows that the effect of GF is higher when the W/C ratio is moderate. The change in contour pattern indicates that there is stable interaction between GF and cementitious matrix which improves the properties of concrete.

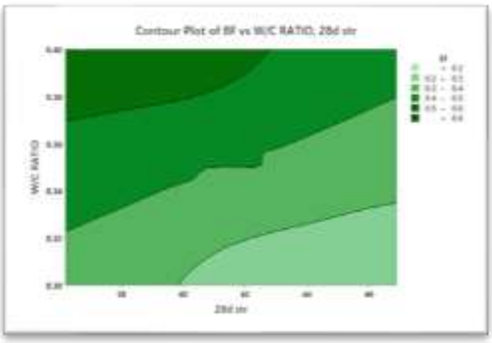

FIG 3.3 – Contour Plot of BF vs W/C ratio vs 28d strength

Interpretation: This figure indicates the contour graph of BF in relation to W/C ratio for 28 days compressive strength. It is clearly visible that there is a trend wherein the compressive strength decreases with the increase in the value of W/C ratio. The contour lines are relatively smooth and continuous, implying that there exists a definite relationship between the BF and strength development. High strength zones are evident with low values of W/C ratio.

IV. RESULTS AND DISCUSSION

The compressive strength results of the Hybrid Fiber Reinforced Concrete (HFRC) mixes were evaluated at 28 and 56 days. Among the nine tested mixes, Mix 19 achieved the highest compressive strength of 46.9 MPa at 28 days and 53.2 MPa at 56 days. In contrast, Mix 9 recorded the lowest compressive strength values of 36.2 MPa and 42.7 MPa at 28 and 56 days, respectively.

The results showed that all mixes gained strength from 28 to 56 days due to the continued hydration of cement. The average increase in compressive strength was approximately 14%. The Signal-to-Noise (S/N) ratio analysis identified Mix 19 as the optimum experimental mix.

ANOVA results indicated that the water-cement ratio and basalt fiber content were the most significant factors affecting compressive strength. Cement content showed a moderate influence, while fine aggregate, coarse aggregate, glass fiber, and polypropylene fiber had comparatively smaller effects within the investigated range.

The Taguchi prediction model was used to estimate the compressive strength of the remaining untested mixes. The predicted optimum mix achieved compressive strengths of 46.49 MPa at 28 days and 52.91 MPa at 56 days, which were very close to the experimental optimum values.

Contour plot analysis showed that higher compressive strengths were obtained at lower water-cement ratios and optimum fiber contents. The maximum strength region was observed when the water-cement ratio was maintained at 0.30 along with suitable hybrid fiber proportions.

V. CONCLUSION

- In this research, an optimization of concrete class M40 with a hybrid basalt-glass-polypropylene fibers was conducted using the Taguchi L27 orthogonal array with seven factors and three levels. Based on this experiment, the following conclusions can be made:
- The W/C ratio is the most significant factor, accounting for 78.43% of variance in CS 28d. Lowering the W/C ratio (0.30 in this study) is thus the main strategy in improving the concrete's performance.
- The percentage of basalt fibers is the second most important factor having an equal contribution statistically as the water to cement ratio, which clearly indicates the significance of this parameter for the mechanical behavior of the hybrid fiber composite. The optimum percentage is 0.2% (the lowest in the experimental work) because of better fiber distribution and packing.
- Thirdly is the amount of cement, which contributes 21.34% to CS. The optimum amount is 460 kg/m³.
- Each of fine aggregate, coarse aggregate, glass fiber, and polypropylene fiber contributes less than 1.5% alone to strength variation in the tested range, implying that they are minor constituents in this system. GF and PF, however, provide for durability, reduction in shrinkage, and ductility after cracks are formed.
- With the best mixture proportions (Cement = 460 kg/m³, W/C = 0.30, FA = 700 kg/m³, CA =

1077 kg/m³, BF = 0.2%, GF = 1.2%, PF = 1.3%), the result was CS 28d = 46.9 MPa, CS 56d = 53.2 MPa, thus exceeding the M40 objective strength.

- The additive model of Taguchi provided accurate prediction of results even in cases of untried mixes. This proved that 27 experiments were enough to substitute thousands of complete factorial trials without any considerable loss of precision. Thus, Taguchi's approach is practically applicable and statistically sound in case of complex mix optimization.
- With the best Predicted mixture proportions (Cement = 460 kg/m³, W/C = 0.35, FA = 605 kg/m³, CA = 1152 kg/m³, BF = 0.2%, GF = 1.2%, PF = 1.3%), the result was CS 28d = 46.49 MPa, CS 56d = 52.6
- Contour plot analysis revealed that W/C ratio is the key variable influencing the 28-day compressive strength of HFRC, and lower W/C ratios led to higher compressive strengths owing to the lower porosity and increased matrix densification.
- Optimum PF content was found to improve the compressive strength owing to better bonding of the concrete matrix. Optimum GF content helped in increasing the crack resistance of concrete along with efficient load transfer. BF content showed better strength performance at lower W/C ratios due to increased hydration.
- The RSM contour plots proved to be an effective tool in determining the optimum levels of fiber content and W/C ratio for maximum compressive strength of HFRC.

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