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Flexural Strength Characteristics of Composite Concrete Based on Pet Fiber and Fly Ash

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ABSTRACT – Conventional Portland cement concrete production entails substantial carbon emissions, while the resulting matrix remains susceptible to microcracking. To mitigate these drawbacks, incorporating industrial by-products and recycled polymers offers a viable sustainable solution. This study investigated the flexural strength characteristics of eco-friendly concrete incorporating fly ash as a partial cement replacement at 15% by mass and recycled polyethylene terephthalate (PET) fibers at volume fractions of 0.25%, 0.5%, 0.75%, and 1%. A plain concrete mixture served as the control baseline. Flexural strength was evaluated using beam specimens at 28 days. The results showed that the optimum flexural strength was achieved at a PET fiber volume fraction of 0.25%, reaching 3.95 MPa. This value was higher than that of concrete containing 15% fly ash without PET fibers (3.02 MPa) and the plain concrete mixture (3.33 MPa). Increasing the PET fiber content beyond 0.25% resulted in a decline in flexural strength, with a value of 3.29 MPa at 1% PET fiber. The findings demonstrated that incorporating a low PET fiber content in fly ash concrete improved flexural strength, while excessive fiber content reduced flexural performance. These results highlight the potential of combining fly ash and recycled PET fibers as materials for developing more sustainable concrete.

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INTRODUCTION

The global volume of waste generation continues to increase significantly. The World Bank projects that by 2025, global urban waste production will reach 2.2 billion tons per year, with developing countries serving as the primary contributors at 572 million tons per year, and a per capita generation rate of 1.1–3.7 kg per person per day [1]. In Indonesia, approximately 65.83% of waste is still disposed of in landfills, with total generation reaching 68.7 million tons per year. The waste is dominated by organic matter, particularly food waste (41.27%), with households contributing 38.28% of the total volume. The increase in waste volume is closely related to human activities and socioeconomic development, and is further influenced by geographical factors, demographics, culture, time and seasons, technological advancements, as well as waste characteristics [2]. The high daily consumption of plastic causes plastic waste to account for approximately 17% of the total municipal waste generation, making it a critical issue that garners both national and global attention [3].

Based on the influence of temperature, plastics are classified into thermoplastics and thermosets. Thermoplastics possess linear polymer chains that are reversible, allowing them to be remelted, recycled, and reshaped—such as PET, PE, PP, PS, and PVC—whereas thermosets have a three-dimensional structure that is irreversible, meaning they cannot be remelted [4]. Plastic waste, which is difficult to degrade, has the potential to cause long-term environmental pollution, public health issues, aesthetic degradation, and flood risks due to accumulation. These conditions have driven research to modify the properties of plastic so that it can be utilized as an alternative material in construction products [3]. The plastic waste problem in Indonesia remains an unresolved challenge due to the high daily consumption of society, which leads to waste accumulation in the environment. Given that plastic waste characteristics prevent it from decomposing naturally, utilization innovations are required, one of which includes using it as an additive material in concrete mixtures to support the concept of sustainable green infrastructure [5].

Concrete is the dominant composite construction material in infrastructure development due to its durability and ease of implementation in the field [6]. However, its brittle nature and low ductility make concrete weak against tensile and flexural forces, thereby requiring steel reinforcement [7]. As an alternative to control microcracks from propagating into macro-cracks, the random use of fibers through a crack-bridging mechanism effectively improves concrete ductility [8]. Although conventional steel fibers can enhance tensile strength, their susceptibility to corrosion can degrade the long-term performance of the structure [9]. Modern infrastructure development is currently shifting toward the concept of sustainability through the utilization of eco-friendly materials. The conventional concrete industry contributes significantly to environmental degradation due to high energy consumption and carbon emissions generated by cement production. Therefore, material substitution strategies utilizing industrial waste and by-products are employed to increase the resource efficiency of construction materials [10].

The utilization of polyethylene terephthalate (PET) waste as fibers offers an eco-friendly concrete solution due to its high tensile strength, as well as its resistance to water and chemicals [11]. The length of plastic fibers significantly influences the workability and mechanical performance of concrete. Fibers measuring 40 mm in length with a width of 2 mm have been proven to deliver an optimal and balanced performance compared to other sizes [12]. The addition rate of PET fibers is also crucial; several studies indicate that the optimal addition ranges from 0.5% to 1%, while levels above that actually reduce performance due to a decline in matrix bond quality and workability [13]-[16]. On the other hand, the production of cement as the primary binder in concrete contributes significant emissions to the environment [6]. Consequently, the partial substitution of cement using industrial waste such as fly ash continues to be developed [17]. Fly ash derived from coal combustion waste has the potential to pollute the environment if left unmanaged [18]. However, within concrete, fly ash undergoes a pozzolanic reaction with calcium hydroxide to form secondary calcium silicate hydrate (C-S-H) compounds, which refine the concrete matrix and improve its durability properties [6].

On the other hand, maritime and coastal activities are also major contributors to plastic waste pollution in Indonesia. This pollution not only threatens marine life and the sustainability of coastal ecosystems but also contributes to environmental degradation in the area currently being prepared as the new government center. This innovative concrete material is expected not only to meet urban infrastructure needs resilient to tropical-maritime climate conditions but also to make a tangible contribution to reducing plastic waste pollution in the waters surrounding East Kalimantan. Utilizing PET plastic fibers and fly ash as substitutes in eco-friendly concrete mixtures offers a dual approach: first, as a strategy to mitigate marine and terrestrial contamination by reducing the volume of waste ending up in the ocean or landfills; and second, as a means of providing innovative construction materials that support circular economy principles in the sustainable infrastructure development of the IKN (New Capital City). Fly ash functions to density the porous matrix, while PET plastic fibers play an active role in controlling cracks and enhancing flexural strength [19, 20]. Based on ACI 232.2R.03 recommendations and prior research, a safe fly ash substitution rate to optimize matrix densification without compromising long-term performance is between 15% and 20% [21, 22, 19, 23].

Although independent research on PET fibers or fly ash has been widely conducted, studies investigating the macro performance of concrete combining fly ash and PET fibers remain limited. Based on this research gap, this study aims to analyze the effect of variations in PET plastic fiber content (0%, 0.25%, 0.5%, 0.75%, and 1%) with a fixed fly ash substitution composition of 15% on the macro behavior of concrete. This Study aimed to investigate the effect of fly ash and recycled PET fiber incorporation on the flexural strength of concrete. The results of this study are expected to provide a new scientific reference in the development of alternative concrete materials that are more economical, ductile, and supportive of sustainable construction.

MATERIAL AND METHODS

The research stages initiated with a literature study to collect references related to the characteristics of PET fiber and fly ash concrete. The subsequent stage involved gathering and preparing the concrete raw materials, followed by testing the characteristics of both fine and coarse aggregates to ensure compliance with technical specification standards for concrete mix preparation. Once the material characteristics were obtained, the concrete mix design proportion calculations were performed. The concrete mixing process was performed using a concrete mixer for approximately 10–20 minutes. The constituent materials were introduced sequentially into the mixer, starting with the coarse aggregate, followed by the fine aggregate, PET fibers, cement, fly ash, and water. After mixing, the fresh concrete was subjected to a slump test for each casting process to evaluate its workability. The concrete was then placed into beam molds measuring 15 × 15 × 60 cm and compacted by rodding, followed by tapping the mold with a hammer to improve compaction. After 24 hours, the specimens were demolded and cured by water immersion for 28 days at room temperature under normal ambient conditions. Three beam specimens were prepared for each mixture variation, and the flexural strength value for each variation was determined from the average of the three specimens. The slump test was conducted for each casting, while the baseline concrete mix design was used as the primary reference for determining the initial mixture proportions. The final stage of this study involved mechanical testing of the concrete, which included flexural strength test, followed by data analysis of the test results to draw conclusions

Mechanical Properties and Material Characteristics Portland Cement and Fly Ash

The cement used in this study was Type I Portland Cement under the Conch brand. Fly ash was obtained from the coal combustion waste of the Balikpapan Steam Power Plant (PLTU Balikpapan). Fly ash functions to trigger a secondary pozzolanic reaction with calcium hydroxide $Ca(OH)_2$ resulting from cement hydration, producing additional calcium silicate hydrate (C-S-H) that contributes to densifying the interfacial transition zone.

Figure 1. Fly Ash

In this study, 15% fly ash was used as a partial substitute for cement because it provides the best balance between early strength and microstructural improvement, and enhances the effectiveness of plastic fibers in controlling cracking.

Table 1. Fly Ash Composition

Parameter	Unit	Results		Method
		Fly ash	Bottom Ash	
Moisture Content	%wt	1.86	0.25	Gravimetric
Unburned Carbon	%wt	0.20	1.52	ASTM D 6316
Loss on Ignition	%wt	2.10	1.07	Gravimetric
Ash Analysis				
Silicon Dioxide ($\mathbf{SiO_2}$)	%wt	39.55	74.47	ASTM D 3682-13
Alumunium Trioxide ($\mathbf{SiAl_2O_3}$)	%wt	12.72	8.22	ASTM D 3682-13
Iron Oxide ($\mathbf{Fe_2O_3}$)	%wt	20.87	6.66	ASTM D 3682-13
Calcium Oxide (Na$\mathbf{O_2}$)	%wt	11.20	4.81	ASTM D 3682-13
Magnesium Oxide (MgO)	%wt	7.48	2.08	ASTM D 3682-13
Potassium Oxide ($\mathbf{K_2O}$)	%wt	0.68	0.36	ASTM D 3682-13
Sodium Oxide ($\mathbf{Na_2\ O}$)	%wt	0.16	0.42	ASTM D 3682-13
Manganese Dioxide	%wt	0.21	0.10	ASTM D 3682-13
Titan Dioxide	%wt	1.71	1.47	ASTM D 3682-13
Phosphorus Pentaoxide	%wt	0.55	0.60	ASTM D 2795-95
Sulfur Trioxide	%wt	4.23	0.12	ASTM D 5016-08e1
Undeternibed	%wt	0.64	0.69	Calculation

The test results indicate that the fly ash and bottom ash from Balikpapan Bay are classified as Class F, where the total content of (SiO_2), ($SiAl_2O_3$), and (Fe_2O_3) is greater than or equal to 70% (24).

PET Plastic Fibers

The fibers were manually produced from transparent plastic bottle waste, cut into fibers with a length of 40 mm and a width of 2 mm. The dimensions of the fibers were selected based on the optimal fiber size value for the crack-bridging mechanism without disrupting the concrete mix (Mouna et al., 2024). The volume variations of the PET fibers used include 0%, 0.25%, 0.5%, 0.75%, and 1% of the total concrete volume.

Figure 2. PET Fiber

Aggregate Characteristics Testing (Moisture Content)

Aggregate moisture content is utilized to measure the free water content contained within the aggregate pores. The moisture content can be calculated using the following equation:

$$\text{Moisture Content} = \frac{W_1 - W_2}{W_2} \text{ x } 100\% \tag{1}$$

Where:
W_1 = initial weight of the aggregate sample
W_2 = weight of the sample after being oven-dried for 24 hours

Specific Gravity

Specific gravity is used to determine the ratio of the material's unit weight to the unit weight of water. The specific gravity can be calculated using the following equation:

$$\text{Specific Gravity} = \frac{W_d}{W_s-(W_w-W_a)} \tag{2}$$

Where:
W_d = dry sample weight
W_s = weight of the sample in saturated surface-dry (SSD) condition
W_w = weight of the pycnometer filled with the sample and water
W_a = weight of the pycnometer filled only with water

Mix Design

The mix design proportioning, the mixture proportions can be seen in Tables 2 below.

Table 2. Mix Proportion of Concrete Beams

Description	Cement	Water	Fine Aggregate	Coarse Aggregate	Unit
Proportion (1m^3)	390.48	204.42	694.14	960.97	Kg
1 sample	5.27	2.76	9.37	12.97	Kg
3 sample	15.81	8.28	28.11	38.92	Kg
SF 1.5	23.72	12.42	42.17	58.38	Kg

Fabrication and Testing of Specimens

The mixing process was carried out using a concrete mixer, introducing the constituent materials, fly ash, and plastic fibers gradually. Subsequently, a slump test was performed to measure the workability of the concrete. The concrete was cast 15 x 15 x 60 cm beam molds. After 24 hours, the specimens were demolded and cured using the water immersion method up to 28 days. The equations for the compressive and flexural strength tests are detailed as follows:

Flexural Strength of Beam Concrete

The compressive strength of concrete is determined through laboratory testing by gradually applying a compressive load using a testing machine to a cylindrical test specimen until it fails. The compressive strength of concrete is calculated by dividing the maximum compressive load at the point of failure by the cross-sectional area of the test specimen, and is expressed in megapascals (MPa).

$$\text{Flexural Strength} = \frac{P \times L}{b \times h^2} \tag{3}$$

Where:

P	=	maximum flexural load
L	=	span length between supports (mm)
b	=	width of the beam cross-section (mm)
h	=	height of the beam cross-section (mm)

RESULTS AND DISCUSSION

Slump Test

The slump test results for all concrete mixtures are presented in Table 3. The measured slump values ranged from 9.0 to 11.4 cm, which were within the target slump range of 10 ± 2 cm. The plain concrete mixture recorded a slump of 11.4 cm, while the concrete containing 15% fly ash had a slump of 10.0 cm.

Table 3. Mix Proportion of Concrete Beams

Description	Slump Value (cm)	
	Design Slump	Field Slump
Normal Concrete	10 ± 2	11.4
Fly ash 15%	10 ± 2	10
FA 15% PET 0,25%	10 ± 2	9
FA 15% PET 0,5%	10 ± 2	11.3
FA 15% PET 0,75%	10 ± 2	10.4
FA 15% PET 1%	10 ± 2	11

The addition of PET fibers resulted in slump values of 9.0, 11.3, 10.4, and 11.0 cm for PET fiber contents of 0.25%, 0.5%, 0.75%, and 1%, respectively. These results indicate that all mixtures satisfied the predetermined slump requirement and were considered acceptable for the casting process.

Flexural Strength Analysis of Concrete

Flexural strength testing was performed on beam specimens measuring 15 × 15 × 60 cm at an age of 28 days.

Table 4. Flexural Test Results of Beams

Sample Code	Mix Proportion	Weight (kg)	Flexural Strength (MPa)
BN1	Normal Concrete	31.76	3.33
BF1	*Fly ash* 15%	31.81	3.02
BFP11	FA 15% PET 0.25%	32.58	3.95
BFP12	FA 15% PET 0.5%	32.36	3.64
BFP13	FA 15% PET 0.75%	31.33	3.38
BFP14	FA 15% PET 1%	31.67	3.29

The optimum PET fiber content obtained in this study was 0.25%, which differs from the higher PET contents reported in several previous studies. This difference may be attributed to variations in fiber geometry, fiber surface characteristics, concrete composition, and incorporation method. For example, Khalid et al. [16] used PET fibers measuring 45 × 2 mm with a scrubbed surface and reported the highest split tensile strength at 0.5% PET. In contrast, the present study used manually cut PET fibers measuring 40 × 2 mm without surface treatment and incorporated them into concrete containing 15% fly ash. The difference in fiber geometry and surface condition may influence fiber–matrix interaction and the resulting mechanical response. Furthermore, Adajar and Ubay-Anongphouth [13] investigated fly ash concrete with a substantially higher fly ash content of 30% and PET used as a partial replacement for fine aggregate, with 5% PET producing the highest flexural strength. These differences in fly ash content, PET incorporation method, and fiber characteristics indicate that the optimum PET content is strongly dependent on the composition and configuration of the concrete mixture. Therefore, the optimum value of 0.25% obtained in the present study reflects the specific interaction between 15% fly ash and the PET fibers used in this experimental configuration.

Figure 3. Specimens and Flexural Strength Test

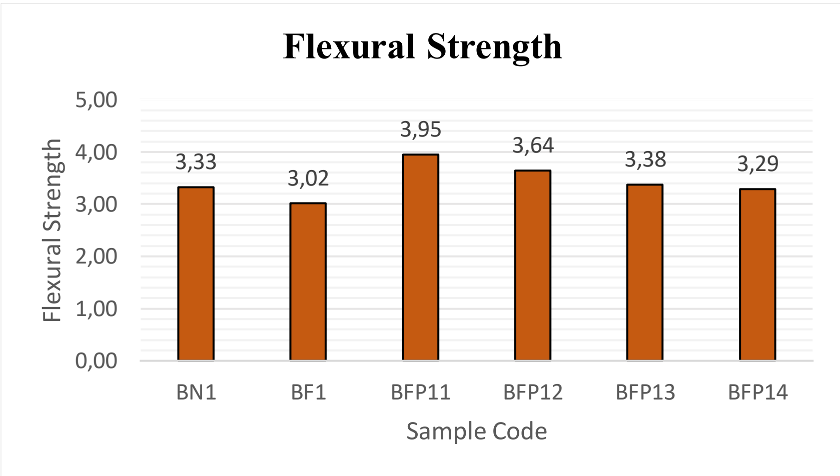

Figure 4. Flexural Test Resut Diagram of Concrete Beam

CONCLUSION

This study demonstrates that incorporating recycled PET fibers into concrete containing 15% fly ash can improve flexural performance, with 0.25% PET identified as the optimum fiber content within the investigated range. The findings highlight the importance of fiber content, geometry, and mixture composition in determining the mechanical performance of fly ash–PET concrete, and demonstrate that a lower PET content can provide favorable flexural performance compared with higher contents reported in some previous studies. From a sustainability perspective, the combined use of fly ash and recycled PET fibers provides a practical approach for reducing reliance on conventional cement and utilizing plastic waste in concrete applications. Future research should investigate the durability performance of the developed concrete, evaluate its behavior at structural scale, and examine the effects of different fly ash replacement levels and PET fiber characteristics.

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