The Performance of Concrete with Various Recycled Aggregates and Blended Admixtures in Different Replacement Ratios

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ABSTRACT

The rising demand for sustainable construction materials has spurred extensive research into using Recycled Aggregates (RA) and mineral admixtures as partial replacements for Natural Coarse Aggregates (NCA) and cement, respectively. This study tackles the critical challenge of balancing environmental benefits with mechanical performance in concrete production. Specifically, it examines the combined effect of partially replacing NCA with RA (ranging from 10% to 30%) and substituting cement with a blend of mineral admixtures, Fly Ash (FA), Silica Fume (SF), Ground Granulated Blast Furnace Slag (GGBS), and Metakaolin (MK), in M20 grade concrete with a fixed water-cement ratio of 0.36. The methodology includes preparing multiple concrete mixes according to the IS standards, varying the proportions of RA and mineral admixtures, and conducting comprehensive compressive strength tests at various curing ages (7, 14, 28, 45, 60, and 90 days). The results show that increasing the RA content generally lowers the compressive strength due to its higher porosity and weaker Interfacial Transition Zone (ITZ), but the addition of mineral admixtures improves the microstructure, reducing the strength loss and enhancing durability. Mixes with up to 30% RA and 30% Supplementary Cementitious Materials (SCMs) still meet acceptable M20 grade concrete strength for many applications. This research offers valuable insights into the mix design strategies that support resource conservation and environmental protection in the Indian construction industry. The findings also align with existing literature, confirming the potential of RA and mineral admixture blends as eco-friendly alternatives in concrete.

Keywords-Recycled aggregate; mineral admixtures; fly ash; silica fume; GGBS; metakaolin; compressive strength; sustainable concrete; M20 grade

I. INTRODUCTION

The growth in global concrete demand has led to excessive use of natural resources, such as NCA and Ordinary Portland Cement (OPC), raising serious environmental concerns. The extraction of natural aggregates depletes the limited reserves and disrupts ecosystems, while cement production accounts for about 8% of global CO_2 emissions [1, 2]. At the same time, the increasing volume of Construction and Demolition (C&D) waste has created significant disposal and pollution challenges [3, 4]. To mitigate these issues, researchers are focusing on sustainable alternatives specifically, replacing NCA with RA and substituting OPC with SCMs, such as FA, SF, GGBS, and MK [5–7]. This study investigates the combined effects of partially replacing NCA with RA (10%–30%) and OPC with blended SCMs (10%–30%) in M20-grade concrete, maintaining a constant water–cement ratio of 0.36 and using locally available Indian materials for practical relevance. The compressive strength was tested at different curing ages (7–90 days) according to [26]. While most previous studies examined RA or SCMs separately, few have explored their combined influence, especially using multiple SCMs within the framework of Indian standards [8–11]. By systematically varying RA and SCM contents and analyzing both early-age and long-term strength, the present study addresses this gap, accounting for the slower pozzolanic reaction of certain SCMs and the physical effects of RA on concrete performance [1, 13].

It has been indicated that incorporating RA typically reduces the compressive strength of concrete due to the presence of porous, weakly bonded residual mortar and a compromised ITZ [5]. Authors in [12, 14] found that RA exhibits higher water absorption (up to 8%) and lower density, leading to a 10%–25% strength reduction when 20%–30% of Natural Aggregate (NA) is replaced. However, performance can be improved through treatments, such as removing adhered mortar or applying surface sealing [12]. Authors in [2, 4] reported that optimized mix designs using pre-treated RA can restrict the strength loss to less than 10%, particularly when combined with SCMs. Moisture conditioning of RA, such as ensuring a Saturated Surface-Dry (SSD) condition, also enhances hydration and minimizes strength reduction. Indian studies confirm these trends under local conditions, showing that concrete mixes incorporating RA in accordance with [26] maintain acceptable structural performance [10, 11]. The advantages of SCMs in concrete are well established. Authors in [15] demonstrated that FA and GGBS enhance durability and long-term strength through pozzolanic reactions, though they tend to reduce early strength due to slower hydration. Authors in [1] reported that replacing cement with up to 30% FA typically decreases 28-day strength by about 15%, but comparable or higher strengths are achieved at 90 days. SF and MK, owing to their high pozzolanic reactivity and fine particle size, accelerate hydration and can boost early strength by up to 20% at replacement levels of 5%–10% [5, 16]. These SCMs also refine the pore structure, improve the ITZ, and increase the resistance to chemical attack, collectively enhancing both the mechanical and durability properties of concrete [17].

The combined use of multiple SCMs has shown synergistic effects that surpass those of individual SCMs. Authors in [18] demonstrated that ternary blends of FA, GGBS, and SF in Recycled Aggregate Concrete (RAC) enhance both strength and durability by improving hydration and densifying the microstructure. Similarly, authors in [6] reported that blended SCMs reduce porosity and chloride penetration, mitigating the negative influence of RA on concrete performance. Authors in [19] found that the incorporation of SCMs can restore RAC compressive strength to levels comparable with conventional concrete, even at 30% RA replacement. Further, in [12], it was observed that blended SCMs significantly enhance mechanical and durability properties with extended curing periods. Long-term testing beyond 28 days is crucial to capture the latent pozzolanic activity of SCMs and the gradual improvement of RAC's microstructure. Authors in [20, 21] highlighted continuous strength gains up to 90 days, along with improved resistance to environmental degradation. Indian-specific studies [11, 22] also confirmed the practical viability of RAC with SCMs under local material and code conditions. In a related context, the performance of Geopolymer Concrete (GPC) depends heavily on the optimal combination of binders, such as FA and GGBS, along with alkaline activators like sodium hydroxide and sodium silicate. Although GPC lacks organic polymer additives, the careful selection and proportioning of these inorganic components produce a dense, durable matrix with high strength while substantially lowering environmental impact by eliminating Portland cement and utilizing industrial by-products [23–25]. Building upon this foundation, the present study investigates the combined influence of recycled coarse aggregate (10%–30%) and blended mineral admixtures (10%–30%) on the compressive strength of M20-grade concrete at various curing ages. The work adheres to the standards of [26] and aims to promote sustainable construction through the efficient use of recycled materials and improved durability.

II. EXPERIMENTAL METHODOLOGY

Figure 1 illustrates the particle size analysis of Cement, FA, SF, and MK. Figure 2 exhibits that XRD patterns of OPC cement, FA, and MK reveal the presence of key crystalline phases along with amorphous content. Major phases, such as alite and belite in OPC, quartz and mullite in FA, and amorphous alumino-silicates in MK, are clearly identified, confirming their characteristic mineral compositions as displayed in Table III.

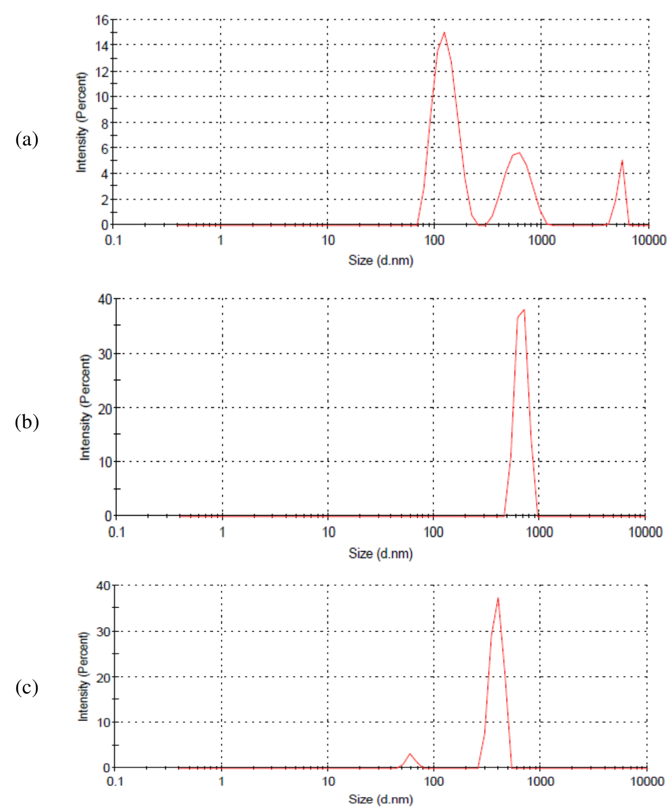

Fig. 1. Particle size analysis (a) OPC cement, (b) FA, (c) Metakolin.

TABLE I. PHYSICAL PROPERTIES OF NATURAL/RA

Physical properties	NA	RA
Flakiness index	15.38	9.69
Elongation index	10.86	11.67
Abrasion loss (%)	-98.2	-96.9
Avg. Crushing value (%)	3.06	2.43
Avg. Impact value (%)	12.27	7.645
Specific gravity	2.87	2.75

(a)

(b)

(c)

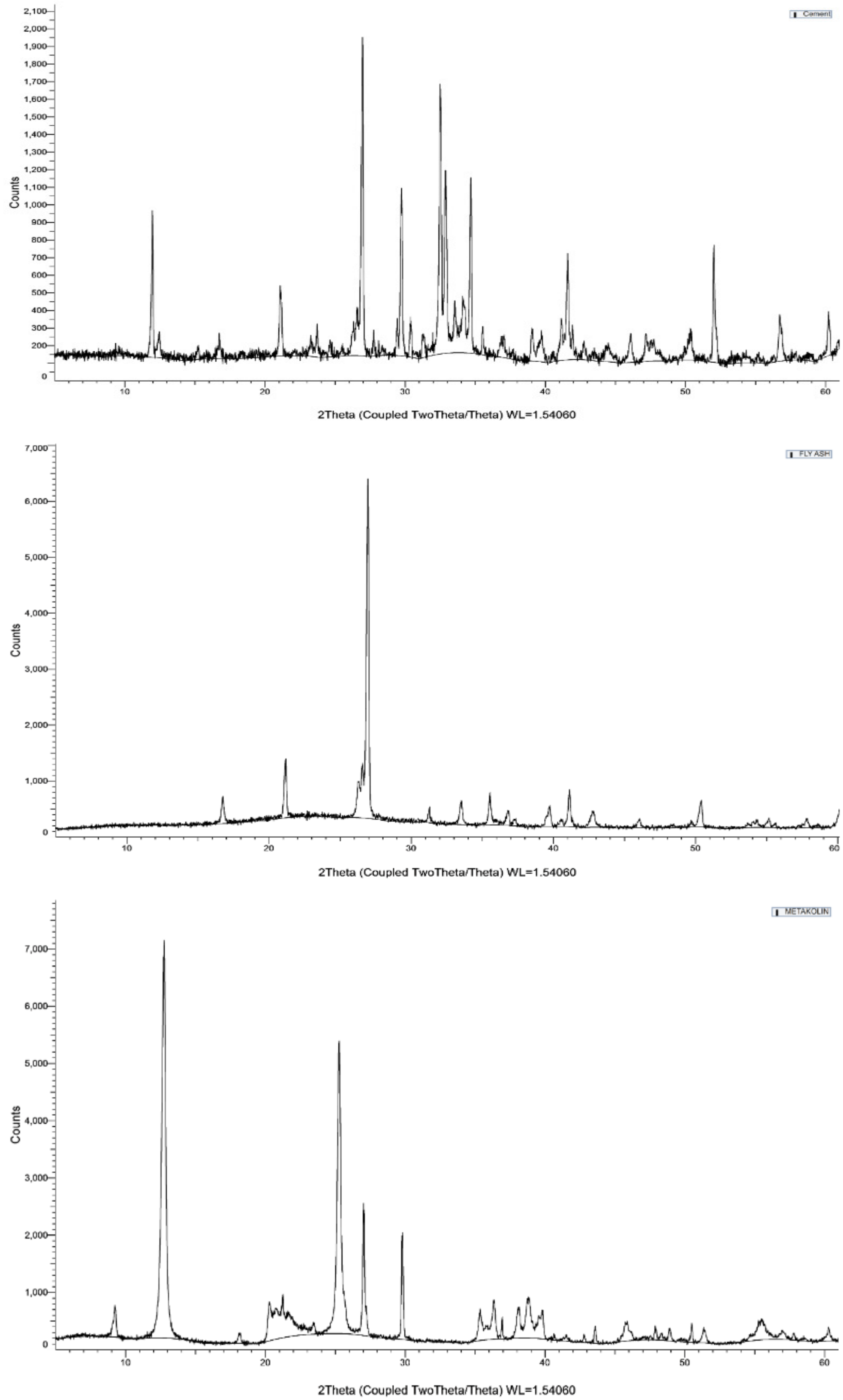

Fig. 2. XRD of (a) OPC, (b) FA, (c) MK.

TABLE II. CHEMICAL COMPOSITION OF MATERIALS (%)

Element	Cement	FA	SF	MK
SiO_2	96.5	59.38	90.20	30.97
CaO	0.4	1.94	0.75	36.77
Fe_2O_3	0.3	6.11	1.38	1.03
Al_2O_3	0.7	23.59	1.10	17.41
MgO	0.5	0.97	0.40	9.01
Na_2O	0.3		0.29	0.69
K_2O	0.85			0.46
SO_3	0.5	0.76		1.82

Cement has the highest SiO_2 content (96.5%), which is essential for strength through the Calcium Silicate Hydrate (C-S-H) formation, while SF's high SiO_2 (90.2%) enhances concrete density and strength. MK, rich in CaO (36.77%), boosts durability by forming extra C-S-H gel, and FA's high Fe_2O_3 (6.11%) and Al_2O_3 content improve pozzolanic activity, contributing to long-term concrete strength, as shown in Table II.

TABLE III. MAJOR CRYSTALLINE PHASES AND AMORPHOUS CONTENT IN OPC CEMENT, FA, AND MK

Material	Identified phases	Major peaks (2θ, approx.)	JCPDS reference
OPC	Alite (Ca_3SiO_5)	29.4°, 32.3°, 51.7°	49-0442
	Belite (Ca_2SiO_4)	31.1°, 34.3°	33-0302
	Gypsum ($CaSO_4 \cdot 2H_2O$)	11.6°	33-0311
	Calcite ($CaCO_3$)	29.5°	05-0586
FA	Quartz (SiO_2)	20.8°, 26.6°, 50.1°	46-1045
	Mullite ($3Al_2O_3 \cdot 2SiO_2$)	16.4°, 26.0°, 33.2°, 35.4°	15-0776
	Hematite (Fe_2O_3)	33.1°, 35.6°, 49.5°	33-0664
	Amorphous Phase	20°–35°	—
MK	Quartz (SiO_2)	20.8°, 26.6°, 50.1°	46-1045
	Kaolinite ($Al_2Si_2O_5(OH)_4$)	~12.3°, 24.9°	14-0164
	Amorphous Alumino-silicate	Broad hump at 15°–30°	—

The RA used in this study is Crushed Concrete Aggregate (CCA) cleaned before use to ensure the removal of obstructions, obtained from processed C&D waste. The key characteristics of the CCA include a higher water absorption rate, lower density, and the presence of adhered mortar, which contributes to increased porosity and reduced strength compared to natural aggregate. The physical properties of the aggregates are depicted in Table I. The parameters considered and the replacement materials and percentages are (see Table IV):

- RA replacing NCA: 10%, 20%, 30% by weight of total coarse aggregate.
- Cement replacement by a combination of mineral admixtures: 10%, 20%, 30% of the total binder: made up of FA + SF + GGBS + MK, as illustrated in Table IV.
- FA: GGBS: SF: MK = 4: 3: 2: 1 (for 30% total replacement: FA = 12%, GGBS = 9%, SF = 6%, MK = 3% (of the total binder).
- RA%: Percentage of RA in total CA.
- Binder = 1 (360 kg typical).
- Cement + FA + GGBS + SF + MK = 1.
- Water: The water–cement ratio was fixed at 0.36 (equivalent to 129.6 kg when the binder content is 360 kg). This relatively low ratio was intentionally selected to counteract the potential reduction in strength and increased porosity typically associated with RCA. Moreover, the inclusion of mineral admixtures, such as FA, SF, and GGBS, enhances both workability and long-term strength, enabling the use of a lower water–cement ratio without compromising performance. The chosen ratio of 0.36 also conforms with [23] for durable concrete, being suitable for moderate to severe exposure conditions and ensuring an optimal balance between mechanical performance and durability.
- Fine Aggregate: Set at 2.20 (≈792 kg if binder = 360 kg).
- NCA & RA: Coarse Aggregate split (total = 3.4 fractions = 1224 kg approx.). SP: Superplasticizer 1% of binder (e.g., 3.6 kg if binder = 360 kg).

TABLE IV. MIX PROPORTIONS OF VARIOUS COMBINATIONS

Case	RA %	PC %	FA %	GGB %	SF %	MK %	NCA	RA	Slump (mm)	Work-ability
A_1	10	0.9	0.04	0.03	0.02	0.01	3.06	0.34	75–85	M
A_2		0.8	0.08	0.06	0.04	0.02	3.06	0.34	65–75	M-L
A_3		0.7	0.12	0.09	0.06	0.03	3.06	0.34	55–65	L
B_1	20	0.9	0.04	0.03	0.02	0.01	2.72	0.68	65–75	M-L
B_2		0.8	0.08	0.06	0.04	0.02	2.72	0.68	50–60	L
B_3		0.7	0.12	0.09	0.06	0.03	2.72	0.68	40–50	VL
C_1	30	0.9	0.04	0.03	0.02	0.01	2.38	1.02	50–60	L
C_2		0.8	0.08	0.06	0.04	0.02	2.38	1.02	35–45	VL
C_3		0.7	0.12	0.09	0.06	0.03	2.38	1.02	25–35	SF

(M-medium, L- low, VL- very low, SF- stiff mix)

The methodology chart shown in Figure 3 illustrates the systematic process used to evaluate concrete mix designs. The procedure begins with material preparation, including careful selection and characterization of all constituents. This is followed by the preparation of mix designs and casting of concrete samples. Subsequently, compressive strength tests are conducted at various curing ages, and the resulting data are analyzed to evaluate the performance and durability of each mix.

III. RESULTS AND DISCUSSION

As shown in Figure 4, the compressive strength decreases with increasing RA content. This reduction occurs because RA often contains residual mortar and micro-cracks, which weaken the bond with new cement paste and compromise the ITZ, ultimately reducing the concrete's mechanical integrity. Similarly, mixes with higher proportions of SCMs, such as FA, GGBS, MK, and SF, exhibit lower early-age strength due to their slower hydration rates compared to OPC, as portrayed in Table V. However, the long-term strength (60–90 days) improves as ongoing pozzolanic and latent hydraulic reactions continue to refine the microstructure and enhance the material's performance. These values are based on literature data, experimental observations, and the standard code principles in [26].

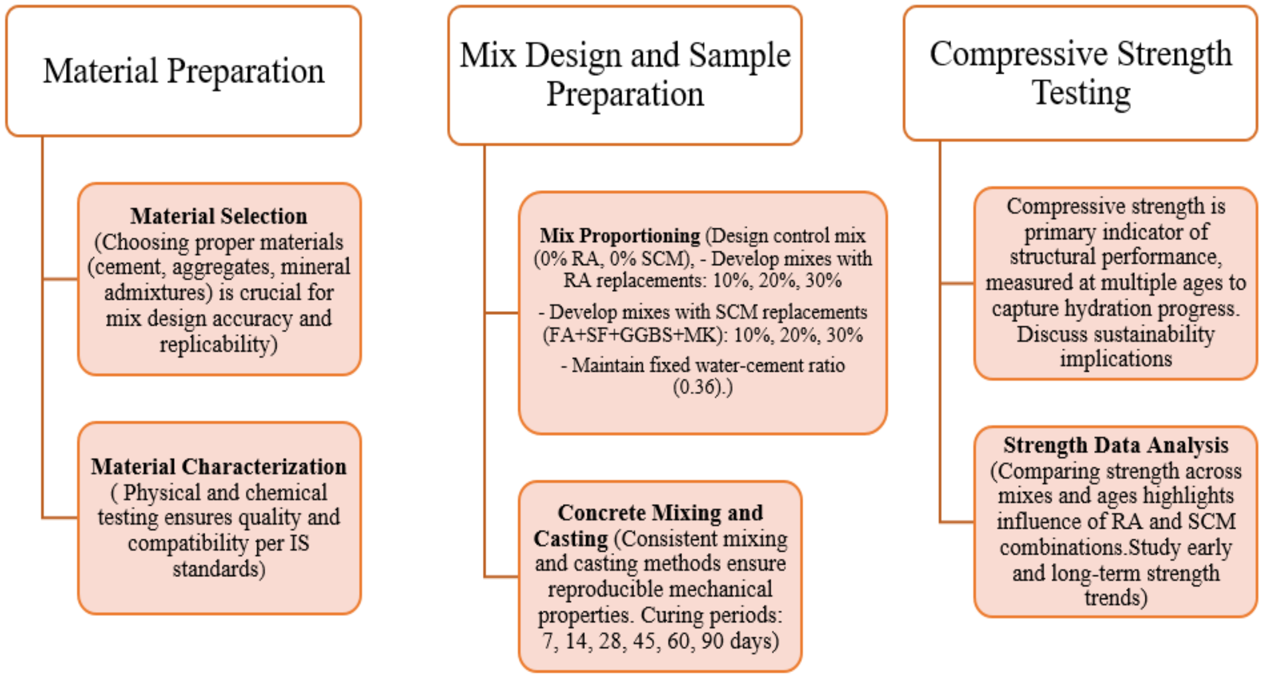

Fig. 3. Methodology setup for experimental work.

TABLE V. COMPRESSIVE STRENGTH OF VARIOUS COMBINATIONS (MPA)

Case	RA %	SCM%	7 days	14 days	28 days	45 days	60 days	90 days
A_1	10	10	15.5	19	23	24.5	25	25.5
A_2		20	14	17.5	21.5	23.5	24	24.5
A_3		30	12.5	16	20	22	22.5	23
B_1	20	10	14.5	18	22	23.5	24	24.5
B_2		20	13	16.5	20.5	22.5	23	23.5
B_3		30	11.5	15	19	21	21.5	22
C_1	30	10	14	17.5	21.5	23	23.5	24
C_2		20	12.5	16	20	22	22.5	23
C_3		30	11	14.5	18.5	20.5	21	21.5

A. *Effect of RA Replacement (10% to 30%)*

The incorporation of RA in concrete significantly influences its compressive strength, primarily due to the inherent characteristics of RA compared to NCA. RA typically contains residual mortar attached to the original aggregate particles, resulting in higher porosity and water absorption. This leads to a weaker ITZ between the RA and the new cement matrix, which is often the weakest link in concrete microstructure. Increasing the RA content in concrete leads to a moderate reduction in compressive strength across all curing ages compared to conventional concrete. The strength loss ranges from 5% to15% depending on the RA percentage, with 30% RA mixes showing the lowest values yet still meeting the requirements for M20 grade concrete. The quality and variability of RA, based on its source and processing, further influence mechanical performance.

B. *Effect of Mineral Admixture Replacement (10% to 30%)*

Increasing the replacement level of cement with FA, SF, GGBS, and MK leads to a noticeable reduction in early-age compressive strength (7–14 days) because these SCMs hydrate more slowly than OPC. At 28 days, the mixes containing 10% SCM replacement typically achieve strengths close to those of the control concrete (within about 5%), whereas 30% replacement levels may result in a 10%–20% strength reduction. Despite this early loss, the long-term strength (60–90 days) improves as pozzolanic and latent hydraulic reactions progress, partially offsetting the initial reductions. These mineral admixtures play a critical role in modifying concrete's strength characteristics. Through ongoing pozzolanic and hydraulic reactions, SCMs consume calcium hydroxide and generate additional C–S–H, refining the microstructure and enhancing density and strength. Among the SCMs, SF and MK are particularly effective in improving both early and later-age strength due to their high reactivity and ultrafine particle size. In contrast, FA and GGBS contribute more significantly to long-term strength and durability improvements. Beyond strength enhancement, SCMs improve workability, reduce permeability, and enhance the resistance to environmental degradation. When properly selected and proportioned, these mineral admixtures can optimize the mechanical performance and sustainability of concrete, meeting the requirements of modern construction practices and relevant Indian standards.

C. *Combined Effects (RA + SCM):*

The combination of RA and higher SCM content has an additive effect in reducing the early and 28-day strengths. For instance, the mixes with 30% RA and 30% SCM show up to ~20% reduction in 28-day strength compared to the control. Nonetheless, by 90 days, the gap narrows slightly as SCM hydration progresses. Concrete mixes with separate incorporation of RA and SCMs (A1, B1, C1) show higher durability than combined higher levels of both (A3, B3, C3), indicating that increased SCMs cannot fully offset the negative durability impact of a higher RA content. Durability consistently decreases as RA and SCM percentages increase together.

Fig. 4. Concrete cube testing under CTM.

D. Durability and Sustainability

India generates approximately 10–12 million tons of C&D waste annually, along with about 110 million tons of FA and 5 million tons of granulated slag that can be effectively utilized as SCMs. The use of these materials in blended concrete mixes achieves a balanced combination of performance and sustainability, making them suitable for non-structural and lightly loaded structural applications consistent with Indian construction practices. This approach can reduce CO_2 emissions by an estimated 20%–25%, primarily through decreased cement consumption and reduced aggregate quarrying. Additionally, recycling C&D waste into RA diverts material from landfills, mitigating environmental pollution and promoting sustainable resource management. The inclusion of SCMs further enhances durability by refining the pore structure and reducing the calcium hydroxide content, which lowers permeability and improves resistance to chemical attack. These long-term benefits are well-documented in prior studies and validated by the present findings.

E. Generalization of Results with Existing Literature

The reduction in compressive strength observed when replacing NCA with RA is primarily attributed to the presence of adhered mortar, which is more porous and less dense than natural aggregate, thereby increasing the overall porosity and weakening the ITZ. This leads to a decline in mechanical performance. Authors in [1] reported a 10%–20% reduction in compressive strength when RA replacement exceeded 30%, which aligns closely with the strength reduction trends observed in this study. Similarly, the findings of [2] emphasize that a proper mix design and the pre-treatment of RA are essential to minimize the strength loss and performance variability. The results of this study, which demonstrate reduced early-age strength but enhanced long-term strength due to the SCM incorporation, are consistent with established literature. Authors in [12] noted that FA and GGBS improve strength beyond 28 days because of the ongoing pozzolanic activity, despite slower early hydration. Conversely, SF and MK enhance both early and later-age strength because of their higher reactivity and finer particle size [4, 5]. The findings in [6] demonstrated that blended SCM systems can effectively optimize strength and durability while reducing cement consumption. Overall, the experimental outcomes of this study reinforce the established understanding of sustainable concrete behavior and its alignment with prior research.

IV. CONCLUSIONS

An increase in RA content from 10% to 30% generally results in a 5%–20% reduction in compressive strength compared to conventional concrete, primarily due to higher porosity and a weaker ITZ. However, this strength loss can be mitigated through optimized mix design and appropriate RA treatment. Similarly, partial cement replacement (10%–30%) with mineral admixtures, such as FA, SF, GGBS, and MK, tends to reduce early-age strength but enhances long-term performance through continued pozzolanic and hydraulic reactions. Among these, SF and MK are particularly effective in improving early strength due to their high reactivity, while FA and GGBS primarily contribute to long-term strength and durability. When RA and mineral admixtures are used together, their combined effect leads to an additive reduction in early (7–28 days) strength. However, notable strength recovery occurs between 45 and 90 days as secondary hydration progresses. Concrete mixes incorporating up to 30% RA and 30% SCMs still meet the requirements for M20-grade concrete, making them suitable for non-structural and lightly loaded structural applications. These results align with [26] and international research, supporting the practical feasibility of sustainable concrete production. The observed reductions in early compressive strength are effectively balanced by the gains in durability and environmental performance. By lowering the cement consumption and aggregate extraction, such eco-friendly concrete mixtures contribute to significant reductions in CO_2 emissions and natural resource depletion. The findings demonstrate that RAC, with blended mineral admixtures, offers a viable, sustainable alternative for the construction industry. This approach not only promotes resource efficiency and waste reduction but also upholds the mechanical and durability standards, necessary for safe application. The current study's novelty lies in its evaluation of multiple replacement levels for both aggregates and binders, an area less explored for lower-strength concretes, thereby providing practical insights for developing environmentally responsible concrete mix designs compliant with the Indian and global standards.

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