Heliyon 10 (2024) e38065

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Mechanical and physical characteristics of concrete mixed with sugarcane bagasse ash and recycled polyethylene terephthalate

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ARTICLE INFO

Keywords:
Sustainable concrete
Waste materials
Material properties
Fresh and hardened concrete

ABSTRACT

The goal of this study was to produce sustainable concrete by reducing reliance on cement, which contributes to high carbon footprints, and natural sand, which is being depleted. Sugarcane bagasse ash (SCBA) was used to partially replace cement at 5 %, 10 %, and 15 %, while recycled polyethylene terephthalate (RPET) was used to partially replace sand at 5 %, 10 %, 15 %, and 20 %. The effects of these substitutions on concrete's mechanical and physical properties were examined after 28 days of water curing. The study observed a decrease in fresh density by 0.36 %–2.67 % with SCBA and RPET inclusion. The slump values ranged between 93 mm and 140 mm, indicating good workability. The reference concrete's compressive strength was 39.65 MPa, while the mix with 5 % SCBA and 10 % RPET achieved 38.23 MPa. This mix also showed a 1.2 % higher split tensile strength than the reference concrete. Although the reference concrete's flexural strength was the highest at 4.56 MPa, all SCBA-RPET mixes remained within 86 % of this value. All modified mixes weighed less than the reference concrete, with the compressive strength-to-weight ratio of the mix with 5 % SCBA and 10 % RPET being closest to the reference mix with only a 2.44 % reduction. These findings suggest that SCBA and RPET can be effectively used to produce sustainable concrete with comparable mechanical properties to conventional concrete.

1. Introduction

About 6 % of worldwide emissions of greenhouse gas are attributed to cement. In order to reduce greenhouse gas emissions, a number of authors have carried out a great deal of research and development work. These studies include an opportunity for the replacement of cement with fly ash [1–5], municipality waste ash [6], marble powder [7], granite powder [8], brick powder [9], wheat straw ash [10], and sugarcane bagasse ash [11]. Sugarcane bagasse ash (SCBA) is a waste product mostly indiscriminately disposed of in landfills. This material can partially replace cement and boost concrete's compressive strength [12–15].

Additionally, sand and gravel account for about 65–85 % of concrete's natural material consumption [16]. Plastics take 20–500 years to decompose [17] and can be an environmental menace. Studies have unveiled the suitability of plastic usage in concrete production [18–20]. This niche has recently emerged as one of the leading research subjects [21]. When natural aggregates were substituted with lightweight materials in the mixing constituent of the cement-based materials, some physical properties such as unit

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https://doi.org/10.1016/j.heliyon.2024.e38065
Received 1 June 2024; Received in revised form 14 September 2024; Accepted 17 September 2024
Available online 18 September 2024

weight decreased [22–28]. Colangelo et al. [29] assert that the merits of lightweight concrete include minimizing concrete manufacturing and placement time. Other advantages include a reduction of construction expenses and the improvement of thermal insulation of the structure. There can also be a reduction in the sizes of the material sections [30] and improved sound insulation [31].

Recycled polyethylene terephthalate (RPET) has been considered as a fibre in concrete [32,33]. The appending of recycled plastic fibres purportedly boosted the concrete's ductility. Figueiredo et al. [19] investigated RPET as aggregates in concrete. The authors revealed an increase in void index and water absorption but a decrease in tensile and compressive strength. They reported that surface texture, shape, bond, and voids of the RPET aggregates influence the mechanical strength performance. Islam [20] investigated RPET as partial substitutions of coarse aggregates. The author reported that the concrete produced revealed reduced compressive strength of up to 53 %. It was found that the RPET's form and smooth surface are responsible for its concrete's higher workability performance. Bamigboye et al. [34] substituted fine aggregate with RPET, which underwent melting, solidification, grinding, and sieving. The authors reported a decline in strength attributed to poor bonding and weak absorption of the modified aggregate.

Meanwhile, in the realm of sustainable construction, the utilization of SCBA as a component in concrete production has also garnered significant attention. Various studies highlight the potential of SCBA to enhance the mechanical and durability properties of concrete. For instance, Ali et al. [35] studied the compressive strength of concrete with varying percentages of SCBA, finding that a 10 % replacement yielded the highest strength activity index. Similarly, Praveenkumar and Sankarasubramanian [36] investigated high-performance concrete blended with SCBA at various replacement levels of ordinary Portland cement (OPC), demonstrating that SCBA significantly enhanced the concrete's strength and durability. Additionally, Bisanal et al. [37] focused on the use of SCBA as a mineral admixture, demonstrating its effectiveness in improving the compressive, tensile, and flexural strengths of concrete. Furthermore, Quedou et al. [38] assessed the mechanical and durability characteristics of SCBA as a partial OPC replacement, noting that a 10 % SCBA mix exhibited optimal performance in terms of compressive strength, though higher replacement levels increased water absorption and carbonation. These studies collectively underscore the versatility and efficacy of SCBA as a sustainable alternative in concrete production, contributing to both environmental conservation and improved material performance.

Therefore, this study addresses the pressing need for more sustainable concrete by investigating the partial replacement of cement with SCBA and natural sand with RPET. SCBA, an agricultural byproduct of the sugar industry, is rich in silica and has pozzolanic properties, making it a viable supplementary cementitious material [39–42]. On the other hand, RPET, derived from post-consumer plastic bottles, offers a promising solution to the dual challenges of plastic waste management and sand depletion [19,20,34].

The selection of SCBA and RPET for this research is rooted in their environmental benefits and potential to enhance the mechanical and physical properties of concrete. SCBA utilization not only reduces cement consumption but also diverts agricultural waste from landfills, thus contributing to waste management. RPET, as a substitute for sand, addresses the critical issue of plastic waste while mitigating the environmental impacts of sand mining. The combination of these materials aims to produce a concrete mix that is both eco-friendly and structurally efficient.

Despite the growing interest in alternative materials for concrete, there is a scarcity of comprehensive studies that simultaneously address the replacement of both cement and sand with sustainable materials. Previous research has primarily focused on the individual effects of SCBA and RPET on concrete properties, leaving a research gap regarding their combined impact. This study seeks to fill this gap by examining the effects of SCBA and RPET on the mechanical and physical characteristics of concrete.

By addressing these aspects, the study aims to contribute valuable insights into the development of sustainable concrete with reduced environmental impact, promoting the broader adoption of eco-friendly construction practices.

Therefore, experiments were conducted to probe the concrete mixes' fresh density, workability, weight, split tensile strength, flexural strength, and compressive strength. Therefore, this research first characterised the constituent materials from coarse aggregates, sand, cement, RPET and SCBA. Subsequently, the hardened and fresh qualities of the concrete mixes were determined based on relevant standards as outlined in section 2. Section 3 reveals the findings. Section 4 includes the conclusion of the study.

2. Methodology

The study considered the influence of varying percentages of SCBA that have been sieved and ground to be used as a partial cement substitute. Similarly, differing portions of RPET that have undergone regrind and shredding were used as partial substitutes for fine aggregates. Slump, fresh density, flexural strength, compressive strength, and split-tensile strength tests were conducted on the concrete samples. The mixtures contained RPET as a volume percentage of fine aggregates and SCBA as a weight percentage of cement. This decision was based on earlier reporting on SCBA and RPET use in concrete [28,34,72]. The results were contrasted with the control sample of natural sand and ordinary Portland cement (OPC). The comparison was done to uncover the optimum aggregation of SCBA and RPET.

2.1. Materials

2.1.1. Cement and SCBA

Ordinary Portland Cement 42.5 is the cement type utilized in this investigation. The reputable and widely used Bamburi cement was purchased from a local supplier. The raw SCBA obtained from West Kenya Sugar Company, Kakamega, Kenya, was cured in the sun, sieved through 300 μm, and ground in the ball mill for 1 h. The rotating ball mill used 28.8 Hz, and the grinding media plus the volume of ash fed into the ball mill were held constant throughout the process. The resulting SCBA is with a specific gravity of 1.92.

2.1.2. Aggregates and RPET

Maximum sizes for natural sand and crushed stone were 4.75 mm and 20 mm, respectively. These were purchased from Warren Concrete Ltd. in Nairobi, Kenya. The RPET was purchased from General Plastics Ltd., Nairobi, Kenya. The received RPET was further shredded using a plastic shredder to ensure all particles passed the 4.75 mm sieve.

2.2. Mixture proportions

The experimental work consisted of one control concrete with no addition of SCBA or RPET and twelve blended mixes of SCBA and RPET. The cement was substituted by weight at 5 %, 10 %, and 15 %, while RPET was substituted at 5 %, 10 %, 15 % and 20 % volume of fine aggregates. The British Department of Environment mix design is employed to get a mean desired strength of 39 MPa after 28 days.

The various quantities for concrete mixtures are revealed in Table 1. The table shows the mix proportions of the 13 mixes of one conventional concrete and 12 SCBA-RPET concretes.

The coarse and fine aggregates underwent washing and drying before being added to the mixes. The mixes were undertaken in a mechanical dry mixer and mixed to consistency. The prisms, cylinders, and cubes were refined and greased before casting. Cube samples of 10 cm breadth, 10 cm width, and 10 cm height were used for the compressive strength tests. Cylindrical samples of 20 cm in height and 10 cm in diameter were employed for the split-tensile strength. The flexural strength tests used unreinforced concrete prisms of 35 cm length, 10 cm width, and 10 cm depth. Samples were made for all the mixtures. All tests were done following 28 days of water curing. All specimens were left in moulds after casting and were removed to curing tanks at least 16 h after placement as conditioned in BS EN 12390-2:2019 [43].

2.3. Laboratory tests

2.3.1. Chemical tests conducted

a) X-ray fluorescence chemical tests for SCBA and OPC

The chemical composition of OPC and SCBA was investigated per BS EN 196-2:2013 [44] using X-ray fluorescence (XRF). In Nairobi, Kenya, the Ministry of Mining and Petroleum carried out this experiment. The utilized XRF gun is shown in Fig. 1.

b) X-ray Diffraction Test for Processed SCBA

A diffractometer was used to evaluate the X-ray diffraction (XRD) patterns of the processed SCBA. The National Geosciences Research Laboratories in Kaduna, Nigeria, conducted the evaluation. The SCBA sample was examined using an X-ray diffractometer (Rigaku D/Max-lllC) manufactured in Tokyo, Japan by Rigaku Int. Corp. The device generates room temperature diffractions in the 2 to 500 range using a CuKα radiation set at 40 kV and 20 mA. A scanning rate of 0.5 per minute was used.

2.3.2. Physical tests conducted

(a) Sieve Analysis

The particle size distribution for the fine aggregates was determined using sieve analysis according to BS EN 933-1:2012 [45]. Stacked sieves of varying sizes were used, with the sample placed in the uppermost sieve and manually shaken. Grading graphs were created by plotting cumulative percentages passing through each sieve on the vertical axis against sieve openings on a logarithmic

Table 1
Proportions of all designed mixtures.

Designation	SCBA (%)	RPET (%)	Water (kg/m^3)	Cement (kg/m^3)	SCBA (kg/m^3)	Fine Aggregate (kg/m^3)	RPET (kg/m^3)	Coarse Aggregate (kg/m^3)
Control	0	0	218	375.86	0.00	722.46	0.00	1083.68
S5P5	5	5	218	357.07	18.79	686.33	11.58	1083.68
S5P10	5	10	218	357.07	18.79	650.21	23.15	1083.68
S5P15	5	15	218	357.07	18.79	614.09	34.73	1083.68
S5P20	5	20	218	357.07	18.79	577.96	46.30	1083.68
S10P5	10	5	218	338.27	37.59	686.33	11.58	1083.68
S10P10	10	10	218	338.27	37.59	650.21	23.15	1083.68
S10P15	10	15	218	338.27	37.59	614.09	34.73	1083.68
S10P20	10	20	218	338.27	37.59	577.96	46.30	1083.68
S15P5	15	5	218	319.48	56.38	686.33	11.58	1083.68
S15P10	15	10	218	319.48	56.38	650.21	23.15	1083.68
S15P15	15	15	218	319.48	56.38	614.09	34.73	1083.68
S15P20	15	20	218	319.48	56.38	577.96	46.30	1083.68

Fig. 1. An XRF gun for the analysis of chemical composition.

scale on the horizontal axis.

(b) Bulk Density of Aggregates

Following BS 812:2:1995 [46] a bulk density test was performed on oven-dried specimens utilizing a bulk cylinder. Fig. 2 depicts an example of a cylinder being weighed in preparation for a density test. We measured the bulk densities of coarse aggregates, natural sand, and RPET. The compacted density and the loose density (without compaction) were calculated using Equation (1).

Fig. 2. Weighing a cylinder for density test.

$$\text{Bulk Density} = \frac{M_B - M_A}{V} \quad (1)$$

where:

M_A: the cylinder's mass
M_B: the total mass of the sample and the cylinder
V: the empty cylinder's volume

c) Water Absorption and Specific Gravity

The RPET, fine, and coarse aggregates were examined for specific gravities according to BS EN 1097-6:2013 [47] testing protocols. This also assisted in determining the water absorption (WA) of the fine and coarse aggregates. A mesh setup enabled the coarse aggregates' specific gravity (SG) determination. A pycnometer bottle, shown in Fig. 3, was used to evaluate the SG of RPET and natural sand.

For the SG test, 2000 g of coarse aggregates were used. Weighing the basket after it was submerged in water allowed us to determine its mass in water. The sample was totally submerged when it was placed into the basket, and its weight was recorded. The sample was dried for 24 h at 105 °C in an oven. After drying in the oven, the sample was cooled and weighed to find its mass.

Natural sand samples were submerged in water for 24 h, then patted dry and weighed to determine the saturated and surface-dried weight (M1). Using a pycnometer, the weight of the sample plus the pycnometer (M2) was measured. Water was added to the pycnometer, and the new weight (M3) was recorded. The sample was then dehydrated in an oven at 105 °C for 24 h, and the cooled sample's weight (M4) was determined. SG in saturated surface dry (SSD) condition were calculated using Equation (2). Water absorption was determined using Equation (3).

$$\text{SG based on SSD condition} = \frac{M4}{M1 - (M2 - M3)} \quad (2)$$

$$\text{WA } (\%) = \frac{M1 - M4}{M4} x\,100 \quad (3)$$

where:

$M1$ is the mass of the sample in SSD condition.
$M2$ is the combined mass of the sample and the testing container.
$M3$ is the combined mass of the sample and a testing container filled with water.
$M4$ is the total mass of what remains after it has dried in the oven.

2.3.3. *Concrete's fresh properties*

(i) Slump test

The slump test was carried out following BS EN 12350-2:2019 [48]. Concrete's consistency is assessed using the slump test. The purpose of this test is to evaluate the flowability and workability of freshly mixed concrete. In this research, slump tests were performed on each batch of freshly mixed concrete. An example of the slump test being done is shown in Fig. 4. In conducting the test, the

Fig. 3. A sample of a filled pycnometer being weighed.

Fig. 4. A sample of the slump test that was done on the concrete mixes. (a) before the removal of the slump cone (b) following the removal of the slump cone (ii) Fresh Density.

cone was put up on a level, flat surface with its base plate in place (Fig. 4a). A rod was inserted 25 times after each level of concrete was poured at a height of 1/3. The concrete's slump was later discovered when the cone was removed vertically (Fig. 4b).

(ii) Fresh Density

Fresh density was determined using BS EN 12350-6:2019 [49]. Fresh density is the density of the wet concrete mixtures after they have fully compacted. In this research, fresh density was calculated using the compacted concrete specimen's weight and volume. Equation (4) provides the mathematical expression for the fresh density. Fig. 5 represents an occasion when the weight of concrete mix samples was measured for fresh density.

$$\text{Fresh density} = \frac{FM}{V} \tag{4}$$

where:

FM: the fresh concrete's mass (kg).

V: the specimen's volume (m^3).

Fig. 5. A fresh concrete sample being used to measure fresh density.

2.3.4. Concrete's hardened properties

(i) Cube Compressive Strength

The 100 × 100 × 100 mm cubes were used to measure the compressive strength. BS EN 12390-3:2019 [50] was followed in the execution of the compressive strength test. Following 28 days of curing, tests were conducted on the concrete specimens. A standard test setup is shown in Fig. 6. We tested the samples using the Universal Testing Machine (UTM). In all cases, a loading rate of 0.5 MPa/s was used.

The samples were compressed by a moving crosshead, and the load indicator indicated the highest load at which the sample failed. Equation (5) was utilized to ascertain the compressive strength.

$$\text{Compressive Strength} = \frac{P}{A} \tag{5}$$

where:

P: the ultimate compressive load of the concrete (N).

A: the surface area of the concrete sample (mm^2).

ii) Split Tensile Strength

The split tensile test was performed using cylindrical specimens with a diameter of 100 mm and a height of 200 mm. BS EN 12390-6:2009 [51] was used to conduct the experiment. The samples were extracted from the curing tank and allowed to air dry. Thereafter, the samples were mounted on the UTM in the manner depicted in Fig. 7, and an incremental load was applied.

The split tensile strength was calculated using Equation (6).

$$\text{Split Tensile Strength} = \frac{2P}{\pi \text{ x } l \text{ x } d} \tag{6}$$

where:

P: the ultimate split-tensile load experienced by the concrete sample (N).

π: the proportion of the circle's circumference to its diameter

l: the length of the specimen (mm).

d: the diameter of the specimen (mm).

iii) Flexural Strength

The flexural strength test of an unreinforced prism was executed using BS EN 12390-5:2019 [52]. This test was also conducted using the UTM. The samples were inserted into the machine, supported by the rollers, as seen in Fig. 8, and a load was applied.

Equation (7) was used to calculate the flexural strength. To align with the results of other researchers who might have employed the standard two-point technique, the data were downsized by 13 %. According to BS EN 12390-5:2019 [52], the centre-point method can

Fig. 6. An example of a sample experiencing compressive strength test.

Fig. 7. An example of a sample experiencing a split tensile strength test.

Fig. 8. An example of a sample experiencing the flexural strength test.

yield results up to 13 % higher than the two-point technique.

$$\text{Flexural Strength} = \frac{3 \text{ x } P \text{ x } l}{2 \text{ x } d_1 \text{ x } d_2^2} \tag{7}$$

where:

P: the maximum load experienced by the concrete sample (N).
l: the spacing between the lower rollers (mm).
d_1: the width of the specimen (mm).
d_2: the depth of the specimen (mm).

iv) Dry Weight of Cubes

The cubic specimen's dry weight was determined following BS EN 12390-7: 2019 [53]. An example of a sample being weighed is shown in Fig. 9. Using a balancing scale, the specimens' masses were determined and recorded in kilograms (kg).

v) Compressive Strength-to-weight ratio

Each concrete mix's compressive strength-to-weight ratio was calculated by dividing the concrete's compressive strength by the concrete's measured weight before crushing.

3. Results and discussion

3.1. Features of the OPC and SCBA

Fig. 10 shows the diffraction results from the X-ray of the SCBA after grinding in the ball mill. The XRD analysis provides a comprehensive overview of the mineralogical composition of the sample. The identified phases (Quartz, Muscovite, Orthoclase, and Chlorite) give insights into the geological history, conditions of formation, and potential applications of the sample. The sharpness and intensity of the peaks suggest that the sample contains well-crystallized minerals. Broader peaks would indicate the presence of amorphous materials or smaller crystallite sizes. Table 2 contains the chemical makeup of the used cementitious substances with the SCBA supplement. This confirms the agreement with standard specifications for use.

3.2. Characteristics of the fine and coarse aggregates

Fig. 11 shows the particle size distribution of both natural sand and RPET. The natural and modified fine aggregates are seen within the limits. The coarse aggregates utilized in this study had a particle size range of 4.75 mm–19 mm. Table 3 reveals the physical characteristics of the utilized coarse and fine aggregate. The aggregates are seen to be suitable for use in concrete production.

Several studies have reported on the physical properties of similar materials. For example, Bheel et al. [56] and Pal et al. [57] reported a specific gravity of 2.61 and 2.60, respectively, for natural sand, which is close to our finding of 2.64. Similarly, Neufville et al. [58] found a bulk density (compacted) of 1690.68 kg/m^3 for natural sand, which aligns well with our result of 1704 kg/m^3. Additionally, Neufville et al. [58] reported a bulk density (loose) of 1598.8 kg/m^3, which is similar to our result of 1586 kg/m^3.

For RPET, Dawood et al. [59] reported a specific gravity of 1.38, and Kangavar et al. [60] reported 1.47, which is somewhat more than our result of 0.98. These variations may be attributed to differences in the processing and origin of the RPET materials.

The coarse aggregate properties in our study are consistent with those reported by Neufville et al. [58], who found a specific gravity of 2.56, a loose and compacted bulk density of 1385.29 kg/m^3 and 1525.93 kg/m^3. These comparisons indicate that our aggregate properties are within the expected range reported in the current literature, confirming their suitability for concrete production.

3.3. Slump

The slump test is used to determine workability or concrete flow without segregation. It regulates the strength and durability of the concrete and guarantees that it is handled properly. Fig. 12 displays slump test results for all mixes relative to the control mix. The control concrete yielded a slump of 126 mm. The closest slump to the control concrete was with 5 % SCBA and 15 % RPET inclusion, at 128 mm. The slumps for all mixes were between 93 mm and 140 mm. The slumps were within the targeted range of 60 mm–180 mm.

Fig. 9. A cubic specimen sample that is being weighed using a balance.

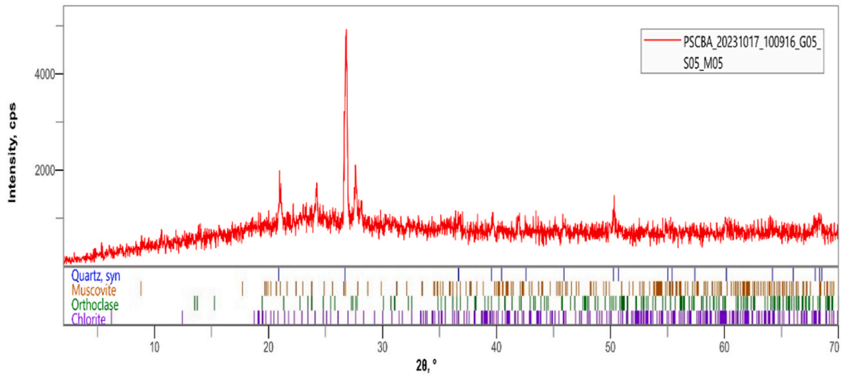

Fig. 10. XRD results on processed SCBA.

Table 2
Cement and SCBA chemical composition.

Components	Cement composition	Limits for Cement [54]	Processed SCBA composition	Limits for Fly Ash [55]
SiO_2 (%)	21.316	17–25	**76.415**	**∑(SiO_2, Fe_2O_3, and Al_2O_3 and) > 70**
Al_2O_3 (%)	5.098	3–8	9.063	
Fe_2O_3 (%)	2.941	0.5–6.0	3.476	
CaO (%)	63.859	60–67	2.820	–
MgO (%)	0.000	0.5-4.0	2.369	–
K_2O (%)	0.457	–	4.002	–
[a]AR	1.733	1.5-2.5	–	–
[b]LSF	0.943	0.66-1.02	–	–

[a] Alumina Ratio ($AR = Al_2O_3/Fe_2O_3$).
[b] Lime Saturation Factor (LSF) = $CaO/(2.8 \times SiO_2 + 1.2 \times Al_2O_3 + 0.65 \times Fe_2O_3)$.

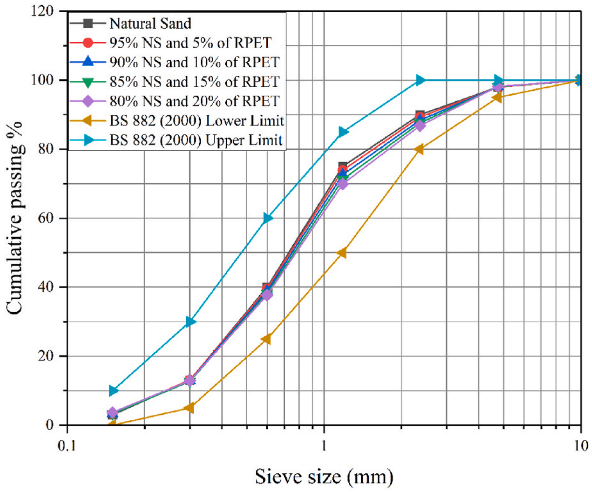

Fig. 11. Sieve analysis of fine aggregates.

Table 3
Physical characteristics of coarse and fine aggregates.

Properties	Bulk density (loose) (kg/m^3)	Bulk density (compacted) (kg/m^3)	Specific gravity	Water absorption (%)
RPET	468	546	0.98	–
Natural sand	1586	1704	2.64	2.88
Coarse aggregate	1373	1532	2.54	2.88

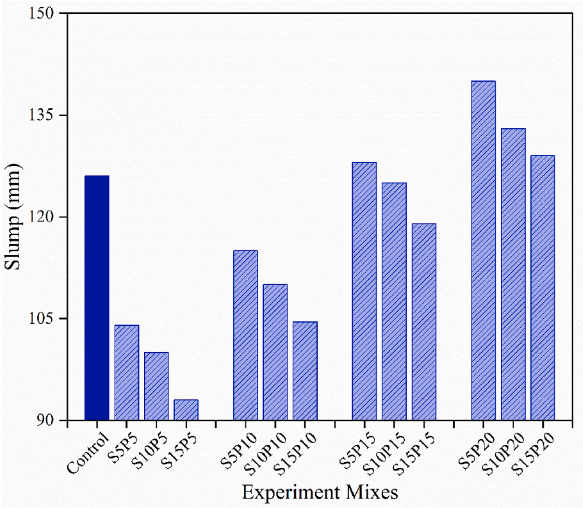

Fig. 12. Slump of concrete mixtures.

The lowest slump was recorded for 15 % SCBA and 5 % RPET inclusion. The highest slump was recorded for 5 % SCBA and 20 % RPET inclusion.

Lower slump values indicate a stiffer mix, which can be advantageous in reducing segregation and bleeding, leading to improved uniformity and potentially higher strength and durability. This is particularly useful for applications requiring high structural integrity. However, reduced workability may pose challenges during placement, compaction, and finishing, especially in heavily reinforced sections or intricate formwork. Additional measures, such as increased vibration or the use of plasticizers, may be necessary to ensure proper consolidation.

In contrast, higher slump values suggest improved workability, making the concrete easier to place, compact, and finish. This is beneficial for ensuring the complete filling of moulds and achieving smooth surface finishes, particularly in complex geometries. However, excessive slump can lead to segregation and bleeding, negatively impacting the homogeneity and strength of the concrete. It may also reduce the stability of the fresh mix, leading to potential settlement issues.

For this study, the decrease in slump with increasing SCBA inclusion is corroborated by the findings of Landa-Ruiz et al. [61] and Abdalla et al. [62]. The increase in slump as RPET content increases was also reported by Silva et al. [63], Kore [64], and Bamigboye et al. [34].

The behaviour of SCBA in decreasing the slump may be due to the higher porosity of SCBA particles compared to OPC, which can absorb more water and reduce the free water available for workability. The increase in slump with increasing RPET content can be attributed to the texture of the RPET particles, which differ from those of sand. The irregular and rough surfaces of RPET particles reduce internal friction, facilitating better flow and workability in the fresh concrete mix. The amount of water on the particle surface

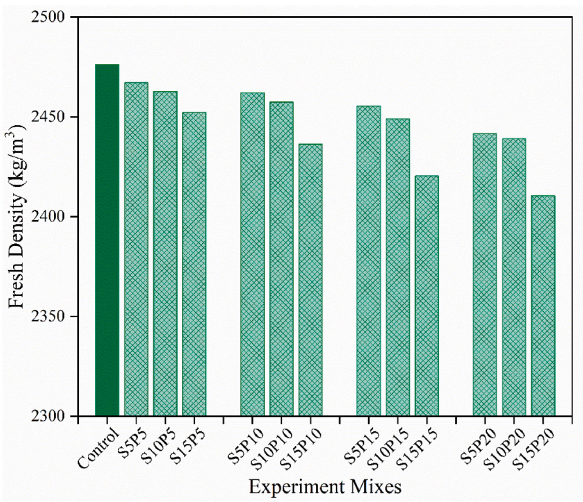

Fig. 13. Fresh density of concrete mixes.

of concrete affects its ability to be handled.

3.4. Fresh density

The density of the wet concrete mixtures upon complete compaction is known as fresh density. It depends on the ingredients' unit weight and concrete mix proportions. Fig. 13 reveals the concrete mixes' fresh densities, including the reference concrete and concretes containing both SCBA and RPET. The control concrete showed an average fresh density of 2476 kg/m^3. All the concrete mixes have fresh densities between 2410 kg/m^3 and 2476 kg/m^3. The reference concrete is the densest. The concrete mix with 15 % SCBA and 20 % RPET is the least dense. Incorporating SCBA and RPET achieved a 0.36 %–2.67 % reduction in control concrete density.

Lower fresh density in concrete mixes containing SCBA and RPET can lead to lighter structures. This is particularly advantageous in applications where weight reduction is critical. In contrast, lower fresh density might correlate with reduced mechanical strength. Overall, the decrease in fresh density due to the incorporation of SCBA and RPET, while presenting some challenges, offers significant benefits in terms of sustainability and potential weight reduction. These benefits make the modified concretes suitable for various conventional construction applications, provided that their mechanical property is carefully evaluated and optimized.

Specific gravities of SCBA (2.14 [65]) and RPET (0.98) being lower than OPC's (3.11 [58]) and natural sand (2.64) must have contributed to lower fresh density concretes in this research. Le et al. [66], Zareei et al. [67], and Memon et al. [15] earlier reported similar behaviour of SCBA within the concrete. Azhdarpour et al. [68] and Almeshal et al. [69] documented similar behaviour of RPET in concrete.

3.5. Compressive strength

Fig. 14 shows how the resistance to compressive forces varies across the concrete mixes. The reference concrete attained 39.65 MPa at 28 days. All other mixtures' compressive strengths were less than the reference concrete's. The most robust compressive strength possible for the SCBA-RPET mix was discovered at 5 % SCBA and 10 % RPET inclusion. The compressive strength attained for this mix was 38.23 MPa. The mix yielded the slightest reduction, 3.58 %, compared to the conventional concrete. The lowest strength among the mixes was 15 % SCBA and 20 % RPET inclusion. The average compressive strength is 35.31 MPa. The mix yielded the most reduction at 10.85 %. All the concrete mixes exceeded the characteristic cube strength of 25 MPa. The compressive strength decreased as SCBA addition increased, with optimum at 5 % SCBA. In the case of RPET, a 10 % addition was shown to be the optimum dosage.

These findings align with previous research. For instance, Ali et al. [70] reported reduced strength of concrete with silica fume and plastic, with the lowest strength at 36.56 MPa. This report is similar to the findings of our research. Farooq et al. [71] reported a control concrete with a strength of 37.4 MPa, but the inclusion of e-plastic and silica fume resulted in concretes with strengths in the range of 37.3 MPa–32.9 MPa. This is also similar to the findings of our research.

Furthermore, Ahmad et al. [72] observed that incorporating SCBA into concrete enhances its pozzolanic activity, improving compressive strength up to an optimal percentage, beyond which the strength diminishes due to the dilution effect. Quedou et al. [38] noted a decline of at least 2.8 % compressive strength on the 28th day when SCBA was used in concrete. In contrast, when concrete with 5 % SCBA was compared with the control mix, Hussein and Oan [65] discovered a 9.75 % increase on the 28th day. Similarly, Kangavar et al. [60] reported a 9.07 % increase in compressive strength when 10 % RPET were included in the concrete but declined with more inclusion of RPET. Additionally, when compared to control concrete Dawood et al. [59] found that 5 %, 7.5 %, 10 %, and 12.5 % RPET inclusion were superior. It is noteworthy that excessive amounts of RPET can negatively impact compressive strength.

Therefore, the observed compressive strength trends in this study are consistent with established literature, reinforcing the notion that RPET can behave unpredictably in concrete and SCBA in higher dosages may lead to reduced performance. This comparison supports the study's conclusions on the beneficial use of SCBA and RPET in concrete mixes. Despite the reduced compressive strength performance of the SCBA-RPET concretes, the mixes still passed the 25 MPa characteristics strength on the 28th day. The mixes are also still close to the control mixes. Therefore, they are still useable in safe concrete production.

3.6. Split tensile strength

Fig. 15 displays the obtained split tensile strength (STS) values for all the concrete mixes. The concrete with 5 % SCBA and 10 % RPET, with STS of 2.5 MPa, exceeds the reference concrete's strength of 2.47 MPa. This mix showed a 1.2 % increment. The remaining mixes show strength of 2.23 MPa–2.45 MPa. The concrete mix with 15 % SCBA and 20 % RPET is the least in STS. This mix reduced by 9.72 % of the reference concrete's STS.

Earlier, Almeshal et al. [69] reported an STS of 3.11 MPa for the control concrete and at 30 % RPET, the STS was 2.01 MPa. Hussien and Oan [65] reported 2.23 MPa for control concrete's STS, and 2.97 MPa–2.54 MPa for concrete including SCBA at 5 %–10 %, respectively.

Furthermore, our findings align with Azhdarpour et al. [68], who reported an increase in STS with the inclusion of RPET, followed by a decrease beyond 10 % RPET inclusion. The maximum increase in our study was observed at 10 % RPET inclusion, which supports Azhdarpour et al.'s findings. Similarly, Dawood et al. [59] and Bamigboye et al. [34] documented enhancements in STS with the use of RPET. Dawood et al. [59] noted improvements in tensile strength up to a 12 % inclusion of RPET, after which a decline was observed. Our study's optimal RPET content of 10 % closely matches their results, suggesting that RPET contributes positively to tensile strength up to a specific percentage before negatively impacting the mix's integrity.

Our results indicating a reduction in STS with increasing SCBA content are consistent with the findings of Klathae et al. [73]. They

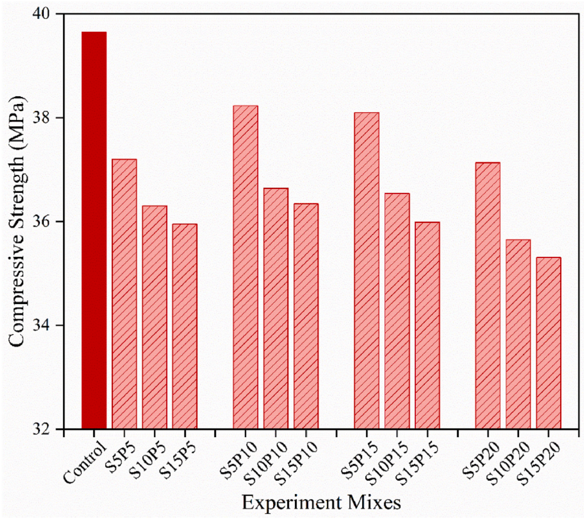

Fig. 14. Results of concrete mixes' compressive strength.

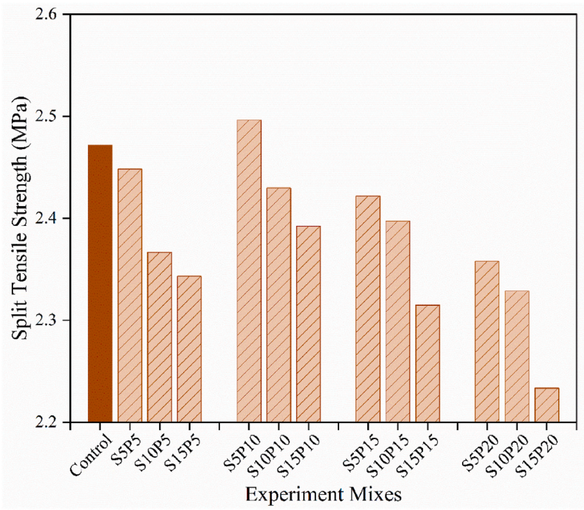

Fig. 15. Results of concrete mixes' splitting tensile strength.

observed a similar trend where higher SCBA content led to decreased tensile strength, which they attributed to the lower pozzolanic reactivity of SCBA. Farrant et al. [74] also reported comparable behaviours, noting that while SCBA can enhance certain properties of concrete, its excessive use tends to reduce tensile strength due to weaker bonding and increased porosity.

The inclusion of RPET up to 10 % improves the STS of concrete, corroborating the results found in current literature. Beyond this percentage, the tensile strength declines, which is in agreement with previous studies. For SCBA, an increase in its content results in reduced STS, a trend similarly documented in recent studies. These comparisons reinforce our findings and demonstrate that the combination of 5 % SCBA and 10 % RPET yields the most favourable balance for enhancing concrete's tensile strength.

3.7. Flexural strength

Fig. 16 displays the findings of flexural strengths of both the concrete mixes. The reference concrete performed best in flexure, with 4.56 MPa. This is 5.48 % more than the closest SCBA-RPET mix, 5 % SCBA and 10 % RPET. The lowest concrete mix in flexural strength is concrete with 15 % SCBA and 20 % RPET. This concrete mix revealed a strength of 3.94 MPa, which is 13.6 % lower than the reference mix. Flexural strength decreases as more SCBA is added to the mixes. RPET peaks at 10 % addition but subsequently declines. These behaviours may be attributed to trade-offs between the flexibility of RPET, compactness, and bond.

Comparing these results with current literature, Dawood et al. [59] observed similar behaviours in RPET-modified concrete, where the flexural strength initially increased with RPET content but decreased beyond a certain percentage. Kangavar et al. [60] noted a

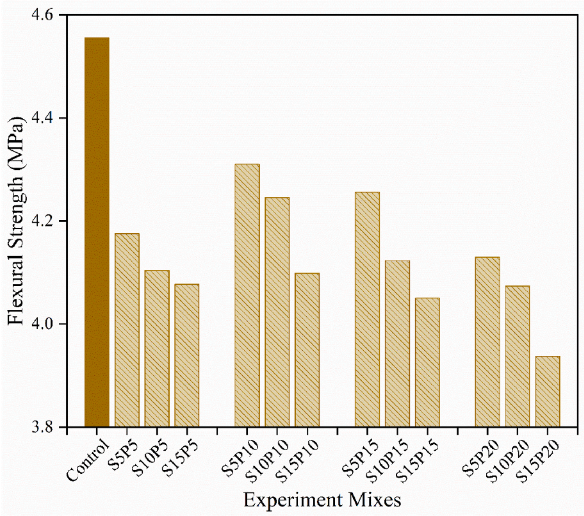

Fig. 16. Flexural strength response of all concrete mixtures.

decrease in flexural strength beyond the 10 % inclusion of RPET (4.3 MPa). This strength is in tandem with our flexural strength results. Quedou et al. [38] noted that the inclusion of SCBA in concrete mixes generally reduced the flexural strength of the control concrete by up to 20.7 % on the 28th day. This finding is consistent with our results showing a decrease in strength with higher SCBA content.

These comparisons highlight that while the flexural strength of our SCBA-RPET mixes is slightly lower than the reference mix, the reductions are within an acceptable range. The observed decrease of up to 13.6 % at most suggests that these mixes can still be used in structural concrete applications, provided that steel reinforcements are included to compensate for the reduced bending capacity. This supports the viability of using SCBA and RPET as partial replacements in concrete, aligning with sustainable construction practices by utilizing waste materials without significantly compromising structural performance.

3.8. Dry weight

The weights of cubic samples cured for 28 days are reported. Fig. 17 shows the weight results for all the concrete mixes. The SCBA and RPET mixtures all have lesser weight than the reference mix. The reference samples are the heaviest, at 2.42 kg. The concrete mix with 15 % SCBA and 20 % RPET is the lightest, at 2.37 kg, which is 2.07 % lighter than the control. The weight of the concrete mixes decreases as SCBA and RPET content increases. The RPET particles are about three times less dense than natural sand. The SCBA is about one-half times less dense than cement. The behaviours of these materials in the mixes may be due to the lower densities. Several earlier researchers also arrived at this conclusion, including Almeshal et al. [69], Bheel et al. [56], Dawood et al. [75], and Memon et al. [15].

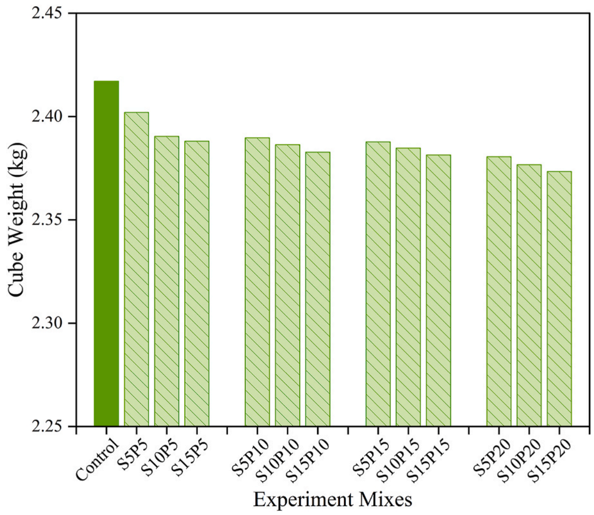

Fig. 17. The dry weight of concrete mixtures.

Reduced concrete weights contribute to enhanced sustainability and potential cost savings in transportation and handling. The beneficial impact of using lower-density materials on the environmental footprint of concrete can also not be overemphasized. Overall, the consistent reduction in weight with the inclusion of SCBA and RPET supports the potential for these materials to create more sustainable and lighter concrete mixes, suitable for various construction applications where weight reduction is advantageous.

3.9. Compressive strength-to-weight ratio

Further investigation was undertaken to relate the mixes' compressive strength to the corresponding weight. Compressive strength is concrete's prime property. Evaluating the compressive strength-to-weight ratio provides insight into the efficiency and practicality of using SCBA and RPET in concrete mixes. This ratio is particularly important for structural applications where both strength and weight are critical factors [58,76,77]. Fig. 18 shows the findings of the compressive strength-to-weight ratio of all the concrete mixes. The reference mix revealed a performance of 16.4 MPa/kg at 28 days. This performance is better than all performances of the SCBA-RPET concrete mixes. The combination closest to the reference concrete is 5 % SCBA and 10 % RPET. This mix revealed a compressive strength-to-weight ratio of 16 MPa/kg, only 2.44 % lower than the control concrete. The concrete mix with 15 % SCBA and 20 % RPET is the lowest, at 14.88 MPa/kg, 9.27 % less than the control mix.

The performance of the SCBA-RPET mixes may be attributed to the strength yielded not corresponding to the weight. The SCBA also could have performed better. Further processing or sourcing SCBA with higher amorphous silica content could potentially yield better performance in future applications. However, most SCBA-RPET mixes demonstrated about 90 % of the control concrete's compressive strength-to-weight ratio. This indicates that, while there is a reduction in strength compared to the control, the mixes still retain a substantial portion of their structural integrity. The compressive strength-to-weight ratio is a crucial parameter, especially for applications where weight reduction is beneficial, such as in high-rise buildings or lightweight structures. The SCBA-RPET mixes, with their reduced weight and comparable strength, offer a viable alternative to conventional concrete, promoting sustainability without significantly compromising structural performance. Overall, the SCBA-RPET concrete mixes demonstrate promising potential for use in structural applications, contributing to sustainability by incorporating waste materials.

4. Conclusion

This study investigated the potential of using sugarcane bagasse ash (SCBA) and recycled polyethylene terephthalate (RPET) as partial replacements for cement and natural sand, respectively, in concrete mixes. The findings reveal that incorporating these materials can produce sustainable concrete with mechanical and physical properties comparable to conventional concrete.

- The research shows that the optimal mix, consisting of 5 % SCBA and 10 % RPET, provides the best balance between sustainability and mechanical performance. This mix demonstrated a compressive strength of 38.23 MPa, only 3.58 % less than the reference concrete. The mix also achieved a split tensile strength 1.2 % higher than the reference. Additionally, the fresh density and weight of the SCBA-RPET concrete mixes were slightly reduced, offering benefits such as reduced structural weight and enhanced sustainability.
- The study observed that the workability of the concrete mixes varied with the content of SCBA and RPET. The slump values ranged from 93 mm to 140 mm, indicating that all mixes were workable and suitable for concrete applications. The decrease in fresh

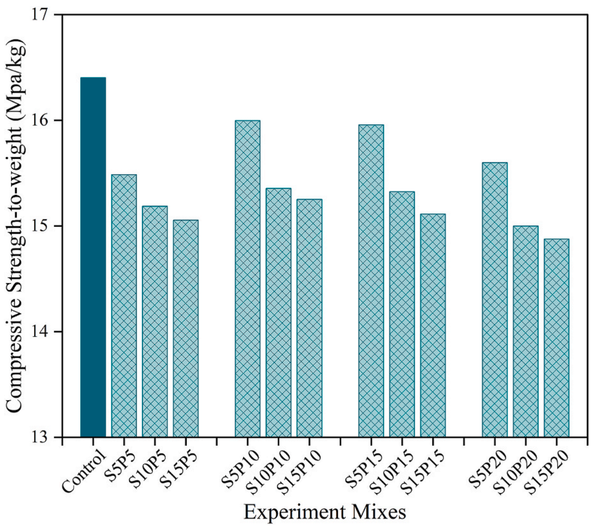

Fig. 18. Compressive strength-to-weight ratio of concrete mixes.

density, though minimal, still aligns with the acceptable ranges for conventional construction, suggesting that these mixes can be utilized effectively in structural applications.
- The flexural strength of the mixes, while lower than the reference concrete, remained within acceptable limits for structural use, particularly when adequate reinforcement is provided. The compressive strength-to-weight ratio of the mix with 5 % SCBA and 10 % RPET was closest to the reference concrete, reinforcing the suitability of this combination for practical applications.

In conclusion, the incorporation of SCBA and RPET in concrete mixes offers a viable solution for sustainable construction, leveraging the benefits of waste material utilization while maintaining essential mechanical properties. The optimal dosages of 5 % SCBA and 10 % RPET provide a balanced approach to enhancing the sustainability of concrete without compromising its structural integrity.

4.1. Applications

The findings of this study have significant implications for sustainable construction practices. The partial replacement of cement with SCBA and natural sand with RPET reduces the carbon footprint, alleviates the depletion of natural resources, and also manages agricultural and plastic waste effectively. The optimal mix of 5 % SCBA and 10 % RPET offers concrete that is comparable to conventional concrete in terms of mechanical properties while being more sustainable. The SCBA-RPET concrete mixes can be applied in various construction projects, including residential, commercial, and infrastructure developments. These mixes are especially suitable for projects where reducing the carbon footprint and minimizing the use of natural resources are critical considerations.

4.2. Scope for subsequent research

Future research should explore long-term durability, cost analysis, and the environmental impact assessment of SCBA-RPET concrete. Additionally, the potential for scaling up these sustainable practices in various construction applications should be evaluated to further promote eco-friendly alternatives in the construction industry.

Data availability statement

No, data associated with this study has not been deposited into a publicly available repository. Data will be made available on request.

CRediT authorship contribution statement

Chukwuemeka Daniel: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Richard Ocharo Onchiri:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Benard Otieno Omondi:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors appreciate all who contributed to actualizing this research. The authors specifically thank the Pan African University Institute of Basic Sciences Technology and Innovation (PAUSTI) for funding this research.

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