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Original Research Article

Partial Replacement of Cement with Carbon Powder in Concrete

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ABSTRACT

The high carbon footprint associated with Portland cement production has intensified the search for sustainable supplementary cementitious materials for concrete. This study investigates the feasibility of using carbon powder (charcoal powder), a biomass-derived waste material, as a partial replacement for cement in concrete. Concrete mixtures were produced with carbon powder replacement levels of 0%, 5%, 10%, 15%, and 20% by weight of cement, using a mix ratio of 1:1.5:3 and a water–cement ratio of 0.45. Experimental investigations included chemical characterization of the carbon powder using X-ray fluorescence analysis, assessment of workability through slump tests, and evaluation of compressive and flexural strengths under normal water curing and lagoon water curing conditions. Results indicate that increasing carbon powder content led to reduced workability and a general decline in mechanical strength. However, concrete incorporating 5% carbon powder demonstrated the most favorable performance among the modified mixes, with acceptable compressive and flexural strengths relative to the control. Higher replacement levels resulted in significant strength reductions due to cement dilution and limited pozzolanic reactivity. The study concludes that carbon powder can be utilized as a partial cement replacement at low levels, offering environmental benefits through waste valorization and reduced cement consumption, particularly for non-structural concrete applications.

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1. INTRODUCTION

Concrete is one of the most widely used construction materials in the world due to its strength, durability, and cost-effectiveness. However, the production of Portland cement, a key ingredient in concrete, contributes significantly to global carbon dioxide (CO_2) emissions, accounting for nearly 8%

of total anthropogenic CO_2 emissions (Scrivener *et al.,* 2018). This has raised concerns about the environmental impact of cement production, prompting the search for sustainable alternatives. One promising approach is the incorporation of supplementary cementitious materials (SCMs) that partially replace Portland cement without compromising the mechanical properties of concrete. Previous studies have shown that concrete incorporating alternative cementitious materials can exhibit adequate mechanical performance when properly proportioned (Abiodun, 2023). Carbon powder (charcoal powder), a byproduct of biomass combustion, has been identified as a potential SCM due to its pozzolanic characteristics and abundance (Chindaprasirt *et al.,* 2020).

The incorporation of carbon powder as a partial cement replacement can provide several benefits, including a reduction in CO_2 emissions, enhancement of concrete durability, and the promotion of waste valorization. Several studies have investigated the potential of biomass-based materials, including rice husk ash, sawdust ash, and fly ash, as cement replacements in concrete (Ashraf *et al.,* 2021). However, the application of carbon powder remains relatively unexplored, necessitating further research to evaluate its feasibility in concrete production. Additionally, the effect of carbon powder on fresh and hardened concrete properties such as workability, setting time, and strength development needs to be systematically analyzed. Understanding the hydration kinetics of carbon powder blended cement and its interaction with other cementitious materials is also essential for ensuring long-term performance.

Furthermore, with the growing global emphasis on sustainability, alternative materials that can partially replace cement in construction must be thoroughly studied and documented. Carbon powder, produced from various organic sources such as wood, agricultural residues, and biomass waste, is abundantly available and often considered a waste material. Utilizing carbon powder in concrete production not only reduces waste disposal issues but also offers an opportunity for industries to incorporate more environmentally friendly materials in construction practices. The possibility of improving the thermal insulation properties of concrete by using carbon powder also presents an additional advantage, particularly in regions with extreme temperature variations.

Incorporating carbon powder into concrete aligns with global sustainability goals by reducing reliance on Portland cement, lowering construction costs, and utilizing waste materials effectively. It also provides a pathway for local industries to leverage agricultural and biomass waste, promoting a circular economy in the construction sector. Therefore, this study aims to comprehensively investigate the properties of carbon powder as a cement replacement material and its potential impact on concrete performance.

2. MATERIALS AND METHODS

2.1. Materials

Materials needed for the research were procured from different but reliable sources. A portion of the charcoal powder was collected and taken to the laboratory for X-Ray Fluorescence Spectroscopy (XRF). The charcoal collection site was at Bariga. The average size of 10mm was ground for use as a partial cement replacement in concrete, typically achieving an average residue of 20 – 25% retained on a 75 µm. In this study, coarse aggregates (granite) ranging from 20 mm down to 12.5 mm aggregate sizes was used according to BS EN 933-2 (2020). For the fine aggregate, Ogun River sand (natural sand), with particle sizes ranging from 0.075 mm to 1.8 mm, was used. The physical properties of the fine aggregate like aggregate size, grading and surface texture were carried out according to BS 882 (1992). Limestone Portland cement, whose production was in accordance to BS EN 197-1 (2011) and classified as CEM II in NIS 444-1 (2003) standard, was used.

2.2. METHODS

2.2.1. X-ray fluorescence (XRF) test

The X-ray fluorescence (XRF) test for carbon powder began with the preparation of the sample. The carbon powder was first dried to eliminate any moisture content and then finely ground to achieve a uniform particle size. Once the powder is adequately processed, it is either pressed into a pellet using a suitable binder or fused into a glass disc, depending on the analysis requirements. Before analyzing the sample, the XRF spectrometer (Philips PW 1830) was calibrated using certified reference materials with known elemental compositions to ensure measurement accuracy. The prepared pellet or disc was then carefully placed in the sample holder of the XRF machine. The instrument exposes the sample to primary X-rays, which excite the atoms within the material. This excitation causes the atoms to emit secondary, or fluorescent, X-rays, each with energy levels characteristic of specific elements. These emitted X-rays are detected by the spectrometer, which processes the data to identify and quantify the elements present in the carbon powder. The resulting spectrum was analyzed against known standards to determine the concentrations of various elements such as silicon, aluminum, iron, calcium, potassium, magnesium, and others. This technique is rapid, non-destructive, and highly effective for the elemental analysis of powdered materials like charcoal.

2.2.2. Design mix

Concrete with a mix ratio of 1:1.5:3 and water cement ratio of 0.45 was adopted in this study. The percentage replacement of carbon powder by weight of cement was varied at 0%, 5%, 10%, 15%, and 20%.

2.2.3. The production of carbon powder concrete

Known weight of fine aggregates, coarse aggregate, cement, and carbon powder was thoroughly mixed together until a homogenous mix was achieved on a clean and impervious platform. Water of a determined quantity was added and mixed together until there was a uniform concrete mix. The freshly prepared concrete was cast into a cube of 150 × 150 ×150 mm, and a concrete beam of 150 mm ×150 mm ×750 mm was well compacted using a manual rod tapping. Afterwards, the cast concrete cubes were cured in water under both normal curing conditions (7, 14, 21, and 28 days) and lagoon water curing (28, 56, and 90 days). The cast concrete beams were cured in water under normal curing conditions for 28, 56, and 90 days. The cured concrete at each particular curing age was brought out of water, weighed, and subjected to specific tests such as compressive and flexural strength tests.

The compressive strength of the samples was then computed and calculated using Equation (1):

$$\mathrm{CS} = \frac{P}{A} \tag{1}$$

Where P is the loading force in N (Newton), A is the area of the concrete in mm^2 and CS is the compressive strength in N/mm^2.

The results were compared to the standards and recommendations according to BS EN 12390-3 (2019). Additionally, Equation (2) was used to determine the concrete's flexural strength:

$$\mathrm{F} = \frac{PL}{bd^2} \tag{2}$$

Where ‘F’ is the Flexural Strength, P’ is the maximum load, ‘L’ is the span length, ‘b’ is the specimen length and ‘d’ is the specimen depth.

The result was expressed in units of force per unit area, typically Newton per square millimeter (N/mm^2). The results were compared to the standards and recommendations according to BS EN 12390-5 (2019).

3. RESULTS AND DISCUSSION

This section contains the results, interpretation, and discussion of values based on the laboratory tests carried out. The results obtained were used to compute tables, charts, and graphs for the presentation as statistical techniques to test for the relatedness of the research objectives, and practical issues were discussed.

3.1. X-Ray Fluorescence Spectroscopy Results

XRF chemical analysis of the carbon powder shows a predominantly calcareous composition with (CaO: 41.996%), (K_2O: 18.243%), (MgO: 8.302%), aluminium oxide (Al_2O_3: 8.318%), silicon dioxide (SiO_2: 9.712%), and smaller amounts of Fe_2O_3, SO_3, and Cl. The high CaO fraction suggests the material is lime-rich and may act as a hydraulic or hydraulic-like filler depending on its mineralogical form; however, the relatively low SiO_2 and Al_2O_3 contents indicate limited intrinsic pozzolanicity compared with standard SCMs (e.g., fly ash).

3.2. Workability of Carbon Powder Concrete

Figure 1 displays the workability of the samples. Slump values of 40 mm, 37 mm, 32 mm, 27 mm, and 24 mm were recorded for 0%, 5%, 10%, 15%, and 20% carbon powder replacement, respectively. The results for slump values revealed that the slump value decreased with an increase in carbon powder. The values of the slump test in this study were lower when compared with the results (55 – 95 mm) obtained by Jimoh *et al.* (2025), who worked on waste clay brick powder as a partial replacement in concrete.

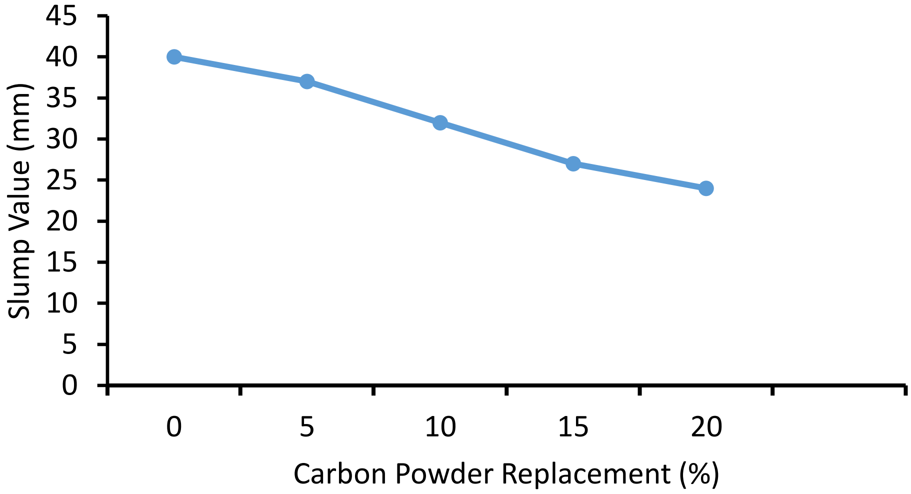

Figure 1: Slump Values of carbon powder concrete

3.3. Compressive Strength of Carbon Powder Concrete

According to Figure 2, the compressive strength behaviour of concrete incorporating carbon powder as partial cement replacement was evaluated at replacement levels of 0%, 5%, 10%, 15%, and 20% under both normal curing conditions (7, 14, 21, and 28 days) and lagoon water curing (28, 56, and 90 days). The results reveal a consistent reduction in compressive strength with increasing carbon powder content across all curing regimes. For specimens cured under normal environmental conditions, the control mix (0% carbon powder) exhibited progressive strength development, achieving compressive strengths of 19.58 N/mm^2, 22.74 N/mm^2, 24.15 N/mm^2, and 25.65 N/mm^2 at 7, 14, 21, and 28 days, respectively. In contrast, carbon powder–modified concrete showed lower strength values at all curing ages, with strength loss becoming more pronounced as the replacement level increased. Among the modified mixes, the 5% replacement level consistently recorded the highest compressive strength, followed by 10% and 15%, while the 20% replacement exhibited the lowest strength performance. This trend confirms that limited incorporation of carbon powder is more favourable for maintaining mechanical performance.

Under lagoon water curing (L), a further reduction in compressive strength was observed for all mixes compared to specimens cured in the normal environment. At 0% replacement, compressive strengths of 17.78 N/mm², 18.00 N/mm², and 18.67 N/mm² were recorded at 28, 56, and 90 days, respectively. At 5% replacement, the corresponding strengths were 9.56 N/mm², 13.41 N/mm², and 13.70 N/mm², while at 10% replacement, values of 9.41 N/mm², 12.30 N/mm², and 13.48 N/mm² were obtained. Higher replacement levels of 15% and 20% resulted in significantly lower strengths, particularly at early curing ages. The reduced performance in lagoon water is attributed to the aggressive nature of the curing medium, which interferes with cement hydration and progressively weakens the cementitious matrix due to chemical attack and microstructural degradation (Mehta and Monteiro, 2014).

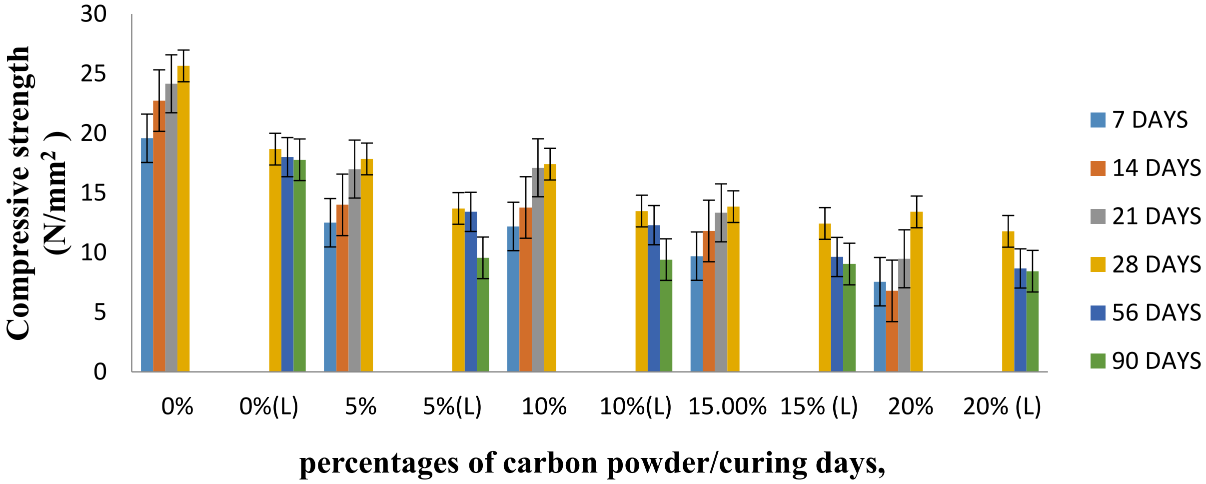

Figure 2: Compressive Strength results of carbon powder concrete

Overall, the results indicate that compressive strength decreases with increasing carbon powder content, and that lower replacement levels (particularly 5%) provide comparatively better performance under both curing environments. The observed strength reduction at higher replacement levels is primarily associated with cement dilution, reduced availability of calcium hydroxide for hydration, and the limited pozzolanic reactivity of carbon powder.

These findings are largely consistent with previous studies. Abalaka and Okoli (2013) and Adekunle *et al.* (2020) similarly reported that concrete containing carbon or charcoal powder exhibited declining compressive strength beyond 10% cement replacement, attributing the reduction to weakened binder continuity and poor early-age hydration. The present study also agrees with Akinwumi and Olofinnade (2015), who observed that low replacement levels (5–10%) can yield compressive strengths comparable to control mixes, while excessive replacement leads to significant strength loss.

However, a partial contradiction exists with studies such as Zhang *et al.* (2021), who reported slight compressive strength enhancement at 5% replacement due to improved particle packing and pozzolanic interaction. In the present study, although the 5% replacement performed best among the modified mixes, it did not exceed the strength of the control concrete. This discrepancy may be attributed to differences in carbon powder source, fineness, chemical composition, and curing conditions, particularly the high alkali and porous nature of the carbon powder used in this study, which may have increased water demand and limited effective hydration.

3.4. Flexural Strength of Carbon Powder Concrete

According to Figure 3, the flexural strength of carbon powder–modified concrete was evaluated to assess the effect of partial cement replacement on the tensile performance of the material. Tests were conducted at carbon powder replacement levels of 0%, 5%, 10%, 15%, and 20% under standard curing conditions at specified curing ages. The results demonstrate a clear reduction in flexural strength with increasing carbon powder content, although the magnitude of reduction varied across replacement levels.

The control mix (0% carbon powder) consistently exhibited the highest flexural strength at all curing ages, reflecting the intact cementitious matrix and optimal bond between cement paste and aggregates. Concrete incorporating carbon powder showed comparatively lower flexural strength values, with the 5% replacement level producing the most favourable performance among the modified mixes. As the replacement level increased beyond 5%, a progressive decline in flexural strength was observed, with the 20% replacement level recording the lowest values.

The improved performance at 5% replacement is attributed to the micro-filler effect of finely ground carbon powder, which may have contributed to partial pore refinement and improved particle packing within the concrete matrix. However, at higher replacement levels, the dilution of cementitious content became dominant, resulting in reduced formation of calcium silicate hydrate (C–S–H) gel and weaker interfacial transition zones. This adversely affected the tensile resistance of the concrete, which is critical in flexural loading conditions.

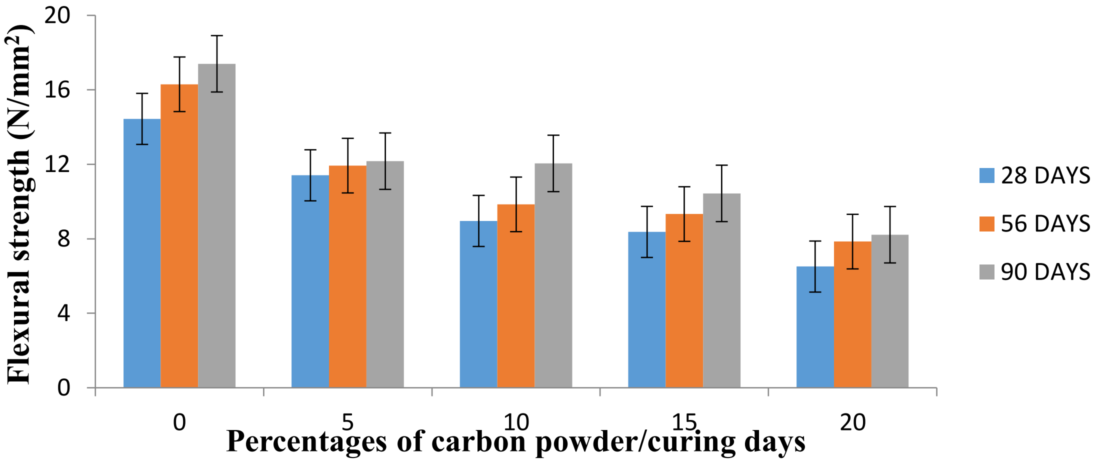

Figure 3: Flexural Strength results of carbon powder concrete

Overall, the flexural strength trends closely mirrored those observed for compressive strength, indicating that carbon powder has limited contribution to tensile load transfer when used beyond low replacement levels. The reduction in flexural strength at higher replacement percentages suggests that excessive carbon powder content compromises the cohesion and crack-bridging capacity of the cement matrix.

The findings of this study are in agreement with earlier investigations. Abalaka and Okoli (2013) reported a similar reduction in flexural strength of concrete incorporating charcoal powder beyond 10% cement replacement, attributing the decline to weakened paste–aggregate bonding. Likewise, Akinwumi and Olofinnade (2015) observed that low-level incorporation (5–10%) of agro-based carbon materials produced flexural strengths comparable to conventional concrete, while higher replacements resulted in significant performance deterioration. These observations align with the present study, particularly regarding the optimum performance at 5% replacement.

4. CONCLUSION

From the experimental program, the following conclusions were derived.

i. X-ray fluorescence (XRF) analysis revealed that the carbon powder is predominantly calcareous, with a high calcium oxide (CaO) content alongside moderate amounts of silica (SiO_2) and alumina (Al_2O_3). Although the relatively low silica and alumina contents indicate limited intrinsic pozzolanic activity compared with conventional supplementary cementitious materials, the chemical composition suggests that carbon powder can function as a filler with potential secondary hydraulic contribution at low replacement levels.

ii. The incorporation of carbon powder resulted in a progressive reduction in concrete workability as the replacement level increased. Slump values decreased from 40 mm for the control mix to 24 mm at 20% replacement, indicating increased water demand due to the porous structure and high surface area of the carbon powder. This reduction in workability highlights the need for mix design modification or the use of admixtures when higher replacement levels are considered.

iii. Compressive strength decreased with increasing carbon powder content under both normal water curing and lagoon water curing conditions. While the control mix consistently achieved the highest strength, concrete containing 5% carbon powder exhibited the best performance among the modified mixes at all curing ages. Higher replacement levels (≥15%) resulted in significant strength reductions, attributed to cement dilution, reduced calcium silicate hydrate (C–S–H) formation, and limited pozzolanic reactivity. Exposure to lagoon water further reduced compressive strength across all mixes, confirming the adverse influence of aggressive curing environments on carbon powder concrete.

iv. Flexural strength followed a trend similar to compressive strength, with strength decreasing as carbon powder content increased. The 5% replacement level consistently recorded the highest flexural strength among the carbon powder concretes, while the 20% replacement level exhibited the lowest values. The marginally improved performance at low replacement levels is attributed to the micro-filler effect and improved particle packing, whereas higher replacements weakened the cementitious matrix and interfacial transition zones, reducing tensile resistance.

v. From both compressive and flexural strength perspectives, carbon powder replacement should be limited to low levels, with 5% identified as the optimum replacement level in this study. At this level, the reduction in strength relative to the control mix was minimal, and acceptable mechanical performance was maintained.

vi. The partial replacement of cement with carbon powder offers environmental benefits by reducing cement consumption and promoting the utilization of biomass-derived waste materials. However, excessive replacement levels compromise mechanical performance and are unsuitable for structural concrete applications.

Overall, the study confirms that carbon powder can be considered a viable supplementary cementitious material at low replacement levels for non-structural and low-load applications. Its use contributes to sustainability goals through waste valorization and reduced carbon footprint, but careful control of replacement percentage and curing conditions is essential to ensure acceptable performance.

5. ACKNOWLEDGMENT

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6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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