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Research Article

Performance assessment of ternary blended fiber-reinforced recycled aggregate concrete

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Abstract

Amid growing environmental concerns and the urgent need for sustainable construction practices, recycled concrete aggregates (RCA) have garnered significant attention. This research explores the enhancement of recycled aggregate concrete (RAC) performance while increasing the substitution level of RCA. The study investigates the mechanical and durability properties of M30-grade RAC, incorporating various combinations of OPC, PPC, Alccofine, manufactured sand, natural aggregates, and recycled coarse aggregates across 27 mixes. The results reveal that the mix containing 80% RCA with PPC, 10% Alccofine, and 0.50% glass fiber achieved a compressive strength of 39.74 MPa, surpassing the target strength. The flexural strength for this mix was 3.89 MPa, exceeding the requirements for low-volume road applications. The performance of RAC improved significantly in binary, ternary, and fiber-reinforced ternary blends, with fiber-reinforced ternary blends demonstrating superior performance and sustainability benefits. The durability of RAC was found to be improved with the inclusion of Alccofine and glass fibers. Alccofine showed superior improvement in durability properties such as chloride penetration, Sorptivity, and drying shrinkage. Compressive strength results were validated using response surface methodology (RSM). These findings highlight the viability of fiber-reinforced ternary blends for applications like pavements, which demand large quantities of aggregates. The study underscores the potential of recycling construction waste, reducing the carbon footprint, and advancing sustainable construction practices, paving the way for a greener future in the industry.

1. Introduction

The urgency of sustainable development in the construction sector is paramount. It is crucial to create buildings and infrastructure that are environmentally responsible and resource-efficient throughout their lifecycle. This includes using sustainable materials, designing for energy efficiency, and incorporating renewable energy sources to reduce carbon footprint and environmental impact. It also involves practices that minimize waste, conserve water, and improve indoor environmental quality, which promotes healthier living and working conditions. Every raw material used in concrete will considerably impact nature and raise concerns about sustainability issues [1]. Sustainable development balances economic growth, environmental stewardship, and social well-being, ensuring that construction activities contribute positively to present and future generations. The significance of this topic cannot be overstated, as it shapes the future of our built environment and the well-being of our society.

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Using Ordinary Portland Cement (OPC) in construction has numerous challenges. OPC production has a significant environmental impact due to high carbon dioxide emissions, contributing to global warming. The process is energy-intensive and heavily relies on fossil fuels, causing further ecological degradation. Furthermore, it depletes natural resources like limestone and clay [2]. OPC structures are susceptible to chemical attacks, and their production demands large amounts of water, posing issues in water-scarce regions. Exploring alternative materials and sustainable practices to address these issues is crucial, and using natural coarse aggregates in construction activities poses various challenges. These include the depletion of natural resources due to extensive mining and quarrying, leading to habitat destruction and ecological imbalance. The extraction and transportation processes are energy-intensive, contributing to greenhouse gas emissions and air pollution. Moreover, using natural coarse aggregates can lead to significant land degradation. As the availability of high-quality natural aggregates diminishes, there is a growing need to explore sustainable alternatives such as recycled or alternative aggregates to reduce environmental impact and ensure the sustainability of construction practices. Based on the above concerns, the current research is focused on utilizing materials that will reduce the problems associated with the degradation of the environment. For this purpose, Portland pozzolana cement (PPC), Manufactured sand (M-sand), and recycled concrete aggregates (RCA) were chosen. PPC incorporates fly ash, reducing the clinker content in cement production, which lowers carbon dioxide emissions, promotes the utilization of industrial waste like fly ash, enhances durability, and improves energy efficiency. Similarly, M-sand, produced by crushing stones or rocks, eliminates the need for riverbed mining, thereby protecting natural ecosystems. Additionally, M-sand is often produced locally, which reduces transportation requirements and further decreases carbon emissions.

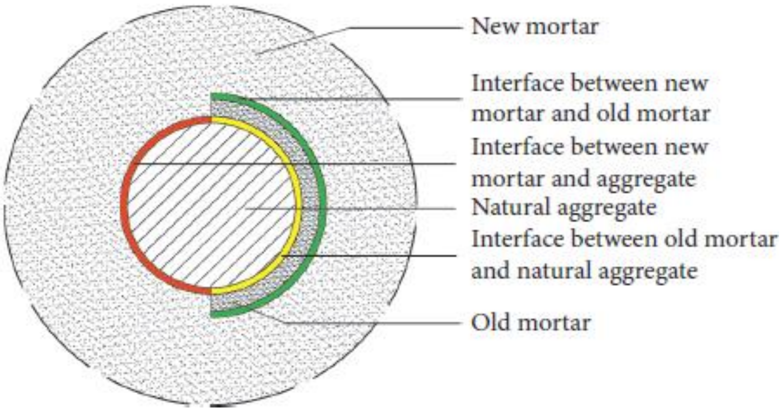


Fig. 1. Microstructure and scanning electron microscope (SEM) image of recycled concrete showing old and new mortars with ITZs [7]

As the RCA possesses inferior properties to NCA, its usage is mostly limited to non-structural applications. Water absorption (WA) of RCA is one such significant factor that affects the performance of recycled aggregate concrete (RAC) [3]. The mechanical behavior of RAC is found to be inferior to conventional concrete as RCA contains a layer of old mortar; it results in the formation of additional ITZ (Interfacial Transition Zone), absorbs more water during mixing, increases porosity, and results in the generation of micro-cracks [4,5]. The Interfacial Transition Zone (ITZ), or aggregate-paste interface [6,7], consists of calcium hydroxide, calcium silicate hydrate, and ettringite, with a higher water-to-cement (w/c) ratio than the mortar, making it porous and weak [8,9]. This weakness reduces the macro-mechanical properties of concrete. Recycled coarse aggregate (RCA) introduces two ITZs: (a) the old ITZ from residual mortar and (b) the new ITZ formed during mixing, as shown in Fig. 1. Pedro et al. observed the declining nature of the performance of workability and density of RAC with increasing levels of RCA [10]. Saha and Rajasekaran investigated the mechanical behavior of RAC, and they observed that an increase in the substitution level of RCA content led to a decrease in the performance of the RAC [11]. The behavior of RAC in durability parameters was also found to be inferior to that of conventional concrete [12,13].

For structural and non-structural applications of RCA, different nations published guidelines stating the amount of RCA (limitations of RCA in RAC) that can be used for a particular application up to a specific concrete grade. Indian Standards IS-383-2016 [14] limits the RCA to 25%, 20% (up to M20), and 100% (up to M15) for plain, reinforced, and lean concrete applications, respectively. The current research aimed at maximizing the utilization of RCA and applying it to higher grades of concrete. For this purpose, in the current study, Portland Pozzolana cement (PPC) is obtained by intergrinding the Portland clinker with gypsum in combination with fly ash, which is an industrial waste from thermal power plants possessing cementitious properties is used as a complete replacement and compared their properties. Alccofine C-1203, which comes under the category of Supplementary cementitious materials (SCM), is partially replaced for the binding material, and glass fibers were used, resulting in the fiber-reinforced ternary concrete matrix.

2. Research Significance

The research on fiber-reinforced concrete blends using recycled concrete aggregates (RCA), PPC, Alccofine, and glass fibers holds significant importance in advancing sustainable construction. By incorporating RCA, the study promotes waste recycling and reduces dependence on natural aggregates, addressing resource depletion and environmental degradation. The use of PPC and Alccofine enhances the sustainability and durability of the blends by lowering clinker content, reducing carbon emissions, and improving material performance. Glass fibers further reinforce the blends, enhancing tensile and flexural strength, crack resistance, and overall durability, making them suitable for demanding applications such as pavements and low-volume roads. These innovative blends demonstrate cost-effectiveness by utilizing industrial by-products and minimizing maintenance needs.

The study aims to enhance the mechanical and durability properties of RAC. It examines key parameters such as compressive strength, flexural strength, modulus of elasticity, drying shrinkage, chloride ion diffusion resistance, and sorptivity. This research contributes to developing eco-friendly construction materials, supporting the circular economy, and reducing the carbon footprint, paving the way for a greener, more sustainable future in the construction industry.

3. Methodology

Ordinary Portland Cement (OPC) of 53grade and Portland Pozzolana cement (PPC) confirming to IS:12269 [15] and IS:1489 [16] are used as binding agents. Alccofine (AL) C-1203 is used as a Supplementary cementitious material (SCM) as a partial substitute to the binding agent (PPC), forming a ternary blend. The trial studies are conducted to determine the optimum dosage of alccofine by conducting compressive strength on concrete, and it is found that a 10% substitution of alccofine yields optimum strength. for the current study, 10% of Alccofine is chosen as a replacement for the binding material. Table 1 shows the oxide compositions of the cementitious materials used. Alccofine is used as an SCM due to its calcium oxide, silica, and aluminum oxide content. Manufactured sand (M Sand) serves as a fine aggregate (FA) with a specific gravity of 2.68 and 1% water absorption. Crushed granite of 20mm nominal size is used as a natural coarse aggregate (NCA) with a specific gravity of 2.79 and water absorption of 0.50%, and recycled concrete aggregate (RCA) is substituted at different levels of NCA. The test results of the aggregates' physical properties and gradation analysis satisfy the codal requirements of IS:2386-Part I & III [17,18] and IS:383-2016. The gradation analysis of fine aggregate meets the Zone-II specifications, and the gradation analysis for the aggregates is shown in Fig. 2. The RCA is obtained from Hyderabad's construction and demolition waste (C&D) recycling plant. However, the physical properties of RCA exhibit inferior properties compared to the NCA, such as higher water absorption, crushing, and abrasion values. RCA's specific gravity and water absorption are 2.64 and 3.54%, respectively. The RCA is cleaned with water to remove the dust particles and soaked in water for 24 hours so that the RCA reaches an SSD state. When used in concrete, it reduces the absorption of mixing water. RCA is brought to be a saturated surface dry condition (SSD) by ensuring no water remains on the aggregate surface before it is used in the concreting. To achieve the desired workability, maintaining a uniform slump of 50±5 mm, a super-plasticizer named conplast SP-430 was used. By using SP at the rate of 1% by the weight of cement, reduces the water content by 23% which is observed from the trial studies.

Table 1. Oxide composition and physical properties of binders

	Al_2O_3	SiO_2	MgO	CaO	Fe_2O_3	SO_3	Na_2O	K_2O	LOI	Specific gravity
Alccofine	24.57	37.53	5.23	29.46	0.92	0.18	0.032	0.61	0.58	2.86
OPC	6.2	21.20	1.26	62.05	4.75	0.67	0.13	0.34	2.01	3.14
PPC	11.04	36.40	1.0	42.29	4.68	2.1	0.18	0.4	2.66	3.08

Table 2. Classification and notations of the mixes

Series	Notation	Expansion of Notation
Unary mixes	A0	Concrete consisting of OPC and 100% NCA
	A1	Concrete consisting of OPC, 80% NCA, and 20% RCA
	A2	Concrete consisting of OPC, 60% NCA, and 40% RCA
	A3	Concrete consisting of OPC, 40% NCA, and 60% RCA
	A4	Concrete consisting of OPC, 20% NCA, and 80% RCA
	A5	Concrete consisting of OPC, 0% NCA, and 100% RCA
Binary blended mixes	B0	Concrete consisting of PPC and 100% NCA
	B1	Concrete consisting of PPC, 80% NCA, and 20% RCA
	B2	Concrete consisting of PPC, 60% NCA, and 40% RCA
	B3	Concrete consisting of PPC, 40% NCA, and 60% RCA
	B4	Concrete consisting of PPC, 20% NCA, and 80% RCA
	B5	Concrete consisting of PPC, 0% NCA, and 100% RCA
Ternary blended mixes	C0	Concrete consisting of PPC, Alccofine 10%, and 100% NCA
	C1	Concrete consisting of PPC, Alccofine 10%, 80% NCA, and 20% RCA
	C2	Concrete consisting of PPC, Alccofine 10%, 60% NCA, and 40% RCA
	C3	Concrete consisting of PPC, Alccofine 10%, 40% NCA, and 60% RCA
	C4	Concrete consisting of PPC, Alccofine 10%, 20% NCA, and 80% RCA
	C5	Concrete consisting of PPC, Alccofine 10%, 0% NCA, and 100% RCA
Fiber-reinforced ternary blended mixes	D1	Concrete consisting of PPC, Alccofine 10%, 40% NCA, 60% RCA, and glass fiber 0.25%
	D2	Concrete consisting of PPC, Alccofine 10%, 40% NCA, 60% RCA, and glass fiber 0.50%
	D3	Concrete consisting of PPC, Alccofine 10%, 40% NCA, 60% RCA, and glass fiber 0.75%
	E1	Concrete consisting of PPC, Alccofine 10%, 20% NCA, 80% RCA, and glass fiber 0.25%
	E2	Concrete consisting of PPC, Alccofine 10%, 20% NCA, 80% RCA, and glass fiber 0.50%
	E3	Concrete consisting of PPC, Alccofine 10%, 20% NCA, 80% RCA, and glass fiber 0.75%
	F1	Concrete consisting of PPC, Alccofine 10%, 0% NCA, 100% RCA, and glass fiber 0.25%
	F2	Concrete consisting of PPC, Alccofine 10%, 0% NCA, 100% RCA, and glass fiber 0.50%
	F3	Concrete consisting of PPC, Alccofine 10%, 0% NCA, 100% RCA, and glass fiber 0.75%

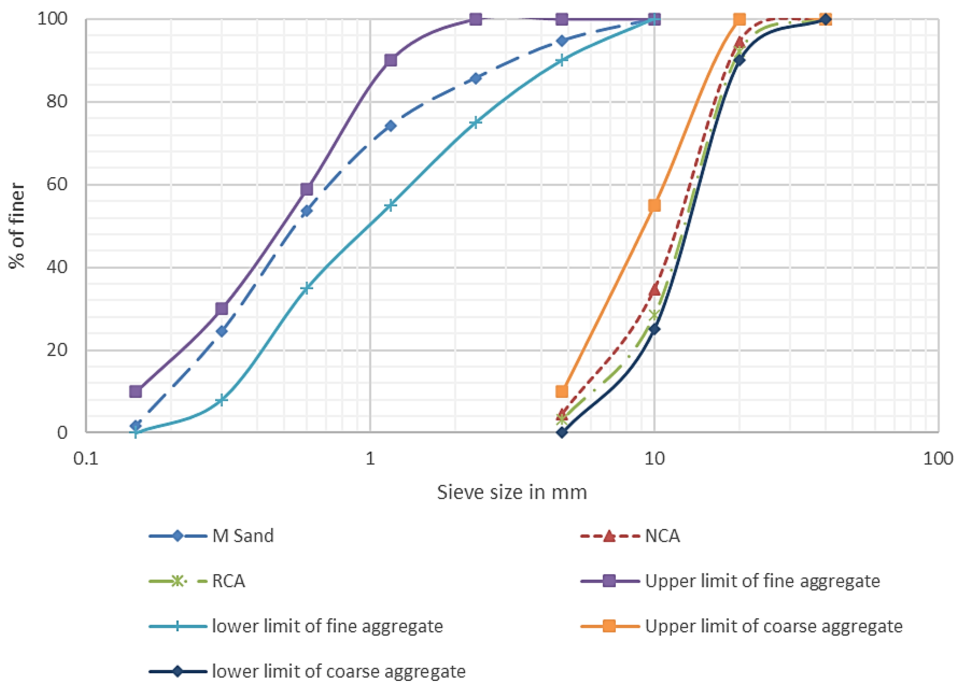


Fig. 2. Gradation analysis of aggregates

Table 3. Mix proportions for 1 m³ of concrete

Mix ID	Cement (kg)	M sand (kg)	NCA (kg)	RCA (kg)	Alccofine (kg)	Glass fibers (%)	Water (kg)	Slump (mm)	SP (%)
A0	376	676	1256	0	0	0	170	51	0.65
A1	376	676	1005	231	0	0	170	50	0.69
A2	376	676	754	462	0	0	170	49	0.75
A3	376	676	502	692	0	0	170	47	0.83
A4	376	676	251	923	0	0	170	45	0.89
A5	376	676	0	1154	0	0	170	45	0.96
B0	376	676	1256	0	0	0	170	53	0.59
B1	376	676	1005	231	0	0	170	52	0.61
B2	376	676	754	462	0	0	170	51	0.67
B3	376	676	502	692	0	0	170	50	0.76
B4	376	676	251	923	0	0	170	48	0.82
B5	376	676	0	1154	0	0	170	47	0.89
C0	338.4	676	1256	0	37.6	0	170	55	0.48
C1	338.4	676	1005	231	37.6	0	170	54	0.50
C2	338.4	676	754	462	37.6	0	170	52	0.56
C3	338.4	676	502	692	37.6	0	170	52	0.66
C4	338.4	676	251	923	37.6	0	170	50	0.72
C5	338.4	676	0	1154	37.6	0	170	49	0.79
D1	338.4	676	502	692	37.6	0.25	170	53	0.79
D2	338.4	676	502	692	37.6	0.50	170	51	0.92
D3	338.4	676	502	692	37.6	0.75	170	49	1.09
E1	338.4	676	251	923	37.6	0.25	170	51	0.92
E2	338.4	676	251	923	37.6	0.50	170	49	1.12
E3	338.4	676	251	923	37.6	0.75	170	48	1.33
F1	338.4	676	0	1154	37.6	0.25	170	50	1.14
F2	338.4	676	0	1154	37.6	0.50	170	48	1.36
F3	338.4	676	0	1154	37.6	0.75	170	45	1.55

Glass fibers (GF) of 12mm length were used, forming fiber-reinforced ternary blended concrete. The raw materials used in the current study are shown in Fig. 3. The guidelines for the mix design M30 (target strength is 38.25 MPa) are followed as per the IS:10262-2019 [19]. In all the mixes, the water-cement ratio and fine aggregate quantity are maintained as a constant. The variables were NCA (0%, 20%, 40%, 60%, 80%, and 100%), RCA (0%, 20%, 40%, 60%, 80%, and 100%), and glass fibers (0.25%, 0.50%, and 0.75%). Twenty-seven mixes were cast and tested to evaluate the performance of concrete. The 27 mixes were split into four series, as shown in Table 2, and the details of the mix proportions are shown in Table 3.

Fig. 3. Raw materials employed in the study: (a) OPC, (b) Alccofine, (c) PPC, (d) NCA, (e) RCA, (f) Glass fibers, (g) M-sand

4. Details of The Experiments Performed

As per IS:516-1959 [20], cube specimens of 150 mm size and prism of 500 mm X 100 mm X 100 mm size were cast to evaluate the behavior of concrete in compression and flexure, respectively, after 28 days of curing. Three specimens were cast for each mix, and the average of the three sample results was considered. Three cylinders of 150 mm diameter with 300 mm height were cast for every mix to evaluate concrete's Modulus of Elasticity (MOE) at 28 days. The durability properties of concrete, such as rapid chloride penetration test (RCPT), sorptivity, and drying shrinkage, were performed as per ASTM C-1202 [21], ASTM C-1585-04 [22], and IS:516- part 6 [23], respectively. Disc specimens 50 mm thick with 100mm diameter are used for RCPT and sorptivity. Test on concrete by RCPT helps evaluate the penetration resistance of concrete against the movement of chloride ions, and the charge passed is noted down at regular intervals. The sorptivity test evaluates the ability of concrete to resist water ingress through capillary action. To occur the capillary action, the specimens are placed in the water so that the bottom of the specimen is placed at a certain height, and the water level is maintained at a height of 5mm from the bottom. The circumferential surface of the specimens used for sorptivity is sealed with a water-proofer so that the water enters the concrete from its bottom only. The weights of the specimens are noted down at respective time intervals. Executing a drying shrinkage test helps in noting the contraction behavior of concrete that occurs due to the loss of moisture when exposed to the environment. For this purpose, 300 mm X 75 mm X 75 mm size specimens were used and tested after 90 days. The test setup and sample cast are shown in Fig. 4.

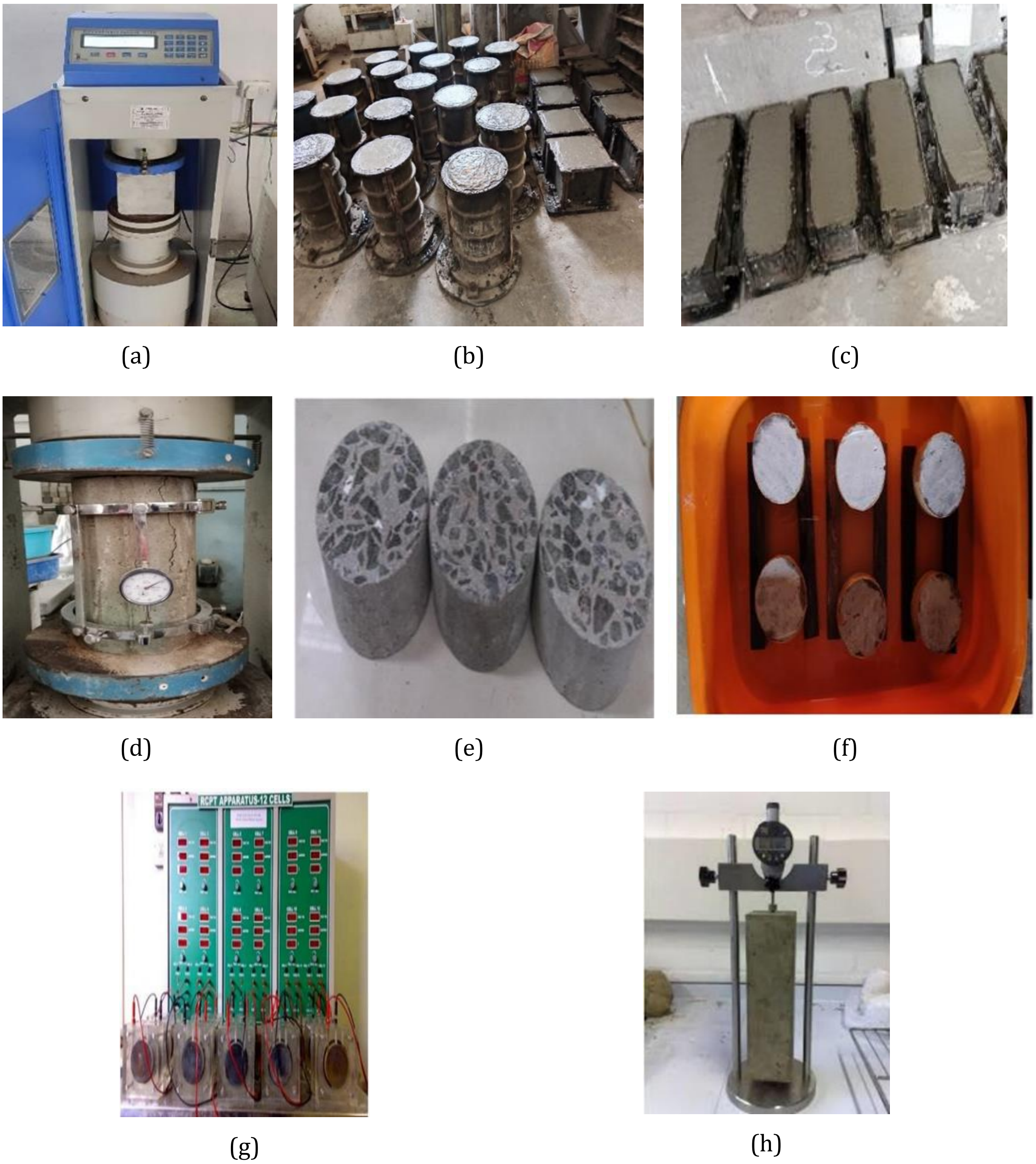


Fig. 4. a) Compressive strength test set up, b) Cube and cylindrical specimens, c) Prism specimens, d) Test set up for MOE, e) Disc-shaped specimens for RCPT and sorptivity, f) Sorptivity test set up, g) RCPT test set up, and h) Test set up for drying shrinkage

5. Results and Discussions

5.1 Compressive Strength

5.1.1 Effect of RCA on CS in Unary Mixes

Fig. 5 shows the variations in the outcomes of the compressive strength. The compressive strength (CS) of concrete exhibits a declining nature with an increase in the substitution level of RCA. The decrease in strength increases as the replacement level of RCA rises. The strength is reduced by 8.72% to 16.34% compared to the traditional unary mix at different levels of RCA. The reduction in strength is attributed to the inferior properties of RCA, such as higher water absorption and the inferior quality of old mortar on the surface of RCA. The decline in the strength is also due to the formation of multiple ITZs in the RAC matrix [24]. In the work by Babar Ali et al., the CS is reduced by 18% when NCA was completely replaced by RCA [25]. In the work by Job Thomas et al., the CS decreases by 11-19% when 100% RCA was used [26].

5.1.2 Effect of Binary Blends, Ternary Blends, and Glass Fiber in CS of RAC

In the case of binary blends, the CS was reduced by 9.26% to 18.13% compared to the traditional binary mix. However, in the case of binary blends, the CS was enhanced by 1.37% to 3.59% when compared to the respective unary mixes. The increase in CS is due to the pozzolanic nature of PPC, which consists of fly ash particles. This resulted in the formation of additional C-S-H gel, which is denser and more stable than the primary hydration products. The newly formed C-S-H fills micro-pores and voids within the cement matrix, effectively reducing porosity and enhancing packing density.

In the case of ternary blended mixes, Alccofine, an SCM, has ultra-fine particles that fill the micro-pores and voids, forming a dense concrete matrix. Alccofine reacts with the leftover CH produced during the hydration of cement, resulting in the C-S-H gel formation, which resulted in strength gain at all ages of curing. The fine particles of Alccofine improved the bond between the aggregates and the cement paste and reduced the formation of micro-cracks, enhancing concrete performance. The enhancement in strength was observed to be 5.88%- 9.62% when compared to the respective binary mixes. In ternary blend mixes, the strength of the mix C3(60%RCA) was found to be 38.67MPa, which is higher than that of the required target strength.

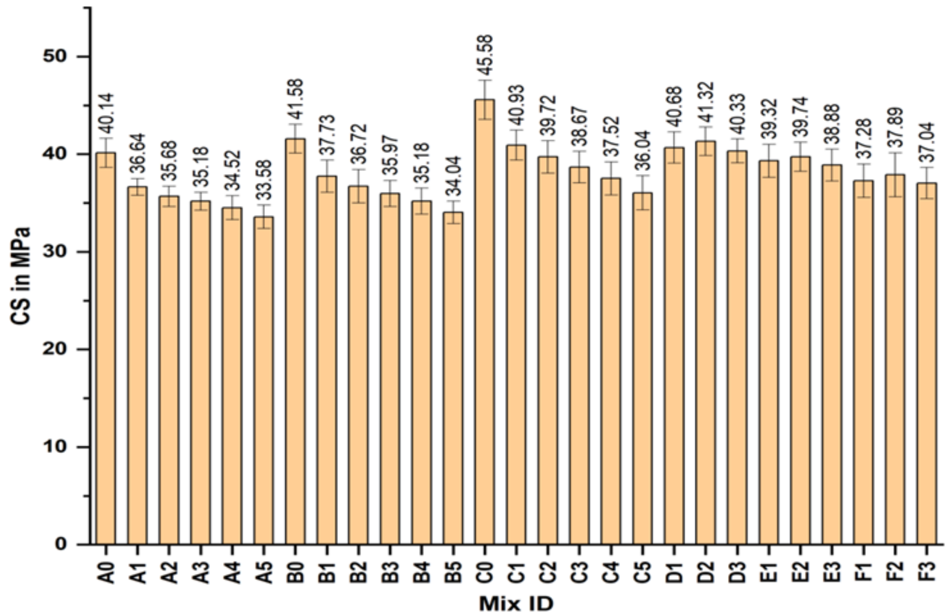


Fig. 5. Variations in Compressive strength outcomes after 28 days

The fibers are uniformly distributed in fiber-reinforced concrete mixes at lower dosages (0.25% and 0.50%). This helped to control the micro-cracks by preventing the cracks from propagating and widening, resulting in a strength gain. However, the dispersion is not uniform at higher fiber dosages due to the balling effect that creates voids, reducing the strength and other concrete performances. The presence of fiber enhanced the performance of fiber-reinforced concrete by 2.77% to 6.85% when compared to the respective ternary mixes. The percentage of change in the CS is shown in Fig. 6, and the typical failures of the specimen are shown in Fig.7.

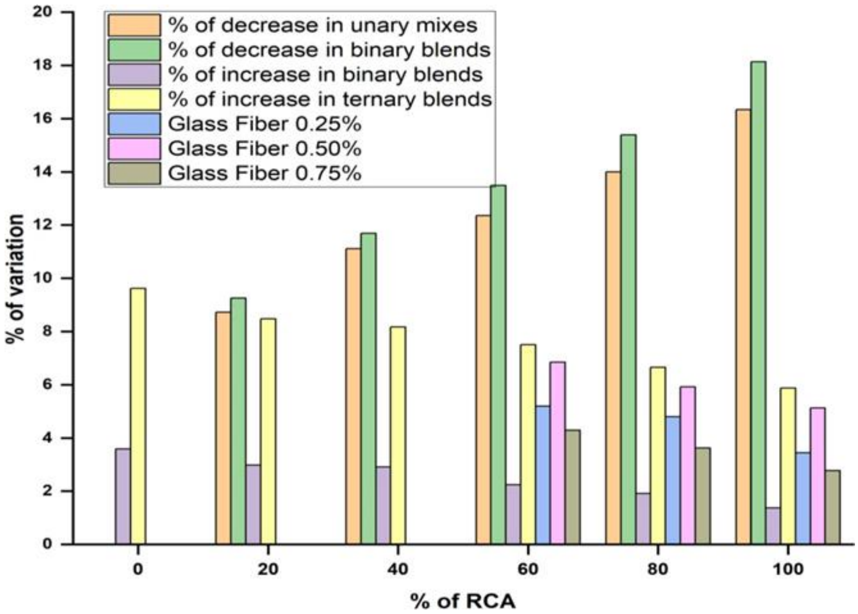


Fig. 6. Variations in Compressive strength outcomes after 28 days

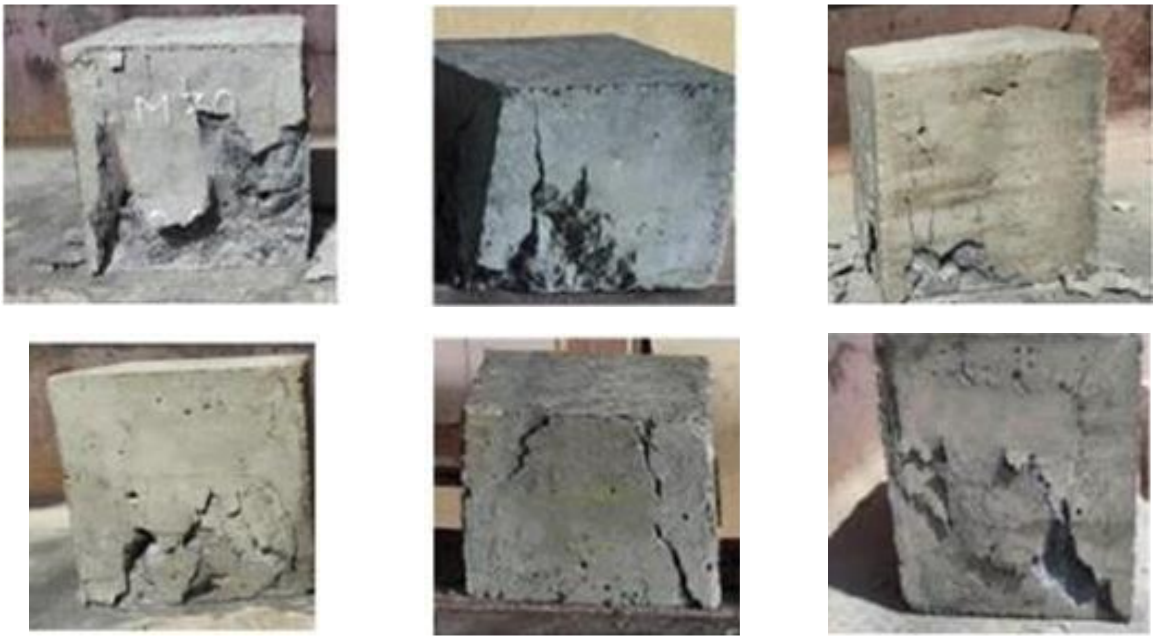


Fig. 7. Failure patterns in cubical specimens

5.2 Flexural Strength

Flexural strength is another crucial mechanical property of concrete, as it measures the material's ability to resist bending or cracking under applied loads. Figure 8 shows the variation of flexural test outcomes. The FS of the concrete with 100% NCA (A0) is 4.18 MPa, and it is reduced to 3.08 when 100% RCA (A5) is used, which shows a decline in strength of 26.32%. The reduction in strength is due to the newly formed ITZ between the RCA and the cement matrix. This newly formed ITZ is weaker than the ITZ formed between the NCA and the cement matrix. This newly formed weaker ITZ contributes to the reduced flexural strength and crack propagation under loading.

From Fig. 8, it can be seen that the optimum strength values are observed in fiber-reinforced blends and then followed by ternary, binary, and unary blends. Mixes with higher levels of RCA exhibited poorer performance, and the relationship between the RCA levels and flexural strength is inversely proportional, which means that the higher the RCA, the lower the strength. In ternary mixes, due to the combined action of PPC and Alccofine, the strength was enhanced due to the fine nature of the materials, which resulted in the improved packing density of the concrete matrix. Mixes with glass fibers have shown the highest strength improvement among all the series. The FS was enhanced by 6.81% to 12.97% for mixes with glass fibers. Typical failures in flexure are shown in Fig. 9. For concrete to be used in rural road applications, the minimum flexural strength should be 3.8 MPa per IRC: SP:62-2014 [27]. Achieving the minimum flexural strength in concrete is essential for rural road applications, as it significantly influences the pavement's structural performance and durability. In rural areas, where maintenance resources are often limited, ensuring sufficient flexural strength minimizes the risk of cracking, deformation, and premature failure. In the present study, flexural strength was found to be 3.89 MPa for the mix E2 (80% RCA), which can be used safely for rural road pavement applications as it satisfies the minimum strength requirement.

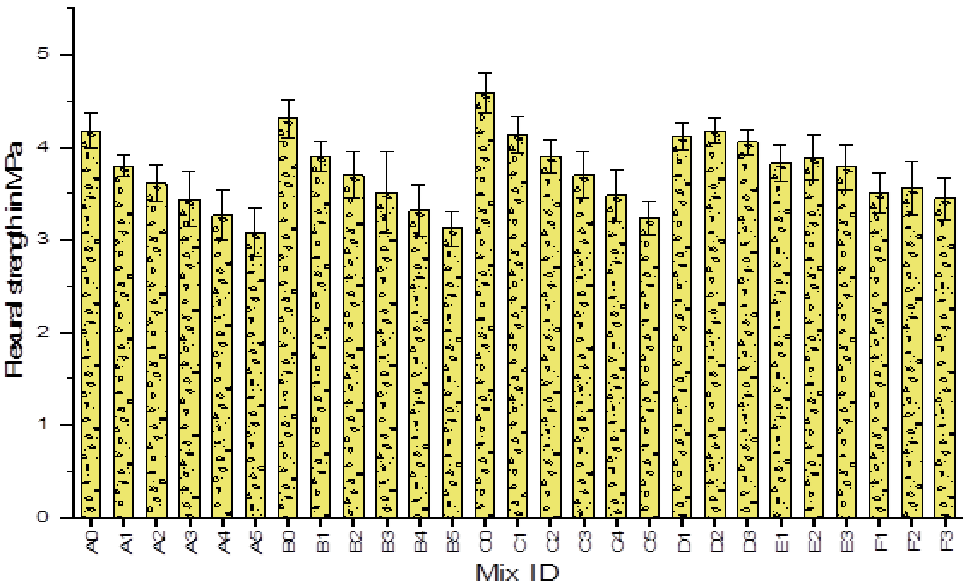


Fig. 8. Test outcomes of flexural strength

Fig. 9. Typical failures of prisms under flexure

5.3 Modulus of Elasticity

The modulus of elasticity is one of the essential mechanical parameters as it represents the compactness and stiffness of the concrete. The elastic modulus after 28 days with different levels of RCA, Alccofine, and glass fibers is investigated in the present study, and its outcomes and variations are shown in Fig. 10 and 11. Fig. 10 shows that the performance of RAC in MOE declined with the rise in the substitution level of RCA in all the series. The MOE for the concrete with 100%

NCA (A0) is 33.82 MPa, and 27.34 MPa (A5) when 100% RCA is used, which shows the MOE is reduced by 19.16%. The decline in the performance of MOE is due to the weaker bond between the cement paste and RCA. The MOE of concrete decreases with an increase in the level of RCA due to the existence of residual mortar, which has lower stiffness and strength, reducing the overall stiffness of the concrete when RCA content increases. In the mixes with PPC, i.e., binary blend series, the MOE with 100% NCA is 34.68 MPa (B0) and 27.73 MPa (B5) when 100% RCA is used. Comparing the outcomes of binary mixes with unary blends, the MOE is enhanced by 1.43% - 2.54% at different levels of RCA. This increase in strength is due to the pozzolanic nature of PPC, which helps maintain the integrity of the concrete matrix by reducing the cracking and shrinkage parameters. In ternary blends, the Alccofine improved the particle packing density, and due to its finer particle size, it enhanced the bond between the aggregates and the cement paste, and MOE was found to be between 36.42 MPa(C1) to 28.64 MPa(C5), which resulted in an improvement of 3.28%-5.02% when compared to binary blends. The variations in the percentage of strength gain or decline are shown in Fig. 11. Fiber-reinforced mixes exhibited superior performance as the presence of glass fibers helps reduce shrinkage, minimizes the risk of cracking, and improves the ductility of concrete, making it withstand deformation without cracking.

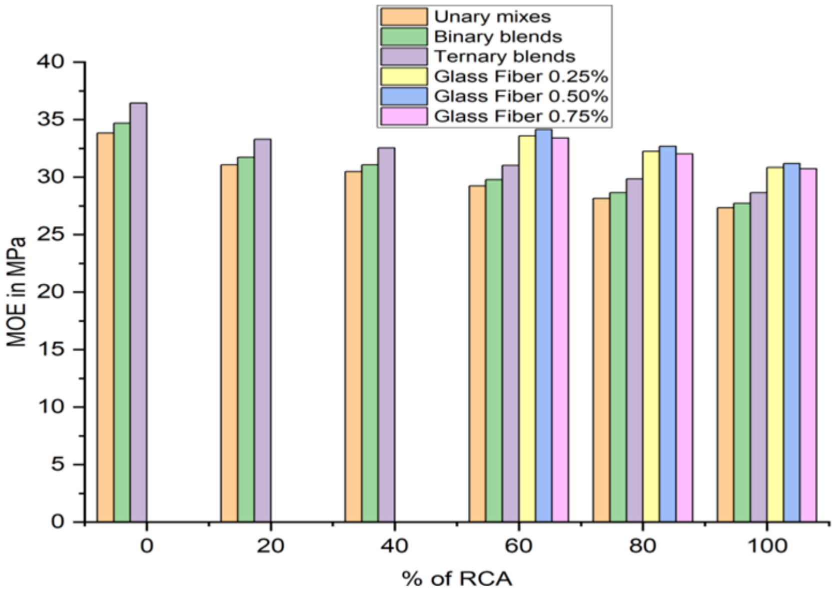


Fig. 10. Modulus of elasticity outcomes after 28 days

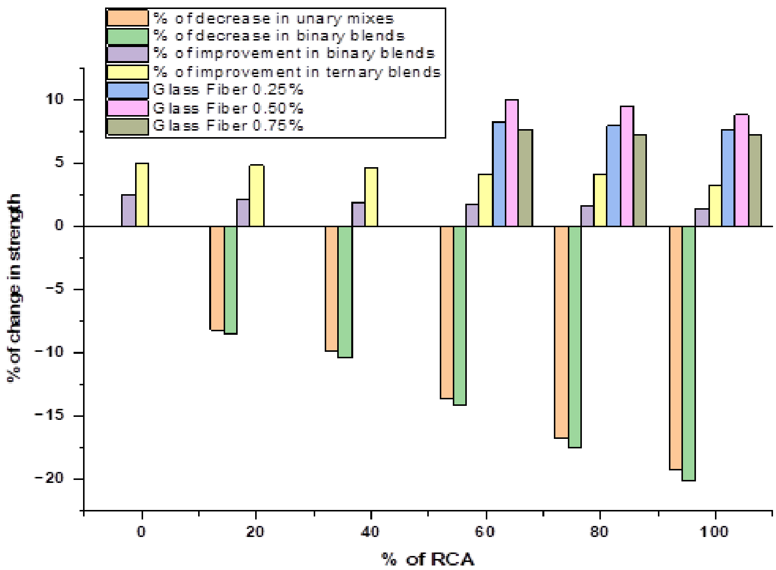


Fig. 11. Variation in modulus of elasticity

5.4 Rapid Chloride Penetration Test

Rapid chloride penetration test helps determine the concrete matrix's efficacy in impeding the ingress of chloride ions. The charge passed in coulombs is 1822 for the concrete mix having 100% NCA (A0), and the charge passed is increased to 2266 coulombs for the RAC having 100% RCA (A5), which shows the decline in the performance by 24.37%. From Fig. 12, an increase in the percentage of RCA in RAC typically results in higher chloride ion permeability. This is due to micro-cracks on the residual mortar on the surface of RCA, which acts as an additional channel for chloride ions to penetrate, increasing the permeability of RCA in RAC. Also, due to the porous nature of RCA, which increased permeability, leading to the faster passage of chloride ions, the concrete is less resistant to the passage of chloride ions. A similar pattern of outcomes was observed in the work carried out by other researchers [4,28]. In the binary mixes, the charge passed is 1692 coulombs for the mix having 100% NCA (B0) and 2176 coulombs for the RAC mix having 100%RCA (B5). However, the penetration resistance was enhanced in binary and ternary mixes due to the C-S-H gel formation, which improved the concrete impermeability by densifying the microstructure and by refining the pore structure due to the micro-filling ability and pozzolanic reactivity, respectively and the variation is shown in Fig. 12.

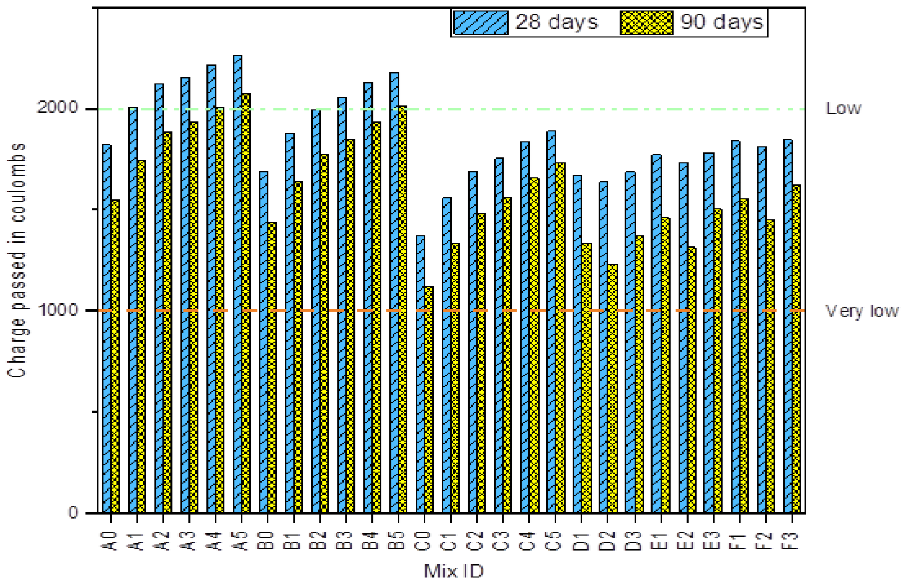


Fig. 12. Variations in RCPT

In binary blends, the charge passed is 1692 coulombs for mix B0 (100% NCA) and 2176 coulombs for mix B5 (100%RCA). This shows that in binary mixes, the penetration resistance is improved by 3.97% to 7.14% compared to the unary mixes. The improvement is due to the pozzolanic reactivity of PPC. In ternary blends, the charge passed is 1374 coulombs for mix C0 (100% NCA) and 1888 coulombs for mix C5 (100% RCA). The test results of the ternary mixes show that the chloride penetration resistance of RAC improved by 13.24% to 18.79% compared with the binary mixes. For fiber-reinforced ternary blends, the resistance was further enhanced. However, for the 90-day curing period, the charge passed through the concrete matrix was further reduced in all the mixes compared to 28 days. In unary and binary blends, at low RCA, the RCPT falls into the low category; as RCA increases, the RCPT shifts to the moderate category. In the case of ternary and fiber-reinforced ternary mixes, RCPT is in the low category region for both samples of different ages. Table 4 shows the classification of chloride ion permeability based on ASTM-C-1202. Based on the ASTM classification mentioned in Table 4, the RCPT outcomes shown in Fig. 12 say that the RCPT is in the range of moderate and low chloride ion penetrability for the unary and binary mixes. The charge passed for different ages of curing samples in the ternary and fiber-reinforced mixes lies in the low chloride ion permeability category.

Table 4. Classification of chloride ion penetrability based on ASTM – C – 1202

Charge passed in coulombs	>4000	2000 – 4000	1000 – 2000	100 – 1000	<100
Chloride ion penetrability	High	Moderate	Low	Very low	Negligible

5.5 Sorptivity

Sorptivity is one of the essential durability parameters of concrete, and the concrete matrix's resistance against water penetration in uni-directional is evaluated. Like the other concrete parameters, the sorptivity exhibited poorer behavior with the increasing level of RCA. The sorptivity of concrete increased with an increase in RCA in all the series. Similar observations were found in the work done by other researchers [29-31]. The variation in the test outcomes is shown in Fig. 13. From Fig. 13, it can be seen that for 28 days results in unary, binary, and ternary blends, the sorptivity ranged from 0.154 mm/min$^{1/2}$ to 0.218 mm/min$^{1/2}$, 0.141 mm/min$^{1/2}$ to 0.209 mm/min$^{1/2}$ and 0.118 mm/min$^{1/2}$ to 0.194 mm/min$^{1/2}$ respectively.

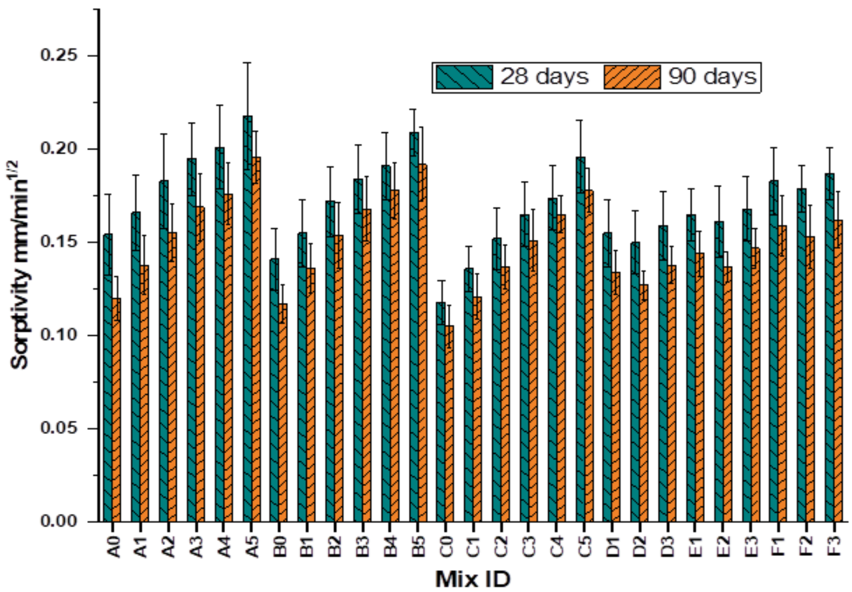


Fig. 13. Variations in Sorptivity

The performance dropped by 41.56% for 100% RCA (A5) compared to the unary conventional mix after 28 days. However, in the binary blends and ternary blends, the resistance of the concrete matrix was enhanced by 4.13% - 8.44% and 7.18% to 16.31% when compared with the unary and binary blends, respectively, after 28 days curing period. In fiber-reinforced ternary mixes, up to the optimum dosage of fibers, the resistance of the concrete matrix was enhanced, but beyond that, the matrix's resistance dropped. The classification of concrete acceptance criteria based on sorptivity is given in Table 5. From Fig. 13, it can be seen that the acceptance criteria were acceptable for ternary and fiber-reinforced ternary blends. Still, for unary and binary blends, it is between acceptable and poor for test results with 28 days of curing samples. The test results of 90 days of samples showed acceptable criteria for all the mixes shown in Fig. 13.

Table 5. Acceptance criteria for sorptivity

Criteria	Very good	Acceptable	Poor
Sorptivity (mm/min$^{1/2}$)	< 0.1	0.10 – 0.20	> 0.20

5.6 Drying Shrinkage

Drying shrinkage is another critical parameter of concrete, which causes an increase in tensile stress, which may result in cracking, external deflection, and internal warping[32]. Various factors, such as the water-cement ratio, the binder's content, and the aggregate type, influence the drying shrinkage behavior [33].

5.6.1 Effect of RCA on Drying Shrinkage

Fig. 14 shows the variations in outcomes of drying shrinkage. In the unary mix series, the drying shrinkage was found to be 250 micro-strains for mix A0 (0%RCA), and it was 908 micro-strains for 100% RCA (A5), which is 3.63 times higher than the conventional mix (A0). The drying shrinkage was found to be increased with an increase in the replacement level of RCA. A similar pattern of increasing outcomes is observed in the work carried out by [34]. Micro-cracks and voids on the outer surface of RCA are prone to moisture loss, leading to higher drying shrinkage in concrete.

5.6.2 Effect of PPC, Alccofine, and Glass fibers on drying Shrinkage

Drying shrinkage for 100% RCA (mix A5) in the unary series is 908 micro-strains, and it was reduced to 863 micro-strains for 100% RCA (mix B5) in the binary series, which showed a reduction of 4.95%. The inclusion of PPC led to the additional C-S-H gel formation, which reduced the amount of free lime that helped minimize the potential for developing micro-cracks, reducing the shrinkage of concrete. As the heat of hydration is lower in PPC than in OPC, it reduces the risk of thermal shrinkage and cracking. Alccofine, an ultra-fine material with high pozzolanic reactivity, refines the micro-structure of concrete, reducing the permeability and resulting in lower shrinkage strains. The drying shrinkage strain in ternary mixes for the mix C5 (100% RCA) is found to be 752 micro-strains, which is reduced by 12.86% compared with the binary mix (B5). Due to the crack-arresting capability of glass fibers, fiber-reinforced ternary blends exhibited lower strain values than ternary blends.

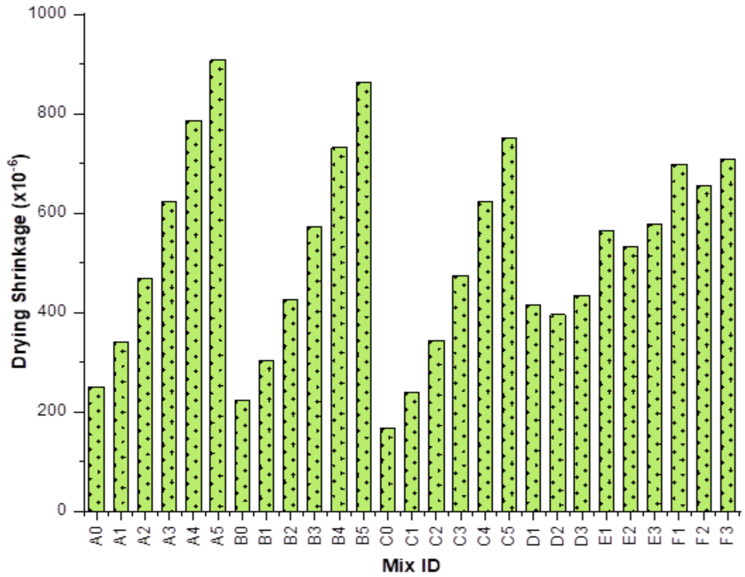


Fig. 14. Outcomes of drying shrinkage

6. Response Surface Methodology (RSM)

Response Surface Methodology (RSM) is a statistical and mathematical tool for modeling and optimizing processes. This technique focuses on understanding the complex relationships between multiple input variables and a single response variable, typically an output parameter [35]. RSM plays a vital role in process optimization and improvement by identifying key input variables influencing the response, Modeling the relationship between input and output variables, and predicting optimal input combinations for desired outcomes. By utilizing experimental data, RSM fits regression models and creates response surfaces, enabling the identification of optimal conditions. This approach provides predictive mathematical models that simplify the analysis of how variations in one factor affect others. A crucial component of RSM is the Design of Experiments (DoE), which enables efficient and systematic testing of input variables.

Initially developed for physical experiments, RSM and DoE strategies are widely applied in numerical investigations, offering valuable insights into complex systems. RSM integrates with Design of Experiments (DoE) to systematically plan experiments and minimize the number of trials while maximizing information. RSM offers visual tools like contour and surface plots to interpret results and understand relationships between factors easily. RSM's Key benefits are enhanced process understanding, improved output variable optimization, reduced experimentation costs, and increased efficiency in numerical investigations.

In the current research, Alccofine, RCA, and GF were input variables in percentages for generating the RSM model. Surface plots for the compressive and flexural strength are shown in Fig. 14 and 15, whereas contour plots are shown in Fig. 16 and 17, respectively.

6.1 Inference from Surface Plots of CS and FS

Surface plots help visualize the relationship between multiple variables and how different factors affect strength. Fig. 15 shows the surface plot outcomes for the compressive strength. From Fig. 15, it can be concluded that the CS increased with an increase in the alccofine dosage and with the glass fibers up to its optimum dosage. The decline in the outcomes of CS is observed with an increase in levels of RCA.

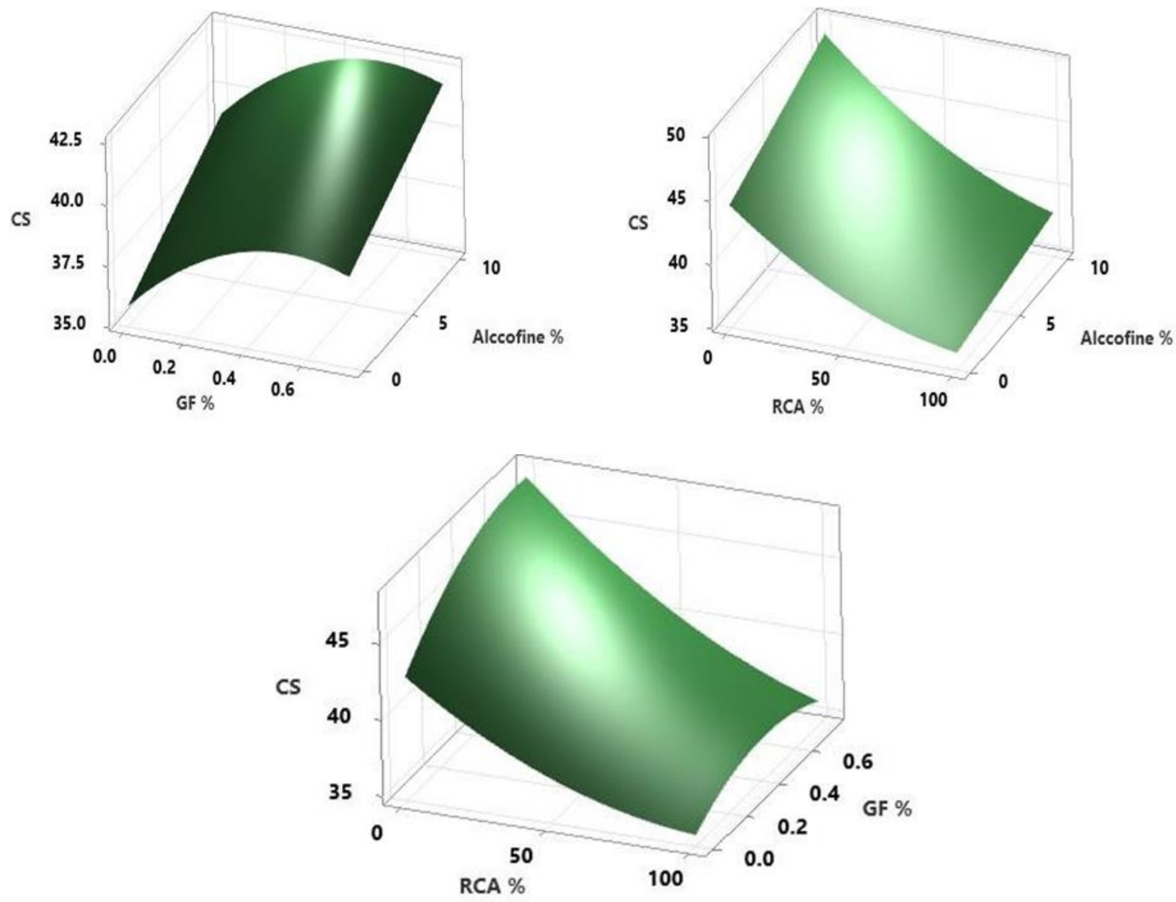


Fig. 15. Surface plots among the variables for CS

Fig. 16 shows the variations in flexural strength using surface plots. From Fig. 16, it can be seen that the lower the levels of RCA, the better the performance of concrete in flexure. The inclusion of alccofine and glass fibers enhanced the flexural behavior of concrete. However, the optimum performance in flexure is observed with the optimum dosage of glass fiber. The response surface regression equations 1 and 2 for the compressive and flexural strength are given.

The following equations are generated using Minitab, a statistical software. The steps involved in generating these equations are as follows. Open Minitab. Enter the input variables in the worksheet. Go to the menu bar, click on the Stat tab, then select DOE, followed by the response surface option. Then, select the analyze response surface design option. Select the continuous factors and the responses, and then click ok. Then, select the required parameters and click ok. The outputs are displayed in the worksheet, and the plots with regression data will be displayed in the output datasheet.

$$\text{Compressive strength} = 40.275 - 0.1212\,RCA + 15.25\,GF + 0.4571\,\text{Alccofine} + 0.000599\,RCA{*}RCA - 11.33\,GF{*}GF - 0.0578\,RCA{*}GF - 0.00249\,RCA{*}\text{Alccofine} \quad (1)$$

$$\text{Flexural strength} = 4.1996 + 0.03461\,\text{Alccofine} - 0.01486\,RCA + 2.510\,GF + 0.000040\,RCA{*}RCA - 1.931\,GF{*}GF - 0.000213\,\text{Alccofine}{*}RCA - 0.00819\,RCA{*}GF \quad (2)$$

For the CS, the R^2, MSE, and RMSE were 95.10%, 0.358692, and 0.598909, respectively. For the FS, the R^2, MSE, and RMSE were found to be 98.25%, 0.002466, and 0.04966, respectively.

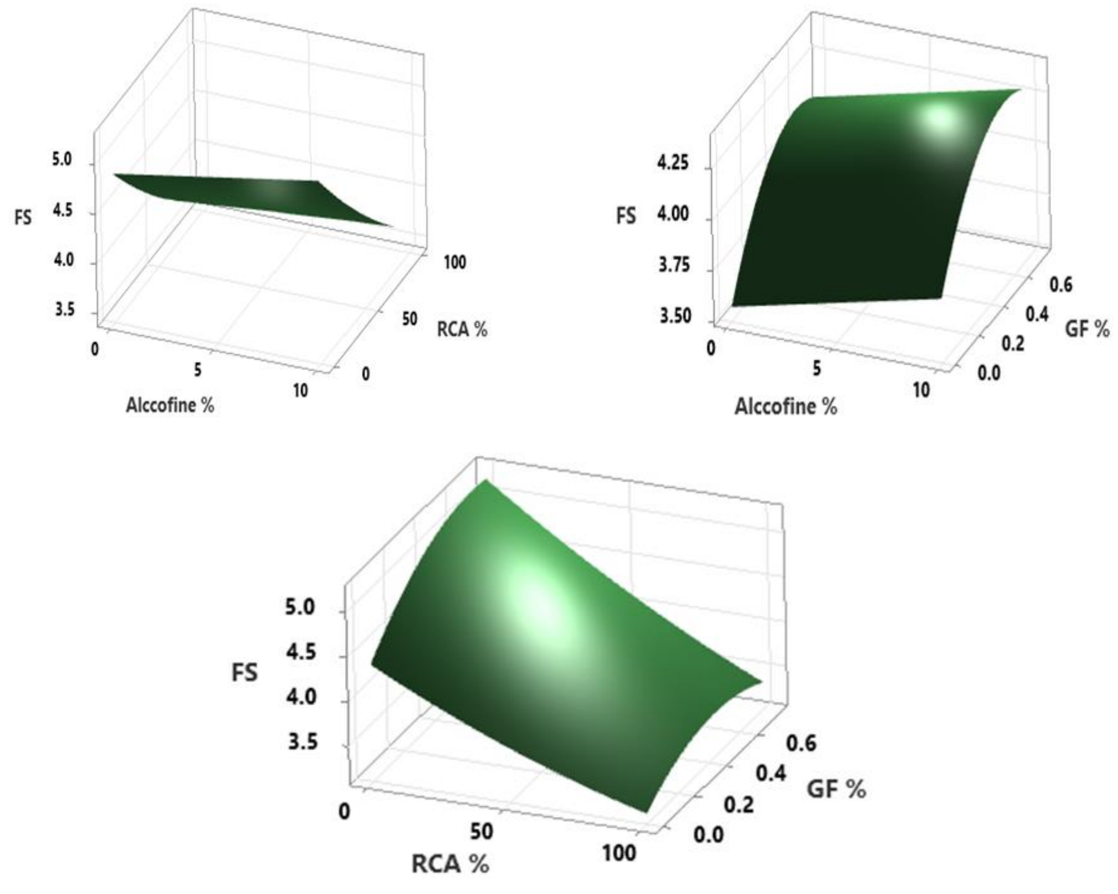


Fig. 16. Surface plots among the variables for FS

6.2 Inference from Contour Plots of CS and FS

Contour plots visually represent the relationship between multiple variables and their impact on a response, which can be a strength or durability parameter. Fig. 17 shows the contour plots for compressive strength. In Fig. 17, from the GF% vs RCA% plot, compressive strength decreases as RCA% increases at higher GF levels. In the Alccofine% vs RCA% plot, strength improves with higher Alccofine% for all RCA levels. Areas with higher CS (e.g., green regions) indicate the combinations of variables that yield better compressive strength. These regions are critical for optimizing the mix design.

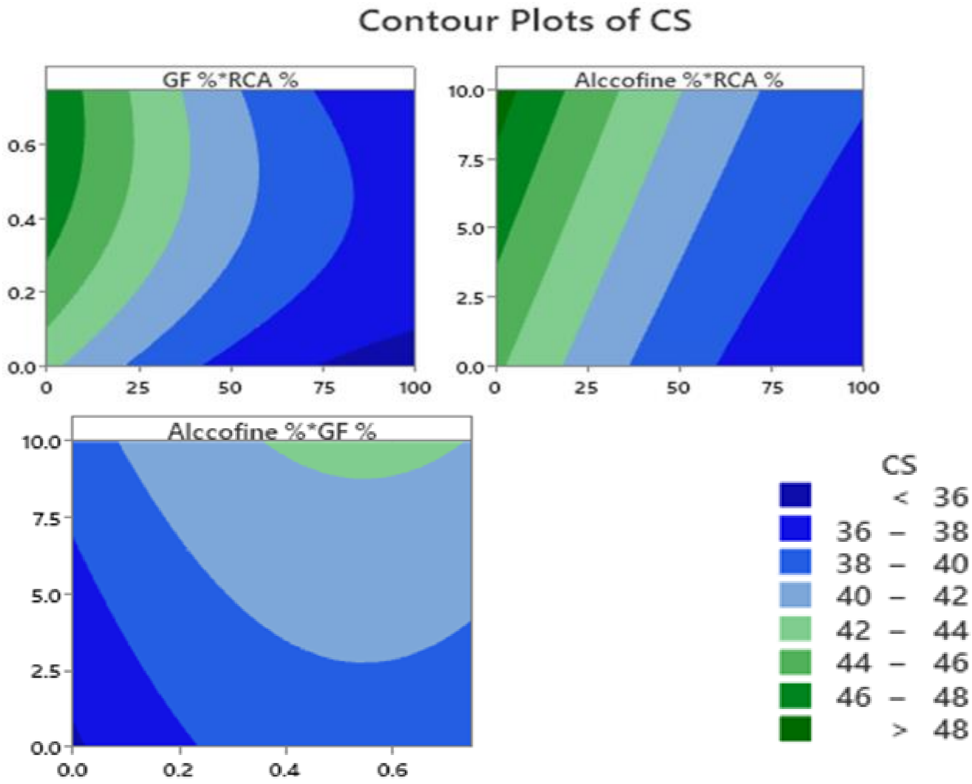
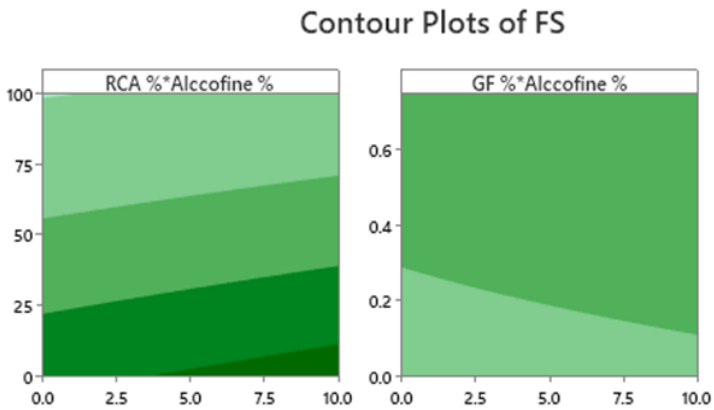


Fig. 17. Contour plots among the variables for CS

Fig. 18 shows the contour plot for the flexural strength. In the RCA (%) vs Alccofine(%) plot, flexural strength increases with higher Alccofine (%), as indicated by the darker green regions. Higher levels of RCA% slightly reduce FS, but this reduction is mitigated at high Alccofine percentages. In the GF (%) vs Alccofine (%) plot, FS improves significantly with increasing Alccofine%, regardless of GF levels. In the GF% vs NCA% plot, FS decreases with increasing RCA% for all GF levels, as indicated by the lighter regions toward the right. Higher GF% helps counterbalance the adverse effects of RCA%, as FS improves slightly in darker green zones at high GF levels. A combination of high GF% and low RCA% yields the highest FS, showing that GF can enhance the interfacial properties in RCA mixes. The surface and contour plots illustrate the relationships between key variables, offering valuable insights for optimizing concrete mix proportions. These visualizations enable designers to determine the ideal balance of materials required to achieve targeted performance characteristics, such as enhanced durability, strength, and water resistance.



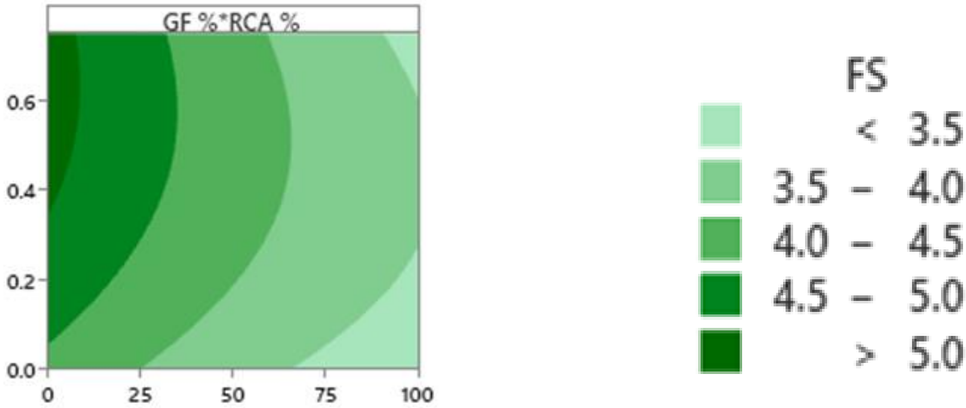


Fig. 18. Contour plots among the variables for FS

7. Microstructural Observations

Microstructural observations for the present study are carried out using scanning electron microscopy (SEM). SEM analysis is performed on the A0, A1, B1, and C1 mixes to understand the concrete matrix's micromorphology. These high-resolution images reveal each specimen's microstructure and surface morphology at a microscopic level.

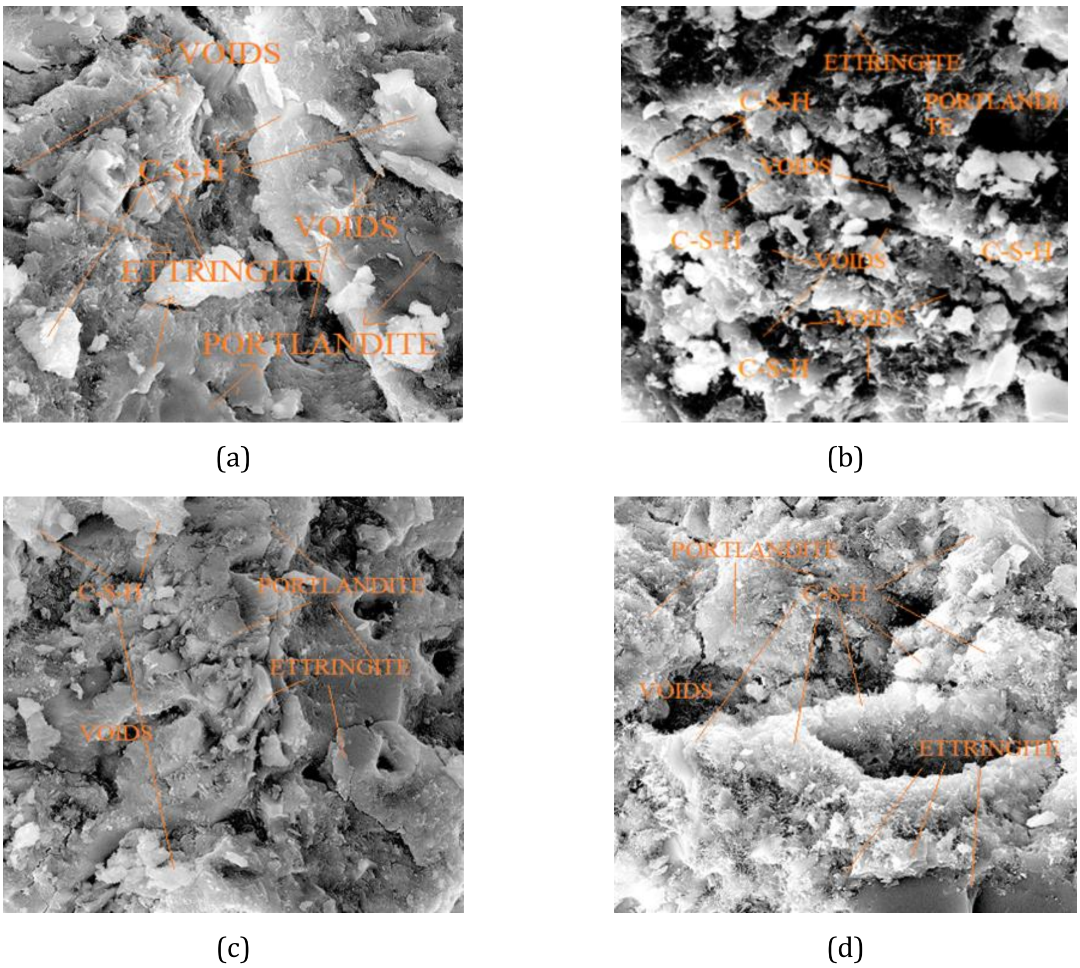


Fig. 19. SEM images a) A0 mix, b) A1 mix, C) B1 mix , d) C1 mix

The SEM image of mix A0, representing conventional concrete, reveals a flaky and fragmented structure, as shown in Fig. 19(a). In mix A1, voids resulting from including RCA are evident, as depicted in Fig. 19(b). For mix B1, additional C-S-H gel formations are observed, filling the voids and contributing to strength enhancement, as shown in Fig. 19(c). In mix C1, the ultra-fine particles of Alccofine effectively fill the voids, leading to dense C-S-H gel formations and a compact microstructure, as seen in Fig. 19(d). This dense microstructure in mix C1 significantly improves strength compared to the other mixes.

8. Conclusions

- The test results of the coarse aggregate indicate that RCA shows inferior performance compared with NCA. This is due to the existence of old mortar on the surface of the aggregates.
- Compared to OPC, mixes with PPC test outcomes exhibit better performance. Adding RCA lowers the compressive strength performance by 16.34% and 18.13% in series one and two, respectively. The partial substitution of Alccofine in RAC leads to remarkable enhancements in its properties. Consequently, incorporating Alccofine yields a maximum compressive strength augmentation of 9.62%. Incorporating glass fibers in RAC improves its behavior, with optimal benefits achieved at a fiber dosage of 0.50%. The compressive strength results achieve the target strength with an even 80% RCA level. As the desired target strength is achieved with 80% of RCA in the mix E2, it can be used for structural applications.
- The flexural strength test results show that fiber-reinforced ternary blends exhibit optimal behavior. Glass fiber inclusions result in higher strength gain in flexural behavior than concrete compression behavior. Mix E1 and E2 test results surpass rural road applications' minimum flexural strength requirements. Improved RAC can be used for low-volume rural road applications, reducing reliance on natural aggregates.
- The modulus of elasticity of concrete decreases with increased RCA replacement. The MOE lowers by 19.16% and 20.04%, respectively, for series one and two with 100% RCA. Glass fibers contribute to a higher strength gain in MOE.
- PPC exhibits minor improvements in all the mechanical properties of concrete. However, replacing PPC will help reduce construction costs and carbon footprint. At the same time, Alccofine and glass fibers exhibited a considerable strength gain. The performance of RAC improves as it transitions from unary to fiber-reinforced ternary blends.
- The test results of RCPT indicate that the charge passed in coulombs is directly proportional to the amount of RCA at all ages of curing. Binary and ternary blends exhibit superior performance in restricting the passage of chloride ions. The chloride ion permeability improves from moderate to low at all curing ages. Concrete with low RCPT values can be used in constructing pavements near coastal areas and in constructing basements to enhance the structure's lifespan.
- Similar to the RCPT results, the sorptivity outcomes also exhibit a proportional relationship with the amount of RCA. The test results reveal that the sorptivity performance of concrete improves from poor to acceptable levels. Since the sorptivity values fall within the acceptable range, the material is suitable for use in structures subjected to moderate environmental stresses, ensuring durability and reducing maintenance costs.
- Drying shrinkage outcomes indicate that the shrinkage strain with 100% RCA is 3.69 and 3.83 times higher than the conventional mix results. The drying shrinkage performance was improved by adding alccofine and glass fibers.
- Fiber-reinforced ternary blends offer notable economic and scalability benefits in construction by improving material efficiency and performance. Combining supplementary cementitious materials like Alccofine with Portland cement and reinforcing fibers reduces reliance on expensive, carbon-intensive cement, cutting costs and lowering CO_2 emissions. These blends enhance strength, durability, and crack resistance, extending structural lifespan and reducing maintenance expenses.

9. Future Work

Future studies could focus on evaluating freeze-thaw cycles, assessing carbonation depth, analyzing structural behavior, and conducting fatigue tests to provide a more comprehensive understanding.

Abbreviations

RCA – Recycled Concrete Aggregate/Recycled Coarse Aggregate
RAC – Recycled Aggregate Concrete
CS – Compressive Strength
FS – Flexural Strength
MOE – Modulus of Elasticity
GF – Glass Fiber
C&D waste – Construction and demolition waste
SCM - Supplementary Cementitious Material
OPC – Ordinary Portland Cement
PPC – Portland Pozzolana Cement
RCPT – Rapid Chloride Penetration Test
C-S-H – Calcium – Silicate – Hydrate
ITZ – Interfacial Transition Zone
WA – Water Absorption
SP – Super-Plasticizer

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