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Preface

We would like to present, with great pleasure, the volume-12, Issue-9, September 2026, of a scholarly journal, *International Journal of Engineering Research & Science*. This journal is part of the AD Publications series *in the field of Engineering, Mathematics, Physics, Chemistry and science Research Development*, and is devoted to the gamut of Engineering and Science issues, from theoretical aspects to application-dependent studies and the validation of emerging technologies.

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Neural Networks	Plastic Engineering

Each article in this issue provides an example of a concrete industrial application or a case study of the presented methodology to amplify the impact of the contribution. We are very thankful to everybody within that community who supported the idea of creating a new Research with IJOER. We are certain that this issue will be followed by many others, reporting new developments in the Engineering and Science field. This issue would not have been possible without the great support of the Reviewer, Editorial Board members and also with our Advisory Board Members, and we would like to express our sincere thanks to all of them. We would also like to express our gratitude to the editorial staff of AD Publications, who supported us at every stage of the project. It is our hope that this fine collection of articles will be a valuable resource for *IJOER* readers and will stimulate further research into the vibrant area of Engineering and Science Research.



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Valorization of Waste Polyethylene Terephthalate as a Partial Fine Aggregate Replacement in Concrete: An Experimental Assessment of Fresh and Hardened Properties

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Abstract— The escalating accumulation of plastic waste, particularly Polyethylene Terephthalate (PET), poses a significant environmental challenge, especially in developing regions with inadequate waste management systems. This study investigated the valorization of Waste Polyethylene Terephthalate (WPET) as a partial substitute for fine aggregate in concrete production, with a view to addressing both plastic waste disposal and the depletion of natural aggregate resources. WPET sourced from industrial plastic waste was collected, mechanically crushed, washed, and characterized through sieve analysis and specific gravity determination to assess its suitability as a lightweight aggregate prior to incorporation into concrete mixes. Concrete cubes were cast at a 1:2:4 mix ratio, with WPET substituting fine aggregate at 1%, 2%, 4%, 6%, and 8% by weight, using both washed gravel and crushed granite as coarse aggregates. Slump, density, and compressive strength tests were conducted at curing ages of 7, 14, 21, and 28 days to evaluate the fresh and hardened properties of the resulting concrete, with results benchmarked against relevant British Standard specifications. Findings revealed a progressive decline in workability, density, and compressive strength with increasing WPET content, attributable to the hydrophobic nature of plastic particles and their effect on bonding within the cement matrix. Nonetheless, specimens with lower replacement levels (up to 4%) met acceptable thresholds for lightweight and non-structural applications. The study concludes that WPET can serve as a viable partial fine aggregate substitute within optimized replacement limits, offering a practical pathway for plastic waste valorization, reduction of environmental pollution, conservation of natural aggregates, and promotion of sustainable construction practices.

Keywords— Plastic waste valorization; WPET; fine aggregate substitution; lightweight concrete; compressive strength.

I. INTRODUCTION

Plastics have become integral to modern life, owing to their durability, affordability, versatility, light weight, and ease of manufacture. They find application across a wide range of sectors, including packaging, transportation, healthcare, construction, electronics, agriculture, water supply systems, and household goods. The steady rise in urbanization, industrial activity, and consumer demand has driven a corresponding surge in global plastic production and consumption. Yet the persistence of most plastics in the environment has created a pressing ecological problem, a challenge that is especially acute in developing countries where waste management infrastructure remains weak. Polyethylene terephthalate (PET), widely used for beverage and water bottles, makes up a substantial share of municipal solid waste and ranks among the most conspicuous forms of plastic pollution in both urban and rural settings (Qaidi et al., 2023; Mostafaei et al., 2026). Worldwide, plastic waste is generated at a scale of millions of tonnes annually, with PET accounting for a sizeable proportion owing to its dominance in the packaging sector. Poor disposal practices, ranging from open dumping and burning to indiscriminate littering, have given rise to a host of environmental problems, including drainage blockages, soil contamination, flooding, visual blight, and harm to aquatic life. In Nigeria and other developing countries, discarded PET bottles are a familiar sight along roadsides, in drains, around markets, on construction sites, and in public spaces. Given that PET can take centuries to break down, its continued

accumulation represents a long-term environmental hazard (Uche et al., 2026; Oke et al., 2025). These concerns have prompted researchers and environmental agencies to step up efforts toward sustainable waste management strategies centred on recycling, reuse, and resource recovery. Among the most promising avenues is the incorporation of waste materials into construction products, particularly concrete. As the most extensively used construction material in the world, concrete owes its popularity to its versatility, strength, durability, and comparatively low cost. However, the ongoing extraction of natural aggregates such as sand and gravel for concrete production has taken a toll on the environment, depleting natural resources and disrupting ecosystems. This has fuelled growing interest in alternative, sustainable materials that can partially replace conventional concrete constituents without substantially compromising structural integrity (Qaidi et al., 2023; Reana et al., 2026). Against this backdrop, the use of waste PET as a partial fine aggregate replacement in concrete has emerged as an attractive solution that simultaneously addresses plastic pollution and resource conservation. A growing body of research has shown that incorporating PET particles into concrete mixes affects key engineering properties, including compressive strength, tensile strength, density, workability, thermal insulation, shrinkage, and durability. PET-modified concrete also tends to be lighter, making it a candidate for non-structural and lightweight construction uses. Beyond its technical merits, recycling PET into concrete reduces pressure on landfills and supports circular economy principles within the construction sector (Mostafaei et al., 2026; Uche et al., 2026). More recent studies have reinforced this picture, showing that controlled replacement levels of fine aggregate with PET can yield compressive strengths suitable for specific applications. The general trend reported is that lower PET replacement percentages tend to preserve mechanical performance better, whereas higher proportions can weaken the bond between cement paste and aggregate due to the hydrophobic nature of plastic. Even so, several researchers maintain that PET concrete holds considerable promise for sustainable construction provided the replacement ratio is carefully optimized (Qaidi et al., 2023; Xiao et al., 2026). This expanding interest has, in turn, spurred further investigation into how PET-based concrete performs under varying mix proportions and curing regimes. In the Nigerian context, where plastic waste management remains a persistent challenge, repurposing waste PET bottles into construction materials offers a potentially valuable dual benefit: environmental relief and economic gain. Such an approach could ease pollution, conserve natural fine aggregate resources, cut material costs, and support more sustainable infrastructure development. It is against this backdrop that evaluating the engineering performance of PET-incorporated concrete, with particular attention to compressive strength, becomes an important step toward establishing its practical suitability for construction. This study, accordingly, investigated the effects of waste PET on the compressive strength of lightweight concrete when used as a partial fine aggregate replacement. Specifically, the research compared the compressive strength behaviour of concrete produced with two different coarse aggregates, namely washed gravel and crushed granite, while varying the proportion of PET waste substituted for sand. The study further examined how different PET replacement levels influenced strength development at curing ages of 7, 14, 21, and 28 days, with a view to identifying the optimum replacement level capable of delivering satisfactory compressive strength. In addition, the suitability of the resulting PET-modified concrete for construction use was assessed by benchmarking the results against relevant British Standard specifications for concrete. The impetus for this research stems from the mounting accumulation of PET bottle waste in the environment and the corresponding need for sustainable approaches to its disposal. The non-biodegradable nature and long environmental lifespan of PET waste have made it a significant ecological concern, while the construction industry continues to face mounting demand for conventional materials such as sand and gravel. Integrating waste PET into concrete production therefore offers a means of tackling environmental pollution while conserving natural resources and lowering construction costs. In this way, the study contributes to ongoing efforts to develop construction materials that are both environmentally sustainable and economically viable through innovative recycling approaches. The scope of the study was confined to the use of PET waste as a partial fine aggregate replacement in concrete prepared at a 1:2:4 mix ratio, using two types of coarse aggregate, washed gravel and granite. The experimental work comprised slump testing, specific gravity determination, and compressive strength testing, with PET replacement levels varied up to a maximum of 8%. The results obtained were assessed in line with the relevant British Standard specifications.

II. MATERIAL AND METHODOLOGY

This section outlines the materials, experimental procedures, laboratory tests, and analytical methods employed in evaluating the effect of Waste Polyethylene Terephthalate (WPET) as a partial replacement for fine aggregate in concrete production. The experimental framework was structured to systematically assess both the physical characteristics of the WPET material and its influence on the fresh and hardened properties of concrete. Accordingly, the methodology encompassed the sourcing, processing, and preparation of materials, particle size analysis, determination of specific gravity, batching and casting of concrete specimens, slump testing, curing, and compressive strength testing at varying curing ages. This systematic approach was adopted to ensure that the data generated would be reliable, reproducible, and suitable for comparison with relevant

standard specifications. Similar trends have been reported by previous researchers investigating the use of recycled PET materials in concrete production (Zulkernain et al., 2021; Qaidi et al., 2023).

2.1 Materials Used

The materials used in this study were Ordinary Portland Cement, river sharp sand, washed natural gravel, crushed granite, waste polyethylene terephthalate (WPET), and potable water. The cement used was Grade 32.5N cement, while the fine aggregate was river sharp sand obtained from Balogun Aruna village, Akinyele Local Government Area, Ibadan. The coarse aggregates consisted of washed natural gravel obtained from Ikire, Osun State, and crushed granite obtained from a quarry along the Lagos–Ibadan Expressway. WPET material was obtained from BevPak Nigeria Limited, Ibadan, and potable water was used for washing, mixing, and curing. The selection of these materials was based on their availability, suitability for concrete production, and compliance with standard engineering requirements for lightweight concrete applications (ASTM International, 2018; BSI, 2017).

2.1.1 Preparation of Waste Polyethylene Terephthalate Material (WPET)

In this section, the processes followed from the acquisition of the WPET to its preparation and application in the concrete mixes are discussed. Proper preparation of WPET is important because it improves particle uniformity, enhances bonding within the cement matrix, and contributes to better workability and strength characteristics of the concrete (Gu & Ozbakkaloglu, 2019; Xiao et al., 2026; Zulkernain et al., 2021).

2.1.1.1 Acquisition of the WPET Material

Approximately 22.5 kg of Waste Polyethylene Terephthalate (WPET), commonly referred to as purge material, was obtained from BevPak Nigeria Limited, located along Km 3, Lagos-Ibadan Expressway, Sanyo Bus Stop, Ibadan, Oyo State, Nigeria. The company is involved in the production of plastic bottles and food/drink packaging materials using processed chemical compounds under controlled manufacturing conditions. The WPET collected for this study consisted of waste PET materials that had solidified from their molten state before being introduced into the plastic moulding machines.

The use of waste PET materials from industrial plastic manufacturing processes has gained considerable attention in recent years because of increasing environmental concerns associated with plastic waste disposal and landfill accumulation. Recycling and incorporating WPET into concrete production help to reduce environmental pollution, conserve natural aggregate resources, and promote sustainable construction practices (Gu & Ozbakkaloglu, 2019; Zulkernain et al., 2021; Reana et al., 2026). Previous studies have shown that properly processed PET waste can be effectively utilized as partial replacement for fine aggregates in lightweight concrete production without significantly compromising engineering performance.

2.1.1.2 Crushing of the WPET

After acquisition, the Waste Polyethylene Terephthalate (WPET) material was mechanically crushed using a hammer mill machine to obtain smaller granular particles suitable for use as partial replacement for fine aggregate in concrete production. The crushed WPET was subsequently sieved using a 6.70 mm mesh sieve in order to separate the coarse particles from the fine particles. The coarse-sized particles retained on the sieve were discarded, while the finer particles passing through the sieve were collected for concrete mixing.

Due to the presence of impurities and contaminants introduced during the grinding process, the fine-sized WPET particles were soaked in potable water for several hours, thoroughly washed, drained, and air-dried before use. Proper cleaning and drying of recycled PET materials are important because they improve the bonding characteristics between the plastic particles and cement paste, thereby enhancing the workability and strength properties of the concrete. Previous studies have reported that adequate processing, washing, and particle size reduction of PET waste significantly influence the engineering performance of PET-incorporated concrete (Gu & Ozbakkaloglu, 2019; Xiao et al., 2026; Reana et al., 2026).

2.1.1.3 Sieve (Particle Size) Analysis on WPET and Sharp Sand

The dried WPET material was subjected to sieve analysis to determine its particle size distribution and grading characteristics. The purpose of the test was to evaluate the percentage of different grain sizes present in the WPET material and to ensure that the particles satisfied the standard size requirements for use as lightweight aggregate in concrete production. Proper particle size distribution is essential because it affects the workability, density, strength, and overall performance of concrete. Well-graded aggregates improve particle packing and reduce voids within the concrete matrix (Alexander et al., 2025; ASTM C136/C136M-19, 2019).

The equipment used for the sieve analysis included a weighing balance, a set of standard sieves, a mechanical sieve shaker, and a wire brush. The test was carried out in accordance with standard procedures for aggregate grading, and the results obtained were used to assess the suitability of the WPET material for lightweight concrete applications. Similar procedures have been adopted by researchers investigating the use of recycled plastic aggregates in sustainable concrete production (Kamal et al., 2021; Babafemi et al., 2018).



PLATE 1: Photograph showing the waste polyethylene terephthalate (WPET) material obtained from BevPak Nigeria Limited before processing and crushing



PLATE 2: Photograph of the hammer mill machine used to crush waste polyethylene terephthalate into smaller particles suitable for concrete production



PLATE 3: Photograph showing finely crushed WPET particles obtained after sieving through a 6.70 mm mesh sieve



PLATE 4: Photograph showing washed and air-dried WPET particles prepared for laboratory testing and concrete production



PLATE 5: Photograph showing the sieve analysis equipment, including sieves, weighing balance, and WPET sample used for particle size distribution testing

The sieve analysis was conducted in accordance with ASTM C136/C136M-19 (2019) to determine the particle size distribution and grading characteristics of the WPET material and sharp sand. Proper aggregate grading is important because it influences the workability, density, and strength properties of concrete (Alexander et al., 2025; Babafemi et al., 2018). The set of sieves (sieve stack) were thoroughly cleaned with a clean, dry cloth to remove dust and other retained particles that could affect the accuracy of the test results. The weight of each sieve and its bottom pan were determined using a weighing balance. 500g of dried WPET was weighed and carefully poured into the set of sieves with mesh sizes from 6.70 mm (topmost sieve) to 0.212 mm (bottom sieve), with the pan placed below the bottom sieve. A sieve cap was used to cover the topmost sieve, in order to prevent loss of some of the dried WPET particles during vibration of the sieve equipment. The sieve stack was placed in the sieve shaker and vibrated for 10 minutes. The sieve stack was then carefully removed from the shaker, and each individual sieve with its retained WPET material was weighed. The bottom pan and the retained WPET material in it were also weighed. The weight results obtained were used to calculate the percentage retained and percentage passing WPET. The grading characteristics obtained were then used to assess the suitability of the WPET material for lightweight concrete production (ASTM C136/C136M-19, 2019).

2.1.1.4 Determination of the Specific Gravity (SG) of the WPET and Sharp Sand

The Specific Gravity (SG) of the WPET was determined after the sieve analysis in order to evaluate the density and lightweight characteristics of the material. Previous studies have shown that PET materials generally possess lower specific gravity values compared to natural aggregates, making them suitable for lightweight concrete applications (Xiao et al., 2026; Zulkernain et al., 2021). The equipment used included two 500 ml density bottles with stoppers, a wash bottle containing air-free distilled water, an oven, weighing scale, and a plain white sheet of paper.

The density bottles, labeled as 1 and 2, were first washed, and then dried with an oven at temperatures ranging from 105–110°C. The bottles were then weighed. 50g (denoted as W_1) of WPET was transferred into density bottle 1. The weight of density bottle 1 and the 50g WPET sample was recorded as W_2 . Air-free distilled water was then poured into density bottle 1, up to the level of the marked line on the bottle. Density bottle 1 (containing the WPET and distilled water) was then weighed. This was recorded as W_3 . Density bottle 1 was then emptied, rinsed with clean water, and refilled with only distilled water. The bottle was then weighed and recorded as W_4 . The procedure was repeated for density bottle 2. The weights recorded were used to determine the average Specific Gravity (SG) of the WPET material. Previous studies have shown that PET materials possess lower specific gravity values than natural aggregates, thereby making them suitable for lightweight concrete applications (Xiao et al., 2026; Uche et al., 2023).

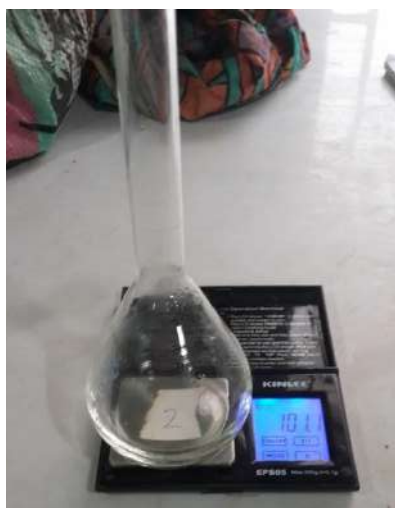


PLATE 6: Photograph showing the equipment used for determining the specific gravity of WPET, including density bottles, weighing balance, and distilled water

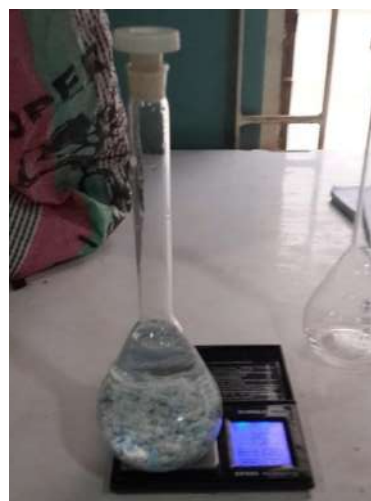


PLATE 7: Photograph showing a density bottle containing WPET and distilled water being weighed during the specific gravity determination test

2.2 Preparation of Other Aggregates

This section discusses the procedures followed in the acquisition, preparation, and application of other concrete aggregates used for the production of concrete mixes in this study. The aggregates used included fine aggregate (river sharp sand) and

coarse aggregates (washed gravel and granite). These materials were carefully selected and prepared to ensure that they satisfied the standard requirements for concrete production. Proper preparation of aggregates is important because the physical properties, cleanliness, grading, and moisture condition of aggregates significantly influence the workability, strength, durability, and overall performance of concrete (Alexander et al., 2025; ASTM C33/C33M-20, 2018).

The aggregates were sourced from approved local suppliers and were subjected to preliminary treatment processes such as cleaning, washing, drying, and sieve analysis before use in the concrete mixes. The preparation procedures were carried out to remove impurities, achieve proper grading, and ensure uniformity of the aggregate particles. Similar aggregate preparation methods have been adopted by researchers investigating lightweight and sustainable concrete production using recycled materials and conventional aggregates (Babafemi et al., 2018; Qaidi et al., 2023).

2.2.1 Acquisition of Coarse Aggregates

The coarse aggregates obtained were: 6 bags of 50kg brown colored gravel/natural unwashed gravel, and gray-white colored granite respectively. The granite material with 0.25mm size was obtained from Express quarry site, along Lagos-Ibadan expressway, Nigeria. The natural unwashed gravel was obtained from Ikire, Osun State.

2.2.1.1 Washing of the Unwashed Natural Gravel

The unwashed gravel was washed thoroughly with safe water several times, to remove the dirt in form of silt and strands of roots through sieving with the aid of a large sieve, hand picking and applying sedimentation to remove the silt.

2.2.1.2 Sieve Analysis of Coarse Aggregates

The sieve analysis carried out on the coarse aggregates followed the same procedure discussed earlier in Section 2.1.1.3 for the WPET material. The test was conducted to determine the particle size distribution and grading characteristics of the coarse aggregates used for concrete production. Proper grading of coarse aggregates is essential because it influences the workability, density, strength, and durability properties of concrete (Alexander et al., 2025; ASTM C136/C136M-19, 2019). The only modification to the procedure was the inclusion of an additional 13.7 mm sieve to the existing set of sieves ranging from 6.70 mm to 0.212 mm, in accordance with the requirements of the British Standard (BS) code for coarse aggregate grading. The inclusion of the larger sieve size was necessary to adequately classify the coarse aggregate particles and ensure compliance with standard specifications for concrete aggregates (BS EN 933-1, 2012). The results obtained from the sieve analysis were used to evaluate the suitability of the coarse aggregates for concrete production and to ensure proper particle distribution within the concrete mix.



Plate 8: Photograph showing unwashed natural gravel together with debris, roots, and silt removed during the cleaning process



Plate 9: Photograph showing washed gravel used as coarse aggregate in concrete production



Plate 10: Photograph showing granite aggregate used as coarse aggregate in concrete production

2.2.2 Acquisition of Fine Aggregate

The fine aggregate obtained were 6 bags of 50kg sharp brown sand/river sand. It was obtained from Balogun Aruna village, Akinyele LGA, Ibadan, Oyo State.

2.2.3 Acquisition of Cement

The cement used was manufactured by Lafarge Cement WAPCO Nigeria Plc. Elephant Cement House, Central Business District, Alausa, Ikeja, Lagos State. The Elephant Limestone Cement used is of Grade 32.5N.

2.3 Preparation of Different Concrete Mixes

This section discusses the mix ratio of the concrete, percentage of WPET introduced to each mix batched and slump test performed on every mix.

2.3.1 Concrete Mix

The concrete mixes used in this study were prepared using a mix ratio of 1:2:4, which represents one head pan of cement, two head pans of fine aggregate, and four head pans of coarse aggregate. This mix proportion was adopted because it is commonly used for normal concrete production and provides adequate strength and workability characteristics for structural applications (Alexander et al., 2025; BS EN 206, 2017). The selected mix ratio was used in determining the quantities of materials required for the production of all concrete specimens used in this research.

According to British Standards Institution standard specifications, concrete test specimens are preferably prepared in cube form with dimensions of 100 mm × 100 mm × 100 mm for compressive strength evaluation (BS EN 12390-1, 2021). Therefore, the volume of each concrete cube cast was calculated as:

$$100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm} = 0.001 \text{ m}^3 \quad (1)$$

A total of 144 concrete cubes were cast for the experimental investigation. Hence, the total volume of concrete produced was calculated as:

$$0.001 \text{ m}^3 \times 144 = 0.144 \text{ m}^3 \quad (2)$$

Assuming the density of normal concrete as 2400 kg/m³, the total mass of concrete required for the study was determined as:

$$2400 \text{ kg/m}^3 \times 0.144 \text{ m}^3 = 345.6 \text{ kg} \quad (3)$$

Table 1 and Table 2 present the quantities of materials used for each concrete mix. The ground WPET was introduced as partial replacement for fine aggregate (river sharp sand) in the concrete mixes at replacement levels of 1%, 2%, 4%, 6%, and 8%, while the proportions of other constituent materials remained constant throughout the experiment. The incorporation of WPET as partial replacement for fine aggregate was intended to evaluate its effect on the physical and mechanical properties of concrete, while also promoting sustainable waste management practices through the recycling of plastic waste materials (Babafemi et al., 2018; Qaidi et al., 2023; Zulkernain et al., 2021). Controlled concrete samples containing no proportion of

WPET were also prepared for each category of concrete mix in order to provide a basis for comparison with the modified concrete specimens.



PLATE 11: Photograph showing river sharp sand used as fine aggregate in the concrete mixtures



PLATE 12: Photograph showing Ordinary Portland Cement (Grade 32.5N) used for concrete production

TABLE 1
QUANTITY OF MATERIALS USED FOR THE CONCRETE MIX CONTAINING WASHED GRAVEL

Sand Replaced with Ground WPET (%)	Cement (kg)	Sand (kg)	Plastic (kg)	Washed Gravel (kg)	W/C (kg)
0%	4.1	8.2	0	16.5	2.5
1%	4.1	8.1	0.1	16.5	2.5
2%	4.1	8	0.2	16.5	2.5
4%	4.1	7.9	0.3	16.5	2.5
6%	4.1	7.7	0.5	16.5	2.5
8%	4.1	7.5	0.7	16.5	2.5

TABLE 2
QUANTITY OF MATERIALS USED FOR THE CONCRETE MIX CONTAINING GRANITE

Sand Replaced with Ground WPET (%)	Cement (kg)	Sand (kg)	Plastic (kg)	Granite (kg)	W/C (kg)
0%	4.1	8.2	0	16.5	2.5
1%	4.1	8.1	0.1	16.5	2.5
2%	4.1	8	0.2	16.5	2.5
4%	4.1	7.9	0.3	16.5	2.5
6%	4.1	7.7	0.5	16.5	2.5
8%	4.1	7.5	0.7	16.5	2.5

2.3.2 Procedures Taken to Cast the Concrete Mixes

The concrete materials were batched by weight in accordance with the quantities presented in Tables 1 and 2. Cement, river sharp sand, coarse aggregate, WPET, and water were weighed separately before mixing. For the WPET-modified mixtures, WPET was introduced as a partial replacement for river sharp sand at 1%, 2%, 4%, 6%, and 8% by weight, while the quantities of cement, coarse aggregate, and water were maintained according to the mix design. The control mixture contained no WPET. The materials were mixed thoroughly on a clean concrete platform until a uniform concrete mixture was obtained. The slump

test was subsequently conducted to assess the workability of each fresh concrete mixture. The concrete was then placed into 100 mm × 100 mm × 100 mm cube moulds and compacted. Twelve cubes were prepared for each mixture to provide three specimens for each curing age of 7, 14, 21, and 28 days. After casting, the specimens were allowed to remain in the moulds before being removed and cured. At each testing age, three cubes were weighed before crushing, and their compressive strengths were determined using a compression testing machine. The same procedure was followed for concrete containing washed gravel and concrete containing granite. The only difference between the two groups was the type of coarse aggregate used.

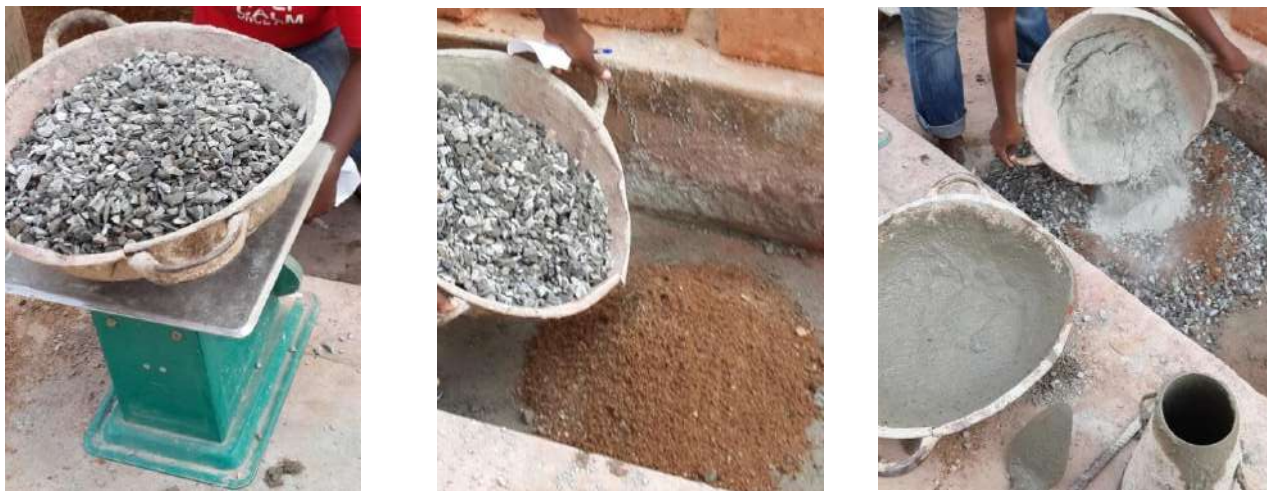


Plate 13: Photograph showing the weighing of coarse aggregate, river sharp sand, and cement using an analog weighing balance during batching

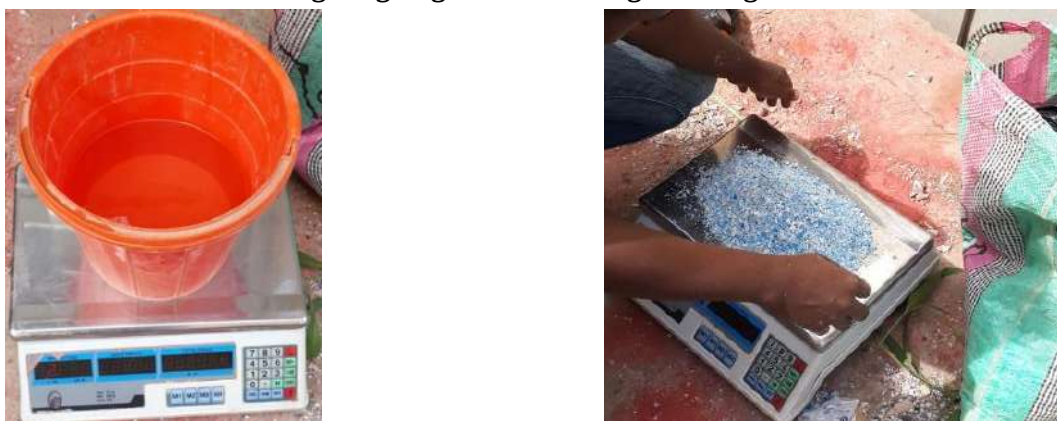


Plate 14: Photograph showing the weighing of water and WPET particles using a digital weighing balance during concrete preparation



Plate 15: Photograph showing a freshly mixed concrete batch containing 8% WPET replacement



Plate 16: Photograph showing a slump test being performed to evaluate the workability of fresh concrete



Plate 17: Photograph showing freshly cast concrete cube specimens in moulds during the curing process



Plate 18: Photograph showing concrete cube specimens being tested in a compression testing machine to determine compressive strength

III. RESULTS AND DISCUSSION

This section presents the particle-size distribution, specific gravity, workability, density, and compressive-strength results of concrete containing WPET as a partial replacement for fine aggregate. The results are compared with the control concrete to determine the influence of WPET incorporation on the fresh and hardened properties of concrete. Particular attention is given to the changes in workability, density, and compressive strength at the different WPET replacement levels and curing ages. The results of the sieve analysis, specific gravity test, slump test, density test, and compressive strength test are presented, analyzed, and discussed in detail. The effects of WPET incorporation on the fresh and hardened properties of concrete were systematically evaluated and compared against the control mix in order to establish the extent to which the WPET content influenced overall concrete performance. Furthermore, the findings are discussed in relation to previous studies on recycled plastic concrete, with the aim of assessing the suitability of WPET as a viable material for sustainable and lightweight concrete production (Babafemi et al., 2018; Uche et al., 2023).

3.1 Results from the Particle Size Analysis Conducted

This section shows tables and graphs that represent results obtained for the particle size analysis of both the fine aggregates (river sharp sand and WPET) and the coarse aggregates (washed gravel and granite). The weight of the sample of fine aggregates used were 500g each according to BS 812-103.1 (1985) for their particle grain size distribution to be achieved.

TABLE 3
RESULT OF PARTICLE SIZE ANALYSIS OF RIVER SHARP SAND USED

Sieve opening (mm)	Mass of soil retained (g)	Percentage of soil retained (%)	Percentage of soil passing (%)
6.7	16.9	3.3	96.7
4.75	25.7	5.02	91.68
2.35	82.3	16.06	75.62
1.18	124.4	24.28	51.34
0.85	61.5	12	39.34
0.6	79.2	15.46	23.88
0.425	66.4	12.96	10.92
0.212	46.7	9.12	1.8
Pan	9.2	1.8	0

Note: Weight of Pan = 165.5g; Weight of Sample (River Sharp Sand) = 500g

$$\text{Fineness Modulus} = \text{Cumulative \% Retained} / 100 = 608.72 / 100 = 6.09 \quad (4)$$

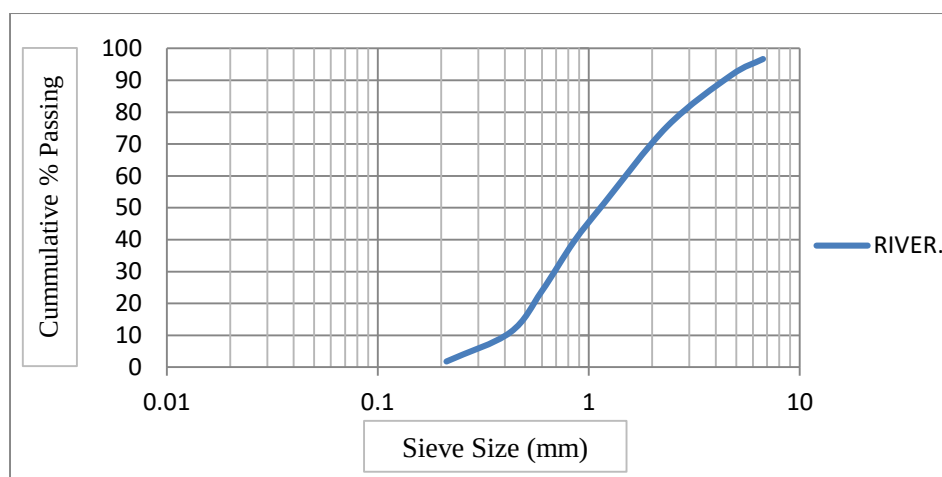


FIGURE 1: Particle size distribution curve for river sharp sand

Particle size distribution curve showing the cumulative percentage passing against sieve size for river sharp sand used as fine aggregate. The curve indicates a well-graded sand with particle sizes ranging from 0.212 mm to 6.70 mm and a fineness modulus of approximately 6.09. $D_{10} = 0.40$ mm, $D_{30} = 0.70$ mm, $D_{60} = 1.06$ mm, $C_u = 2.65$, $C_c = 1.16$.

TABLE 4
RESULT OF PARTICLE SIZE ANALYSIS OF WPET USED

Sieve opening (mm)	Mass of soil retained (g)	Percentage of soil retained (%)	Percentage of soil passing (%)
6.7	3.1	0.62	99.38
4.75	2.4	0.48	98.9
2.35	265.1	52.74	46.16
1.18	147	29.24	16.92
0.85	39.1	7.78	9.14
0.6	28.7	5.71	3.43
0.425	11.6	2.31	1.12
0.212	4.4	0.88	0.24
Pan	-1.3	0.26	-0.02

Note: Weight of Pan = 165.1g; Weight of Sample (WPET) = 500g

$$\text{Fineness Modulus} = \text{Cumulative \% Retained} / 100 = 624.73 / 100 = 6.26$$

(5)

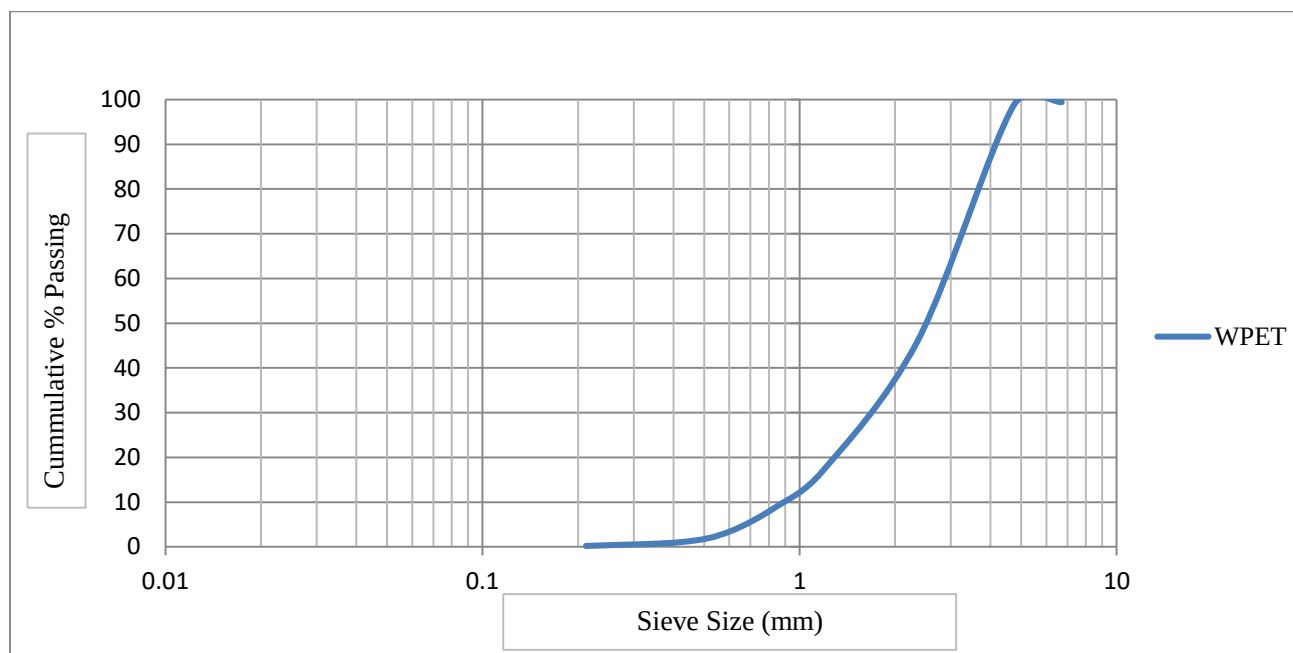


FIGURE 2: Particle size distribution curve for WPET

Particle size distribution curve showing the cumulative percentage passing against sieve size for Waste Polyethylene Terephthalate (WPET) particles used as partial fine aggregate replacement. The curve illustrates the grading characteristics of the processed WPET material with particle sizes ranging from 0.212 mm to 6.70 mm and a fineness modulus of approximately 6.26. $D_{10} = 0.90$ mm, $D_{30} = 1.08$ mm, $D_{60} = 1.20$ mm, $C_u = 1.33$, $C_c = 1.08$.

TABLE 5

COMBINED RESULTS OF PARTICLE SIZE ANALYSES FOR THE FINE AGGREGATES USED

Sieve opening (mm)	Percentage of R.S.S. passing (%)	Percentage of WPET passing (%)
6.7	96.7	99.38
4.75	91.68	98.9
2.35	75.62	46.16
1.18	51.34	16.92
0.85	39.34	9.14
0.6	23.88	3.43
0.425	10.92	1.12
0.212	1.8	0.24
Pan	0	-0.02

TABLE 6

RESULT OF PARTICLE SIZE ANALYSIS OF COARSE AGGREGATE – WASHED GRAVEL USED

Sieve opening (mm)	Mass of soil retained (g)	Percentage of soil retained (%)	Percentage of soil passing (%)
19	0.01	0.01	99.99
13.2	24.49	24.5	75.5
9.5	35.06	59.56	40.44
6.7	29.92	89.48	10.52
4.75	7.34	96.8	3.18
Pan	3.18	100	0

Note: Weight of Pan = 160.0g; Weight of Sample (Washed Gravel) = 2500g

$$\text{Fineness Modulus} = \text{Cumulative \% Retained} / 100 = 370.35 / 100 = 3.70$$

(6)

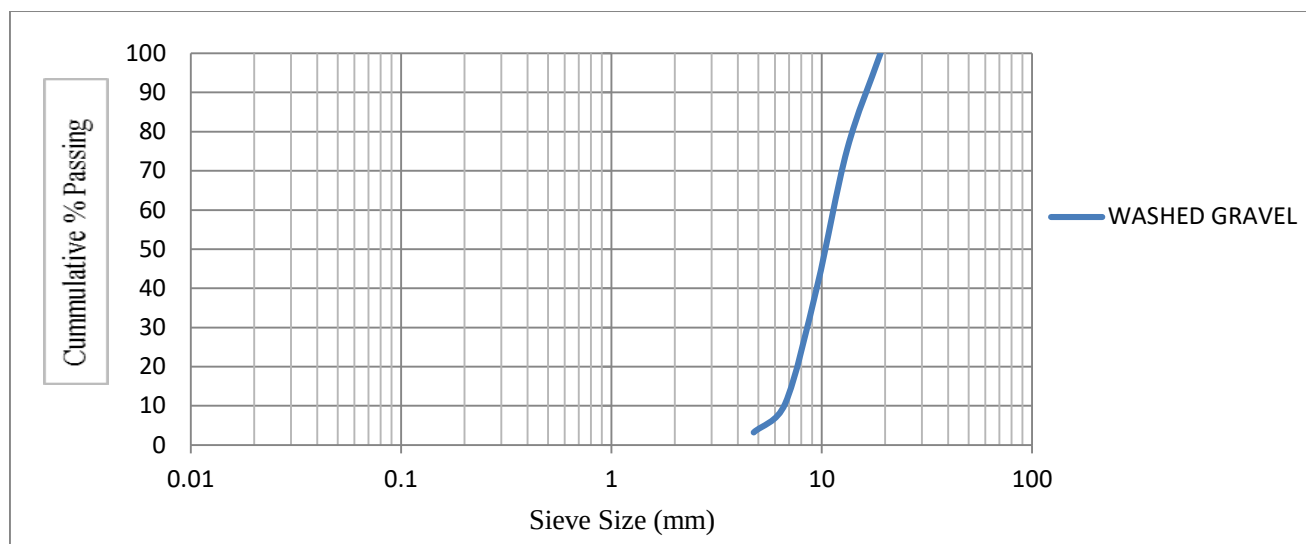


FIGURE 3: Particle size distribution curve for washed gravel

Particle size distribution curve showing the cumulative percentage passing against sieve size for washed gravel used as coarse aggregate in concrete production. The graph indicates the grading distribution of gravel particles with sieve sizes ranging from 4.75 mm to 19 mm and a fineness modulus of approximately 3.70. $D_{10} = 6.80$ mm, $D_{30} = 8.50$ mm, $D_{60} = 10.20$ mm, $C_u = 1.50$, $C_c = 1.04$.

TABLE 7
RESULT OF PARTICLE SIZE ANALYSIS OF COARSE AGGREGATE – GRANITE USED

Sieve opening (mm)	Mass of soil retained (g)	Percentage of soil retained (%)	Percentage of soil passing (%)
19	127.6	5.1	94.9
13.2	224.3	8.97	80.83
9.5	357.7	14.31	52.45
6.7	587.2	23.48	0.59
4.75	565.8	22.63	-73.9
Pan	637.8	25.51	-173.9

Note: Weight of Pan = 160.0g; Weight of Sample (Granite) = 2500g

$$\text{Fineness Modulus} = \text{Cumulative \% Retained} / 100 = 273.90 / 100 = 2.73 \quad (7)$$

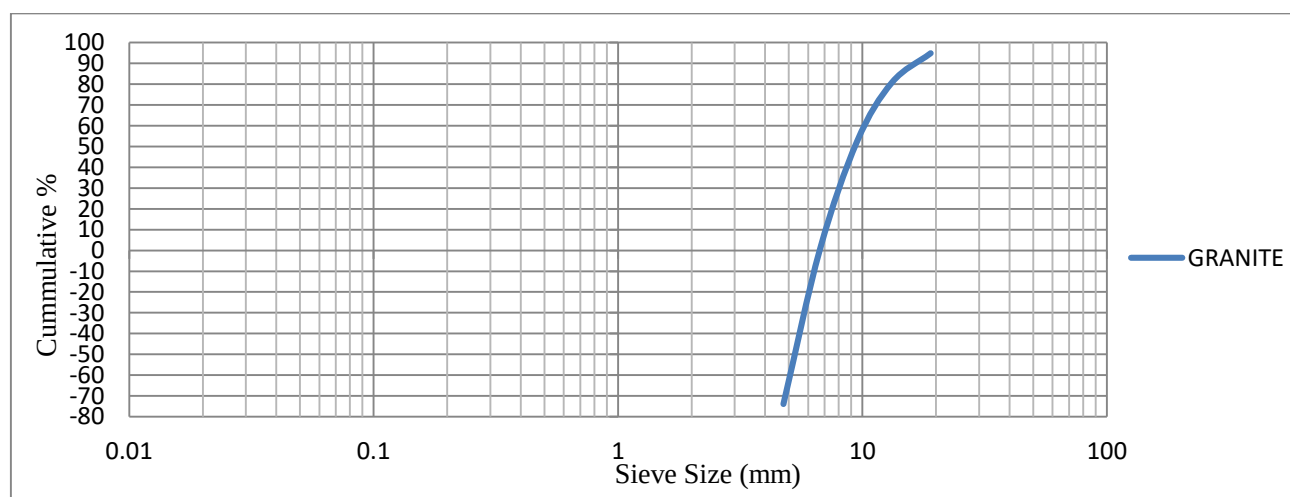


FIGURE 4: Particle size distribution curve for granite aggregate

Particle size distribution curve showing the cumulative percentage passing against sieve size for granite aggregate used as coarse aggregate in concrete production. The graph illustrates the grading characteristics of granite particles with sieve sizes ranging from 4.75 mm to 19 mm and a fineness modulus of approximately 2.73. $D_{10} = 7.20$ mm, $D_{30} = 8.20$ mm, $D_{60} = 10.00$ mm, $C_u = 1.39$, $C_c = 0.93$.

TABLE 8
COMBINED RESULTS OF PARTICLE SIZE ANALYSES FOR THE COARSE AGGREGATES USED

Sieve opening (mm)	Percentage of washed gravel passing (%)	Percentage of granite passing (%)
19	99.99	94.9
13.2	75.5	80.83
9.5	40.44	52.45
6.7	10.52	0.59
4.75	3.18	-73.9
Pan	0	-173.9

3.1.1 Specific Gravity (SG)

The specific gravity of the fine aggregates were determined as described in Section 2.1.1.4. The formula shown below in Tables 9 and 10 was used to express the results mathematically.

TABLE 9
SPECIFIC GRAVITY OF THE RIVER SHARP SAND USED

River Sharp Sand Sample	Sample Trial 1 (g)	Sample Trial 2 (g)
W ₁ (Weight of Empty Pycnometer)	105.6	100.4
W ₂ (Weight of Empty Pycnometer + Sample)	155.7	150.4
W ₃ (Weight of Empty Pycnometer + Sample + Water)	386.2	381
W ₄ (Weight of Pycnometer + Water)	355	349.8

Calculation:

$$\text{Trial 1: GS} = (155.7 - 105.6) / [(355.0 - 105.6) - (386.2 - 155.7)] = 50.1 / (249.4 - 230.5) = 50.1 / 18.9 = 2.65$$

$$\text{Trial 2: GS} = (150.4 - 100.4) / [(349.8 - 100.4) - (381.0 - 150.4)] = 50.0 / (249.4 - 230.6) = 50.0 / 18.8 = 2.66$$

$$\text{Average Specific Gravity (ASG)} = (2.65 + 2.66) / 2 = 2.655 \approx 2.66 \quad (8)$$

TABLE 10
SPECIFIC GRAVITY OF THE WPET USED

WPET Sample	Sample Trial 1 (g)	Sample Trial 2 (g)
W ₁ (Weight of Empty Pycnometer)	105.5	100.4
W ₂ (Weight of Empty Pycnometer + Sample)	155.5	150.4
W ₃ (Weight of Empty Pycnometer + Sample + Water)	368.8	363.5
W ₄ (Weight of Pycnometer + Water)	355.1	350

Calculation:

$$\text{Trial 1: GS} = (155.5 - 105.5) / [(355.1 - 105.5) - (368.8 - 155.5)] = 50.0 / (249.6 - 213.3) = 50.0 / 36.3 = 1.38$$

$$\text{Trial 2: GS} = (150.4 - 100.4) / [(350.0 - 100.4) - (363.5 - 150.4)] = 50.0 / (249.6 - 213.1) = 50.0 / 36.5 = 1.37$$

$$\text{Average Specific Gravity (ASG)} = (1.38 + 1.37) / 2 = 1.375 \approx 1.38 \quad (9)$$

3.1.2 Slump Test for Each Concrete Mix

The results of the slump tests as described in Section 2.3.2 were recorded in Tables 11 and 12.

TABLE 11
SLUMP TEST FOR THE CONCRETE MIX CONTAINING WASHED GRAVEL

Day	% of WPET Present	Slump 1 (cm)	Slump 2 (cm)	Slump 3 (cm)	Average Slump (cm)
Day 1	0%	5.9	5.1	4.3	5.1
	1%	4	3.3	2.6	3.3
	2%	2.3	2.2	1.25	1.92
Day 2	4%	5.8	3.6	2.6	4
	6%	3	1.9	2.15	2.35
	8%	3.95	2.85	1.8	2.87

TABLE 12
SLUMP TEST FOR THE CONCRETE MIX CONTAINING GRANITE

Day	% of WPET Present	Slump 1 (cm)	Slump 2 (cm)	Slump 3 (cm)	Average Slump (cm)
Day 1	0%	2.75	2.85	3.05	2.88
	1%	4.55	4.65	2.45	3.88
	2%	4	2.85	2.15	3
Day 2	4%	2.55	2.15	1.95	2.22
	6%	2.95	1.95	2.8	2.57
	8%	2.1	1.9	1.55	1.85

3.1.3 Dry Density of Concrete Mixes

The mass of each cube cast were weighed before curing. The volume of each cube is 0.001 m³ (100 mm × 100 mm × 100 mm = 1,000,000 mm³). The results are in Tables 13 and 14 for the washed gravel and granite respectively.

$$\text{Dry Density} = \text{Mass of Each Cube Cast (kg)} / \text{Volume of the Cube (m}^3\text{)} \quad (10)$$

TABLE 13
DRY MASS FOR EACH CONCRETE CUBE CONTAINING WASHED GRAVEL

	0% (kg)	1% (kg)	2% (kg)	4% (kg)	6% (kg)	8% (kg)
% WPET	2.205	2.335	2.175	2.35	2.46	2
	2.28	2.415	2.18	2.45	2.305	2.47
	2.245	2.375	2.25	2.58	2.375	2.33
	2.185	2.27	2.47	2.32	2.185	2.125
	2.295	2.24	2.345	2.31	2.29	1.915
	2.16	2.31	2.39	2.075	2.325	2.235
	2.325	2.34	2.38	2.335	2.205	2.2
	2.175	2.345	2.345	2.175	2.275	2.25
Total Weight (TW) (kg)	26.87	27.875	28.135	27.745	27.8	26.525
Average Weight (AW) (kg) = TW/12	2.239	2.323	2.345	2.312	2.317	2.21
Average Dry Density (kg/m ³) = AW/Volume	2239	2323	2345	2312	2317	2210

TABLE 14
DRY MASS FOR EACH CONCRETE CUBE CONTAINING GRANITE

	0% (kg)	1% (kg)	2% (kg)	4% (kg)	6% (kg)	8% (kg)
% WPET	2.295	2.29	2.27	2.11	2.42	2.155
	2.3	2.405	2.24	2.42	2.47	2.225
	2.265	2.645	2.355	2.305	2.27	2.44
	2.4	2.38	2.265	2.375	2.37	2.57
	2.155	2.38	2.25	2.32	2.365	2.54
	2.425	2.115	2.235	2.4	2.325	2.375
	2.3	2.395	2.505	2.475	2.32	2.35
	2.335	2.405	2.245	2.255	2.255	2.43
Total Weight (TW) (kg)	27.605	28.875	27.8	28.025	28.07	28.29
Average Weight (AW) (kg) = TW/12	2.3	2.406	2.317	2.335	2.339	2.358
Average Dry Density (kg/m³) = AW/Volume	2300	2406	2317	2335	2339	2358

3.1.4 Wet Density

The cubes cast were weighed after their curing days before they were crushed. See Tables 15 and 16 for the summary of washed gravel and granite respectively. To calculate the average wet density, similar procedure as in Table 13 was used.

TABLE 15
WET DENSITY OF CONCRETE CONTAINING WASHED GRAVEL (kg/m³)

% WPET	7 days	14 days	21 days	28 days
0%	2297	2235	2281	2352
1%	2402	2356	2352	2403
2%	2453	2457	2278	2417
4%	2403	2375	2335	2382
6%	2398	1933	2233	2358
8%	2224	2215	2245	2265

TABLE 16
WET DENSITY OF CONCRETE CONTAINING GRANITE (kg/m³)

% WPET	7 days	14 days	21 days	28 days
0%	2262	2308	2463	2355
1%	2290	2530	2527	2482
2%	2355	2350	2302	2433
4%	2375	2399	2357	2358
6%	2372	2389	2415	2362
8%	2457	2277	2485	2408

3.1.5 Compressive Strength

TABLE 17
COMPRESSIVE STRENGTHS OF CONCRETE CONTAINING WASHED GRAVEL WITH DIFFERENT PERCENTAGES OF WPET

% WPET	Compressive Strengths of Concrete Containing Gravel (N/mm ²)			
	7 days	14 days	21 days	28 days
0%	5.7	5.9	7.6	8.5
1%	7.8	8.1	9.1	9.9
2%	8.1	9.2	8.1	10.2
4%	6.6	9.6	8.4	8.7
6%	6.9	12	5.4	7.8
8%	2.1	2.1	2.6	2.5

*Note: Compressive Strength = Maximum Applied Load Just Before Failure (N) / Plan Area of the Cube Mould (mm²);
Plan area = 100 × 100 = 10,000 mm²*

TABLE 18
COMPRESSIVE STRENGTHS OF CONCRETE CONTAINING GRANITE WITH DIFFERENT PERCENTAGES OF WPET

% WPET	Compressive Strengths of Concrete Containing Granite (N/mm ²)			
	7 days	14 days	21 days	28 days
0%	5.7	7.5	7.3	7.2
1%	6.5	13	12.2	13.2
2%	7.7	8.5	9.6	8.5
4%	4.7	7.5	5.9	8
6%	7.9	10.5	10.8	11.3
8%	9.4	8	10.1	10.4

*Note: Compressive Strength = Maximum Applied Load Just Before Failure (N) / Plan Area of the Cube Mould (mm²);
Plan area = 100 × 100 = 10,000 mm²*

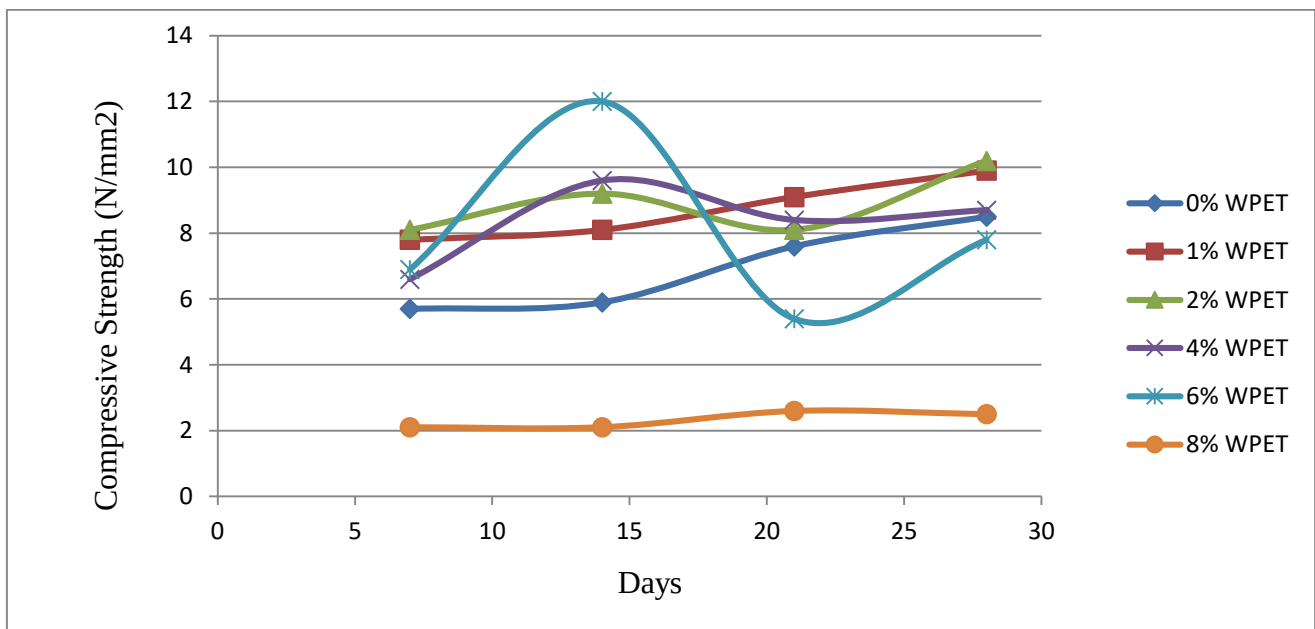


FIGURE 5: Compressive strength of concrete containing washed gravel and varying percentages of WPET
Graph showing the compressive strength of concrete containing washed gravel and varying percentages of WPET (0–8%) at curing ages of 7, 14, 21, and 28 days. Compressive strength increases with curing age and generally increases up to 2% WPET replacement, then decreases with increasing WPET content. The highest 28-day strength of 10.2 N/mm² was achieved at 2% WPET replacement.

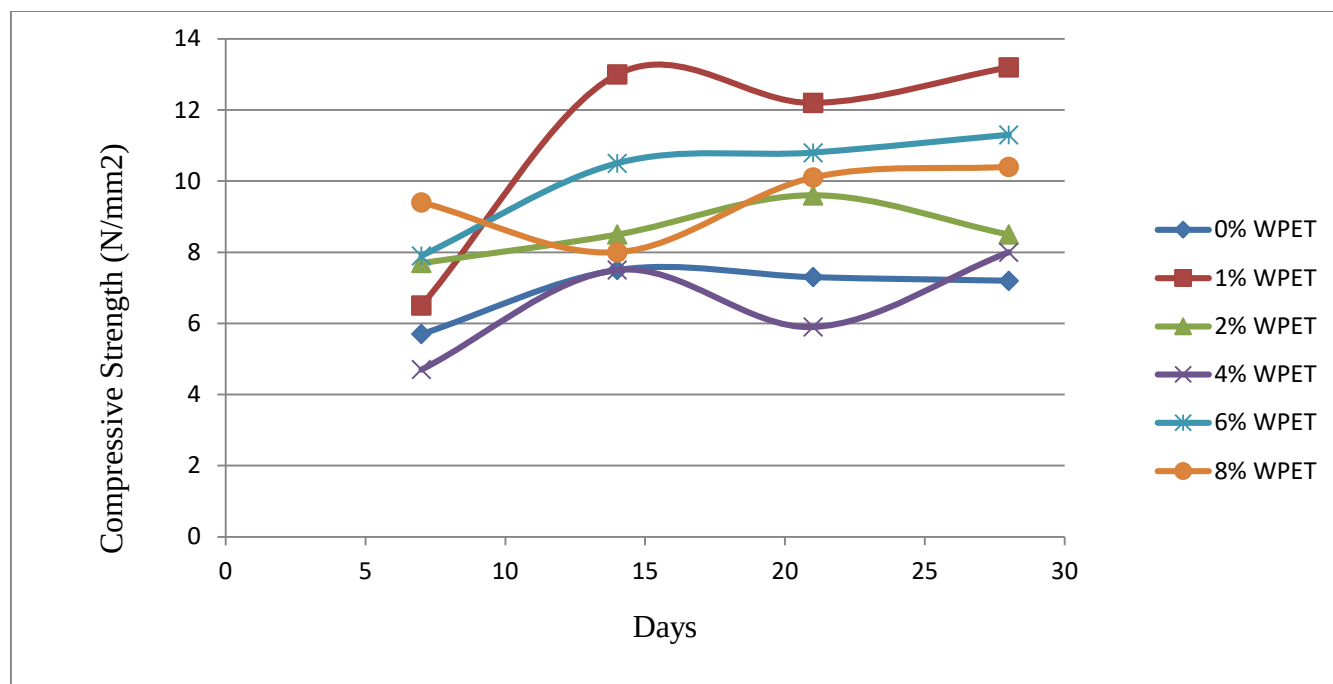


FIGURE 6: Compressive strength of concrete containing granite and varying percentages of WPET
Graph showing the compressive strength of concrete containing granite and varying percentages of WPET (0–8%) at curing ages of 7, 14, 21, and 28 days. Compressive strength increases with curing age and shows the highest 28-day strength of 13.2 N/mm² at 1% WPET replacement. Higher replacement levels show variable performance with 6% and 8% WPET also achieving competitive strengths.

3.2 Discussion

The results obtained from this study showed that the incorporation of Waste Polyethylene Terephthalate (WPET) as partial replacement for fine aggregate influenced the physical and mechanical properties of concrete. The sieve analysis results indicated that the WPET particles were suitably graded for use as lightweight aggregate material in concrete production. The specific gravity results also confirmed that WPET possesses lower density compared to natural aggregates, thereby contributing to the production of lighter concrete. The slump test results revealed that workability generally reduced as the percentage of WPET increased. This reduction may be attributed to the irregular shape and lower water absorption characteristics of the plastic particles, which affected the consistency of the concrete mix (Babafemi et al., 2018). The density results showed that the incorporation of WPET reduced both the dry and wet densities of the concrete mixes, indicating the lightweight nature of the concrete produced. Furthermore, the compressive strength results demonstrated that concrete strength decreased gradually with increasing WPET content. However, moderate replacement levels still produced acceptable strength values suitable for lightweight and non-structural concrete applications. Similar trends have been reported by previous researchers investigating the use of recycled PET materials in concrete production (Zulkernain et al., 2021; Qaidi et al., 2023). Consequently, the study demonstrated that WPET can be successfully utilized as partial replacement for fine aggregate in concrete production, thereby promoting sustainable waste management and reducing environmental pollution associated with plastic waste disposal.

3.2.1 Sieve Analysis

This test was performed to determine the percentage of different grain sizes contained within the soil (River Sharp Sand and WPET). From Table 3, the set of sieves were arranged in descending order from top to bottom. D_{10} , D_{30} and D_{60} are the particle size corresponding to 10%, 30% and 60% percentile respectively on the particle size distribution curve. From the curve of Figure 1, for the River Sharp sand: $D_{10} = 0.40$ mm, $D_{30} = 0.70$ mm and $D_{60} = 1.06$ mm which resulted to Coefficient of Uniformity, $C_u = 2.65$ and Coefficient of Curvature, $C_c = 1.16$ while that of WPET, from the curve of Figure 2, $D_{10} = 0.90$ mm, $D_{30} = 1.08$ mm and $D_{60} = 1.20$ mm which resulted to $C_u = 1.33$ and $C_c = 1.08$. With the results obtained, it can be said that the fine aggregates used were well graded.

From the curve of Figure 3, for the washed gravel: $D_{10} = 6.80$ mm, $D_{30} = 8.50$ mm and $D_{60} = 10.20$ mm which resulted to $C_u = 1.50$ and $C_c = 1.04$ while that of granite, from the curve of Figure 4, $D_{10} = 7.20$ mm, $D_{30} = 8.20$ mm and $D_{60} = 10.00$ mm

which resulted to $C_u = 1.39$ and $C_c = 0.93$. With the results obtained, it can be said that the coarse aggregates used were also well graded.

3.2.2 Specific Gravity

The objective of this test is to determine the density of the soil particles. The value obtained for the specific gravity of the river sharp sand and WPET used were 2.66 and 1.38 respectively. It is seen that the specific gravity for the river sharp sand is higher than that of WPET; this indicates that WPET is a light material which can be used to replace river sharp sand in lightweight concrete.

3.2.3 Slump Test

The slump results are presented in Tables 11 and 12. For the washed-gravel concrete, the control mixture recorded an average slump of 5.10 cm, while the mixtures containing 1%, 2%, 4%, 6%, and 8% WPET recorded average slump values of 3.30, 1.92, 4.00, 2.35, and 2.87 cm, respectively. For the granite concrete, the corresponding average slump values were 2.88, 3.88, 3.00, 2.22, 2.57, and 1.85 cm. The results indicate that WPET incorporation generally reduced the workability of the concrete, although the reduction was not perfectly linear. The decrease may be associated with the irregular particle shape, smooth surface, and low water absorption of WPET, which can affect the distribution of water and the cohesiveness of the fresh concrete. The non-linear pattern observed at some replacement levels may also be related to differences in particle packing and the interaction between WPET and the other aggregate particles. The results demonstrate that increasing WPET content may require adjustment of the mix design or the use of a suitable water-reducing admixture where higher workability is required.

3.2.4 Dry Density of Concrete Mixes

The dry-density results are presented in Tables 13 and 14. For the washed-gravel concrete, the average dry densities ranged from 2,210 to 2,345 kg/m³, while the granite concrete recorded average dry densities ranging from 2,300 to 2,406 kg/m³. The results did not show a perfectly progressive reduction in density with increasing WPET content. This may be due to differences in particle packing, specimen mass, and the distribution of WPET within the concrete matrix. Although WPET has a lower specific gravity than river sharp sand, the replacement levels used in this study were relatively small. Consequently, the influence of WPET on the overall density of the concrete was limited and was affected by the type of coarse aggregate used. The specific gravity of WPET was 1.38, compared with 2.66 for the river sharp sand, confirming that WPET is substantially lighter than the conventional fine aggregate.

3.2.5 Wet Density

3.2.5.1 Wet Density of Concrete Containing Washed Gravel

From Tables 15 and 16, the highest wet density on the 28th day of crushing was 2,417 kg/m³ containing 2% of WPET. The wet density containing 2% WPET in washed gravel concrete had 2,453 kg/m³ on the 7th day, which increased to 2,457 kg/m³ on the 14th day (0.16% increase), decreased to 2,278 kg/m³ on the 21st day (7.29% decrease), and later increased to 2,417 kg/m³ on the 28th day (6.10% increase). On the 28th day, the average density increased from 0% WPET (control mix) to 1% WPET then to 2% WPET by 2.17% and 2.76% respectively. From 2% WPET, it decreased as WPET increased to 8% by 3.70%. However, the average densities at 4% and 6% are still greater than those of corresponding control mixes by 1.28% and 0.26% respectively.

3.2.5.2 Wet Density of Concrete Containing Granite

From Tables 15 and 16, the highest wet density on the 28th day of crushing was 2,482 kg/m³ containing 1% WPET. The wet density containing 1% WPET in granite concrete was 2,290 kg/m³ on the 7th day, increased to 2,530 kg/m³ on the 14th day (10.48% increase), decreased to 2,527 kg/m³ on the 21st day (0.12% decrease), and decreased to 2,482 kg/m³ on the 28th day (1.78% decrease). The average density increased from 0% to 1% WPET by 5.39%. From 1% WPET, it decreased as WPET increased to 4%, and then later increased as WPET increased to 8%. However, the average densities at 2%, 4%, 6% and 8% are still greater than the control mixes by 3.31%, 0.13%, 0.30% and 2.25% respectively.

3.2.6 Compressive Strength

The compressive-strength results are presented in Tables 17 and 18. The results show that the influence of WPET was dependent on both the replacement level and the type of coarse aggregate used. For the washed-gravel concrete, the 28-day compressive strength increased from 8.5 N/mm² for the control mixture to 9.9 N/mm² at 1% WPET and 10.2 N/mm² at 2%

WPET. However, the strength decreased to 8.7, 7.8, and 2.5 N/mm² at 4%, 6%, and 8% WPET, respectively. The highest 28-day strength for the washed-gravel concrete was therefore obtained at 2% WPET. For the granite concrete, the 28-day compressive strength increased from 7.2 N/mm² for the control mixture to 13.2 N/mm² at 1% WPET. The strength subsequently decreased to 8.5 N/mm² at 2% WPET and 8.0 N/mm² at 4% WPET, before increasing to 11.3 N/mm² at 6% WPET and 10.4 N/mm² at 8% WPET. The highest 28-day strength for the granite concrete was therefore obtained at 1% WPET. These results indicate that low WPET replacement levels may improve compressive strength under particular mix conditions, possibly because of improved particle packing or the contribution of the plastic particles to the internal structure of the concrete. However, higher replacement levels may reduce strength because of the low stiffness, smooth surface, and weak interfacial bonding of WPET particles with the cement paste. The results do not support a uniformly linear relationship between WPET content and compressive strength. Instead, the response is dependent on the replacement level, curing age, and coarse aggregate type.

3.2.6.1 Compressive Strength of Concrete Containing Washed Gravel

BS 8110-1 recommends that concrete grades below 20 MPa are unsuitable for reinforced concrete applications due to strength and durability requirements (BSI, 1997). From Figure 5, at different percentages of WPET introduced to the concrete, on the 7th day of crushing, the compressive strength increased with increasing WPET proportion (from 0% to 2%), and then declined at 4% WPET proportion. The compressive strength afterwards slightly increased at 6% WPET proportion and drastically decreased at 8% WPET proportion. However, there was increase in compressive strength at all the WPET proportions (1%, 2%, 4% and 6%) by 36.84%, 42.10%, 15.79% and 21.05% respectively except at 8% WPET by -63.16%. At 14th day, the compressive strength increased progressively with increasing WPET proportion (from 0% to 6% at the introduction of WPET to the concrete) by 37.29%, 55.93%, 62.71% and 103.39% respectively, and then drastically reduced at 8% WPET by 64.41%. At 21st day, the increase in compressive strength from 0% to 1% WPET was well pronounced compared to its 7th and 14th day trends, thereafter, there was a slight increase of its compressive strength from 1% to 2% WPET. From 2% to 4% WPET, there was a slight decrease in compressive strength, the compressive strength drastically decreased at 6% WPET, and finally further decreased at 8% WPET. At 28th Day, the trend is slightly similar to the trend of the compressive strength on the 21st day. The increase from 0% to 1% WPET was well pronounced compared to its 7th and 14th day trends. Thereafter, there was a slight increase of its compressive strength from 1% to 2% WPET. From 2% to 4%, there was a decrease in compressive strength, the compressive strength further decreased at 6% WPET, and finally drastically decreased at 8% WPET. It was further observed that the highest compressive strength on the 28th day was at the introduction of 2% WPET to the concrete mix which is 10.2 N/mm².

3.2.6.2 Compressive Strength of Concrete Containing Granite

From Figure 6, at different percentages of WPET introduced to the concrete, on the 7th day of crushing, the compressive strength progressively increased from 0% to 1% and then to 2% WPET by 14.03% and 35.09% respectively, it declined in compressive strength at 4% WPET (-17.54%), it slightly increased at 6% WPET (38.60%) and further increased at 8% WPET (64.91%). At 14th day, the compressive strength increased from 0% to 1% WPET at the introduction of WPET to the concrete by 73.33%, it drastically reduced in compressive strength from 1% to 4% WPET, it later increased in compressive strength at 6% WPET, then slightly reduced at 8% WPET. Although at the introduction of 2%, 6% and 8% WPET, it increased by 13.33%, 40% and 6.67% respectively except at 4% WPET whereby there was no significant change in its compressive strength. At 21st day, the increase in compressive strength from 0% to 1% WPET was well pronounced compared to its 7th and 14th day trends. Thereafter, there was a drastic decrease of its compressive strength from 1% to 4% WPET. From 4% WPET, there was a sharp increase in strength to 6% WPET, thereafter, the compressive strength slightly decreased from 6% WPET to 8% WPET. At 28th day, the trend is slightly similar to the trend of the compressive strength on the 21st day. The increase in compressive strength from 0% to 1% WPET was well pronounced compared to its 7th and 14th day trends, thereafter, there was a drastic decrease of its compressive strength from 1% to 4% WPET. From 4% WPET, there was a sharp increase in strength to 6% WPET, thereafter, the compressive strength slightly decreased from 6% WPET to 8% WPET. It was further observed that the highest compressive strength on the 28th day is at the introduction of 1% WPET to the concrete mix which is 13.2 N/mm².

IV. CONCLUSION

This study evaluated the use of waste polyethylene terephthalate (WPET) as a partial replacement for fine aggregate in concrete containing washed gravel and crushed granite. The WPET material had a lower specific gravity than river sharp sand, confirming its potential to reduce the mass of concrete when incorporated under suitable mix conditions. However, the density

results varied with replacement level, curing age, and coarse aggregate type and did not show a uniform reduction at every WPET content. The slump results indicated that WPET incorporation generally reduced workability, although the response was not perfectly linear. The compressive-strength results showed that the optimum replacement level depended on the coarse aggregate used. The highest 28-day strength for the washed-gravel concrete was 10.2 N/mm² at 2% WPET, while the highest value for the granite concrete was 13.2 N/mm² at 1% WPET. Higher replacement levels did not consistently improve strength and, in some mixtures, resulted in substantial strength reduction. The findings indicate that WPET may be used as a controlled partial replacement for fine aggregate in selected lightweight or non-structural concrete applications. However, the results do not establish that WPET concrete is suitable for all structural applications. Further investigations involving durability, water absorption, fire performance, long-term behaviour, leaching, life-cycle assessment, and detailed cost-benefit analysis are required before large-scale application. The study demonstrates the technical potential of recovering WPET for concrete production, but the economic feasibility of the process will depend on the cost of collection, transportation, cleaning, crushing, drying, and sieving relative to the cost of the natural sand replaced.

RECOMMENDATIONS

Based on the findings of this study, WPET should be incorporated at low replacement percentages, preferably not exceeding 4%, to maintain adequate workability, density, and compressive strength while still achieving meaningful plastic waste utilization in concrete production. Further research should be conducted to evaluate the durability and long-term performance of WPET-modified concrete, including its resistance to water absorption, sulphate attack, freeze-thaw cycles, and other aggressive environmental conditions, in order to establish its suitability for varied service environments. Future studies should explore methods of improving the bonding characteristics between WPET particles and the cement matrix, such as the use of chemical admixtures, surface treatment of plastic particles, or the incorporation of supplementary cementitious materials, to mitigate the strength reduction associated with higher replacement levels. Government bodies, regulatory institutions, and environmental agencies should formulate policies and incentive schemes that encourage the collection, processing, and utilization of plastic waste, particularly PET, in construction applications, thereby fostering sustainable waste management and reducing the environmental burden of plastic pollution. Construction stakeholders, including contractors and material suppliers, should be sensitized on the potential applications and limitations of WPET-modified concrete to facilitate its adoption in appropriate lightweight and non-structural construction projects. Finally, further studies should be carried out using larger-scale specimens and structural elements to validate the findings of this laboratory-based investigation under real construction conditions.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are openly available in Zenodo at <https://doi.org/10.5281/zenodo.20771259>. The repository contains the experimental dataset used in this study, including mix design information, particle size distribution data, specific gravity results, slump test results, density measurements, and compressive strength results for concrete incorporating waste polyethylene terephthalate (WPET) as a partial replacement for fine aggregate.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Predicting the Modulus of Elasticity of Recycled Aggregate Concrete Using an Artificial Neural Network Model in The Gambia

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Abstract— Recycling construction and demolition waste is essential in reducing its environmental impacts such as occupied land space and the leaching of harmful substances into the underlying soil. Understanding the mechanical properties of such waste ensures the strength and quality of concrete with recycled waste aggregates are not compromised. This study is divided into two components. The experimental component compared the compressive strength and elastic modulus of natural aggregate concrete (NAC) with that of recycled aggregate concrete (RAC). The RAC consisted of natural coarse aggregates replaced 100% by recycled concrete aggregates (RCAs) and was seen to do just as well as the NAC, showing that RAC is a viable option for structural use. In the artificial neural network (ANN) development component, the network model was trained using a dataset sourced from about 90 previous studies and used to predict the elastic modulus of RAC. With a mean absolute error (MAE) of 2.23, this study concludes that ANNs can be used to successfully predict mechanical properties of structural concrete.

Keywords— Recycled Concrete, Recycled Aggregate, Modulus of elasticity, Artificial Neural network.

I. INTRODUCTION

The Elastic Modulus (E) is an important mechanical property of materials universally defined as the ratio of stress to strain below the proportional limit. Greater values of elasticity, E, imply smaller strains resulting from larger stresses and, in concrete, indicate greater stiffness or more strength [1]. The elastic modulus of concrete, E_c , is not easily determined as concrete is not an elastic material and does not follow Hooke's law. E_c must be determined in designing structures as it shows the ability of concrete to withstand stresses and not deform elastically, that is, undergo deflections, or produce strains [2, 3]. E_c is also needed to satisfy requirements of ultimate and serviceability limit states [1]. Determining the elastic modulus of concrete involves using a Universal Testing Machine (UTM) or a Compression Testing Machine, and using the compressive strength, C_s , and/or stress-strain graph obtained, to calculate E_c . (Compressive strength is a measure of the compressive forces or loads a material can bear before cracking or fracturing.) This is a tedious, time-consuming process and is not always accurate as there are many formulas available to use [3].

As buildings age, they get to a point where they are deemed unsafe and demolished. Structures may also be demolished for other reasons and this demolition produces construction waste. To catapult into a more environmental and economic industry, the Gambian construction industry can look into how recycled aggregates (RAs) from construction waste can be reused in new upcoming projects/buildings, especially Recycled Concrete Aggregates (RCA). This RCA is derived by separating concrete

rubble from the mortar content, rubble, bricks, tiles, sand, dust, timber, plastics, metals, cardboard, and paper, of construction and demolition waste, and crushing it to required sizes [4]. Determining the Ec of concrete made with RCAs proves to be a difficult task as RCAs are sourced from different places and the properties of the original concrete are not always known. As the world becomes more aware and concerned about our environment, reusing RAs helps to reduce the number of debris and construction waste that takes up land space and leaches into the ground, making it agriculturally unusable even in the event of a transfer of materials in the future [5]. Environmental risks of RA causing pollution include Chromium (Cr) leaching.

In the past decade, the advancement of Artificial Intelligence (AI) has been useful in application to various human problems, including civil engineering ones. Data-Driven Models (DDMs) are heuristic techniques that have been employed in the concrete industry and successfully predicted the mechanical properties of several types of concrete. Artificial Neural Networks (ANNs) have been particularly outstanding in predicting these properties as compared to other DDMs such as Multivariate Adaptive Regression Splines (MARS), Grasshopper Optimisation Algorithm (GOA), Extreme Learning Machine (ELM), Random Forest (RF), M5 Prime Model Tree (M5p), etc. [6]. ANNs are also much simpler to use. ANNs may be defined as computational models that can perform pattern recognition and retention of information-based knowledge by imitating brain activity. The brain is a complex organ; ANNs run a simplified version of its operations. Thus, ANNs are made up of an input layer, one or more hidden layers, and an output layer. Each layer can have a different number of nodes (i.e., artificial neurons) [7].

It is important to understand the mechanical properties of recycled aggregate concrete (RAC) in reusing it in the construction industry to ensure the quality of buildings produced is not affected by the replacement. The elastic modulus of concrete is one of the most important mechanical properties. Thus, this study seeks to accurately predict the elastic modulus of Recycled Aggregate Concrete in The Gambia using an ANN model, and this is achieved by predicting the compressive strength of Recycled Aggregate Concrete (RAC) in The Gambia, comparing the compressive strength of the Natural Aggregate Concrete (NAC) with that of RAC, comparing the elastic modulus of NAC with that of RAC and predicting the applicability of ANNs in solving further problems within the civil engineering field.

Several RAs have been used to replace natural aggregates (NAs) in concrete mixes such as recycled mortar, recycled bricks, etc. This study limits itself to the use of Recycled Concrete Aggregates (RCAs). The RCAs replaced 100% of the NAs in the experimental component of the study as coarse aggregates for the RAC mix. Fine Aggregates were not replaced in the study and all mixes were designed for normal-weight concrete. The ANN for the study was constructed only for the RAC using TensorFlow [8], Keras API [9], and run on Google Colab [10]. About 90 papers from previous studies were sourced manually in compiling the dataset for the model. The output parameter considered was the elastic modulus of RAC and the study's dataset had a total of 11 input parameters which did not include factors such as the type/nature of curing, the type of natural aggregate, and the moisture state of the RCA.

II. MATERIALS AND METHODS

In carrying out this research, the mix proportions were designed for normal-weight concrete consisting of cement (C), coarse aggregate (CA), fine aggregates (FA), and water (W). The mix proportions are shown in Table 1 below with a target strength of 25–30 MPa:

TABLE 1
CONCRETE MIX PROPORTIONS

Mix ID	C (kg/m ³)	W (kg/m ³)	FA (kg/m ³)	NA (kg/m ³)	RA (kg/m ³)
NAC	300	165	580.5	1354.5	0
RAC	300	165	580.5	0	1354.5

(C: Cement, W: Water, FA: Fine Aggregates, NA: Natural Coarse Aggregates, RA: Recycled Coarse Aggregates)

Additional water (about 500 ml) was added to the recycled aggregate mix (RAC) for better workability. No admixtures were added to either mix. Mixing of concrete, casting of cubes and crushing of cubes is as shown in Figures 1–7 below.



FIGURE 1: Crushing of RCA



FIGURE 2: Mixing of NA



FIGURE 3: NAC and RAC casted in moulds



FIGURE 4: Casted cubes after 24 hours

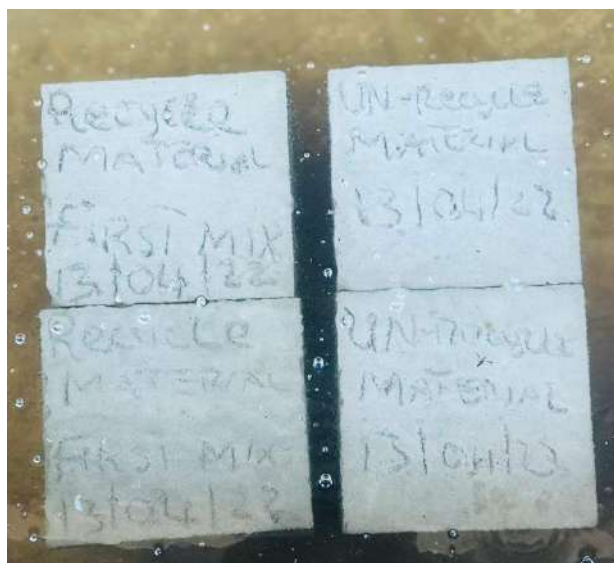


FIGURE 5: Cubes in curing tank

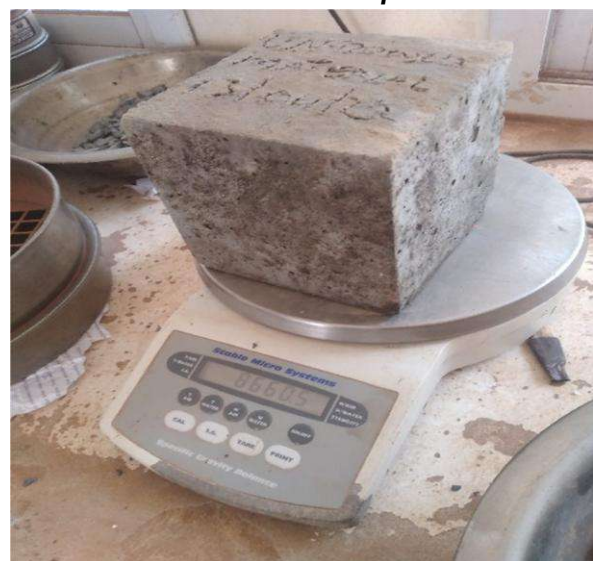


FIGURE 6: Cube being weighed



FIGURE 7: Crushing of cube in the Compressive Testing Machine

Mix Components:

- **Cement:** Salam cement, 42.5N.
- **NA:** Basalt imported from Senegal of particle size gradation, 8/16.
- **RA:** Demolished concrete taken from a Construct Ltd. site located in Bijilo, The Gambia.
- **FA:** Beach sand.

Mixes were filled into prepared cube moulds in three layers and given 25 blows per layer. The cubes were left to solidify for 24 hours (1 day), before they were removed from the mould and placed into the curing tank.

The cubes casted were tested at 7, 14, 21 and 28 days and their respective compressive strengths were determined utilizing a compressive testing machine and Universal Testing Machine (UTM) in the laboratory of National Roads Authority (NRA), The Gambia.

The Compressive Strength Test is a "mechanical test measuring the maximum amount of compressive load a material can bear before fracturing. The test piece, usually in the form of a cube, prism, or cylinder, is compressed between the platens of a compression-testing machine by a gradually applied load" [11].

The compressive strengths obtained were used to determine the elasticity of the mixes using established formulae from BS 8110-2:1985 [12] for normal-weight concrete:

$$\varepsilon_c = 4700\sqrt{f_{cu}} \quad (1)$$

$$\varepsilon_c = k_o + 0.2f_{cu_{28}} \quad (2)$$

Where:

ε_c is Elastic Modulus of Concrete

f_{cu} is Compressive Strength of Concrete

$f_{cu_{28}}$ is Compressive Strength of Concrete at Twenty-Eight Days

k_o is A constant closely related to the modulus of elasticity of the aggregate (taken as 20 kN/mm² for normal-weight concrete)

2.1 ANN Development Component

The ANN for this study was set up once all experimental work had ended. The network was built using the Keras API with TensorFlow [8, 9], on the Google Colab development environment [10]. This was preferred to other options such as MATLAB

[13] because Keras is a deep-learning API run in the background by Python and is simple, flexible and powerful. TensorFlow is also particularly focused on training deep neural networks. An additional advantage is that the combination of this software can be run on the web. A classification of studies done on RAC showed that many authors' studies were limited to the C_s of concrete and did not venture further into E_c [14]. Considering that E_c varies with equations of different standards [15], it was a tough task to find enough concrete data with E_c values. As such, two ANN models were developed to predict the compressive strength and elasticity of concrete respectively.

The data for our models were compiled manually and sourced from about 90 studies/papers [4, 15-22].

TABLE 2
DATASET RANGE OF VARIABLES

Parameter	Input/Output	Unit	No. of App. (801)	Min	Max	Average
Water-to-Cement Ratio (W/C)	Input	–	649	0.25	0.75	0.48
Water (W)	Input	Kg/m ³	755	3	262	183.2
Cement (C)	Input	Kg/m ³	801	6	864	378.87
Sand / Fine Aggregate (FA)	Input	Kg/m ³	781	12	1172	702.24
Natural Aggregate (NA)	Input	Kg/m ³	585	9.6	2860	740.56
Recycled Aggregate (RA)	Input	Kg/m ³	622	2.4	2230	642.16
Rubber	Input	Kg/m ³	3	39.8	79.6	59.7
Steel Fibre	Input	Kg/m ³	3	19.9	39.8	29.87
Silica Fume (SF)	Input	Kg/m ³	47	17.5	89	46.52
Fly Ash (FA)	Input	Kg/m ³	96	18	227.5	114.87
Limestone Powder	Input	Kg/m ³	10	166	370.2	276.08
Superplasticizer (SP)	Input	Kg/m ³	326	0.096	90.23	4.32
Compressive Strength (fcu)	Output	MPa	801	6.7	108.51	41.92
Elastic Modulus (E)	Output	GPa	463	8.69	50.41	28.93

(No. of App.: Number of appearances)

In ANN I, a total number of 801 data entries included 12 input parameters: water-to-cement ratio, water (kg/m³), cement (kg/m³), sand/fine aggregate (kg/m³), natural aggregate (kg/m³), recycled aggregate (kg/m³), rubber (kg/m³), steel fibre (kg/m³), silica fume (kg/m³), fly ash (kg/m³), limestone powder (kg/m³), and superplasticizer (kg/m³); and an output one: compressive strength (MPa). The range of variables of both datasets are shown in Table 2.

In ANN II, a total number of 463 data entries included 11 input parameters: water-to-cement ratio, water (kg/m³), cement (kg/m³), sand/fine aggregate (kg/m³), natural aggregate (kg/m³), recycled aggregate (kg/m³), silica fume (kg/m³), fly ash (kg/m³), limestone powder (kg/m³), superplasticizer (kg/m³), and compressive strength (MPa); and an output one: the elastic modulus of concrete (GPa).

The networks' architecture and parameters are described in Table 3. Forward-feed, back-propagation networks were developed. This type of network determines the difference between processed output and target output to give an error. It then proceeds to adjust the weights itself taking into account the error it generated. It continues to adjust weights until the error generated is insignificant, that is, the processed output is pretty close to the target output. The weights used at that point are stored as the correlation values. Most of the input data had correlation values of less than 0.5 between themselves and the output values, calculated using Spearman's rank correlation coefficient formula (Equation 3). Those with correlation values greater than that were not excluded from the dataset as they did not outright affect the model's performance.

$$\rho = 1 - \frac{6\epsilon d^2}{n(n^2-1)} \quad (3)$$

ρ — Spearman's Rank Correlation Coefficient

d — Difference between the Two Ranks of each Observation

n — Number of Observations

TABLE 3
ANN ARCHITECTURE AND PARAMETERS

Parameter	ANN I	ANN II
Architecture	12-4-2-1	11-4-2-1
Number of Input Layers	1	1
Number of Input Nodes	12	11
Number of Hidden Layers	2	2
Number of Hidden Nodes (i.e., Weights)	4, 2	4, 2
Number of Output Layers	1	1
Number of Output Nodes	1	1
Momentum Rate	0	0
Learning Rate	1×10^{-4}	1×10^{-4}
Epochs	150	150
Dataset Shape	(801,13)	(463,12)

Figures 8 and 9 below show flowcharts of the ANNs adopted:

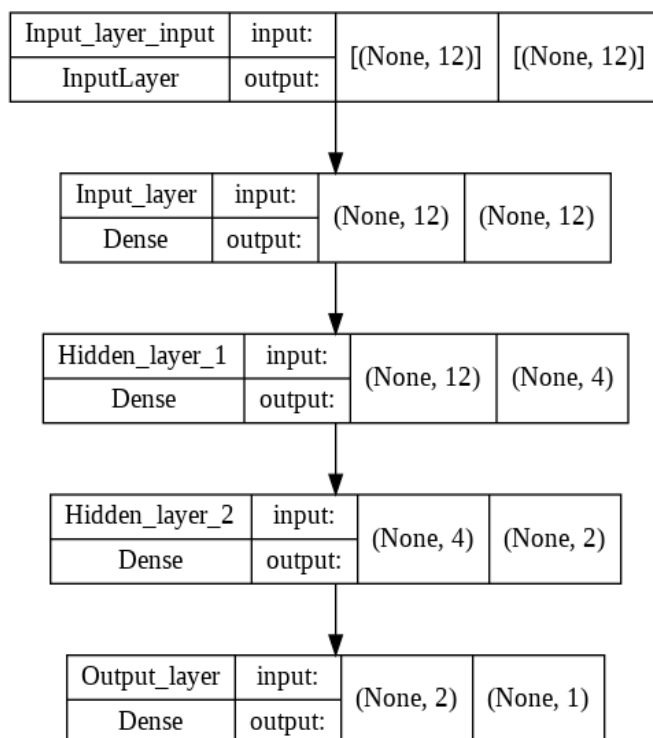


FIGURE 8: ANN I flowchart

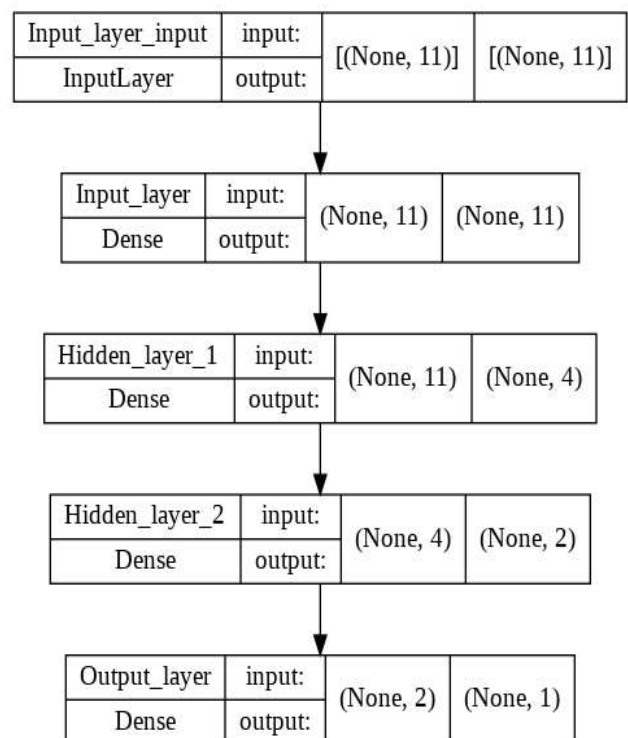


FIGURE 9: ANN II flowchart

The datasets were divided into two for training and subsequent testing. Approximately 14% of the data was kept for validation of the model whilst the remaining 86% was used in training. Additionally, the input parameters data was normalised in rescaling it for better learning.

III. RESULTS AND DISCUSSION

As seen in Table 4, the compressive strength of the cubes attained for both RAC and NAC were not up to standard. Even more surprisingly, the RAC was stronger than the NAC (Figure 10), which does not conform to trends in the large majority of previous studies [16, 20, 21, 22], although a few studies show results with RAC stronger than NAC even without the addition of superplasticizers, especially with differing coarse aggregate replacement percentages and water-to-cement ratios [17, 20].

TABLE 4
COMPRESSIVE STRENGTH RESULTS

Cube ID	Curing Time	Cast Date	Test Date	A (mm ²)	W (g)	L (KN)	fcu (MPa)	fcu Avg. (MPa)
Natural Aggregate Samples								
NAC1	7 days	13-04-2022	20-04-2022	22500	8661	119.2	5.3	5.9
NAC2					8263	144.7	6.4	
NAC3	28 days	13-04-2022	11-05-2022	22500	8548	233.1	9.1	9.7
NAC4					8495	229.3	10.2	
Recycled Aggregate Samples								
RAC1	7 days	13-04-2022	20-04-2022	22500	8065	174	7.7	8.9
RAC2					7593	228.3	10.1	
RAC3	28 days	13-04-2022	11-05-2022	22500	7738	308.2	13.7	13.9
RAC4					7834	317.3	14.1	

(A: Cube Surface Area, mm²; W: Weight, g; L: Load at Failure/Cracking, KN; fcu: Compressive Strength, MPa)

Where the water-to-cement ratio of the RAC is lower than that of the NAC, the compressive strength of the RAC can be equal to or even higher than that of the NAC. However, it is more common for RAC compressive strength to be 10–25% lower than that of similar NAC [4].

The observed comparable strength between the two mixes can be attributed to a number of reasons: Firstly, the composition of the original concrete recycled as RCA is not known – it may have possessed superplasticizer or other concrete enhancing admixtures. Secondly, it would be expected that the total porosity of the RAC would be more than that of the NAC [19]. However, considering that the RCA in this study did not undergo a particle size distribution, there is the likelihood that the fines present in the RCA filled up pore spaces in the RAC mix thus reducing its porosity and giving it similar strength to the NAC. Finally, the cement brand used in the original concrete for the RCA may have been 'GACEM' or 'Tiger Cement', which could be of higher grade than the cement used in this study (Salem cement). This may also be responsible for the overall low strength results in both of the mixes.

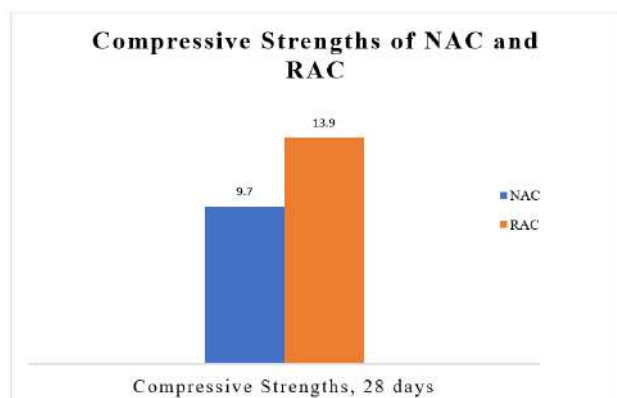


FIGURE 10: Comparison between Experimental Compressive Strengths of NAC and RAC

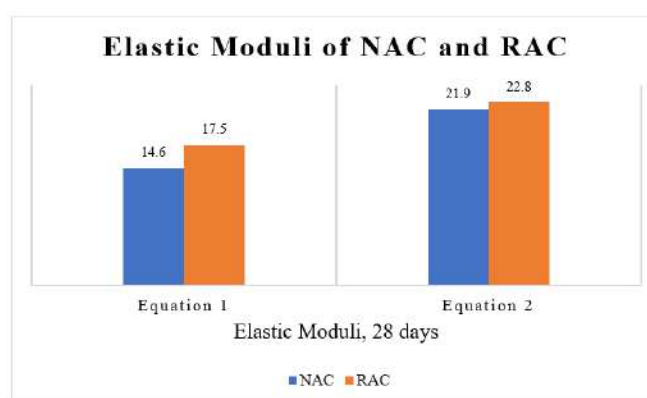


FIGURE 11: Comparison between Elastic Moduli of NAC and RAC

Similarly, the elastic moduli of the RAC were higher than the NAC using both Equations 1 and 2, as seen below in Figure 11.

3.1 ANN Results

Losses that arose in the training of ANNs were expressed as mean squared errors (MSEs) which can be calculated using Equation 4 below. Table 5 shows the performance of the ANN models: their losses and mean absolute errors (MAEs). The formula for the generation of MAEs is shown in Equation 5.

$$MSE = \frac{1}{n} \sum \varepsilon (y - y')^2 \quad (4)$$

$$MAE = \frac{1}{n} \sum \varepsilon |y' - y| \quad (5)$$

Where:

MSE is Mean Squared Error

MAE is Mean Absolute Error

n is Number of Data Points

y is True / Observed Values

y' is Predicted Values

TABLE 5
PERFORMANCE OF ANN MODELS

Results	Training Loss	Training MAE	Validation Loss	Validation MAE
ANN I	95.07	7.46	109.61	7.98
ANN II	14.24	2.7	9.84	2.23

In general, the closer the losses and MAE values are to zero (0), the better the performance of a model, although this is also dependent on the size of the dataset and other properties of the model. As such, our models' performances were acceptable as seen in Table 5.

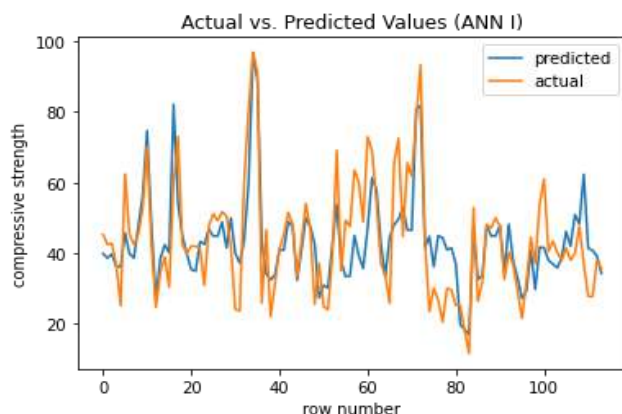


FIGURE 12: ANN I – Actual vs. Predicted Cs Values

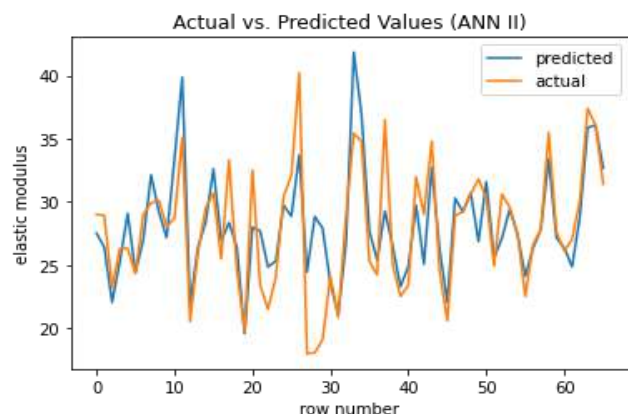


FIGURE 13: ANN II – Actual vs. Predicted Ec Values

Figures 12 and 13 show comparisons between the actual values of the Cs and Ec of models I and II and the predicted values using the validation dataset. The graphs clearly show that the predictions were mostly similar. The model was also able to accurately predict the compressive strength and elastic modulus of RAC and the RAC mix in the experimental component of this study. Table 6 compares the predicted values with those determined experimentally and shows the error percentage of the results calculated using Equation 6.

$$Error (\%) = \left| \frac{\text{predicted value} - \text{actual value}}{\text{actual value}} \right| \times 100 \quad (6)$$

The predicted results for the RAC mix show that the experimental results were subpar as concluded above, particularly the compressive strength.

TABLE 6
EXPERIMENTAL RESULTS COMPARED WITH PREDICTED ANN RESULTS

Mix ID	Experimental Results [†]		Predicted Results by ANN Model			
	F _{cu} (MPa)	E _c (GPa)	F _{ANN} (MPa)	Error (%)	E _{ANN} (GPa)	Error (%)
RAC*	13.9	17.5	30.46	119.14	18.39	5.09
RAC**	13.9	22.8	30.46	119.14	18.39	19.34

****RAC at 28 days; *Calculated from Equation 1; *Calculated from Equation 2**

IV. CONCLUSION

The following conclusions can be derived from this study:

- 1) RCAs are a viable option for structural concrete in The Gambia.
- 2) The compressive strength and elastic modulus of RAC can be higher than that of NAC with varying water-to-cement ratios and coarse aggregate replacement percentages.
- 3) The compressive strength and elastic modulus of RAC can be predicted using ANN models, as they were acceptable and performed better than the established correlation equations from the BS code.
- 4) Concretes made with a replacement ratio greater than 50% require lower water/cement ratios (about 6–21%) and higher cement consumption (about 5–20%) than concretes made with 100% natural aggregate.
- 5) Results of the ANN model proposed in this work showed a reduction of 8% in elastic modulus for concretes made with 100% recycled aggregate when the WCR increased 25%. On the other hand, when analyzing concrete produced only with natural aggregate, an increase of 25% in the WCR generated a 15% reduction on the concrete elastic modulus.
- 6) ANNs can be used within the civil engineering field to solve further problems. They could also easily be used to model mechanical properties of concrete made with RAs derived from different sources (recycled brick aggregates, recycled mortar aggregates, etc.).

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interest before, during and after carrying out the research work.

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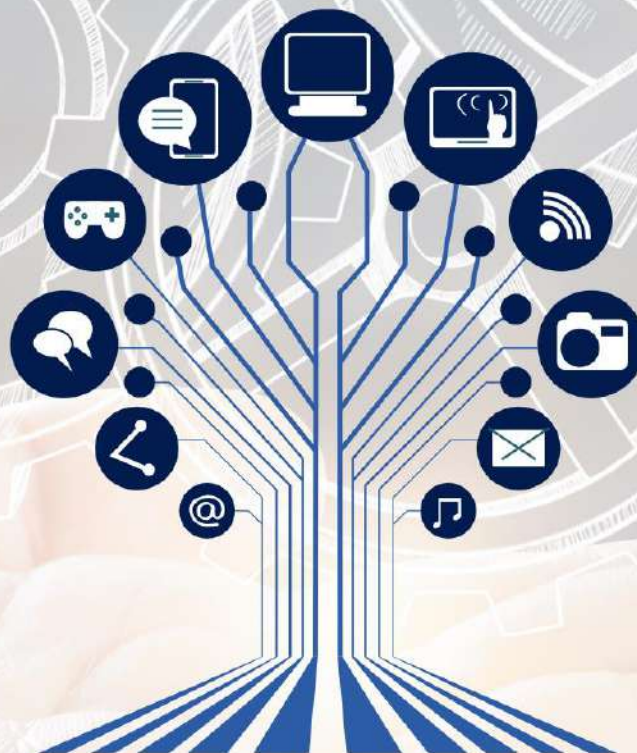
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