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Research Article

Mechanical performance of concrete using rice husk ash–plastic artificial aggregates with varying particle sizes

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ABSTRACT

The increasing consumption of plastic and its long decomposition period necessitate innovative strategies for utilizing Polyethylene Terephthalate (PET) plastic waste in civil engineering applications, particularly through its conversion into artificial coarse aggregates for concrete. This study investigates the effect of Rice Husk Ash (RHA) fineness used as a filler in PET-based artificial aggregates on the mechanical properties of concrete. Three RHA particle size ranges were considered: ASP50 (RHA passing sieve No. 50 and retained on sieve No. 100), ASP100 (RHA passing sieve No. 100 and retained on sieve No. 200), and ASP200 (RHA passing sieve No. 200). PET plastic waste and RHA were mixed at a ratio of 1:4, melted, cast, and crushed to produce artificial coarse aggregates with particle sizes ranging from 5 to 10 mm. A conventional concrete mixture with natural coarse aggregate was prepared as the control specimen for comparison. Concrete specimens were cast in cylindrical molds and tested for compressive strength and splitting tensile strength at 28 days. The results showed that concrete incorporating ASP200–PET aggregates achieved the highest compressive strength (17.42 MPa) and splitting tensile strength (1.58 MPa) among the modified mixtures. A consistent improvement in mechanical performance was observed with decreasing RHA particle size, attributed to better particle packing and denser concrete. However, the mechanical properties of concrete containing artificial PET aggregates remained lower than those of conventional concrete with natural aggregates. Despite this reduction in strength, the significant decrease in concrete density indicates the potential of RHA–PET artificial aggregates for lightweight and non-structural concrete applications.

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1. Introduction

The development of sustainable concrete materials has attracted increasing attention due to the growing environmental concerns associated with plastic waste accumulation and the depletion of natural aggregate resources. Among various plastic wastes, Polyethylene Terephthalate (PET) is one of the most widely generated and persistent materials, creating serious disposal and environmental concerns (Soong et al. 2022; Wang et al. 2022; Bohre et al.

2023; Tladi et al. 2023). Consequently, the incorporation of PET waste into concrete has gained attention as a sustainable approach to reduce landfill disposal while decreasing the environmental footprint associated with conventional construction materials (Askar et al. 2023; Marvila et al. 2022; Sosoi et al. 2022; Qaidi et al. 2023). However, despite its environmental benefits, the incorporation of PET aggregates often leads to reductions in mechanical performance, highlighting the need for effective strategies to improve the properties of PET-based concrete.

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In addition to environmental concerns related to plastic waste, the construction sector faces increasing pressure due to the extensive consumption of natural aggregates. Continuous extraction of natural aggregates has resulted in resource depletion and environmental degradation, motivating researchers to explore recycled and alternative aggregate materials (Zulkernain et al. 2021; AbdelMoti and Mustafaa 2019; Mousavimehr and Nematzadeh 2020; M. Correa et al. 2020). PET waste has therefore been investigated as a potential aggregate replacement because of its availability, low density, and contribution to circular economy principles.

Previous studies have demonstrated that PET can be used as a substitute aggregate in concrete, producing lighter concrete and providing an environmentally friendly solution for plastic waste utilization (Dawood et al. 2021; Qaidi et al. 2023; Almeshal et al. 2020; Jaskowska-Lemańska et al. 2022; Bachtiar et al. 2020). However, despite these environmental benefits, many researchers have reported reductions in mechanical properties, particularly compressive strength, due to the relatively smooth surface texture and lower stiffness of PET compared with conventional mineral aggregates (Dawood et al. 2021; Almeshal et al. 2020; Qaidi et al. 2023). These findings suggest that additional measures are required to improve the performance of concrete incorporating PET aggregates.

Rice Husk Ash (RHA), an abundant agro-industrial by-product in many developing countries, has emerged as a promising supplementary cementitious material because of its high silica content and pozzolanic reactivity (Endale et al. 2023; Kang et al. 2019; Jittin et al. 2020; Zareei et al. 2017; Amran et al. 2021; Siddika et al. 2018). Numerous studies have shown that RHA can enhance the mechanical and durability properties of concrete through both pozzolanic reactions and filler effects (Faried et al. 2021; Satwarnirat et al. 2023; Gencel et al. 2021; Abolhasani et al. 2022; Siddika et al. 2021). In particular, the fineness of RHA plays a critical role in determining its effectiveness. Finer RHA particles provide a larger specific surface area, resulting in greater pozzolanic activity, improved particle packing, and a denser concrete microstructure. Consequently, the use of finely ground RHA has been reported to improve compressive strength and long-term durability more effectively than coarser RHA (Sandhu and Siddique 2017; Farid and Zaheer 2023; Lin et al. 2023; Pu et al. 2024).

The combined utilization of PET waste and RHA offers a promising strategy for producing more sustainable concrete while simultaneously addressing plastic waste management and agricultural waste disposal (Awolusi et al. 2023; Hu et al. 2020; Tayeh et al. 2021; Hasan et al. 2022). Likewise, the development of lightweight and environmentally friendly cementitious materials has attracted increasing research interest as a means of reducing the environmental impact of the construction industry. For example, Paikara and Gyawali (2023) developed aerated lightweight mortar using aluminum powder to reduce material density and improve sustainability. Although their study employed a different lightweight mechanism and material system, it highlights the growing need to develop sustainable lightweight construction materials with acceptable mechanical performance. In

the context of PET-RHA artificial aggregates, recent studies have demonstrated their potential for sustainable concrete production; however, reductions in mechanical performance remain a major challenge. Moreover, limited attention has been given to the influence of RHA fineness on the quality of PET-based artificial aggregates and the resulting concrete performance. Therefore, further research is required to clarify the role of RHA particle size in enhancing the properties of concrete containing PET-based artificial aggregates.

This gap is particularly important because the mechanisms of the two materials may complement each other. While PET aggregates tend to reduce mechanical strength due to weaker aggregate–paste bonding, finer RHA particles can enhance matrix densification and improve the interfacial transition zone. Therefore, it is reasonable to hypothesize that increasing RHA fineness may compensate for the strength reduction commonly associated with PET aggregate utilization.

Accordingly, this study investigates the effect of RHA fineness on the mechanical performance of concrete containing PET-based artificial aggregates. Unlike previous PET-RHA studies that mainly examined material replacement levels, the present research systematically evaluates the influence of different RHA fineness levels on the strength development of PET aggregate concrete. This approach provides new insight into the interaction between PET aggregates and finely ground RHA and establishes whether RHA fineness can be used as an effective strategy to overcome the mechanical limitations of PET-based concrete. The PET waste utilized in this study was processed into artificial aggregates through the treatment procedure shown in Fig. 1, while the RHA was obtained and prepared following the process illustrated in Fig. 2. The findings are expected to contribute to the development of sustainable concrete materials that effectively utilize both plastic and agricultural wastes while maintaining adequate mechanical properties.

2. Methodology

2.1. Materials

Ordinary Portland Cement (OPC) Type I, manufactured by Semen Gresik (Indonesia), was used as the cementitious binder throughout this study. Potable tap water, free from visible impurities and suitable for concrete production, was used for both mixing and curing. Natural fine aggregate and natural coarse aggregate were obtained from local suppliers in Jember, East Java, Indonesia, and their physical properties are summarized in Table 1.

The rice husk ash (RHA) used for manufacturing the artificial coarse aggregates was obtained from CV. Pabrik Beras Rajawali, Rambipuji, Jember, East Java, Indonesia. The RHA was produced by controlled combustion of rice husks at approximately 450–500 °C for 4–6 h before being sieved into the designated particle-size ranges. Since the objective of this study was to investigate the effect of RHA particle fineness as a filler in PET-based artificial aggregates rather than its pozzolanic activity as a cement replacement material, chemical characterization of the RHA (e.g., SiO₂ content and loss on ignition) was not conducted.



Fig. 1. Treatment process of waste PET plastic:
(a) Raw waste PET plastic; (b) Cutting process of PET plastic; (c) Processed PET plastic after cutting.



Fig. 2. Production process of rice husk ash (RHA):
(a) Red brick firing process; (b) Produced RHA; (c) Sieving of RHA.

Table 1. Test results of natural aggregates.

Testing	Fine aggregate	Coarse aggregate
Sieve analysis	Zone 2	Pass 20 mm
Specific gravity	2.40	2.69
Bulk density (g/cm ³)	1.34	1.41
Water absorption (%)	3.99	2.46
Moisture content (%)	3.45	2.01

2.2. Artificial coarse aggregate

Artificial coarse aggregates were manufactured from waste PET plastic and rice husk ash (RHA). The RHA was used exclusively as a filler material within the PET matrix rather than as a supplementary cementitious material. Therefore, the primary experimental variable in this study was the particle fineness of the RHA. All RHA fractions were obtained from the same source and production batch, ensuring identical chemical composition while varying only the particle size through sieving. The artificial coarse aggregates were produced using a constant RHA-to-PET ratio of 1:4. For each production batch, 400 g of shredded PET plastic and 100 g of RHA were used, corresponding to an RHA-to-PET ratio of 1:4. The mixture was sufficient to produce approximately three cube specimens measuring 50 × 50 × 50 mm prior to crushing and sieving.

To evaluate the effect of RHA fineness, three different RHA particle size ranges were utilized. As summarized in Table 2, the artificial coarse aggregates were classified as

ASP50, ASP100, and ASP200, corresponding to RHA particles passing sieve No. 50 (300 μm) and retained on sieve No. 100 (150 μm), passing sieve No. 100 (150 μm) and retained on sieve No. 200 (75 μm), and passing sieve No. 200 (75 μm), respectively. The resulting artificial coarse aggregates were produced with particle sizes ranging from 5 to 10 mm.

Artificial coarse aggregates were produced by melting shredded PET plastic in a metal pan under continuous heating. The melting process was conducted in a well-ventilated area to minimize the accumulation of fumes generated during heating and to ensure operator safety. The PET was heated for approximately 1 h until complete melting was achieved. Subsequently, rice husk ash (RHA) was gradually added to the molten PET at the specified proportion, and the mixture was continuously stirred until a homogeneous blend was obtained. During the mixing process, the molten mixture gradually turned black. The homogeneous mixture was then poured into cube molds measuring 50 mm × 50 mm × 50 mm and allowed to cool at room temperature until fully solidified.

After hardening, the molded specimens were removed from the molds and crushed manually using a hammer. The crushed material was subsequently sieved to obtain

artificial coarse aggregates with particle sizes ranging from 5 to 10 mm. The detailed production process of the artificial coarse aggregate is illustrated in Fig. 4(a–j).

Table 2. Composition of artificial coarse aggregate.

Gravel code artificial	Proportion (RHA:PET)	Size of RHA
ASP50	1:4	Passing sieve No. 50 (300 μm) and retained on sieve no. 100 (150 μm)
ASP100	1:4	Passing sieve No. 100 (150 μm) and retained on sieve No. 200 (75 μm)
ASP200	1:4	Passing sieve No. 200 (75 μm)

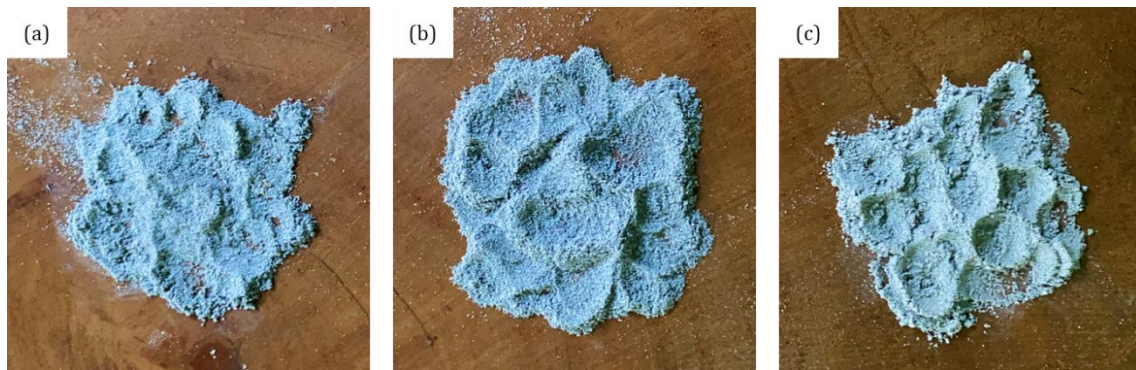


Fig. 3. Sieving results of rice husk ash (RHA): (a) ASP50; (b) ASP100; (c) ASP200.

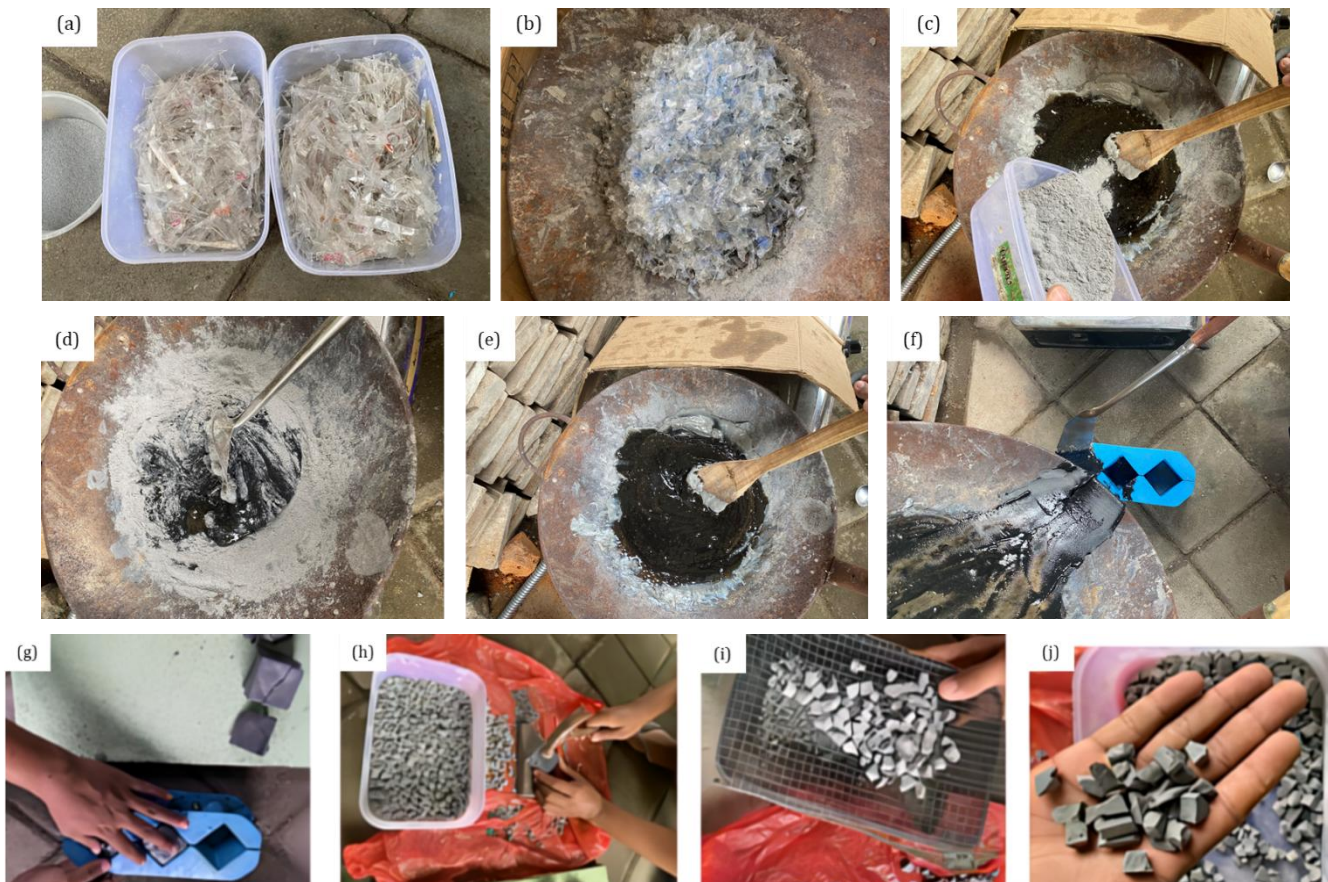


Fig. 4. Production process of artificial coarse aggregate: (a) Preparation of equipment and materials; (b) Melting of PET; (c) Mixing with rice husk ash (RHA); (d) Stirring PET and RHA until homogeneous; (e) Melt ready for casting; (f) Pouring into molds; (g) Demolding; (h) Crushing using a hammer; (i) Sieving; (j) Artificial coarse aggregate after sieving.

Fig. 5 illustrates the influence of RHA fineness on the physical characteristics of the produced artificial coarse aggregates. Finer particles may fill internal voids within the artificial aggregate, resulting in a denser structure, improved mechanical integrity, and enhanced bonding with the surrounding cementitious matrix (Al-Baghdadi et al. 2021; Stratoura et al. 2023).

Table 3 shows that ASP200-PET had the highest specific gravity (1.40) and bulk density (0.77 g/cm³), whereas ASP50-PET had the highest water absorption (1.40%) and moisture content (0.21%). According to the test results, the fineness of rice husk ash used as a filler for

plastic aggregate affects the properties of the artificial aggregate. The test results indicate that the fineness of the rice husk ash used as a filler in the PET-based artificial aggregates significantly influenced their physical properties. As the RHA fineness increased, both the specific gravity and bulk density of the artificial aggregates increased, indicating the formation of a denser aggregate structure (Al-Baghdadi et al. 2021; Kannur and Chore 2023; Shiringire et al. 2024). In contrast, water absorption and moisture content decreased with increasing RHA fineness, reflecting the reduction in pore volume within the artificial aggregates (Ganasen et al. 2023; Abellan-Garcia et al. 2023).



Fig. 5. Manufacturing results and material testing of artificial coarse aggregate.

Table 3. Test results of artificial lightweight coarse aggregate.

Testing	ASP50-PET	ASP100-PET	ASP200-PET	Condition	Control	Reference
Sieve analysis	Pass 20 mm	Pass 20 mm	Pass 20 mm	Max. 37.5mm	OK	ACI E1-07 (2007)
Specific gravity	1.35	1.38	1.40	Lightweight aggregate (1.0-1.8)	OK	SNI 03-2461-2002 (2002)
Bulk density (g/cm ³)	0.72	0.75	0.77	Lightweight aggregate < 0.88	OK	ASTM C29/C29M-97 (1997)
Water absorption (%)	1.40	1.04	0.92	0.5-4%	OK	ACI E1-07 (2007)
Moisture content (%)	0.21	0.19	0.10	Difference test max. 0.79%	OK	ASTM C566-04 (2004)

To further explain the physical and mechanical properties of the artificial aggregates, microscopic observations were conducted using a digital microscope. The microstructural characteristics of the aggregates are presented in Fig. 6(a-d). The ASP50-PET aggregate exhibited a rougher surface texture and a greater number of visible pores compared with ASP100-PET and ASP200-PET. In contrast, ASP200-PET displayed a denser and more homogeneous surface with fewer visible pores. These observations indicate that increasing the fineness of the rice husk ash filler contributed to a reduction in pore formation within the PET-RHA composite aggregate.

The observed microstructural differences are consistent with the measured physical properties of the aggregates. Aggregates containing a larger number of pores generally exhibit lower specific gravity and bulk density because a greater proportion of their volume consists of void spaces. Conversely, the presence of interconnected pores increases the capacity of the aggregate to absorb and retain water, resulting in higher water absorption and moisture content values (Bouarroudj et al. 2023; Duan et al. 2022; Rao et al. 2020; Théréné et al. 2020). Therefore, the denser microstructure observed in ASP200-PET is expected to contribute to higher density and lower water absorption compared with ASP50-PET.

Furthermore, the microstructure of the artificial aggregate directly influences its mechanical behavior and its interaction with the surrounding cementitious matrix. The finer RHA particles in ASP200-PET act as fillers that occupy void spaces within the PET matrix, producing a denser internal structure and reducing stress concentration points associated with pores. As a result, the aggregate becomes mechanically stronger and less susceptible to cracking under load. The denser aggregate structure also promotes improved contact and bonding with the sur-

rounding mortar, leading to a more effective transfer of stresses across the aggregate–paste interface. These mechanisms explain the higher compressive strength obtained for concrete containing ASP200-PET aggregates compared with ASP50-PET and ASP100-PET aggregates. Therefore, the improvement in concrete mechanical performance can be attributed not only to the increased density of the artificial aggregate but also to the enhancement of its microstructural quality and aggregate–mortar interfacial bonding (Rocha et al. 2023; Herrera Rosas et al. 2023).

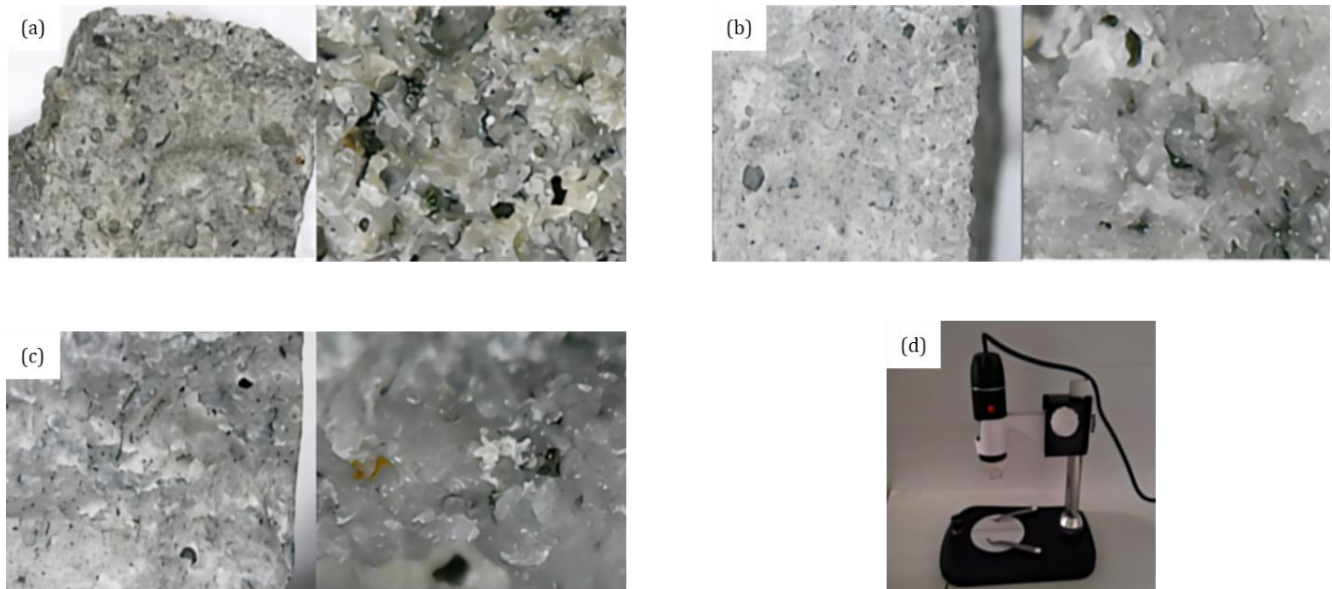


Fig. 6. Digital microscope observations of artificial coarse aggregates: (a) ASP50-PET; (b) ASP100-PET; (c) ASP200-PET; (d) Digital microscope.

2.3. Mix proportion

The concrete mixtures were prepared using Ordinary Portland Cement (OPC) Type I, manufactured by Semen Gresik, as the binder; potable tap water as the mixing water; natural fine aggregate; and either natural or artificial coarse aggregate. The target compressive strength was 25 MPa. The mix proportions, expressed on a per-cubic-meter basis (kg/m^3), are presented in Table 4. The constituent materials were proportioned on a 1 m^3 basis. The quantities of the artificial coarse aggregates were calculated based on their specific gravities to provide an equivalent coarse aggregate volume to that of the control mixture while maintaining the target concrete volume. For laboratory production, the mix proportions were proportionally scaled down to produce approximately 15 L of concrete per batch, which was sufficient to cast six cylindrical specimens ($100 \text{ mm} \times 200 \text{ mm}$) for compressive strength and splitting tensile strength testing.

Three types of artificial aggregates were produced using a mixture of PET plastic waste and rice husk ash (RHA), namely ASP50, ASP100, and ASP200. BN0 denotes the control mixture consisting of conventional concrete with natural gravel as the coarse aggregate. BN1 incorporates artificial coarse aggregate coded ASP50 with an RHA ratio of 1:4. The ASP50 aggregate was produced through a melting–mixing process using

RHA passing sieve No. 50 ($300 \mu\text{m}$) and retained on sieve No. 100 ($150 \mu\text{m}$), combined with PET plastic waste. BN2 incorporates artificial aggregate coded ASP100 with the same RHA ratio of 1:4. The ASP100 aggregate was manufactured using RHA passing sieve No. 100 ($150 \mu\text{m}$) and retained on sieve No. 200 ($75 \mu\text{m}$), mixed with PET plastic waste through the same process. BN3 contains artificial aggregate coded ASP200 with an RHA ratio of 1:4 and was produced by melting and mixing PET plastic waste with RHA passing sieve No. 200 ($75 \mu\text{m}$). The resulting artificial aggregates were subsequently used as coarse aggregate replacements in the concrete mixtures.

Concrete mixing was carried out using a 50 L capacity concrete mixer. Each laboratory batch consisted of approximately 15 L of fresh concrete, prepared by proportionally scaling the 1 m^3 mix design presented in Table 4. The constituent materials were weighed according to the required proportions. The mixing process began with the dry mixing of cement, fine aggregate, and coarse aggregate (natural or artificial aggregate) for approximately 2 min to ensure uniform distribution of the materials. Subsequently, water was gradually added while the mixer was in operation, and mixing was continued for an additional 3 min until a homogeneous concrete mixture was obtained. After mixing, the fresh concrete was immediately subjected to slump testing and then cast into cylindrical molds ($100 \text{ mm} \times 200 \text{ mm}$) for compressive strength and splitting tensile strength tests.

Table 4. Concrete mix design.

Code	Cement (kg/m ³)	Water (kg/m ³)	Sand (kg/m ³)	Gravel (kg/m ³)	ASP50 (kg/m ³)	ASP100 (kg/m ³)	ASP200 (kg/m ³)
BN0	385	211	739.06	1039.74	–	–	–
BN1	385	211	739.06	–	521.80	–	–
BN2	385	211	739.06	–	–	533.40	–
BN3	385	211	739.06	–	–	–	541.13

2.4. Compressive strength and splitting tensile strength testing

The mechanical properties of the concrete were evaluated through compressive strength and splitting tensile strength tests using cylindrical specimens. The specimens had a diameter of 100 mm and a height of 200 mm. After casting, the specimens were cured under laboratory conditions until the designated testing age.

Compressive strength tests were conducted in accordance with ASTM C39/C39M (2021) using a compression testing machine with a maximum capacity of 1500 kN. The load was applied continuously at a rate of 2.5–6.0 kN/s until specimen failure occurred. The compressive strength was calculated by dividing the maximum applied load by the cross-sectional area of the specimen.

Splitting tensile strength tests were performed in accordance with ASTM C496/C496M (2017) using the same compression testing machine. The cylindrical specimens were positioned horizontally between the loading platens, and the load was applied continuously until splitting failure occurred. The splitting tensile strength was determined from the maximum load recorded during the test.

For each concrete mixture, three cylindrical specimens were tested for compressive strength and three cylindrical specimens were tested for splitting tensile strength at 28 days. The reported strength values represent the arithmetic mean of the three test results. To evaluate the variability of the experimental data, the standard deviation (SD) was calculated using the sample standard deviation ($n - 1$), while the coefficient of variation (COV) was calculated as the ratio of the sample standard deviation to the mean value and expressed as a percentage.

3. Results and Discussion

3.1. Workability

The slump test was conducted to evaluate the workability of fresh concrete. The test was performed using a standard slump cone with a top diameter of 100 mm, a bottom diameter of 200 mm, and a height of 300 mm. The slump values reported in Table 5 represent the results of a single slump test conducted for each concrete mixture.

Based on Table 5 and Fig. 7, the slump values of BN0, BN1, BN2, and BN3 were 110 mm, 100 mm, 95 mm, and 80 mm, respectively. All mixtures satisfied the target slump range of 60–180 mm, indicating acceptable workability for concrete placement. However, a gradual reduction in slump was observed as the fineness of the RHA used in the PET-based artificial aggregates increased.

**Fig. 7.** Slump test results.**Table 5.** Slump test results.

Test object code	Slump value	Unit
BN0	110	mm
BN1	100	mm
BN2	95	mm
BN3	80	mm

This reduction in workability can be attributed to the finer RHA particles incorporated into the artificial aggregates. Finer RHA possesses a larger specific surface area, which increases water demand and reduces the amount of free water available for lubrication within the concrete mixture. In addition, the denser microstructure of aggregates produced with finer RHA may contribute to greater internal friction among solid particles during mixing. As a result, BN3 concrete containing ASP200-PET aggregate exhibited the lowest slump value. Nevertheless, the measured slump values indicate that all mixtures maintained adequate workability despite the reduction associated with increasing RHA fineness (Liang et al. 2024; Mohsen et al. 2023; Shaheen 2025; Tanash et al. 2025; H. Wang et al. 2023)

The observed reduction in slump with increasing RHA fineness is consistent with findings reported by previous researchers. Liang et al. (2024) and Wang et al. (2023) reported that finer ash particles increase the specific surface area of the solid constituents, thereby increasing water demand and reducing the amount of free water available for flow. Similarly, Mohsen et al. (2023) and Tanash et al. (2025) observed that the incorporation of fine pozzolanic materials can decrease concrete workability due to enhanced particle packing and internal friction. The trend obtained in the present study therefore agrees with previous investigations, confirming that the use of finer RHA in PET-based artificial aggregates contributes to lower slump values while maintaining acceptable workability for concrete placement.

3.2. Compressive strength

Based on Fig. 8 and Table 6, the 28-day compressive strength results indicate that BN3 concrete incorporating ASP200–PET artificial coarse aggregate achieved the highest compressive strength among the modified mixtures, with an average value of 17.42 MPa. In comparison, BN1 concrete containing ASP50–PET aggregate and BN2 concrete containing ASP100–PET aggregate achieved average 28-day compressive strengths of 14.58

MPa and 15.52 MPa, respectively. The control concrete (BN0) incorporating natural coarse aggregate exhibited the highest 28-day compressive strength overall, with an average value of 27.50 MPa.

To evaluate the variability of the compressive strength results, the sample standard deviation (SD) and coefficient of variation (COV) were calculated from the three specimens tested for each concrete mixture. The control concrete (BN0) exhibited a low COV of 3.50%, indicating excellent test consistency. Similarly, BN2 and BN3 showed COV values of 6.82% and 9.13%, respectively, demonstrating acceptable repeatability of the compressive strength results. In contrast, BN1 exhibited a relatively high COV of approximately 23.20%, indicating greater variability among the test specimens. This higher variability is likely associated with the more porous and heterogeneous microstructure of the ASP50–PET artificial aggregate, which may have caused non-uniform stress distribution and specimen-to-specimen variation during testing. Therefore, the BN1 results should be interpreted with caution and represent a limitation of the present study. Nevertheless, despite the greater variability observed for BN1, the overall trend of increasing compressive strength with increasing RHA fineness (BN1 < BN2 < BN3) remained consistent across the experimental program.

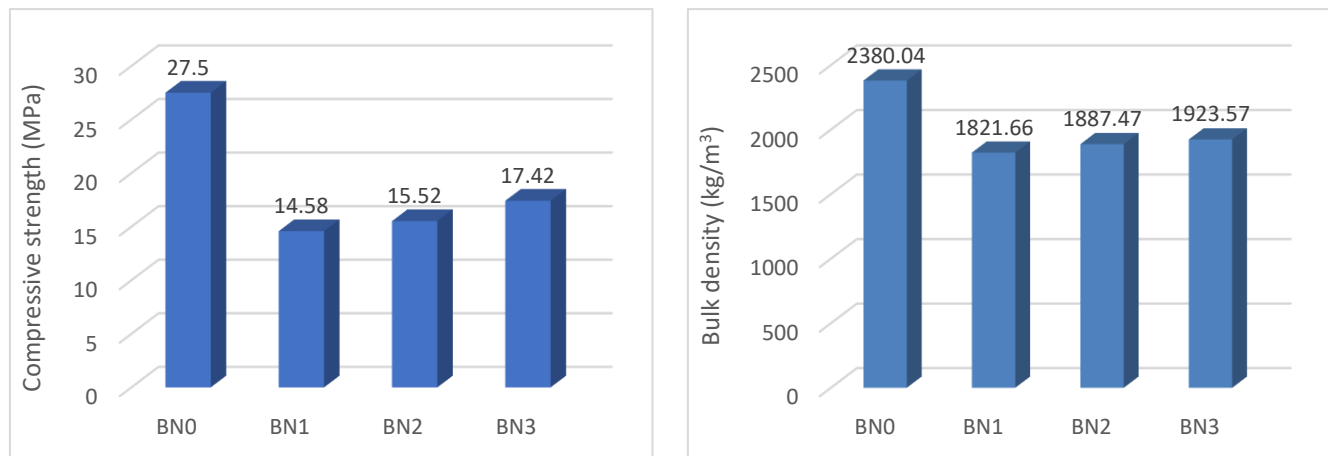


Fig. 8. Compressive strength and bulk density of concrete.

Although the target compressive strength of 25 MPa was not achieved by the PET-based artificial aggregate concretes, compressive strength increased consistently with increasing RHA fineness. BN3 reached 17.42 MPa (approximately 69.7% of the target strength), demonstrating that finer RHA improved the performance of PET-based artificial aggregates. This improvement can be attributed to the filler effect of fine RHA particles, which reduced pore volume within the PET matrix, produced denser artificial aggregates, and enhanced stress transfer between the aggregate and the surrounding mortar. Unlike conventional applications in which RHA acts as a supplementary cementitious material, the RHA in this study functioned primarily as a micro-filler during artificial aggregate production, improving aggregate quality through physical densification rather than pozzolanic reactions.

The compressive strength results were consistent with the density measurements. Concrete containing natural coarse aggregate exhibited the highest average density (2380.04 kg/m³), whereas BN1, BN2, and BN3 exhibited average densities of 1821.66, 1887.47, and 1923.57 kg/m³, respectively. The increase in density with increasing RHA fineness indicates that finer RHA particles reduced internal voids within the PET–RHA artificial aggregates, producing a denser and more homogeneous microstructure. Consequently, ASP200–PET exhibited the highest density and compressive strength among the modified mixtures.

The observed improvement in compressive strength with increasing RHA fineness agrees with previous studies reporting that finer RHA enhances particle packing and reduces porosity, resulting in a denser microstructure. Although the PET-based aggregate concrete exhib-

ited lower strengths than conventional concrete because of the lower stiffness of PET and its weaker bond with the cementitious matrix, BN3 provided the most favorable balance between mechanical performance and reduced density. These results demonstrate the potential of PET–RHA artificial aggregates for lower-density, non-

structural and semi-structural concrete applications, including partition walls, paving blocks, pedestrian walkways, and landscape elements. Further optimization of the aggregate production process and concrete mixture design is recommended to improve mechanical performance for broader engineering applications.

Table 6. Density and compressive strength of all specimens.

Specimen code	Coarse aggregate type	Density (kg/m ³)	Density average	Compressive strength (MPa)	Compressive strength average (MPa)	SD (MPa)	COV (%)
BN0	Normal concrete	2,528.66		28.32			
BN0	Normal concrete	2,254.78	2380.04	26.44	27.50	0.96	3.50
BN0	Normal concrete	2,356.69		27.74			
BN1	ASP50-PET	1,840.76		18.04			
BN1	ASP50-PET	1,796.18	1821.66	11.28	14.58	3.38	23.20
BN1	ASP50-PET	1,828.03		14.42			
BN2	ASP100-PET	1,859.87		16.00			
BN2	ASP100-PET	1,847.13	1887.47	16.26	15.52	1.06	6.82
BN2	ASP100-PET	1,955.41		14.31			
BN3	ASP200-PET	1,993.63		16.38			
BN3	ASP200-PET	1,808.92	1923.57	16.62	17.42	1.59	9.13
BN3	ASP200-PET	1,968.15		19.25			

3.3. Splitting tensile strength

Based on Fig. 9 and Table 7, the 28-day splitting tensile strength results indicate that BN3 concrete incorporating ASP200-PET artificial coarse aggregate achieved the highest splitting tensile strength among the modified mixtures, with an average value of 1.58 MPa. In comparison, BN1 concrete containing ASP50-PET aggregate and BN2 concrete containing ASP100-PET aggregate achieved average splitting tensile strengths of 1.35 MPa and 1.53 MPa, respectively. The control concrete (BN0) incorporating natural coarse aggregate exhibited the highest splitting tensile strength overall, with an average value of 2.67 MPa.

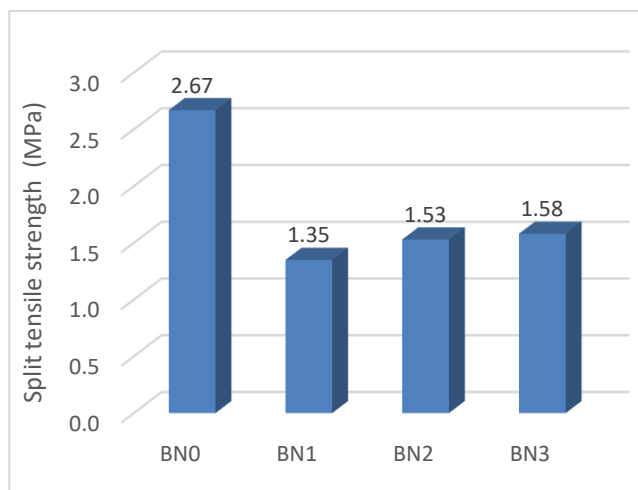


Fig. 9. Splitting tensile strength of concrete.

To evaluate the reliability of the splitting tensile strength results, the standard deviation (SD) and coefficient of variation (COV) were calculated from the three specimens tested for each mixture. The control concrete (BN0) exhibited an SD of 0.055 MPa and a COV of 2.07%, while BN1, BN2, and BN3 exhibited SD values of 0.044 MPa, 0.046 MPa, and 0.156 MPa, respectively, corresponding to COV values of 3.23%, 3.01%, and 9.89%. These relatively low COV values indicate good repeatability of the splitting tensile strength tests and demonstrate that the observed strength trends are consistent among the tested specimens.

Although the incorporation of PET-based artificial aggregates reduced the splitting tensile strength compared with natural coarse aggregate concrete, a clear improvement was observed with increasing RHA fineness. The lower tensile strength of the PET-based mixtures can be attributed to the relatively smooth surface texture and lower stiffness of PET aggregates, which may weaken the interfacial bond between the aggregate and the surrounding cementitious matrix (Zahid et al. 2024; Xiong et al. 2023; Badache et al. 2025). However, the use of finer RHA particles improved the internal structure of the artificial aggregates by reducing pore content and producing a denser aggregate matrix. Consequently, BN3 containing ASP200-PET aggregate achieved the highest splitting tensile strength among the PET-based mixtures.

The results further indicate that increasing RHA fineness increased the density of the PET-RHA artificial aggregates and improved their mechanical performance. The denser aggregate structure likely enhanced the aggregate–mortar bond and facilitated more effective stress transfer under tensile loading, thereby contributing to the observed increase in splitting tensile strength.

Table 7. Density and splitting tensile strength of all specimens.

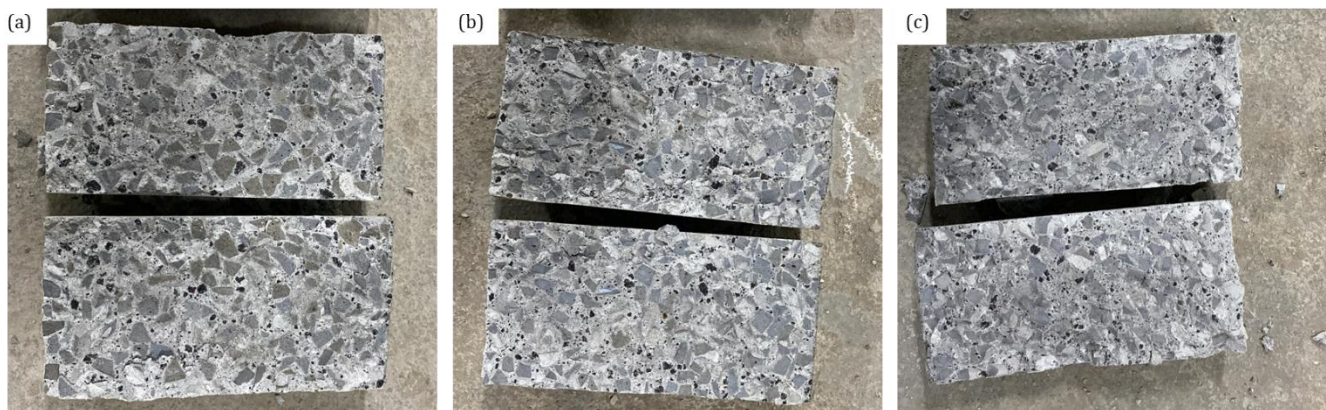
Specimen code	Coarse aggregate type	Density (kg/m ³)	Density average	Splitting tensile Strength (MPa)	Splitting tensile strength average (MPa)	SD (MPa)	COV (%)
BN0	Normal concrete	2,452.23		2.73			
BN0	Normal concrete	2,509.55	2460.72	2.63	2.67	0.055	2.07
BN0	Normal concrete	2,420.38		2.64			
BN1	ASP50-PET	1,834.39		1.30			
BN1	ASP50-PET	1,783.44	1821.66	1.38	1.35	0.044	3.23
BN1	ASP50-PET	1,847.13		1.37			
BN2	ASP100-PET	1,955.41		1.48			
BN2	ASP100-PET	1,828.03	1893.84	1.56	1.53	0.046	3.01
BN2	ASP100-PET	1,898.09		1.56			
BN3	ASP200-PET	1,923.57		1.76			
BN3	ASP200-PET	1,898.09	1895.97	1.50	1.58	0.156	9.89
BN3	ASP200-PET	1,866.24		1.48			

The splitting tensile strength results are also consistent with previous studies investigating plastic-based aggregates and supplementary cementitious materials. Previous researchers have reported that concretes containing PET aggregates generally exhibit lower tensile strength than conventional concrete because of the relatively smooth surface texture and weaker interfacial transition zone between the aggregate and cement matrix. Nevertheless, improvements in tensile strength have been observed when finer pozzolanic materials are incorporated, owing to their ability to refine the microstructure and enhance aggregate–matrix bonding. The increase in splitting tensile strength from 1.35 MPa for BN1 to 1.58 MPa for BN3 obtained in this study supports

these observations and confirms the positive influence of finer RHA on the mechanical performance of PET-based artificial aggregate concrete.

Fig. 10(a–c) presents the fracture patterns of concrete specimens after the splitting tensile strength test. The BN3 concrete incorporating ASP200-PET exhibits the roughest fracture surface, followed by BN2 concrete with ASP100-PET, while the smoothest fracture surface is observed in BN1 concrete with ASP50-PET.

These observations indicate that concretes with higher compressive strength and splitting tensile strength tend to produce rougher fracture surfaces, reflecting improved internal bonding and crack propagation resistance within the concrete matrix.

**Fig. 10.** Fracture patterns of concrete specimens: (a) BN1; (b) BN2; (c) BN3.

4. Conclusions

This study investigated the mechanical properties of concrete incorporating rice husk ash (RHA)–PET artificial coarse aggregates produced using different RHA particle sizes. The control concrete (BN0) achieved a 28-day compressive strength of 27.50 MPa, exceeding the target strength of 25 MPa and confirming the adequacy of the reference mixture. In contrast, the incorporation of PET-based artificial aggregates reduced the compressive

strength to 14.58–17.42 MPa. Nevertheless, compressive strength increased with increasing RHA fineness, with BN3 (ASP200–PET) exhibiting the highest compressive strength among the modified mixtures (17.42 MPa), followed by BN2 (15.52 MPa) and BN1 (14.58 MPa).

The density measurements obtained from the compressive-strength specimens (Table 6) indicate that the incorporation of PET-based artificial aggregates substantially reduced concrete density. While the control concrete exhibited an average density of 2380.04 kg/m³,

the average densities of BN1, BN2, and BN3 were 1821.66 kg/m³, 1887.47 kg/m³, and 1923.57 kg/m³, respectively. The density measurements obtained from the splitting tensile-strength specimens (Table 7) showed similar trends, with minor differences attributable to normal specimen-to-specimen variability because separate sets of cylinders were used for each mechanical test. Overall, increasing the fineness of the RHA produced denser artificial aggregates, resulting in a gradual increase in concrete density. These results demonstrate that the incorporation of PET–RHA artificial aggregates produced lower-density concrete compared with conventional concrete.

The splitting tensile strength followed a trend similar to that of compressive strength. The control concrete achieved the highest tensile strength (2.67 MPa), whereas BN1, BN2, and BN3 achieved average values of 1.35 MPa, 1.53 MPa, and 1.58 MPa, respectively. The improvement observed with increasing RHA fineness suggests that finer RHA particles enhanced the internal structure of the PET-based aggregates and improved stress transfer within the concrete matrix.

Overall, the incorporation of RHA–PET artificial aggregates reduced the mechanical properties of concrete compared with conventional natural aggregate concrete but substantially decreased its density. Among the investigated mixtures, BN3 (ASP200–PET) exhibited the most favorable combination of compressive strength (17.42 MPa), splitting tensile strength (1.58 MPa), and density (1923.57 kg/m³). Therefore, BN3 is considered the optimum mixture in this study and shows potential for use in lightweight partition walls, non-load-bearing masonry blocks, paving blocks, pedestrian walkways, landscape elements, and other lightweight precast products where reduced self-weight and sustainable material utilization are desirable. Further optimization of the aggregate production process and concrete mixture design is required to achieve higher strength levels suitable for broader structural applications.

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Conflict of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this manuscript.

Data Availability

The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author upon reasonable request.

AI Assistance

No AI-based tools were used in the preparation of this manuscript.

Author Contributions

All authors made substantial contributions to the conception and design of the study, acquisition of data, analysis and interpretation of data; drafted or critically revised the manuscript for important intellectual content; and approved the final version to be published.

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