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ORIGINAL ARTICLE

Effect of silica fume on strength of recycled aggregate concrete

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Abstract

The present study deals with investigating the effects of using coarse recycled concrete aggregates (RCA) on compression & split-tensile resilience of M25 grade concrete mixes. Five different mixes of modified recycle aggregate concrete (RAC) were designed and prepared considering replacement proportion of normal coarse aggregates as 0, 25, 50, 75, and 100 % with RCA. The specimens were prepared according to Indian standard codal provisions and experimentally tested for its mechanical characteristics in laboratory conditions. A steep degradation in compressive and tensile strength on increasing RCA proportion was observed, which may result due to improper bonding at interfacial region in RAC mixes. To overcome this strength deterioration, the effect of adding pozzolanic materials like silica fumes is also studied for making strength improvements. The silica fumes as admixture, in percentages of 4%, 8% and 12%, was added in RAC mixes for finding the optimum proportions. Overall, the study provides a sustainable solution for problematic concrete waste dumping while utilizing it in casting new concrete structures of significant strengths.

1. Introduction

In the quest for sustainable construction practices, the concrete industry has seen significant innovations, particularly with the incorporation of recycled materials. Recycled aggregate concrete, which utilizes waste concrete as an aggregate, is one such example. However, despite its environmental benefits, RAC often faces scepticism due to concerns over its mechanical properties compared to conventional concrete. One promising approach to enhance these properties is through the use of supplementary cementitious materials, such as silica fumes. Silica fumes, a byproduct of silicon and ferrosilicon alloy production, have been identified as a viable additive that can improve the durability and strength of concrete mixtures. The synergistic effect of silica fumes within recycled aggregate concrete is not only a study of material performance but also of sustainable resource management. Given the pressing need for greener construction methodologies and the vast quantities of construction waste generated annually, the refinement of RAC through additives like silica fumes could have significant implications for the construction industry.

Several studies have investigated the impacts of silica fumes on the compression resilience of RACs. Wang et al. (2017) [1] conducted experimental investigations and observed that incorporating silica fume in RAC resulted in a notable enhancement in compressive strength compared to plain RAC. Similarly, Liu et al. (2019) [2] revealed that the inclusions of silica fumes led to a substantial advancement in compressive strength, attributed to the densification of the microstructure and improved interfacial-transition-zone (ITZ) between the cement matrix and recycled aggregates. In addition to compressive strength, the flexural and split tensile resilience of RACs can be significantly uplifted by incorporating silica fumes. Wang and Li (2018) [3] discussed that the inclusion of

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silica fume enhanced the flexural strength of RAC due to the refinement of the pore structure and increased bonding between the cementitious matrix and recycled aggregates. Moreover, Zhang et al. (2020) [4] conducted experiments and concluded that silica fume contributed to the enhancement of split tensile strength by promoting a denser microstructure and reducing the porosity of RAC specimens. Durability is a crucial aspect of concrete performance, particularly in harsh environmental conditions. Silica fume has been proven to enhancing the durability properties of RACs. Cheng et al. (2019) [5] analysed the impacts of silica fume on the chloride ion permeabilities of RAC and found that the incorporation of silica fume effectively reduced the chloride ion penetration depth, indicating improved resistance to chloride ingress. Furthermore, Li et al. (2021) [6] studied the sulfate resistance of RAC containing silica fume and observed superior sulfate resistance compared to plain RAC due to the formation of more impermeable products that mitigate sulfate attack. Microstructural analysis provides insights into the mechanisms underlying the enhancement of mechanical properties in silica fume-modified recycled aggregate concrete. Liang et al. (2018) [7] utilized scanning electron microscopy (SEM) to investigate the microstructure of RAC specimens and revealed a denser and more uniform microstructure with reduced voids and cracks in existence of silica fume. Additionally, X-ray diffraction (XRD) analysis conducted by Deng et al. (2020) [8] confirmed the development of additional calcium-silicate-hydrate (C-S-H) gel in RAC containing silica fume, contributing to improved mechanical performance and durability. The dosage of silica fume plays a crucial role in determining its effectiveness in improving the mechanical characteristics of RACs. Zhu et al. (2019) [9] conducted a comprehensive study investigating the impacts of different silica fume dosages on the mechanical performance of RAC and found that an optimum dosage range exists for achieving the highest compressive strength and durability. However, excessive silica fume content may lead to undesirable effects such as increased viscosity and difficulties in workability, as highlighted by Li et al. (2020) [10]. The curing regime significantly influences the development of mechanical properties in silica fume-modified RACs. Hu et al. (2018) [11] compared the effects of different curing conditions on the compressive strength of RAC and found that moist curing resulted in higher strength gains compared to air curing. Moreover, extended curing durations were found to be beneficial in promoting the pozzolanic reaction and improving the overall performance of RAC specimens, as demonstrated by Zhao et al. (2020) [12].

This paper takes a holistic approach, reviewing current literature and producing original data to extend the understanding of RAC's potential in a circular economy. Our findings aim to support industry professionals & other stake-holders in deciding with knowledge concerning the utilization of recycled materials in construction and the advancement of sustainable building practices. To investigate the mechanical and structural properties of concrete, four series of concrete mixes were formulated with varying substitutions of Natural Coarse Aggregate (NCA) by Recycled Coarse Aggregate (RCA) at rates of 0%, 25%, 50%, 75%, and 100%. The study aimed to assess the impact of these NCA replacements on the compressive and splitting tensile strengths of concrete. The compression and splitting-tensile resilience's of M25 grade concrete were evaluated at 7-days & 28-days after casting to determine the effects of NCA replacements. Comparisons of RCA concrete mixes with varying RCA content and silica fume were made with a control concrete mix, represented by the reference sample R0, to identify the optimal level of NCA replacement.

2. Materials and methods

2.1 Materials used

The section explores a brief discussion of utilized materials and their physical & chemical properties. Fig. 1 shows the materials used for preparing recycled aggregate concrete mixes. The Ordinary Portland-Cement of Grade-43 conforming to IS:8112-1989 was used as a binding material. Fine sand conforms to the specifications outlined in IS 383-1970 was utilized for preparing test specimens. The sand is selected based on its ability to pass through a 4.75 mm screen and be retained on a 150 mm sieve. On the other side, crushed granite or quartzite rock, classified as natural coarse aggregate with a particle size of 10mm and 20 mm has been employed. This particular natural aggregate has demonstrated its capability to yield high-quality natural aggregate concrete, meeting the stipulated criteria outlined in IS 2386–1963, with regards to particle size distribution.

Recycled coarse aggregates were sourced from a singular origin, originating specifically from tested and discarded laboratory samples encompassing cubes, beams, and cylindrical specimens. These materials were no longer in use within the concrete laboratory, designated as construction and demolition waste. The recycled material had an age of 3 years at the time of its utilization. The physical & mechanical characteristics of recycled-aggregates were assessed and juxtaposed with those of natural aggregate in accordance with the specified standards outlined in IS 2386-1963. The physical and mechanical properties of the cement, fine aggregate and coarse aggregate are detailed in Tables 1, 2 and 3. The silica fumes, also known as microsilica, is a by-product of the production of silicon-metal or ferrosilicon alloys. It is a finely divided powder composed of amorphous silica particles, which are extremely small, with an average particle diameter of less than 1 micron. Silica fume is a highly reactive pozzolan and is used as a supplementary cementitious material in the production of high-performance concrete. The physical & chemical attributes of silica's worked in preparing the mix specimens are depicted in Table 4. Conforming to the guidelines of IS: 456-2000, potable-water is commonly deemed adequate for the mixing & curing of concrete.

Figure 1: Materials used

Table 1: Properties of Cement

S. No.	Properties	Observed value	Requirement as per IS:8112-1989
1	Setting Time (minutes) (a) Initial (b) Final	 28.5 552	 30 600
2	Compressive strength of 1:3 cement sand & mortar(N/mm^2) (a) 3d (b) 7d	 19.8 27.6	 22.50 32.40
3	Tensile-strength of 1:3 cement sand mortars(N/mm^2) (a) 3d (b) 7d	1.78 2.17	– 2.50
4	Percentage of water requirement for normal consistencies	26.9	–

Table 2: Properties of fine aggregate

S. No	Property	Observed Value
1	Class	Locally-available coarse-sand
2	Fineness-moduli	2.62
3	Specific-gravity	2.64

Table 3: Physical and mechanical properties of coarse aggregates

S. N	Description	Coarse aggregate		
		Natural aggregate	Recycled aggregate	Permissible range as per IS:2386 (1997)
1	Specific Gravity	2.70	2.62	2.5 to 3.0
2	Fineness moduli	7.21	6.95	6.00 to 8.00
3	Water Absorptions (%)	0.61	2.0	0.1 to 2.0
4	Crushing Values (%)	17.66	32.55	45.0
7	Density(g/cc)	2.52	2.44	2.0

Table 4: Silica fume

Composition (%)	90.2%	Amorphous SiO_2
	9.8%	Na_2O, K_2O, Cao, MgO, Fe_2O_3, Al_2O_3
Physical & Chemical Attributes	Colour	Bright Grey
	Density	2210kg/m^3
	Melting Point	1545ºC-1565ºC
	Appearance	Power

Table 5: Concrete mix proportions

Mix	W/C	Cement	Silica fume	FA	NCA	RCA	Slump	Mix Proportion
		(kg/m^3)					mm	
R0					1170.8	0	95	
R25					886.35	295.45	88	
R50		380	0		590.9	590.9	82	
R75					295.45	886.35	72	1:1.69: 2.90
R100	0.5			645	0	1170.8	65	
R25SF4		364.8	15.2		886.35	295.45	64	
R25SF8		349.6	30.4		886.35	295.45	62	
R25SF12		334.4	45.6		886.35	295.45	60	

2.2 Preparation of specimens

The cube specimens of dimensions 150x150x150mm^3 to study the compressive strength, and cylindrical specimens of dimensions 100mm (dia.) x 200mm (length) for tensile strength testing were utilized. The design mix of concrete as per IS 10262-2009 and IS 456-2000 are carried out. Design mix of M25 concrete is given in Table 5. A total of 48 cube and 48 cylinders specimens were prepared using conventional methods. Dry materials were weighed and arranged for mixing using a trowel before the addition of a precisely calculated amount of water. Recycled aggregates were thoroughly blended into the concrete mix. The prepared concrete was introduced into the mould in three-successive levels, with the mould having been previously greased with oil before casting. Notably, care was taken to position and compact the concrete adequately. Subsequently, the specimens were immersed in water for the curing process. For each concrete grade, three specimens were meticulously prepared. After a duration of 24 hours, all specimens were carefully removed from the moulds. Suitable water was employed for the curing of cube and cylinder specimens before underweening into a 28-day curing process.

2.3 Experimental Testing

In the ongoing experimental program, cubes with dimensions of 150×150×150mm^3 were subjected to uniaxial compression testing at both 7 and 28 days as per code IS 516-1959. The primary focus of the study was to evaluate the compressive strength of M25 grade concrete, incorporating various percentages of recycled aggregate coarse concrete ranging from 0% to 100% by weight of normal coarse aggregates (NCA) and the silica fume replacing the cement by 4%, 8% and 12% in 25% RAC sample. The compressive strength values for 24 cube samples labelled as R0, R25, R50, R75, and R100 (without silica fume) as well as R25SF4, R25SF8 and R25SF12 (with silica fumes) were determined at 7 and 28 days. In parallel for tensile testing, a compressive line load is uniformly applied along the entire length of a horizontal concrete cylinder positioned between compressive platens. For this particular test, 24 cylindrical specimens with dimensions of 100 mm in diameter and 200 mm in length were tested as per IS 5816-1999 at both 7 and 28 days.

Figure 2: Specimens preparations and experimental testing.

The primary focus of the study was to evaluate the splitting tensile strength of M25 grade concrete, incorporating various percentages of recycled aggregate coarse concrete ranging from 0% to 100% by weight of normal coarse aggregates (NCA) and the silica fume replacing the cement by 4%, 8% and 12% in 25% RAC sample. The preparation of specimens and consequent testing under compression and tension carried out in laboratory-controlled conditions are illustrated in Fig. 2.

3. Results and discussions

Figure 3a and 3b show compressive strength of concrete mixes on increasing RCA content. For M25 grade concrete cubes, the uniaxial compression test conducted at 7 days revealed an average compressive strength of 24.4 MPa for the reference sample R0. Throughout various stages of concrete curing and across all levels of Natural Coarse Aggregate substitution, it is apparent that Recycled Aggregate Concrete consistently demonstrates reduced compressive strength in contrast to Natural Aggregate Concrete.

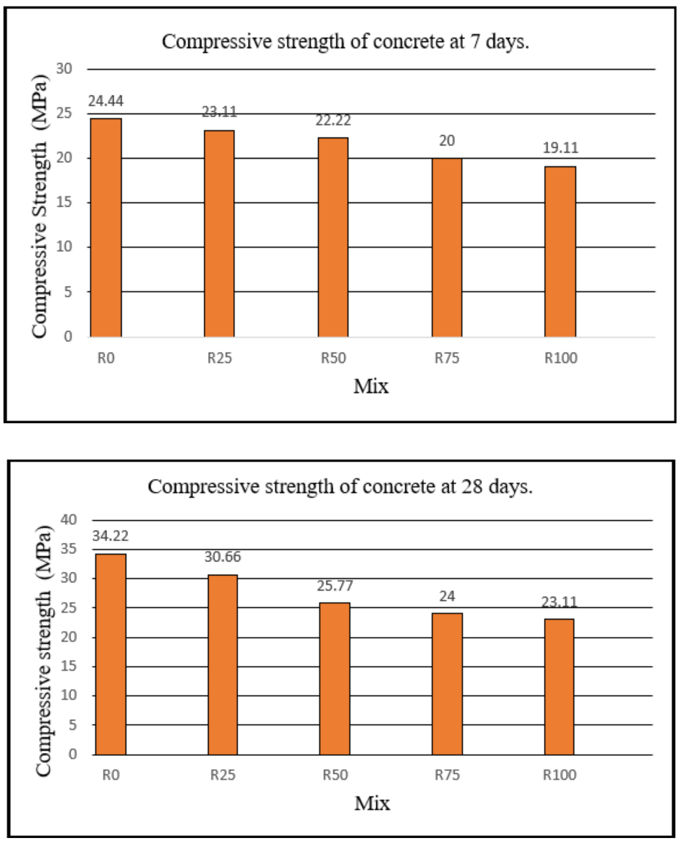


Figure 3: Compressive strengths for concrete's with increasing RA content after (a) 7d (b) 28d curing.

Upon incorporating 25% recycled aggregates into the mix, the mean compressive strength measured at 23.11 MPa. Subsequently, with 50% recycled aggregates introduced, the average compressive strength decreased to 22.22 MPa. Upon increasing the recycled aggregates to 75%, the average compressive strength further declined to 20 MPa. Finally, upon utilizing 100% recycled aggregate, the average compressive strength recorded was 19.11 MPa. The peak compressive strength of M25 cubes without recycled aggregates, designated as the reference value R0, stands at 24.44 MPa. Subsequent additions of 25, 50, 75, & 100% recycled-aggregates result in reductions in compressive strength by 5%, 9%, 18%, and 23%, respectively, relative to the reference value R0. Moreover, the peak compressive resilience of M25 cubes without recycled aggregates is 34.22 MPa, also denoted as R0. Incorporation of 25, 50, 75, & 100% as recycled aggregates lead to decreases in compressive resilience by 10.4, 24.69, 29.86, and 32.46%, respectively, compared to cubes without recycled aggregates.
The reduction in strength has been made balanced by adding pozzolanic materials like silica fumes. The peak compressive strength of R25 cubes without silica fume is 23.11 MPa, denoted as the reference value (R25), with no inclusion of silica fume. Subsequently, upon adding 4%, 8% and 12% silica fume, the corresponding 7-day compressive strength experiences rises of 1.24%, 4.50% and 6.05% respectively. Subsequently, upon adding 4%, 8% and 12% silica fume, the corresponding 28 day-compressive strength experiences rises of 1.6%, 6.62% and 12% respectively.

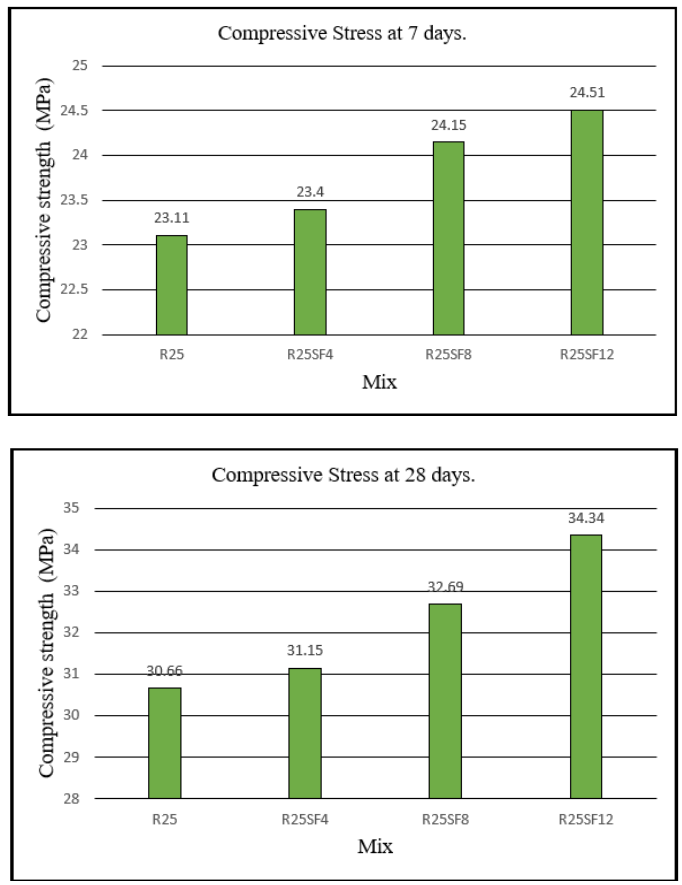


Figure 4: Compression strengths of concrete at 25% RA and varying silicas after (a) 7d (b) 28d curing.

In terms of splitting-tensile strengths, compared to the observed value of the referenced prototype R0, the concrete with 25% RCA displays a 14.05% strength reduction at 7d and a 13.12%s strength reduction at 28 days. The concrete with 50% RCA exhibits a 22.64% strength decrease at 7 days and a 15.75% strength decrease at 28 days. The concrete with 75% RCA shows a 34.15% strength reduction at 7 days and a 23.57% resilience reduction at 28 days, while the concrete with 100% RCA demonstrates a 48.66% resilience reduction at 7d & a 28.95% resilience reduction at 28d.

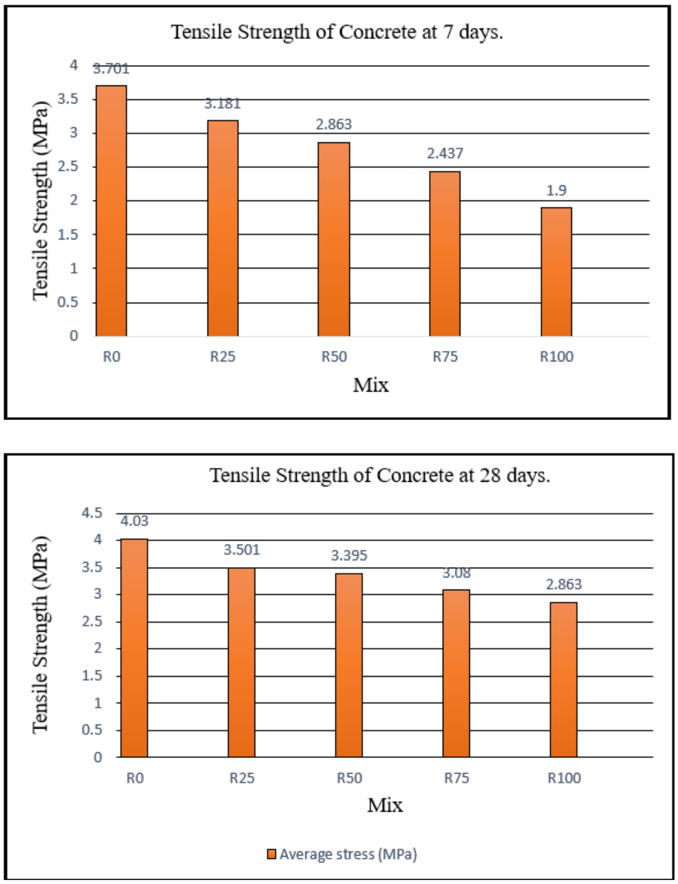
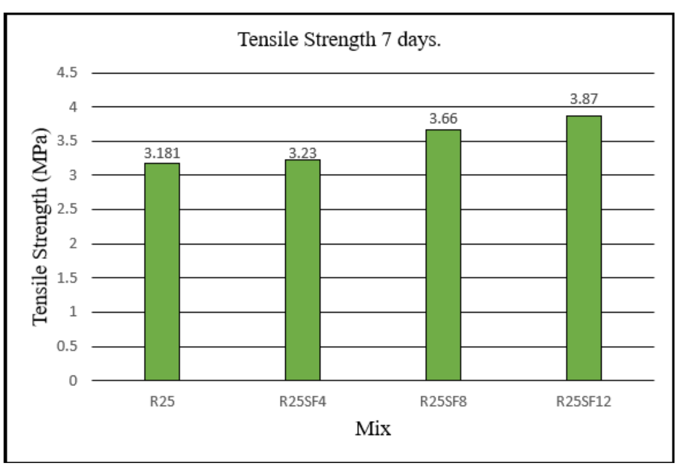


Figure 5: Split-tensile resilience of concretes with increasing recycled aggregate content after (a) 7d, and (b) 28d curing.



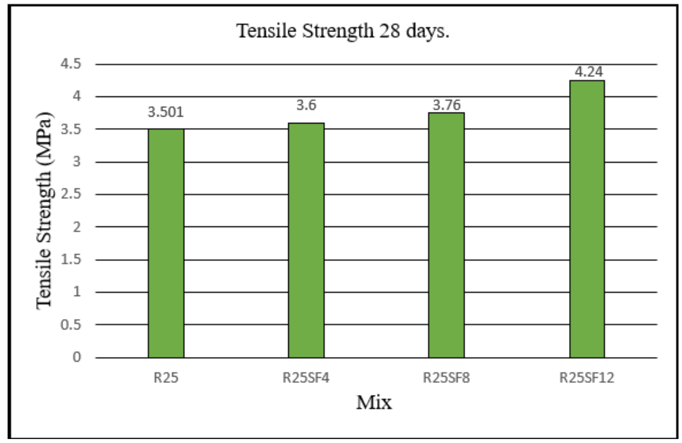


Figure 6: Split-tensile resilience of concretes at 25% recycled aggregate and varying silica fume content after (a) 7d, and (b) 28d curing.

In contrast to the observed splitting tensile resilience value of the reference specimen R25, the concretes with 25% RCAs & 4% silica fume exhibits a 1.54% strength increment at 7 days and a 2.82% strength increment at 28 days. The concrete with 25% RCA and 8% silica fume experiences a 15.05% strength increment at 7 days and a 7.4% strength increment at 28 days. Similarly, the concrete with 25% RCA and 12% shows an 21.66% strength increment at 7 days and a 21.10% strength increment at 28days.

4. Conclusions

The primary objective of the study was to formulate concrete incorporating different proportions of recycled coarse aggregate and silica fumes experimentally to assess its mechanical attributes at 7d and 28d of curing ages. The following conclusions are drawn:

- The substitutions of NCA with Recycled Coarse Aggregate (RCA) ranging from 0% to 100% results in a compressive strength reduction ranging from 5% to 20% at 7 days and 10% to 33% at 28 days.
- The substitution of silica fume at 4%, 8% and 12% with cement in 25% RCA results in a compressive strength increment ranging from 1.24% to 6.05% at 7 days and 1.6% to 12% at 28 days.
- Likewise, substituting natural coarser aggregates with recycled coarser aggregate in varying proportions from 0% to 100% results in a decline in splitting tensile strength, varying between 14% to 49% at 7d and 13% to 29% at 28d.
- The substitution of silica fume variation 4%, 8% and 12% with cement in 25% RCA results in a splitting tensile strength increment ranging from 1.54% to 21.66% at 7 days and 2.82% to 21.1% at 28 days.
- Future investigations could explore blending silica fume-fly ash-Ground Granulated Blast-Furnace Slag (GGBFS) in varying ratios to examine their characteristics, aiming to diminish the reliance on cement and natural aggregates.

The research scope could also be broadened to encompass variations in water-to-cement (w/c) ratios, the inclusion of mineral admixtures, plasticizers, and super plasticizers. Furthermore, the investigation could extend to incorporate the use of fibre reinforcement in these novel recycled aggregate concrete mixes to provide sustainability and durability to the modern construction.

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