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Mechanical Behavior of Concrete Beams with HDPE Plastic Waste as Partial Fine Aggregates Replacement

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Abstract

This study is related to using HDPE plastic bag waste applied to building structural components, specifically concrete beams. An innovation utilizes HDPE plastic waste not in shredded form but by taking advantage of the rigid physical properties of HDPE plastic waste after it is burned, crushed, and sieved to the size of sand to be used as a partial replacement (substitution) for fine aggregate (sand). The type of research conducted is experimental quantitative research to determine the flexural capacity of concrete beams made from HDPE plastic bag waste as a partial replacement for fine aggregates using the normal flexural strength testing method with two-point loading. The test specimens prepared were concrete beams with dimensions of 15 × 15 cm cross-section and 65 cm in length, with varying amounts of HDPE plastic bag waste replacement: 0.00% (normal concrete), 0.50%, 0.70%, and 0.90% of the weight of the sand. The concrete beam specimens were cured using a wet curing method and tested at 14 and 28 days of age. The results showed that at 14 days, the concrete beam specimens with variations of 0.00%, 0.50%, 0.70%, and 0.90% achieved flexural strengths of 3.16, 3.35, 2.91, and 2.97 MPa, respectively. Meanwhile, at 28 days, the specimens with variations of 0.00%, 0.50%, 0.70%, and 0.90% reached flexural strengths of 3.39, 3.95, 3.06, and 3.07 MPa, respectively. The highest flexural strength was achieved by the concrete beam specimen with a 0.50% substitution variation, both at 14 and 28 days, with values of 3.35 and 3.95 MPa, respectively, exceeding the flexural strength of the beam without HDPE plastic waste substitution (0.00%).

Keywords: Concrete Beam; Flexural Strength; HDPE Plastic; Substitution.

1. Introduction

Plastic is a readily available material in our society, yet it takes an extraordinarily long time to decompose, leading to environmental pollution if not managed and recycled appropriately. Plastic bags significantly contribute to the vast amounts of plastic waste generated. According to the Ministry of Environment and Forestry (KLHK), the total national waste production in 2020 reached 67.8 million tons. This figure indicates that approximately 185,753 tons of waste are produced daily by a population of 270 million, equating to around 0.68 kilograms of waste per person each day [1]. In response to this growing issue, researchers have been exploring innovative ways to utilize plastic waste in the construction industry, particularly concrete production [2, 3]. Several studies have demonstrated that incorporating plastic waste in concrete can improve its mechanical properties and address sustainability concerns [4].

Concrete is the most widely used construction material due to its high compressive strength, durability, and availability of raw materials. However, the increasing demand for concrete has led to excessive exploitation of natural

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resources, particularly fine aggregates such as river sand [5, 6]. This over-extraction has resulted in environmental degradation, resource depletion, and increased construction costs. As a sustainable alternative, incorporating HDPE plastic waste as a partial replacement for fine aggregates in concrete has gained significant attention [7, 8]. Research has shown that such replacements can reduce environmental impact while maintaining or enhancing the structural properties of concrete [9].

Several studies have investigated the feasibility of using HDPE and other plastic waste materials in concrete to enhance its mechanical and durability properties. Previous research has demonstrated that incorporating plastic waste in concrete can improve its flexural strength, reduce density, and enhance resistance to cracking [10-12]. For instance, studies by Sina et al. [2] and Adibroto et al. [7] have shown that HDPE plastic waste can contribute to the bending strength of concrete, making it a viable alternative for sustainable construction. Furthermore, multiple researchers have investigated the use of HDPE plastic in reinforced concrete beams, highlighting its potential in structural applications [13, 14].

Research examining HDPE plastic bag waste as a fine aggregate substitution was conducted [14], focusing on powdered plastic waste in concrete. The studies by Suvidha et al. [6] and Suvidha et al. [13] further reinforced that HDPE and polypropylene (PP) plastic can be integrated into self-compacting concrete for improved mechanical, durability, and thermal properties. Research has also demonstrated that polyethylene terephthalate (PET) granules can serve as a fine aggregate alternative in sustainable concrete development [5]. Additionally, studies by Espindola-Flores et al. [9] and Harahap et al. [15] explored the use of HDPE and PET plastic waste in lightweight concrete, highlighting their effects on strength and durability.

Despite the extensive research on plastic waste utilization in concrete, specific gaps remain unaddressed. Many previous studies have focused primarily on incorporating HDPE as a coarse aggregate replacement [11, 15] or as reinforcement fibers [16-18]. However, limited research has been conducted on its effectiveness as a partial fine aggregate replacement. Additionally, the mechanical behavior of reinforced concrete beams incorporating HDPE waste as fine aggregate remains underexplored, particularly regarding its flexural performance, durability, and structural integrity under various loading conditions [19-21].

The relatively novel innovation in this study, which has not been undertaken by the researchers, as mentioned earlier, was carried out in Nasruddin et al. [22]. The experiment utilized HDPE plastic bag waste, not in its shredded form but by exploiting the rigid physical properties of HDPE plastic waste after it has been burned, then crushed and sieved to a sand-like size, to be used as a partial replacement for aggregates, both fine aggregates and coarse aggregates. Results show that partial replacement of fine aggregate with HDPE plastic bag waste in variations of 0.50%, 0.70%, and 0.90% demonstrates an enhancement in the compressive strength of concrete across all ages (7, 14, and 28 days). For instance, the compressive strengths of concrete at 28 days, with substitution rates of 0% (normal), 0.50%, 0.70%, and 0.90% of HDPE plastic bag waste, are recorded as 15.12 MPa, 17.92 MPa, 15.55 MPa, and 15.69 MPa, respectively. The highest compressive strength for concrete at a 28-day age is achieved through a 0.50% substitution rate of HDPE plastic waste.

This study aims to fill these gaps by evaluating the mechanical behavior of concrete beams incorporating HDPE plastic waste as a partial replacement for fine aggregates. The research focuses on assessing the flexural strength and structural integrity of concrete beams with varying proportions of HDPE waste. By addressing these gaps, this study will contribute to the ongoing efforts in sustainable construction practices by providing an environmentally friendly solution for plastic waste management and reducing reliance on natural fine aggregates.

2. Theoretical Approach

Incorporating high-density polyethylene (HDPE) as a fine aggregate in concrete significantly alters its mechanical properties, necessitating a review of key theoretical frameworks. The theory of elasticity, based on Hooke’s Law, explains stress-strain relationships, suggesting that HDPE, due to its flexibility compared to sand, may reduce the modulus of elasticity [23]. Empirical models such as Hirsch and Voigt-Reuss predict changes in modulus resulting from aggregate modifications [24]. Failure mechanisms are analyzed through the Mohr-Coulomb and Drucker-Prager theories, which assess shear and normal stress interactions and the effects of aggregate replacement on stress distribution [25]. While HDPE lowers concrete density and compressive strength due to weak cement adhesion, it enhances impact resistance because of its elasticity [26, 27]. From a fracture mechanics perspective, HDPE influences crack propagation and brittleness, affecting stress distribution and crack patterns across tensile (Mode I), shear (Mode II), and torsional (Mode III) failures [28]. Overall, substituting traditional fine aggregates with HDPE modifies concrete's mechanical properties, particularly in elasticity, strength, and fracture behavior, which is essential for optimizing concrete performance in engineering applications.

3. Methods

The type of research used is experimental quantitative research to determine the flexural capacity of concrete beams made from HDPE plastic bag waste as a partial replacement for fine aggregates, using the normal flexural strength testing method with two-point loading according to SNI 4431-2011 [29]. The variations of partial substitution used are as follows: 0.00% (normal concrete), 0.50%, 0.70%, and 0.90% of the weight of the sand. The stages and procedures of this research are outlined in the scheme shown in Figure 1.

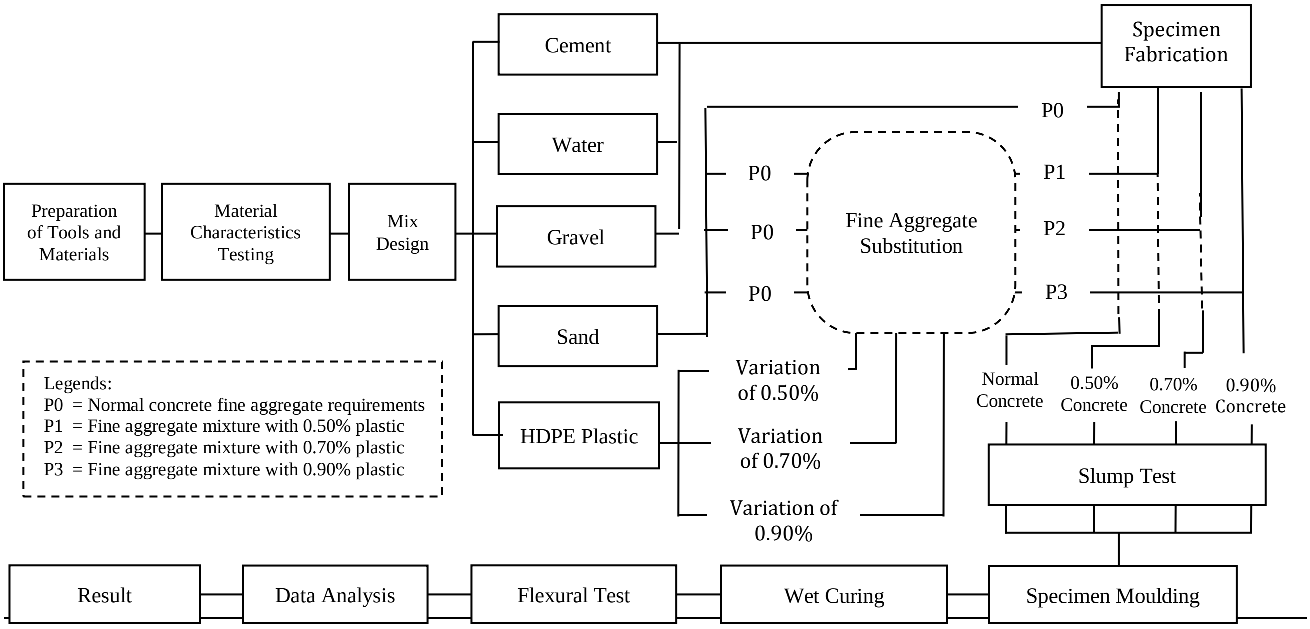
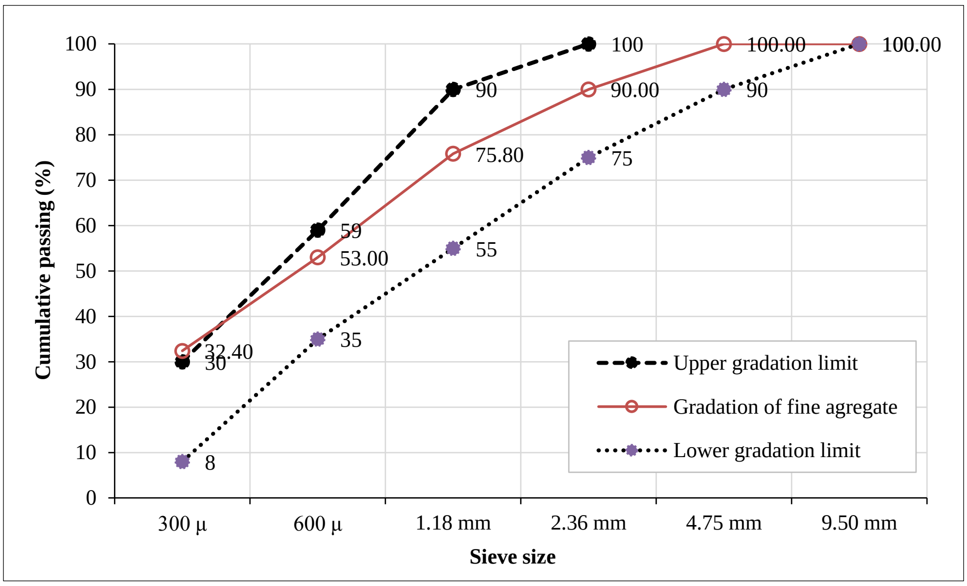
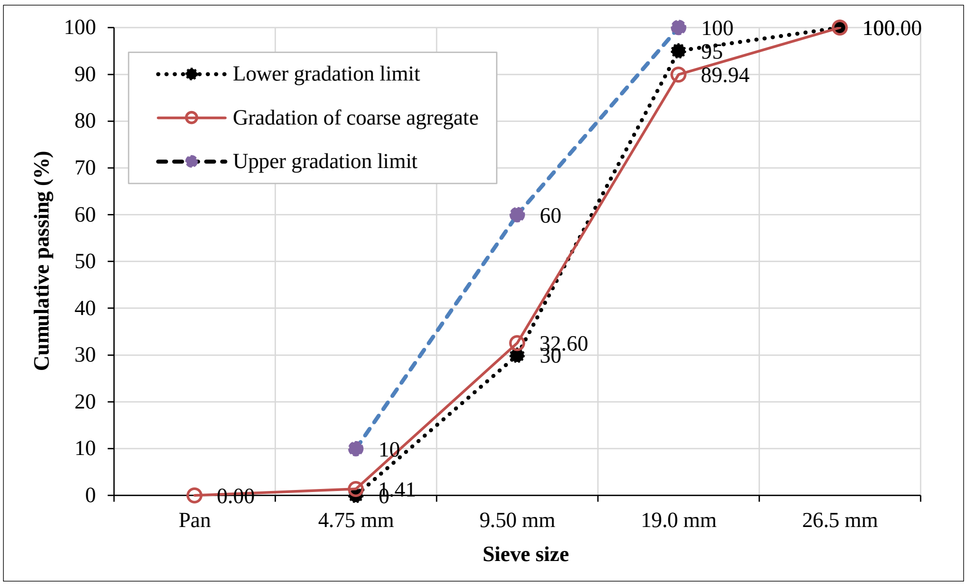


Figure 1. Scheme of research stages and procedures

In a concrete mixture or other construction materials, the particle size distribution of each aggregate component plays a crucial role in determining its mechanical properties and structural performance. Aggregate gradation, represented by the relationship between cumulative passing (%) and sieve size, helps identify the extent to which a material is distributed across various particle sizes. As shown in Figure 2, the curve indicates that the fine aggregate exhibits a relatively uniform particle distribution within the upper and lower gradation limits. The cumulative passing percentage gradually increases from smaller to larger sieve sizes, with nearly 100% of the particles passing through the 4.75 mm sieve. This suggests that the fine aggregate consists of relatively small particles proportionally distributed within a specific size range (Figure 2-a). The curve shows a sharp increase in cumulative passing after the 9.50 mm sieve. Most coarse aggregate particles are retained on larger sieve sizes, indicating that this aggregate predominantly comprises larger fractions. A small portion of the material passes through smaller sieves, suggesting a minimal presence of fine particles within the coarse aggregate (Figure 2-b).



(a) Gradation of fine aggregate

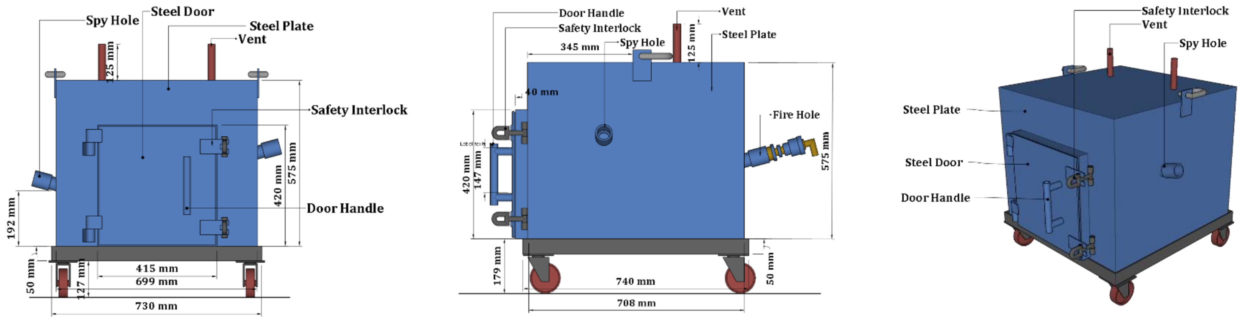


(b) Gradation of coarse aggregate

Figure 2. Graph of natural aggregate gradation

3.1. Processing of HDPE Plastic Waste

The collected HDPE plastic waste is cleaned with clean water and soap and then scrubbed to remove any dirt attached to the plastic. In addition, the plastic is cleared of any adhering waste, such as tape, wire clips, and other debris. After being cleaned, the plastic is dried under direct sunlight for 3 hours or until completely dry and ready for processing. The HDPE plastic is then burned in a fire-resistance test furnace, as shown in Figure 3.



(a) Front view (b) Side view (c) Perspective view

Figure 3. Fire Resistance Test Furnace

The process of converting HDPE plastic bag waste into plastic sand is shown in Figure 4. The HDPE plastic bag waste is burned gradually using a gas torch in a metal container (Figure 4-a). After melting, the plastic solidifies into chunks, as shown in Figure 4-b. The chunks of HDPE plastic are then crushed using a hammer until broken into small pieces (Figure 4-c) and sieved with a 4.75 mm sieve to obtain granules with an average sand-sized particle (Figure 4-d).

(a) HDPE plastic combustion process (b) Burned plastic chunks (c) Crushing of HDPE plastic chunks (d) Filtered HDPE plastic

Figure 4. Process of converting HDPE plastic bag waste into a sand substitution material

The gradation curve of HDPE waste exhibits a different trend compared to natural aggregates (Figure 5). Most of the material falls within a smaller size range, with cumulative passing gradually increasing but remaining lower than that of fine and coarse aggregates at certain sieve sizes. This indicates that HDPE waste has a more varied particle size distribution and is likely lighter than conventional aggregates.

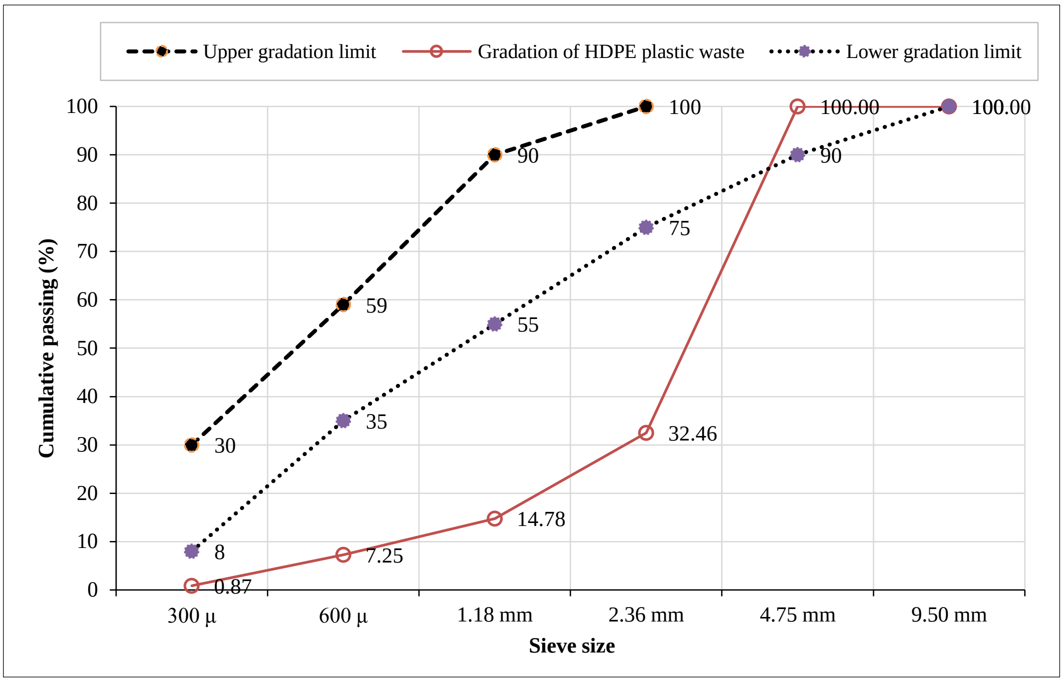


Figure 5. Graph of HDPE plastic waste gradation

The next step is to prepare the sand required for the control beam specimens (0.00%) and the sand substituted with HDPE plastic at 0.50%, 0.70%, and 0.90% of the sand weight. A hand mixer is used to mix the sand and HDPE plastic to ensure that each HDPE plastic variation is evenly mixed with the sand. The results of the bulk density testing for both normal sand and HDPE plastic-substituted sand at variations of 0.50%, 0.70%, and 0.90% are summarized in Table 1.

Table 1. Recapitulation of testing results for normal sand and HDPE plastic-substituted sand

Testing Items	Standard Requirements	Testing Results	Remarks
	Normal Sand		
Bulk Density (Compacted)	1.40 – 1.90	1.53	Compliant
Bulk Density (Loose)		1.33	Non-Compliant
Aggregate Modulus	1.5 – 3.8	2.09	Compliant
	HDPE Plastic-Substituted Sand Variation of 0.50%		
Bulk Density (Compacted)	1.40 – 1.90	1.53	Compliant
Bulk Density (Loose)		1.33	Non-Compliant
Aggregate Modulus	1.5 – 3.8	2.22	Compliant
	HDPE Plastic-Substituted Sand Variation of 0.70%		
Bulk Density (Compacted)	1.40 – 1.90	1.50	Compliant
Bulk Density (Loose)		1.33	Non-Compliant
Aggregate Modulus	1.5 – 3.8	2.20	Compliant
	HDPE Plastic-Substituted Sand Variation of 0.50%		
Bulk Density (Compacted)	1.40 – 1.90	1.50	Compliant
Bulk Density (Loose)		1.36	Non-Compliant
Aggregate Modulus	1.5 – 3.8	2.16	Compliant

Based on the bulk density data in compacted conditions in Table 1, both normal sand and HDPE plastic-substituted sand comply with the standards. The highest bulk density is found in normal sand at 1,533.64 kg/m³, while the bulk densities of plastic-substituted sand at 0.50%, 0.70%, and 0.90% are lower than normal sand, with values of 1,527.27

kg/m³, 1,495.45 kg/m³, and 1,501.82 kg/m³, respectively. In addition to bulk density, fineness modulus testing was also conducted. Figure 6 summarizes the calculation results of the fineness modulus of normal sand and HDPE plastic-substituted sand with variations of 0.50%, 0.70%, and 0.90%. The smallest fineness modulus is found in normal sand, while the highest fineness modulus is achieved by the plastic-substituted sand variation of 0.50%. The trend decreases successively for the 0.70% and 0.90% variations, with values of 2.20 and 2.16, respectively.

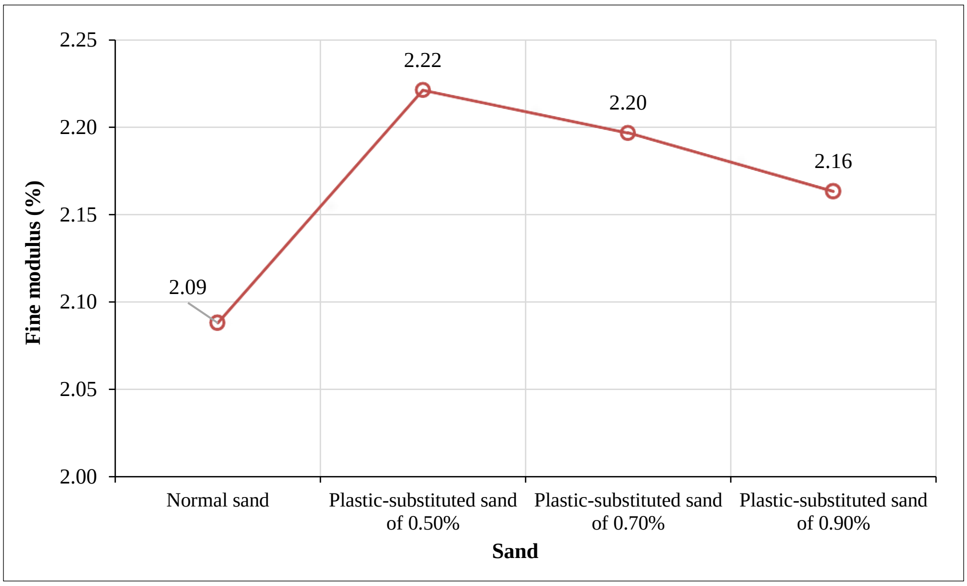


Figure 6. Graph of fineness modulus calculation for normal sand and plastic-substituted sand

3.2. Specimen Fabrication

The beam molds for the test specimens, measuring 15 cm × 15 cm × 65 cm beams, were made from 12 mm thick plywood, totaling 12 molds. Specimen fabrication was carried out in four mixing processes, corresponding to the planned variations of HDPE plastic substitution. The fabrication process began by preparing and coating the molds with grease. Then, the materials to be mixed were weighed according to the material requirements calculated in the mix design. Gravel and some waters were first added to the concrete mixer. While the mixer was running, normal sand or HDPE plastic-substituted sand, cement, and the remaining water were gradually added to avoid clumping the mixture (Figure 7-a). The fresh concrete was evenly mixed and ready for molding, with the mixer running at an appropriate speed. For each variation, a portion of the fresh concrete was set aside for a slump test (Figure 7-b). After being placed into the molds, both cylinder and beam specimens were immediately covered with plastic and wet clothes for 24 hours (Figure 7-c). The beam specimens were then placed into a water curing tank for further treatment using the wet curing method (Figure 7-d)

(a) Materials added to the concrete mixer (b) Slump Test (c) Specimen molding (d) Wet curing method

Figure 7. Specimen fabrication process

A total of 12 cylindrical specimens with a diameter of 10 cm and a height of 15 cm were prepared for concrete compressive strength testing, along with 24 beam specimens measuring 15 cm × 15 cm × 65 cm for beam flexural strength testing. The specimens were labeled based on the variables used in this study, namely the variation of HDPE plastic substitution and the age of the concrete at the time of testing. The number of samples and the labeling of the cylindrical concrete specimens can be seen in Table 2, while the number of samples and the labeling for the beam flexural strength testing can be seen in Table 3. For the cylindrical concrete specimens, testing was only performed at 28 days.

Table 2. Number of samples and labeling of cylindrical concrete specimens

Plastic Variation	Specimen Age Variation	Specimens Number	Code
0.0%	28 days	3	PR0.0 – C1 – A28 PR0.0 – C2 – A28 PR0.0 – C3 – A28
0.50%	28 days	3	PR0.5 – C1 – A 28 PR0.5 – C2 – A 28 PR0.5 – C3 – A 28
0.70%	28 days	3	PR0.7 – C1 – A 28 PR0.7 – C2 – A 28 PR0.7 – C3 – A 28
0.90%	28 days	3	PR0.9 – C1 – A 28 PR0.9 – C2 – A 28 PR0.9 – C3 – A 28
Total Numbers of Specimen		12	

Notes: PR = Partial Replacement of HDPE plastic waste (0.0, 0.5, 0.7 and 0.9); A = Specimen Age (14 and 28); C = Cylinder (1, 2, 3).

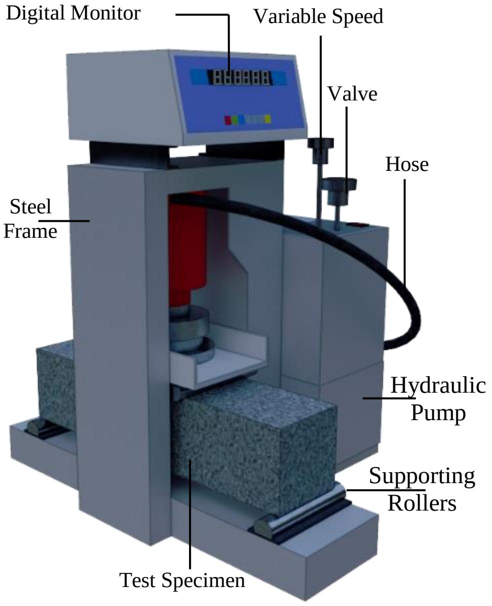
Table 3. Number of samples and labeling of beam test specimens

Plastic Variation	Specimen Age Variation	Specimens Number	Code
0.00%	14 days	3	PR0.0 – B1 – A14 PR0.0 – B2 – A14 PR0.0 – B3 – A14
	28 days	3	PR0.0 – B1 – A28 PR0.0 – B2 – A28 PR0.0 – B3 – A28
0.50%	14 days	3	PR0.5 – B1 – A 14 PR0.5 – B2 – A 14 PR0.5 – B3 – A 14
	28 days	3	PR0.5 – B1 – A 28 PR0.5 – B2 – A 28 PR0.5 – B3 – A 28
0.70%	14 days	3	PR0.7 – B1 – A 14 PR0.7 – B2 – A 14 PR0.7 – B3 – A 14
	28 days	3	PR0.7 – B1 – A 28 PR0.7 – B2 – A 28 PR0.7 – B3 – A 28
0.90%	14 days	3	PR0.9 – B1 – A 14 PR0.9 – B2 – A 14 PR0.9 – B3 – A 14
	28 days	3	PR0.9 – B1 – A 28 PR0.9 – B2 – A 28 PR0.9 – B3 – A 28
Total Numbers of Specimen		24	

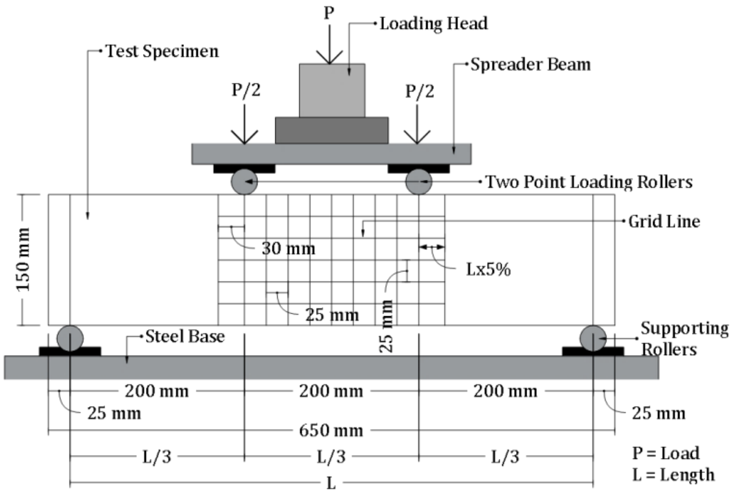
Notes: PR= Partial Replacement of HDPE plastic waste (0.0, 0.5, 0.7 and 0.9); A= Specimen Age (14 and 28); B= Beam (1,2,3).

3.3. Testing Equipment Setup and Flexural Strength Testing

After curing the specimens using the wet curing method, the flexural strength test of the beams was performed using a hydraulic concrete beam testing machine with two-point loading, in accordance with SNI 4431-2011 [29], as shown in Figure 8-a. This testing began by removing the concrete beams from the curing tank, drying them with a cloth, measuring their dimensions to calculate their volume, and weighing them to obtain the concrete's specific gravity data. Grid lines were drawn on the beams to facilitate the reading of the crack patterns. The concrete beams were then set up on the testing equipment for flexural strength testing, as shown in Figure 8-b.



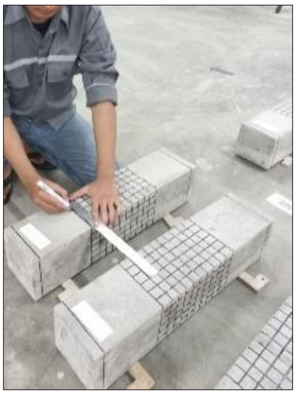
(a) Hydraulic concrete beam testing



(b) Two-point loading setup in flexure

Figure 8. Experimental Setup of Concrete Beam in Laboratory

Flexural strength testing was conducted in two stages according to the concrete's age variations, at 14 and 28 days, with 12 specimens tested for each age variation. During the flexural strength testing process, recordings and documentation were carried out. After testing, the beams were carefully moved to prevent the crack patterns from being damaged or altered. For the 28-day-old beam specimens, compressive strength testing of the concrete cylinders was conducted before the flexural strength testing to determine the compressive strength at 28 days. The overall testing process conducted in the laboratory is shown in Figure 9.



(a) Drawing grid lines

(b) Weighing the concrete beam

(c) Flexural strength testing of the concrete beam

(d) Condition of the concrete beam after testing

Figure 9. Stages of flexural strength testing process for concrete beams in the laboratory

4. Results and Discussion

4.1. Slump Test

Slump testing was conducted based on SNI 03-1972-1990 [30] using the Abrams cone and a height-measuring tool. Slump testing for each variation followed the same method: filling the Abrams cone with fresh concrete in three layers.

Each layer of fresh concrete was compacted 25 times using a tamping rod. Once filled, the top surface of the concrete was leveled, and the Abrams cone was lifted straight upward slowly. The slump value is the distance between the height of the Abrams cone and the highest point of the concrete mixture after it collapses. The test was repeated twice with the same batch to ensure accuracy, and the average value was reported. Figure 10 illustrates the slump shapes for each partial replacement variation after the slump test was conducted.

(a) 0.00% variation concrete (b) 0.50% variation concrete (c) 0.70% variation concrete (d) 0.90% variation concrete

Figure 10. The shape of the slump for each partial replacement variation after testing

Figure 11 shows the slump test results with average values of 11.9 cm for normal concrete, 10.8 cm for the 0.50% variation, 15 cm for the 0.70% variation, and 14.95 cm for the 0.90% variation. The smallest slump value was observed in the 0.50% variation concrete, at 10.8 cm, which is 1.1 cm lower than the normal concrete. The largest slump value was observed in the 0.70% variation concrete, at 15 cm, which is 3.1 cm higher than the normal concrete. The slump value for the 0.90% variation concrete was 14.95 cm, with a difference of 3.05 cm from the normal concrete. Overall, all variations met the slab value standards for concrete used in beams, ranging from 7.5 cm to 15 cm [31]. From the graph, the 0.50% HDPE variation provided the most ideal slump value.

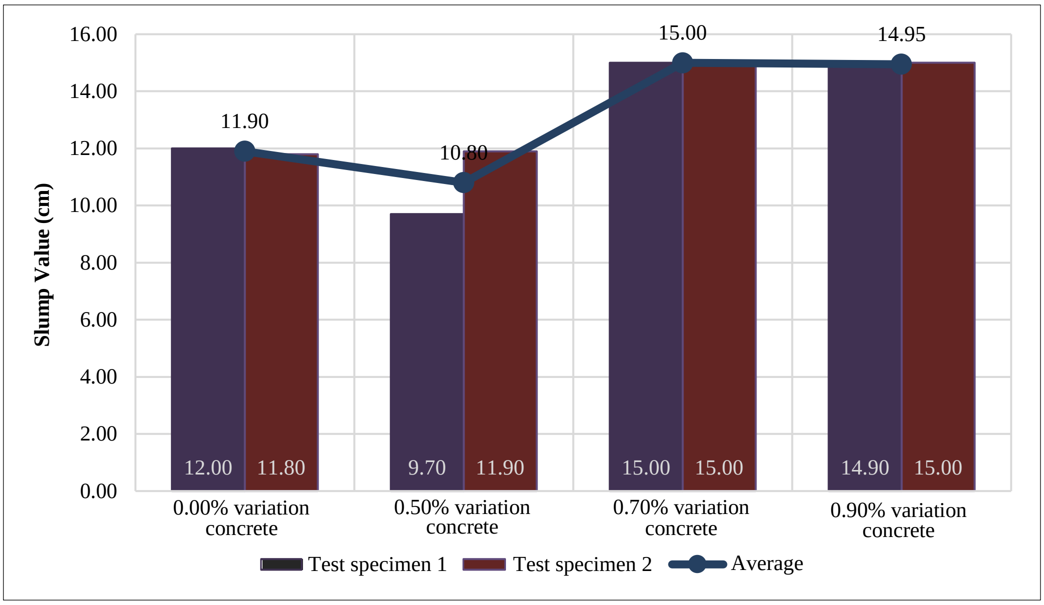


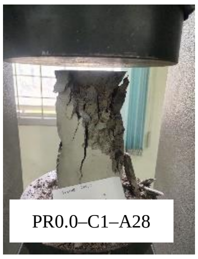
Figure 11. Graph of average slump test results

4.2. Concrete Cylinder Compressive Strength Test

The compressive strength test was conducted using a Universal Testing Machine with a capacity of 1000 kN [32]. This test determined the concrete's strength at 28 days before conducting the flexural strength test on concrete beams at 28 days. Table 4 shows the results of the compressive strength test for concrete cylinders. On average, the highest compressive strength was achieved by the concrete cylinders without HDPE plastic (0.00%) at 22.70 MPa, followed by 0.50%, 0.70%, and 0.90% variations with compressive strengths of 19.73 MPa, 18.67 MPa, and 18.67 MPa, respectively. However, overall, the highest compressive strength among all cylinder specimens was achieved by the specimen PR0.5–C1–A28, the first specimen with a 0.50% HDPE plastic variation at 24.18 MPa.

In terms of crack patterns or failures observed, all exhibited columnar crack patterns, with the propagation of failure increasing as the amount of HDPE plastic in the concrete mix increased. The specimen PR0.9–C2–A28 showed the most severe failure, requiring reconstruction before being photographed.

Table 4. Results of compressive strength test for concrete cylinders

Variation	Test Specimen 1	Test Specimen 2	Test Specimen 3	Average Strength
0.00% variation concrete	 23.55 MPa	 22.91 MPa	 21.64 MPa	22.70 MPa
0.50% variation concrete	 24.18 MPa	 16.55 MPa	 18.45 MPa	19.73 MPa
0.70% variation concrete	 14.00 MPa	 20.36 MPa	 21.64 MPa	18.67 MPa
0.90% variation concrete	 17.82 MPa	 19.73 MPa	 18.45 MPa	18.67 MPa

4.3. Concrete Beam Flexural Strength Test

The calculation of flexural strength is based on the formula for the flexural strength of concrete beams according to [29] for normal flexural strength testing with two-point loading, as follows:

$$\sigma_1 = \frac{P.L}{b.h^2} \tag{1}$$

where σ_1 is the flexural strength of the specimen, *P* is the peak load, *L* is the distance between two support lines, *b* is the width of the beam cross-section, and *h* is the height of the beam cross-section. This formula is used because all specimen failures occurred in the central region, within 1/3 of the span between the support points, on the tensile side of the concrete.

Figure 12 shows each concrete beam specimen's flexural strength test results and their averages at 14 days. The flexural strength and average values for the HDPE plastic variation beam at 14 days are as follows: 3.16 MPa for the 0.00% (normal) variation, 3.35 MPa for the 0.50% variation, 2.91 MPa for the 0.70% variation, and 2.97 MPa for the 0.90% variation. The beam with the highest flexural strength was the 0.50% variation beam, with a value of 3.35 MPa, which is 0.19 MPa higher than the normal variation beam. The beam with the lowest flexural strength was the 0.70% variation beam, with a value of 2.91 MPa, about 0.25 MPa lower than the normal variation beam. The flexural strength of the 0.90% variation beam was 2.97 MPa, about 0.19 MPa lower than the normal variation beam. Overall, the trend indicates that moderate material additions enhance concrete flexural strength, whereas excessive modifications may degrade its mechanical properties.

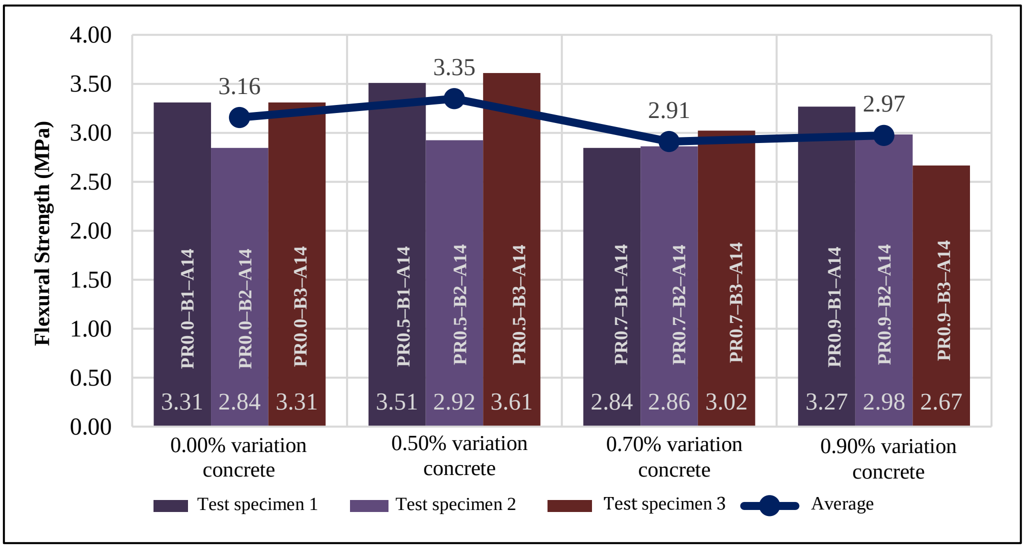


Figure 12. Results of flexural strength testing of beams at 14 days

Figure 13 shows each concrete beam specimen's flexural strength test results and their averages at 28 days. The average flexural strength values are as follows: 3.39 MPa for the 0.00% (normal) variation, 3.95 MPa for the 0.50% variation, 3.06 MPa for the 0.70% variation, and 3.07 MPa for the 0.90% variation. The beam with the highest flexural strength was the 0.50% variation beam, with a value of 3.95 MPa, which is 0.56 MPa higher than the normal variation beam. The beam with the lowest flexural strength was the 0.70% variation beam, with a value of 3.06 MPa, about 0.33 MPa lower than the normal variation beam. The flexural strength of the 0.90% variation beam was 3.07 MPa, about 0.32 MPa lower than the normal variation beam. This indicates that excessive dosage may increase porosity or disrupt the internal structure of the concrete, thereby negatively affecting its mechanical properties.

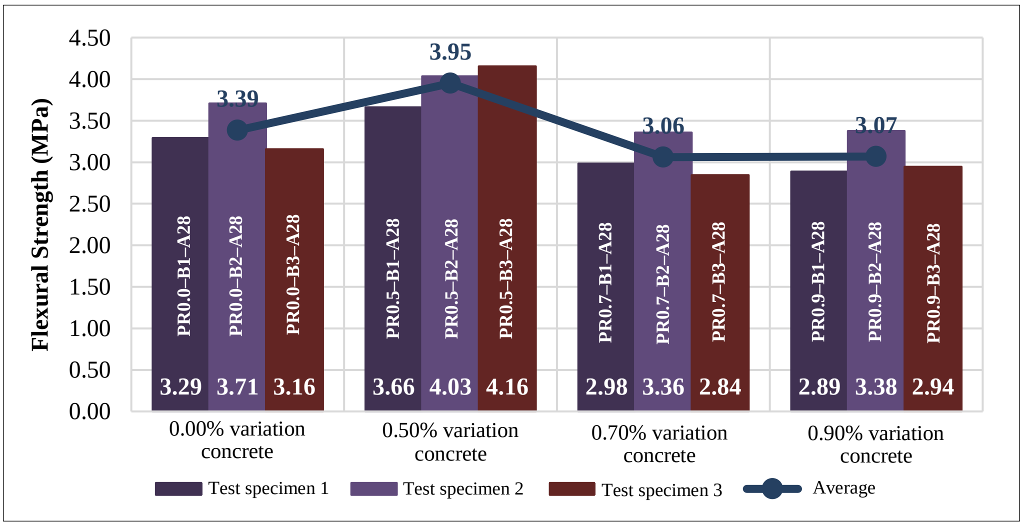
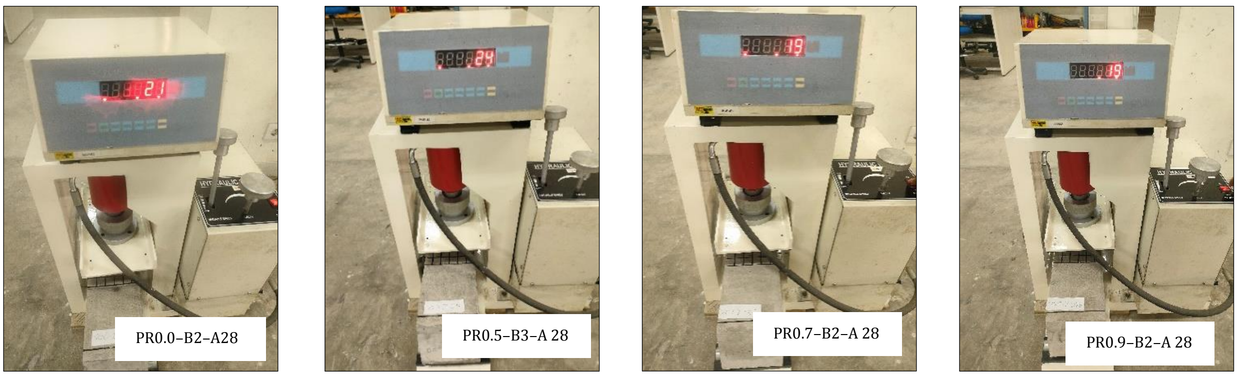


Figure 13. Flexural strength test results for beams at 28 days



(a) 0.00% variation concrete (b) 0.50% variation concrete (c) 0.70% variation concrete (d) 0.90% variation concrete

Figure 14. Highest peak load of specimens for each variation at 28 days

Figure 14 shows the testing conditions of concrete beams at the highest peak load for each variation at 28 days. Specimen PR0.5–B3–A28 achieved the highest peak load, with a peak load of 24 kN. Specimen PR0.0–B2–A28 came in second with a peak load of 21 kN, while specimens PR0.7–B2–A28 and PR0.9–B2–A28 followed with peak loads of 19 kN each.

As shown in Figure 15, all concrete variations exhibit higher flexural strength at 28 days compared to 14 days. This indicates that the cement hydration reaction continues beyond 14 days, leading to further hardening and strength development until the concrete reaches its optimal condition. As Neville [23] explained, the cement hydration process contributes to the densification of the concrete microstructure, ultimately enhancing its resistance to mechanical loads.

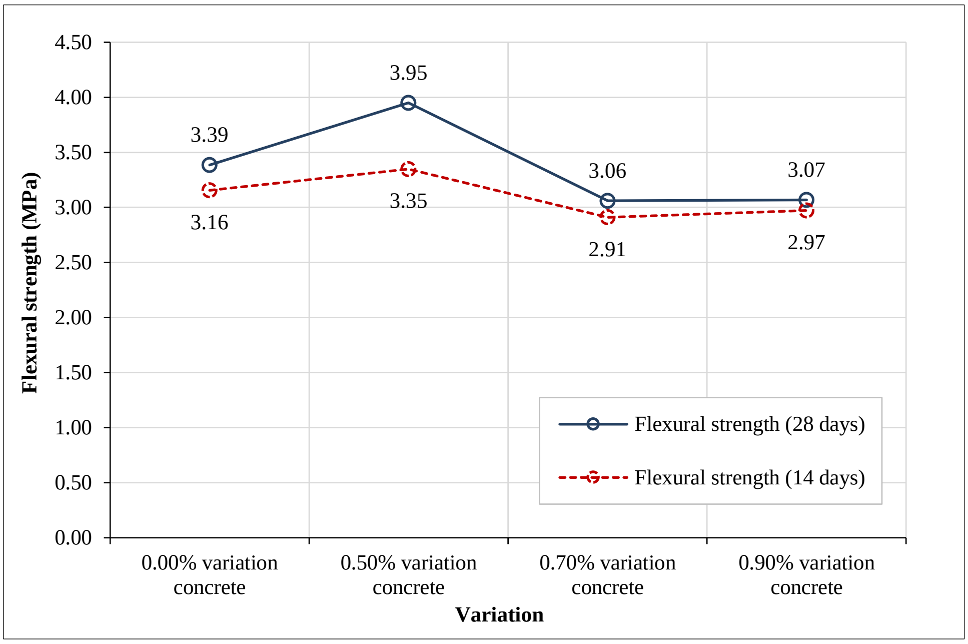


Figure 15. Recapitulation of flexural strength test results for concrete beams at 14 and 28 days

Among the tested variations, the 0.50% modification yielded the highest flexural strength at 28 days, reaching 3.95 MPa. This suggests that the 0.50% proportion optimizes concrete's flexural performance. The observed improvement is consistent with studies highlighting that moderate modifications in concrete composition can refine its microstructure, thereby increasing its strength and durability [24].

However, beyond the 0.50% variation, a decline in flexural strength is observed. This trend implies that excessive modification may have adverse effects, possibly due to issues such as increased porosity, reduced cohesion within the matrix, or suboptimal particle packing. Similar findings in previous studies have shown that excessive additions of certain admixtures or supplementary materials can lead to reduced mechanical properties due to disturbance in the hydration process and internal structural integrity [33].

4.4. Crack Pattern

Table 5 shows the crack patterns and types of failure observed. All concrete beam specimens experienced flexural failure, as all specimens failed within the central 1/3 span of the concrete beam. The cracking process began at the bottom of the beam in the central 1/3 section and propagated upward within the same central 1/3 area. This is consistent with the description of flexural failure, where cracks initiate at the tensile side and move vertically toward the load. Therefore, the HDPE plastic substitution beams with variations of 0.00%, 0.50%, 0.70%, and 0.90% in this study exhibited flexural failure. This occurs because concrete has very low tensile strength. As the load increases, the tensile fibers at the bottom of the beam experience stress that exceeds the tensile capacity of the concrete, resulting in cracking. Given that the initial crack location, crack pattern characterized by vertical propagation from the bottom upward, and its distribution remain consistent across all specimens, it can be concluded that the addition of HDPE plastic does not influence the crack pattern or failure mechanism.

Table 5. Crack patterns and types of failure in concrete beam

Variation	Age	Test Specimen	Crack Pattern	Photo	Types of Failure
0.00% variation concrete	14 Days	PR0.0–B1–A14			Flexural Failure
		PR0.0–B2–A14			Flexural Failure
		PR0.0–B3–A14			Flexural Failure
	28 Days	PR0.0–B1–A28			Flexural Failure
0.50% variation concrete	14 Days	PR0.5–B1–A14			Flexural Failure
		PR0.5–B2–A14			Flexural Failure
		PR0.5–B3–A14			Flexural Failure
	28 Days	PR0.5–B1–A28			Flexural Failure
		PR0.5–B2–A28			Flexural Failure
		PR0.5–B3–A28			Flexural Failure
0.70% variation concrete	14 Days	PR0.7–B1–A14			Flexural Failure
		PR0.7–B2–A14			Flexural Failure
		PR0.7–B3–A14			Flexural Failure
	28 Days	PR0.7–B1–A28			Flexural Failure
		PR0.7–B2–A28			Flexural Failure
		PR0.7–B3–A28			Flexural Failure
0.90% variation concrete	14 Days	PR0.9–B1–A14			Flexural Failure
		PR0.9–B2–A14			Flexural Failure
		PR0.9–B3–A14			Flexural Failure
	28 Days	PR0.9–B1–A28			Flexural Failure
		PR0.9–B2–A28			Flexural Failure
		PR0.9–B3–A28			Flexural Failure

5. Conclusion

The study results indicated that at 14 days, the concrete beam specimens with variation levels of 0.00%, 0.50%, 0.70%, and 0.90% achieved flexural strengths of 3.16 MPa, 3.35 MPa, 2.91 MPa, and 2.97 MPa, respectively. By 28 days, these values increased to 3.39 MPa, 3.95 MPa, 3.06 MPa, and 3.07 MPa, respectively, demonstrating a time-dependent improvement in flexural strength due to the continued hydration process of cement. The highest flexural strength was observed in the concrete beam specimens containing a 0.50% variation, with values of 3.35 MPa at 14 days and 3.95 MPa at 28 days, surpassing the strength of the control specimen (0.00% variation). This indicates that incorporating up to 0.50% substitution enhanced flexural performance, likely due to improved material cohesion and reduced porosity.

However, beyond this threshold, flexural strength declined, as seen in the 0.70% and 0.90% variations, where excessive substitution may have led to increased porosity and weakened the interfacial bond between cement paste and aggregates. This aligns with previous research, such as Mehta and Monteiro [24] and Aïtcin [33], emphasizing the importance of optimal mix design to achieve maximum performance. An excessively high content of substitute materials can disrupt the internal matrix, leading to a weaker overall structure due to non-uniform stress distribution and an increase in microcracks over time. Additionally, all concrete beam specimens exhibited flexural failure within the central third of the span, which is consistent with typical bending failure mechanisms in reinforced concrete beams under loading. These findings highlight the significance of optimizing material composition to balance strength enhancement and structural integrity.

6. Declarations

6.1. Author Contributions

Conceptualization, N. and P.M.; methodology, I.; software, Z.; validation, N., P.M., and I.; formal analysis, I.; investigation, P.M.; resources, N.; data curation, P.M.; writing—original draft preparation, Z.; writing—review and editing, Z.; visualization, Z.; supervision, N.; project administration, N.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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