Enhancing Cement Mortar Performance with Cornstalk Ash and Graphene Quantum Dots

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Abstract

This study investigates the effects of incorporating cornstalk ash and graphene quantum dots (GQDs) into cement mortar, focusing on flowability, compressive strength, flexural strength, and porosity. Additionally, the total embodied carbon dioxide emissions were assessed. Cornstalk ash was used as a partial cement replacement at 20% by weight, while GQDs were added at varying proportions of 0.3%, 0.6%, 0.9%, and 1.2% by weight of the binder. The results revealed that incorporating 0.3% GQDs significantly enhanced mechanical performance, increasing compressive and flexural strength by 42% and 43%, respectively, compared to the control mixture. In terms of environmental impact, the 0.3% GQD mixture achieved an eco-strength efficiency of up to 81% relative to the control. These findings suggest that the addition of 0.3% GQDs offers an optimal balance between improved mechanical properties and reduced environmental footprint.

Keywords: Cornstalk Ash, Graphene Quantum Dots (GQDs), Cement Mortar, Embodied Carbon Emissions.

1. Introduction

The advancement of civilization and the global industrial revolution have significantly increased atmospheric carbon dioxide (CO_2) levels, rising from 280 ppm in the early 20th century to over 427 ppm by 2024 [1]. This industrial expansion has also fueled the growth of the construction industry, as the increasing demand for infrastructure and urban development is closely linked to socioeconomic progress, leading to the escalation of cement consumption [2]. The production of cement is attributed to contribute over 6 billion tons of carbon emissions annually [3]. To reduce CO_2 emissions, several researchers have attempted to explore effective strategies for discovering replacement materials for cement. One promising approach involves utilizing industrial by-products with pozzolanic properties as supplementary cementitious materials (SCMs) to partially replace cement, thereby decreasing overall cement consumption.

Pozzolanic materials are siliceous or siliceous-aluminous substances with low calcium content that do not possess self-cementing properties in the presence of water. The term 'pozzolanic activity' refers to the ability of SCMs to react with calcium hydroxide in the presence of water, forming additional calcium silicate hydrate (C-S-H) phases, which contribute to the strength and durability of cementitious composites [4]. Previous research [5,6] has shown that partially replacing cement with natural pozzolans or fly ash in small percentages can enhance the mechanical and durability properties of concrete, particularly at later ages. One of the numerous by-products generated from biomass power plants is cornstalk ash, which possesses pozzolanic activity, making it an ideal candidate for use in cementitious systems [7]. However, the use of cornstalk ash as a partial cement replacement has been minimally explored, primarily because this agricultural byproduct is typically disposed of through landfilling or ground burial, contributing to landfill space shortages.

Graphene quantum dots (GQDs) are nanoscale carbon particles composed of one or a few graphene layers. Their hydrophilic properties enable them to be water-soluble and well-dispersed in aqueous solutions, making them particularly advantageous for applications involving water interactions [8]. Win et al. [8] reported that incorporating 0.3% GQDs led to the enhancement of compressive strength and flexural strength due to the enhancement of hydration product, causing an increased amount of C-S-H gels, resulting in refined pore structure within the cement matrix. Thus, the outstanding characteristics of GQDs is the catalytic material, which is a suitable application as an additive material for properties improvement. In addition to enhancing mechanical properties, the utilization of GQDs in cementitious materials also contributes to reducing CO_2 emissions, as reported by Raj et al. [9]. This demonstrates the potential of GQDs in developing eco-friendly construction materials.

To develop high-performance, low-carbon-emission cementing materials that align with the UN sustainability goals, this study explores the incorporation of cornstalk ash and GQDs in cementitious materials. The flowability, mechanical properties, and environmental impact were evaluated. Additionally, the optimal level of GQDs addition was determined. A suitable mixture was proposed in terms of strength and environmental considerations for practical scenarios.

2. Materials and methods

2.1 Materials

The materials used in this study include hydraulic cement, cornstalk ash, fine aggregate, water, and GQDs. The details of these materials are presented as follows:

The hydraulic cement used in this study, illustrated in Fig. 1, complies with the TIS 2594-2566 standard. Its chemical composition consists of CaO (66.0%), SiO_2 (15.5%), Al_2O_3 (3.2%), Fe_2O_3 (2.1%) and SO_3 (2.9%), with specific gravity of 3.04.

Cornstalk ash, shown in Fig. 2(a), was prepared in accordance with ASTM C618 [10] and obtained from the Mae Krating biomass power plant. Its chemical composition consists of SiO_2 (39.0%), CaO (11.7%), K_2O (8.0%), Al_2O_3 (4.9%) and P_2O_5 (2.7%), with specific gravity of 2.35. Fig. 2(b) illustrates scanning electron microscopy image of cornstalk ash.

Fine aggregate used in this study is natural river sand in saturated surface-dry (SSD) with a density of 2550 kg/m³, an absorption rate of 0.7%, and a fineness modulus of 2.4.

GQDs, as illustrated in Fig. 3, are a nanomaterial synthesized via the electrochemical reduction of a saturated CO_2-MEA (monoethanolamine) solution. The density of MEA solution containing GQDs used in the study is 1080 kg/m^3.

2.2 Mixture proportion

The mix proportions are presented in Table 1. Cement is partially replaced with cornstalk ash at 20% by weight of cement, while GQDs are incorporated at varying the dosage ranging from 0.3% to 1.2% by weight of binder. The water-to-binder (W/B) ratio and sand-to-binder ratio (S/B) are maintained 0.6 and 2.75, respectively.

2.3 Cement mortar mixing preparation

The mixing procedure of the cement mortar involved four steps. First, the dry components, including cement and cornstalk ash, were mixed for one minute using a mechanical mortar mixer. Next, water containing GQDs was added and mixed for 30 seconds. After that, sand in a SSD condition was introduced and mixed for two minutes. Finally, the fresh cement mortar was poured into molds and covered with plastic sheets to prevent water evaporation for 24 hours. After demolding, the samples were air-cured until the testing date.

Fig. 1 Hydraulic cement

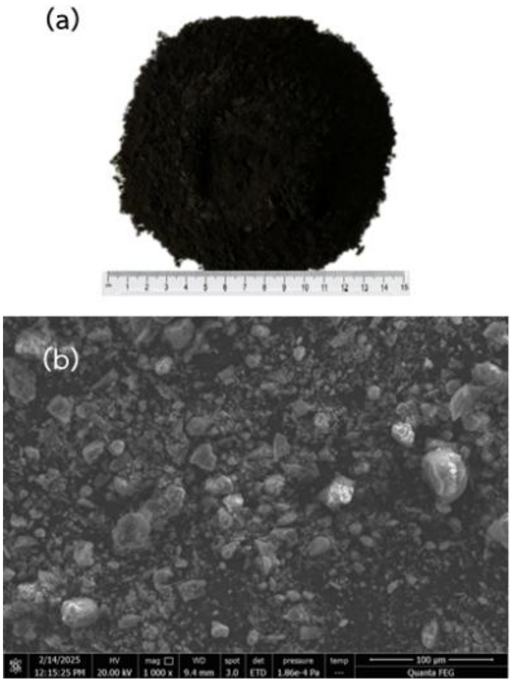

Fig. 2 (a) Cornstalk ash, (b) Scanning electron microscopy imaging of cornstalk ash

Fig. 3 GQDs

Table 1 Mix proportions of cement mortar

Mix	Cement (kg/m^3)	Cornstalk ash (kg/m^3)	Water (kg/m^3)	Sand (kg/m^3)	GQDs (kg/m^3)
C00	507.0	0	306.0	1394.0	-
C20	405.6	75.9	306.0	1394.0	-
C20-GQD0.3	405.6	75.9	306.0	1394.0	1.52
C20-GQD0.6	405.6	75.9	306.0	1394.0	3.04
C20-GQD0.9	405.6	75.9	306.0	1394.0	4.56
C20-GQD1.2	405.6	75.9	306.0	1394.0	6.08

2.4 Experimental investigations

This study examines the effects of incorporating cornstalk ash and GQDs in cement mortar, focusing on both mechanical properties and environmental impact. The mechanical properties investigations, including flowability, compressive strength, flexural strength and porosity, were carried out. In terms of environmental assessment, the total embodied CO_2 emission and eco-strength efficiency were determined.

2.4.1 Flowability

To evaluate the workability of cement mortar, the flowability of mortar was tested according to ASTM C1437 [11].

2.4.2 Compressive strength

The compressive strength of cement mortar was conducted according to ASTM C109 [12]. The three cube of 50×50×50 mm³ were employed in the testing. Curing ages at 7, 14, and 28 days were considered.

2.4.3 Flexural strength

The flexural strength of the mortar was tested in accordance with ASTM C348 [13]. The testing was conducted by using three prism specimens of 40×40×160 mm^3 cured at 28 days.

2.4.4 Porosity

The porosity was determined according to ASTM C642 [14]. The three cubes of 50×50×50 mm^3 were applied for testing. Percentage of Porosity can be calculated in Eq. (1).

$$\text{Porosity (\%)} = [1 - \frac{A-D}{C-D}] \times 100 \qquad (1)$$

where *A* is the mass of the oven-dry sample in air (g); *B* is the mass of the surface-dry sample in air after immersion (g); *C* is the mass of the surface-dry sample in air after immersion and boiling (g); and *D* is the mass of the sample in water after immersion and boiling (g).

2.4.5 Environmental impact assessment

To evaluate the environmental impact, the total equivalent CO_2 emissions and eco-strength efficiency were assessed. The total equivalent CO_2 emissions of cement mortar incorporating cornstalk ash and GQDs were calculated using Eq. (2), with the corresponding CO_2 emission factors presented in Table 2. In terms of both strength and environmental considerations, the eco-strength efficiency was determined using Eq. (3).

$$\text{Total equivalent } CO_2 \text{ emissions} = \sum_{i=1}^{n}(QM \times EFM) \quad (2)$$

$$\text{Eco} - \text{strength efficiency} = \frac{\text{Compressive strength}}{\text{Total equivalent } CO_2 \text{ emissions}} \quad (3)$$

where *QM* is the quantity of material (kg/m^3), *EFM* is the equivalent CO_2 emission factor of material (kg $CO_{2\text{-}e}$/kg).

Table 2 Equivalent CO_2 emission factor

Material	Equivalent CO_2 emission factor (kg $CO_{2\text{-}e}$/kg)
Cement	0.742 [15]
Cornstalk ash	0.008 [16]
GQDs	-0.630 [17]
Sand	0.004 [18]

3. Results and discussions

3.1 Flowability

Fig. 4 presents the flowability of flesh cement mortar. The flow diameter gradually increased with the escalation of GQDs addition levels, compared to the control mixture. Notably, the highest flowability of 119% was observed, which is about 9% increases compared to C20. This is possibly due to the occurrence of hydrophilic properties when GQDs added in the cementitious system [8]. In contrast, C20 exhibits a flowability of 110%, representing a 2% decrease compared to control. This effect possibly occurs because the rough shape of cornstalk ash restricts particle movement, while its porous structure absorbs water, confirmed by microstructural image presented in Fig. 2(b).

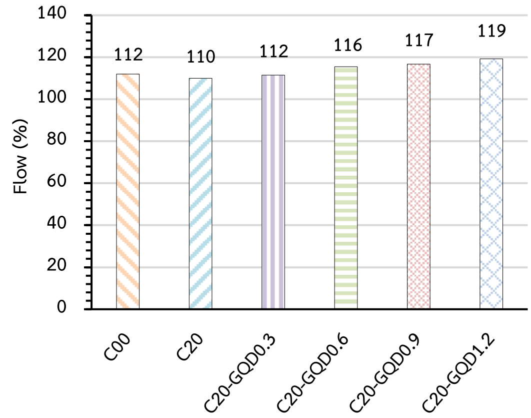

Fig. 4 Flowability of cement mortar

3.2 Compressive strength

Fig. 5 illustrates the compressive strength at 7, 14, and 28 days of cement mortars incorporating cornstalk ash and varying GQDs contents. The results indicate that replacing 20% of the cement with cornstalk ash enhanced the 28-day compressive strength, with C20 exhibiting a slight increase to 30.1 MPa—a 4% improvement over the control. This is primarily attributed to the pozzolanic reaction of cornstalk ash, which contributes to additional C-S-H gel formation [7].

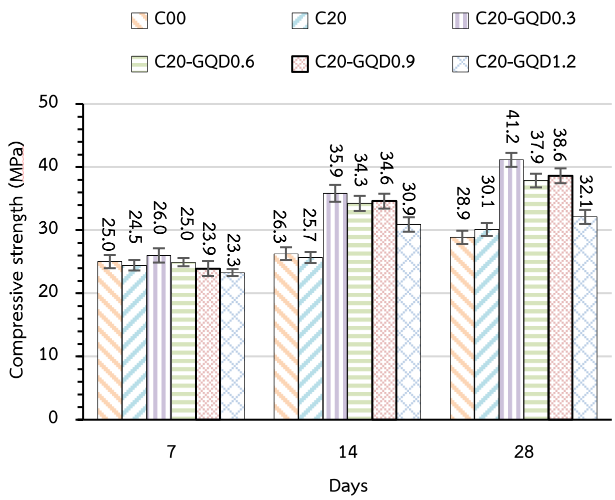

Fig. 5 Compressive strength of cement mortar

Furthermore, incorporating GQDs further enhanced compressive strength, with C20-GQD0.3 achieving the highest value of 41.2 MPa, which represents an increase of 43% compared to the control, indicating an optimal GQDs content is 0.3% by weight of binder. However, exceeding this content led to a reduction in compressive strength. The enhanced compressive strength in C20-GQD0.3 mixtures likely results from accelerated strength development due to improved hydration kinetics due to the presence of GQDs addition. This acceleration enhances the hydration reaction, promoting the formation of C-S-H gels, which significantly contribute to strength improvement [8]. Moreover, GQDs interact with the cement matrix, promoting successive hydration. However, the excessive content of GQDs can block nucleation sites, leading to the inhibition of hydration kinetics, resulting in the decrease of mechanical strength [9].

3.3 Flexural strength

The flexural strength at 28 days of cement mortars incorporating cornstalk ash and GQDs is illustrated in Fig. 6. The results showed that the flexural strength of C20 reached 7.3 MPa, marking a 22% increase over the control mix (C00). This improvement is likely due to the pozzolanic reaction of cornstalk ash, which enhances C-S-H gel formation [7].

Further enhancement was observed in C20-GQD0.3, which achieved a flexural strength of 8.6 MPa—a 43% increase compared to the control. This effect is likely attributed to graphene derivatives, which induce a bridging mechanism similar to microfiber reinforcement, thereby enhancing flexural strength [8]. However, adding GQDs beyond 0.3% by weight of binder resulted in decrease of flexural strength. Exceeding the optimal GQDs dosage of 0.3% by weight of the binder reduces strength, likely due to the blockage of nucleation sites, which inhibits hydration kinetics [9].

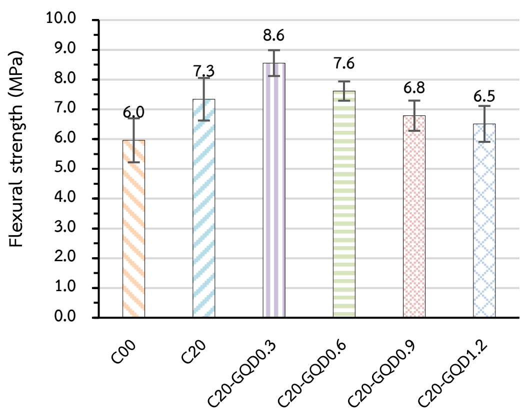

Fig. 6 Flexural strength of cement mortar

3.4 Porosity

Fig. 7 presents the porosity of cement mortar. The results indicate that C20 exhibited a porosity of 17.64%, representing a 3.42% reduction compared to the control. The reduction in porosity is possibly due to the activate pozzolanic reaction in the cementitious system which generates an extra amount of C-S-H.

Additionally, C20-GQD0.3 demonstrated a porosity of 14.7%, corresponding to a 6.36% decrease relative to the control and an approximately 2.94% reduction compared to C20. Adding 0.3% GQDs in mixture can be attributed to the filling effect in cement matrix, leading to compact microstructure [8]. On the other hand, incorporating GQDs beyond 0.3% led to a gradual increase in porosity, possibly due to the formation of entrapped air voids, which contributed to the overall porosity.

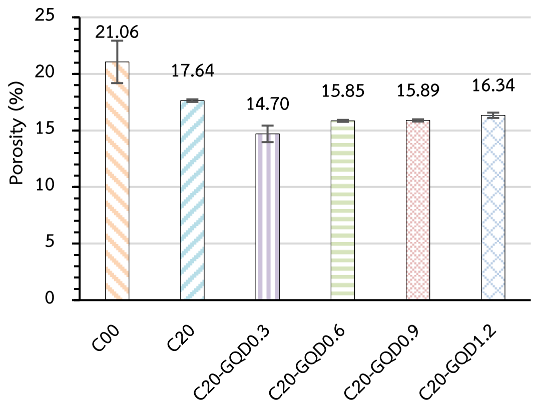

Fig. 7 Porosity of cement mortar

3.5 Environmental impact evaluation

Fig. 8 and Fig. 9 illustrate the total embodied carbon emissions and eco-strength efficiency, respectively. The results indicate that incorporating cornstalk ash as a partial binder replacement in cement contributed to a reduction in total embodied carbon emissions due to the decreased cement usage in the cementitious system. Meanwhile, the addition of GQDs, a carbon-negative material, resulted in a slight reduction, likely due to the limited quantity incorporated [9].

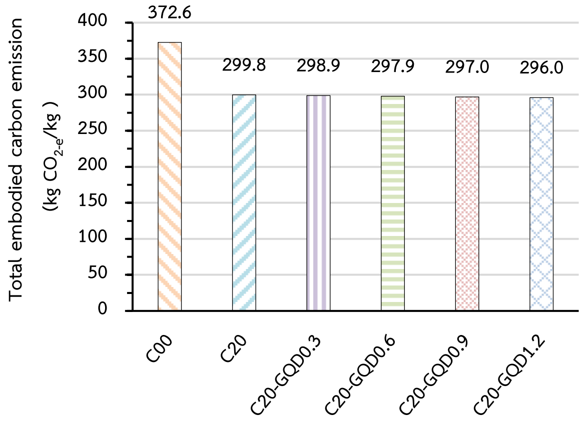

Fig. 8 Total embodied carbon emission

In aspect of strength and environmental considerations, the eco-strength efficiency of C20-GQD0.3 is 82% higher compared to the control. Therefore, it could be concluded that C20-GQD0.3 is identified as the most optimal mixture in aspect of strength and environment. This presents an effective approach for developing eco-friendly construction materials in practical applications.

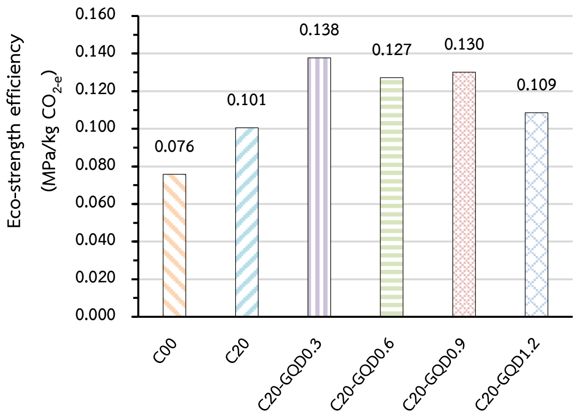

Fig. 9 Eco-strength efficiency

4. Conclusions

The study investigates the effects of incorporating cornstalk ash and GQDs in cement mortar, focusing on flowability. mechanical properties, and environmental impact. Additionally, incorporating 20% cornstalk ash and 0.3% GQDs significantly improved mechanical performance, increasing compressive and flexural strength by 42% and 43%, respectively. Furthermore, the addition of GQDs at 0.3% contributed to a reduction in porosity due to the filling effect within the cement matrix, resulting in a more compact microstructure. However, higher GQDs dosages beyond 0.3% negatively affected strength development due to nucleation site blockage. The eco-strength efficiency analysis indicated that the incorporation of 20% cornstalk ash and 0.3% GQDs achieved the optimal balance between mechanical performance and environmental impact. Therefore, it can be considered a suitable approach for the development of eco-friendly construction materials.

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