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Mechanical performance and eco-strength efficiency of sustainable concrete incorporating fly ash, glass powder, and recycled plastic

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Abstract

This study assesses the performance and environmental sustainability of concrete using supplementary cementitious materials (SCMs), fly ash (FA), silica fume (SF), and bottom ash (BA), as cement partial replacements, and waste glass powder (GP) and recycled plastic (RP) as fine aggregates partial replacements. Eight concrete mixes with different replacement levels were tested for workability, fresh density, compressive strength, indirect tensile strength, dry density, void ratio, and water absorption at 14 and 28 days.

The mixture combining 10% FA and 15% GP (Mix 1) performed best, with compressive strength gains of 7.9% and 9.2% and indirect tensile strength gains of 48% and 42.3% at 14 and 28 days, respectively, compared with the control. Mixtures with high RP content or high simultaneous replacement levels (e.g., 50% RP in Mix 7) experienced significant strength losses, with compressive strength reductions exceeding 95% in extreme cases. Workability generally decreased with SF, BA, and high GP or RP contents due to higher specific surface area and particle angularity. All modified mixtures showed lower density, especially those with RP.

A sustainability assessment using embodied carbon (EC) and eco-strength efficiency (ESE) showed that high SCM content reduced CO_2 emissions by up to 37.5% at 45% cement replacement. Mix 1 achieved the highest ESE, with an 18.4% increase over the control mix. Overall, very high replacement levels can severely reduce mechanical properties, but well-optimized SCMs and waste-derived combinations, particularly FA with GP, can improve mechanical performance while lowering environmental impact.

Keywords: sustainable concrete, fly ash, silica fume, bottom ash, glass powder, recycled plastic, eco-efficiency, mechanical properties.

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1. Introduction

Concrete is a universal material essential for modern infrastructure and urban development. It is favored for its widespread accessibility, durability, and economic viability. The significant reliance on concrete, and particularly its production process, has substantial environmental impacts (Turk et al., 2024). As the most widely used concrete material, and considered second only to water as the most heavily consumed substance on earth, above 10 billion tons of concrete are produced annually worldwide (Eshetu Aweke & Alemu Mohammed, 2020).

However, its production particularly that of Ordinary Portland Cement (OPC), has significant environmental consequences. The cement industry is a major contributor to global greenhouse gas emissions, accounting for approximately 5–7% of the total (Gradinaru et al., 2018), and some sources suggest up to 8% of worldwide CO_2 emissions (Turk et al., 2024). The clinker production stage is particularly energy-intensive, accounting for over 90% of total energy use and virtually all fuel use in cement manufacturing (Şanal, 2018). The heavy reliance on energy, often derived from coal, leads to high CO_2 and other pollutant emissions (Barbhuiya et al., 2024).

Beyond cement, the extraction of natural resources such as aggregates (sand and gravel) also raises environmental concerns, including resource depletion and habitat disruption. Aggregates make up about 70-80% of reinforcement concrete cement, with coarse aggregates accounting for 40-50%, whereas fine aggregates account for 25-30% (K, 2019). The mining, processing, and transport of these large quantities of aggregates consume considerable energy, produce greenhouse gases, and can adversely affect the ecology of extraction areas, with the global aggregate production totaling approximately 40 billion tons per year (Şanal, 2018). Addressing these challenges requires the development of sustainable alternatives and innovative practices in concrete production.

Additional environmental concerns include water pollution. Wash water generated from cleaning concrete mixing trucks and batching plants is a significant threat to water resources. This concrete wash water (CWW) has a high pH, often ranging from 11 to 12, due to the concentration of limestone (Turk et al., 2024). It also contains suspended and dissolved solids, posing a risk of contaminating nearby water sources if improperly disposed of, which is a significant global environmental challenge. Furthermore, concrete contributes to solid waste problems, being a major component of construction and demolition waste. Waste materials are frequently dumped in

open areas and landfills, leading to health hazards and environmental pollution (Al Biajawi et al., 2022).

In response to these growing environmental pressures, particularly the depletion of natural resources and pollution from waste, there is an increasing demand and necessity for sustainable concrete production. The construction sector has actively participated in the challenge of utilizing sustainable, ecological, and recycled materials. Sustainable concrete aims to reduce environmental impact by incorporating waste materials and industrial by-products as partial replacements for cement and natural aggregates. This approach not only conserves natural resources and lowers greenhouse gas emissions but also helps manage accumulating waste materials. Supplementary Cementitious Materials (SCMs), such as fly ash, bottom ash, and silica fume, are widely used to partially replace cement due to their pozzolanic properties and ability to enhance concrete performance and durability. While concrete can recycle waste, the industries supporting it produce vast amounts of hazardous by-products, which can pollute soil and water if not properly managed.

Simultaneously, utilizing recycled materials like waste glass and plastic as aggregates can decrease reliance on natural sources and divert waste from landfills. Disposing of non-biodegradable waste materials like glass and plastic has become a global crisis. Plastic production surged from 1.5 million tons in the 1950s to 359 million tons in 2018 (Statista, 2022) and is expected to reach 590 million tons in 2050 (Jaganmohan, 2024). A considerable portion of this plastic is used in the manufacture of single-use plastic products, thereby causing the accumulation of plastic waste. On the other hand, glass is one of the materials found in many human-made products, ranging from homes to appliances and containers. In 2017, 20.255 million tons of waste glass were generated in China alone, among which 9.268 million tons were recycled, accounting for a recycling rate of 45.2% (Lu et al., 2017a). Among its disadvantages, it is important to mention that due to the extremely stable properties of waste glass, its natural degradation time exceeds 1000 years (Lu et al., 2017b).

Reusing these waste materials, such as bottom ash, glass powder, and recycled plastic, helps conserve main resources and mitigate carbon emissions, as well as having positive impacts on human health by reducing hazards associated with waste disposal.

Various studies have quantified the impact of replacing cement with SCMs on the workability, fresh density, compressive and tensile strengths, dry density, and porosity of concrete samples.

As a by-product of coal combustion in thermal power plants, fly ash is a well-known pozzolanic material, reacting with calcium hydroxide released during cement hydration to form additional Calcium Silicate Hydrate (C-S-H) gel, which enhances strength and durability (Şanal, 2018). Class F fly ash, known for its low calcium content and pozzolanic nature, is commonly used to enhance mechanical properties and durability (Turk et al., 2024).

Silica fume is an ultrafine industrial by-product with high amorphous silica content (Pasha et al., 2025). It acts as a highly reactive pozzolanic material, significantly enhancing concrete strength and durability due to its ability to fill interstitial voids and react with calcium hydroxide (Pasha et al., 2025). Silica fume improves the microstructure and bonding within the cement matrix. It is known to enhance resistance to chemical attacks and is particularly effective at optimum replacement levels, often cited around 10-15%. Silica fume is often used in combination with other SCMs like fly ash to improve properties, including offsetting reduced early strength (Anwar & Emarah, 2020).

Bottom ash is generated during coal combustion, remaining on the bottom of the furnace, distinct from fly ash, which is carried by flue gases (Şanal, 2018). It accounts for approximately 20% of total coal ash waste from power plants. Bottom ash has a granular structure, composed mainly of silica, alumina, and iron, and its appearance and particle-size distribution are similar to those of river sand. Bottom ash is often used as landfilled material, but is being explored as a substitute material in concrete, particularly as a partial replacement for both cement and fine aggregates.

Waste glass can be finely ground and used as a partial replacement for fine aggregate (sand) (Ganiron, 2013). Utilizing waste glass as aggregate not only saves landfill space but also reduces the demand for natural sand extraction (Rashad, 2014). Fine glass powder (with particle sizes typically less than 75-100 μm) can also exhibit pozzolanic behavior, contributing to strength development and durability enhancement, particularly reducing Alkali-Silica Reaction (ASR) expansion (Khan et al., 2020).

Recycled plastic waste, particularly from e-waste, can be processed into aggregates (PCA) to replace natural fine aggregates (Thorneycroft et al., 2018). This integration reduces plastic waste accumulation and lowers reliance on natural aggregates. Recycled plastic is being explored for use in lower-strength applications, with replacement levels typically studied ranging from 10% to 20% or more (Pasha et al., 2025).

The replacement levels investigated in this study were selected to assess a range of practically relevant and performance-critical scenarios commonly reported in the literature. A lower replacement level of 10% was selected to evaluate a conservative incorporation of SCMs, a range that has frequently been shown to maintain or marginally enhance the mechanical properties of concrete through filler effects and pozzolanic reactions. A moderate replacement level of 15% was selected based on prior studies indicating that this interval is often optimal for simultaneously achieving favorable strength development and durability performance when using SCMs such as fly ash, silica fume, and bottom ash. In contrast, higher replacement levels of up to 45% were incorporated to investigate the upper bounds of material substitution from a sustainability perspective, particularly with respect to cement reduction and associated embodied carbon. Although such high substitution levels may negatively affect mechanical performance, their inclusion enables a more comprehensive assessment of performance–sustainability trade-offs and provides insight into the feasibility of high-volume utilization of waste-derived materials.

1.1.Research significance

This study presents an extensive experimental and sustainability assessment of concrete incorporating multiple SCMs and recycled materials, specifically fly ash, silica fume, bottom ash, glass powder, and recycled plastic. While most previous investigations have predominantly focused on single waste materials or binary blends, the novelty of the present study lies in the analysis of their complementary performance effects within a single concrete system. This approach facilitates the analysis of complex interaction effects among different cement and fine aggregate replacement alternatives, with particular emphasis on identifying mixture compositions that optimally balance mechanical performance and environmental impacts.

The non-uniform, multi-material combination strategy employed here enables the identification of both complementary performance and cumulative negative effects among the incorporated materials, which cannot be fully captured through single-factor or simple binary substitution studies. Moreover, this multi-material substitution framework more accurately reflects real-world sustainable concrete production scenarios, in which multiple industrial by-products and waste materials are typically available concurrently.

A key contribution of this research is the identification of complementary performance effects between SCMs and recycled aggregates, demonstrating that certain material combinations (e.g., fly ash with glass powder) can enhance mechanical performance. In contrast, others, particularly those with elevated recycled plastic content, result in significant degradation of strength. In addition, this study covers the eco-strength efficiency (ESE) index as an integrated performance–sustainability indicator that combines compressive strength and embodied carbon into a single metric. This index provides a more meaningful basis for evaluating concrete mixtures by explicitly quantifying the trade-off between structural performance and environmental burden.

The proposed framework is employed to determine mixture designs that concurrently improve mechanical properties and reduce carbon emissions. Overall, the findings contribute to the development of multi-material optimization strategies for sustainable concrete design, offering both experimental evidence and a decision-support framework to assist engineers in rationally balancing structural performance with environmental impact.

2. Materials specifications

2.1. Cement and mixing water

CEM II 42.5 cement was used in this investigation in accordance with ASTM C150/C150M-24 requirements (*Standard Specification for Portland Cement*, 2024). To achieve a minimum compressive strength of 42.5 megapascals (MPa) after 28 days of curing, the concrete was designed using 42.5-grade Ordinary Portland Cement in compliance with ASTM standards. The physical properties of the OPC include a specific gravity of 3.18 g/cm^3, a fineness of 290 m^2/kg, and a particle size distribution ranging from 10 to 15 microns.

To comply with the standard requirements of ASTM C1602/C1602-22 (*Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete*, 2022) the mixing and curing process was conducted using tap water with a pH between 6.5 and 7.5, free of salts, chemicals, oils, and other organic compounds.

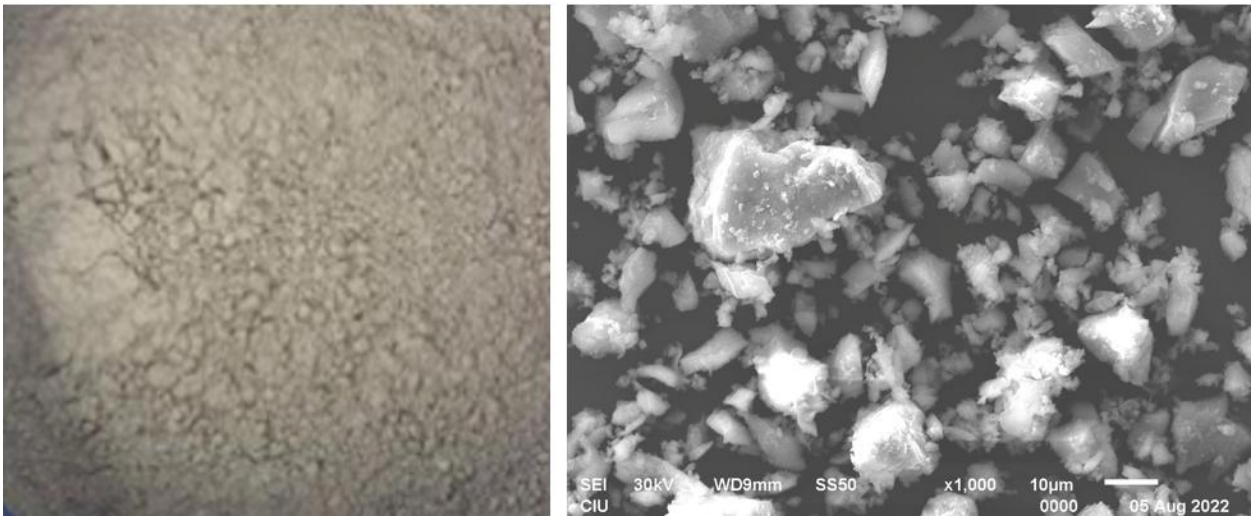


Fig. 1 CEM II cement and its SEM

2.2. Fine aggregates

Crushed fine aggregates were used in this experiment. Fine aggregates are particles smaller than 4.75 mm, used as gaps filler between coarse aggregates. The aggregates were sieved in accordance with the specifications of ASTM C136/C136M-25 (*Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates*, 2025). To minimize water absorption and prevent errors due to water absorption during the batching process, the aggregates were used in a saturated surface dry (SSD) state in accordance with ASTM C128-25 (*Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate*, 2025). The physical characteristics of the fine aggregates used in this study are shown in Table 1 below.

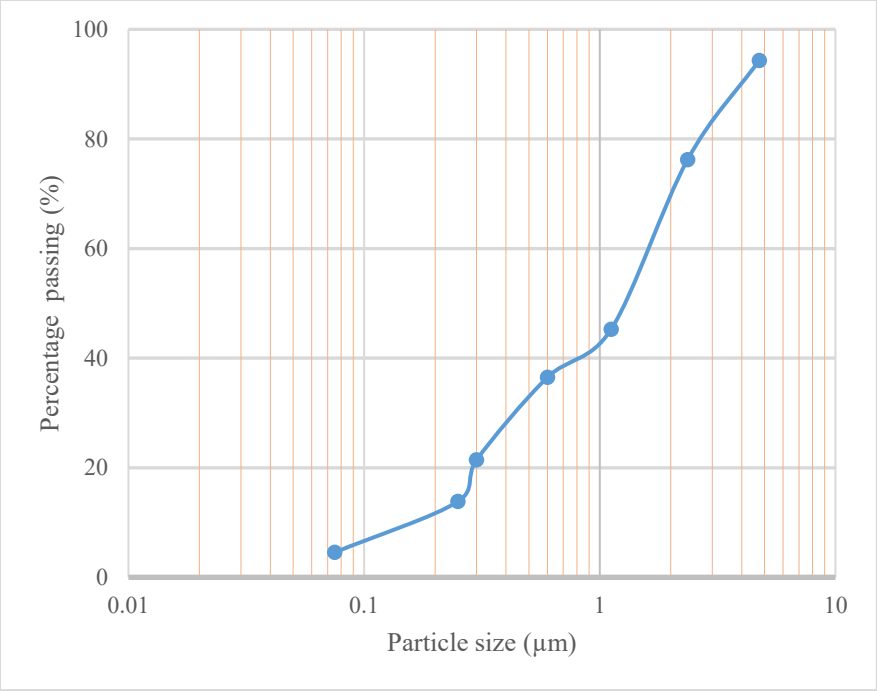


Fig. 2 Fine aggregates particle size distribution



Fig. 3 Fine aggregates

2.3. Coarse aggregates

Coarse aggregates collected from a local quarry in the Turkish Republic of Northern Cyprus were used in this experiment. Coarse aggregates were conditioned to an SSD state in compliance with ASTM C127-25 (*Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate*, 2025). Fig. 4 and Fig. 5 respectively represent the 10-mm and 20-mm coarse aggregate types used in this study.

Table 1 Properties of the fine and coarse aggregates

Characteristics	Fine aggregates	Coarse aggregates	Standards
Water absorption (%)	1.5	1	ASTM C127 &ASTM C128-15
Specific gravity (SSD)	2.63	2.7	ASTM C128-15 & ASTM C127-24
Fineness modulus	2.79	6.32	ASTM C136/ C136M-14
Loose bulk density (kg/m^3)	1576	1139	ASTM C29/ C29M
Compact bulk density. (kg/m^3)	1728	1525	ASTM C29/ C29M



Fig. 4 10-mm coarse aggregates



Fig. 5 20-mm coarse aggregates

2.4. Fly ash (FA)

ASTM C 618-87 categorizes fly ashes into Class C and Class F, also known as Pulverized Fuel Ash (PFA) (*Standard Specification for Coal Ash and Raw or Calcined Natural Pozzolan for Use in Concrete*, 2025). The Class F fly ash used in this study to partially replace cement at various percentages was imported from Turkey and stored in the university laboratory to facilitate innovative studies on sustainability. Often alkaline, gray in color, refractory by nature, and frequently abrasive, the class F FA used in this study had a 75-micron particle size with a specific gravity of 2.10. Table 2 below shows the chemical composition of the FA that was used, whereas Fig. 6 below shows the physical appearance and its SEM image.

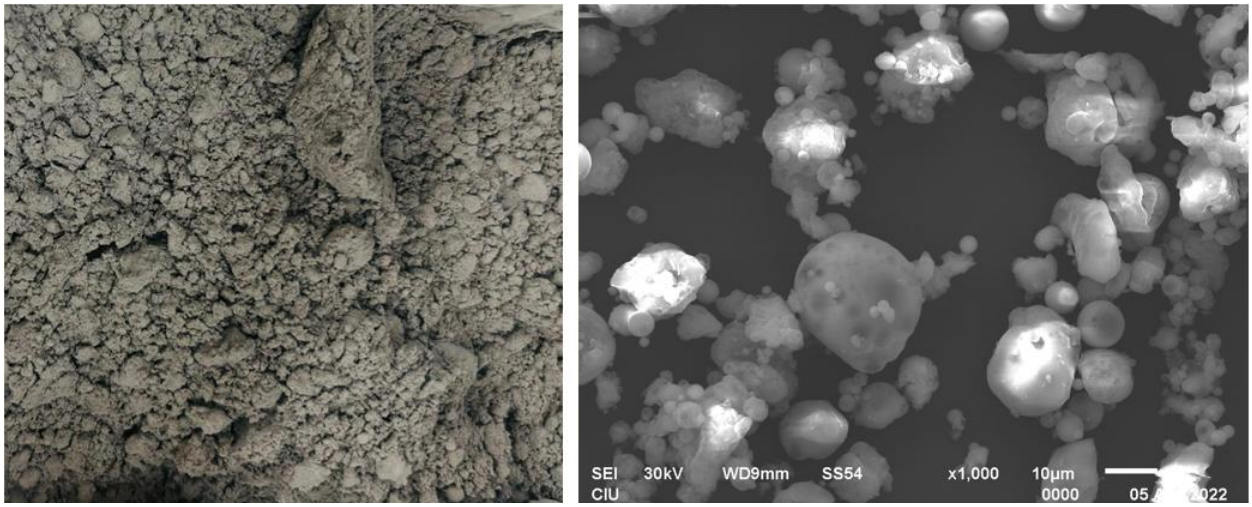


Fig. 6 Class F fly ash

2.5. Silica Fume (SF)

As an ultrafine industrial by-product, SF particles that were used in this investigation, Fig. 7, have a spherical and amorphous form, with a diameter of less than 0.5 microns. They have a surface area of 20 m^2/g and a specific gravity of 2.2g/cm^3. Table 2 shows the chemical composition of SF.



Fig. 7 Silica fume

2.6. Bottom Ash (BA)

The bottom ash (BA) employed in this investigation was sourced from a local coal-fired thermal power plant in Northern Cyprus. Following discharge from the furnace, the BA was air-cooled and then sieved to remove oversized particles and residual unburned carbon fragments. The processed BA, with a characteristic particle size of 75 μm, was subsequently used as a partial substitute for ordinary Portland cement (OPC).

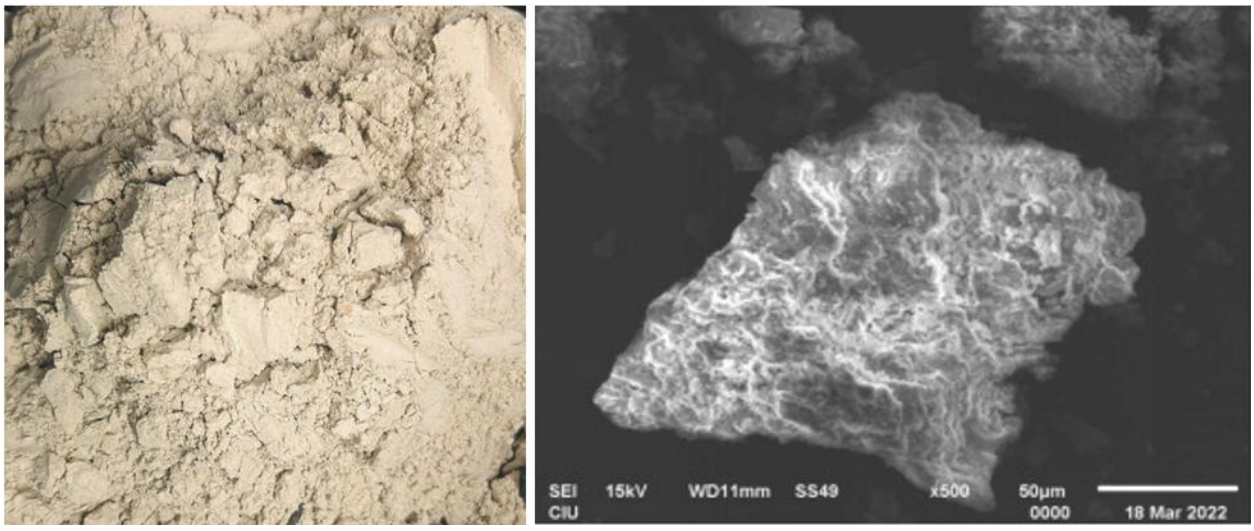


Fig. 8 Bottom ash

2.7. Glass Powder (GP)

The waste glass powder (GP) utilized in this study was produced from crushed post-consumer glass bottles and containers. Before processing, the glass was washed to remove labels, adhesives, and other adhering contaminants, followed by drying and mechanical grinding in a Los Angeles abrasion machine until the particles passed through a 75 μm sieve. The resulting GP (Fig. 9) exhibited a fine, angular morphology and a specific gravity of approximately 2.55 g/cm³. This GP was incorporated as a partial replacement for natural fine aggregates in the concrete mixtures without any additional surface treatment or chemical modification.



Fig. 9 Glass powder and its SEM image

Table 2 Chemical composition of FA, SF, BA, and GP

Chemical component	FA	SF	BA	GP
SiO_2	62.13	92.26	66.66	72.14
Al_2O_3	21.74	0.89	17.09	-
Fe_2O_3	3.16	1.97	0.31	0.34
CaO	3.59	0.49	5.40	10.79
MgO	3.15	-	0.28	1.57
Na_2O	0.09	0.42	0.86	13.12
K_2O	3.34	1.31	0.47	0.64
MnO	0.63	-	-	-
Mn_2O_3	2.62	-	-	-

SO_2	0.09	-	-	-
TiO_2	-	0.01	-	0.07
SO_3	-	0.33	-	-
Cr_2O_3	-	-	-	0.22
Loss On Ignition	-	3.32	1.92	-

2.8. Recycled Plastic (RP)

RP used as a natural fine aggregates partial replacement in this study was obtained from a recycling plant in the Turkish Republic of Northern Cyprus. Plastics were shredded into small pellets with sizes varying from 300 microns to 4.75 mm. The recycling process included a mixture of high-density polyethylene plastics (HDPE), medium-density polyethylene (MDPE), and post-consumer polyvinyl chloride (PVC) to obtain the RP shown in Fig. 10 below.

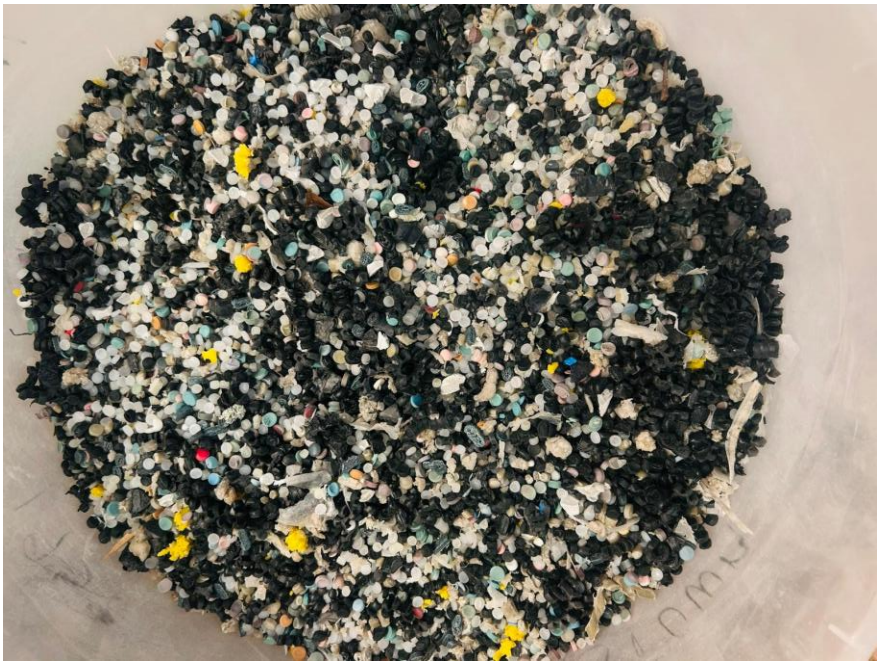


Fig. 10 Recycled plastic

3. Experimental methodology

This study involves the preparation and testing of various concrete mixes incorporating specified sustainable materials. The experimental program is designed to evaluate the properties of both

fresh and hardened concrete. It is important to note that the present study was designed as a screening study of multi-component mixtures rather than a full factorial design. Consequently, the study does not aim to isolate and qualify statistical interaction effects between individual materials, but instead, it evaluates the net performance of these combinations against the control mix and identifies mixture designs that show promise for balancing mechanical and environmental performance.

3.1. Mix design

Test mixes were prepared by partially replacing cement with FA, SF, and BA at predetermined percentages, and partially replacing natural fine aggregates with GP and RP at predetermined percentages, with the same amounts of water and coarse aggregates and the same water-to-binder ratio as in the control mix. The total binder content (cement + SCMs) was kept constant at 436 kg /m^3, and the water to binder ratio was fixed at 0.47.

Table 3 Description of the mixes

Mix ID	Mix description				
	FA (%)	SF (%)	BA (%)	GP (%)	RP (%)
Control mix	-	-	-	-	-
Mix 1	10	-	-	15	-
Mix 2	-	10	15	15	-
Mix 3	-	-	10	-	15
Mix 4	15	15	15	-	-
Mix 5	-	-	-	30	20
Mix 6	-	-	-	50	25
Mix 7	15	15	-	-	50
Mix 8	-	-	-	50	-

Table 4 Mix design of the concrete mixes

Mix ID	Mixes	w/b	W	C	FA	SF	BA	NFA	GP	RP	10 mm CA	20 mm CA
			kg /m^3	kg /m^3	kg /m^3	kg /m^3	kg /m^3	kg /m^3	kg /m^3	kg /m^3	kg /m^3	kg /m^3
Control mix	100% C 100% NFA 100% CA	0.47	204.9	436	-	-	-	670.7	-	-	465.3	564.3
Mix 1	10% FA 15% GP	0.47	204.9	392.4	43.6	-	-	570.1	100.6	-	465.3	564.3
Mix 2	10% SF 15% GP 15% RP	0.47	204.9	392.4	-	43.6	-	469.5	100.6	100.6	465.3	564.3
Mix 3	10% BA 15% RP	0.47	204.9	392.4	-	-	43.6	570.1	-	100.6	465.3	564.3
Mix 4	15% FA 15% SF 15% BA	0.47	204.9	239.8	65.4	65.4	65.4	670.7	-	-	465.3	564.3
Mix 5	30% GP 20% RP	0.47	204.9	436	-	-	-	335.4	201.2	134.1	465.3	564.3
Mix 6	50% GP 25% RP	0.47	204.9	436	-	-	-	167.7	335.4	167.7	465.3	564.3
Mix 7	15% FA 15% SF 50% RP	0.47	204.9	305.2	65.4	65.4	-	335.4	-	335.4	465.3	564.3
Mix 8	50% GP	0.47	204.9	436	-	-	-	335.4	335.4	-	465.3	564.3

*w/b water to binder ratio, W Water, C Cement, FA Fly Ash, SF Silica Fume, BA Bottom Ash, NFA Natural Fine Aggregates, GP Glass Powder, RP Recycled Plastic, CA Coarse Aggregates

3.2. Sample preparation

In accordance with ASTM C192/C192M-24 (*Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory*, 2024), the mixing procedure is defined as the sequence in which the constituent materials are introduced into the mixer and the duration of mixing at each stage. To achieve high workability, the coarse aggregates, one-half of the cement, and one-half of the mixing water were first combined and mixed for 60 seconds. Subsequently, the remaining half of the cement, the fine aggregates, and an additional 25% of the water were added and mixed for 2

minutes. Finally, the remaining 25% of the water was introduced, and mixing was continued for a further 3 minutes.

Immediately after completion of the mixing procedure, measurements of fresh density, slump, and compaction factor tests were carried out in parallel to minimize any delay before casting. The concrete was then placed into 100 mm × 100 mm × 100 mm molds, with three specimens prepared per mixture and per testing age (14 and 28 days) for each experimental series, compacted using a tamping rod and a vibrating table. After 24 h, the specimens were demolded and subsequently cured by full immersion in a water tank maintained at 20 ± 2 °C and free from salts, chemical contaminants, oils, and organic matter for periods of 14 and 28 days.

3.3. Testing procedures

3.3.1. Slump test and compaction factor

The workability of the fresh concrete, representing its rheological behavior in terms of fluidity and ease of handling and placement, was determined using the slump test (Fig. 11) in accordance with ASTM C143 (*Standard Test Method for Slump of Hydraulic-Cement Concrete*, 2026). Workability is a fundamental property of fresh concrete, characterizing the ease with which it can be mixed, transported, placed, compacted, and finished without inducing segregation or excessive bleeding. As a complementary procedure for the evaluation of workability, particularly appropriate for mixtures exhibiting low slump, the compaction factor test was performed.



Fig. 11 Slump test of concrete mix

3.3.2. Fresh density

The density of the fresh concrete mixtures was determined immediately after casting into molds, in accordance with ASTM C138 (*Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete*, 2024), to quantify the unit weight of the unhardened concrete.

3.3.3. Compressive strength test

The load-bearing capacity of the hardened concrete was evaluated by compressive strength testing at 14 and 28 days of curing. For each mixture and at each curing age, conforming to BS EN 12390-

3:2019, three 100mm x 100mm x 100mm specimens were tested using a compression testing machine (Fig. 12). Then, the average value and the standard deviation were calculated.



Fig. 12 Compressive strength machine

3.3.4. Indirect tensile strength test

The splitting tensile strength test assessed the tensile behavior of hardened concrete samples. For each mixture and at each curing age (14 and 28 days), three specimens were tested in accordance with BS EN 12390-6. All reported compressive and tensile strengths represent the mean of three specimens, with error bars in the figures indicating the standard deviation.

3.3.5. Dry density, void ratio, and water absorption

The dry density, void ratio, and water absorption of hardened concrete specimens were measured after 14- and 28-day curing to determine the dry unit weight of the hardened material. Dry density, void ratio, and water absorption values shown in this study represent the mean of three specimens, with error bars in the figures indicating the standard deviation.

4. Results and discussion

4.1. Workability

Across the different mix designs, the influence of partial cement and aggregate replacement materials on concrete workability varied as a function of the material type, its physical properties, and the replacement ratio.

Fly ash can improve workability and contribute to long-term strength development. This improvement is commonly attributed to the predominantly smooth spherical morphology of FA particles, which imparts a ball-bearing effect that releases trapped water within cement particles, thereby reducing interparticle friction between cement and providing lubrication (Kurda et al., 2017).

(Nath & Sarker, 2011) reported that the incorporation of FA enhances the workability of fresh concrete, as evidenced by increased slump values. In comparison to their reference concrete, an increase in slump height of 16.67 and 6.67% was recorded with 30% and 40% FA substitution, respectively, at a 0.29 w/b ratio. However, according to their findings, replacing cement with FA by up to 10% increased the slump values, and substituting more than 10% reduced the workability of fresh concrete (Fantu et al., 2021). Moreover, (Haque & Kayali, 1998) concluded that a FA replacement level of 10% was identified as optimal; beyond this threshold, the increased specific surface area appears to counteract the ball-bearing effect, resulting in a marked reduction in workability at 15% replacement.

However, when FA was used in combination with other supplementary materials, such as GP (Mix 1), BA with silica fume (Mix 4), and SF with RP (Mix 7), the slump was reduced by 82%, 88.2%,

and 82%, respectively, relative to the control mix. According to a study on the influence of FA and recycled plastic waste on concrete (Paliwal & Maru, 2017), when 20% FA was combined with 0.6% shredded polythene, the compaction factor increased from 0.91 to 0.931 compared to the control mix. The results further indicated a systematic reduction in workability for all mixtures incorporating SF. In contrast to FA, SF is well documented to decrease concrete workability and slump, while increasing mixture cohesiveness, with mixtures described as more cohesive and less susceptible to segregation (American Concrete Institute, 2000). A 10% cement replacement with SF in Mix 2 led to an approximately 82% reduction in slump and produced a compaction factor of 0.7680. This behavior is primarily attributed to the extremely high specific surface area and ultrafine particle size of SF, which substantially increases the water demand of the mixture. To achieve a target workability when using SF, it is usually necessary to increase the initial slump and/or employ high-range water-reducing admixtures (superplasticizers).

Mix 3, containing 10% BA, showed a modest slump reduction of 29% relative to the control mixture. Studies investigating BA as a partial cement replacement have reported a progressive reduction in workability with increasing BA content compared to conventional concrete. This decline in workability is largely governed by the physical characteristics of BA, including particle surface area, texture, fineness, fineness modulus, and gradation, all of which significantly influence the rheological behavior of fresh concrete (Al Biajawi et al., 2022).

Increasing RP content was generally associated with a reduction in slump. At higher replacement levels (Mix 7), a sharp decrease in workability of 82.4% was observed, accompanied, however, by a 6% increase in the compaction factor. The reduction in flowability is typically attributed to the irregular geometry, angularity, and/or rough surface texture of plastic particles, which collectively elevate internal friction within the mix (Guo et al., 2023). Although RP can improve certain properties, such as impact resistance and resistance to sulfuric acid attack, it may adversely affect porosity, water absorption, drying shrinkage, and fire resistance (Ullah et al., 2022). However, some studies have reported improved workability with RP substitution, which is consistent with the slump value of Mix 5 containing 20% RP, where a 5.9% increase in workability relative to the control was observed. Such improvements are generally linked to specific particle characteristics, particularly spherical or rounded shapes and smooth surfaces, that reduce internal friction (Lokeshwari & Ostwal, 2019). Another contributing factor is the typically lower water absorption

capacity of RP compared with natural aggregates, which leaves a greater proportion of free water available in the mixture (Pasha et al., 2025).

A reduction in slump of approximately 82.4% was observed when GP was used to replace 50% of the fine aggregate. This decrease in workability is commonly associated with the geometry of the particles of waste glass, such as sharp edges, angular forms, rough surfaces, and a lower fineness modulus relative to natural sand, which collectively increase interparticle friction and diminish fluidity (Arivalagan & Sethuraman, 2021; Hakim et al., 2024). Finely ground glass powder itself can also reduce workability, with the reviews reporting a range of optimum replacement levels (e.g., 10%, 20%, and up to 60%), depending on the targeted performance indices (Ismail & AL-Hashmi, 2009). In general, increasing waste glass content tends to reduce slump, although appropriate modifications to the mix design and the use of chemical admixtures can partially or fully compensate for these adverse effects on workability.

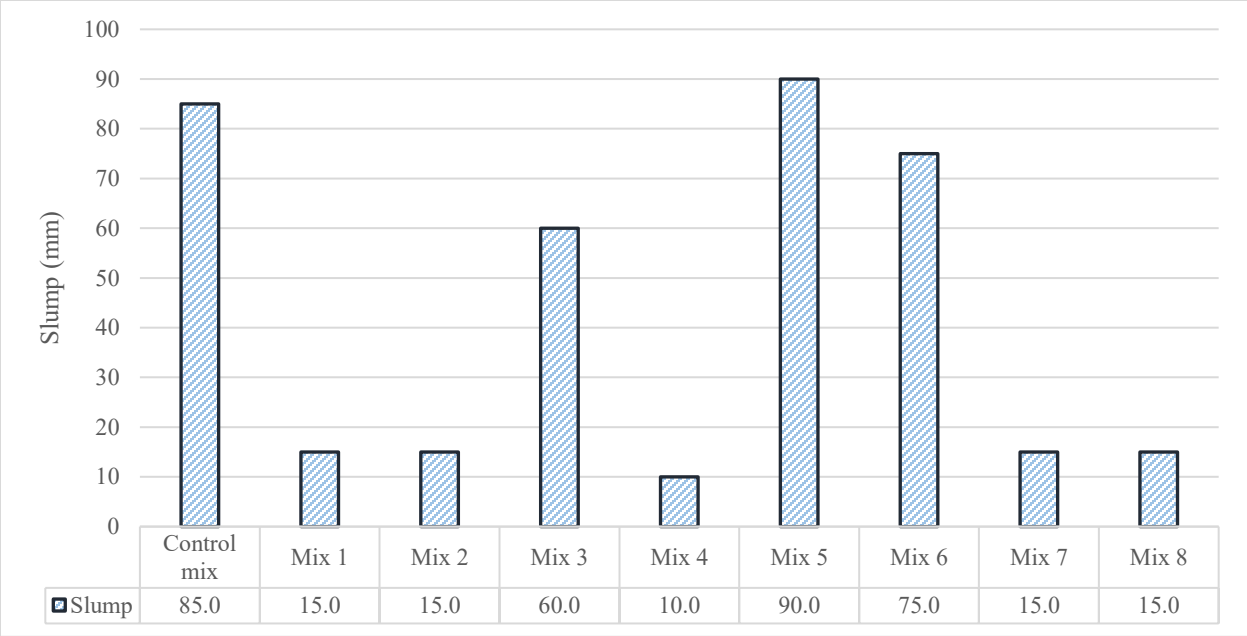


Fig. 13 Slump test

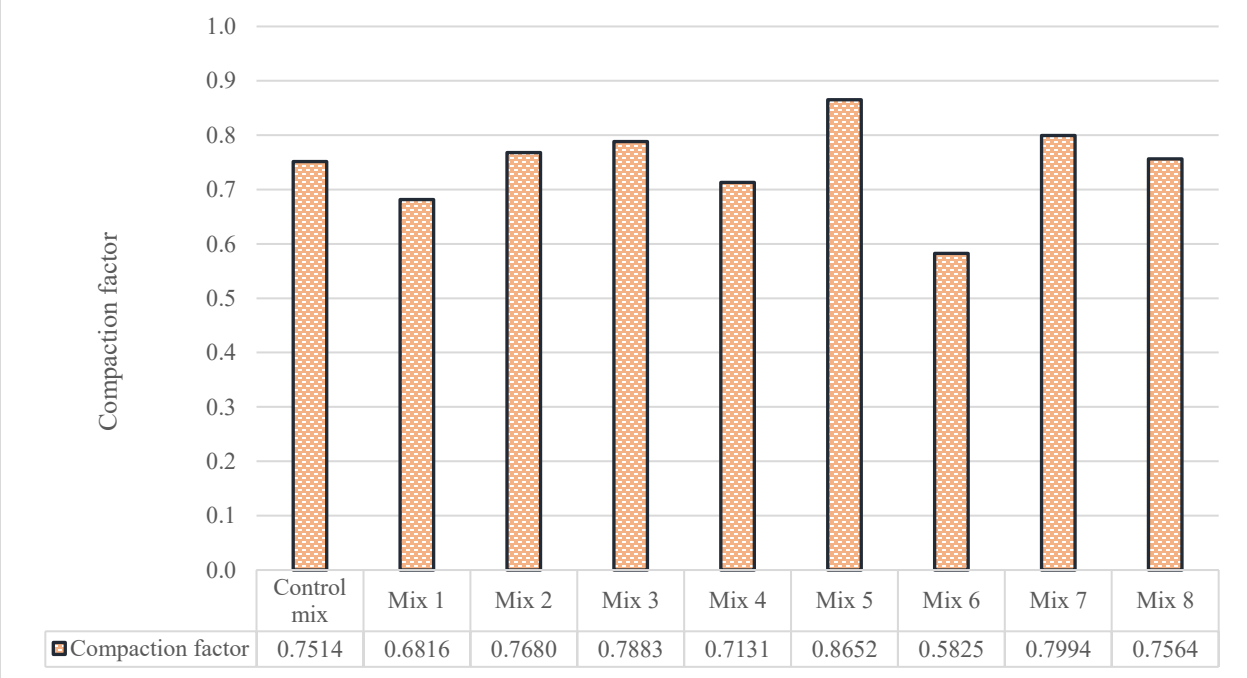


Fig. 14 Compaction factor

4.2. Fresh density

The fresh density, or unit weight, of concrete is directly governed by the constituent materials in the mixture. Unit weight is a key property that influences both the structural performance and the

self-weight of concrete elements. Consequently, the effect of partial replacement materials on fresh density depends on both the intrinsic characteristics of the substitute material and its replacement level.

Experimental results indicated that partial substitution of cement with FA led to a reduction in the fresh density of concrete. For instance, the incorporation of 10% FA together with 15% GP in Mix 1 yielded a fresh density decrease of about 1.82%, 2356.9 kg/m³, compared to 2400.5 kg/m³ for the control mixture. This reduction is likely attributed to the lower density of FA relative to OPC, with reported densities of 2360 kg/m³ and 3150 kg/m³, respectively. Moreover, replacing natural fine aggregates with GP generally led to a reduction in the fresh density of concrete. This trend is primarily due to the lower specific density of waste glass compared with natural sand *(Abdallah & Fan, 2014)*. The magnitude of the density reduction is proportional to the replacement level. For example, other studies reported decreases in fresh density of 0.72%, 0.72%, and 1.1% at GP replacement levels of 5%, 10%, and 15%, respectively *(Rashad, 2014)*. Also, *(Ismail & AL-Hashmi, 2009)* reported that, when incorporating 10%, 15%, and 20% of GP as natural sand replacement, the fresh density of concrete mixtures decreased by 1.26%, 1.96% and 2.26%.

All mixtures incorporating BA exhibited reduced fresh density values. The use of BA as a partial cement replacement markedly decreased the fresh density of the concrete. This decline is associated with the porous microstructure of BA and its elevated water demand, which can increase both the number and size of pores, thereby lowering the fresh density. Consistent with these findings, previous studies have reported a progressive reduction in density with increasing cement replacement levels (0%, 10%, 20%, and 30%) due to the lower density of BA compared with cement *(Arivalagan & Sethuraman, 2021)*.

Although SF has a lower specific gravity than OPC, its use as the sole replacement material does not substantially alter the unit weight of concrete. Observed variations in fresh density in mixtures containing SF are therefore more plausibly attributed to other simultaneous partial replacements included to accommodate SF. For example, in Mix 4, where 15% SF was combined with 15% BA and 15% FA, the fresh density decreased by 16.5%.

Mixes incorporating RP exhibited lower fresh densities than the control mixture. In the present study, the control mixture had a fresh density of 2400.5 kg/m³, whereas mixtures with higher RP contents (Mix 7 and Mix 6) recorded fresh densities of 1381 kg/m³ and 1985.6 kg/m³, which

account for 42.5% and 17.3% decrease, respectively. This pronounced reduction is primarily attributed to the much lower density (specific gravity) of plastic aggregates relative to natural fine aggregates (Pasha et al., 2025). For example, reported densities for RP and sand are 386.7 kg/m³ and approximately 1573 kg/m³, respectively, indicating that RP is about 69.7% lighter than sand *(Ismail & AL-Hashmi, 2008)*. Nonetheless, it was observed that the incorporation of 10% RP in combination with 15% BA produced a slight increase of about 1% in the fresh density, suggesting an interaction between these constituents that partially offsets the density reduction typically associated with RP.

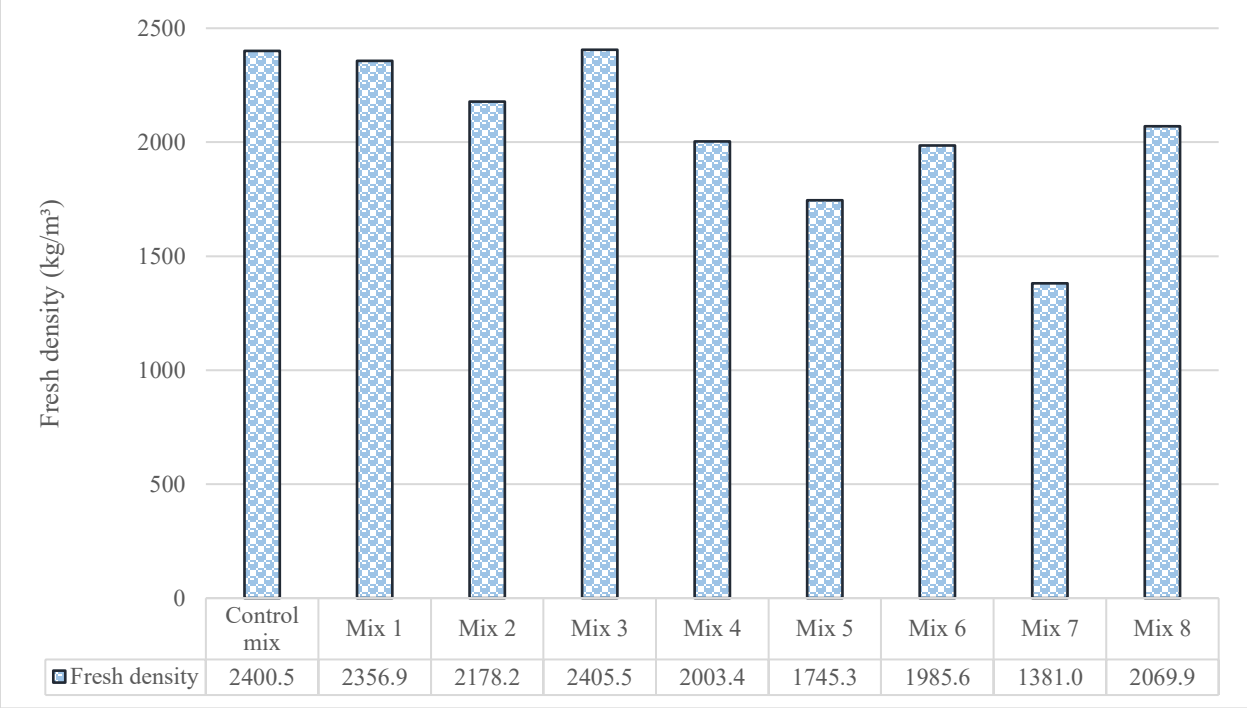


Fig. 15 Fresh density

4.3 Compressive strength and indirect tensile strength

All reported compressive and tensile strengths represent the mean of three specimens, with error bars in the figures indicating the standard deviation.

Mix 1 (10% FA and 15% GP) exhibited the highest compressive strength among all mixes, with increases of 7.9% after 14 days of curing and 9.2% after 28 days relative to the control mix. Similarly, the indirect tensile strength increased by 48.2% and 42.31% at 14 and 28 days, respectively. These enhancements are attributed to the combined use of FA as a partial cement

replacement and GP as a partial replacement for fine aggregate. The incorporation of FA was reported to demonstrate significant positive effects on compressive strength of concrete, particularly at later curing ages *(Hefni et al., 2018)*. The optimal FA replacement level for maximizing 28-day compressive strength is frequently reported in the range of 5–20% of the cement mass *(Reddy & Reddy, 2013)*. For example, *(Sharma et al., 2022)* reported strength gains of 4.71% and 10.06% at 28 days for FA replacement levels of 5% and 10%, respectively.

Furthermore, the incorporation of GP at moderate replacement levels (approximately 10–30%) generally enhances compressive strength. This improvement has been attributed to the angular morphology of glass particles, which improves mechanical interlocking and paste–aggregate bonding, as well as potential pozzolanic reactions associated with the finest particle fractions *(Ismail & AL-Hashmi, 2008; Tamanna et al., 2020)*. Several studies have also reported increases in split tensile strength, with a maximum typically observed at around 20% replacement, followed by a decline at higher replacement ratios *(Arivalagan & Sethuraman, 2021)*.

Mix 2 (10% SF, 15% GP, and 15% RP) showed, relative to the control mix, substantial reductions in compressive strength of 37% and 38% after 14 and 28 days of curing, respectively. Correspondingly, indirect tensile strength decreased by approximately 8.7% at 14 days and 30.1% at 28 days. Although low contents of GP are generally reported to enhance concrete strength, and SF is well documented to significantly increase compressive strength, the combined presence of GP and RP at the investigated levels led to net strength losses. Silica fume modifies the cementitious matrix through both physical and pozzolanic mechanisms, with its extremely fine particles reducing bleeding and increasing cohesiveness in the fresh state *(American Concrete Institute, 2000)*. SF also contributes to the densification of the interfacial transition zone between the cement paste and aggregates by reducing voids, thereby improving the bond strength at the paste–aggregate interface. Chemically, SF is a highly reactive pozzolan; it consumes calcium hydroxide (CH) and forms additional calcium silicate hydrate (C-S-H) gel, which is the primary binding phase in concrete *(Korjakins et al., 2012)*. However, by replacing 15% of cement with SF, and 15% of natural fine aggregates with GP, *(Damdelen et al., 2025)* recorded 8.3% compressive strength loss, concluding that the introduction of higher proportions of GP or SF disrupts the optimal void filling within the concrete, reducing the overall density and structural integrity.

In contrast to SF and GP, the partial replacement of natural fine aggregates by RP typically induces a significant reduction in compressive strength. This reduction is commonly attributed to the poor interfacial bonding and low adhesive capacity between the hydrophobic plastic surface and the cement paste, as well as the increased likelihood of entrapped voids *(Guo et al., 2023)*.

Mix 3 (10% BA and 15% RP) showed moderate reductions in compressive strength of 37% and 38% at 14 and 28 days, respectively. *(Al Biajawi et al., 2022)* concluded that BA, when acting as a pozzolanic material, generally contributes to strength development, especially beyond 28 days, where finely divided BA can enhance the packing density of the microstructure and promote the formation of a denser C-S-H gel, thereby improving mechanical performance. However, early-age strength (before 28 days) may be reduced, and several studies indicate that the long-term compressive strength can approach that of conventional concrete, with strength gains from pozzolanic reactions becoming more pronounced at later ages (e.g., 90 days).

In this mix, the inclusion of RP contributed to the observed strength reduction. Plastic aggregate substitution generally leads to decreased compressive strength, mainly due to weaker interfacial bonding with the cement paste compared with natural aggregates *(Guo et al., 2023)*. Surface treatments, such as sand coating, have been shown to partially mitigate this effect by improving bond quality. Despite the compressive strength reduction, the indirect tensile strength for Mix 3 increased by 41.1% at 14 days and decreased only slightly (12.62%) at 28 days compared to the control. This early-age increase has been associated with improved packing and redistribution of fine particles in the matrix *(Al Biajawi et al., 2022)*.

Mix 4 (15% FA, 15% SF, and 15% BA) experienced severe reductions in both compressive and indirect tensile strength. At 14 days, compressive and indirect tensile strengths decreased by 77.8% and 14.3%, respectively, while at 28 days they decreased by 54.6% and 7.2%, respectively, relative to the control.

Mix 5 (30% GP and 20% RP) exhibited substantial strength reductions, with compressive and indirect tensile strengths decreasing by 46.9% and 10.4% at 14 days, and by 43.7% and 40.7% at 28 days, respectively. The pozzolanic activity of GP involves the reaction of its reactive silica, particularly in finely ground form, with calcium hydroxide released during cement hydration to form additional C-S-H gel. This process enhances strength and refines the pore structure *(Kamali & Ghahremaninezhad, 2015)*. The rate of strength gain between 14 and 28 days is influenced by

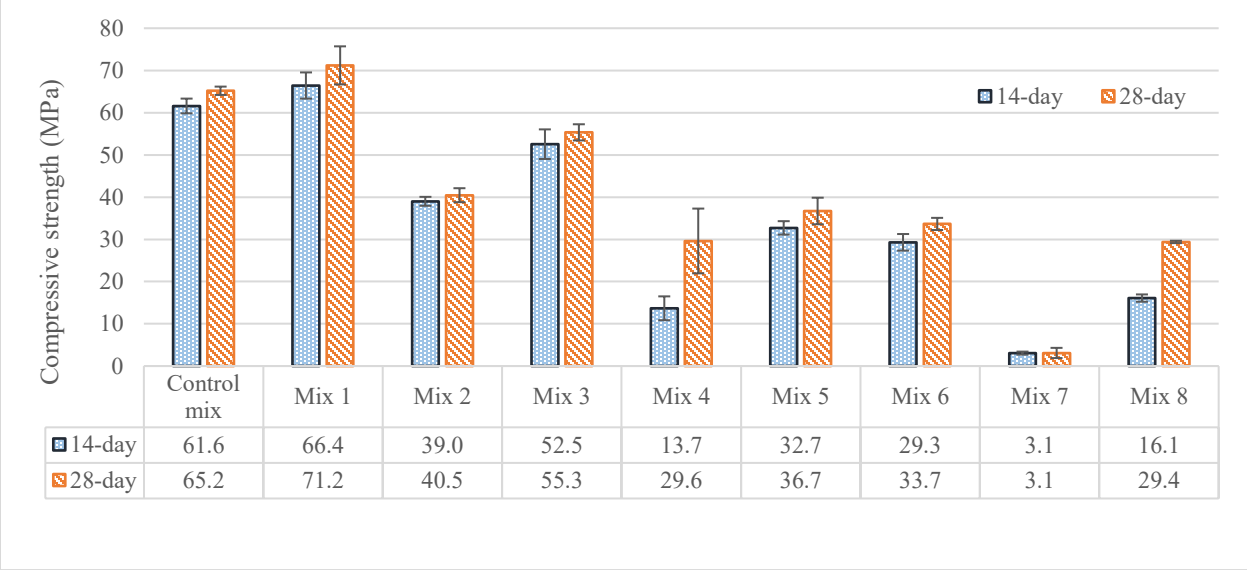
both the GP replacement level and its particle size distribution. Finer GP particles tend to promote a more pronounced pozzolanic reaction and a greater strength increase at later ages than coarser particles *(Khan et al., 2020)*. However, the concurrent presence of RP can counteract these benefits. The irregular geometry and rough surface texture of many plastic particles can adversely affect workability and compaction, which in turn reduces achievable strength *(Thorneycroft et al., 2018)*.

Mix 6 (50% GP and 25% RP) showed pronounced strength reductions, with compressive strengths decreasing by 52.4% at 14 days and 48.4% at 28 days, and indirect tensile strengths decreasing by 12.05% and 34.4% at 14 and 28 days, respectively.

Mix 7 (15% FA, 15% SF, and 50% RP) resulted in an extreme reduction in compressive strength of approximately 95% at both 14 and 28 days. Similarly, indirect tensile strength decreased by approximately 72.8% and 79.3% at 14 and 28 days, respectively. These drastic strength losses are primarily attributed to the high replacement level of RP and its associated adverse effects, including poor paste–plastic bonding, hydrophobic surface characteristics, increased void content and overall porosity, lower stiffness and intrinsic strength of the plastic phase, variations in effective water–cement ratio, and inappropriate particle size distributions. Through their study, *(Oluwole et al., 2025)* reported that using up to 30% RP as partial NFA replacement yielded around 49% reduction in strength compared to the control mix. Under tensile loading, a weak interfacial bond promotes pull-out of plastic particles rather than fracture of the plastic or the surrounding matrix, indicating that failure is often governed by bond rather than material rupture *(Ferreira et al., 2012; Ullah et al., 2022)*. Particle shape and surface texture further influence pull-out behavior; more angular and rougher plastic particles can reduce workability and complicate adequate compaction *(Harihanandh & Karthik, 2022)*.

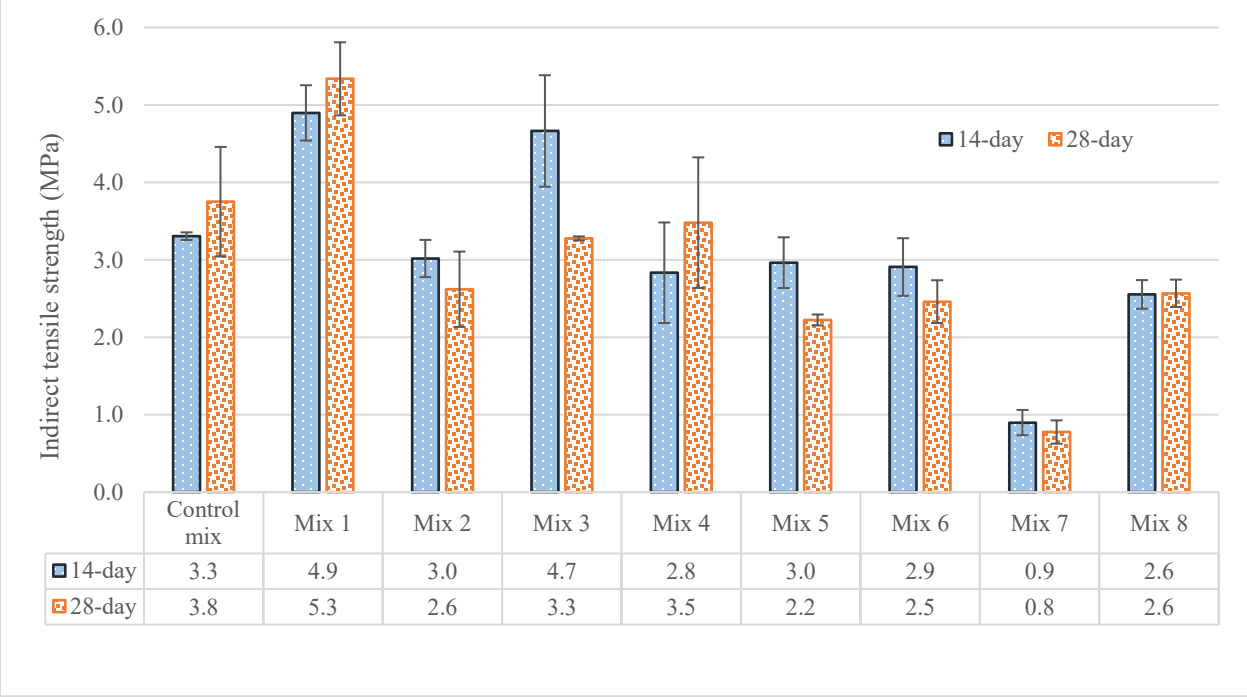
Mix 8 (50% GP) exhibited high reductions in both compressive, 73.9% and 54.9%, and indirect tensile strengths, 21.2% and 31.6%, at 14 and 28 days, respectively. In his study, *(Borhan, 2012)* reported 22% decrease in the 28-day splitting tensile strength of concrete containing 60% of GP. For both Mix 6 and Mix 8, the pronounced early-age strength losses can be associated in part with the relatively slow pozzolanic reaction of GP. The reaction between the silica in GP and calcium hydroxide generated during cement hydration typically progresses more slowly than the primary hydration reactions of Portland cement *(Korjakins et al., 2012)*. Consequently, at early ages such

as 14 and 28 days, the full potential of strength development associated with the pozzolanic activity of GP may not yet be realized, whereas additional strength gains may occur at later ages (e.g., 90 days or more) *(Korjakins et al., 2012)*.



	Control mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
14-day	61.6	66.4	39.0	52.5	13.7	32.7	29.3	3.1	16.1
28-day	65.2	71.2	40.5	55.3	29.6	36.7	33.7	3.1	29.4

Fig. 16 Compressive strength



	Control mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
14-day	3.3	4.9	3.0	4.7	2.8	3.0	2.9	0.9	2.6
28-day	3.8	5.3	2.6	3.3	3.5	2.2	2.5	0.8	2.6

Fig. 17 Indirect tensile strength

4.4. Dry density, void ratio, and water absorption

Mix 1 (10% FA and 15% GP) produced, at 14 and 28 days, respectively, a 6.7% and 2% reduction in dry density, a 31.4% and 19.6% reduction in water absorption, and a 35.4% and 26.7% reduction in void ratio. The decrease in dry density is consistent with the investigation conducted by (Mardani-Aghabaglou et al., 2013) where density reductions of about 1.2, 4.6, and 6.9% were observed with the incorporation of 20, 40, and 60% FA in concrete. The partial substitution of cement with FA typically leads to a reduction in the dry density of concrete (Gradinaru et al., 2018). This behavior is predominantly attributed to the finer and often spherical morphology of FA particles (Babor et al., 2009) and to their lower specific gravity relative to Portland cement. FA usually exhibits a specific gravity in the range of 2.1–2.5, whereas cement typically ranges from 3.12 to 3.16 (Reddy & Reddy, 2013; Sharma et al., 2022).

With respect to void ratio, the principal effect of FA is the refinement of the pore structure. FA tends to reduce the proportion of larger pores and to promote the development of a more homogeneous pore network. This refinement, particularly the reduction of capillary pores, substantially decreases the permeability of concrete to water and gases (Kamali & Ghahremaninezhad, 2015). The incorporation of FA generally lowers water absorption and permeability, thereby limiting the ingress of moisture and aggressive agents (Ganiron, 2013; Reddy & Reddy, 2013). Owing to their very fine size, FA particles can act as fillers, occupying interstitial spaces between larger cement grains and aggregate particles. Furthermore, because the pozzolanic reaction of FA proceeds more slowly than the initial hydration of cement, its densification effects, especially pore refinement, tend to become more pronounced at later curing ages.

Partial replacement of natural fine aggregates with GP also generally reduces both fresh and hardened concrete densities (Ganiron, 2013; Korjakins et al., 2012; Mishra et al., 2020). This effect mainly comes from the lower specific gravity of GP compared with natural sand (Mishra et al., 2020). GP usually has a specific gravity between 2.0 and 2.6 and is therefore expected to decrease concrete density when incorporated (Hakim et al., 2024; M. Adaway & Y. Wang, 2015). The pozzolanic reactivity of GP can additionally contribute to pore refinement and densification of the cementitious matrix (Omran et al., 2017). The commonly observed reduction in water absorption with GP inclusion is attributed to the essentially impermeable character of glass particles relative to sand and to their negligible intrinsic water absorption(Mishra et al., 2020; Rashad, 2014).

Mix 2 (10% SF, 15% GP, and 15% RP) resulted in a 6.8% and 9% decrease in dry density at 14 and 28 days, respectively, a 41.1% and 56.4% increase in water absorption, and a 77% and 78.6% increase in void ratio. Partial replacement of cement with SF is generally reported to have only a limited effect on concrete dry density. Although SF has a lower specific gravity (approximately 2.2) than Portland cement (approximately 3.12), observed changes in unit weight are often associated with modifications in mixture proportions made to accommodate SF rather than with SF itself. SF is known to substantially reduce concrete permeability; however, this does not necessarily translate into an increase in mass per unit volume (Wattanapornprom & Stitmannaithum, 2015).

SF significantly modifies the pore structure of cement paste and mortar. Its main effect is the homogenization of the pore network through a reduction in the number and volume of large and capillary pores (American Concrete Institute, 2000). Numerous studies have reported that partial substitution of cement with SF reduces the water absorption of concrete, a trend also observed in mortars and fiber-reinforced concretes incorporating SF.

The RP, as a partial replacement for fine aggregates, generally leads to a reduction in the dry density of concrete (Lokeshwari & Ostwal, 2019), primarily due to the considerably lower specific gravity of RP in comparison with natural fine aggregates, reported to be as low as 69.7% of that of natural sand (Ismail & AL-Hashmi, 2008). The incorporation of RP has been associated with increased concrete porosity. This increase is commonly ascribed to voids formed at the interface between plastic aggregates and the cementitious matrix, as well as to intrinsic differences in porosity between plastic particles and natural aggregates (Guo et al., 2023).

Mix 3 (10% BA and 15% RP) exhibited, at 14 and 28 days, respectively, a 4.9% and 3.8% reduction in dry density, a 39.7% and 23.8% increase in water absorption, and a 28.6% and 51.9% increase in void ratio. The use of BA as a partial cement replacement is generally associated with a reduction in concrete dry density, which often becomes more pronounced as BA content increases; for instance, a decrease in density from 1106 to 996 kg/m³ has been reported when BA content increased from 0% to 100% (Al Biajawi et al., 2022). The primary factors underlying this reduction include the lower intrinsic density of BA, the higher porosity of BA particles, and the increased fineness and specific surface area of ground BA.

BA has also been observed to increase concrete porosity, as BA particles typically contain more internal pores than cement. Contributing factors to this increased porosity include the inherently porous particle structure, higher water demand, particle fineness and angularity, and the characteristics of BA's pozzolanic activity.

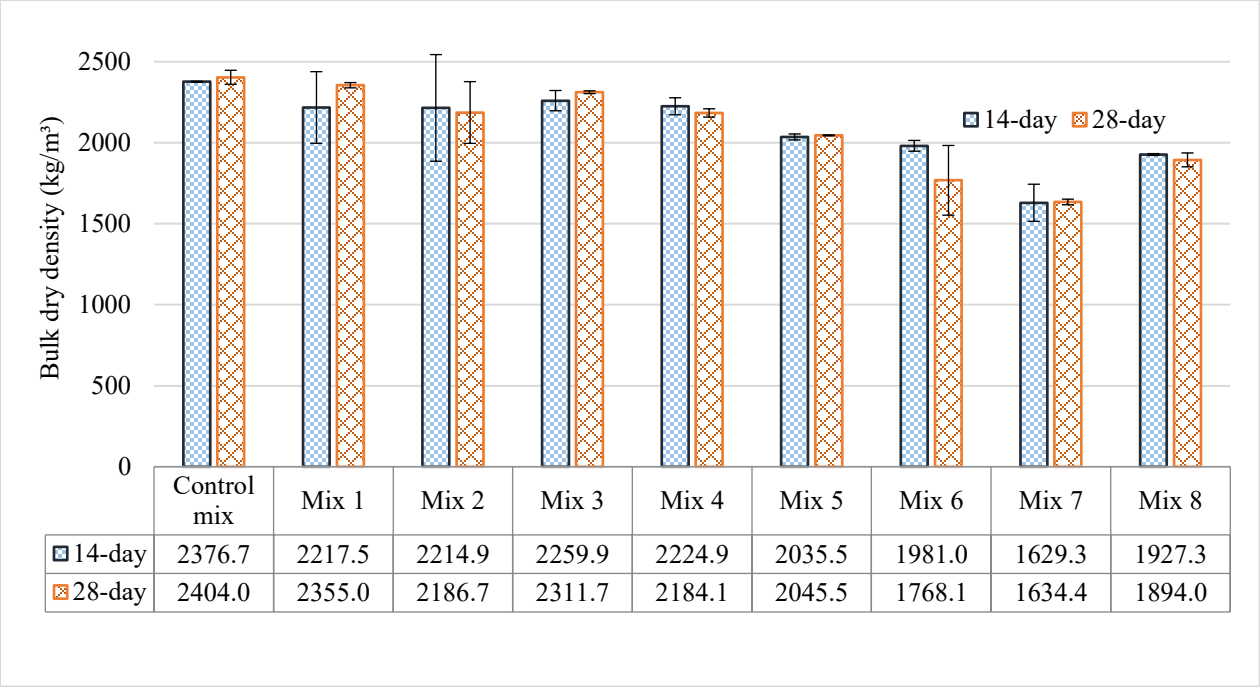
Mix 4 (15% FA, 15% SF, and 15% BA) resulted, at 14 and 28 days, respectively, in a 6.4% and 9.1% reduction in dry density, a 43.8% and −7.31% change in water absorption (i.e., an increase at 14 days and a net decrease at 28 days), and a 26.7% and 20.7% increase in void ratio.

Mix 5 (30% GP and 20% RP) showed, at 14 and 28 days, respectively, a 14.4% and 14.9% reduction in dry density, a 43.7% and 37.7% increase in water absorption, and a 56.9% and 85.2% increase in void ratio.

Mix 6 (50% GP and 25% RP) produced, at 14 and 28 days, respectively, a 16.6% and 26.4% reduction in dry density, a 34% and 42.3% increase in water absorption, and a 52.9% and 29.1% increase in void ratio.

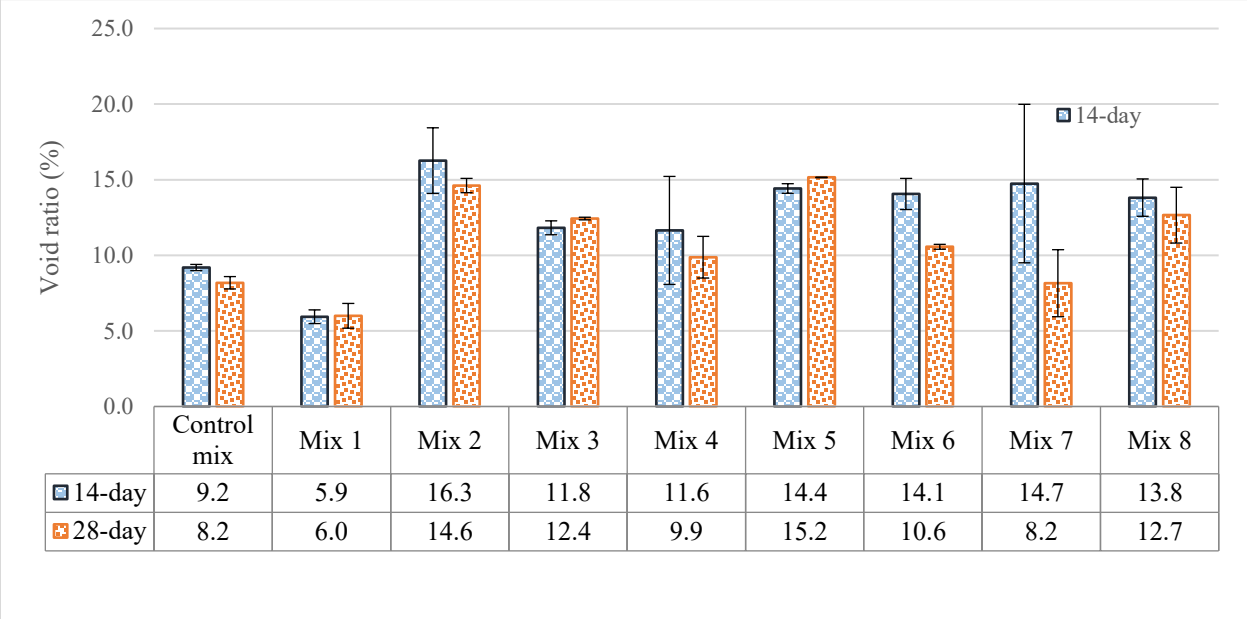
Mix 7 (15% FA, 15% SF, and 50% RP) resulted, at 14 and 28 days, respectively, in a 31.4% and 32% reduction in dry density, a 94.3% and 69% increase in water absorption, and a 60.4% increase in void ratio at 14 days, followed by a 0.4% decrease at 28 days.

Mix 8 (15% GP) yielded, at 14 and 28 days, respectively, an 18.9% and 21.2% reduction in dry density, a 32.7% and 76.8% increase in water absorption, and a 50.3% and 54.7% increase in void ratio.



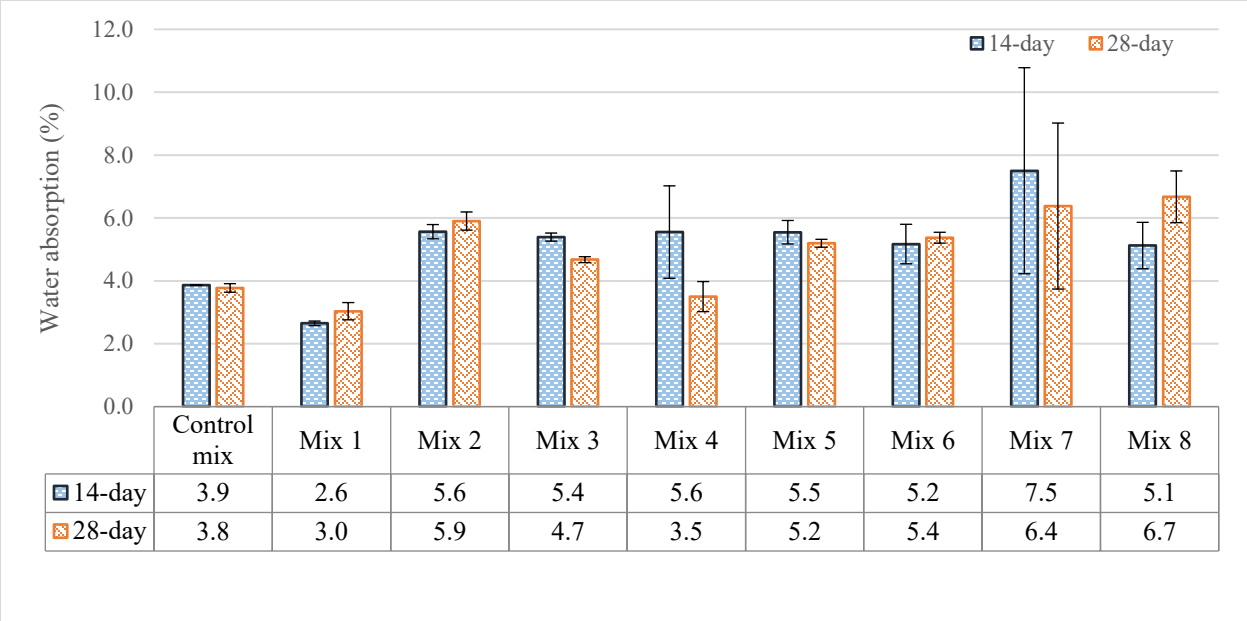
	Control mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
14-day	2376.7	2217.5	2214.9	2259.9	2224.9	2035.5	1981.0	1629.3	1927.3
28-day	2404.0	2355.0	2186.7	2311.7	2184.1	2045.5	1768.1	1634.4	1894.0

Fig. 18 Bulk dry density



	Control mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
14-day	9.2	5.9	16.3	11.8	11.6	14.4	14.1	14.7	13.8
28-day	8.2	6.0	14.6	12.4	9.9	15.2	10.6	8.2	12.7

Fig. 19 Void ratio



	Control mix	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
14-day	3.9	2.6	5.6	5.4	5.6	5.5	5.2	7.5	5.1
28-day	3.8	3.0	5.9	4.7	3.5	5.2	5.4	6.4	6.7

Fig. 20 Water absorption

5. Sustainability evaluation

5.1. Embodied carbon

The transition towards sustainable concrete production is not optional; it is an urgent imperative, primarily due to the considerable environmental burden associated with conventional concrete. This section evaluates the sustainability implications of incorporating fly ash (FA), silica fume (SF), and bottom ash (BA), together with glass powder (GP) and recycled plastic (RP), as partial replacement materials for cement and fine aggregates, respectively.

The concrete industry consumes vast quantities of natural resources and contributes substantially to greenhouse gas emissions. In this study, the embodied carbon (EC) of the investigated concrete mixes was quantified using previously published data, with the corresponding embodied carbon factors presented in Table 5, extracted from the relevant literature. The use of SCMs, such as FA, SF, and BA, as partial substitutes for cement, and the use of waste glass and recycled plastic as partial replacements for fine aggregates are key strategies for mitigating the carbon footprint of concrete mixtures.

In a recent investigation, (Oluwole et al., 2025) reported reductions in EC of 9.2%, 0.65%, and 9.86% for mixes incorporating 10% SF, 30% RP, and a combined 10% SF + 30% RP, respectively. Similarly, (Damdelen et al., 2025) observed that the incorporation of 20% SF, 20% GP, and 20% SF + 20% GP in separate mixtures led to EC reductions of 14.17%, 11.98%, and 30.23%, respectively, relative to a control mix.

Analysis of the data presented in Fig. 21 indicates a general reduction in CO_2 emissions when SCMs are used as partial replacements for cement. Among the mixes examined, Mix 4 (containing 15% FA, 15% SF, and 15% BA) exhibited the greatest reduction in CO_2 emissions relative to the control mix, attributable to the replacement of 45% of the total cement volume with SCMs, resulting in a 37.53% decrease in embodied CO_2. In contrast, Mix 5, Mix 6, and Mix 8 exhibited higher CO_2 emissions per cubic meter than the control mix, with increases of 0.99%, 1.79%, and 2.23 %, respectively. Given that cement is the principal source of CO_2 emissions in concrete, this increase is attributed to the absence of cement substitution by alternative materials, together with the incorporation of GP in these mixes, GP having a 36.67% higher EC factor than fine aggregates.

Table 5 Embodied carbon factors of materials

Materials	Embodied carbon factor (kg CO_2/kg)	References
Cement	0.82	(Collins, 2010)
Tap water	0.00091	(Botto, 2009)
Fine aggregates	0.01577	(G. Hammond et al., 2011)
Coarse aggregates	0.0408	(Turner & Collins, 2013)
Fly ash	0.027	(Turner & Collins, 2013)
Silica fume	0.028	(Black, 2016)
Bottom ash	0.075	(Darhamsyah et al., 2025)
Glass powder	0.043	(Raut et al., 2023)
Recycled plastic	0.0051	(G. P. Hammond & Jones, 2008)

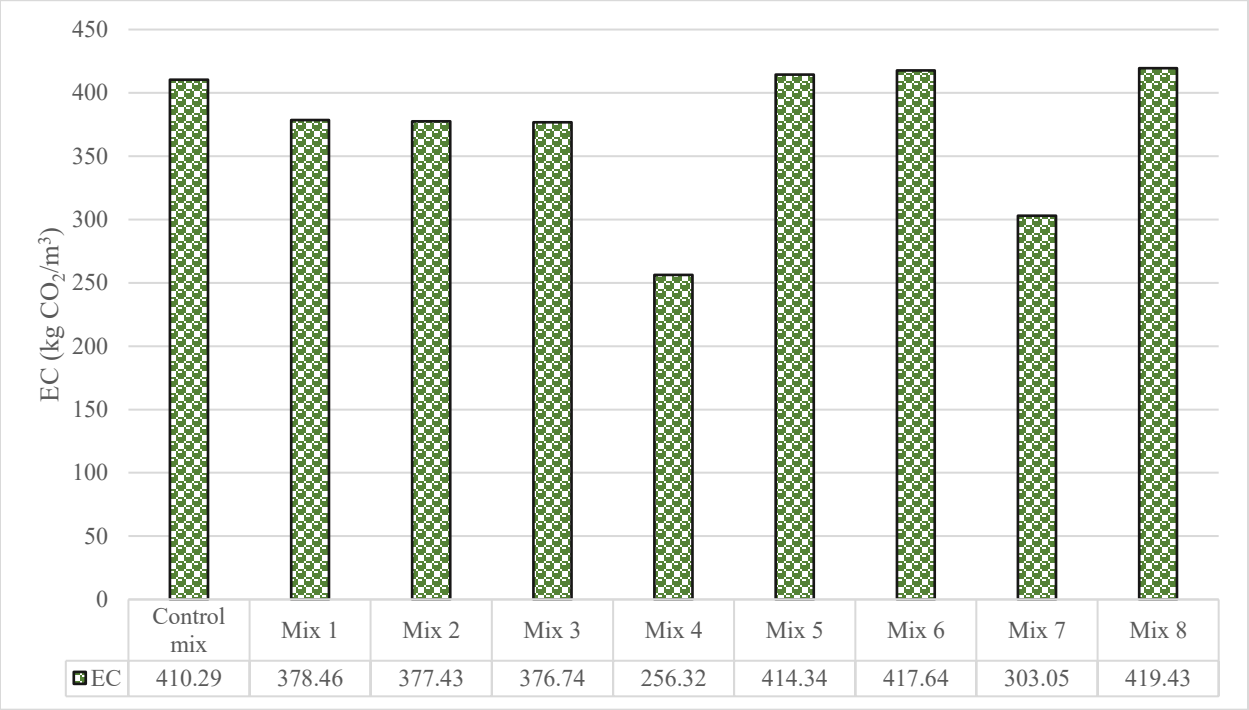


Fig. 21 Embodied carbon per mix

5.2. Eco-strength efficiency (ESE)

Defined as the strength per unit of embodied CO_2 (MPa/kg $CO_2.m^{-3}$), Eq. 1, eco-strength efficiency in concrete measures the ratio of the 28-day compressive strength (MPa) to the embodied carbon (EC), identifying the mixtures that maximize performance while minimizing environmental impact. ESE tends to minimize the total EC emissions by decreasing reliance on OPC, maintaining compressive strength while minimizing the environmental impact, reducing dependency on natural raw materials with industrial by-products and waste materials, and finally enhancing the service life of concrete structures.

$$ESE = \frac{Compressive\ strength\ (28\ days)}{Embodied\ carbon} \qquad \left[\frac{MPa}{kg\ CO_2.m^{-3}}\right]$$

Eq. 1

The ESE results of this investigation are shown in Fig. 22. Only Mix 1 resulted in a higher ESE compared to the control mix by about 18.41%, whereas the lowest recorded was associated with Mix 7, with over 93.58% reduction.

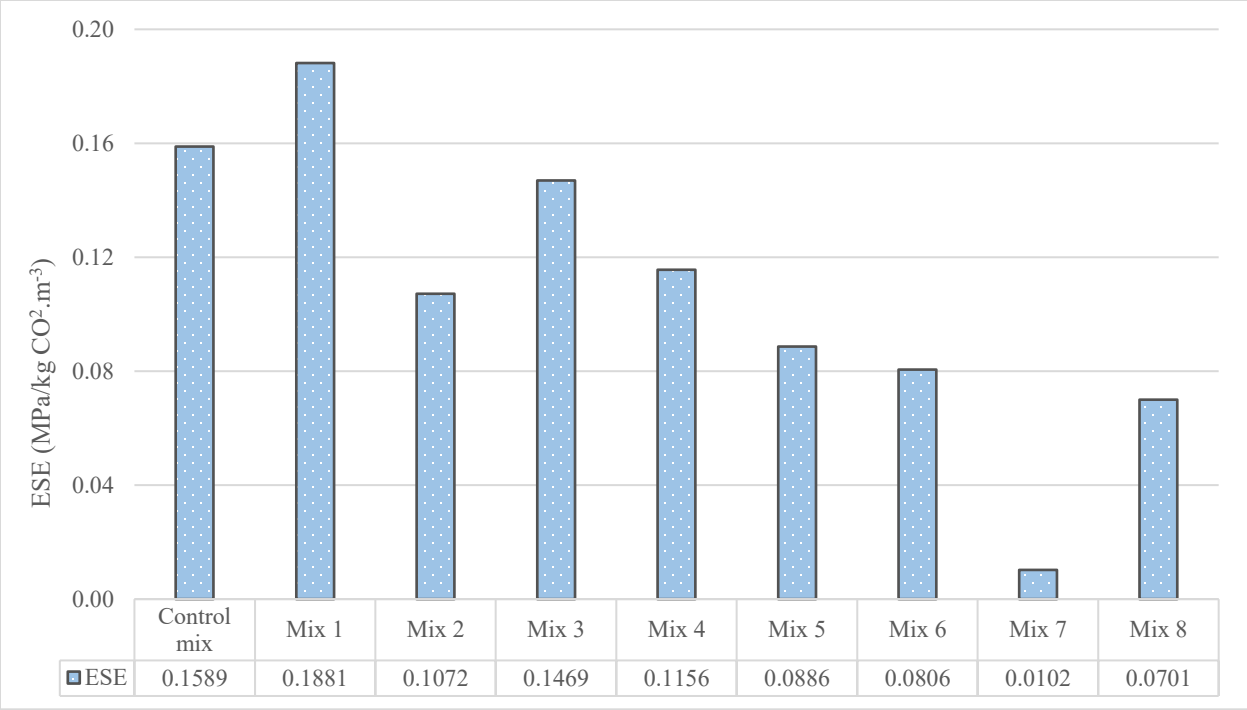


Fig. 22 Eco-strength efficiency per mix

6. Conclusion, recommendations, and limitations

This study systematically evaluated the combined incorporation of fly ash (FA), silica fume (SF), and bottom ash (BA), glass powder (GP), and recycled plastic (RP) in concrete, with the objectives of assessing mechanical performance and embodied carbon for environmental impact assessment. The experimental design was not factorial; therefore, the observed performance reflects the effect of multi-material mixtures.

6.1. Key findings

1. The mixture containing 10% FA and 15% GP (Mix 1) exhibited the most favorable overall performance, with increases in 28-day compressive strength of up to 9.2% and tensile strength improvements exceeding 40%, while simultaneously reducing density, water absorption, and embodied carbon.
2. Mixtures with high levels of RP (≥20-25%) consistently led to substantial reductions in compressive and tensile strength. In extreme cases (Mix 7: 50%RP combined with 15%FA and 15% SF), compressive strength losses exceeded 95% at both 14 and 28 days. These

reductions are primarily attributed to weak interfacial bonding, increased porosity, and disruption of optimized particle packing within the cementitious matrix.

3. Workability, measured by slump and compaction factor, decreased for most modified mixtures, particularly those containing SF, BA, or high GP/ RP contents. An exception occurred at Mix 5 (20% RP), which showed a modest 5.9% increase in slump, possibly due to RP's lower water absorption relative to natural sand.
4. All modified mixtures had lower fresh and dry densities than the control mix, with the largest reductions, up to 42.5% in fresh density, observed for high RP mixtures.
5. From a sustainability standpoint, mixtures with higher SCMs contents achieved notable reductions in embodied carbon, with the maximum decrease of 37.5% when up to 45% of the cement was replaced in Mix 4. However, these environmental gains were often accompanied by substantial reductions in mechanical performance (a 56.4% reduction in 28-day compressive strength), highlighting the need for a balanced, sustainability- and performance-based mix design strategy.
6. The inclusion of the eco-strength efficiency (ESE) index identified Mix 1 as the only mixture that outperformed the control mix on a combined strength-per-carbon basis, with an 18.4% increase in ESE. These findings suggest that sustainable concrete design should prioritize optimized combinations of alternative materials rather than maximizing replacement levels.

6.2.Recommendations

Based on these results, the following recommendations are made for future mix design and application:

- Moderate replacement levels of FA and GP (approximately 10–15%) can simultaneously improve mechanical performance and enhance sustainability metrics in concrete, provided workability is managed.
- High RP replacement levels (>20–25%) should be avoided in structural applications due to severe strength reductions and increased porosity.
- The concurrent use of multiple SCMs requires careful optimization, as excessive overall replacement levels can lead to significant performance degradation despite large embodied carbon reductions.

- Performance-based indicators, such as ESE, should be adopted when selecting optimal concrete mixtures to ensure an appropriate balance between mechanical capacity and environmental impact.
- The use of chemical admixtures, particularly superplasticizers, should be considered in future mix designs to compensate for the loss of workability associated with fine or high–specific-surface-area materials.

6.3.Limitations

This study provides valuable insights but is subject to several limitations.

First, the experimental program was restricted to relatively short curing ages (14 and 28 days), and therefore, long-term performance was not assessed. Some mixtures may still experience strength gains beyond 28 days.

Second, durability-related properties such as chloride ion penetration, freeze–thaw resistance, and sulfate attack were not investigated, limiting the ability to fully evaluate long-term sustainability and service life.

Third, the experimental design did not systematically isolate individual variables, limiting the quantification of interaction effects among different materials. The observed performance of multi-component mixtures reflects the net combined influence of all constituents, not the independent contribution of any single material.

Finally, the embodied carbon analysis relied on literature-based emission factors rather than project-specific life cycle assessment (LCA) data and does not include transportation, GP grinding, and RP reprocessing energies, introducing slight uncertainty into the environmental evaluation.

7. Future scope and practical implications for construction

In light of these limitations, the following areas are recommended for future research:

- Conduct long-term performance studies (e.g., at 56, 90, and 180 days) to capture ongoing pozzolanic reactions of SCMs and their influence on strength development and microstructural refinement.

- Investigate durability parameters, including chloride ion penetration, resistance to chemical and sulfate attack, and freeze–thaw durability, to more comprehensively assess the suitability of these materials for structural applications.
- Perform detailed microstructural characterization (e.g., X-ray diffraction (XRD), scanning electron microscopy (SEM), and analysis of the interfacial transition zone) to understand mechanisms governing changes in strength, porosity, and bonding.
- Explicitly quantify synergistic and antagonist interaction effects; a statistically designed factorial experiment is recommended.
- Extend the sustainability assessment through comprehensive LCA, incorporating stages such as raw-material extraction, transportation, processing, and end-of-life scenarios.

From a practical engineering perspective, this study provides guidance for the development of performance and sustainability-oriented concrete mixtures. The results show that mechanical performance and environmental benefits can be achieved concurrently, but only within carefully controlled replacement ranges. In particular, moderate levels of FA and GP addition can enhance strength while reducing embodied carbon, making these mixtures promising for structural applications without compromising structural integrity. Conversely, the significant strength losses associated with high RP contents indicate that such replacements should be restricted to non-structural elements unless additional measures such as surface treatment of RP or modified matrix design are implemented. The application of the eco-strength efficiency metric offers a pragmatic decision-making tool for practitioners, enabling mix selection based on an integrated assessment of mechanical performance and environmental impact rather than strength criteria alone.

Abbreviations

SCMs	Supplementary Cementitious Materials
FA	Fly ash
SF	Silica fume
BA	Bottom ash
GP	Glass powder
RP	Recycled plastic

OPC	Ordinary Portland Cement

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Author contributions

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Data availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Competing interests

The authors declare no competing interests.

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