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Statistical optimization of fibre reinforced polymer concrete made with recycled plastic aggregates by central composite design

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ABSTRACT

To meet the present needs of concrete consumption, it is the need of the hour to discover different alternatives and unique techniques. By Incorporating the latest trends, Polymer Concrete (PC) and Fibre-Reinforced Concrete (FRC) are being used to improve the strength of concrete. It is proposed to produce M30 grade Fibre Reinforced Polymer Concrete (FRPC) with the help of Polyester Resins (PR), Polypropylene Fibres (PF) and Recycled Waste Plastics (RWPA). FRPC is a combination of three different variables of different replacement percentages, which requires extensive and detailed experimentation to optimize each variable used in this investigation. In this study (research), optimization was done by keeping the two variables constant. To reduce the number of experiments, optimization of ingredients was done by statistical modelling technique of Central Composite Design (CCD). In conclusion, the optimal input parameters for achieving a 28-day CS are determined to be 12.05% PR, 2.19% PF, and 30% RWPA. These findings are based on the analysis of experimental results, statistical modelling, and the CCD approach, demonstrating the successful optimization and correlation between the input parameters and the desired CS output.

Keywords: Fibre-Reinforced Polymer Concrete; Recycled Waste Plastic Aggregates; Response Surface Methodology; Central Composite Design.

1. INTRODUCTION

In the realm of construction, cement has emerged as a ubiquitous material over the past century, owing to its extensive array of advantages including superior resistance to compression, abrasion, wear and tear, and harsh environmental conditions. Consequently, the global demand for cement has witnessed a rapid surge over time. However, in the wake of the COVID-19 pandemic, global cement consumption experienced a decline of 0.23% in 2020 compared to the previous year, with an average per capita demand of 540 kg. Nevertheless, it is projected that by the close of 2022, cement consumption will rebound, showcasing a 6% increase compared to previous years. To curtail global cement consumption, diverse techniques have been employed, and researchers, engineers, and scientists have explored alternative materials for substitution [1]. Among these advancements, the utilization of polymeric substances in concrete stands out as a remarkable innovation, capable of enhancing strength, facilitating rapid setting, and bolstering corrosion resistance.

Despite the numerous advantages it offers, pozzolana cement, like many other construction materials, also exhibits certain limitations such as low tensile strength and brittleness. However, there are effective measures to address these drawbacks, one of which involves incorporating small discrete fibrous elements into concrete mixes, commonly known as Fibre Reinforced Concrete (FRC). The addition of fibers to concrete enhances its resistance against tensile forces, reduces the formation of micro-cracks, and improves its post-elastic properties. The strength of concrete mixes is influenced by various factors, including the type, shape, and size of the fibers, as well as the aspect ratio [2].

Polymer modified concrete (PC) has found diverse applications in fields such as prestressed concrete elements, marine structures, and nuclear power plants [3]. Compared to ordinary Portland cement (OPC) concrete, PC exhibits superior mechanical properties, making it a promising construction material. The ultimate

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mechanical strength properties of PC are directly influenced by the type of resin used [4]. In a study conducted by ESMAEILI *et al.* [5] the mechanical behaviour of Polymer concrete mixes was investigated. The mixes were prepared and tested with varying polymer content (10%, 15%, and 20%), filler contents (20% and 30%), and steel fiber content (0.5%, 1%, and 2%). The results revealed that increasing the polymer content from 10% to 15% enhances the mechanical properties of polymer concrete. However, further increasing the polymer content beyond 15% up to 20% leads to a reduction in the mechanical properties of the polymer composite.

Over the years, a wide range of products has been developed for the betterment of humanity. In 1950, approximately 1.5 million metric tons (MMT) of plastics were manufactured for various applications. However, by 2020, this number had skyrocketed to 367 MMT. Plastics possess the distinct advantage of being easily molded into any desired shape and size to suit our needs. Nevertheless, the downside is that when plastic is discarded as waste, it can take hundreds of years to decompose completely. Considering the current pace of development, plastic production is projected to reach 700 MMT by the end of 2034. Alarming statistics reveal that a staggering 79% of the produced plastics have been released into the environment as waste, with a mere 9% being recycled [6]. Conventional waste management methods are inadequate for effectively managing solid plastic waste. Therefore, it is imperative to identify alternative methods for managing plastic waste before it contaminates the entire ecosystem. Simultaneously, as the market demand grows, it is crucial to explore substitute materials for coarse aggregate usage in cement concrete. Plastic waste can be transformed into aggregates through alternative thermal treatments such as heating and cooling.

Recycled plastic aggregates present a sustainable alternative to natural aggregates in concrete production, offering numerous benefits. These aggregates are derived from processed plastic waste such as bottles and packaging materials, thereby contributing to waste reduction and fostering a circular economy. By incorporating plastic waste into concrete, not only is it diverted from landfills, but it also reduces the demand for natural aggregates, conserving valuable resources. Furthermore, the addition of recycled plastic aggregates enhances the mechanical properties of concrete by increasing its strength and durability. Their lighter weight makes them particularly suitable for lightweight structures and applications with load-bearing constraints. Moreover, plastic aggregates provide thermal insulation properties and offer design flexibility, allowing for customization with various sizes and colors. Additionally, they exhibit excellent chemical resistance, making them well-suited for structures in aggressive environments [7]. While challenges exist in sorting and cleaning plastic waste and ensuring consistent properties of the recycled aggregates, proper processing and stringent quality control measures enable their use as an innovative and sustainable solution in the construction industry. This helps to reduce the environmental impact and improve concrete performance. In this study, it is proposed to partially replace the coarse aggregate with recycled waste plastic aggregates, ranging from 0% to 50%.

As mentioned previously, an approach that combines the advantages of Fiber Reinforced Concrete (FRC) and Polymer Concrete (PC) is to create a Fibre Reinforced Polymer Concrete (FRPC) using Polyester Resins (PR) in varying proportions (0% to 15% at 2.5% intervals), Polypropylene Fibres (PF) in varying proportions (0% to 3% at 0.5% intervals), and recycled waste plastic aggregates (RWPA) in varying proportions (0% to 50% at 10% intervals). In this study, PR, PF, and RWPA are considered as input parameters, while the 28-day strength (CS) is considered as the output parameter. It is observed that these three input parameters have a significant impact on the output parameter. Consequently, predicting the precise optimum range of input parameters is challenging and necessitates extensive experimental investigations.

To streamline the experimental process and minimize the number of required runs, a statistical modelling equation was developed using the DESIGN EXPERT software. This allowed for the identification of precise optimum input parameters to achieve the target strength and ultimate strength of the concrete. It offers a comprehensive range of design options, including factorial designs, fractional factors, and compound designs. It can effectively handle both process variables and mixed variables. The software encompasses various features such as variable comparison and testing, screening, characterization, and optimization of input parameters. It also supports robust parameter design, mixed designs, and combined designs. Response Surface Methodology (RSM) is employed, which encompasses a collection of statistical techniques for experimental design, model creation, evaluation of effects, and optimization of factors to achieve desirable responses [7]. The Central Composite Design (CCD) is specifically utilized to determine the optimum concentrations of specific input variables and investigate the interactions among them.

CCD was employed in this investigation for the optimization of concrete ingredients which offers several advantages over the other methods. CCD allows for the efficient exploration of the factor space by systematically varying the proportions of concrete ingredients. This design reduces the number of experimental runs required compared to a full factorial design, saving time, resources, and costs associated with conducting experiments. And it also includes the star points that enable the assessment of nonlinearity and interactions between ingredients which employs statistical techniques such as regression analysis and analysis of variance (ANOVA) for data analysis. The response surface model provides a mathematical representation of the system, enabling predictions and optimization of ingredient proportions beyond the experimental design space. By utilizing these models, engineers and researchers can estimate optimal ingredient proportions and explore different scenarios without conducting additional experiments [8].

2. MATERIALS AND METHODS

2.1. Portland cement

Portland cement plays a crucial role in providing strength and durability to concrete as it acts as a binder for its components. Before utilizing cement in concrete, it is essential to have a deep understanding of its various properties. OPC 53 grade cement is employed in accordance with the compliance of BIS (Bureau of Indian Standards) codes. This type of cement typically exhibits a greenish-grey colour and possesses specific characteristics such as consistency limit, specific gravity, and fineness. The consistency limit of OPC 53 grade cement is 33.8%, while its specific gravity is 3.16. In terms of fineness, it has a value of 385 m^2/kg. The initial setting time of this cement is completed within 40 minutes, and the final setting time takes approximately 560 minutes to complete.

2.2. Aggregates

In concrete, a significant portion, approximately 2/3rd of its volume is occupied by aggregates, which serve as the primary volume filler. To mitigate the excessive consumption of river sand and coarse aggregate, which can lead to depletion of natural resources, various alternative approaches have been proposed for utilizing fine and coarse aggregates in concrete. In this study, M-Sand is employed as a complete replacement for natural river sand, which falls under Zone II classification. Additionally, RWPA are suggested as a partial replacement for coarse aggregate, ranging from 0% to 50%, adhering to the guidelines specified in IS 383:2016. The RWPA is produced through a series of mechanical operations, including segregation, crushing, heating, cooling, and classification, all conducted under controlled environmental conditions. Table 1 presents the various properties of the aggregates used in this investigation.

2.3. Polymer resin

In this study, commercially available synthetic polyester resins were employed to initiate the polymerization reaction in concrete [1]. The inclusion of these resins played a significant role in enhancing the rigidity and strength of the concrete. Table 2 provides an overview of the various properties of the polyester resin utilized in this investigation. Polyester resins stand out among other resins due to their distinct advantages, which make them a preferred choice for various applications. One of their key benefits is their cost-effectiveness, providing a favorable price-performance ratio. Additionally, polyester resins offer fast curing times, thereby enhancing productivity in manufacturing processes. Their excellent chemical resistance makes them well-suited for use in corrosive environments, while their high strength and durability ensure long-lasting performance [3, 4]. Polyester resins demonstrate versatility across industries and exhibit good adhesion to diverse surfaces. Their easy handling and processing further streamline manufacturing processes. Moreover, polyester resins are available in a wide range of colors, enabling customization and enhancing aesthetic appeal. However, when selecting a resin, it is crucial to consider specific application requirements, such as the desired mechanical properties, chemical resistance, and environmental conditions, to ensure optimal performance [9–11].

2.4. Polypropylene fibres

Synthetic polypropylene fibre (RECRON 3S) of aspect ratio 400 was incorporated in this investigation which in term has ultimate tensile strength and young's modulus of 650MPa and 2800MPa respectively.

Table 1: Properties of aggregates.

TYPE OF AGGREGATE	BULK DENSITY (kg/m^3)	FINENESS MODULUS	SPECIFIC GRAVITY	WATER ABSORPTION
M-Sand	1875	2.99	2.86	1.64
Coarse Aggregate	1625	6.74	2.76	0.92
RPWA	1320	6.59	2.62	0.34

Table 2: Properties of polyester resin.

MELT TEMPERATURE (ºC)	SHRINK RATE (%)	SPECIFIC GRAVITY	STRENGTH (MPa)	
			FLEXURAL	TENSILE
260	0.1 – 0.3	1.56	110	152

Table 3: Mix proportioning.

MIX PROPORTION	INGREDIENTS OF CONCRETE				
	CEMENT	FINE AGGREGATE	COARSE AGGREGATE	WATER	CHEMICAL ADMIXTURE
kg/m^3	354	683	1245	165	3.51
Ratio	1	1.93	3.52	0.47	0.01

Table 4: Work methodology.

INPUT VARIABLES		
PR (%)	PF (%)	RWPA (%)
0	0	0
2.5	0.5	10
5	1	20
7.5	1.5	30
10	2	40
12.5	2.5	50
15	3	60

2.5. Super plasticizer

CONPLAST SP430 served as a superplasticizer in this investigation and is added with the concrete mix whenever required based on the requirement of slump value. Sulfonated polymers are the building blocks for this liquid which is brown in color and soluble in water with a specific gravity of 1.22.

2.6. Mix proportioning and methodology

As per BIS 10262:2019 guidelines, a mix design for M30 concrete mix is prepared which is illustrated in Table 3 [12]. In the initial stage, the cement and M-sand are mixed together without the addition of water. Once a homogeneous mixture is achieved, the prescribed amounts of PF content are added to the concrete and mixed thoroughly to ensure uniform dispersion. Following this, the coarse aggregate or RWPA are incorporated into the dry mixture. In the subsequent step, a portion of water is added to the dry mixture along with varying percentages of polyester resins. The addition of water and polyester resins is carefully done to achieve the desired consistency and properties of concrete. If there is a loss of workability observed during the mixing, superplasticizers may be added to improve the flow and workability of concrete. It is important to note that the specific proportions of water, polyester resins & superplasticizers may vary depending on the requirements of concrete mixture and the desired performance characteristics. From Table 4, it is evident that it is quite challenging as 200+ experimental combinations must be carried out to predict the precise optimum value of ingredients from the three different variables.

3. RESULT AND DISCUSSION

In this study, M30 grade FRPC is made with PR, PF, and RWPA. Initially, experiments are carried out on samples consisting of varying percentages of PR and 0% of PF, and RPWA. From the results, the second phase of experiments is conducted for varying percentages of PF, 0% of RWPA and optimum PR percentage. As part of phase three, experiments are conducted on varying percentages of RWPA and optimum percentages of PR and PF (Table 5).

Polymer modified concrete has demonstrated superior properties compared to conventional concrete, including excellent adhesion, high waterproof qualities, high abrasion resistance, and enhanced chemical resistance [13]. The addition of polymers to the concrete matrix improves its workability by reducing friction between

Table 5: Effect of PR on strength properties of FRPC.

PR (%)	0	2.5	5	7.5	10	12.5	15
CS (MPa)	37.45	38.1	38.37	39.1	39.32	39.49	37.76

Table 6: Effect of PF on strength properties of FRPC.

PR (%)	12.5						
PF (%)	0	0.5	1	1.5	2	2.5	3
CS (MPa)	39.49	40.43	42.11	43.47	46.19	45.1	42.46

Table 7: Effect of RWPA on strength properties of FRPC.

PR (%)	12.5					
PF (%)	2					
RWPA (%)	0	10	20	30	40	50
CS (MPa)	46.19	48.24	49.57	48.64	44.92	39.75

the concrete ingredients. Furthermore, incorporating PR into the concrete enhances the formation of calcium silicate hydrates (CSH) gel (Table 6). Notably, it has been observed that adding 12.5% PR to M30 grade concrete results in a compressive strength (CS) of 39.49 MPa at 28 days, which is 5.45% higher than the conventional mix. This highlights the positive impact of PR on the strength of the concrete [13]. In a study conducted by JO *et al.* [14], it was noted that the CS of PC improved with increasing resin content. However, beyond a certain resin content (around 13–17% resin), the strength did not exhibit significant changes with further increases in resin content. This suggests that there is an optimum range of resin content for achieving maximum strength improvements in recycled PCs.

There is data which indicates that the increase in PF content in concrete diminishes the workability because of its increased frictional resistance between fibres and aggregates. Research demonstrates that the escalating percentage of Fibres and presence of polymers in the concrete mix, resulting in improved strength properties over time [9, 15]. An additional 2% of PF in the concrete shows CS of 46.19MPa at 28 days of curing. It happens because the PF has an ultimate tensile strength of about 650MPa which enhances the microstructural bonding between the ingredients of concrete. A further increase in PF content slightly decreases the strength properties over the entire period of curing. According to MARTÍNEZ-CRUZ *et al.* [11], increment of 50% in average of the compressive and flexural strength as well as on the deformation when adding 1.2 vol% of recycled-fibers were observed when the PC specimens were prepared with 70% of silicious sand, 30% of polyester resin and various fiber concentrations. Hence, 2% addition of PF in the FRPC made with 12.5% of polyester resins and the same will be utilized in the further stages of various other investigations (Figure 1).

The addition of RWPA to concrete leads to an increase in workability due to the lower dry density of RWPA compared to conventional coarse aggregates. This allows for easier mixing and improved flow of the concrete mixture. It has been observed that concrete can be successfully made by incorporating RWPA and PF in polymer concrete. From Table 7, it is evident that increasing the percentage of RWPA in FRPC yields notable results up to a replacement level of 20%. However, a slight decrease in strength properties is observed at a 30% replacement, and a significant decrease in strength properties is noted at a 50% replacement. Despite the FRPC containing 50% RWPA, it exhibits significantly lower results compared to the optimum replacement percentage of 20% [16]. It is worth noting that the FRPC with 20% RWPA replacement achieves the target strength after 28 days of curing. Specifically, the replacement of 20% RWPA with coarse aggregate in FRPC results in a CS of 49.57 MPa at 28 days of curing, which is 7.37% higher than the specimens made without RWPA content. This highlights the positive impact of incorporating RWPA in FRPC on the strength properties of the concrete [16].

According to BATAYNEH *et al.* [17], up to 20% of plastic was utilized in concrete, and the strength of concrete exhibits lower resistance against compression and tension than normal concrete using natural aggregates. Thus, it is suggested that concrete containing recycled materials of lower strength be used in certain civil engineering applications, particularly in non-structural applications, where lower strength up to 25 MPa is required. This will contribute to diminishing the cost of using non-structural concrete. As per ISMAIL and AL-HASHMI [7], at 28 days, 20% of waste plastic in concrete produces the lowest flexural strength, viz. 30.5% below the value of the reference concrete mix without any admixtures [18]. So, it is concluded that optimum

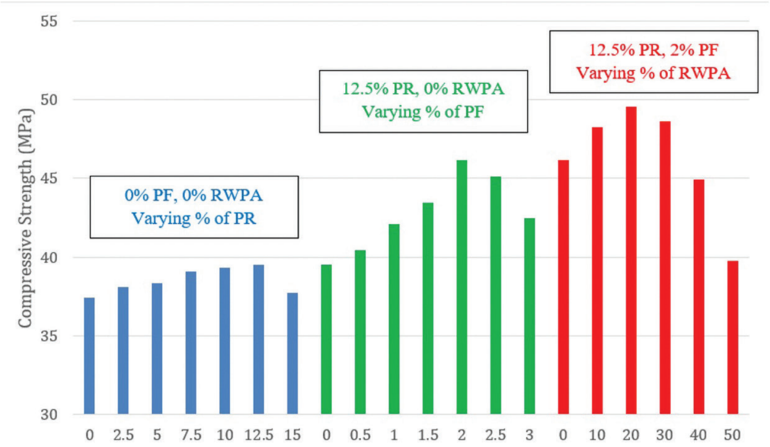

Figure 1: Effect of PR, PF, and RWPA on strength properties of FRPC.

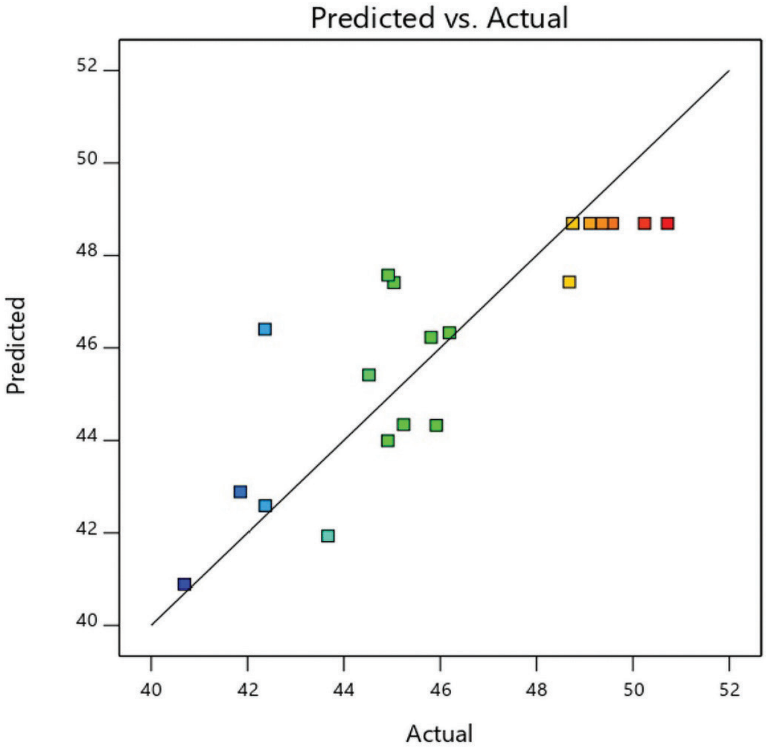

Figure 2: Predicted vs actual curve from CCD matrix.

results could be achieved in M30 grade FRPC made with 12.5% of PR, 2% of PF and 20% of RWPA. It is also concluded that the addition of above-mentioned ingredients which are prepared for M30 grade concrete can produce 50MPa strength in 28 days [19–22].

3.1. Statistical modelling

Statistical modelling is one of time efficient processes and it is also able to reduce the number of experimental combinations. CCD is employed to predict the relationship between the input variables at a time. Usually, the runs depend on the number of variables. The number of experiments to be run is usually based on $N = 2k (k - 1) + Cp$, where k and Cp are the number of factors and the number of center points [8]. For example, of 3 variables, there are a minimum of 13 experimental points are created for modelling. The number of repetitions of the experiments at the center allows you to measure the pure error and stabilize the variance of the predicted response (Figure 2). The thumb rule for stabilizing the variance is to do 3 to 5 runs at the midpoint when the α is close to $\sqrt{\alpha}$, which accurately estimates the output results which is replicated. In this study, instead of 13 runs,

Table 8: CCD matrix.

STD	**RUN**	**INPUT VARIABLES**			**28 DAYS CS (MPa)**		**ACTUAL / PREDICTED**
		A: PR (%)	**B: PF (%)**	**C: RWPA (%)**	**ACTUAL**	**PREDICTED**	
1	7	10	1	0	42.37	42.59	0.99
2	3	15	1	0	40.69	40.89	1.00
3	11	10	3	0	41.85	42.89	0.98
4	14	15	3	0	45.92	44.33	1.04
5	13	10	1	40	44.52	45.42	0.98
6	15	15	1	40	43.67	41.93	1.04
7	16	10	3	40	45.24	44.34	1.02
8	19	15	3	40	44.91	43.99	1.02
9	2	10	2	20	48.68	47.43	1.03
10	5	15	2	20	42.36	46.40	0.91
11	1	12.5	1	20	45.81	46.23	0.99
12	17	12.5	3	20	45.04	47.41	0.95
13	12	12.5	2	0	46.19	46.33	1.00
14	10	12.5	2	40	44.92	47.57	0.94
15	8	12.5	2	20	49.57	48.69	1.02
16	6	12.5	2	20	49.11	48.69	1.01
17	20	12.5	2	20	48.75	48.69	1.00
18	18	12.5	2	20	50.24	48.69	1.03
19	4	12.5	2	20	49.36	48.69	1.01
20	9	12.5	2	20	50.72	48.69	1.04

20 runs were conducted to predict the precise error estimation [23]. The design matrix consisting of 20 experimental runs with 6 replicates of centre points for 3 selected variables and their corresponding experimental data of 28 days CS was illustrated in Table 8.

$$\begin{aligned} CS = {} & 0.65 + 6.46 * PR + 4.51 * PF + 0.35 * RWPA + 0.31 * PR * PF - 0.0089 * PR * RWPA \\ & - 0.0172 * PF * RWPA - 0.285 * PR^2 - 1.874 * PF^2 - 0.0044 * RWPA^2 \end{aligned} \tag{1}$$

The equation formulated in terms of codes allows for predictions about the response based on given levels of each factor. In this equation, the high and low levels of factors are coded as +1 and -1, respectively. The coded equation is particularly useful for evaluating the relative impact of factors by comparing their coefficients. To make forecasts about the response for specific levels of each factor, the equation can be transformed into actual factors (Figure 3). In this form, the levels are expressed in their original units for each factor [24]. It is important to note that an intercept is included in the equation to account for the scaling of coefficients, which enables accommodation of the units of each factor. The intercept is not positioned at the center of the design space.

To analyze the interaction between the response (in this case, CS) and the experimental levels of selected variables within the design space, 2D contour plots and 3D plots are used. These plots illustrate the relationship between the response and the levels of the variables. Figure 3 and Figure 4 display the 2D contour plots and 3D plots, respectively, showcasing the variation in the 28-day CS of FRPC based on the selected variables. These visual representations provide valuable insights into the influence and interaction of different factors on the response, allowing for a better understanding of the experimental outcomes (Figure 4).

The significance of model is confirmed through the determination coefficient (R^2), which measures the linear relationship between the experimental and predicted values. In the case of the CS attainment, the coefficient of determination is calculated to be 0.9947. Generally, an R2 > 0.75 indicates the adequacy of the model. In this case, the R2 value of 0.9947 indicates that 99.47% of the variations in the response (CS) can be explained by the model. Furthermore, the probability of occurrence of an error in model is estimated to be 2.68%. To ensure the reliability of the model, experiments are conducted in triplicate using the optimized conditions determined

Table 9: Reliability test.

DESCRIPTION	OPTIMIZED INPUT PARAMETERS (%)			PREDICTED CS (MPa)	RELIABILITY TEST RESULTS ON CS (MPa)	PREDICTED / RELIABILITY
	PR	PF	RWPA			
For Ultimate Strength	12.144	2.110	23.724	48.822	49.74	0.98
Fixed RWPA content	12.048	2.185	30	48.632	49.91	0.97

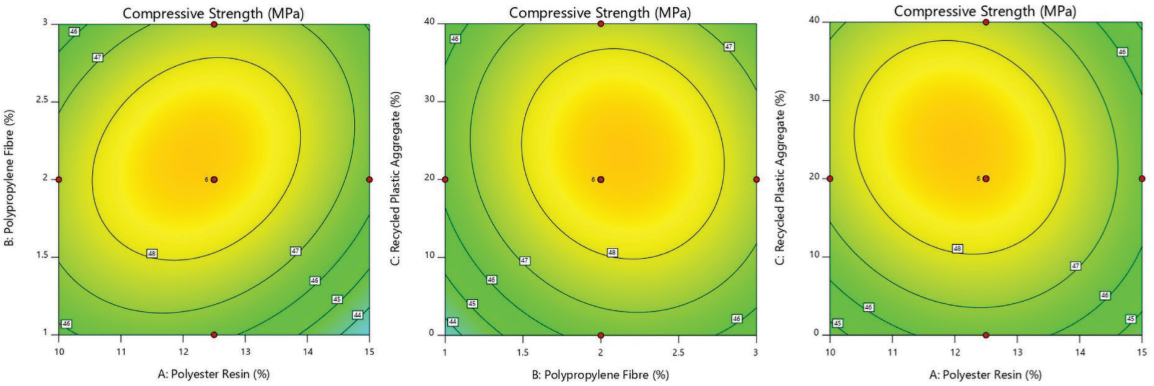

Figure 3: 2D contour plots.

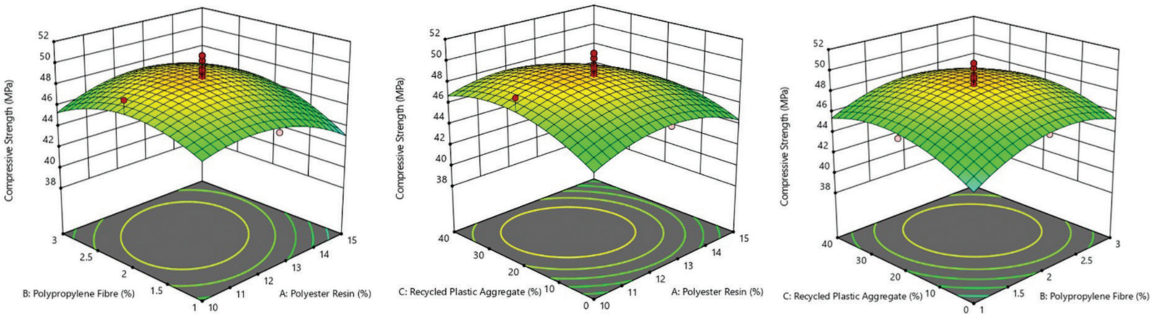

Figure 4: 3D contour plots.

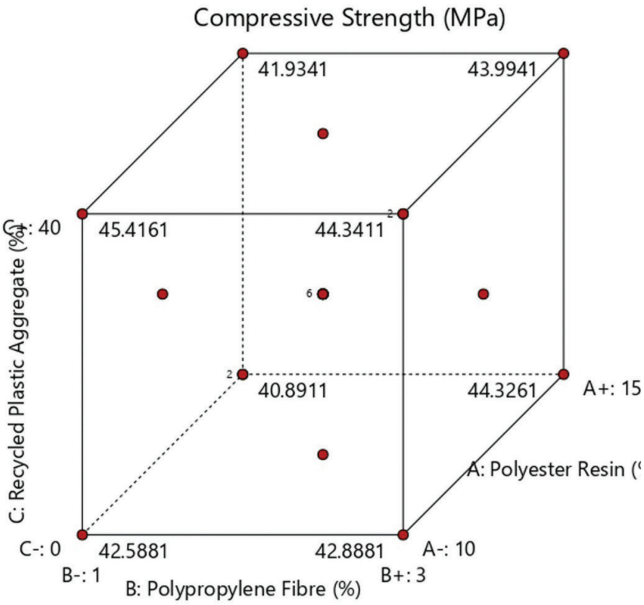

Figure 5: 3D cubical model.

by the aforementioned model. This repetition helps validate the consistency and reproducibility of the results obtained from the model (Figure 5). By conducting the experiments in triplicates & comparing the results with predictions made by model, the reliability and accuracy of the model can be further assessed. This iterative process ensures that the model's predictions align with the observed experimental outcomes, strengthening confidence in its reliability for future use.

According to the reliability test results shown in Table 9, based on the optimized input parameters, it is observed that it is possible to produce ultimate CS of 48.822MPa with the help of 12.14% PR, 2.11% PF, and 23.72% RWPA. Hence the 28 days experimental CS values are closely matched together with the predicted CS values. In the experimental investigation, it is found that beyond 20% replacement of RWPA in FRPC, the CS showed a reduction for constant percentages of PF and PR. However, a statistical model developed by CCD suggests that coarse aggregate could replace RWPA by 30%. It is concluded that the optimum input parameters for the attainment of 28 days CS are 12.05% of PR, 2.19% of PF and 30% of RWPA [25].

4. CONCLUSIONS

On the basis of the experimental and statistical analysis on the FRPC made with PR, PF, and RWPA, following are the major conclusions drawn.

- It is possible to produce polymer concrete with the addition of polypropylene fibres and it is also feasible to utilize the RWPA as an effective alternative material for conventional coarse aggregate up to a certain limit.
- From the experimental results, it is inferred that the optimum parameters for the preparation of M30 grade FRPC are 12.5% of PR, 2% of PF and 20% of RWPA that produces 49.57MPa strength in 28 days which is 32.36% higher than the conventional mix made without PR, PF and RWPA.
- In statistical modelling, the suggested value of R2 is 0.9947, and from the predicted design equation desirable solutions on input parameters are found.
- From CCD, it is possible to produce ultimate CS of 48.822MPa with the help of 12.14% PR, 2.11% PF and 23.72% RWPA. Hence the 28 days experimental CS values closely match with the predicted CS values which were validated with experimental results and show a better correlation of 0.98.
- It is concluded that the optimum input parameters for the attainment of 28 days CS are 12.05% of PR, 2.19% of PF and 30% of RWPA.

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