Effect of Graphene Quantum Dots (GQDs) on the Mechanical Properties of Polypropylene Fiber-Reinforced Concrete

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Abstract

This study aims to explore the impact of incorporating graphene quantum dots (GQDs) into fiber-reinforced concrete (FRC) to enhance its mechanical performance. In the experiment, FRC mixtures were prepared with polypropylene (PP) fiber contents of 0.5% and 1.5% by volume, while a fixed dosage of 0.3% GQDs by cement weight was added to assess their influence. A total of 30 specimens, consisting of cylindrical and beam-shaped samples, were prepared and cured for 28 days. Compressive and flexural tests were performed to evaluate critical mechanical properties, including compressive strength, elastic modulus, flexural strength, and flexural toughness factor. Results indicated that the addition of 0.3% GQDs increased compressive strength by 13.1%, flexural strength by 23.1%, and flexural toughness factor by 25.2%, compared to the mix without GQDs. The findings provide insights into the combined effects of GQDs and PP fibers on enhancing the mechanical performance of FRC, offering potential for advanced construction materials.

Keywords**:** Graphene quantum dots, Fiber-reinforced concrete, Polypropylene fibers, Mechanical performance.

1. Introduction

Concrete is extensively used in the construction industry due to its high compressive strength, durability, and cost-effectiveness [1,2]. However, conventional concrete has inherent limitations such as low tensile strength, brittleness, and a tendency to crack under stress [3], which can significantly reduce the durability and lifespan of structures. To mitigate these issues, fiber-reinforced concrete (FRC) has been introduced, incorporating fiber into the concrete matrix to improve tensile strength, crack resistance, toughness, and overall mechanical performance. Among various types of fibers, polypropylene (PP) fiber has become a popular material used in the concrete industry due to its unique characteristics [4], including chemical resistance, thermal stability, and cost-effectiveness [5]. Despite these advantages, polypropylene fiber-reinforced concrete (PP-FRC) still exhibits weaker mechanical properties compared to concrete reinforced with steel or glass fibers, limiting its use in high-performance structural applications [6,7]. Therefore, further research incorporating nanotechnology, such as graphene quantum dots (GQDs), is necessary to enhance the performance of FRC at the microstructural level [8-11].

Recent advancements highlight GQDs as innovative nanomaterials for improving concrete performance. GQDs, nanoscale carbon particles composed of one or few graphene layers, have excellent dispersibility in aqueous solutions due to their hydrophilic nature, making them highly compatible with cementitious matrices. Raj et al. [9] demonstrated that incorporating GQDs at an optimal dosage of 0.3% significantly improved the mechanical properties of normal concrete. Their findings showed increases of 10.8% in compressive strength, 23% in split tensile strength, and 11% in flexural strength. These improvements are primarily attributed to matrix densification caused by increased formation of calcium silicate hydrate (C-S-H) gel. Consequently, GQDs emerge as promising additives for enhancing FRC performance, particularly in applications exposed to harsh environments where superior long-term durability is essential.

Integrating fiber reinforcement with nanotechnology offers the potential to enhance concrete performance by achieving improvements at both the macro and micro levels. Fibers provide the essential structural reinforcement, while nanomaterial like GQDs strengthen the internal matrix at the nano level, effectively addressing limitations that fibers alone cannot overcome. However, gaps in understanding the mechanical behavior of this integrated system remain. Therefore, further research is necessary to explore, optimize, and validate this combined approach. Advancing this field could lead to the development of next-generation concrete.

The objective of this study is to explore the benefits of integrating GQDs into PP-FRC, focusing on enhancing its mechanical performance. Experimental investigations were conducted to evaluate the effects of incorporating a fixed dosage of 0.3% GQDs by cement weight into FRC mixtures containing PP fibers at 0.5% and 1.5% by volume. The study specifically assessed critical mechanical properties, including compressive strength, elastic modulus, flexural strength, and flexural toughness factor. The outcome of this investigation aims to optimize the combined use of GQDs and PP fibers, providing valuable insights for developing advanced, durable, and sustainable construction materials suitable for modern infrastructure requirements.

2. Materials and experimental investigations

2.1 Materials

This study utilized hydraulic cement with a specific gravity of 3.05 as the primary binder, conforming to ASTM C1157 [12]. The fine aggregate was well graded natural sand with a specific gravity of 2.62, while the coarse aggregate had a specific gravity of 2.70. To improve the workability of the concrete, a high-range water-reducing superplasticizer was used. This superplasticizer, conforming to ASTM C494 Type F and G, was obtained from Sika in Thailand and had a specific gravity of 1.215.

2.2 Graphene quantum dots

GQDs are synthesized by CrystalLyte Co., Ltd. The GC86s (liquid GQDs) are patented under the number WO2024147021A1, registered with the World Intellectual Property Organization (WIPO) under the Patent Cooperation Treaty (PCT). These GQDs contain approximately 6.6% carbon by weight and exhibit fluorescence properties, with an excitation wavelength of 365 nm and an emission wavelength of 465 nm ± 10 nm. The GQD used is shown in Fig. 1.

Fig. 1 Graphene Quantum Dots (GQDs).

2.3 Polypropylene fiber

PP fibers with a fiber length of 48 mm, as shown in Fig. 2, were used to produce FRC in this study. These fibers are specifically optimized for precast, paving, and flooring applications. The PP fibers used in this study exhibited a tensile strength of 640 MPa and an elastic modulus of 12 GPa, contributing to enhanced tensile resistance and structural integrity. The mechanical and physical properties of the PP fibers, as provided by the manufacturer, are detailed in Table 1.

Table 1 Fiber properties.

Fiber	Properties
Tensile Strength	640 MPa
Young's Modulus	12 GPa
Length	48 mm
Anchorage	Continuous embossing
Base Material	Virgin polypropylene
Alkali Resistance	Excellent

Fig. 2 Polypropylene fiber.

Table 2 Mix proportions of the concrete.

Mix ID	W/C	GQDs (wt. %)	PP Fiber (Vol. %)	Mix proportion (kg/m^3)						Superplasticizer (ml/m^3)	Slump (cm)
				Cement	Sand	Coarse aggregate	Water	GQDs	PP Fiber		
NC-PP0.0	0.31	-	-	470	780	1080	145.0	-	-	11200	22.0
NC-PP0.5	0.31	-	0.5	470	780	1080	145.0	-	4.55	11200	19.0
NC-PP1.5	0.31	-	1.5	470	780	1080	145.0	-	13.65	11200	5.0
GC-PP0.5	0.31	0.3	0.5	470	780	1080	143.7	1.41	4.55	5600	24.0
GC-PP1.5	0.31	0.3	1.5	470	780	1080	143.7	1.41	13.65	5600	4.5

2.4 Mix proportions

Table 2 presents the mix proportions used in this study. A total of five concrete mixtures were prepared, all with a constant water-to-cement (W/C) ratio of 0.31 and identical proportions of cement, sand, and coarse aggregate. The study focused on two main types of concrete: normal concrete (NC) and concrete incorporating GQDs as an additive (GC). Based on previous research [9,10], a GQDs content of 0.3% by weight of cement was selected to achieve optimal performance. Since GQDs consist of 93.4% water, the additional water introduced through the GQDs was accounted for to maintain the target W/C ratio. In addition, previous studies have shown that GQDs influence the fresh properties of concrete, particularly by increasing the slump due to their hydrophilic nature and fluidity-enhancing effects [9,10]. As a result, the dosage of superplasticizer was reduced by 50% in the GQDs mixtures to prevent segregation and maintain a uniform concrete matrix.

To assess the effects of GQDs in FRC, PP fibers were incorporated into both NC and GC at two different concentrations: 0.5% and 1.5% by volume. NC-PP0.0 was used as the control mix, containing neither fibers nor GQDs. The fiber-reinforced NC mixtures, designated as NC-PP0.5 and NC-PP1.5, included PP fibers at 0.5% and 1.5% by volume, respectively. The GC mixtures incorporated both 0.3% GQDs and PP fibers, designated as GC-PP0.5 and GC-PP1.5, containing PP fibers at 0.5% and 1.5% by volume, respectively.

2.5 Experimental investigations

2.5.1 Compressive strength and elastic modulus test

The compression test was conducted to assess the compressive strength of the concrete in accordance with ASTM C39 [13]. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were prepared as specified by the standard. The specimens were tested at the age of 28 days. During the test, axial deformation of concrete specimens was measured using linear variable differential transducers (LVDTs) to calculate the elastic modulus in accordance with ASTM C469 [14], as shown in Fig. 3. A uniaxial compressive load was applied to the specimens at a controlled rate of 0.25 ± 0.05 MPa/s until failure. Three specimens were tested for each concrete mix, and the average values were reported.

Fig. 3 Compression test.

2.5.2 Flexural tests

The flexural strength of concrete specimens was evaluated using prismatic beams measuring 100 × 100 × 400 mm³, tested under a four-point bending configuration in accordance with ASTM C1609 [15]. As shown in Fig. 4, each specimen was simply supported over a span of 300 mm, with the load applied at two points symmetrically placed at the middle third of the span to induce bending.

Fig. 5 illustrates the experimental setup and instrumentation used for the flexural toughness test. Two LVDTs were installed at mid-span to monitor deflection, while a load cell recorded the applied load. Load and deflection data were continuously recorded during testing to determine both the peak flexural strength and flexural toughness factor—key parameters in evaluating the performance of FRC. Specimens were tested under a constant deflection rate until either failure occurred or a deflection of 2 mm was reached.

Fig. 6 presents a typical load-deflection curve used to analyze the flexural toughness factor, which was calculated using Eq. (1) [16]:

$$\text{Flexural toughness factor} = \frac{T_b}{\delta_{tb}} \times \frac{L}{bh^2} \quad (1)$$

where, T_b is the area under the load-deflection curve up to a deflection of 2 mm, L is the span length, δ_{tb} is the deflection corresponding to $\frac{1}{150}$ of span, b is the width of the specimen, and h is the height of the specimen.

Three specimens were tested for each concrete mix, and the average values of first-peak strength, peak flexural strength, and flexural toughness factor were calculated and reported.

Fig. 4 Flexural toughness test.

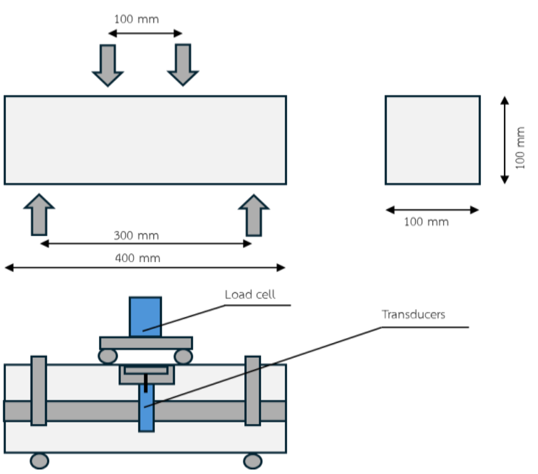

Fig. 5 Test set-up and instruments of flexural toughness test.

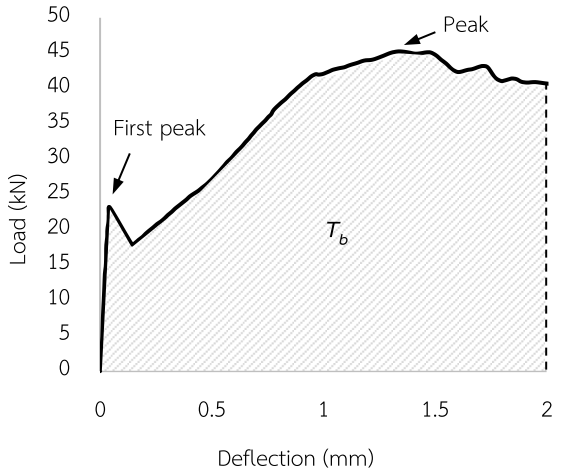

Fig. 6 Example of flexural toughness curve and analysis of the flexural toughness factor.

3. Results and discussions

3.1 Compressive strength

Fig. 7 illustrates the effect of incorporating GQDs on the compressive strength of concrete. Concrete mixes containing liquid GQDs at a constant dosage of 0.3% by cement weight exhibited significantly higher compressive strengths than their normal concrete (NC) counterparts with the same fiber volume.

The GC-PP0.5 mix, which included GQDs, achieved the highest compressive strength of 58.9 MPa, representing an increase of approximately 13.1% compared to the NC-PP0.5 mix without GQDs. Similarly, the GC-PP1.5 mix reached 56.7 MPa, showing a 3.5% improvement over NC-PP1.5, confirming the consistent positive effect of GQDs on compressive performance.

The enhancement in compressive strength can be attributed to the role of GQDs in refining the concrete's microstructure. GQDs serve as nucleation sites that accelerate the crystallization and growth of calcium silicate hydrate (C–S–H) gel during hydration. This leads to a denser microstructure through a significant reduction in the number and size of nano-, meso-, and micro-pores [9,10]. Consequently, the improved integrity of the cement matrix enhances the compressive strength of PP-FRC.

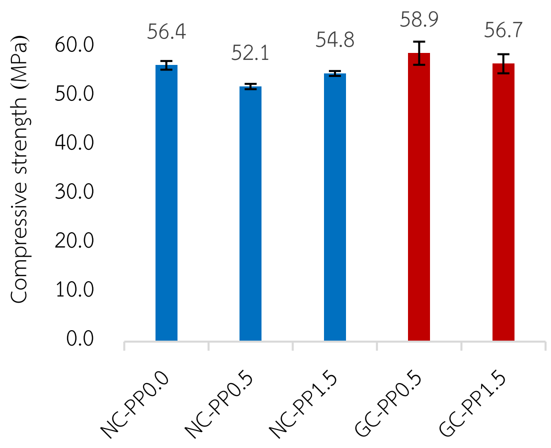

Fig. 7 Results of compressive strengths.

When comparing the present results with those reported by Raj et al. [9], it was found that the improvement in compressive strength due to the addition of 0.3% GQDs in PP-FRC was greater. Raj et al. [9] achieved a compressive strength increase of approximately 10.8%, whereas the present study obtained a higher increase of 13.1%. This suggests that the combined effects of polypropylene fibers and GQDs contribute synergistically to further densify the cementitious matrix, thus enhancing compressive strength more significantly than using GQDs alone.

3.2 Elastic modulus

The results presented in Fig. 8 illustrate the influence of PP fiber incorporation and GQDs on the elastic modulus of concrete. The control mix (NC-PP0.0) achieved the highest elastic modulus at 45.9 GPa. Within the NC series, the inclusion of 0.5% PP fibers (NC-PP0.5) reduced the elastic modulus by approximately 4.4%, bringing it down to 43.9 GPa. However, increasing the fiber content to 1.5% (NC-PP1.5) slightly improved the modulus to 44.6 GPa, narrowing the reduction to about 2.8% relative to the control. This suggests that a higher fiber content may help offset the initial stiffness loss due to limited fiber–matrix interaction at lower fiber dosages.

In contrast to the trends observed in compressive strength, the addition of GQDs had a less pronounced effect on the elastic modulus. The GC-PP0.5 mix exhibited a modulus of 44.2 GPa, which is nearly identical to NC-PP0.5, indicating minimal enhancement from GQD incorporation at this fiber level. More notably, the elastic modulus of GC-PP1.5 dropped to 40.3 GPa, representing a 9.6% decrease compared to NC-PP1.5. This suggests that at higher fiber volumes, the potential stiffening benefits of GQDs may be compromised, possibly due to increased porosity or poor dispersion of fibers and GQDs within the matrix.

Overall, while GQDs positively influence the compressive strength of concrete, their impact on elastic modulus appears to be limited and highly dependent on the fiber content.

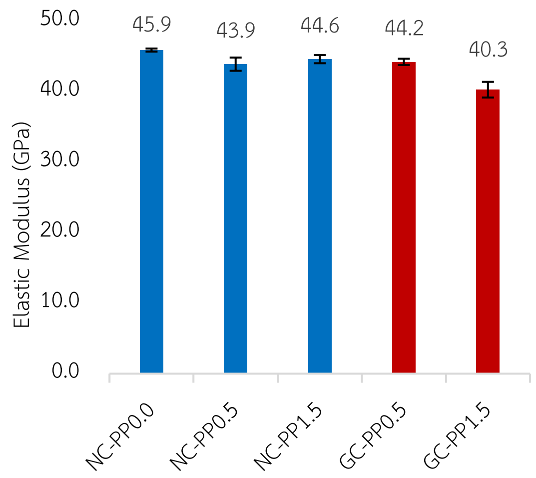

Fig. 8 Results of elastic modulus.

3.3 Flexural strength and flexural toughness factor

The flexural strength results and the load-deflection curve for the various concrete mixes are presented in Table 3 and Fig. 9. The inclusion of PP fibers significantly enhanced the flexural performance of the concrete, particularly in terms of flexural toughness. Adding 0.5% PP fibers increased the flexural toughness factor from 0.47 MPa in the plain mix (NC-PP0.0) to 4.47 MPa, representing an approximate ninefold increase. Increasing the fiber content from 0.5% to 1.5% further improved the overall flexural response.

Although the first-crack strengths of the fiber-reinforced mixes were similar—6.61 to 6.79 MPa—the NC-PP1.5 mix achieved a peak flexural strength of 10.41 MPa, marking a 55.8% increase compared to NC-PP0.5. Correspondingly, the flexural toughness factor of NC-PP1.5 reached 8.15 MPa, an 82.3% improvement over the 0.5% fiber mix. These enhancements are attributed to the crack-bridging effect of PP fibers, which improves ductility and increases energy absorption capacity after cracking [17,18].

Table 3 Flexural strength results.

Mix ID	First-peak strength (MPa)	Peak strength (MPa)	Flexural toughness factor (MPa)
NC-PP0.0	6.61 ± 0.19	6.61 ± 0.19	0.47 ± 0.16
NC-PP0.5	6.68 ± 0.19	6.68 ± 0.19	4.47 ± 0.39
NC-PP1.5	6.79 ± 0.12	10.41 ± 1.51	8.15 ± 1.55
GC-PP0.5	7.22 ± 0.11	7.22 ± 0.11	4.52 ± 0.35
GC-PP1.5	7.64 ± 0.20	12.75 ± 0.90	10.20 ± 0.58

Remark: The experimental results are presented as the mean ± standard error, calculated from three replicate samples.

The addition of GQDs to the fiber-reinforced mixes further improved flexural performance. At the lower fiber dosage (0.5%), GQD incorporation increased the first-crack strength by 8.1% (from 6.68 MPa to 7.22 MPa), although it had negligible effect on post-crack behavior, as the flexural toughness factor remained similar at approximately 4.50 MPa. However, at the higher fiber dosage (1.5%), GQDs led to more substantial improvements. The first-crack strength rose by 12.5% (from 6.79 MPa to 7.64 MPa), and peak flexural strength increased by 22.5% (from 10.41 MPa to 12.75 MPa). As a result, the flexural toughness factor improved by 25.2%, increasing from 8.15 MPa to 10.20 MPa. These improvements are likely due to the nano-reinforcement role of GQDs, which promote more efficient cement hydration and refine the microstructure. This results in a denser matrix with enhanced mechanical interlocking and energy dissipation capacity [8–10].

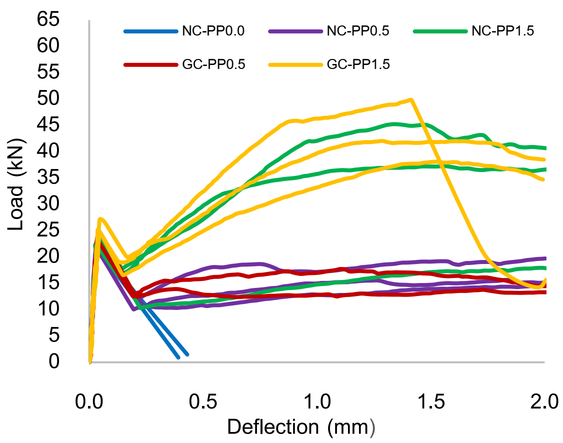

Fig. 9 Load-deflection curve.

Furthermore, the results of the present study showed a notable improvement in flexural strength due to the addition of 0.3% GQDs in combination with polypropylene fibers, achieving a 23.1% increase compared to the control. In contrast, Raj et al. [9], who incorporated GQDs into normal concrete without fiber reinforcement, reported an 11% increase. This suggests that the synergistic effects between GQDs and polypropylene fibers significantly enhance flexural performance, particularly by improving crack-bridging efficiency, ductility, and post-crack toughness.

4. Conclusions

This study investigated the effects of incorporating graphene quantum dots (GQDs) into polypropylene fiber-reinforced concrete (PP-FRC) on its mechanical properties, including compressive strength, elastic modulus, and flexural performance. Based on the experimental results, the following conclusions can be drawn:

(1) The addition of GQDs significantly enhanced the compressive strength of PP-FRC. At a 0.5% fiber dosage, GQDs increased compressive strength by 13.1% compared to the corresponding mix without GQDs. Even at a higher fiber content (1.5%), a 3.5% improvement was observed, confirming the beneficial role of GQDs in improving matrix densification and overall strength.

(2) The incorporation of PP fibers slightly reduced the elastic modulus of concrete. Moreover, the addition of GQDs had a minimal—and in some cases negative—impact on stiffness, particularly at higher fiber volumes. This suggests that the stiffening effect of GQDs may be limited when used in combination with high fiber content.

(3) PP fibers significantly improved the flexural toughness factor of concrete. Increasing the fiber dosage from 0.5% to 1.5% resulted in an 82.3 % increase in the flexural toughness factor, demonstrating the fibers' effectiveness in enhancing post-crack energy absorption and ductility.

(4) The inclusion of GQDs further enhanced the flexural performance of fiber-reinforced concrete, particularly at higher fiber contents. At a 1.5% fiber dosage, GQD incorporation led to increases of 12.5% in first-crack strength, 22.5% in peak flexural strength, and 25.2% in flexural toughness factor compared to the

corresponding non-GQD mix. These improvements are attributed to the nanoscale reinforcement effect of GQDs, which promote hydration and refine the concrete microstructure.

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