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ORIGINAL PAPER

Mechanical performance enhancement of recycled aggregate concrete using GGBS and fly ash for sustainable construction

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Abstract
The pursuit of sustainable construction practices has led to a growing interest in the utilization of recycled materials in concrete production. To enhance the utilization of recycled aggregate concrete, its performance in terms of mechanical characteristics need to be optimized. This study investigates the effect of fly ash and ground granulated blast furnace slag (GGBS) as cementitious materials on the mechanical characteristics of recycled aggregate concrete. In this research, various combinations of recycled aggregate concrete were prepared with partial replacement cement by GGBS and fly ash. The mechanical characteristics including compressive strength, split tensile strength, and flexural strength tests are conducted on all concrete mixes and the results are compared to the control mix. The results of this study will help advance sustainable concrete technology and serve as a foundation for designing RAC for structural applications that incorporate recycled coarse aggregate, fly ash, and GGBS. The results confirm that the concrete mix with 40% recycled aggregate, 15% fly ash and 15% GGBS as cement replacements is optimum for enhancing the mechanical characteristics of concrete. The enhanced pozzolanic activity and filler effect of these fly ash and GGBS enhances the strength characteristics of recycled aggregate concrete. The findings contribute to sustainable construction practices by promoting the utilization of recycled materials and optimizing the properties of concrete mixtures.

Keywords GGBS · Fly ash · Compressive strength of concrete · Split tensile strength · Flexure strength · Partial replacement · Recycled aggregate concrete

1 Introduction

Every year an immense volume of aggregates is consumed in the construction of various structures using concrete. Aggregates (natural or crushed) come from the earth, and getting these quantities would have a damaging impact on the ecosystem (Singh et al. 2017). Destroying concrete buildings and discarding the debris would only exacerbate the problem (Dos Reis et al. 2021). As a result, it becomes important to recycle the crushed concrete and include it in fresh concrete mixtures as coarse aggregate (Collins et al. 1994).

The fundamental component of any nation's socioeconomic progress is construction. Any building project needs a variety of materials, including concrete, steel material, bricks, stones, glass, clay, mud, and wood, among others (Qureshi et al. 2020). The primary material used in the construction sector is still cement concrete, because of its tremendous compressive strength (Teja Prathipati et al. 2022). In addition, there is a significant shortage of natural resources as a result of the high demand for new buildings (Habert et al. 2010). In India, construction sectors are thought to produce between 10 and 12 million tonnes of garbage per year. RAC is becoming more popular around the world due to environmental benefits and cost savings (Kumar 2017).

Every year, India generates 29.75 million tonnages of construction—waste, and demolition waste, and these numbers are expected to quadruple over the next ten to 15 years and it is 30–40% of global demolition waste (Devi et al. 2020). In affluent nations, construction and demolition (C&D) wastes have been viewed as a resource (Almusawi et al. 2022). Recycling research has underlined the need for the final product to maintain the requisite compressive strength if utilized in

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second-generation concrete (Vijay et al. 2023a). The compressive strength is primarily influenced by adhering mortar, water absorption, aggregate size, original parental concrete strength, age of curing period and replacement percentage, interfacial transition zone, state of moisture content, impurities, and controlled environment conditions, according to a literature review (Nedeljković et al. 2021).

The following are the important reasons for increasing the volume of demolished concrete waste:

1. Many old buildings, concrete pavements in villages, bridge structures, and other structures have outlived their usefulness due to structural deterioration that is beyond repair and must be demolished.
2. Many concrete structures, even those that are fit for use, are being demolished because they no longer meet the needs of the current situation.
3. Many of the structures appear as debris resulting from disasters such as earthquakes and cyclones flooding.

When raw materials for regular cement are quarried, wildlife reserves are damaged. As a result, the major objective of responsible authorities is to either halt the widespread use of ordinary cement or move to a more ecologically friendly method of creating concrete in order to reduce the harm that extensive use of ordinary cement poses to the environment (Mohamad et al. 2021). The Romans found how to create lime by burning crushed limestone, and the Egyptians used crushed gypsum. They also discovered that adding volcanic ash or old bricks and tiles improved the setting characteristics of their cement. After Portland cement was discovered, modern concrete was created (Nagaraj et al. 2014). The rate of early-age strength development in fly ash concrete is relatively slower compared to conventional Portland cement concrete because fly ash, through pozzolanic activity, combines with free lime to form the same cementitious compounds as the hydration process of Portland cement (Teja Prathipati et al. 2022; Vijay et al. 2023b). These substances could be byproducts from less energy-intensive industries, naturally existing substances, or industrial wastes. When combined with calcium hydroxide, these substances, known as pozzolanas, show cementitious properties. Fly ash, silica fume, metakaolin, and powdered GGBS are the most frequently used pozzolanas (Qureshi et al. 2020). Numerous factors contribute to these demands, but as engineers, we must consider how durable the structures made of these elements will be. We have been able to meet the requirements while putting long-term durability concerns to one side. These qualities' concrete will exhibit an odd rheological behavior (Markiv et al. 2016). In order to produce concrete that is extremely dense, with greater compressive strengths and extremely low permeability, ultra-fine materials (GGBS and Fly Ash) will be used to fill the spaces between cement particles (Hawileh et al. 2017; Saha 2018). The concrete density can be increased by adding various mineral admixtures, including metakaolin, GGBS, fly ash, rice husk powder, palm oils, and silica fumes (Siddique 2014). Testing of the behavior of concrete with GGBS at various drying times revealed that while its strength initially is lower, it gradually increases over time (Hawileh et al. 2017). Since nano-silica particles are so small, they perfectly mix and mingle with all the materials, resulting in appropriate bonding. Fly ash reacts with calcium hydroxide to create better-order hydrated products, which increase strength and power (Saha 2018). Currently, fly ash and GGBS are used as a replacement for cement in over 40–45% (Ram et al. 2020). In accordance with IS 10262:2019 (2019) rule for practice for concrete mix design, we can save cement by substituting fly ash for it.

1.1 Recycled aggregate (RA) types

RA is often divided into groups based on grain size. Usually, fine RA (4 mm) is significantly more difficult to use in the manufacturing of concrete than coarse RA (> 4 mm). This is due to the proportion of high-quality natural aggregates being substantially larger in the coarse than in the fine portions of the concrete following standard crushing and screening operations. After using cutting-edge production techniques, coarse RA can primarily be made of natural aggregate. In addition, RA can be utilized to create filler materials with low strength, ecological ingredients, and low or no cement content at all.

1.2 Recycled concrete aggregate's basic properties for concrete

When old concrete is crushed, some of the mortar and cement particles of paste are left bonded to the stone-aggregate particles in the recycled aggregate. The fundamental cause of RCA's inferior quality compared to natural aggregate (NA) is its attached mortar. When compared to NA, RCA has the following qualities:

1. A greater absorption of water.
2. A reduction in bulk density
3. Reduced specific gravity
4. Abrasion loss that is worse.

1.3 Incorporation of GGBS in concrete

For years, the construction industry has substituted GGBS for OP cement. The main components of GGBS by-product of the iron-production process are calcium and alumina silicates. These run at a temperature of roughly 1500 °C and are provided with a precisely measured combination of coke, limestone, and iron ore. After the iron ore is transformed into iron, all that is left are the byproducts from a slag that is floating on top of the iron. If this slag is to be used in the creation of GGBS, it must be swiftly cooled in a lot of water after being often tapped out as a molten liquid. The strength of concrete is increased using GGBS in place of some of the cement (Dos Reis et al. 2021). The addition of 40–50% of GGBS as a replacement for cement shows comparable results with the control mixes (Collins et al. 1994). Further, GGBS greatly enhances the strength and durability of the alkali-activated concrete (Singh et al. 2017).

1.4 Fly ash in concrete

When pulverized coal is burned in a thermal power plant, a charred and powdery by-product of inorganic mineral matter is produced. The main chemical components of the coal's burnt ash are silica, alumina, calcium, and iron. The mineral phases of quartz (SiO_2), mullite ($3Al_2O_3 \cdot 2H_2O$), hematite (FeO_3), magnetite (Fe_3O_4), wustite (FeO), metallic iron, orthoclase (KO ALO, $6SiO_2$), and fused silicates typically occur in crystalline to non-crystalline patterns depending on the coal's burning temperature (Ram et al. 2020; Nath and Sarker 2011). In the classification of thermal plants, silica, and alumina make up roughly 75–95% of the material. Based on reactive calcium oxide content, fly ash is classified as class F (less than 10%) and class C (greater than 10%) (Saha 2018).

Ash's calcium-bearing silica and silicate minerals easily react with water and develop pozzolanic properties. However, the crystalline mineral phases of quartz and Mullite present in the ash are non-hydraulic silica and silicate structures. These two mineral phases are typically the major constituents of fly ash. As a result, the use of fly ash in building materials such as fiber cement sheets is heavily influenced by the mineral structure and pozzolanic property (Saha 2018; Nath and Sarker 2011). The inclusion of fly ash enhances the workability of concrete and strength. The early-age strength of concrete has been reduced by the inclusion of fly ash due to its pozzolanic activity (Teja Prathipati et al. 2022; Solanki and Dash 2022; Tkaczewska 2014). Also, the inclusion of fly ash as sand replacement enhances the after three days as compared to the control mix (Pati and Sahu 2020; Deo and Pofale 2015).

1.4.1 Scope of work

In this project, recycled coarse aggregate (RCA), fly ash (FA), and granulated blast furnace slag (GBFS) are used as limited substitutes for natural coarse aggregate and cement, respectively, In order to explore the characteristic properties of concrete. In the study, concrete specimens with different ratios of RCA, FA, and GBFS are cast, and their compressive, split tensile, and flexural strength are assessed. Analysis and comparison of the outcomes with the reference concrete mixture are performed. Based on the findings, suggestions are made for more studies and optimization of a concrete mix design using RCA, FA, and GBFS.

2 Materials and methodology

2.1 Materials

2.1.1 Cement

Portland cement grade 53 having a specific gravity of 3.15 is used in this test. Cement is an amorphous (glassy) powdered siliceous material that generates extra CSH (calcium silicate hydrate) binder in the concrete's pore structure as a result of the alkali component in cement reacting with lime in the high pH environment of concrete. Pozzolana works with particles as small as minus 325 mesh. Sulfides, carbon, sulfates, and alkalis are just a few of the chemical elements found in some Pozzolana that can substantially impair concrete's long-term durability. The cement's properties met IS 8112:1989 specifications.

2.1.2 Fine aggregate

Both sand and fine aggregate are assemblages of mineral grains generated when rocks are broken down. Although it differs from clays in that it has organic elements, gravel can only be identified from it by the size of the grains or particles.

The fine aggregate from a riverbed free of any form of organic contaminants with a specific gravity of 2.74 is used in this experimental program. The fine aggregate was graded as zone II and passed through a 4.75 mm sieve in accordance with Indian Standard specifications.

2.1.3 Coarse aggregate

The coarse aggregate is the component of concrete that is both the least porous and most resilient. The substance is also stable chemically. The use of coarse aggregate lessens dimensional changes brought on by moisture transport, including drying shrinkage. Concrete can become impermeable if the coarse aggregate is graded correctly and the mix is prepared correctly. The coarse aggregate having a specific gravity of 2.74 is utilized for this investigation and complies with IS criteria. For the coarse aggregate size, a 60:40 graded aggregates ratio—or 60% of 20 mm to 40% of 12.5 mm—was selected. Investigated were the coarse aggregate's physical features, physical properties, plasticity index, and water absorption.

Table 1 Physical and chemical characteristics of GGBS and fly ash

Particulars	Fly ash	GGBS
% Silica (SiO_2)	63.7	29.23
% Alumina (Al_2O_3)	29.30	17.84
% Iron oxide (Fe_2O_3)	4.23	1.27
% Lime (Cao)	1.48	5.89
% Magnesia (Mgo)	1.50	6.72
% Titanium oxide	0.5	–
% Sulfur trioxide	0.3	1.64
Loss of ignition	0.49	0.56
Physical properties		
Specific gravity	2.28	2.85
Fineness (M^3/kg)	320	390
Particle size	112.23	97.10

2.1.4 Fly ash

Fly ash, which comes from coal-fired power plants, is a reactive spherical waste product that is typically finer than cement. Because of its shape, using fly ash, we can improve the workability of concrete and often allow for lower water contents while still enhancing strength and durability. The properties of the fly ash utilized in this study are listed in Table 1.

2.1.5 GGBS

GGBS is produced by melting iron ore with a reducing agent, like coke, to produce pig iron, which is then processed to produce steel. Silica, alumina, and lime are the main components of the slag produced by this method. It cools fast, is quenched with water, and is then finely pulverized. The GGBS utilized in this study is procured from steel factory Piduguralla is a town in Palnadu district of the Indian state of Andhra Pradesh. The physical and chemical properties of GGBS are listed in Table 1.

2.1.6 Water

The water we used for this project is water from Sri Vishnu Educational Society which is free from hazardous concentrations of contaminants that might affect steel or concrete, such as oils, acids, alkalis, salts, sugar, and organic molecules.

2.1.7 Mix proportions of concrete

The mix proportions of concrete are prepared as per IS: 10262–2019 standards (IS 10262:2019 2019). As per IS 10262-2019 standards, the moderate exposure and vibration compaction mode are considered. The mix proportions are listed in Table 2. Further, the mix details for each mix are listed in Table 3.

Table 2 Mix proportion for M30 grade concrete

Cement	Fine aggregate	Coarse aggregate	Water
1	2.62	2.15	0.45

Fig. 1 Arrangement for compressive strength test

2.2 Methodology

The goal of the experiment is to determine the mechanical characteristics of concrete by substituting some of the cement with GGBS and fly ash and some of the coarse aggregate with recycled aggregate.

2.2.1 Compression test

The test has been conducted on all concrete mixes in triplicate using cubes of size 150 mm × 150 mm × 150 mm at varied curing durations of 3, 7, and 28 days as per IS 516 (Part 1/Sec 1) : 2021 (2021). Figure 1 depicts the testing arrangement details for the compressive strength test.

2.2.2 Flexural strength of concrete

Flexural strength, a mechanical property of brittle materials, is the ability of a material to resist deformation under stress. The most common test is the transverse bending test, which entails inspecting a case using either indirect or blockish sampling until yielding or fracture is discovered using a three-point flexural test procedure. The test has been conducted on all concrete mixes in triplicate for a curing period of 28 days as per IS 516 (Part 1/Sec 1) : 2021 (2021). Figure 2

Table 3 Mix proportions of concrete (kg/m^3)

Mix details	Cement	Fly ash	GGBS	Fine aggregate	Coarse aggregate	RA	Water
M0	438.1	–	–	820.2	998.5	–	197.2
M1	438.1	–	–	820.2	798.5	199.7	197.2
M2	438.1	–	–	820.2	599.5	399.4	197.2
M3	438.1	–	–	820.2	399.4	599.5	197.2
M4	394.3	–	43.8	820.2	599.5	399.4	197.2
M5	372.4	–	65.7	820.2	599.5	399.4	197.2
M6	350.5	–	87.6	820.2	599.5	399.4	197.2
M7	328.6	43.8	65.7	820.2	599.5	399.4	197.2
M8	306.7	65.7	65.7	820.2	599.5	399.4	197.2
M9	284.8	87.6	65.7	820.2	599.5	399.4	197.2

Fig. 2 Arrangements for flexural strength test

depicts the testing arrangement for the flexural strength of concrete.

2.2.3 Split tensile strength of concrete cylinders

Tensile strength is an important property of concrete. To calculate the load at which the concrete members may crack, the tensile strength of the concrete must be known. The test has been performed on all concrete mixes in triplicate using 150 mm × 300 mm cylinders for a curing period of 28 days as per IS 516 (Part 1/Sec 1) : 2021 (2021). Figure 3 depicts a testing arrangement for the split tensile strength of concrete.

3 Results

3.1 Compressive strength

The concrete's compressive strength is sometimes regarded as its most trustworthy characteristic since strength is typically a good indicator of concrete quality. The compressive strength values of native and recycled aggregate are evaluated for various mixtures of Fly ash and GGBS. Figure 4 depicts the compressive strength test results of the mixes containing

Fig. 3 Arrangement for split tensile strength test

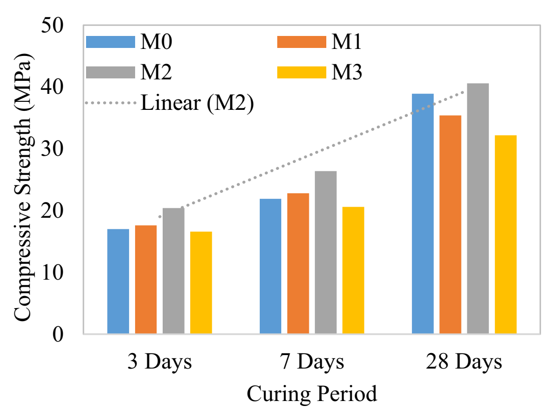

Fig. 4 Concrete's compressive strength includes recycled coarse aggregate

recycled coarse aggregate in different proportions. Figures 5 and 6 depict the compressive strength test results of different concrete mixes with recycled aggregate, GGBS, and fly

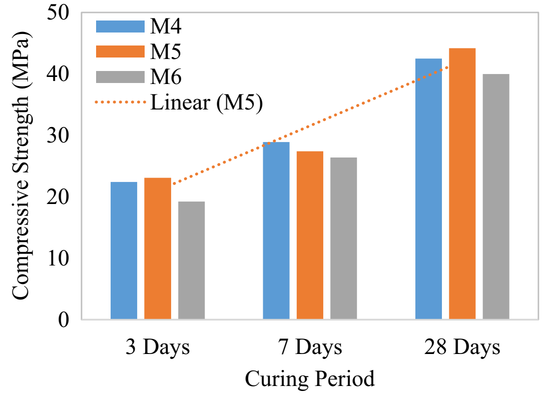

Fig. 5 Concrete with RA and GGBS has a high compressive strength

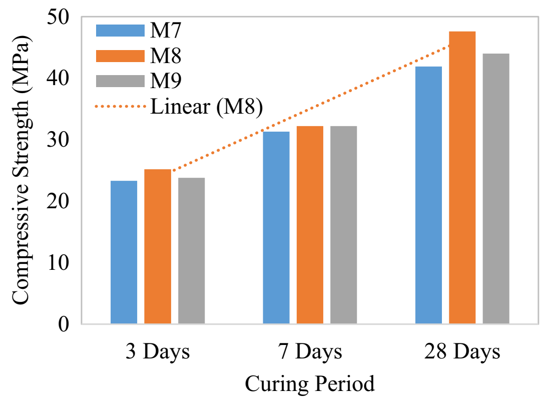

Fig. 6 Concrete compression strength containing RA, GGBS, and FA

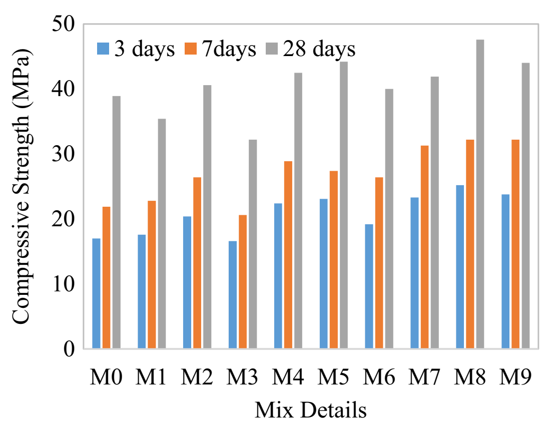

Fig. 7 Compressive strength test results of different mixes

ash. Further, the compressive strength results of mixes with respect to the curing period are listed in Fig. 7, respectively.

From Fig. 4, it is noticed that the addition of recycled aggregate has a positive impact on the compressive strength of the concrete. The mix containing 40% recycled aggregate as a substitute for coarse aggregate shows optimum enhancement in the compressive strength of the concrete as compared to the control mix. Further, the strength of recycled aggregate concrete has been enhanced by the addition of GGBS as a replacement for cement. From Fig. 5, it is noticed that the mix with 40% of recycled aggregate and 15% of GGBS shows better results in compressive strength of concrete. Similarly, the combined effect of fly ash and GGBS as replacements for cement in recycled aggregate concrete has been depicted in Fig. 6. From Fig. 6, it is noticed that the concrete mix with 40% recycled aggregate, 15% fly ash, and 15% GGBS is optimum for enhancing the concrete's strength.

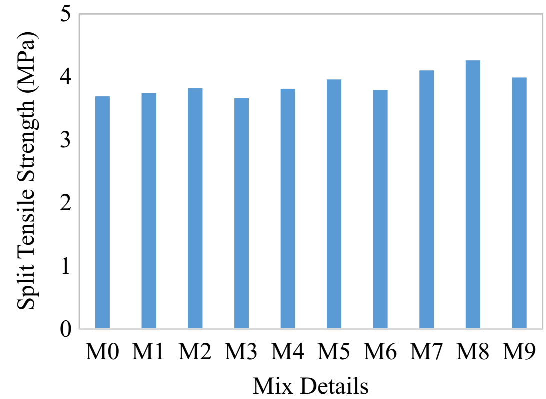

Fig. 8 Split tensile strength results for 28 days

3.2 Split tensile strength

The test results of all concrete mixes for a curing period of 28 days are depicted in Fig. 8. From Fig. 8, is noticed it that the split tensile strength test results followed the same pattern as of compressive strength test results. The mix containing 40% recycled aggregate gives better strength as compared to the 20% and 60% recycled aggregate mixes. The mix with 40% of recycled aggregate and 15% of GGBS further enhances the split tensile strength of the concrete. Similarly, the mix with 40% of recycled aggregate, 15% of fly ash, and 15% of GGBS are optimum for enhancing the split tensile strength of the concrete.

3.3 Flexural strength

The test has been conducted on all concrete samples in triplicate for a curing period of 28 days and the test results are depicted in Fig. 9. From Fig. 9, it is noticed that the accumulation of 40% of recycled aggregate is optimum for considering the flexural strength of concrete. The recycled aggregate concrete with 40% of recycled aggregate and 15% of GGBS further enhances the strength of the concrete. The concrete mix with 40% of recycled aggregate, 15% of fly ash, and 15% of GGBS is optimum for enhancing the mechanical characteristics of the concrete.

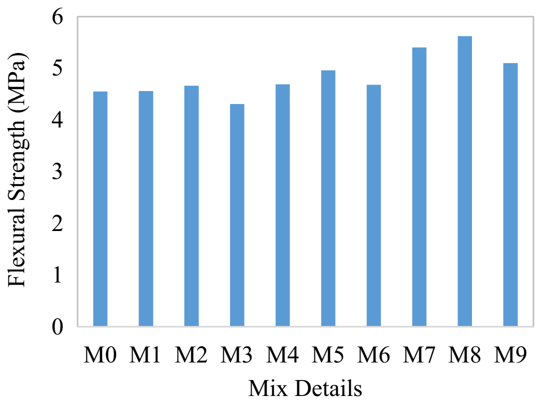

Fig. 9 Flexural strength results of different mixes

4 Discussions

The addition of 40% of recycled aggregate as a substitute for coarse aggregate enhances the strength of the concrete. This is because of the better packing of the aggregates in the concrete mix (Yehia et al. 2015). Further, GGBS has been added as a replacement for cement in recycled aggregate concrete. The accumulation of 40% of recycled aggregate and 15% of GGBS shows 13.6%, 9.25%, and 7.31% enhancement in compressive, flexural, and split tensile strength of concrete in comparison with the control mix. The inclusion of GGBS possesses pozzolanic activity and generates secondary CSH gel thus the strength of the concrete increases (Hawileh et al. 2017). The combined effect of fly ash and GGBS as replacements for cement in RAC has been studied. The mix with 40% of recycled aggregate, 15% of fly ash, and 15% of GGBS show a 22.3%, 23.8%, and 15.44% increase in the compressive, flexural, and split tensile strength of concrete as compared to the control mix for a curing period of 28 days. This is because of the combined effect of fly ash and GGBS. The fly ash is finer than the cement it works as a filler material as well as a pozzolanic material like GGBS (Qureshi et al. 2020). Thus, the voids and micro-cracks in the mix are minimized and the mechanical characteristics of the concrete are increased.

5 Conclusions

The following inferences are made in light of the test results from the current inquiry.

- The addition of 40% of recycled aggregate as coarse aggregate replacement enhances the compressive strength of concrete by 4.37% as compared to the control mix.
- Further, replacing 40% of RCA in coarse aggregate with 15% GGBS and 15% FA as cement substitutes results in a significant 22.3% increase in concrete compressive strength.
- Similarly, split tensile strength and flexure strength of M30 concrete improve by 15.44% and 23.78%, respectively, when 40% of the RCA, 15% of the GGBS, and 15% of the FA are replaced.
- There is a significant improvement found in the concrete when the strength qualities are at an optimal percentage of 40% RCA, 15% GGBS, and 15% FA compared to control concrete.
- The inclusion of supplementary materials in the form of GGBS and FA in RAC leads to a chemical reaction with calcium hydroxide, resulting in the formation of extra binder material. This increased availability of binder material, in turn, enhances the bond between the paste and aggregates in RAC, ultimately improving its strength properties. Therefore, adding a specific percentage of 15% for both GGBS and FA can effectively enhance the strength characteristics of partially used RAC with low initial strength properties.
- The use of recycled concrete aggregate with controlled substitution of cement by GGBS and fly ash powder presents a promising approach that combines sustainability, strength enhancement, and cost-effectiveness in concrete production.

Author contributions The authors confirm contribution to the paper as follows: study conception and design: VVSS, SSA data collection: PGK analysis and interpretation of results: KV draft manuscript preparation: KSS.

Declarations

Conflict of interest The authors declare no competing interests.

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