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A Study on the Mechanical Properties of Green Concrete

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Abstract

Green concrete is a type of concrete that uses waste materials as one of its ingredients. Hazardous wastes like fly ash and silica fume can be used to partially replace cement in concrete, which varies in physical and chemical properties. On the other hand, the increase in automobiles in urban and rural areas has led to an increase in the number of waste tires, which promotes environmental pollution due to disposal issues throughout the world. This study aims to use waste materials which can partially replace cement and conventional aggregates in the concrete mix. Fly Ash (FA), Silica Fume (SF), and Plaster of Paris (PP) replaced cement, whereas Reclaimed Rubber (RR) partially replaced coarse aggregates by weight. This work is focused on experimentation and simulation of M 40 grade mix using the above four materials. 306 cubes were cast by replacing cement with FA, SF, and PP in 3% increments up to 24%. Similarly, coarse aggregates were replaced with RR using the same proportion. Compression tests were carried out using a Universal Testing Machine. 12% silica fume replacement exhibited maximum strength during individual replacement of materials in concrete, which is selected as the optimum percentage replacement. FA and PP developed ultimate strength at 9% replacement of cement in the concrete mix, which is considered the optimum replacement percentage. A Genetic Algorithm (GA) model was developed using a C++ program to simulate various combinations of FA, SF, PP, and RR based on individual optimum replacement percentage. Hence, 1600 combinations were identified with the above four materials. Hence, GA was used as a tool to simulate the compressive strength of concrete to reduce time and cost. During simulation of combined replacement using GA, very high and very low compressive strength values were neglected, and 32 combinations were selected based on optimum compressive strength values. Finally, five combinations (C1-C5) were recognized, which resulted in higher compressive strength than individual optimum values after simulation. The GA-based numerical results were validated by casting 15 cubes for all the five combinations. 15 beam samples of size 100×150×1500 mm were cast with the above five combinations, cured and tested using a loading frame. A load-deflection curve was plotted, which showed that material replacement increased the flexural strength of the concrete mix.

Keywords: Strength Prediction; Compressive Strength; Flexural Strength; Reclaimed Rubber; Admixtures; Genetic Algorithm.

1. Introduction

Currently, different waste materials are being used to prepare the concrete mix. These materials serve as alternate materials to cement, sand, and aggregates in the concrete mix. Utilization of cement concrete has rapidly increased due to the rise in the urban population and new infrastructure projects. Cement concrete is a mixture of cement, fine aggregates, coarse aggregates, and water in a predetermined proportion. Natural resources such as aggregates are

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depleting day by day. Hence, there is a need to find alternate materials to replace coarse as well as fine aggregates in the concrete mix without compromising the mechanical properties of concrete. The huge rise in the number of waste tires from vehicles in recent years has caused these tires to replace coarse aggregates partially by weight in order to reduce the environmental pollution generated due to landfills. Reclaimed rubber obtained from waste tires is used to replace conventional aggregates in concrete mixes. Moreover, supplementary materials like silica fume, fly ash, and plaster of Paris replaced cement partially by weight. A Genetic algorithm is a technique used for optimizing residents of a computer program in line with a suitable site determined by a program's capability to carry out a prearranged computational condition. The application of Genetic algorithms facilitates the simulation of the compressive strength of concrete with various possible combinations of material replacements, which can be easily simulated to reduce the time and cost of the physical experiments on concrete samples.

It is observed that with an increase in mineral admixtures, the quantity of cement decreases, resulting in a higher strength of concrete. Maximum strength is achieved at 10% partial replacement of fly ash and silica fume in the concrete mix [1]. Water absorption is found to decrease to a high extent when silica fume and fly ash are added to the concrete mix. The presence of silica fume supplements the strength lost by adding fly ash to the concrete mix. Silica fume enhances 30% of the strength in the concrete mix [2]. The compressive strength developed by both water and sealed curing shows that as the age of concrete increases, the compressive strength also increases. The increase in compressive strength is due to its hydration process, which allows it to harden and become compact as the concrete ages. When the amount of bottom ash used increases, the compressive strength of concrete decreases both at early and 28-day ages [3]. In earlier research, the ANN model was developed to predict the compressive strength of concrete. From the results, it can be observed that for all the curing days, in both cases R1 (a dataset without substitution of fly ash) or R^2 (a dataset with substitution of 15% fly ash), R^2 is above 0.9. The low values of RMSE for all the mixes at different curing ages also indicate that the model can predict the compressive strength of mixes with high reliability [4].

Previous research concluded that coal bottom ash can be a suitable substitute material for fine aggregate in concrete mix combined with silica fume. 30 % coal bottom ash replacement as fine aggregate along with 12.5 percent silica fume as a cement replacement achieved a maximum compressive strength of 38.45 Mpa which is almost 21% higher than the conventional concrete results [5]. In recent research it is mentioned that waste tires are recycled in four ways whole, cut, chipped or shredded and crumb. Tires are granulated and separated from other materials such as fiber and steel and then passed through several grinding processes to reach the smallest necessary size using a miller [6]. In one of the studies three approaches were used to predict the compressive strength of concrete with waste material. Individual machine learning, Ensemble approach bagging and Gene Expression Programming were used [7]. Silica fume and fly ash filled the pores which helped to attain high compressive strength. The drawback of late strength attainment was compensated by Silica fume with class F fly ash and fly ash reduced the water demand due to the presence of silica fume [8].

It is noticed that maximum tensile and flexural strength was observed at 10% and 15% replacement of silica fume with cement respectively. Moreover, silica fume concrete is used to save the quantity of cement in concrete as well as to reduce the environmental problems by utilizing the industrial waste material [9]. Another study observed that substituting cement with industrial by products such as silica fume, fly ash and Granulated Ground Blast Slag offers technical, economic and environmental advantages which are significant in sustainable construction [10]. Researchers have identified three types of rubber with different dimensions namely chipped rubber, crumb rubber and powdered rubber apart from reclaimed rubber which can be used to replace fine and coarse aggregates based on their size in the concrete mix [11].

The above literatures indicate that research has been done on individual material replacement with mineral and chemical admixtures. Most of the previous research works have commonly used materials like SF, FA and GGBS with higher percentage replacements (10, 15, and 20%) and have not validated their experimental results further by numerical analysis. The current research work fills this gap by partially replacing individual materials at 3% intervals (3 to 24%) which may help to closely analyze their effects in concrete. Apart from individual replacement GA model is developed to find the optimum combined replacement and experiments are conducted to validate these results. Moreover, similar research works used scrap tires in different forms namely shredded, crumb or recycled rubber to replace coarse aggregates in the concrete mix. In this research a novel and innovative material called reclaimed rubber is used in combination with supplementary materials like fly ash, silica fume and plaster of Paris to determine the mechanical properties of concrete mix which has not been studied earlier.

2. Materials and Methods

In this section the properties of various materials used to prepare the concrete mix and the methods used to test the samples are being discussed.

2.1. Cement

Ordinary Portland cement was used in this study. Cement which produces compression strength of 53 N/mm^2 after 28 days of curing is used in the concrete mix along with other materials. Cement is a fine grinded powder which consists of alumina, silica, lime, iron oxide and magnesium oxide burned together in a kiln and used as an ingredient in mortar and concrete [12]. It fills up the voids existing in fine aggregate and makes it impermeable by providing strength to concrete on setting and hardening. The percentage increase in compressive strength from 28 days to 90 days was found to be similar in M30 grade and M40 grade concrete types. Comparable compressive strength values were obtained for Portland Pozzolana Cement and Portland Slag cement types when compared with Ordinary Portland cement concrete strength values [13]. The properties of cement are seen in Table 1.

Table 1. Properties of ordinary Portland cement

Property	Result
Specific gravity	3.1
Standard Consistency	29%
Initial Setting Time	32 minutes
Final Setting Time	180 minutes
Compressive Strength (28 days)	53 N/mm^2

2.2. Aggregates

As aggregates accounts for 50-60% of the concrete volume it is therefore considered as a determinant of concrete strength. It is found that coarse aggregates with a size of 10/20 mm produced a maximum strength of 38.3 Mpa [14]. Fine aggregate is one of the ingredients of the concrete mix. The size of fine aggregate is less than 4.75 mm.

It is found that compressive and tensile strength of concrete with M-sand are on par with conventional natural sand concrete which can be used to replace river sand since its quality is better than river sand [15]. The shape and texture of the aggregate affects the properties of fresh concrete more than hardened concrete. The availability of aggregates is reducing since the quantity of the natural deposit is almost fixed or it requires several years for its formation. Due to high cost of natural sand as fine aggregate and the rising emphasis on sustainable construction there is a need for the construction industry to search for alternative materials as fine aggregates in concrete production [16]. Clean dry river sand was used in the concrete mix as fine aggregate. Coarse aggregate is the concrete mix ingredient which is being replaced partially by reclaimed rubber. Hard granite broken stones of 20 mm size were used as coarse aggregates. Test results show that concrete specimens with 25% replacement of fine recycled concrete aggregate had no effect on the strength of concrete and a further increase of recycled concrete aggregate increases water demand and cement content [17]. Table 2 shows the test results of fine and coarse aggregates.

Table 2. Properties of aggregates

Property	Fine Aggregate	Coarse Aggregate
Specific gravity	2.6	2.7
Water Absorption (%)	1	0.8
Fineness Modulus	3.5	5.2

2.3. Fly Ash and Silica Fume

Fly ash is the most commonly used pozzolana in concrete. The spherical shape and particle size distribution of fly ash improves the fluidity of flow able fill thereby, reducing the amount of mixing water required and contributing to the long-term strength of high strength concrete with fly ash. Replacement of high lime fly ash in concrete generally increases the ultimate strength of concrete. 25-35% fly ash replacement provides the most optimal strength results [18]. Silica fume is an amorphous polymorph of silicon dioxide. It is an ultrafine powder collected as a by-product of silicon and ferrosilicon alloy production. It can enhance various properties of concrete both in the fresh as well as in hardened states like cohesiveness, strength, permeability and durability [19]. It is seen that as the percentage of silica fume increases the strength of concrete increases irrespective of the grade of concrete. The shrinkage of concrete increases with the increase in percentage of silica fume and depends on the grade of concrete [20]. The physical properties of fly ash and silica fume are given in Table 3 which was obtained from the suppliers (Ennore Plant and Astra Chemicals), Chennai. The chemical composition of fly ash and silica fume is shown in Table 4.

Table 3. Physical properties of materials

Property	Fly Ash	Silica Fume
Specific gravity	2.2	2.6
Fineness (m^2/Kg)	450	22000
Bulk Density (Kg/m^3)	1300	1450

Table 4. Chemical Composition of Materials

Compound	Percentage in Fly Ash	Percentage in Silica Fume
Si O_2	56.2	92.3
Al_2O_3	27.3	0.79
Fe_2O_3	3.5	1.57
CaO	4.4	0.43
SO_3	1.3	0.33
MgO	1.7	0.40
Na_2O	0.4	0.38
K_2O	0.5	1.30
LOI	3.1	1.8

2.4. Plaster of Paris

In this study Plaster of Paris replaces cement partially in the concrete mix. It is noted that plaster of Paris has low thermal conductivity and has enough strength. For improvement of thermal insulation saw dust is added since it has less thermal conductivity and improves the mechanical properties [21]. Table 5 shows the properties of Plaster of Paris which was obtained from the manufacturers.

Table 5. Physical Properties of Plaster of Paris

Property	Plaster of Paris
Specific gravity	2.5
Fineness	99%
Bulk Density (Kg/m^3)	710

2.5. Reclaimed Rubber

Reclaim rubber is a rubber compounding agent. Reclaiming takes place as a recycling process through grinding consumed tires. It provides a solution to get rid of consumed rubber [22]. Figure 1 shows reclaimed rubber which was obtained from Inter city Enterprises, Chennai. It was cut to the required shape and size. Table 6 shows the test results of reclaimed rubber such as its specific gravity, density, water absorption and other properties which were obtained from the supplier.

Figure 1. Reclaimed rubber used in concrete mix

Table 6. Test results of reclaimed rubber

Property	Result
Ash content	5.4%
Density	1.12g/cc
Tensile strength	17.7Kg/cm^2
Specific gravity	1.3
Water absorption	8.5 %

2.6. Methodology

In this research work cement and coarse aggregates are replaced with suitable materials in order to obtain individual optimum replacement level and combined optimum replacement levels using GA. Figure 2 shows overall methodology of this research work.

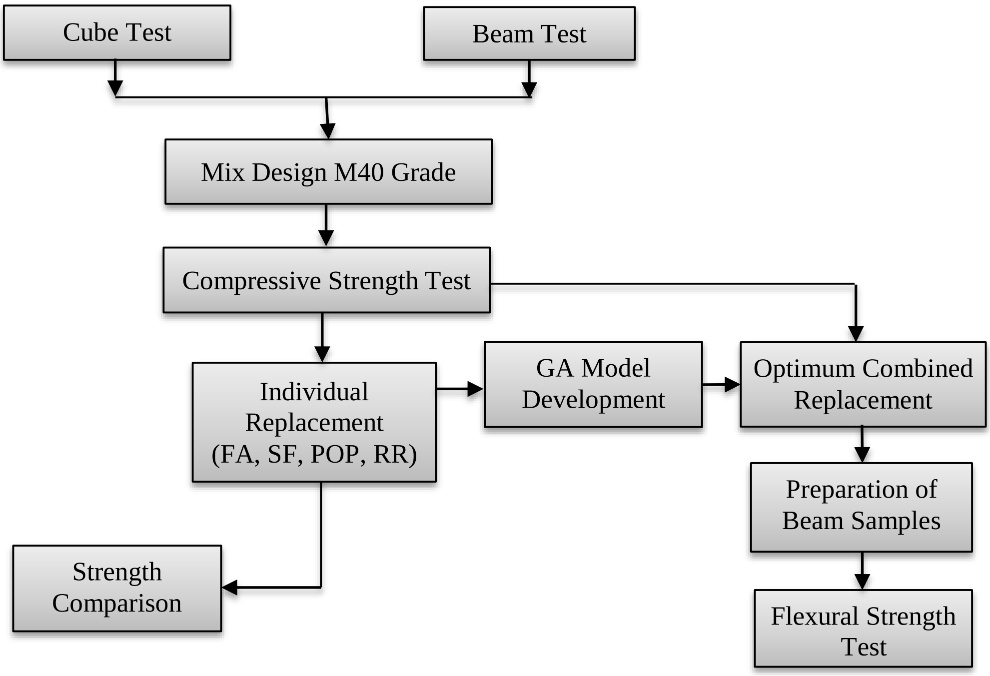

Figure 2. Overall methodology

2.7. Preparation and Testing of Cube Samples

The properties of concrete depend on the quantity and quality of its constituents since cement has the greatest unit cost its selection is significant in obtaining economical balance of desired properties for a particular concrete mixture [23]. In this study the concrete mix was designed as per IS 10262:2009 and the mix proportion was found to be 1: 1.45: 2.54: 0.4. The concrete mix was prepared based on the mix design in a mixer machine. The concrete batch is mixed on a water tight non-absorbent steel platform with a shovel, trowel and suitable equipment. The ingredients of concrete are mixed in the required proportion in a concrete mixer machine after adding the required quantity of water. The mixing is continued until concrete appears to be homogenous and has the desired consistency. Cube molds of size 150 × 150 × 150 mm were used to cast the samples. After mixing the concrete, cube molds are filled in layers, compacted and allowed to harden for a period of 24hours as shown in Figure 3.

Figure 3. Cube Molds filled with Concrete

In one of the research works different sizes of cubes were used to test the compressive strength of concrete. It was observed that increase in compressive strength is recorded with increase in specimen size [24]. All the specimens are demolded and immersed in a curing tank which is maintained at room temperature to attain the required strength as shown in Figure 4-a. There are various types of curing and the adoption of a particular condition depends on the environment and on the nature of work [25]. The cube samples were cured for 7, 14 and 28 days to attain the required strength. All samples have been tested up to failure subjected to axially compressive load using Universal testing machine. Compression test is a significant phenomenon related to concrete. Compressive strength varies depending upon the size of the specimen and the change in strength is different for different geometries [26]. Figure 4-b shows the compressive strength test process which is carried out to determine the compressive strength of individually replaced concrete mix in a UTM which has a capacity of 50 tons.

(a) Curing (b) Testing

Figure 4. Curing and Testing of Cube Samples

2.8. Genetic Algorithm Model

Genetic algorithms are search based algorithms based on the concept of natural selection and genetics. GA is faster and more efficient than traditional methods and optimizes both continuous and discreet functions. Genetic Algorithm was used for the simulation of the compressive strength of M40 grade samples with single material replacement. Based on the compressive strength test results the optimal percent of individual replacement of FA, SF, POP and RR were determined. Many combinations can be generated and each combination must be tested for strength using huge number of samples to obtain most suitable proportion which will consume more time and cost. To solve this problem Genetic Algorithm (GA) model was developed. The results obtained from individual replacement of materials for all proportions including the optimal percentage of individual materials in terms of compressive strength are given as input to the GA model. Figure 5 shows the GA model flowchart which shows the process involved in model development.

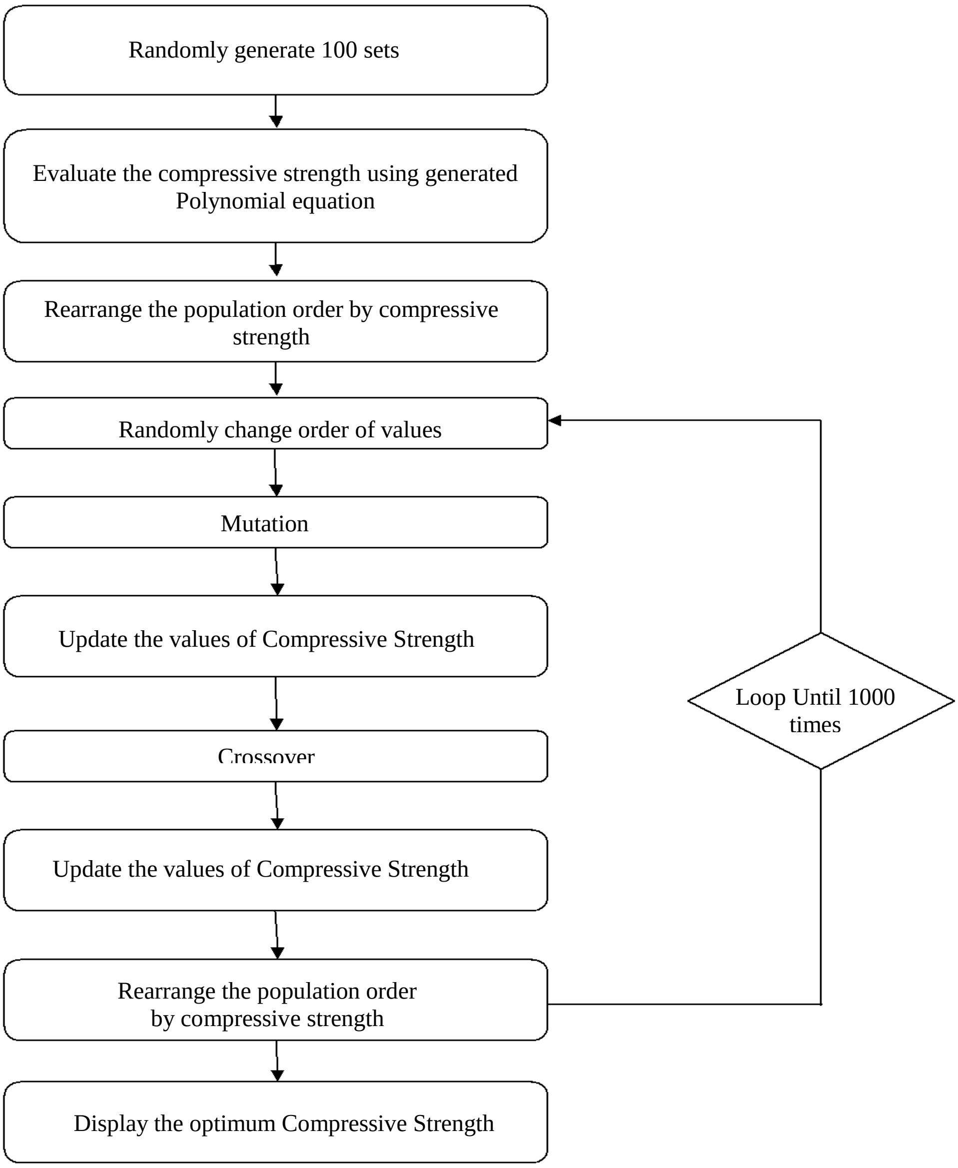

Figure 5. GA Flow Chart

After this process, the GA model was used for simulating the compressive strength of concrete for various combinations of material replacements. Five combinations (C1-C5) were obtained for combined replacement of materials through GA model. These combinations were considered as optimum percentage of combined replacements which were used in the preparation of cube and beam samples. The experimental method was carried out again for the concrete samples prepared based on the combined replacement obtained from the GA model. These samples were tested after 28 days of curing to determine compressive and flexural strength.

2.9. Preparation and Testing of Beam Samples

In this study M40 grade beam samples were prepared with predetermined proportions for both conventional and replaced concrete mix. Eighteen beams were designed as under reinforced section. Beam samples are reinforced with high yield strength deformed bars of two 12 mm diameter on the tension side and two 8mm diameter bars on the compression side. Two legged stirrups of 6 mm diameter bars were provided as shear reinforcement at 150mm c/c throughout the span. Beam reinforcement and loading details are shown in Figure 6.

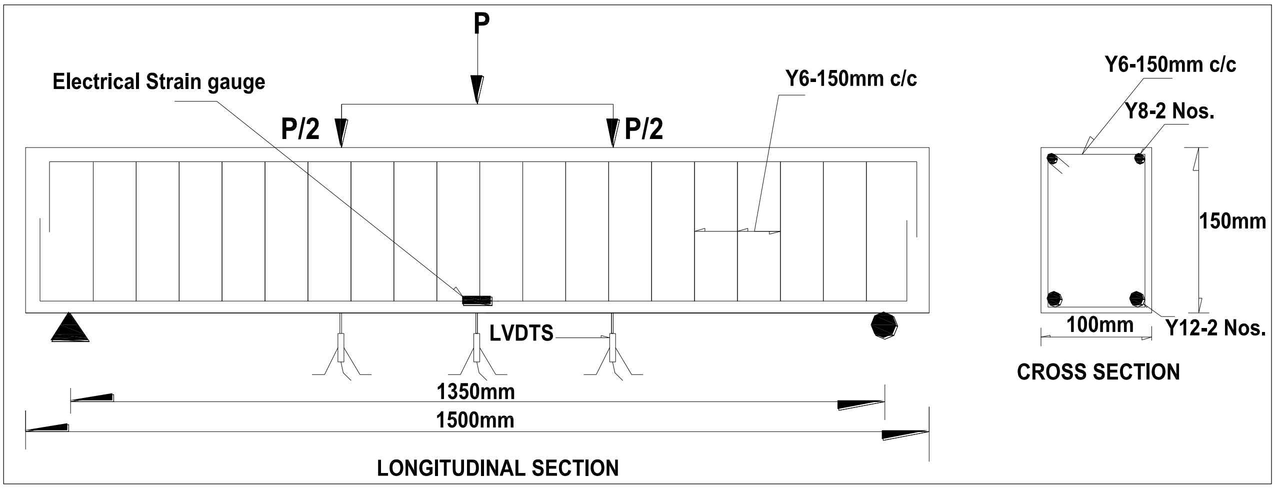

Figure 6. Beam Reinforcement and Loading Details

Concrete mix proportion was 1: 1.45: 2.54 with a water-cement ratio of 0.4. Ordinary Portland cement (53 Grade), natural river sand and coarse aggregates of 20mm size were used to prepare the concrete mix. Molds of size 100mm × 150mm × 1500mm were used to cast the beam samples. Apart from three conventional mix samples fifteen beam samples were cast with the above five combinations (C1-C5) which were obtained using genetic algorithm model. Three samples of each combination were cast simultaneously as shown in Figure 7-a. The molds were removed after 24 hours and the samples were cured in a water tank for a period of 28 days at room temperature and kept ready for testing as shown in Figure 7-b.

(a) Cast beams (b) Cured beams

Figure 7. Cast and cured beam samples

The beams were kept over two supports to act as a simply supported beam and a concentrated load was applied at the mid span using loading frame which was transmitted to two points. The beam was loaded using a 1000 kN capacity loading frame. Three Linear Variable Displacement Transducers (LVDTs) of 0 - 100 mm capacity was used to record deflection at one - third points and the center of the beam. The load was gradually increased until the occurrence of fractures on the beam sample. The deflection of the beam for each load increment was noted which was used to plot load-deflection curve.

3. Results and Discussion

The results of individual material replacements of FA, SF, POP and RR are tabulated and discussed for each material. Moreover, the simulated values of combined replacement and the experimental results of final combinations are also presented and analyzed. Apart from compression test the flexural strength test results are also included for all the five combinations and reviewed. Table 7 shows the compressive strength test results of M40 grade concrete cubes with fly ash replacement in various proportions.

Table 7. Test results of fly ash replaced concrete cubes

Fly Ash (%)	Compressive Strength of M40 Cube (N/mm^2)		
	7th day	14th day	28th day
0	27.00	33.75	40.30
3	29.20	36.50	43.20
6	31.35	37.20	46.40
9	31.90	37.64	51.75
12	29.42	36.70	43.55
15	28.45	35.60	42.10
18	25.20	33.00	39.60
21	22.50	31.40	35.50
24	20.20	28.70	33.30

Fly ash is one of the important materials used as replacement for cement concrete. The percentage of replacement was adopted in multiples of 3 percent starting from 3 up to 24 percent. The cube samples for M40 grade mix with fly ash replacement were prepared and tested after 7 days, 14 days and 28 days of curing at room temperature. Figure 8 represents the test results of various proportions of fly ash replaced mix which is compared with the conventional mix test results.

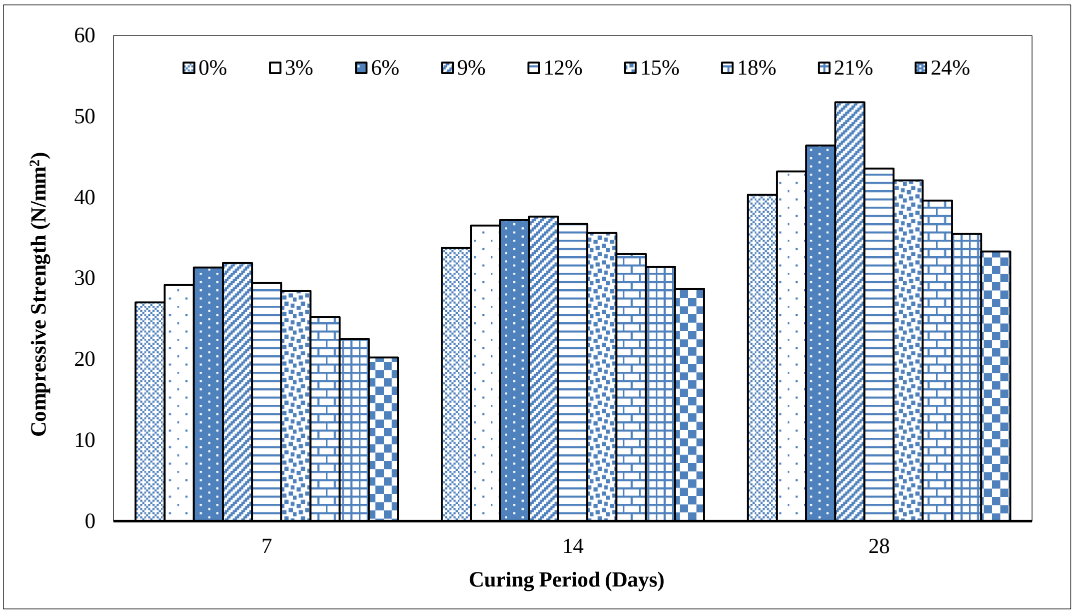

Figure 8. Compressive strength of fly ash replaced concrete

9% replacement of cement with fly ash yields maximum strength of 51.75 N/mm^2 which is 28% and 7% higher than control mix and target strength values respectively after 28days of curing, hence 9% FA replaced concrete mix is considered as optimum replacement percentage of fly ash. Comparing the results of conventional mix with 9% FA replaced mix the strength improvement is less in 7 and 14 days cured samples due to lack of $Ca(OH)_2$ since it is released due to hydration of cement during prolonged curing periods like 28 and 90 days. Comparing the percentage variation in strength in 28 days cured samples it is noticed that for every 3% FA increment in concrete the strength increases up to the optimum replacement level and for consecutive increments the compressive strength starts to decrease gradually since it loses its filling effect in hardened concrete. Beyond 15% fly ash replacement the concrete strength falls below the control mix values. A similar pattern of result is observed while comparing 7 and 14 days cured samples.

Comparing the initial and final percentage replacements it was observed that the percentage reduction in strength was similar in magnitude in 14 and 28 days cured samples whereas the percentage reduction in strength was found to be higher in 7 days cured samples since concrete achieves higher strength at a later age. In this study 28 days compressive strength of 9% FA replaced mix is found to be 51.75 N/mm^2 whereas in previous research work 10% FA replaced concrete mix produced a strength of 53.48 N/mm^2 which is acceptable since it is higher than the ultimate strength of the present study [27]. Further it can be seen that the increment in FA replacement is 3% in current research and 5% increment of FA in the past work.

Table 8 below shows the compressive strength test results of M40 grade concrete cubes with silica fume replacement in various proportions. In order to know the effect of Silica Fume replacement on concrete, the average compressive strength of Conventional M40 grade mix is compared with the average strength obtained after replacing cement with Silica Fume in different proportions.

Table 8. Test results of silica fume replaced concrete cubes

Silica Fume (%)	Compressive Strength of M40 Cube (N/mm^2)		
	7th day	14th day	28th day
0	27.00	33.75	40.30
3	27.20	34.00	40.50
6	27.50	34.40	41.20
9	30.00	37.50	45.00
12	35.50	44.50	54.80
15	33.00	41.25	49.50
18	31.60	39.50	47.70
21	28.70	37.20	45.40
24	26.10	35.30	42.60

Figure 9 is plotted based on the above test results. Three percentages (3, 6, and 24 %) follow a similar pattern on increase in compressive strength with that of the Conventional M40 grade mix. After curing the samples for 7, 14 and 28 days the strength increase was about 32, 31 and 35 percent respectively when compared with the conventional mix value. Three percentages (12, 15, and 18%) showed a substantial improvement in compressive strength. Out of these three percentages 12 percent replacement showed higher compressive strength value hence it is considered as optimum SF replacement percentage in concrete.

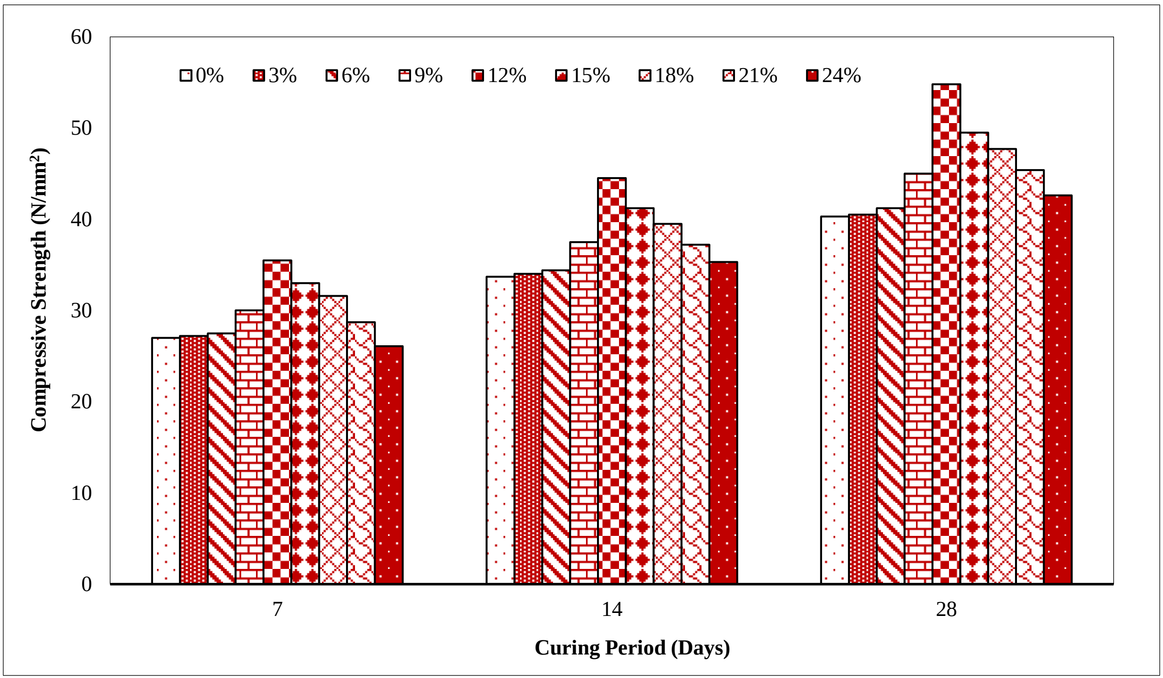

Figure 9. Compressive strength of silica fume replaced concrete

The strength increment between optimum SF replaced mix and conventional mix values is found to be 36%. Comparing the optimum values of fly ash and silica fume it is observed that the percentage increase in strength due to silica fume replacement is found to be twice that of fly ash replacement since silica fume particles are 100 times finer than cement. The compressive strength of concrete decreases gradually for further increments of SF since it does not act as a filler in the concrete mix. The maximum strength achieved after testing 28 days cured specimens through this study is in tune with previous study [28]. The ultimate strength obtained at 12% SF in this study is 54.8 N/mm^2 whereas a maximum strength of 53.76 N/mm^2 was attained at 10% SF replacement level which clearly indicates that a further increase in SF percent will proportionately increase the compressive strength.

Percentage reduction in strength between initial and final replacement of Silica Fume was found to be similar and very less at all curing ages compared to fly ash replacement results. Moreover 15% SF replaced mix results were found to be 49.5 and 50.2 N/mm^2 for the present and previous research works respectively which is almost same in magnitude. Table 9 and Figure 10 shows the compressive strength test results of M40 grade concrete cubes with Plaster of Paris replacement in various proportions.

Table 9. Test results of plaster of Paris replaced concrete cubes

Plaster of Paris (%)	Compressive Strength of Cubes (N/mm^2)		
	7th day	14th day	28th day
0	27.00	33.75	40.30
3	27.50	34.40	41.40
6	29.59	36.90	43.80
9	30.40	38.00	45.00
12	29.42	36.70	43.55
15	28.45	35.60	42.10
18	25.20	33.00	39.60
21	22.50	31.40	35.50
24	20.20	28.70	33.30

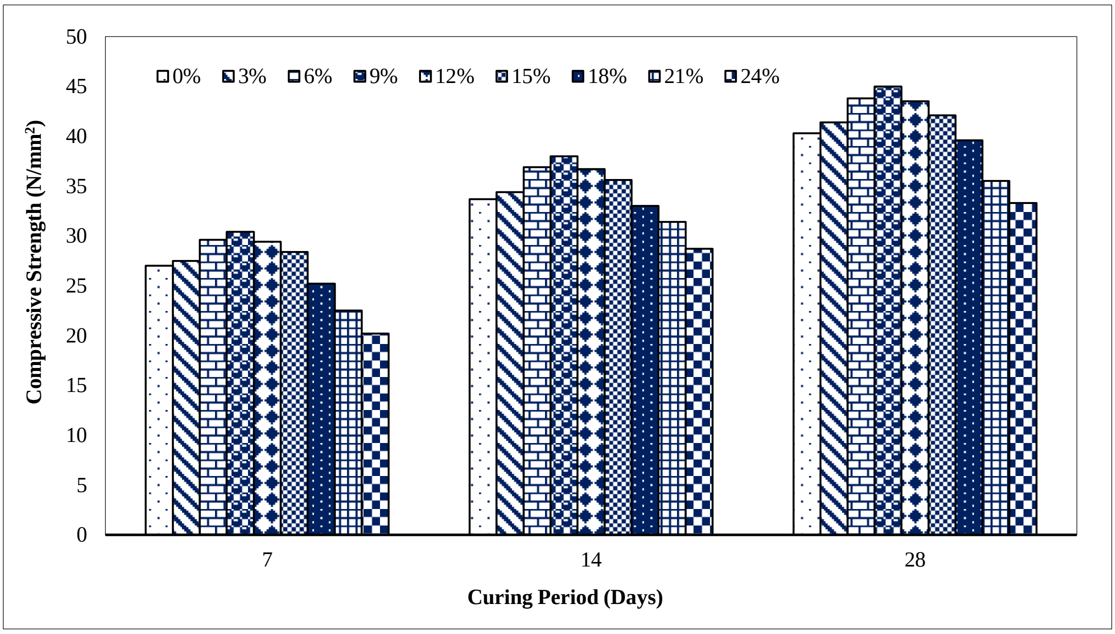

Figure 10. Compressive strength of plaster of Paris replaced concrete

The cube compressive strength of POP replaced concrete was compared with that of the average compressive strength of Conventional M40 grade mix and details are presented in the above figure. Eighteen percent and three percent replacement showed a small reduction and increase in compressive strength respectively. Fifteen percent replacement resulted in a significant increase in compressive strength however, further increments reduced the strength and found to be less than control mix value. Six and twelve percent replacements of POP produced a similar increase in compressive strength of M40 grade. Nine percent replacement of POP resulted in a much higher increase in compressive strength than that of the Conventional M40 grade. It is evident that twenty percent strength is reduced while comparing the initial and final replacements. Only the lowest percentage of replacement (3%) is closer to the conventional mix compressive strength values. The compressive strength for all ages of curing for reclaimed rubber mixed concrete is seen in Table 10 and shown in Figure 11. It is seen that irrespective of the age and mix proportion the compressive strength reduces significantly due to the weak bonding between cement pastes and reclaimed rubber aggregates. Comparing the initial and final replacement values of 28 days cured samples 52% reduction in strength is found whereas it is less between 6% and 18% replacement levels. A strength reduction of 59% is observed while comparing the control mix and final replacement values. Moreover, a similar trend is observed while comparing the control mix and final replacement values of 7 and 14 days cured samples.

Table 10. Test results of reclaimed rubber replaced concrete cubes

Reclaimed Rubber (%)	Compressive Strength of M40 Cube (N/mm^2)		
	7th day	14th day	28th day
0	27.00	33.75	40.30
3	24.40	32.50	34.70
6	21.25	26.30	28.20
9	19.30	25.00	26.30
12	17.50	22.60	24.40
15	15.00	20.00	21.20
18	13.50	17.35	19.10
21	11.00	15.30	16.60
24	9.70	12.62	14.45

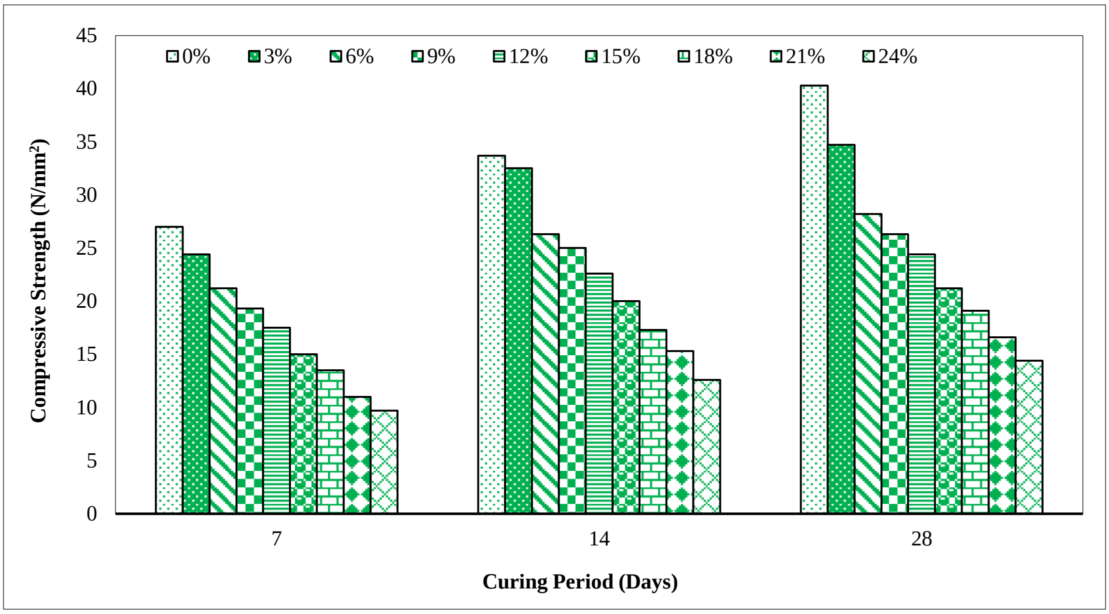

Figure 11. Compressive strength of reclaimed rubber replaced concrete

Genetic Algorithm based model is developed for determining the optimum combined replacement of material to achieve higher strength compared to conventional concrete mix. Four materials were combined and the compressive strength of M40 grade concrete was simulated with the help of GA which had 1600 combinations and all of them were adopted for the reproduction of compressive strength of concrete. Extreme values (both very less and very high) were neglected in this process. Particularly, when the percentage of RR exceeded 2% higher reduction in compressive strength was observed. Out of 1600 possible combinations, 120 combinations were identified on the basis of optimum compressive strength of individual replacement of materials.

In the above combinations, the percentage replacement of SF varied from 5 to 10%, FA 3% to 10%, RR 1% to 2% and POP 1 to 4%. These combinations were further narrowed down based on the compressive strength. Out of 120 combinations, 32 were identified on the basis of a higher compressive strength and presented in Table 11. The compressive strength of these 32 combinations varies from 57.33 to 65.20 N/mm^2. For most of these combinations the RR % is obtained as 1% and few of them 2 %. Further increase in RR resulted in reduction in compressive strength.

Table 11. Final combinations of replacement percentage of materials for M40 grade of Concrete

Sample Designation	Replacement (%)				Compressive Strength (N/mm^2)
	SF	FA	RR	POP	
A1	5	9	1	1	57.57
A2	5	10	1	1	60.61
A3	5	10	1	2	59.53
A4	5	10	1	3	58.29
A5	6	6	1	1	58.01
A6	6	7	1	1	63.15
A7	6	7	1	2	59.96
A8	6	8	1	3	62.28
A9	6	8	1	4	59.09
A10	6	9	1	4	64.97
A11	7	5	1	1	61.12
A12	7	6	1	2	63.47
A13	7	6	1	3	58.65
A14	7	7	1	4	61.54
A15	8	4	1	1	60.49
A16	8	5	1	2	63.25
A17	8	6	1	4	60.24
A18	9	4	1	2	59.27
A19	9	5	1	3	62.80
A20	9	8	2	1	59.31
A21	9	9	2	1	63.33
A22	9	9	2	2	57.33
A23	9	10	2	2	61.55
A24	10	3	1	1	60.64
A25	10	4	1	2	64.41
A26	10	5	1	4	59.80
A27	10	6	2	1	60.77
A28	10	7	2	2	58.98
A29	10	8	2	2	65.20
A30	10	8	2	3	57.56
A31	10	9	2	3	63.99
A32	10	10	2	4	63.15

The compressive strength of 32 combinations have been plotted as shown in Figure 12. The histogram shows five combinations which result in higher compressive strength than the individual optimum values. All five combinations also resulted in smaller variations in compressive strength for M40 grade. In the five combinations Silica Fume ranges between 6 and 10%, Fly Ash from 4 to 9%, plaster of Paris from 1 to 4% and Reclaimed Rubber was maintained at 1 % and 2%. All the above five combinations were tested for the determination of their cube compressive strength by preparing three cube samples for each combination.

Details of the compressive strength of M40 grade concrete with each combined replacement are presented in Table 12. Each sample was tested after 28 days of curing up to the occurrence of complete failure of cube. The load corresponding to the failure was measured for each sample and used for further analysis. The compressive strength of each sample was calculated and the average of all three samples was also determined. The average compressive strength of five combinations varied within a narrow range only. The average compressive strength of M40 grade concrete with each combined replacement varied from 63.19 to 65.36 N/mm^2. The average compressive strengths of five combinations C - 1, C - 2, C – 3, C - 4 and C - 5 were 64.39, 63.19, 63.79, 65.36, and 63.87 N/mm^2.

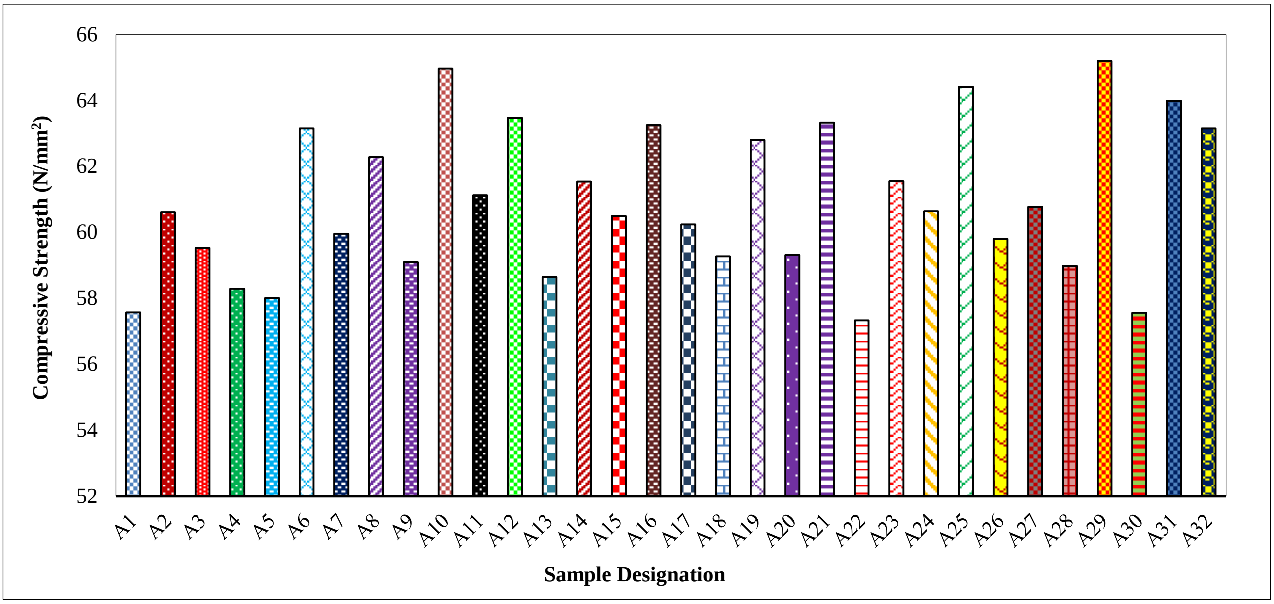

Figure 12. Simulated Compressive strength for Final Combinations of replacement percentage of materials for M 40 Grade

Table 12. Compressive Strength of M40 with Combined Replacement of Materials

Combination Number	Replacement Percentage				Sample 1	Sample 2	Sample 3	Average Compressive Strength (N/mm^2)
	SF	FA	RR	POP	Compressive Strength (N/mm^2)	Compressive Strength (N/mm^2)	Compressive Strength (N/mm^2)	
C -1	6	9	1	4	64.76	64.31	64.09	64.39
C - 2	7	6	1	2	63.51	62.89	63.16	63.19
C - 3	10	4	1	2	63.73	63.47	64.18	63.79
C - 4	10	8	2	2	65.42	65.78	64.89	65.36
C -5	10	9	2	3	63.87	64.04	63.69	63.87

Figure 13 shows five combinations which result in higher compressive strength. They are, (i) SF - 6%, FA – 9%, RR – 1% and POP - 4%, (ii) SF - 7%, FA – 6%, RR – 1% and POP - 2%, (iii) SF - 10%, FA – 4%, RR – 1% and POP - 2%, (iv) SF - 10%, FA – 8%, RR – 2% and POP - 2% and (v) SF - 10%, FA – 9%, RR – 2% and POP - 3%. All five combinations resulted in small variation in the compressive strength. In all these five combinations RR was maintained at 1 % and 2%. Compressive strength obtained experimentally through the above five combinations of replacement were used to validate the GA results.

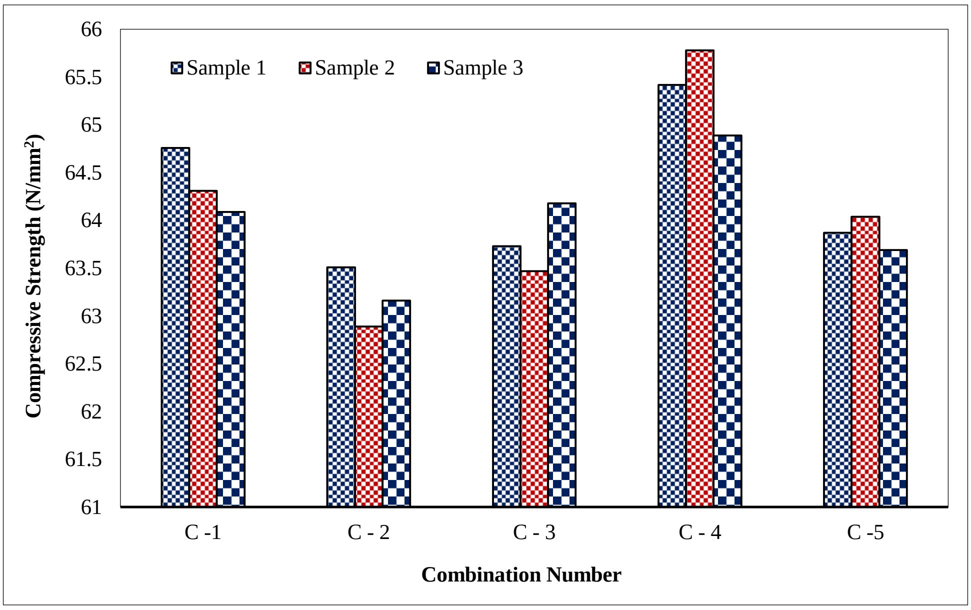

Figure 13. Compressive strength Samples – Combined Replacement

The simulated and the average compressive strength of M40 grade of concrete with the combined replacement of materials is shown in Table 13 and Figure 14. The percentage increase in strength is same comparing the simulated and experimental values of combinations C-1 and C-2.

Table 13. Comparison of Simulated vs. Average Compressive Strength (Combined Replacement)

Combination Number	Replacement (%)				Simulated Compressive Strength (N/mm^2)	Average Compressive Strength (N/mm^2)
	SF	FA	RR	POP		
C -1	6	9	1	4	64.97	64.39
C - 2	7	6	1	2	63.47	63.19
C - 3	10	4	1	2	64.41	63.79
C - 4	10	8	2	2	65.20	65.36
C -5	10	9	2	3	63.99	63.87

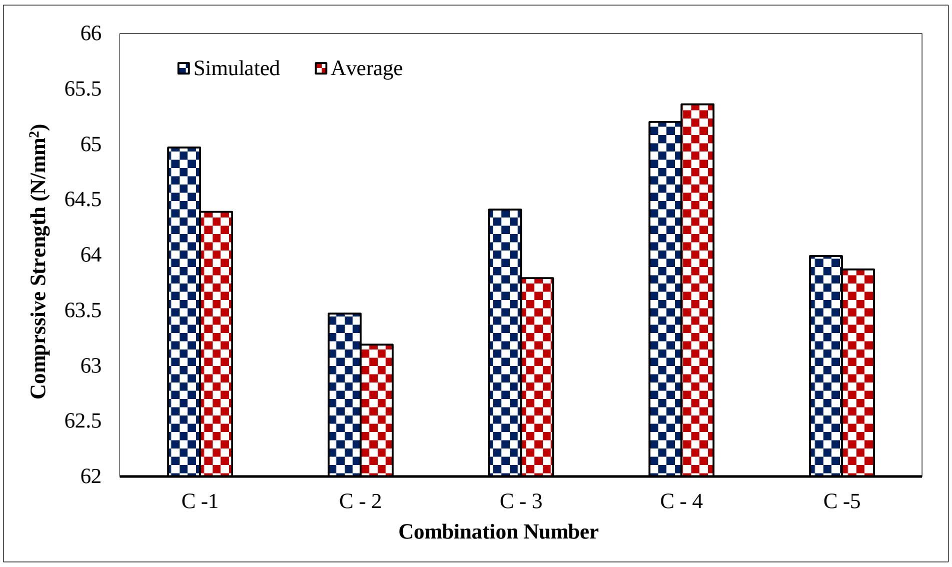

Figure 14. Comparison of Simulated and Average Compressive Strength for M 40 Grade with Combined Replacement

The flexural strength of M40 grade with replacement of materials was tested by preparing the beam samples for all five combinations. The samples were tested after curing with the help of two-point load arrangement. A comparison of load and deflection values for each beam sample with replacement and conventional mix proportion is presented in Table 14. For each increment of load, the corresponding deflection was obtained for each beam sample. The deflection values followed a similar pattern for all five combinations. The linear portion of load vs. deflection curve was seen up to 60 kN load applied for both conventional and replacement mixes of M40 grade. After this point, the load vs. deflection curve is non-linear in nature. In this mix the linear portion is steeper than non-linear portion. The final deflection values varied between 13.7 mm and 15.3 mm, which is less than the conventional mix.

Table 14. Comparison of Conventional vs. Combined Replacement for Flexural Strength of M 40

Conventional		C-1		C-2		C-3		C-4		C-5	
Load (kN)	Δ* (mm)	Load (kN)	Δ (mm)	Load (kN)	Δ (mm)	Load (kN)	Δ (mm)	Load (kN)	Δ (mm)	Load (kN)	Δ (mm)
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28.4	1.2	31.3	1.6	32.1	1.8	31.2	1.5	31.0	1.3	34.1	1.5
52.0	2.3	53.1	2.7	52.6	2.6	51.8	2.2	51.0	2.1	54.2	2.5
69.0	3.7	71.3	4.1	74.1	4.3	73.5	4.0	72.2	3.8	75.5	3.9
74.0	4.5	76.2	4.8	77.2	4.9	76.8	4.7	75.3	4.2	79.8	4.8
81.3	5.8	82.2	5.7	84.3	5.8	84.0	5.7	82.1	5.2	84.9	5.7
87.4	7.2	86.3	6.5	88.3	6.7	86.1	6.5	85.7	6.0	88.1	6.3
93.6	10.0	92.0	8.8	93.6	8.9	90.3	8.1	89.5	7.9	96.2	8.4
96.4	11.4	94.5	10.1	96.1	10.3	95.3	9.8	93.2	9.2	99.2	9.8
97.2	12.2	97.8	11.6	99.7	11.9	97.1	10.3	96.7	10.0	102.2	10.4
98.3	13.5	100.7	14.2	102.0	14.2	100.3	12.1	100.1	11.8	104.7	12.1
99.3	15.6	101.6	14.9	103.5	15.3	102.9	13.9	102.5	13.7	107.5	14.2

*Δ: Deflection.

The final load values were also higher than those of the conventional M40 mix. The increase in load carrying capacity varied from 2.3% to 8.3% and a decrease in deflection varied from 1.9% to 12.2% which shows that material replacement increases the flexural strength of concrete. Load-deflection curve is shown in Figure 15.

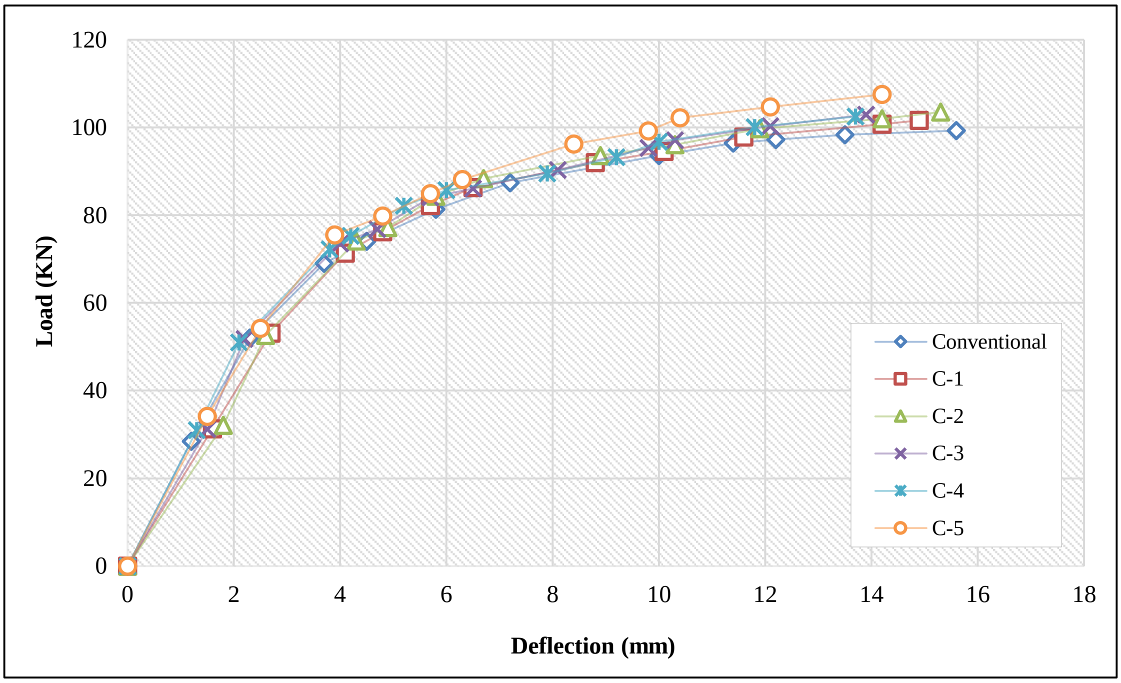

Figure 15. Comparison of Conventional vs. Combined Replacement for Flexural Strength of M 40 Grade-Mix in terms of Load vs. Deflection

Using supplementary materials to replace cement and reclaimed rubber aggregates in concrete to balance and improve its strength is a major advantage since the use of the above materials reduces environmental pollution and material and transportation costs. As storage of waste rubber tires requires large open space, it can be recycled and used to replace fine or coarse aggregates in the concrete mix. The use of rubber aggregates is limited to non-structural applications like road pavements, roofs and other subsidiary activities based on previous research work. Even though the present study reveals strength improvement in combined replacements, further research may be carried out for very low and higher proportions of similar materials or different admixtures in order to ensure their structural stability and application in the field of civil engineering.

4. Conclusions

The main aim of this research work is to identify the optimum proportions of combined replacement of materials for improving the strength of concrete. A Genetic Algorithm based simulation and physical experiments were carried out for comparison of the improvements to the strength characteristics of M40 grade concrete mix before and after combined partial replacement of materials. Based on the results obtained from experiments and simulation of individual and combined replacement of materials, the following conclusions are drawn:

- Among the three different admixtures used in concrete, silica fume exhibited the maximum compressive strength compared to fly ash and plaster of Paris in an M40 grade concrete mix.
- More than 50 percent increase was observed in the compressive strength of SF mixed concrete while comparing the optimum replacement result with control mix values for all ages of concrete.
- The Plaster of Paris replaced mix does not achieve the target strength at the optimum replacement level of nine percent.
- Compared to the optimum values of fly ash and silica fume replaced mix, it is evident that the percentage increase in strength is greater at early ages and less for 28-day cured samples.
- A significant reduction is seen in compressive strength for any proportion of reclaimed rubber replacement, irrespective of the curing period.
- As the variation between simulated and experimental values of C-4 (the highest value) and C-2 (the lowest value) in combined replacement is negligible, all the five combinations (C-1 to C-5) are considered as optimum proportions of replacement.

- In both experimental and simulated results, a marginal increase in strength is found for a 10% replacement of SF combined with other material replacements.
- The deflection values of the replaced mixes for M40 grade are lower than those of the conventional mix, and hence flexural strength increased with combined replacement.
- Reclaimed rubber has a negative effect while replacing aggregates individually, where as it has a positive effect on the compressive strength when it is replaced along with admixtures like SF, FA, and POP.
- GA can be used as a tool to simulate the compressive strength of concrete in order to save time and cost when it is impossible to cast huge numbers of cube samples in the laboratory.

In conclusion, the environmental impact due to disposal of waste rubber tires can be reduced considerably by replacing coarse aggregates with reclaimed rubber and industrial wastes like fly ash and silica fume may replace cement in concrete mix which can reduce the overall construction cost to a certain extent.

4.1. Recommendations for Future Research

- Various proportions of fly ash, silica fume, plaster of Paris, and reclaimed rubber other than those used in current research may be replaced partially to estimate the compressive and flexural strength of concrete mixes in future studies.
- A similar pattern of research can be carried out with different forms of rubber like powder, shredded, and crumb rubber, along with mineral admixtures in the concrete mix.
- Different combinations of material replacements with rice husk ash, granulated blast furnace slag, along with silica fume, fly ash, and reclaimed rubber can be used to determine the optimum individual and combined replacement percentage.
- Apart from genetic algorithms, other tools like artificial neural networks may also be used to predict the compressive strength of concrete mixes with similar combinations.
- Other concrete samples with grades like M20 and M30 can be prepared and tested in order to compare compressive, split tensile and flexural strength of concrete individually and in combinations in future research work.

5. Declarations

5.1. Author Contributions

Conceptualization, K.W.; methodology, K.W.; formal analysis, K.W and B.M.K.; investigation, K.W. and B.M.K,; curation, A.J. and S.P.; writing - original draft preparation, K.W., B.M.K. and A.J.; writing - review and editing, B.M.K., A.J. and S.P.; supervision, B.M.K and A.J.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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