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ORIGINAL PAPER

Mechanical Properties of Concrete Blocks Incorporating Recycled Waste Plastic

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Abstract

Concrete production with waste plastics as a replacement for aggregates has continued to lead discussions on the probable solutions to plastic waste threats. However, investigation on the direct application of concrete incorporating waste plastic for the production of walling units is yet to receive the desired considerations. This study aims to evaluate the effect of fine aggregate substitution with waste plastic aggregate on concrete blocks to determine appropriate material mixes that can satisfy the requirements for application as walling material. Samples of concrete blocks were prepared using natural sand, plastic waste, cement and water at a 1:4 binder-to-aggregate ratio with consistent workability. The composite materials were tested for compressive strength, flexural strength, splitting tensile strength, elastic modulus, water absorption and sorptivity. The study found that waste PA increases the compressive strength of plastic aggregate (PA) concrete blocks at 5% PA, reaching 23.92 N/mm^2 in 28 days. The splitting tensile strength of PA composites and the flexural strength of PA concrete blocks are increased by the replacement of natural sand with PET aggregate, attaining 1.5 and 11.81 N/mm^2, respectively. Beyond 5% PA content, the water absorption of PA concrete blocks increased, while the sorptivity decreased with an increase in the PA content. The study indicates that the use of 5% volume of PA in the production of concrete blocks can substantially enhance mechanical properties and water absorption. This production technique can help the construction industry safely use recycled waste PA in the production of masonry units with enhanced mechanical properties and improved resilience in wet environments.

Keywords Compressive strength · Concrete block · Flexural strength · Plastic waste · Water absorption

Introduction

Bricks and concrete blocks are essential walling units for the construction of homes. The world production of bricks is estimated at over 1391 billion units per year (Korpayev et al. 2022), with various types and production techniques emerging over time depending on available materials and technology. The conventional bricks are made by heating a dry mixture of clay, coal and water in a kiln to a temperature between 700 and 1100 °C. Harris (2009) noted that the entire process generates an enormous amount of CO_2, and the production process is energy-intensive. Clay bricks have been identified as a significant CO_2 emission building material in Malaysia (Gardezi et al. 2014). Finding effective and durable alternatives is necessary to alleviate these production challenges and meet the growing demand for housing.

Interestingly, recent investigations have demonstrated the potential usage of plastic waste for the production of mortar and concrete (Alshkane et al. 2017; Abdullah et al. 2021; Sor et al. 2022) as a feasible solution to plastic waste disposal problems and pressure on the natural environment due to excessive extraction of natural aggregates (Huynh et al. 2023; Rahim et al. 2023; Idrees et al. 2023). Lee and Wong (2023) investigated the use of waste plastic fibre and recycled aggregate for the production of concrete. Shredded waste PET bottles have been incorporated as aggregate in the production of lightweight concrete (Akcaozoglu et al. 2010). The study revealed quiescent benefits such as diminution in the consumption of virgin resources, waste removal,

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pollution prevention and energy conservation. Alawais and West (2019) studied the ultraviolet and chemical treatment of crumb rubber aggregate in a sustainable concrete mix. The study reported a low concrete compressive strength due to the low stiffness of crumb rubber. Loss of strength and premature failure were attributed to the re-distribution of load to the cement paste as crumb rubber deforms under load. To mitigate the loss of strength, the characteristics of the crumb plastic were improved using UV light and another set of the crumb rubber was soaked in sulfuric acid to create a more rigid surface layer. The treatment further enhanced the ability of the concrete to withstand compression load. The incorporation of optimum fraction of nano-silica particles has been found to reduce the negative impact of recycled plastic aggregate in geopolymer concrete (Ahmed et al. 2023a). The use of carbon fiber-reinforced polymer (CFRP) fabrics for confinement has also been reported to improve the compressive strength of concrete made with recycled waste PET fine aggregate (Qaidi et al. 2022). In another study, Alqahtani et al. (2017) observed a brittle failure with Lytag and conventional lightweight concrete mixes. The concrete mixtures incorporating plastic aggregate had a ductile post-peak behaviour. Also, the study showed that the compressive strength of concrete reduced as the percentage of plastic increased in the mixtures. A similar study reported that the strength performance of concrete declined with the increase in plastic pellets (Akinyele and Ajede 2018).

Notwithstanding, some of these studies have shown that the performance of concrete and mortar containing recycled plastic waste can be controlled to enhance specific properties, there is still a paucity of research on the direct application of PA in the production of concrete blocks. Hence, the present study investigates the performance of concrete blocks incorporating varying percentages of recycled waste PA to gain insight into the behaviour of PA concrete blocks and their compliance with critical minimum standards. The study determined optimal production matrix for concrete blocks that satisfies minimum performance standards for use as masonry units through test of compressive strength, flexural strength, splitting tensile strength, elastic modulus, water absorption and sorptivity. This is imperative because PA concrete blocks are potential plastic waste management methods and could significantly contribute to the reduction in depletion of virgin natural resources and also add to the availability of masonry units, an essential walling material for the construction of houses. This solution is expected to significantly contribute in salvaging the construction industry from virgin resource depletion and help the built environment in mitigating the threats of plastic waste. The outcome of the study is anticipated to pave the way for the construction industry to further eco-friendly practices in the production of sustainable and resilient alternative masonry units.

Materials and Experimental Procedures

Six sample mixtures were subjected to tests, with the primary experimental variable being shredded plastic waste to determine appropriate material mixes for the production of PA concrete blocks. The samples were made of cement, sand and shredded PET (see Fig. 1) as a replacement for sand at 0%, 5%, 15%, 25%, 50% and 75% with variable w/c ratio dependent on consistency results.

Materials

Ordinary Portland cement, CEM 1 42.5N, which complies with BS EN 197–1 (2011) and NIS 444–1 (2018), was used in preparing the concrete blocks. The letter "N" stands for cement with typical early strength development, while "42.5" refers to the class strength of 42.5 N/mm^2 at 28 days. This cement is frequently used to produce mortar and concrete materials on construction sites. Tap water that is fit for drinking was used for the experiment.

Natural sand with a bulk density of 1.60 g/cm^3, an ultimate grain size of 4.75 mm, and a coefficient of curvature of 4.15, complying with BS 1199 (1976) and BS 410–2 (2000), was used. The dry apparent bulk density is 1485 kg/m^3. The

(a) Cement **(b) Natural sand** **(c) Plastic aggregate**

Fig. 1 Materials used for sample preparation

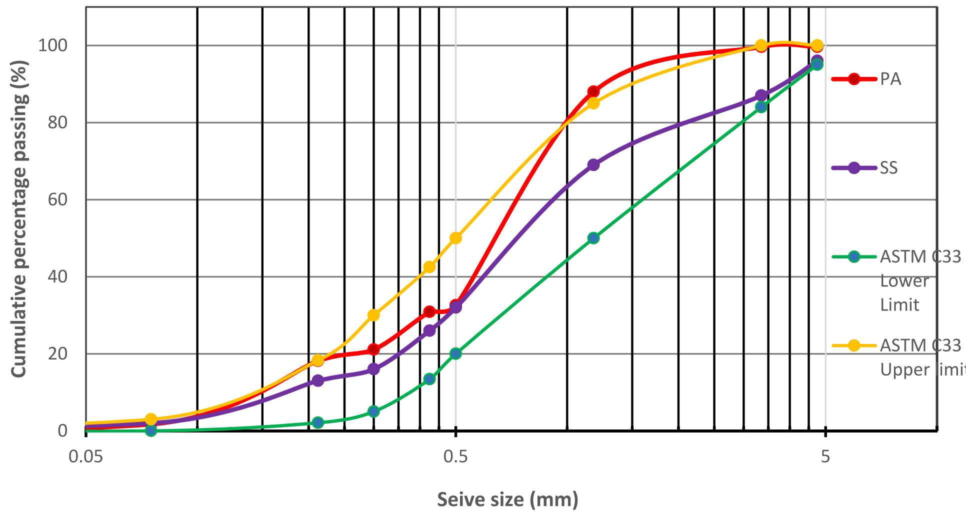


Fig. 2 Particle size distribution of PA and sharp sand

particle cumulative percentage passing sieve sizes conform with ASTM C33 as shown in Fig. 2.

The plastic aggregate consists of shredded Polyethylene Terephthalate (PET) obtained from a plastic waste recycling plant in Lagos, Nigeria. The apparent bulk density of the plastic aggregate is 372 kg/m^3. Figure 2 presents the grain size distribution of PA and natural sand obtained by sieve analysis to evaluate the suitability of the PA material for the replacement of fine aggregate. The sieve analysis of the sharp sand and PA samples was calculated and illustrated in a semi-logarithm graph. The PA substantially conforms with ASTM C33 fone aggregate limits with less than 3% of the PA cumulative percentage particles beyond the upper limit of the 1.18 mm sieve.

The graph shows that the PA and sharp sand samples have a maximum particle size of 4.75 mm to less than 75 µm, which characterises a typical fine aggregate. The Fineness Modulus of the sand is 0.5, which indicates that the 500 µm, sieve size contained the highest sand grains. The plastic aggregate has a Fineness Modulus of 0.425. The computation of the coefficient of curvature C_c of the PA and sharp sand from the graph shows that the C_c values are 4.08 and 5.43, respectively, depicting a well-graded fine aggregate. Also, Uniformity Coefficients of 8 and 7.56 were obtained for the PA and sharp sand, respectively. The Uniformity Coefficients indicate that the fine aggregates are well-graded because the results satisfy the minimum value of six specified in ASTM D2487 (2006) for well-graded fine aggregates.

Samples Preparation

The study produced PA concrete block samples with reference to BS 3921 (1985). The mix designs employed in the production of the concrete blocks are presented in Table 1. The samples were produced with a volumetric binder/sand ratio of 1:4 (i.e., 1 part of binder, CEM I to 4 parts of aggregate), with PA systematically substituting up to 75% by volume of sand. The same volume of recycled plastic aggregates replaced a volumetric portion of sand at 0%, 5%, 10%, 15%, 25%, 50% and 75%. The study controlled the quantity of water in the mixtures to obtain consistent workability for the various samples, in line with the provisions of EN 1015–2 (1998).

Table 1 PA concrete block mix design

Sample ID	Sharp sand substitution (%)	Cement	Sharp sand	PA	w/c ratio
BCB	N/A	N/A	N/A	N/A	N/A
PAB0	0	5	20	0	0.50
PAB5	5	5	19	1	0.50
PAB10	10	5	18	2	0.55
PAB25	25	5	15	5	0.65
PAB50	50	5	10	10	0.65
PAB75	75	5	5	15	0.60

Two control samples were used to compare results and examine the impacts of PA on the performance of concrete blocks. The first control brick is fired clay bricks (BCB) procured from a local brick dealer, while the second control was a concrete block produced with cement and natural sand without PA and the compositions are shown in Table 1. The mixing process involved adding a predetermined volume of sharp sand in the mixer, followed by cement and, thereafter, waste PA, before adding water. After adding water, the mixture is mixed thoroughly to consistent workability and cast into moulds. The specimens were cast in three layers, with each layer being thoroughly vibrated and compacted using 12 strokes of a vibrating rod.

Eighteen 112.5 × 225 × 75 mm^3 concrete block specimens were cast for each sample and preserved in moulds for 24 h at 23 ± 2 °C. During that time, a polyethene membrane was used to cover the specimens to reduce moisture loss from the samples. After that, specimens were removed from the moulds and immersed in water for 3, 14 and 28 days at 23 ± 2 °C. The 75% PA concrete sample was cured in the lab ambience to avoid wearing the surface of the concrete blocks in water, which was a major challenge for PA concrete blocks with high PA content. Also, three specimens of 150 × 300 mm cylinders were moulded using each sample mixture for splitting tensile strength determination.

Experimental Techniques

Compressive Strength Test

The study evaluated the compressive strength of the PA concrete blocks with reference to BS EN 772–1:2011 + A1 (2015). Compressive strength tests were performed on four working-size PA concrete blocks measuring 112.5 × 225 × 75 mm^3. The standard-size PA concrete blocks were subjected to compressive strength tests after 3, 14 and 28 days of curing by immersion in water. The tests were carried out at the Nigeria Building and Road Research Institute (NBRRI), Ota, using a 2000 kN capacity Universal Testing Machine working at a loading of 14.8 kN/s.

Flexural Strength

Concrete block sizes of 112.5 × 225 × 75 mm^3 were prepared to evaluate flexural strength. A three-point force test with a loading rate of 0.05 kN/s was used to determine the flexural strength of the concrete block specimens in accordance with BS EN (1015)–11 1999. The test set-up of a typical specimen undergoing flexural strength tests is shown in Fig. 3b, and the flexural strength was computed using Eq. 1.

$$\sigma = \frac{3FL}{2bd^2} \tag{1}$$

where F = maximum load at yield point (N); σ = flexural strength (N/mm^2); b = width of section (m); L = distance between supports (m); d = depth of section (m).

Splitting Tensile Strength

At 28 days after casting 300 × 150 mm diameter cylinders of the cement-sand-PET composite mixes expressed in Table 1, a splitting tensile strength test was conducted on the cylinders as per BS EN (1015)–11 1999, as shown in the test setup in Fig. 3c.

Modulus of Elasticity

Using additional instrumentation to the compressive strength test setup following BS EN 772–1:2011 + A1 (2015), the elastic moduli of the concrete block specimens were calculated from the experimental data recorded by the 1500 kN capacity compression machine operating under 14.8 kN/s force regime rate (see Eq. 2). Figure 3a depicts a typical Elasticity Modulus test setup.

$$E = \frac{\boldsymbol{\sigma}}{\boldsymbol{\varepsilon}} = \frac{FL_0}{A_0 \Delta L} \tag{2}$$

where σ = stress (N/mm^2); E = elastic modulus (N/mm^2); F = load at failure (N) ; ε = strain; L_0 = original length of material (mm); A_0 = original area of material (mm^2) ; ΔL = change in length.

Poisson's Ratio

The lateral and axial strain measurements acquired using auxiliary apparatus during the elastic modulus tests were used to compute the Poisson's ratios. The axial strain in the direction of loading is compared to the longitudinal strain to determine Poisson's ratio, v, (see Eq. 3).

(a) Elastic Modulus test (b) Flexural strength test (c) Splitting tensile test

Fig. 3 Test set-up

$$v = \frac{\varepsilon_l}{\varepsilon_a} \tag{3}$$

where ε_l is the longitudinal strain, ε_a is the axial strain in the direction of the applied load and v is Poisson's ratio.

Water Absorption

BS EN 772–21 (2011) was used to guide the conduct of the water absorption (W_s) test. Three PA concrete block specimens were dried in the oven to a constant mass (m_d). Immediately after being weighed, the specimens were immersed in water. The water was then heated for 5 h before cooling at ambient temperature for roughly 24 h. Before being weighed to determine the saturated mass, (m_s), the specimens were taken out of the water, and their surfaces were wiped off with a hand towel. Equation 4 illustrates how the increase in the mass of the saturated specimens was divided by the dry mass to calculate the water absorption.

$$W_s = \frac{m_s - m_d}{m_d} \times 100\% \tag{4}$$

Sorptivity

The capillary rise technique was employed to examine the sorptivity of the PA concrete blocks. Sabir et al. (1998) remarked that the capillary rise method is most suitable for building materials because forces due to capillary action are dominant in buildings, and the process is simple and easy to operate. Equation 5 was used to compute the sorptivity.

$$\frac{\Delta_m}{A} = S^{*} t^{0 \cdot 5} \tag{5}$$

where S = sorptivity [kg/(m^2.h$^{0.5}$)]; Δm = the mass of absorbed water (kg); t = the time of water penetration (h); A = area of polymer concrete block surface in contact with water (m^2).

Results and Discussion

The subsections below illustrate and discuss the findings of the compressive, flexural and splitting strength tests, as well as the Poison's ratio and elastic modulus of the PA concrete blocks tested in the lab.

Compressive Strength

The compressive strength of PA concrete blocks produced with different proportions of PA at distinct curing periods is presented in Fig. 4. The figure shows that the 0%, 5%, 10%, 25%, 50% and 75% PA concrete blocks had a compressive strength of 22.78, 23.92, 11.79, 10.36, 10.32 and 16.99 N/mm^2, respectively. This suggests that all the samples of PA concrete blocks satisfied the minimum 2.9 N/mm^2 compressive strength specified in BS En and 771–3 (2011) for masonry units.

The results show an increase in compressive strength of 5% PA content concrete blocks compared to the control concrete block. Mohan et al. (2023) also observed an increase in the strength of concrete beams containing 6% Bakelite plastic waste. Ahmed et al. (2023b) also observed an increase in compressive strength of geopolymer concrete containing 5% PA and 3% nano-silica compared to control geopolymer concrete without PA and nano-silica. These findings are contrary to Wang and Meyer (2012), which found that the substitution of sand for high-impact polystyrene (HIPS) in mortar reduces the compressive strength almost linearly with HIPS aggregate replacement ratio. Although the compressive strength in the present study decreased from 10% sand substitution, there is a

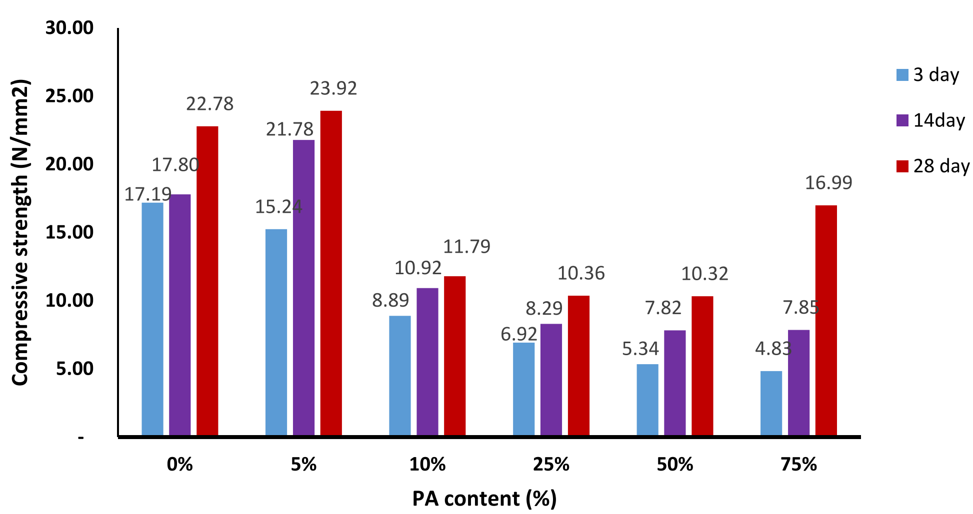


Fig. 4 Effect of PA content on compressive strength of PA concrete blocks

significant improvement in the compressive strength of 75% PA content concrete blocks at 28 days. The relative improvement in compressive strength of PA concrete block at 75% waste PET incorporation is credited to the ambient curing method used for the sample rather than the water immersion method used for the other samples.

The reduction in loss of compressive strength is attributable to the ambient curing method used for the PA concrete block incorporating 75% PA sample, which was implemented to avoid the wearing of PA in water. The air curing eliminated the hydrophobic challenges (particularly the wearing of PA particles from the PA concrete block when immersed in water) between the PA in the concrete block and water.

The low compressive strength of the 10%, 25% and 50% PA content concrete blocks could be related to the weak bond of the interface between the cement paste and the PA aggregates (Wang and Meyer 2012) and also the poor interaction of the curing water and the hydrophobic PA which resulted in the displacement of some of the PA in the concrete blocks.

The loss of compressive strength due to the substitution of sand aggregates is shown in Fig. 5. For PA concrete blocks with PET aggregate content of 10%, 25% and 50% at the curing age of 28 days, there was a decline in compressive strength by 48%, 54.5% and 54.7%, respectively. Wang and Meyer (2012) reported a similar loss of strength for 50% HIPS substitution of sand for mortar production. Almeshal et al. (2020) affirmed that recycled plastic as fine aggregate in cementitious composites often results in loss of strength. However, in the present study, at curing periods of 3 days and 7 days, the decrease in the compressive strength of 25% and 50% PA concrete block is not substantially different from the strength at 28 days of curing.

However, at 75% and substitution, the loss of compressive strength is much less, approximately 25%. The declination in compressive strength is creditable to the interface's weak bond between the cement paste and the aggregates because of the smooth surface of the PA grains.

Flexural Strength

The outcomes of the flexural strengths of recycled PA concrete blocks are shown in Fig. 6. The figure demonstrates that the flexural strength of recycled PA concrete block with 5%, 10%, 25%, 50% and 75% PA content were 11.81, 9.39, 8.55, 8.04 and 8.28 N/mm^2 at 28 days of curing.

The decrease in flexural strength with natural aggregate substitution using PET aggregate is consistent with the findings of Ge et al. (2013), who found a decline in flexural strength as the sand-to-PET ratio decreased in mortar. However, the flexural strength of the concrete blocks with PA content increased, with the 5% PA content concrete blocks having the most remarkable improvement of 65% compared to the control concrete block. A similar increase in flexural strength has been reported by Sau et al. (2023), who found that the replacement of aggregate with 10% waste plastic aggregate improved flexural strength by 20%. The result conflicts with the findings of previous studies involving the application of PA in concrete, where flexural strength decreased with the introduction of PA compared to conventional concrete with the same w/c (Frigione 2010; Juki et al. 2013; Saikia and de Brito 2014). The fact that the current study employed the PA as fine aggregate in concrete block production rather than concrete and the w/c ratio was varied to achieve a consistent mix partly accounts for the improvement in the flexural strength. Also, the PA was well graded and blended significantly with the natural aggregate, and the toughness of PA is generally higher than that of natural aggregate, which could contribute to the enhancement of flexural strength.

The improvement in the flexural strength of the 5% PA content was similar to that of compressive strength, which recorded a substantial increase with 5% PA content but a loss of compressive strength with higher PA content.

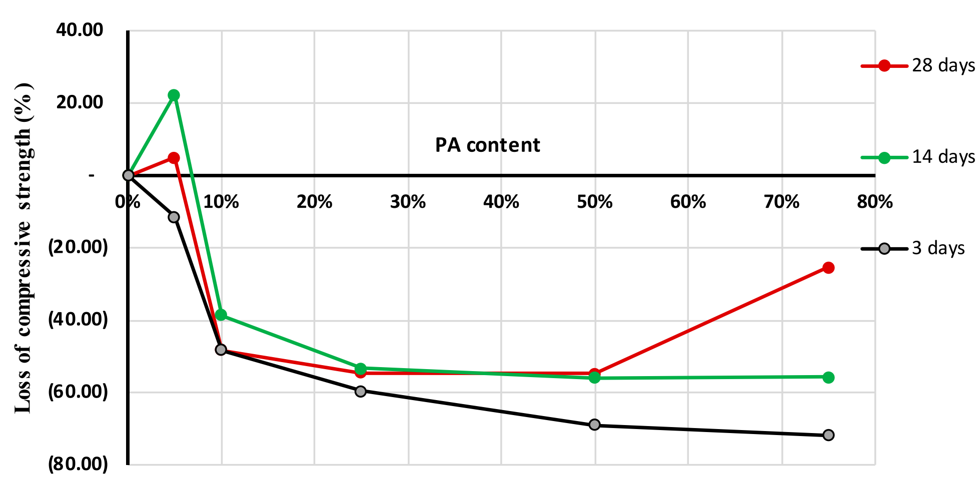


Fig. 5 Effect of PA content on loss of compressive strength of concrete block

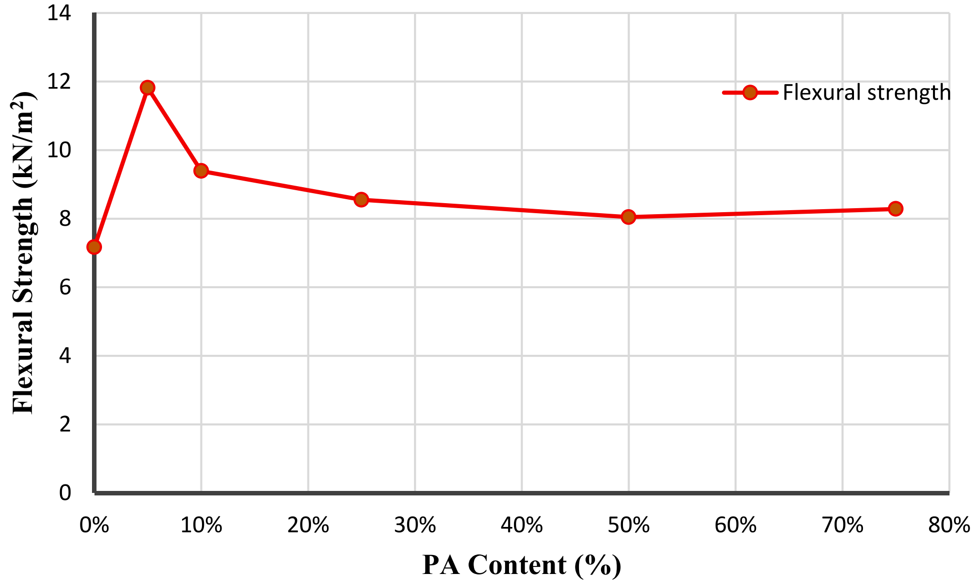


Fig. 6 Effect of recycled PA content on flexural strength of PA concrete block

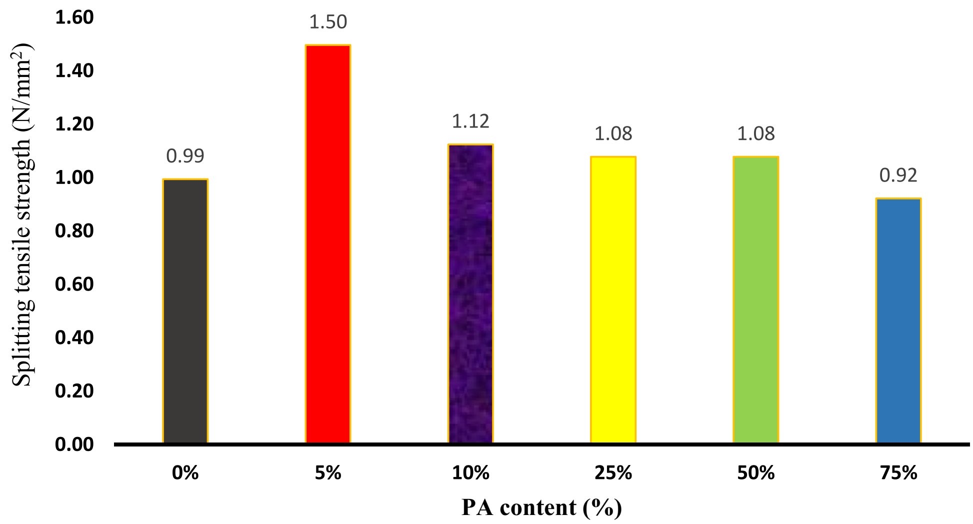


Fig. 7 Effect of PA on splitting tensile strength of PA composite

Splitting Tensile Strength

The splitting tensile strength of composite manufactured with different fractions of PA content declines with increasing PA content (see Fig. 7). However, for the natural aggregate substitution of 10% with PA, the impact on the splitting tensile strength is not substantial at the curing duration of 28 days. A comparison of the percentage strength loss with loss of compressive strength in Table 2 indicates that the impact of the PA content on the compressive strength is much more severe than on the splitting tensile strength.

This could be attributed to the PA, which makes some compensation for the splitting tensile strength of the materials. A similar reduction in the impact of PA on splitting tensile strength compared to compressive strength was found in Wang and Meyer (2012). However, in the current study, an increase in the splitting tensile strength with reference to the control concrete block was observed with an increase in PET aggregate content, except at 75% substitution. This

Table 2 Ratio of the splitting tensile strength to the compressive strength (rS/rC)

PA content (%)	Compressive strength ratio (rC)	Splitting strength ratio (rS)	rS/rC ratio
0	1.0000	1.0000	1.000
5	1.0499	1.5054	1.433
10	0.5176	1.1308	2.185
25	0.4549	1.0844	2.383
50	0.4530	1.0844	2.393
75	0.7457	0.9274	1.243

finding is contrary to previous studies of PA substitution in concrete, which have principally reported a decrease in splitting tensile strength with the replacement of natural aggregate with PA (Asokan et al. 2010; Chaudhary et al. 2014; Ferreira et al. 2012). Besides, improvements in splitting tensile strength have been reported with the use of waste plastic as fibre reinforcement in concrete (Ahmed et al. 2021; De Oliveira and Castro-Gomes 2011; Lopez-Buendia et al. 2013; Pelisser et al. 2012). The well-graded particle distribution of the PET aggregate that blended significantly with the natural aggregate explains the improvement in the splitting tensile strength and the fact that the toughness of PA is higher than that of the natural sand.

The ratio of the splitting tensile strength to the compressive strength (rS/rC) can depict the toughness of cement mortar (Wang and Meyer 2012) and is given in Table 3 for various percentages of PA content.

A comparison of the rS/rC ratio with that of the control concrete block shows an increase by factor 1.43, 2.18, 2.38, 2.39 and 1.24 with the PA contents of 5%, 10%, 25%, 50% and 75%, respectively, at the curing age of 28 days. This implies that the toughness of concrete blocks is enhanced with the substitution of sand by PA up to 50%. The effect could be related to the toughness of PA compared to the natural sand.

Modulus of Elasticity

The modulus of elasticity of recycled PA concrete blocks produced with various percentages of PA is shown in Fig. 8. The elastic modulus declined as the percentage of PA increased. This fact is related to the reduction in the bulk density of the mortar and can be attributed to the low modulus of the PA (Saikia and de Brito 2014).

The elasticity modulus of the fired clay bricks, BCB and the control concrete block is 3360.89 N/mm^2 and 2561.27 N/mm^2, respectively. The 5%, 10%, 25%, 50% and 75% PA content concrete blocks had an elastic modulus of 3362.92 N/mm^2, 1688.38 N/mm^2, 1283.91 N/mm^2, 700.32 N/mm^2 and 476.41 N/mm^2, respectively.

The results of the 50% and 75% PA concrete blocks are comparable to Koltsida (2017), who obtained 447.87 N/mm^2 and 873.33 N/mm^2 for the elastic modulus of burnt clay bricks and mortar, respectively. Higher modulus of elasticity values ranging between 5300 N/mm^2 and 7516 N/mm^2 were reported for commercial clay bricks from four different manufacturers in India (Kaushik et al. 2007). In the current study, the 5% PET content PA concrete block recorded the highest modulus of elasticity over the control concrete block and the fired clay bricks. A similar tendency was found with the compressive strength of the PA concrete blocks. The relatively high

Table 3 Modulus of elasticity and compressive strength ratio

Samples	Modulus of elasticity, E_{mc} (N/mm^2)	Compressive strength, f_{mc} (N/mm^2)	E_{mc}/f_{mc} ratio	Remark
BCB	3360.89	10.60	317.97	Satisfactory
PA0%	2561.27	25.00	102.45	Satisfactory
PA5%	3362.92	25.72	130.77	Satisfactory
PA10%	1688.38	17.12	98.64	Not satisfactory
PA25%	1283.91	17.05	75.40	Not satisfactory
PA50%	700.32	10.33	67.81	Not satisfactory
PA 75%	476.41	7.21	66.09	Not satisfactory

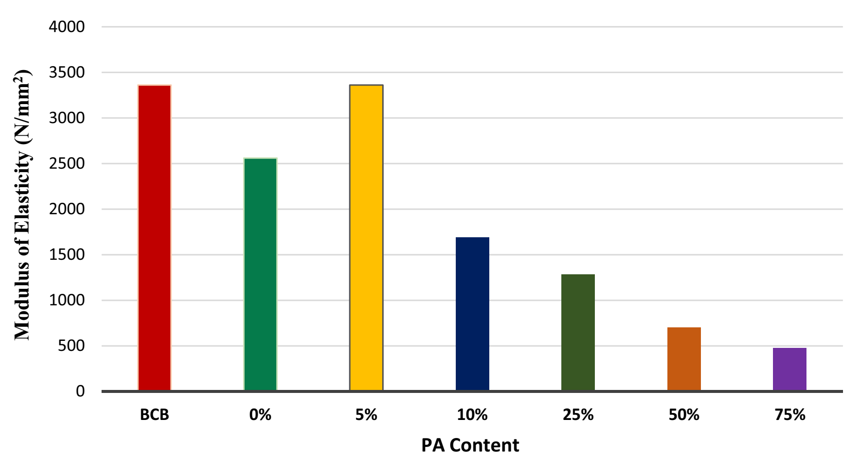


Fig. 8 Variation of PA concrete block modulus of elasticity with PET content

compressive strength of the 5% PA concrete block apparently influenced the result of the elastic modulus. Beyond the 5% PA content, the elastic modulus of the PA concrete blocks diminished with an increase in the PA content.

The E_{mc}/f_{mc} proportions are shown in Table 3 to assess the fulfilment of the PA concrete block samples to a minimum underlining guideline on the modulus of elasticity of bricks, E_{mc} and the compressive strength, f_{mc}. The table indicates that the fired clay brick, the control and 5% PA concrete block satisfied the minimum E_{mc}/f_{mc} ratio of 100 for the elastic modulus and compressive strength ratio. In addition, a modulus of elasticity to compressive strength, E_{mc}/f_{mc} ratio of 317.97, was achieved by the control brick (fired clay brick, BCB).

The fired clay bricks, the control concrete blocks and the 5% PA concrete blocks had E_{mc}/f_{mc} ratios ranging between 100 and 400, fulfilling the recommended provision. Hence, the outcomes indicate that PA concrete block manufactured with 5% PA could considerably support loads without absurd deformation or strain.

In concrete production, concrete mixes with lower compressive strength are known to have a low modulus of elasticity values (Saikia and de Brito 2014). Comparable tendencies are observed with the PA concrete blocks, which shows that PA concrete blocks with higher compressive strength had substantial elastic modulus values. Nonetheless, a comparison of the elastic modulus of the PA concrete block with the fired clay bricks shows that the modulus of elasticity of the PA concrete blocks is considerably low. The lower elastic modulus of the PA concrete blocks could be credited to the low modulus of elasticity of the PA analogised to that of natural aggregate. Saikia and de Brito (2014) stated that the modulus of elasticity of PET is substantially less than that of natural aggregates. Accordingly, high PET-aggregate contents lower the elastic modulus of the resulting concrete. Similarly, higher PA content beyond 5% reduced the elastic modulus of the resulting PA concrete blocks.

Poisson's Ratio

In order to compute the Poisson's ratios of the PA concrete blocks, the specimens were crushed in the direction of the load during the modulus of elasticity test, and the complementary elongations in lateral orientations orthogonal to the applied compressive force were noted. The Poisson's ratios were calculated as a fraction of the axial and lateral strain in the load direction. The Poisson's ratios' outcomes for the fired clay bricks and PA concrete blocks are shown in Fig. 9. The figure reveals that PA concrete block Poisson's ratios decreased with an increase in PA content in the mix from 10 to 75% PA content. Contrary to the compressive strength test findings, the 5% PA concrete block had a decreased Poisson's ratio compared to the 0% PA content control concrete block. The reduction in Poisson's ratio could be attributed to the increase in axial deformation of the concrete blocks under load due to the elastic advantage of the PA.

Apart from the 5% PA concrete block, Poisson's ratio results agree with the compressive strength test results, which also exhibited a decline in compressive strength with increased PA content. The Poisson's ratios of the PA concrete block are convergent with the range of 0.215 and 0.498 obtained by Noaman et al. (2018) for clay bricks at 28 days.

Water Absorption

The results of water absorption of the PA concrete blocks are presented in Fig. 10. The figure indicates that the 5% PA

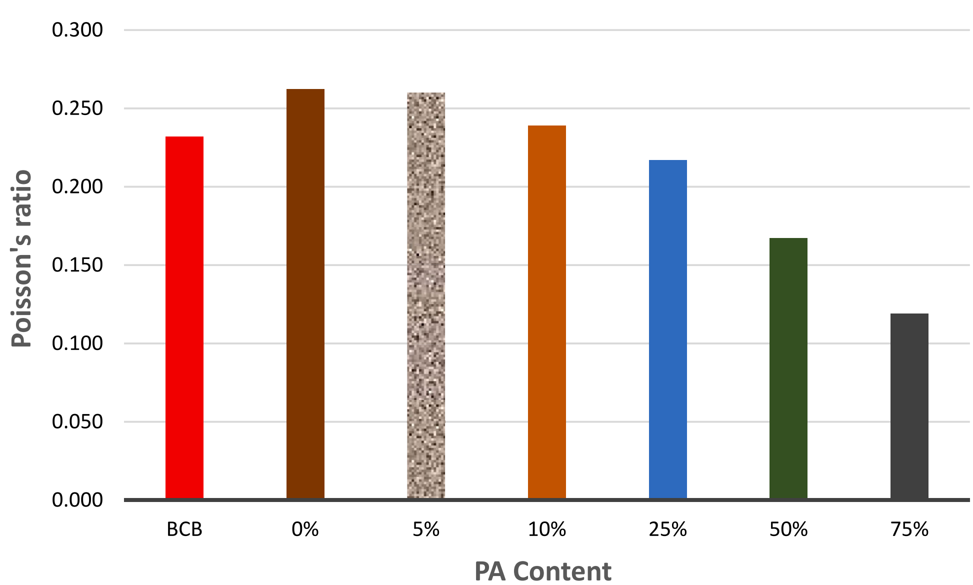


Fig. 9 Effect of PA content on Poisson's ratio of concrete blocks

concrete block has the least water absorption of 6.21% after 28 days of curing. The water absorption of the control concrete block (0% PA concrete block) is 6.67%. The reduction in water absorption of 5% PA concrete blocks is consistent with the findings of He et al. (2022), who asserted that the inclusion of wet-grinding plastic waste in cement paste engenders nucleation, improves early strength and reduces the permeability of cement composites.

The results in Fig. 10 reveal the efficacy of PA in compaction and water resilience properties if present in small quantities. The 10% PA, 25% PA, 50% PA and 75% PA concrete blocks, respectively, had water absorption of 6.75, 9.04, 10.60 and 12.18%, which revealed a consistent rise in water absorption with increasing PA content. The increase in water absorption with increasing PA content could be attributed to an increase in pore space between the particle–matrix as a result of the weaker bond between cement paste and PA in the mixture. Thus, beyond 5% PA substitution in PA concrete blocks, there is a consistent increase in water absorption of plastic waste incorporated concrete blocks. The finding converges with Albano et al. (2009), Bhagat and Savoikar (2022), Idrees et al. (2023), Saikia and de Brito (2013), Silva et al. (2013), which reported that an increase in plastic fine aggregate substitution of natural sand increases the water absorption of concrete and mortar.

The relationship between water absorption and the PA content of PA concrete blocks is shown in Eq. (8), which reveals a polynomial function between the variables. The equation can predict 96% of the variations of water absorption of PA concrete blocks as indicated by the coefficient of determination ($R^2 = 0.9661$).

$$WA = 0.255PA^2 - 0.5561PA + 6.654 \quad (8)$$

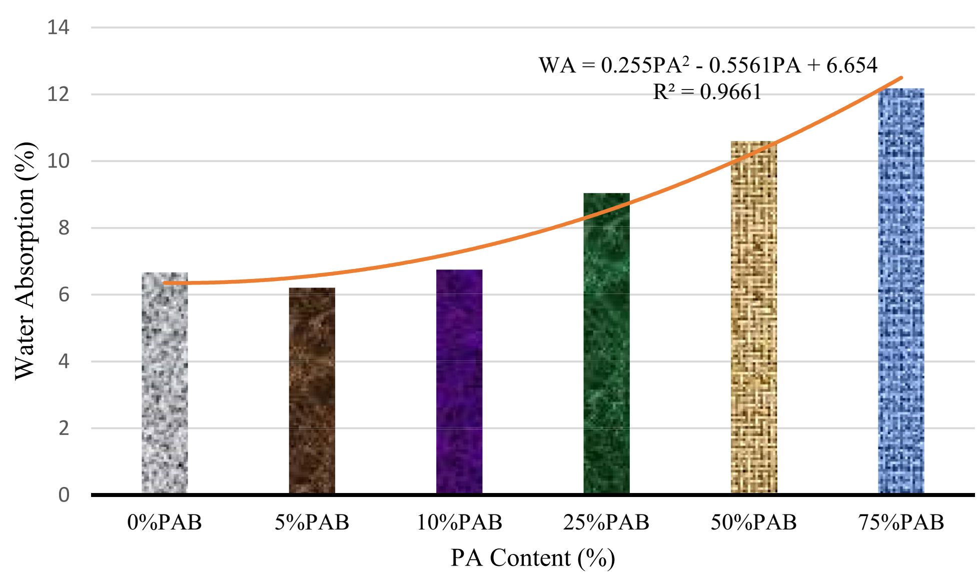
Sorptivity

Sorptivity is an essential parameter of wall materials in wet and dry areas to prevent wall moisture that causes cracks and paint failures. The PA concrete block specimens were tested for sorptivity at the 3, 7 and 28 days of curing under lab ambience temperature. The results of the sorptivity test conducted on the PA concrete blocks and the control is shown in Fig. 11.

The 3-day curing sorptivity test shows that the sorptivity of PA concrete blocks declined with the duration of contact with water. At the 5 min sorptivity test, the 75% PA concrete blocks had the highest value (4.15 kg/m^2.h$^{0.5}$), followed by the 0% PA concrete block, while the 10% PA concrete block had the least sorptivity value. Similar trends were observed with the 10-, 30- and 60-min tests, but with the least sorptivity values at the 25% PA concrete block. The finding corroborates Massazza (1998) and Kubissa and Jaskulski (2013), who stated that sorptivity, like permeability, decreases by increasing curing time. Among the PA concrete blocks, sorptivity varied with sand and PA matrix, which indicates a dependency on the homogeneity of the PA concrete blocks. The more homogeneous the mixtures, the higher the sorptivity. This finding affirms Mermerdas et al. (2017) study that reported high sorptivity values for geopolymer mortar produced with low-range fine aggregate sizes (natural sand; 0–1 mm) compared to the geopolymer mortar manufactured using wide-range and combined fine aggregate sizes (50–50, natural sand and crushed limestone; 0–4 mm).

Figure 11 shows that the sorptivity of PA concrete blocks decreased with the duration of contact with water at 7 days of curing. At 5 min, the 0% PA concrete block had the highest sorptivity value (3.04 kg/m^2.h$^{0.5}$), and the 50% PA concrete block had the least sorptivity value. Similar trends were observed with the 10-, 30- and 60-min tests. Again,

Fig. 10 Impact of PA content on water absorption of PA concrete blocks



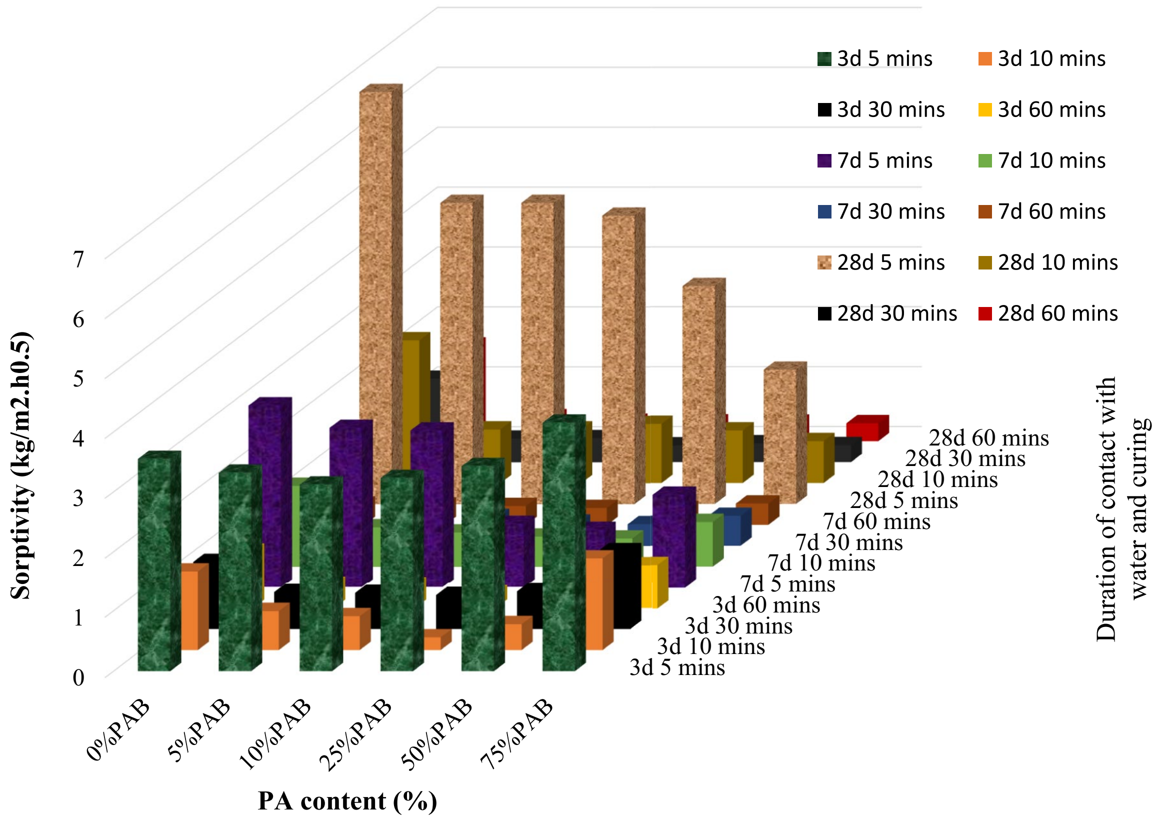


Fig. 11 Effect of contact time and curing on sorptivity of PA concrete blocks

the sorptivity results show a dependency on the homogeneity of the PA concrete blocks matrix as sorptivity decreased with the equilibrium of sand and PA ratio. The equal ratio of sand and plastic aggregate in the PA concrete blocks apparently distorts the capillary pores network, which opposes the capillary action within the PAB. The more homogeneous PA concrete blocks, such as the 0%, 5%, 10% and 75% PA concrete blocks, have relatively strong capillary pores, which enhance sorptivity.

In comparison with the 3 days of curing, sorptivity was observed to decline with an increase in curing duration, which could be credited to drying shrinkage and consequent gradual loss of capillary pores network. The finding agrees with Rong et al. (2020) that volume shrinkage is principally occasioned by thermal stress, and the fragmentation rate gradually decreases due to the lack of newly formed large cracks when the moisture content is less than 4.74%.

At the 28 days of curing, sorptivity of PA concrete blocks also decreased with the duration of contact with water from 5 to 30 min but with a slight increase at 60 min. The increase in sorptivity at 60 min could be a result of a high affinity for water due to dryness as the samples were cured in the lab ambience. Compared to 3 and 7 days of air curing, there is an increase in sorptivity at 28 days. The increase in sorptivity could be attributed to the loss of pore water with the duration of air curing (Zhang et al. 2012). The air curing of the samples caused the PA concrete block to lose pore water with time. Unlike the 3 and 7 days sorptivity, the 75% PA concrete block at the 28 days curing recorded the lowest sorptivity values in all contact durations. Again, this indicates the dominance of drying shrinkage that distorts capillary pores over the homogeneity of the PA concrete blocks matrix. This observation apparently holds the same for the various PA concrete block samples, as there was a consistent decrease in sorptivity with increasing PA content. Thus, at 28 days of air curing, sorptivity decreases with an increase in the PA content of PA concrete blocks. A similar observation was reported by Gouasmi et al. (2019) that the sorptivity coefficients of waste PET lightweight aggregate (WPLAX) mortars decreased from 43 to 65% at 75% and 100% replacement of calcareous aggregate as compared to that of the reference mortar. The low sorptivity of high-content PA concrete blocks heralds the potential application for construction in an aggressive environment such as the marine environment. Sorptivity is a principal factor that influences the penetration of aggressive ions into concrete when exposed to severe environments (Nicolas et al. 2017).

However, the sorptivity results are contrary to the findings of the water absorption test in which an increase in PA content of PA concrete blocks increased water absorption.

The effect could be described by the verity that in the water absorption test, samples were completely immersed in water for 24 h, which is ample time for water molecules to penetrate the samples from all sides.

Conclusion

This study examined the application of PA as a natural aggregate substitute in concrete block production. In particular, six mixtures of natural aggregate substitution are presented to determine the appropriate matrix for application in PA concrete block production and use in the construction of houses. The paper draws the following conclusions.

The compressive strength of PA concrete blocks decreased by replacing natural sand with PA aggregates beyond 5%. The compressive strength of PA concrete blocks increased with a 5% substitution of natural sand with PA and also improved with curing age. For PA concrete blocks prepared with 10%, 25%, 50% and 75% PA, the loss of compressive strength was 48%, 54.5%, 54.7% and 25.43, respectively. Ambient air curing reduced the loss of compressive strength of PA concrete blocks with high PA content compared to curing by immersion. In comparison with the concrete block without PA, the flexural strength of PA concrete blocks increased with the introduction of PA, peaking at 5%. Further substitution of natural aggregate with PA decreased the flexural strength but was still higher than the flexural strength of the concrete block without PA. The splitting tensile strength of PA concrete block is increased by the replacement of natural sand with PA aggregate up to 50%, but a decrease in splitting tensile strength is found at 75% PA substitution. A comparison of the rS/rC ratio with that of the control concrete block revealed that the toughness of concrete blocks improved with the substitution of sand by PA up to 50%.

The modulus of elasticity of concrete blocks increases with a 5% substitution of natural sand with PET fine aggregate but declines with further substitution. The E_{mc}/f_{mc} ratios of the 5% PA concrete block satisfied the minimum E_{mc}/f_{mc} ratio of 100, which suggests that the PA concrete block can substantially sustain load without excessive deformation and thus can be used as a masonry unit for the construction of buildings. The Poisson's ratio reduced with an increase in PA aggregate content occasioned by the elastic advantages of the PA, which contribute to increased axial deformation of the concrete blocks under load. As PA aggregate content increased, the water absorption of the PA concrete blocks increased significantly to 6.75, 9.04, 10.60 and 12.18% of the typical concrete blocks when the PET ratio is 10%, 25%, 50% and 75%, respectively. Interestingly, a 5% substitution of natural sand with PA aggregate reduced the water absorption of PA concrete blocks.

The sorptivity of PA concrete blocks declined with the duration of contact with water and increasing curing time. Also, the sorptivity decreased with the increase in heterogeneity of sand and PA mix ratios. At 28 days of ambient curing, sorptivity decreased with an increase in the PA content of PA concrete blocks. The low sorptivity of high-content PA concrete blocks heralds the potential application of PA concrete blocks for construction in aggressive environments. The satisfactory performance of concrete blocks produced with various proportions of PET offers promise for applications in the construction of buildings, mostly due to its good compressive strength and splitting tensile strengths and sorptivity, while also ameliorating the threats of plastic waste to the environment. The study indicates that the use of 5% volume of PA in the production of concrete blocks can substantially enhance mechanical properties and water absorption. This concrete block production technique has the potential to engender the safe use of recycled waste PA in the production of masonry units with enhanced mechanical properties and improved resilience in wet environments. The solution is expected to significantly contribute to salvaging the construction industry from virgin resource depletion and help the built environment in mitigating the threats of plastic waste.

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Author Contribution UEE: conceptualization, methodology, and formal analysis; OJA: supervision and project administration; HSY: data curation and writing review; ICO: writing review and editing; DON: data curation and editing.

Data Availability Data sets generated during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interests The authors declare no competing interests.

Ethics Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Consent to Participate For this type of study, formal consent is not required.

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