Effect of Oil Palm Empty Fruit Bunch Fiber Length on Flexural Performance and Macrostructure of Palmfiber Reinforced Concrete

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Article Information

Abstract

This study investigates the influence of fiber length of oil palm empty fruit bunch (EFB) on the flexural performance and macrostructure of Palmfiber Reinforced Concrete (PRC) as a sustainable alternative to Glassfiber Reinforced Concrete (GRC). EFB fibers were selected due to their availability, environmental benefits, and potential to improve the mechanical properties of lightweight concrete. Five fiber lengths (3, 4, 5, 6, and 7 cm) were incorporated into PRC specimens. Flexural tests revealed that 5 cm fibers achieved the highest flexural strength of 11.78 kg/cm², while 4 cm fibers provided the maximum modulus of elasticity at 162.2 kg/cm². Macrostructural observations indicated satisfactory fiber–matrix bonding in most specimens; however, variations in fiber distribution and manual compaction affected overall performance. These findings demonstrate that fiber length significantly impacts the mechanical behavior of PRC, emphasizing the need for optimized production techniques to ensure consistent material quality.

1. Introduction

Glassfiber Reinforced Concrete (GRC) is a composite material consisting of cement–sand paste reinforced with glass fibers [1]. GRC combines two materials with distinct mechanical properties, exhibiting high compressive strength but relatively low flexural strength after the cement–sand mixture has cured [2]. Despite its advantages in structural and finishing applications, GRC has several limitations, including high density (1.80–2.10 g/cm³), low impact resistance (100–110), limited flexural strength (~160 kg/cm²), and moderate modulus of elasticity (5–6×10^4 kg/cm²) [3], [4]. These drawbacks, particularly its vulnerability to cracking under heavy loads and low long-term reliability, motivate the exploration of alternative reinforcing fibers.

Natural fibers have emerged as promising substitutes for glass fibers due to their wide availability, eco-friendliness, and cost-effectiveness [5]–[8]. In Indonesia, abundant agricultural residues, such as oil palm empty fruit bunch (EFB), pineapple, areca nut, aloe vera, coconut coir, ijuk, water hyacinth, and sugarcane fibers, can be utilized to reinforce cementitious composites. Among these, fibers derived from Oil Palm Empty Fruit Bunches (EFB), particularly from Oil Palm Empty Fruit Bunch Stalks (TKKS), offer a sustainable and widely available source of reinforcement [9]–[12].

TKKS fibers are rich in cellulose and possess mechanical properties suitable for composite applications. Prior studies report that TKKS fibers exhibit tensile strength of 1074 kg/cm², density of 0.14 g/cm³, and average fiber diameter of 0.55 mm [13]. Historically, TKKS has been primarily used as biomass fuel in power plants, e.g., PT Belitung Energy, and as an organic fertilizer in plantations. Recent research demonstrates that incorporating TKKS fibers into polymer and cementitious matrices can significantly enhance flexural performance. For instance, Suripto et al. [14] reported a maximum flexural stress of 18.48 kg/cm² in composites containing 3.55% glass and plastic fibers blended with TKKS.

Replacing glass fibers with TKKS in GRC boards not only leverages an abundant natural resource but also reduces industrial waste and environmental impact [15], [16]. Palmfiber Reinforced Concrete (PRC) represents a novel composite where TKKS fibers substitute conventional glass fibers, enabling the development of environmentally friendly, lightweight, and cost-effective building materials.

This study investigates the effect of TKKS fiber length on the mechanical and macrostructural properties of PRC. Flexural tests and macrostructural observations are conducted on specimens with varying fiber lengths to evaluate differences in strength and fiber–matrix interaction. The research aims to provide insights into optimizing PRC composition for enhanced performance, sustainability, and practical application in construction.

2. Method

A. Experimental Site

All experiments were conducted at the Material Laboratory, Department of Mechanical Engineering, Institut Teknologi Padang, Indonesia. Flexural testing and macrostructural observation were carried out in the same laboratory under controlled conditions to ensure consistency.

B. Materials and Mix Design

Palmfiber Reinforced Concrete (PRC) specimens were prepared using the composition listed in Table 1. The mixture consisted of cement, sand, TKKS fibers, compound cornice, and water, proportioned to achieve a workable consistency while maintaining structural integrity.

The TKKS fibers were sourced from oil palm empty fruit bunches and cut into varying lengths of 3 cm, 4 cm, 5 cm, 6 cm, and 7 cm to evaluate the effect of fiber length on mechanical performance.

Table 1. Composition of PRC

Component	Percentage / Amount
Compound Cornice	24.66%
Sand	49.25%
Portland Cement (Semen Padang)	24.66%
TKKS Fiber	1.50%
Water	250 mL

C. Specimen Preparation

Specimens were prepared according to ASTM E855 [21] and SNI 03-2493-1991 standards [22] for flexural testing of cement-based composites. The preparation procedure included:

- Specimen Dimensions: Rectangular specimens with a length of 20 cm, thickness of 1 cm, and width adjusted according to fiber length and 45° fiber orientation.

- Number of Specimens: A total of 15 specimens were produced, with three replicates for each of the five fiber lengths.

- Mixing Procedure: Cement, sand, compound cornice, water, and TKKS fibers were thoroughly mixed to ensure homogeneous distribution of fibers. Figure 1 shows the mixing arrangement of cement and TKKS fibers.

- Curing: Specimens were cured under laboratory conditions for 28 days prior to testing to allow for adequate hydration and strength development.
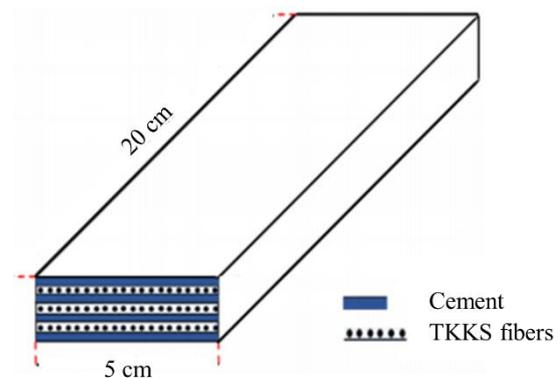

Figure 1. Arrangement of cement paste and TKKS fibers in PRC mixture

D. Flexural Testing

Flexural testing was performed to determine the bending strength, modulus of elasticity, and deflection behavior of PRC specimens. A three-point bending test was conducted using a universal testing machine (UTM) equipped with a load cell appropriate for the specimen size.

The flexural stress σ_f was calculated using the standard bending equation:

$$\sigma_f = \frac{3PL}{2bt^2} \qquad (1)$$

where P is applied load (N), L is span between supports (mm) b is specimen width (mm) and t is specimen thickness (mm).

During testing, the upper fibers of the specimen experienced compressive stress, while the lower fibers underwent tensile stress until failure occurred. Deflection at mid-span was also recorded to evaluate the stiffness and energy absorption capacity of the PRC specimens.

E. Macrostructural Observation

After flexural failure, specimens were examined under a digital microscope to observe fiber–matrix bonding, fiber pull-out, and fracture patterns. These observations provided insight into the influence of fiber length on the composite's internal structure and load transfer mechanisms.

3. Results and Discussion

A. Flexural Performance of PRC

The flexural performance of PRC specimens reinforced with TKKS fibers of varying lengths (3–7 cm) was evaluated using a three-point bending test according to ASTM D790-03 [21]. Each specimen was supported at both ends, and a central load was applied at a constant rate until failure. Figure 2 shows the test setup, illustrating the load application and support positions for accurate bending measurement.

Analysis of the flexural stress (Figure 3) indicates that specimens with 5 cm fibers exhibited the highest flexural strength of 11.78 kg/cm², followed by 3 cm fibers at 10.71 kg/cm². The specimens with longer fibers (6–7 cm) showed slightly lower strength, likely due to fiber entanglement and uneven distribution, consistent with Boimau [10] who observed

similar effects in natural fiber composites. Conversely, shorter fibers (3 cm) provided higher stiffness but reduced ductility. Medium-length fibers (4–5 cm) were found to offer the best balance between strength and flexural performance, in agreement with Suripto et al. [14].

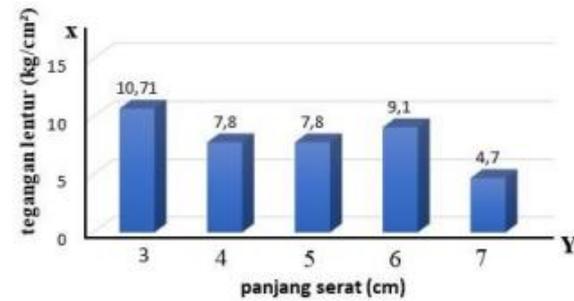Figure 2. Three-point bending test setup for PRC specimens.

Figure 3. Flexural stress of PRC specimens with varying TKKS fiber lengths.

B. Flexural Strain and Modulus of Elasticity

Flexural strain increased with fiber length, reaching a maximum of 10% in 7 cm fiber specimens, whereas 5 cm fiber specimens had the lowest strain at 8.4% (Figure 4). A significant strain increase between 5 cm and 6 cm fibers suggests that longer fibers enhance ductility, allowing the specimen to deform more before failure. However, excessive fiber length may cause localized stress concentrations and slight reductions in ultimate flexural strength [10], [14].

The modulus of elasticity decreased with increasing fiber length (Figure 5). Specimens with 3 cm fibers had the highest stiffness (163 kg/cm²), whereas those with 7 cm fibers exhibited the lowest modulus (155 kg/cm²). These variations are attributed to differences in fiber diameter, manual mixing, and compaction

during specimen preparation, corroborating findings from Alfianti and Wardhono [5]. Medium-length fibers (4–5 cm) optimally balance stiffness and ductility, providing efficient stress transfer and energy absorption.
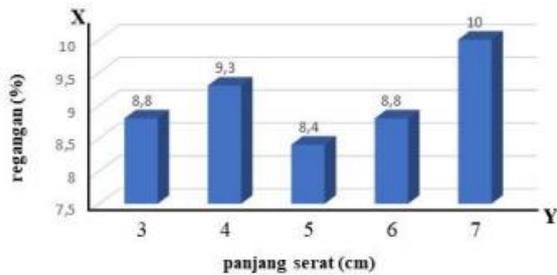

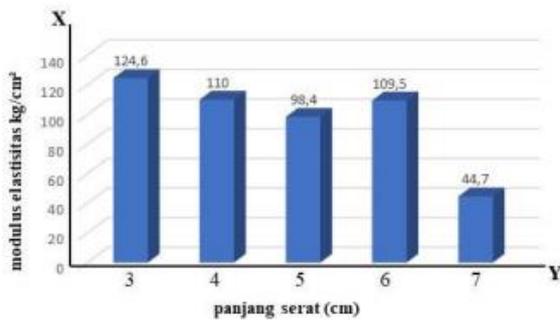Figure 4. Flexural strain of PRC specimens for different fiber lengths.

Figure 5. Modulus of elasticity of PRC specimens with varying fiber lengths.

C. Macrostructural Observations

Macrostructural evaluation using a light microscope at 100× magnification revealed the quality of fiber–matrix bonding and fracture patterns.

For 3 cm fibers, strong bonding was observed with no fiber breakage, which correlates with the high modulus of elasticity (Figure 6). In 4 cm fiber specimens, bonding was generally good, but localized fiber-poor areas led to off-center fractures, suggesting non-uniform fiber dispersion during mixing (Figure 7).

Figure 6. Macrostructure of PRC with 3 cm fibers, showing intact fiber–matrix bonding (100× magnification).

Specimens with 5 cm fibers displayed partial fiber breakage, where larger-diameter fibers resisted fracture, explaining the highest flexural strength observed (Figure 8). For 6–7 cm fibers, the fibers remained largely intact with good matrix adhesion, enhancing ductility but slightly reducing ultimate flexural strength due to fiber entanglement (Figures 9–10). These observations confirm that medium-length fibers optimize stress transfer, while short fibers increase stiffness and longer fibers enhance strain capacity, aligning with prior studies [10], [14], [15], [16].

Figure 7. Macrostructure of PRC with 4 cm fibers, indicating good bonding with minor fiber-poor regions (100× magnification).

Figure 8. Macrostructure of PRC with 5 cm fibers, showing partial fiber breakage and strong adhesion (100× magnification).

Figure 9. Macrostructure of PRC with 6 cm fibers, indicating intact fibers and good bonding (100× magnification).

D. Summary of Mechanical Properties

A summary of flexural stress, strain, and modulus of elasticity for all fiber lengths is presented in Table 2, providing a clear comparison of mechanical performance. Medium-length fibers (4–5 cm) consistently

exhibit optimal strength and moderate strain, supporting the selection of this fiber length for practical PRC applications.

Figure 10. Macrostructure of PRC with 6 cm fibers, indicating intact fibers and good bonding (100× magnification).

Table 2. Flexural stress, strain, and modulus of elasticity of PRC specimens with varying TKKS fiber lengths.

Fiber Length (cm)	Flexural Stress (kg/cm²)	Flexural Strain (%)	Modulus of Elasticity (kg/cm²)
3	10.71	8.6	163
4	11.12	8.9	162.2
5	11.78	8.4	160
6	10.9	9.5	158
7	10.45	10	155

The results indicate that fiber length significantly influences the flexural performance and macrostructural behavior of PRC. Medium-length fibers (4–5 cm) achieved the best combination of flexural strength and stiffness, which can be attributed to the optimal fiber–matrix interaction. This length allows sufficient fiber overlap to effectively transfer tensile stress from the matrix to the fibers, enhancing load-bearing capacity, as reported in other natural fiber-reinforced composites [10], [14], [15].

Short fibers (3 cm) provided higher modulus but slightly lower ultimate flexural strength due to insufficient fiber bridging across cracks, limiting energy dissipation. Conversely, longer fibers (6–7 cm) increased ductility and strain capacity but slightly reduced flexural strength due to fiber entanglement and non-uniform dispersion during mixing, which aligns with findings from Boimau [10] and Purboputro [15] regarding fiber length effects on stress distribution.

Macrostructural analysis confirmed these interpretations. Specimens with medium-length fibers exhibited strong fiber–matrix bonding and partial fiber breakage, indicating effective stress transfer. Short fibers maintained fiber integrity but with limited crack-bridging efficiency, while longer fibers enhanced post-cracking deformation but reduced peak stress due to local stress concentrations. These observations highlight the importance of controlling fiber length and distribution during PRC fabrication to optimize both strength and ductility.

Overall, the results suggest that careful selection of fiber length can balance stiffness, strength, and ductility, improving the performance of sustainable concrete alternatives such as PRC. These findings are consistent with previous studies on natural fiber composites [14], [15], [16] and support the potential for TKKS fibers to replace conventional glass fibers in environmentally friendly building materials.

4. Conclusion

This study demonstrates that the length of Oil Palm Empty Fruit Bunch (TKKS) fibers significantly influences the mechanical behavior and macrostructure of Palmfiber Reinforced Concrete (PRC). Experimental results indicate that medium-length fibers, specifically 4–5 cm, provide the optimal balance between flexural strength, modulus of elasticity, and strain capacity. These fibers exhibit effective fiber–matrix bonding and partial fiber breakage, which facilitates efficient stress transfer and crack bridging, resulting in superior overall performance compared to shorter or longer fibers.

Short fibers, such as those 3 cm in length, enhance stiffness but show limited ductility and energy absorption, reducing their ability to resist crack propagation. On the other hand, longer fibers, 6–7 cm in length, increase ductility and flexural strain, yet may reduce ultimate strength due to fiber entanglement and uneven distribution within the concrete matrix. Macrostructural observations support these findings, confirming that medium-length fibers provide the most consistent fiber–matrix interaction, while extremes in fiber length produce either stiffness-dominant or ductility-dominant behavior.

The results of this study highlight the importance of carefully selecting and controlling fiber length and distribution during PRC production to ensure consistent and

reliable mechanical performance. Overall, TKKS fibers offer a sustainable, environmentally friendly alternative to conventional glass fibers, providing potential benefits in reducing industrial waste, lowering production costs, and enhancing the performance of lightweight concrete in construction applications.

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