SSRG International Journal of Civil Engineering
ISSN: 2348-8352/ https://doi.org/10.14445/23488352/IJCE-V12I7P116

Volume 12 Issue 7, 183-199, July 2025

Original Article

Flexural Performance of Rubberised Concrete with Flyash, Silica Fume and Plaster of Paris: An Experimental and Numerical Analysis

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Received: 14 May 2025 Revised: 17 June 2025 Accepted: 16 July 2025 Published: 31 July 2025

Abstract *- The global demand for concrete, the most widely used construction material, continues to rise due to rapid expansion in residential, commercial, and infrastructure projects. Simultaneously, the increasing cost of cement and aggregates, coupled with the growing volume of solid waste such as discarded automobile tires, poses significant environmental challenges. Addressing both economic and ecological concerns necessitates the adoption of alternative materials to partially replace conventional concrete constituents, such as cement and coarse aggregates. This study explores the partial replacement of cement with mineral admixtures, including Plaster of Paris (POP), Silica Fume (SF), Fly Ash (FA), and the use of Reclaimed Rubber (RR) as a substitute for coarse aggregate. Both experimental and computational methods were employed, focusing on an M20 grade concrete mix. The study determined the most effective replacement level, with optimal results observed at a 9% substitution rate for both FA and POP. A predictive model for compressive strength was implemented in C++ using a Genetic Algorithm (GA), incorporating various mixtures of RR, SF, FA, and POP as input parameters. The simulation results led to the identification of five optimal mix design configurations. Twelve concrete cubes were cast and tested to validate the simulation results, demonstrating strong agreement between experimental and predicted compressive strength values. Furthermore, twelve beams incorporating the selected combinations were prepared and subjected to flexural testing, with load-deflection curves generated for each of them. The findings demonstrated that incorporating these alternative materials led to an improvement in the concrete's bending (flexural) strength.*

Keywords *- Alternative building materials, Strength forecasting, Compressive performance, Flexural performance; Recycled rubber, Genetic Algorithm (GA).*

1. Introduction

1.1. General

The steady rise in global population and the pace of urbanization have contributed to the continual spread of cities and towns. Urban growth is closely linked to infrastructure development, which is crucial for enhancing living standards. The expansion of built environments is largely driven by increasing urban populations and the implementation of new infrastructure projects. In this context, concrete remains a fundamental construction material, produced by mixing cement and other components in specific proportions to meet desired structural requirements. However, the escalating demand for construction has intensified the consumption of natural resources, particularly aggregates, resulting in their rapid depletion. This situation highlights the need to explore alternative materials that can effectively replace traditional fine and coarse aggregates without compromising the strength or durability of concrete. One major environmental concern is the accumulation of waste tires in landfills, which can become breeding grounds for mosquitoes and contribute to air and water contamination, negatively impacting human health and the surrounding ecosystem. A viable response to this issue is the use of recycled rubber from waste tires as a partial replacement for conventional aggregates. This leads to the development of rubberized concrete, where rubber particles substitute a portion of the sand or gravel in the mix. Such an approach not only helps mitigate environmental problems but also shows promise in enhancing certain mechanical properties of concrete. In this research, materials such as plaster of Paris, fly ash, and silica fume were employed to partially replace cement by weight, aiming to create a more sustainable concrete mix. To refine the proportions of these materials, a Genetic Algorithm (GA) was applied. GA is a nature-inspired optimization method that replicates evolutionary principles to find effective solutions, thereby minimizing the need for exhaustive lab testing and saving both time and resources. The purpose of this research is to fulfil the following objectives:

- To identify the most effective proportions of plaster of paris, fly ash, silica fume, and reclaimed rubber for enhancing the strength under compression.
- To predict the strength under compression of concrete containing these supplementary materials through optimization using a Genetic Algorithm (GA).
- To experimentally evaluate the strength under compression of concrete incorporating various supplementary and replacement materials.
- To determine the optimal blend of plaster of paris, silica fume, fly ash, and reclaimed rubber to achieve maximum strength under compression in concrete.
- To investigate the impact of the combined material replacements on the bending (flexural) strength of concrete through beam testing.

Rebound hammer evaluations indicated that concretes incorporating combinations of these materials achieved roughly a 15% gain in compressive strength compared with control mixes. More specifically, mixtures containing 20% fly ash, 10% GGBS, and 2.5% silica fume showed strength improvements of about 6.97%, 12.5%, and 9.68% after 7, 14, and 28 days of curing, respectively [1]. Multiple studies have explored the combined use of fly ash and silica fume as partial replacements for cement in concrete mixtures. Fly ash was incorporated at varying levels 5%, 10%, 20%, and 30% while silica fume was added in proportions of 2.5%, 5%, and 10%. The results consistently showed that the addition of silica fume alongside fly ash contributed to an increase in compressive strength. However, this enhancement in strength was often accompanied by a decline in the workability of the fresh concrete mix [2]. Previous research has shown that the inclusion of silica fume significantly enhances the performance of concrete, particularly by increasing its compressive strength and bond strength. Additionally, concrete modified with silica fume exhibits elastic modulus, tensile strength, and flexural strength values that are comparable to those of conventional Portland cement concrete [3].

Previous studies have investigated how various curing methods influence the properties of concrete. Results indicated that the highest compressive strength was obtained from a mix incorporating 15% fly ash and cured in water for 28 days [4]. The Artificial Neural Network (ANN) model demonstrated high predictive accuracy across all curing periods, with correlation coefficients (R^2) surpassing 0.9 for both datasets: R1 (excluding fly ash) and R2 (containing 15% fly ash). Additionally, the model's reliability was supported by consistently low Root Mean Square Error (RMSE) values across different mix proportions and curing durations [5].

An independent experimental study investigated the effects of replacing cement with Fly Ash (FA) and fine aggregate with Granular Blast Furnace Slag (GBFS) on the properties of concrete. The control mix achieved compressive strengths of 35, 41, 48, and 50 N/mm² after 7, 28, 60, and 90 days of curing, respectively. When 50% of the fine aggregate was substituted with GBFS, the reduction in compressive strength at 28, 60, and 90 days was minimal. In contrast, increasing the proportion of fly ash led to a significant decline in compressive strength. This trend was also reflected in the split tensile and flexural strength results [6]. A separate investigation explored the use of scrap tire rubber chips as a partial replacement for coarse aggregates in concrete. The findings revealed a gradual reduction in compressive strength as the rubber content increased. At a 15% replacement level, the rubberized concrete exhibited noticeably lower compressive strength, along with similar declines in related mechanical properties [7].

Concrete mixtures were developed by partially replacing coarse aggregates with waste tire chips at volumetric proportions of 0%, 10%, 20%, and 30%. Compressive strength was evaluated after 14 and 28 days of curing in both water and acidic environments. Among the tested mixes, the specimens containing 10% waste tire replacement exhibited the highest compressive strengths under water curing, reaching 20.2 N/mm² and 23.1 N/mm², respectively. Similarly, under acidic curing conditions using a 0.5% solution of dilute HCl and NaOH, the 10% rubber substitution mix also delivered the best compressive performance [8]. In the Genetic Programming process, individuals are selected for reproduction based on their fitness levels. This cycle continues across multiple generations until the optimal solution is found.

The outcomes from existing literature were compared with those predicted by the Gene Expression Programming (GEP)-based model. The model achieved an R^2 value of 0.94 and a Mean Squared Error (MSE) of 5.15, indicating a strong correlation and reliable performance. Based on the statistical analysis, the GEP model demonstrated higher accuracy in estimating the compressive strength of concrete [9]. Four concrete mixes were prepared with fly ash replacing cement at 10%, 20%, 30%, and 40% to identify the optimal replacement level. The mix with 30% fly ash demonstrated the highest compressive strength and was selected for further testing.

This mix was then modified by incorporating 10% GGBS and varying proportions of silica fume. Compression testing for these mixes is currently ongoing. To maintain consistent workability and achieve the target strength, Superplast 840 was used across all samples. The highest compressive strength recorded was 40.44 N/mm² for the mix with 30% FA. A similar trend was observed in the split tensile strength tests, where the mix containing 30% FA, 30% SF, and 10% GGBS outperformed the conventional concrete mix [10].

The reviewed literature indicates that most studies have focused on the use of individual mineral or chemical admixtures as partial replacements in concrete. Additionally, different forms of waste tires, such as shredded, crumbed, or recycled rubber, have been employed as partial replacements for coarse aggregates. However, a significant gap remains in research regarding the feasibility of using reclaimed rubber as a substitute for coarse aggregate, both independently and in conjunction with mineral admixtures, across a replacement range of 3% to 24%.

Although various Supplementary Cementitious Materials (SCMs), including metakaolin, GGBS, fly ash, and silica fume, have been widely researched for their impact on the mechanical performance of traditional concrete, their collective influence on rubberized concrete has not been thoroughly examined.

Two critical gaps remain in the current body of research: (i) evaluating whether combinations of SCMs can counteract the typical loss in compressive strength associated with rubber aggregate incorporation, and (ii) determining optimal SCM blending ratios that offer a well-balanced mix in terms of strength, workability, and ductility for rubberized concrete.

Moreover, previous studies did not compare or analyse experimental and simulated results using the specific materials and replacement percentages considered in this study. To address this research gap, the present investigation was undertaken.

2. Materials and Methods

2.1. Cement

Ordinary Portland Cement (OPC), when blended with other materials, aids in filling the gaps between fine aggregates, effectively lowering the permeability and increasing the strength of the hardened concrete [11].

Once mixed with water, hydration initiates, resulting in the formation of Calcium Silicate Hydrate (CSH), the primary compound contributing to strength development in concrete. The outcomes of the cement characterization tests are detailed in Table 1.

Table 1. Results of OPC

Sl.No	Test	Result
1	Specific gravity	3.1
2	Standard Consistency	29%
3	Initial Setting Time	32 minutes
4	Final Setting Time	180 minutes
5	Compressive Strength (28 days)	53 N/mm^2

2.2. Aggregates

Aggregates are typically regarded as inert materials, comprising approximately 60-80% of the total volume and 70-85% of the overall weight of concrete [12]. Replacing conventional natural aggregates with alternative or recycled materials presents a viable strategy for conserving natural resources and promoting sustainability in concrete production [13]. Fine aggregate, defined as material with particle sizes less than 4.75 mm, plays a crucial role in the concrete mix [14]. In this study, clean and Dry River sand was selected as the fine aggregate. The coarse aggregate, partially replaced with reclaimed rubber, consisted of crushed hard stones with a nominal size of 20 mm. Previous research has shown that concrete incorporating recycled aggregates in place of conventional coarse aggregates tends to exhibit lower compressive strength than standard concrete mixes [15]. The fine and coarse aggregates test results are summarized in Table 2.

Table 2. Test results of aggregates

Sl. No.	Test	Fine Aggregate	Coarse Aggregate
1	Specific gravity	2.6	2.7
2	Water Absorption (%)	1	0.8
3	Fineness Modulus	3.5	5.2

2.3. Silica Fume and Fly Ash

Fly ash is a commonly utilized pozzolanic additive in concrete. Due to its fine particle size and spherical shape, it enhances the mixture's flow characteristics, thereby lowering water demand and contributing to improved long-term strength, particularly in high-strength concrete applications [16, 17].

High-performance concrete incorporating 7% silica fume and 0.5% cellulose fibre has been shown to yield optimal compressive strength; however, increasing these proportions beyond this threshold can lead to a reduction in strength [18]. Similarly, replacing cement with silica fume up to a 10% level enhances compressive strength, while higher replacement levels tend to diminish it [19].

The physical properties of silica fume and fly ash used in this study, sourced from Astra Chemicals and the Ennore Plant in Chennai, are presented in Tables 3 and 4, respectively.

Table 3. Physical characteristics of constituent materials

Sl. No	Property	Fly Ash	Silica Fume
1	Specific gravity	2.2	2.6
2	Fineness (m^2/Kg)	450	22000
3	Bulk Density (kg/m^3)	1300	1450

Table 4. Chemical characteristics of constituent materials

Sl. No	Compound	Percentage of Fly ash	Percentage in Silica fume
1	Si O_2	56.2	92.3
2	Al_2O_3	27.3	0.79
3	Fe_2O_3	3.5	1.57
4	CaO	4.4	0.43
5	SO_3	1.3	0.33
6	MgO	1.7	0.40
7	Na_2O	0.4	0.38
8	K_2O	0.5	1.30
9	LOI	3.1	1.8

2.4. Plaster of Paris

This study explores the feasibility of incorporating Plaster of Paris (POP) as a partial replacement for cement in concrete mixtures. Experimental findings indicate that substituting 5% to 15% of cement with POP can achieve up to 80% of the target compressive strength [20]. The inclusion of POP has also been associated with improvements in water resistance and compressive performance. Moreover, it contributes to a reduction in the initial setting time of the mix, without significantly altering the final setting time when used within acceptable limits [21]. The manufacturer-supplied properties of Plaster of Paris are presented in Table 5.

Table 5. Physical characteristics of constituent materials

Sl.No	Property	Plaster of Paris
1	Specific gravity	2.5
2	Fineness	99%
3	Bulk Density (kg/m^3)	710

2.5. Reclaimed Rubber

Reclaimed rubber is a compound material that typically includes rubber, carbon black, oil, stearic acid, and various other additives. It finds extensive application in the tire industry, particularly in components such as inner linings, sidewalls, beads, chafers, and inner casings [22].

In the present investigation, reclaimed rubber was utilized as a partial substitute for conventional coarse aggregate in concrete. This substitution led to a noticeable reduction in concrete density, primarily due to the significantly lower specific weight of rubber aggregates compared to natural aggregates. As the proportion of rubber aggregate increased, a corresponding decrease in the overall unit weight of the concrete mixture was observed (Figure 1). Reclaimed Rubber Test Results are presented in Table 6.

Fig. 1 Reclaimed rubber

Table 6. Reclaimed rubber test results

Sl. No.	Property	Result
1	Ash content	5.4%
2	Density	1.12g/cc
3	Tensile strength	17.7Kg/cm^2
4	Specific gravity	1.5
5	Water absorption	6%

2.6. Preparation and Testing of Samples

In this investigation, the mix design was developed based on the IS 10262:2009 guidelines, utilizing a mix proportion of 1:1.85:3.13:0.5 [23]. The combination of materials and recycled rubber was proportioned individually, considering the intended replacement percentages. The initial concrete batch was produced without any supplementary materials to serve as a control. The mixing process was carried out using a concrete mixer, with the calculated amount of water added gradually to ensure uniform distribution and achieve a consistent, homogeneous mix. Standard cube moulds measuring 150 × 150 × 150 mm were used for casting. The freshly mixed concrete was poured into moulds in successive layers, with each layer properly compacted to remove entrapped air.

The specimens were then allowed to rest undisturbed for 24 hours to complete the initial setting phase. Various cube and cylinder specimens were prepared to assess compressive and split tensile strengths. Experimental findings indicated that cube specimens demonstrated a more pronounced size effect in comparison to cylindrical samples [24]. Curing is the process of maintaining adequate moisture and temperature in freshly cast concrete to facilitate proper cement hydration, which is critical for developing the desired mechanical properties [25]. In this study, concrete cube specimens were subjected to curing durations of 7, 14, and 28 days, as illustrated in Figure 2. The geometry and dimensions of the concrete cubes, along with the configuration of the steel loading plates, significantly influenced load distribution and the resulting failure patterns during compressive strength testing. Different modes of failure were recorded, depending on the size and placement of the steel plate in contact with the specimen surface [26].

Compressive strength was measured using a Universal Testing Machine (UTM) with a 50-ton capacity, as shown in Figure 3.


Fig. 2 Curing of cube samples

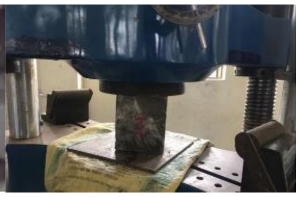
Fig. 3 Compressive strength test

Assessing hardened concrete is crucial for determining its strength and durability, thereby confirming compliance with specified quality standards. A monotonic loading pattern was applied during the testing of specimens to determine their maximum load-bearing capacity. The experimental procedure involved casting concrete samples with predefined mix proportions, followed by curing and subsequent testing. M20 grade concrete was used for both the control mix and the mixes incorporating replacement materials.

Beam specimens were tested under a single-point loading setup to measure deflection behaviour. Each beam was designed as an under-reinforced section, reinforced with two 8 mm diameter bars in tension and two 6 mm diameter hanger bars positioned at the top. The beams were cast using moulds measuring 100 mm × 150 mm × 1500 mm.

A total of twelve beams were prepared across four mix combinations, with three specimens per combination, as illustrated in Figure 4. Specimens were demoulded between 16 and 24 hours after casting and cured in water at room temperature for 28 days. All beams were conditioned and prepared for testing as shown in Figure 5.


Fig. 4 Cast beam samples


Fig. 5 Beam samples ready for testing

A two-point loading system (also known as four-point bending) was employed to evaluate the flexural behaviour of the beam specimens. Load versus deflection curves were recorded under monotonic loading conditions.

2.7. Genetic Algorithm

A Genetic Algorithm (GA) works by evolving a population of potential solutions, often termed individuals. Each individual is assessed for its fitness in relation to a defined objective, adhering to the "survival of the fittest" concept. Individuals with superior fitness scores have a higher likelihood of being chosen for reproduction in the subsequent generation. During this phase, selected parent solutions undergo crossover, either single-point or multi-point, resulting in offspring that combine traits from both parents. A bit mask is used during the crossover process to control the exchange of genetic material between individuals, as depicted in Figure 6.

C1=Mask1&P1+Mask2&P2
C2=Mask2&P1+Mask1&P2
P1, P2 -Parent's chromosomes;
C1, C2 – Children's Chromosomes (Offspring individuals)
Mask1, Mask2 – bit masks (Mask =NOT (Mask)) &- bit operation "AND".

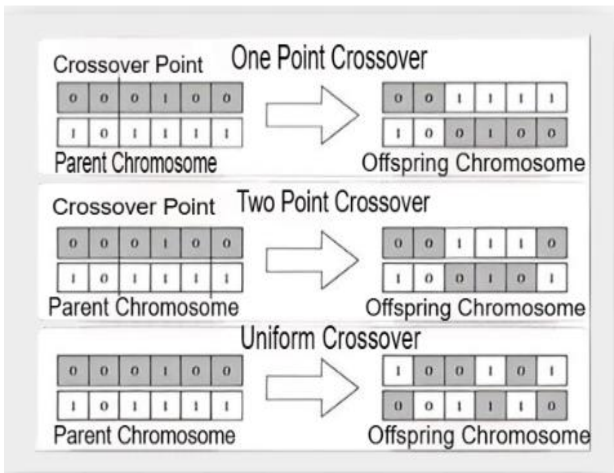

Fig. 6 Crossover with bit mask

The mathematical description of crossover is
$C1 = \gamma P_1 + (1-\gamma) P_2$
$C2 = (1-\gamma) P_1 + \gamma P_2$
$\gamma = (1+2\alpha) r - \alpha$

P_1, P_2 -Parent's chromosomes;

C_1, C_2 – Children's Chromosomes (Offspring individuals)
α – Exploration coefficient – user defined ($\alpha \geq 0$)
r – Random number between 0 and 1

A mutation means a random change of the value of a gene in the population (Figure 7).

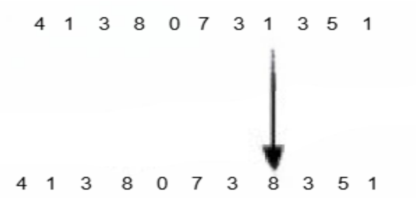

Fig. 7 Mutation in a chromosome

Figure 8 illustrates the positions where mutations occur within the population, while Figure 9 demonstrates the mutation process in the genetic algorithm, where certain bits in a bit string are altered.

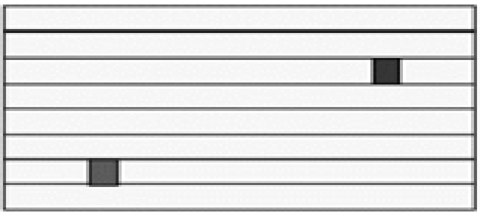

Fig. 8 Mutations occur in the population

Fig. 9 Mutations occur in the population

2.8. Scheme of Evolutionary Algorithm (EA)

EA functions by progressively improving a population of candidate solutions, referred to as chromosomes, through iterative processes that include selection, crossover, and mutation. Each chromosome is evaluated based on its fitness, which reflects how well it solves or adapts to the target problem. The selection mechanism identifies the most promising individuals, whose genetic traits are then combined and propagated to form the next generation. The general framework of an EA is illustrated in Figure 10.

The initial population is typically created by randomly assigning gene values within a specified allowable range. The optimization proceeds iteratively until certain predetermined stopping criteria are satisfied.

- Assessing whether the best individual's function value lies within a predefined proximity to the desired target.
- Implementing a set number of iterations serves as one of the most frequently used stopping criteria.
- In the crossover stage, chosen parents are paired to generate new offspring through gene combination.
- Mutation introduces genetic diversity by randomly altering specific genes.
- The succeeding generation is formed by retaining top-performing individuals and incorporating those produced through crossover and mutation.

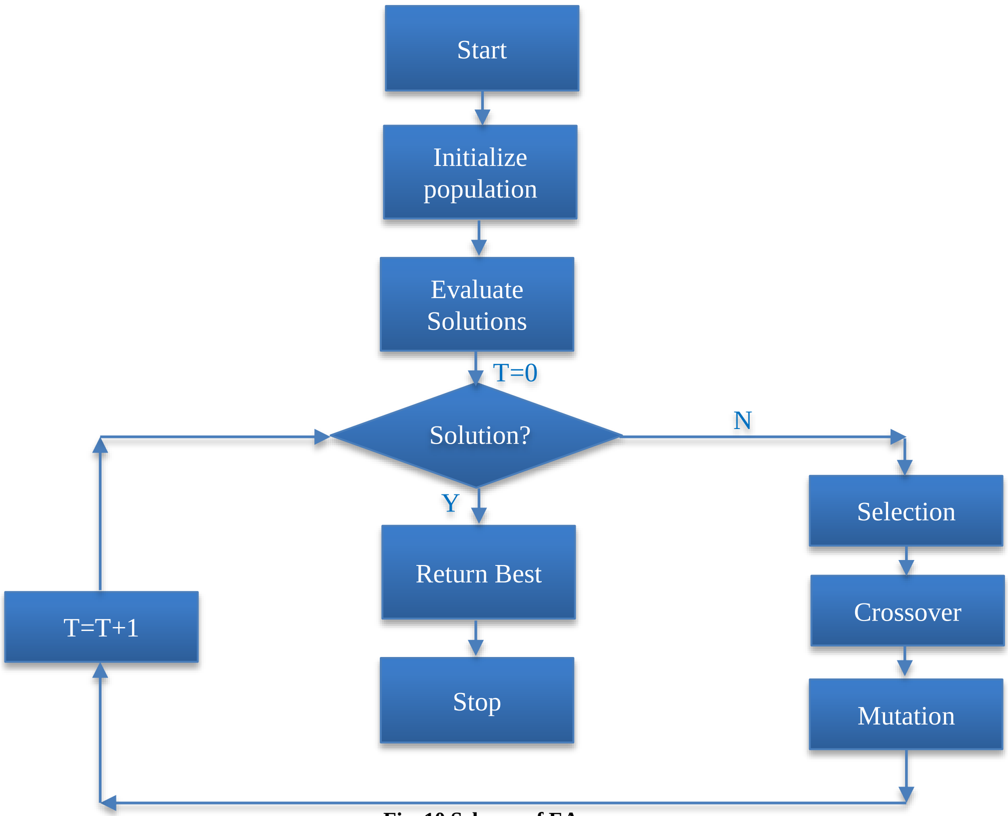

Fig. 10 Scheme of EA

The constructed model was employed to estimate the compressive strength of concrete containing various combinations of replacement materials. Specimens were prepared according to standard experimental protocols, utilising the optimal replacement ratios determined by the Genetic Algorithm. Using the optimized mix proportions, cube and beam specimens were cast and cured for 28 days. Following the curing period, compressive and flexural strength tests were conducted to assess their mechanical properties.

3. Results and Discussion

This section presents the outcomes of individual tests performed for each material replacement, supported by comprehensive explanations and tabulated results. Additionally, it highlights both the simulated and experimental findings for the final combination of replacement materials. The analysis also covers the outcomes of flexural strength tests corresponding to all four replacement scenarios.

Table 7 displays the compressive strength results for M20 grade concrete samples, where cement was partially replaced with fly ash in increments of 3%, covering a range from 3% to 24%. The specimens were cured at ambient temperature and tested at 7, 14, and 28 days.

The outcomes are visually presented and compared with those of standard concrete. As shown in Figure 11, the mix incorporating 12% fly ash achieved the highest compressive strength of 31.7 N/mm² after 28 days, representing a 34% enhancement compared to the control sample.

This indicates that 12% fly ash replacement is the optimal level for maximizing compressive strength.

Table 7. Evaluation of Compressive Strength in Fly Ash-Modified Concrete Mixes

Fly Ash (%)	Strength Characteristics of M20 Concrete Cubes (N/mm^2)		
	7th day	14th day	28th day
0	14.0	17.4	21.2
3	15.8	19.7	25.4
6	17.5	22.0	28.1
9	18.2	22.5	28.5
12	19.6	24.2	31.7
15	14.7	20.4	26.6
18	12.1	16.4	22.3
21	10.5	14.2	19.4
24	8.8	11.6	15.2

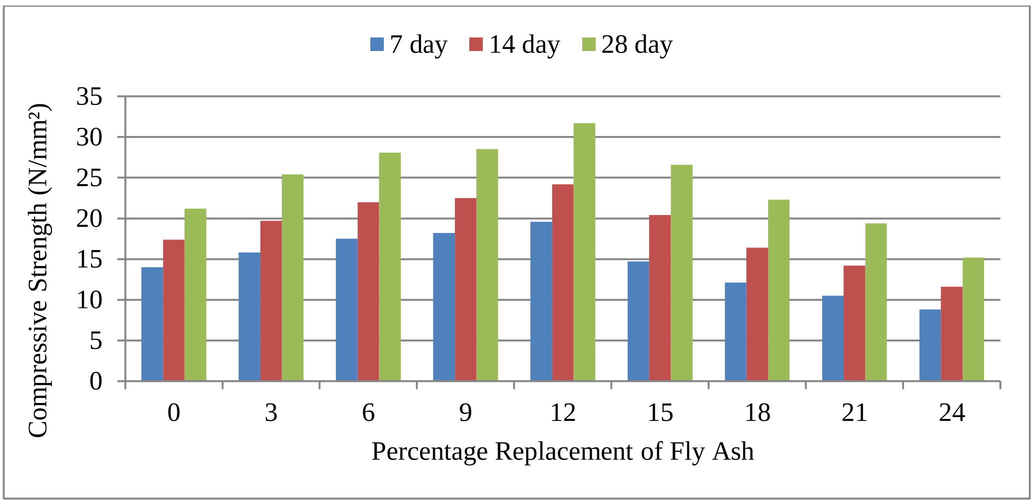

Fig. 11 Strength characteristics of Fly Ash-Replaced concrete

Comparing the standard mix with the optimized replacement mix reveals only slight differences in compressive strength for specimens cured for 7 and 14 days. However, for samples cured over 28 days, the data shows a clear trend: each 3% increment in Fly Ash (FA) content results in a noticeable increase in compressive strength. This improvement is attributed to the pozzolanic reaction between fly ash and cement, which produces calcium silicate hydrates (C–S–H) that contribute to increased compressive strength.

A study on fly ash replacement and compressive strength at the optimum FA level aligns with the findings of this research [27].

In previous studies, the strength under compressive stress of concrete with 10% and 15% FA replacement reached values of 31.15 N/mm² and 36.86 N/mm², respectively, which are comparable to the 31.7 N/mm² strength observed in this study, lying between the 10% and 15% FA replacement results.

Table 8 summarizes the strength under compressive outcomes for M20 grade concrete cubes with varying silica fume replacement levels. The results compare the average compressive strengths of these modified mixes to those of the conventional M20 concrete mix without silica fume.

Table 8. Evaluation of compressive strength in SF-Replaced concrete mix

Silica Fume (%)	Strength Characteristics of M20 Cube (N/mm^2)		
	7th day	14th day	28th day
0	14.0	17.4	21.2
3	16.4	20.7	26.3
6	18.2	22.3	28.4
9	18.6	23.2	30.8
12	17.8	24.5	32.5
15	15.7	20.4	28.6
18	13.4	17.4	24.3
21	11.2	15.0	20.2
24	9.1	11.8	15.5

Figure 12 is generated based on the test data. The mix with 12% Silica Fume (SF) replacement exhibited the highest strength, attributed to its binding properties, making it the optimal SF replacement percentage in the concrete mix. However, increasing the Silica Fume (SF) content beyond this point leads to a gradual decline in compressive strength, primarily due to the increased brittleness of the concrete resulting from the excess binder material.

The peak strength observed in this study for specimens cured for 28 days aligns with previous research by Joe Paulson [28]. The maximum compressive strength recorded in this study was 32.5 N/mm² at the 12% SF level, while a strength of 33.41 N/mm² was achieved with a 13% SF replacement. This indicates that further increases in SF percentage tend to reduce the strength under compression.

Curing the samples for 7, 14, and 28 days resulted in a 15% to 25% increase in compressive strength for concrete mixes containing 3% to 24% silica fume, compared to the control mix. The most notable strength enhancements were observed at 6% and 9% replacement levels.

Beyond the optimal 12% replacement level, the percentage for strength loss remained consistent across different curing periods. Table 9 provides the compressive strength test results for M20 grade concrete cubes incorporating different replacement levels of Plaster of Paris (POP). The results of the POP replacement mixes were compared to the conventional mix, as illustrated in Figure 13.

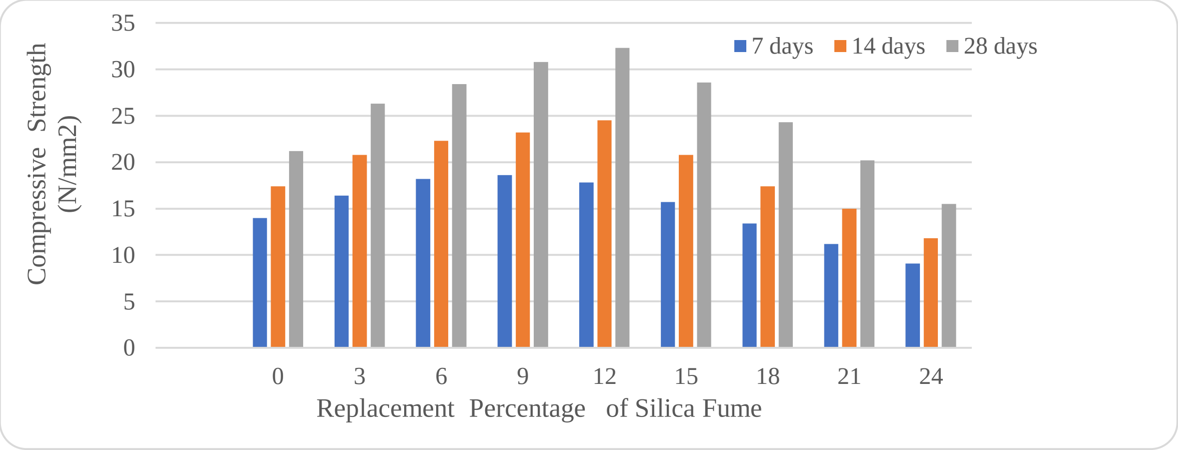

Fig. 12 Strength characteristics of silica fume-replaced concrete

Table 9. Evaluation of compressive strength of POP-Replaced concrete cubes

Plaster of Paris (%)	Strength Characteristics of M20 Cube (N/mm^2)		
	7th day	14th day	28th day
0	14.0	17.4	21.2
3	15.0	18.2	23.4
6	16.6	20.4	26.5
9	17.8	21.3	28.2
12	16.2	19.5	25.7
15	14.0	18.5	24.1
18	12.6	16.4	20.8
21	10.4	13.0	18.7
24	8.3	10.7	16.0

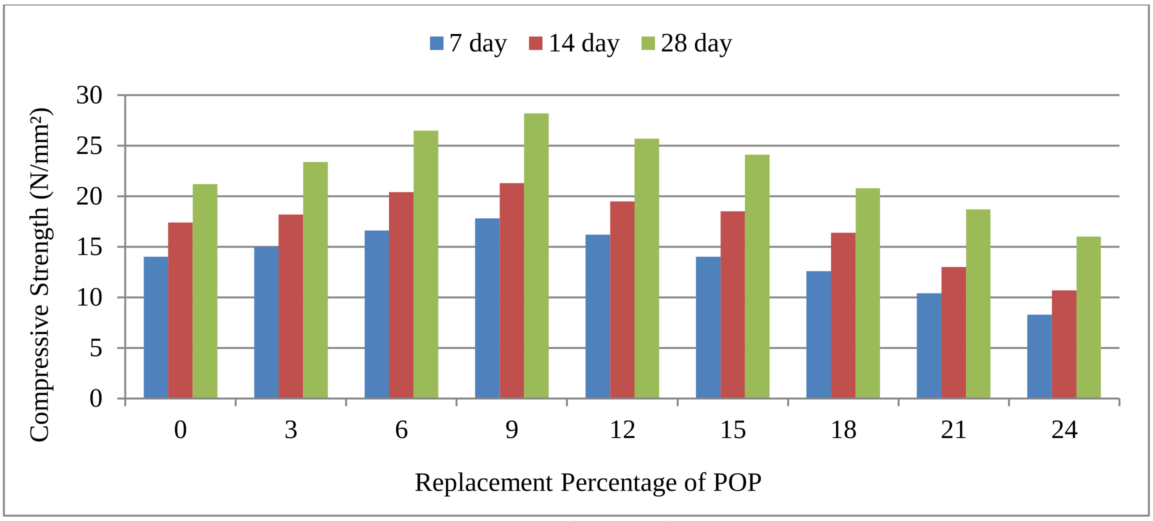

Fig. 13 Strength characteristics of plaster of paris-replaced concrete

The highest characteristics of strength were observed with a 9% replacement of Plaster of Paris (POP) with cement, which is considered the optimal replacement level for POP in concrete. At 18% and 3% replacements, the changes in compressive strength were minimal, with only slight reductions and increases, respectively, compared to the control mix. A 15% replacement of cement with plaster of Paris (POP) led to a slight reduction in compressive strength compared to the optimal mix. Conversely, incorporating POP at 6% and 12% notably improved the compressive strength of M20 grade concrete.

Compressive strength data for concrete incorporating reclaimed rubber at different curing periods are shown in Table 10 and Figure 14. The findings indicate a significant reduction in strength across all replacement levels, except at 3%, when compared to conventional concrete, mainly due to weak adhesion between the rubber particles and the cementitious matrix. Interestingly, the strength difference at the lowest replacement level (3%) is minimal relative to the control mix.

Table 10. Evaluation of compressive strength cubes with RR replacement

Reclaimed Rubber (%)	Strength Characteristics of M20 Cube (N/mm^2)		
	7th day	14th day	28th day
0	14.0	17.4	21.2
3	13.5	16.1	19.4
6	13.0	15.3	17.6
9	12.4	13.2	16.5
12	11.0	12.3	15.6
15	9.7	10.8	14.5
18	8.8	9.5	12.0
21	8.0	8.5	11.2
24	7.4	8.1	10.5

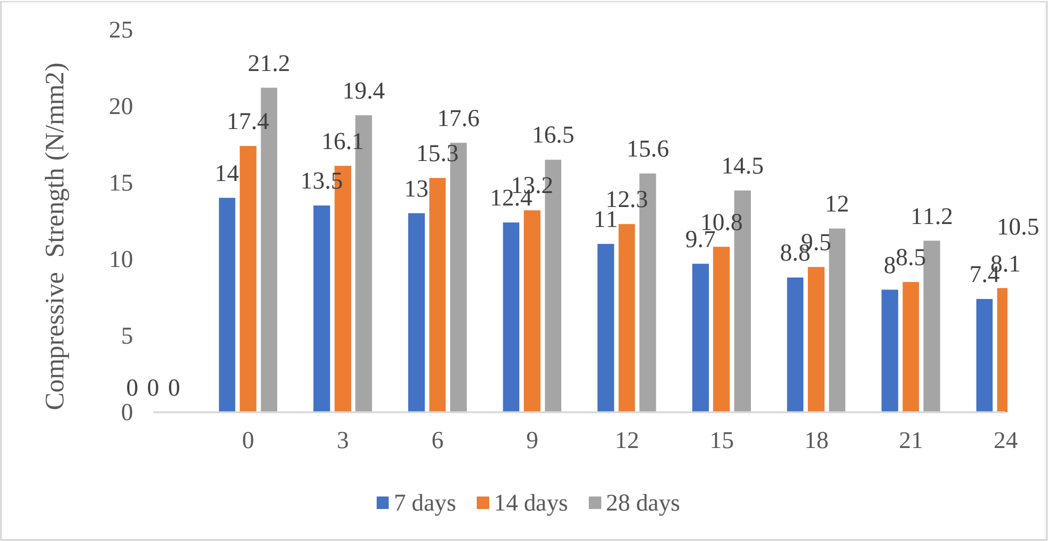

Fig. 14 Strength characteristics of reclaimed rubber-replaced concrete

Compared to the standard concrete mix, an increasing amount of reclaimed rubber (RR) consistently results in a reduction in compressive strength, regardless of the curing duration. To overcome this limitation, a Genetic Algorithm (GA) was utilized to identify the most effective blend of materials capable of producing concrete with improved strength characteristics over the conventional mix. The GA simulated the compressive strength of M20 grade concrete with four different materials, exploring 1600 possible combinations.

Table 11. Simulated strength characteristics (N/mm^2) of combined replacement of materials – I

Replacement (%)				Strength Characteristics (N/mm^2)	Replacement (%)				Strength Characteristics (N/mm^2)
SF	FA	RR	POP		SF	FA	RR	POP	
1	1	4	3	30.76	2	1	3	3	35.13
1	1	3	3	31.27	2	2	4	3	35.21
1	2	4	3	31.35	2	1	2	3	35.66
1	1	2	3	31.81	2	3	4	3	35.72
1	3	4	3	31.86	2	2	3	3	35.72
1	2	3	3	31.87	2	4	4	3	36.14
1	4	4	3	32.29	2	1	1	3	36.22
1	1	1	3	32.36	2	3	3	3	36.23
1	3	3	3	32.38	2	2	2	3	36.26
1	2	2	3	32.40	2	5	4	3	36.49
1	5	4	3	32.63	2	4	3	3	36.66
1	4	3	3	32.80	2	6	4	3	36.74
1	6	4	3	32.88	2	3	2	3	36.77
1	3	2	3	32.91	2	2	1	3	36.81
1	2	1	3	32.95	2	7	4	3	36.91
1	7	4	3	33.06	2	10	4	3	36.92
1	10	4	3	33.06	2	5	3	3	37.00
1	5	3	3	33.14	2	8	4	3	37.00
1	8	4	3	33.14	2	9	4	3	37.00
1	9	4	3	33.14	2	4	2	3	37.19
1	4	2	3	33.34	2	6	3	3	37.26
1	6	3	3	33.40	2	3	1	3	37.32
1	3	1	3	33.46	2	7	3	3	37.43
1	7	3	3	33.57	2	10	3	3	37.43
1	10	3	3	33.58	2	8	3	3	37.51
1	8	3	3	33.66	2	9	3	3	37.52
1	9	3	3	33.66	2	5	2	3	37.53
1	5	2	3	33.68	2	4	1	3	37.75
1	4	1	3	33.89	2	6	2	3	37.79
1	6	2	3	33.93	2	7	2	3	37.96
1	7	2	3	34.10	2	10	2	3	37.97
1	10	2	3	34.11	2	8	2	3	38.05
1	8	2	3	34.19	2	9	2	3	38.05
1	9	2	3	34.19	2	5	1	3	38.09
1	5	1	3	34.23	2	6	1	3	38.34
1	6	1	3	34.49	2	7	1	3	38.52
1	7	1	3	34.66	2	10	1	3	38.52
1	10	1	3	34.66	2	8	1	3	38.60
1	8	1	3	34.75	2	9	1	3	38.60
1	9	1	3	34.75	3	1	4	3	37.68
2	1	4	3	34.61	3	1	3	3	38.19

Table 12. Simulated strength characteristics (N/mm²) of combined replacement of materials –II

Replacement (%)				Strength Characteristics (N/mm²)	Replacement (%)				Strength Characteristics (N/mm²)
SF	FA	RR	POP		SF	FA	RR	POP	
3	2	4	3	38.27	9	2	2	3	42.50
3	1	2	3	38.72	10	1	4	3	36.85
3	3	4	3	38.78	10	1	3	3	37.37
3	2	3	3	38.79	10	2	4	3	37.45
3	4	4	3	39.21	10	1	2	3	37.90
3	1	1	3	39.28	10	3	4	3	37.96
3	3	3	3	39.30	10	2	3	3	37.96
3	2	2	3	39.32	10	4	4	3	38.38
3	5	4	3	39.55	10	1	1	3	38.46
3	4	3	3	39.72	10	3	3	3	38.47
3	6	4	3	39.80	10	2	2	3	38.50
3	3	2	3	39.83	10	5	4	3	38.73
3	2	1	3	39.87	10	4	3	3	38.90
3	7	4	3	39.98	10	6	4	3	38.98
3	10	4	3	39.98	10	3	2	3	39.01
3	5	3	3	40.06	10	2	1	3	39.05
3	8	4	3	40.06	10	7	4	3	39.15
3	9	4	3	40.06	10	10	4	3	39.16
3	4	2	3	40.26	10	5	3	3	39.24
3	6	3	3	40.32	10	8	4	3	39.24
3	3	1	3	40.38	10	9	4	3	39.24
3	7	3	3	40.49	10	4	2	3	39.43
3	10	3	3	40.63	10	6	3	3	39.50
3	8	3	3	40.34	10	3	1	3	39.56
3	9	3	3	40.58	10	7	3	3	39.67
3	5	2	3	40.60	10	10	3	3	39.67
3	4	1	3	40.81	10	8	3	3	39.75
3	6	2	3	40.85	10	9	3	3	39.76
4	1	4	3	39.94	10	5	2	3	39.77
4	1	3	3	40.46	10	4	1	3	39.99
4	2	4	3	40.54	10	6	2	3	40.03
4	1	2	3	41.25	10	7	2	3	40.20
9	1	4	3	39.36	10	10	2	3	40.21
9	1	3	3	39.87	10	8	2	3	40.29
9	2	4	3	39.95	10	9	2	3	40.29
9	1	2	3	40.41	10	5	1	3	40.33
9	3	4	3	40.46	10	6	1	3	40.58
9	2	3	3	40.47	10	7	1	3	40.76
9	4	4	3	40.89	10	10	1	3	40.76
9	1	1	3	41.95	10	8	1	3	40.84
9	3	3	3	42.98	10	9	1	3	40.84

Table 13. Summary of final replacement percentages for M20 Mix design

S.No.	Replacement (%)				Strength Characteristics (N/mm^2)
	SF	FA	RR	POP	
1	3	6	2	3	40.85
2	3	4	1	3	40.81
3	3	5	2	3	40.60
4	3	9	3	3	40.58
5	3	8	3	3	40.34
6	3	10	3	3	40.63
7	3	7	3	3	40.49
8	4	1	2	3	41.25
9	4	2	4	3	40.54
10	9	2	2	3	42.50
11	9	3	3	3	42.98
12	9	1	1	3	41.95
13	9	4	4	3	40.89
14	10	9	1	3	40.84
15	10	8	1	3	40.84
16	10	10	1	3	40.76
17	10	7	1	3	40.76
18	10	6	1	3	40.58

Mix combinations exhibiting extremely low or unusually high compressive strength values were deliberately excluded from the analysis to ensure consistency. A notable reduction in compressive strength was observed when the content of Reclaimed Rubber (RR) exceeded 2%. Among the 1,600 concrete mix variations evaluated, 164 demonstrated favorable strength performance, primarily influenced by the proportions of the individual replacement materials. The optimal replacement levels, which meet or surpass the compressive strength requirements for M20 grade concrete, are presented in Tables 11 and 12. These optimized mixes incorporated Fly Ash (FA) and Silica Fume (SF) in the range of 1% to 10%, RR between 1% and 4%, and a fixed 3% plaster of Paris (POP). Based on a further compressive strength assessment, the selection was narrowed down to 120 mixes, from which 18 were identified for their superior strength, with values ranging from 30.76 N/mm² to 41 N/mm², as detailed in Table 13.

Figure 15 illustrates a histogram displaying the compressive strength outcomes for the 18 chosen combinations. This chart highlights four specific combinations that produced compressive strengths exceeding the individual optimum values. These four mixes also demonstrated minimal variation in strength.

In these top-performing combinations, silica fume was used at 4% and 9%, fly ash ranged from 1% to 3%, Plaster of Paris was consistently used at 3%, and reclaimed rubber ranged between 1% and 2%. Concrete cubes incorporating these mix designs were cast to allow direct performance comparison. For each of these four combinations, three numbers for each case for repeatability were prepared and tested to measure compressive strength.

The compressive strength values for M20 grade concrete incorporating various replacement combinations are presented in Table 14 and illustrated in Figure 16. Each concrete specimen was tested after a 28-day curing period until complete failure occurred. The failure load was recorded for every sample and used in subsequent calculations. Compressive strength was computed for each cube, and the average was determined using the appropriate formula based on the results of three specimens per combination. The average compressive strengths of the leading four mixtures exhibited only slight differences, remaining within a limited range. The mean compressive strength for these combined mixes varied between 40.7 N/mm² and 41.26 N/mm². In particular, the compressive strengths recorded for combinations C-1 to C-5 were 40.7 N/mm², 41.26 N/mm², 41.02 N/mm², and 40.86 N/mm², respectively.

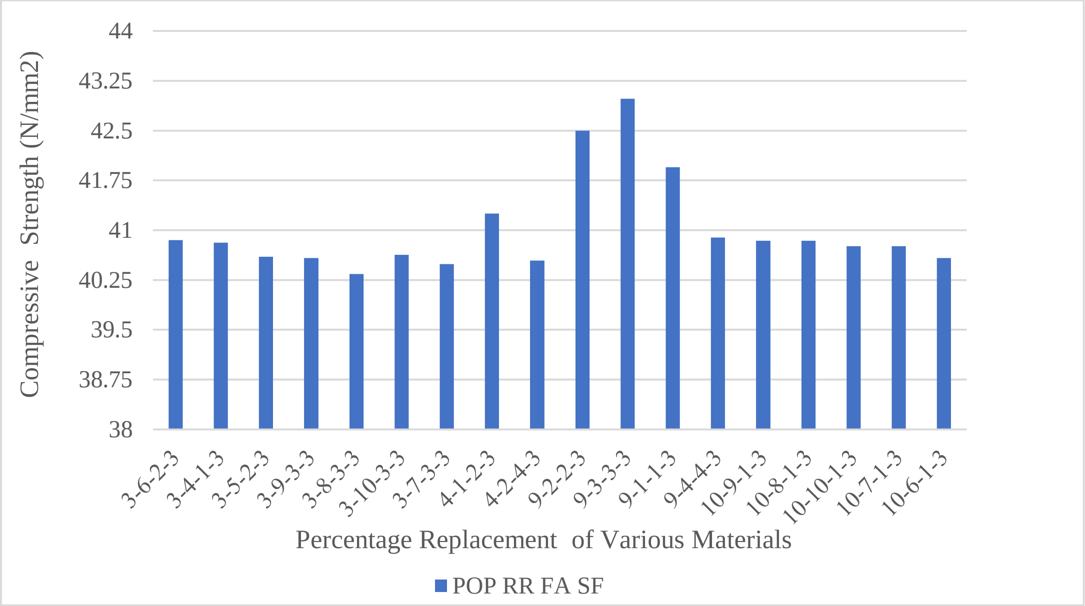

Fig. 15 Simulated Strength Distribution (N/mm²) of Optimized Replacement Mixes for M20 Grade Concrete

Table 14. Evaluation of M20 grade concrete using multiple material substitutions

Combination Number	Percentage Replacement				Sample 1	Sample 2	Sample 3	Average
	SF	FA	RR	POP	Strength Under Compression (N/mm²)	Strength Under Compression (N/mm²)	Strength Under Compression (N/mm²)	Strength Under Compression (N/mm²)
C -1	4	1	2	3	40.62	40.85	41.20	40.90
C - 2	9	2	2	3	42.70	42.65	42.92	42.75
C - 3	9	3	3	3	43.18	43.22	42.90	43.10
C - 4	9	1	1	3	41.58	42.20	41.80	41.86

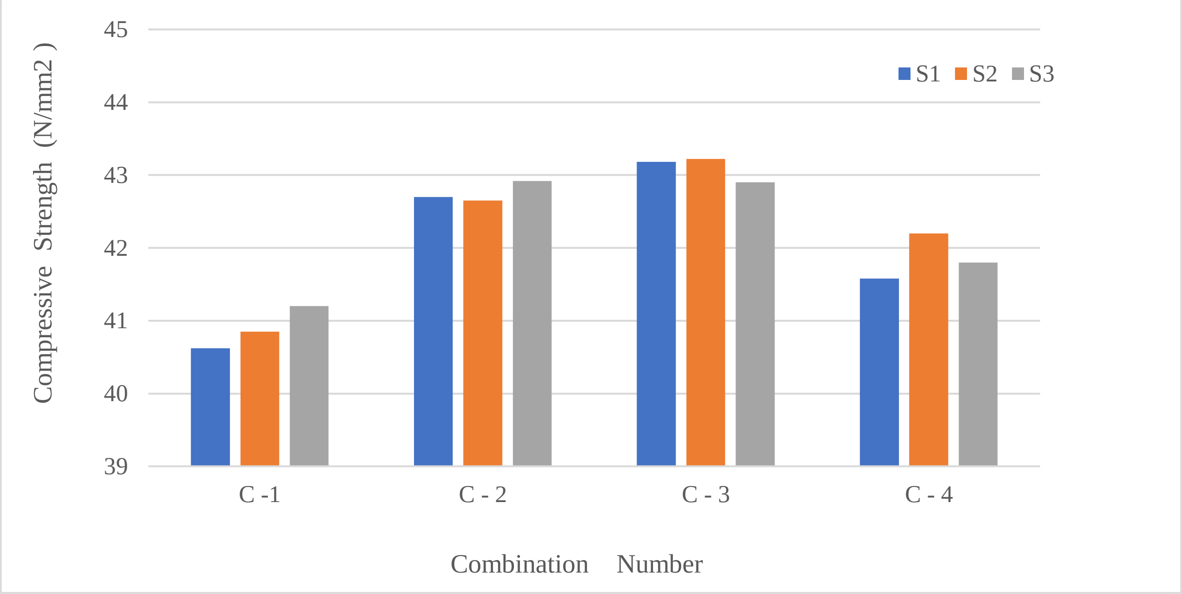

Fig. 16 Strength Characteristics of Concrete Incorporating Multiple Replacement Materials

Four concrete mix combinations demonstrated an increase in compressive strength. These combinations are as follows:
(i) 4% Silica Fume (SF), 1% Fly Ash (FA), 2% Reclaimed Rubber (RR), and 3% Plaster of Paris (POP),
(ii) 9% SF, 2% FA, 2% RR, and 3% POP,
(iii) 9% SF, 3% FA, 3% RR, and 3% POP,
(iv) 9% SF, 1% FA, 1% RR, and 3% POP.

The compressive strength results for all four concrete mixes exhibited only minor variations. These mixes incorporated Reclaimed Rubber (RR) in amounts between 1% and 3%. The combined application of Silica Fume (SF), Fly Ash (FA), Reclaimed Rubber (RR), and Plaster of Paris (POP) produced a synergistic effect, enabling a reduction in the optimal replacement levels silica fume decreased from 12% to 9%, while fly ash was optimized within the 1% to 3% range. Although replacing conventional material with reclaimed rubber alone resulted in reduced compressive strength at higher replacement levels, its combined use with other supplementary materials demonstrated an opposite effect, and an increase in RR content from 1% to 3% was associated with improved strength performance. The compressive strength results obtained experimentally from these four optimized mixes were compared with outputs from the Genetic Algorithm model. Table 15 and Figure 17 present a comparison between the predicted compressive strengths and the experimentally obtained average values for M20 concrete mixes containing partial replacement materials.

Table 15. Evaluation of simulated and observed compressive strength for combined material substitutions

Sl. No.	Combination Number	Replacement (%)				Simulated Compressive Strength (N/mm^2)	Average Strength Under Compressive Strength (N/mm^2)
		SF	FA	RR	POP		
1	C -1	4	1	2	3	41.25	40.90
2	C - 2	9	2	2	3	42.50	42.75
3	C - 3	9	3	3	3	42.98	43.10
4	C - 4	9	1	1	3	41.95	41.86

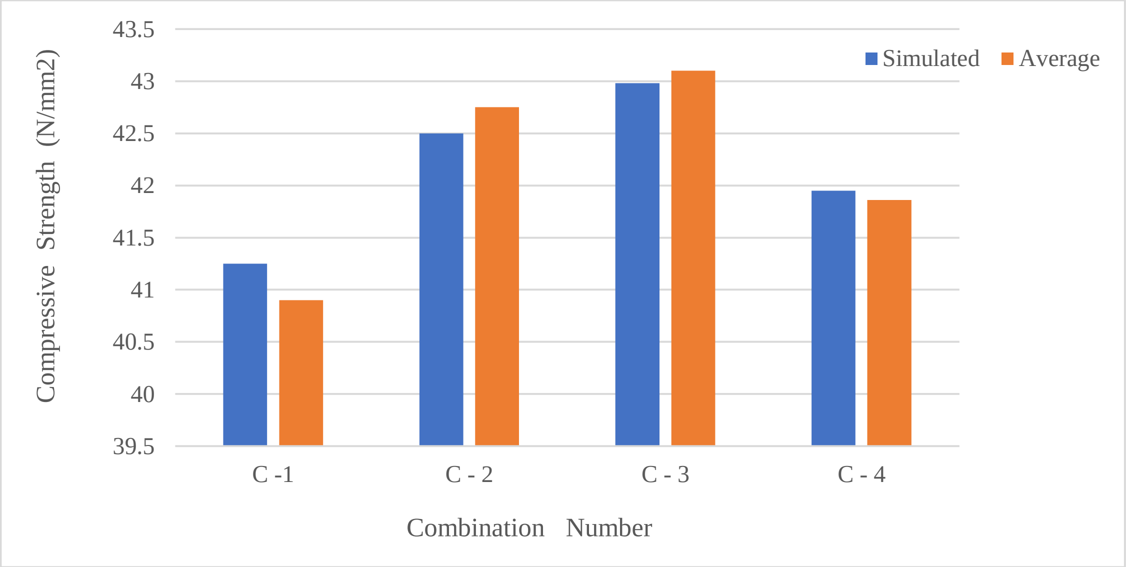

Fig. 17 Experimental Test and Simulation Results

The compressive strength enhancement observed in combinations C-1 and C-2 was identical when comparing both experimental and simulated results. A similar trend was also noted in the deviations between combinations C-3 and C-4. Experimental outcomes showed that over 95% of the strength predicted by the simulation was achieved, indicating a strong correlation between the simulated and actual test data.

Flexural strength of M20 grade concrete incorporating replacement materials was assessed using beam specimens corresponding to all four selected mix combinations. These beams were cured and tested under a single-point loading configuration. A comparison of load-deflection behaviour between the modified mixes and the conventional mix is detailed in Table 16 and Figure 18.

Deflection readings were taken at every loading interval for each specimen. All four alternative mixes displayed a comparable deflection pattern. Up to a load of 50 kN, both the modified mixes and the standard M20 concrete demonstrated a linear relationship between load and deflection. Beyond this threshold, the response shifted to a non-linear trend. The ultimate deflection values ranged from 13.1 mm to 14.3 mm, indicating a clear reduction in comparison to the control concrete. Furthermore, the beams incorporating modified materials demonstrated higher ultimate load capacities than those made with the baseline specimen in the M40 mix. Specifically, the load-bearing performance improved by 8.4% to 12.2%, while deflection reductions ranged from 7.1% to 14.9%. These results indicate that even with a partial replacement of up to 3% of conventional aggregates using reclaimed rubber, the flexural strength and overall structural behaviour of the concrete are positively affected.

Table 16. Flexural strength performance of M40 Mix: Conventional vs Combined replacement approach

Baseline specimen		C-1		C-2		C-3		C-4	
Load (kN)	Def. (mm)	Load (kN)	Def. (mm)	Load (kN)	Def. (mm)	Load (kN)	Def. (mm)	Load (kN)	Def. (mm)
0	0	0	0	0	0	0	0	0	0
31.5	0.9	29.0	1.0	30.0	0.9	32.0	1.2	29.6	1.1
48.6	1.7	51.5	2.1	51.0	1.9	52.8	2.1	53.1	1.9
58.4	2.6	70.0	3.5	71.0	3.3	74.1	3.8	75.1	3.6
66.5	3.7	74.1	4.2	75.2	4.0	76.4	4.3	78.4	4.1
72.4	4.5	81.0	5.4	81.5	5.1	83.0	5.2	84.2	5.0
78.5	6.2	87.6	7.0	88.5	6.9	88.0	6.7	89.5	6.2
83.7	7.8	94.0	10.1	93.2	10.0	94.1	9.0	95.0	8.7
88.2	9.3	97.2	11.6	97.7	11.3	98.1	10.5	98.6	10.2
90.1	11.6	98.3	12.0	98.4	11.8	99.0	11.4	100.5	11.1
90.9	12.3	98.7	13.1	99.0	12.9	99.7	12.7	101.2	12.6
91.2	14.2	99.2	14.0	99.3	13.8	100.1	13.5	102.1	12.9
91.8	15.4	99.5	14.3	99.7	14.1	100.5	13.8	103.0	13.1

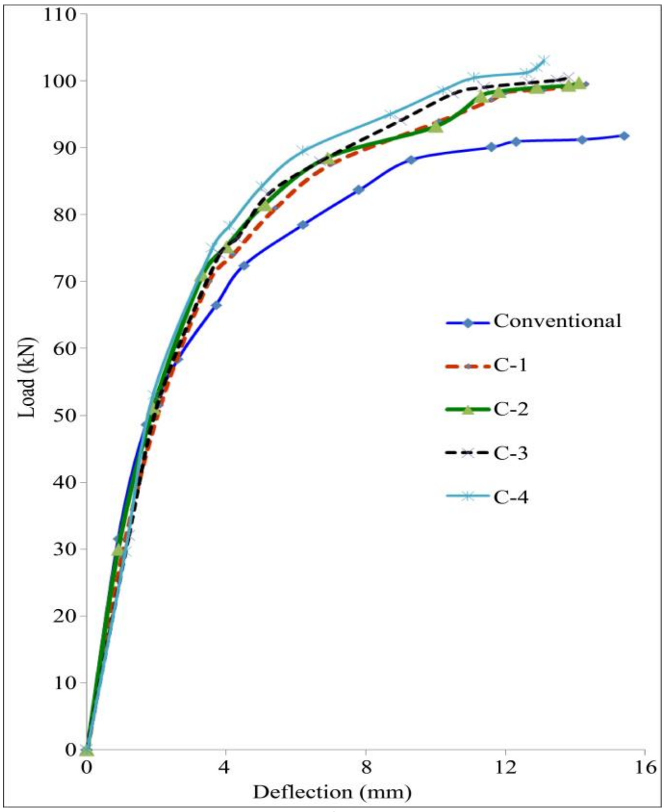

Fig. 18 Load - Deflection Behaviour

4. Conclusion

The main goal of this study was to determine the most effective combinations of alternative materials for partial replacement in concrete, with the aim of improving its compressive strength. A Genetic Algorithm (GA) was utilized to model and optimize various mix proportions, while experimental testing was performed to evaluate the performance of M20 grade concrete incorporating the proposed replacements. Drawing on findings from both the computational simulations and laboratory experiments, the following conclusions were reached:

- Of the three supplementary materials examined, silica fume showed the most significant improvement in compressive strength for M20 grade concrete, outperforming both plaster of Paris and fly ash.
- A compressive strength increase of over 35% was observed in silica fume-modified concrete when the optimal substitution level was compared with the control mix, regardless of curing duration.
- Incorporating reclaimed rubber into the concrete mix consistently led to decreased compressive strength at 7, 14, and 28 days of curing, irrespective of the proportion added.
- The minimal difference between the experimental and simulated compressive strengths for combinations C-1 and C-2 supports the conclusion that combinations C-1 through C-4 represent optimal replacement ratios.
- A marginal improvement in compressive strength was observed in both experimental and simulated results when 10% silica fume was incorporated alongside other replacement materials.
- Beam specimens incorporating replacement materials in M20 grade concrete exhibited lower deflection values than those of the conventional mix, indicating improved flexural performance.
- Individually replacing coarse aggregate with reclaimed rubber had a negative impact on strength; however, when used in conjunction with SF, FA, and POP, a beneficial effect on compressive strength was achieved.
- Genetic Algorithm modelling proved to be an efficient method for predicting compressive strength, offering a cost-effective and time-saving alternative to extensive laboratory testing.
- Given the strong correlation between experimental outcomes and GA-based predictions, reclaimed rubber can be considered a viable partial substitute (1–3%) for traditional aggregates in concrete production.

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