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Engineering Properties of Cement-Paste with Polypropylene and Carbon Fibres

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ABSTRACT

Concrete has strong compressive strength, but it is brittle and vulnerable to tension-induced failure. To address the issue, this research investigated the effect of the addition of fibre on the engineering properties of cement paste. There were two fibres examined in this study, which include polypropylene fibre (PF) and carbon fibre (CF). The engineering properties that were studied include flowability, hardened density, compressive strength, and flexural strength at 7, 28, and 56 days. The results indicated that the addition of fibre had only subtle effects on workability, attributed to a judiciously chosen low-volume fraction of fibres. Notably, a consistent increase in hardened density, compressive strength, and flexural strength was observed over the curing period, driven by ongoing hydration processes. Therefore, it can be concluded that the incorporation of PF and CF significantly improved cement paste engineering properties, outperforming the control specimen in hardened density, compressive strength, and flexural strength.

1. Introduction

Concrete is a widely used construction material due to its strength, durability, and versatility. It consists of Portland cement, water, and aggregate. Despite of high compressive strength, concrete is brittle and prone to tension-induced failure. To address these concerns, engineers turn to fibre-reinforced concrete (FRC), where various fibres (steel, synthetic, or natural) are evenly dispersed throughout the mixture. FRC combines the benefits of traditional concrete with enhanced strength and durability from the fibres. In this study, two (2) fibres were studied which include Polypropylene fibre and Carbon fibre.

Polypropylene fibre is a white, translucent, lightweight, and low friction polymer synthetic fibre. It is widely used in various industries, including chemical engineering, energy, clothing, environmental protection, and construction. It was discovered that the incorporation of polypropylene fibres into the concrete mixtures resulted in an improved tensile strength, ductility,

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and flexural strength of the concrete while mitigating the formation of cracks [1-4]. This reinforcement mechanism acts as a bridge across potential microcracks, improving the concrete's ability to withstand tensile and bending stresses. However, the addition of fibre reduced the workability of the concrete because the fibre obstructed the movement of the fresh concrete mix [1,2]. This can be overcome by using low fibre content below 1% in the concrete mix [3,5]. As a result, the use of polypropylene fibres into concrete offers a reliable solution to enhance its mechanical performance, making it well-suited for a range of construction applications.

Carbon fibre is a material consisting of thin strands of carbon. Generally, the fibres have high elastic modulus and tensile strength, good chemical stabilities, and high thermal and electrical conductivities [6]. Thus, when the fibres are added to concrete, the compressive strength, flexural strength, tensile strength, and resistance to cracking are improved [7,8]. According to Paul *et al.,* [9], the strength improvement in concrete was because the fibre acted as a bridge material that keep the concrete particles near to another. However, the addition of fibres reduced the slump of the concrete [10-13]. This was because the flow of fresh concrete was restricted by the presence of carbon fibre [14].

The present study aimed to investigate the effects of polypropylene fibres and carbon fibres on the engineering properties of cement-paste. First, the diameter and surface topography of the fibres were examined. Then, the flowability, hardened density, and compressive strength, and flexural strength at 7th, 28th, and 56th days of the cement paste containing polypropylene and carbon fibres were investigated.

2. Methodology

2.1 Materials

The cement-paste in this research was made up locally available materials which include Ordinary Portland Cement (OPC), polypropylene fibre, carbon fibre, and water. All materials were retrieved from local suppliers in Kota Kinabalu. The physical appearance of OPC, polypropylene fibre, and carbon fibre are shown in Figure 1(a), 1(b), and 1(c), respectively.

(a) (b) (c)

Fig. 1. Physical appearance of raw materials (a) OPC (b) Polypropylene Fibre (c) Carbon Fibre

2.2 Research Methodology

The diameter and surface topography of the fibres were determined by using Field Emission Scanning Electron Microscopy (FESEM). It was conducted at Pusat Instrumentasi dan Perkhidmatan Sains (PIPS), Universiti Malaysia Sabah.

Meanwhile, the engineering properties of the cement paste were determined based on four (4) tests which include flowability, hardened density, compressive strength, and flexural strength. All these 4 tests followed procedures stated in ASTM C1437, BS EN 1015, ASTM C109, and ASTM C348, respectively. For the hardened density and compressive strength test, the cement paste was prepared in 50 x 50 x 50 mm3 mold, meanwhile the cement paste for the flexural strength test was prepared in 40 x 40 x 160 mm3 mold. The samples were cured for 7 and 28 days.

The flowability, hardened density, and compressive strength test were conducted at Concrete and Material Laboratory, Universiti Malaysia Sabah (UMS). Meanwhile the flexural strength was carried out at the Faculty of Tropical Forestry, UMS. Figure 2 shows the equipment used in this research.

(a) (b) (c) (d)

Fig. 2. (a) Flowability Test (b) Hardened Density Test (c) Compressive Strength Test and (d) Flexural Strength Test

There were three (3) specimens in this study which include Control (cement paste without fibre), PF (cement paste with Polypropylene fibre), and CF (cement paste with Carbon fibre). The mix designs of the specimens are presented in Table 1. The water/cement ratio was fixed at 0.30. The weight of cement, water and the fibres were 0.778, 0.233, and 0.003, respectively. The Control specimen was mixed in accordance to ASTM C305 [15], meanwhile the PF and CF specimens were mixed according to Gao *et al.,* [16].

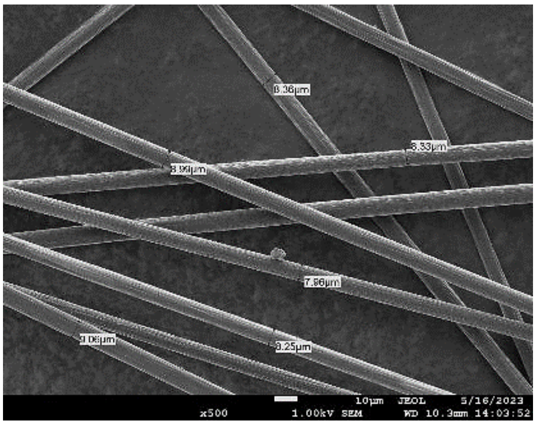
Table 1
Mixture Proportions of Specimen

Specimens	Mixture Proportions			
	Water/cement ratio	Cement (kg)	Water (kg)	Fibre content (kg)
Control	0.30	0.778	0.233	0
PF	0.30	0.778	0.233	0.003
CF	0.30	0.778	0.233	0.003

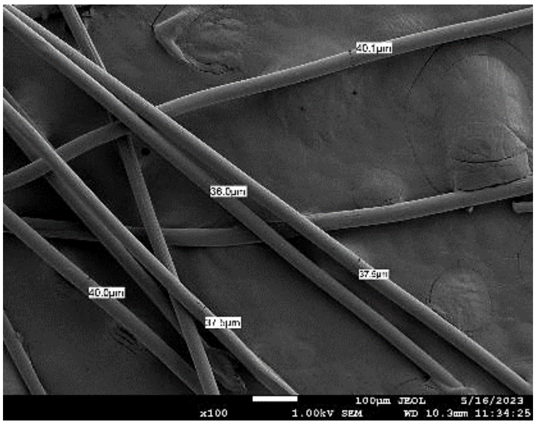
3. Results
3.1 Microstructural Properties of Fibre

Figure 3(a) and (b) shows the diameter of PF and CF, respectively. It was determined that the diameter range of the PF was between 7.96 µm to 9.06 µm, while the diameter for CF was between 36.00 µm to 40.01 µm.

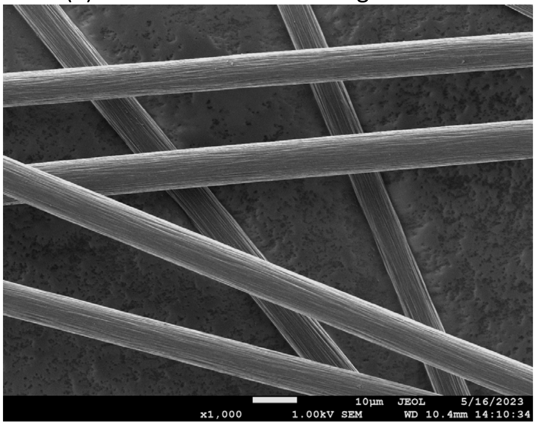
Meanwhile, the surface topography of PF and CF are illustrated in Figure 3(c) and (d), correspondingly. Surface defects and roughness were considered almost negligible in both fibres. It was also observed that CF had more ridges than PF. This observation is consistent with Hu & Ma, [17] who stated that the PF's surface was smooth. Meanwhile, CF had more groves as stated by Tian *et al.,* [18].



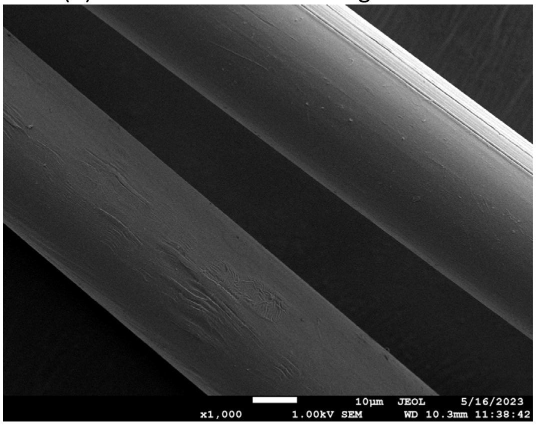
(a) PF diameter at 500x magnification



(b) CF Diameter at x100 magnification



(c) PF at x1000 magnification



(d) CF x1000 magnification

Fig. 3. SEM images of PF and CF fibres

3.2 Flowability of Cement-Paste

The flowability of cement paste is a crucial parameter that governs its ease of handling, placement, and subsequent consolidation. In this study, the flow diameter of Control, PF, and CF was measured to evaluate the impact of fibre reinforcement on workability.

The Control specimen exhibited a flow diameter of 20.5 cm, while both PF and CF specimens displayed slightly reduced flow diameters of 20.4 cm, as shown in Figure 4 This suggests that the the initial workability of fibre-reinforced cement paste was comparable to control specimen, which is consistent with past studies [1,6,10].

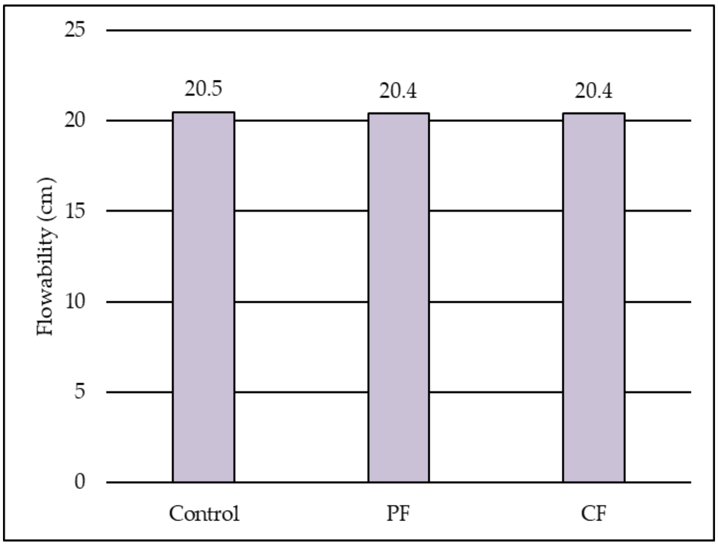


Fig. 4. Flowability of specimens

The observed consistency in flow diameter between the control and fibre-reinforced specimens can be attributed to the relatively low volume fraction of fibres employed in this study. The volume fraction was carefully selected to balance the enhancement of mechanical properties with the potential detriment to workability. This is to ensure the fibres did not dominate the rheological behaviour of the mix, thus minimising their impact on workability.

In comparison, the control specimen exhibited slightly higher flowability than PF and CF due to the absence of fibres. The absence of fibres minimised internal friction, allowing the cement particles to slide past each other more easily [19,20]. This resulted in a slightly larger flow diameter for the control specimen. The fibres in PF and CF introduced additional frictional interactions between the particles, which hindered the flow and thus a marginally a marginally smaller flow diameter.

3.3 Hardened Density of Cement-Paste

Hardened density reflects the compactness and internal structure of cementitious materials after the curing process. In this study, the hardened density of the cement paste samples was measured at 7th, 28th, and 56th days to assess the impact of fibre reinforcement on the density development over time.

The hardened density of all three specimens increased with time as shown in Figure 5, which is consistent with the previous literature [1,2,11,21-23]. Furthermore, hardened density of the cement paste is influenced by length of curing period [24]. The cement particles react with water to form hydration products as the curing process goes on, thus reduced pore volume and increased material density as hydration progressed. It was also discovered that the addition of fibres increased the hardened density of cement paste. The CF specimen had the highest hardened density at the 56th day, followed by CF, and control specimen.

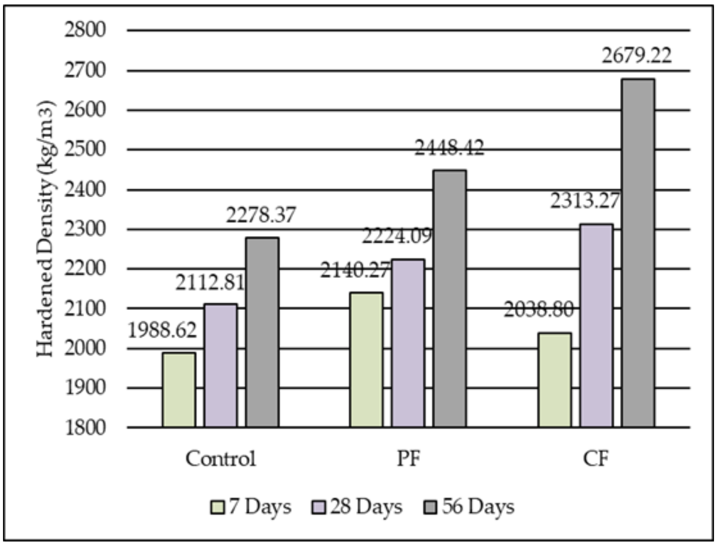


Fig. 5. Hardened density of specimens

The density of concrete is an important factor that affects its mechanical properties, such as compressive strength and durability [22]. The denser the concrete, the higher its compressive strength and durability. The addition of fibres created more interconnected structure by filing up the voids, which reduced the porosity and improved density and compactness of the cement paste [1,2,11,23].

3.4 Compressive Strength of Cement-Paste

Compressive strength assesses the ability of a material to withstand axial loads without failure. The compressive strength for the control, PF, and CF specimen were recorded at day 7, 28 and 56 of curing, as shown in Figure 6. The compressive strength of all three (3) specimens increased with time, which is consistent with the past literature [2,22,23].

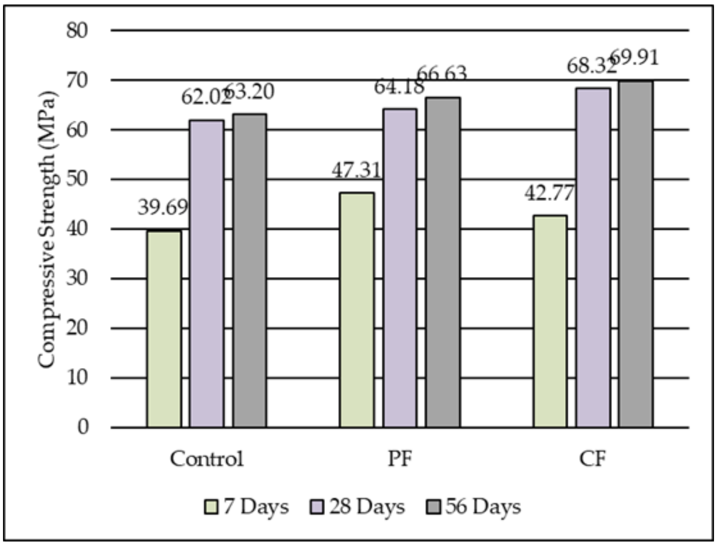


Fig. 6. Compressive strength of specimens

The PF and CF specimens exhibited higher compressive strength than the control specimen for all curing periods. CF demonstrated the highest the highest compressive strength at 28 days and 56 days, while PF the highest compressive strength at 7 days. This indicated that the fibres contributed to the mechanical properties of cement paste which is consistent with previous literature [2,23]. The higher compressive strengths observed in the PF and CF specimens can be attributed to the fibre-matrix interaction. Fibres in the cementitious matrix arrest the propagation of cracks, leading to multiple crack paths and a higher load-bearing capacity [5].

3.5 Flexural Strength of Cement-Paste

Flexural strength reflects a material's ability to withstand bending and tensile stresses. This section discussed the flexural strength for Control, PF, and CF at days 7, 28, and 56 as shown in Figure 7. It is observed that the flexural strength of all specimens increased with time, which is consistent with previous literature [2,22,23].

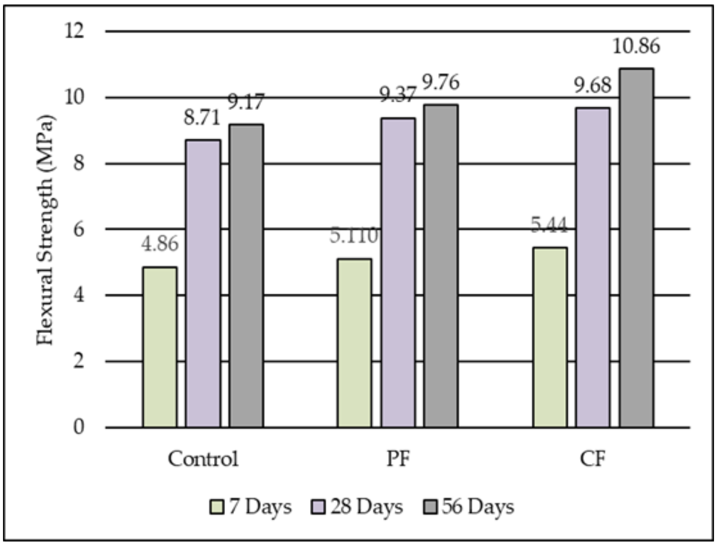
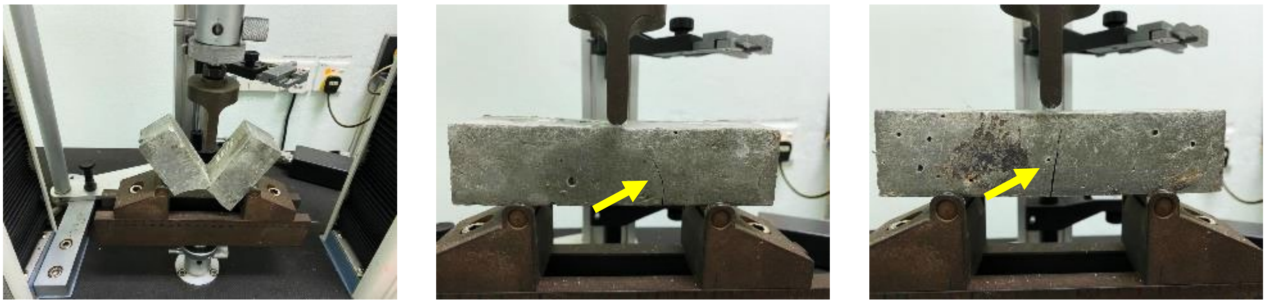


Fig. 7. Flexural strength of specimens

The flexural strength dynamics of the specimens unfolded over the 7th, 28th, and 56th days, revealing the interplay between fibre reinforcement and curing duration. At the 7th day, the CF specimen had higher flexural strength, compared to PF and Control specimens. As curing progressed, all specimen demonstrated strength increased and emphasized fibre-matrix interaction benefits for PF and CF specimens. At the 56th day, CF specimen exhibited the highest flexural strength. This nuanced relationship underscores the intricate influence of fibre and its distribution on the evolving flexural properties of the cementitious samples.

The state of the Control, CF, and PF specimens upon failure is depicted in Figure 8. It demonstrates that the Control specimen split in half after failing, whereas a little crack was seen in the CF and PF specimens. This proves that the fibres keep the cement mixture together to stop the crack from getting bigger.



(a) (b) (c)

Fig. 8. Condition of the (a) Control (b) PF and (c) CF specimens for Flexural strength test after failure

Fibre reinforcement plays a crucial role in enhancing flexural strength by bridging microcracks, resisting crack propagation, and improving load distribution [1,2,11,23]. As fibres in the reinforced specimens become better integrated and aligned within the matrix over time, the fibre-reinforced specimens surpass the control in terms of flexural strength.

4. Conclusions

The study examined the effects of incorporating polypropylene and carbon fibres on the engineering properties of cement paste. Based on the results, the following conclusions are drawn:

i. The addition of PF and CF marginally affected the flowability of cement paste. But the flow diameters were comparable to control specimens.
ii. The hardened density, compressive strength and flexural strength of all specimens increased consistently with longer curing periods driven by ongoing hydration processes that reduce pore volume and increase material density.
iii. Incorporation of PF and CF significantly improved cement paste engineering properties, outperforming control specimen in hardened density, compressive strength, and flexural strength.
iv. This underscores the potential of polypropylene and carbon fibres to enhance engineering properties of cement-paste.

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