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# Study on the Effect of Bamboo Charcoal Powder Addition on Concrete Compressive Strength

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**ABSTRACT**

This research investigates the effect of adding bamboo charcoal powder as a partial replacement for cement in concrete mixtures to develop a more sustainable construction material. The study addresses the environmental impact of cement production, which contributes approximately 7% of global $CO_2$ emissions, by exploring bamboo charcoal powder (a waste product rich in silica and calcium) as an alternative pozzolanic material. Experimental work was conducted by substituting cement with bamboo charcoal powder at levels of 6%, 10%, and 12%, while a control sample without bamboo powder served as a benchmark. A total of 24 cylindrical specimens (150 mm × 300 mm) were tested for compressive strength at 7 and 28 days. The results showed that the 10% bamboo charcoal powder mix achieved the highest compressive strength, recording a 14.5% increase compared to the control at 28 days. However, higher replacement levels (12%) led to strength reduction due to reduced cementitious content. The slump test results indicated decreased workability with increased bamboo powder content, attributable to the material's high water absorption. This research is significant as it offers a sustainable solution to reduce carbon emissions in the construction industry by demonstrating that bamboo charcoal powder, an abundant waste material, can effectively replace a portion of cement in concrete mixtures while enhancing compressive strength and promoting environmentally friendly, low-carbon building practices.

## 1. Introduction

Concrete remains the most widely used construction material globally due to its durability, strength, availability, and cost-effectiveness [1]. Its role is indispensable in infrastructure development, including buildings, bridges, roads, dams, and other civil engineering works. One of the primary reasons for its extensive use is its high compressive strength, making it ideal for load-bearing structures [2]. Despite its benefits, the widespread use of concrete also poses significant

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environmental concerns, especially due to the large-scale production of Portland cement, the primary binding component in concrete [3].

The cement industry is known to be a major contributor to greenhouse gas emissions. According to global data, the cement production process accounts for approximately 8% of total global $CO_2$ emissions [4]. This is mainly due to the high energy consumption during the production of clinker, the main constituent of cement, where limestone is heated at high temperatures, releasing substantial amounts of $CO_2$. On average, producing one ton of cement results in the release of approximately 0.5–0.9 ton of $CO_2$ into the atmosphere [5]. This significant carbon footprint has prompted researchers and industry practitioners to search for eco-friendly alternatives to reduce the reliance on cement.

One of the promising solutions is the use of supplementary cementitious materials (SCMs) derived from industrial or agricultural waste [6]. By partially replacing cement with such materials, it is possible to reduce $CO_2$ emissions and promote sustainable construction practices. Pozzolanic materials like fly ash, silica fume, and rice husk ash have been widely studied for this purpose [7]. These materials react with calcium hydroxide in concrete to form additional cementitious compounds, enhancing the properties of concrete while lowering environmental impacts. However, some of these materials are not always readily available in certain regions, prompting the need for alternative local resources.

Bamboo, an abundant and fast-growing renewable resource, offers potential as a source of SCM [8]. In many parts of Asia, bamboo is widely utilized for construction, scaffolding, furniture, and handicrafts. The by-products and waste generated from bamboo processing often go unused, contributing to environmental waste problems [9]. When bamboo is combusted into charcoal or ash, the resulting material contains high levels of silica, calcium, and alumina, which are key components in pozzolanic reactions. Previous studies have shown that bamboo ash can be used as a cementitious additive in concrete mixtures, potentially improving certain mechanical properties and contributing to waste management solutions [9-13].

The use of bamboo charcoal powder in concrete not only provides a sustainable method of utilizing bamboo waste but also aligns with the global goal of reducing carbon emissions in the construction sector. Bamboo charcoal is known to enhance certain concrete characteristics, such as durability and strength, when properly processed and added in appropriate proportions [14]. However, determining the optimal amount of bamboo charcoal powder to be used in concrete mixtures is crucial, as excessive use may negatively impact workability or structural performance [15].

Based on this background, the present research investigates the influence of adding bamboo charcoal powder on the compressive strength of concrete. The study aims to evaluate the performance of concrete with varying percentages of bamboo charcoal powder, specifically 6%, 10%, and 12% replacement levels, compared to conventional concrete. The ultimate goal is to identify whether bamboo charcoal powder can serve as an effective alternative material to reduce cement consumption while maintaining or improving the compressive strength of concrete. This research is expected to contribute to the development of more sustainable construction practices through innovative material utilization.

## 2. Method

This study adopts an experimental research design, focusing on laboratory testing to evaluate the effects of bamboo charcoal powder on the compressive strength of concrete. The research was conducted through controlled experiments in the Civil Engineering Laboratory of President University. By using a quantitative approach, the study aims to observe how different proportions of bamboo charcoal powder, when added to the concrete mix, affect its compressive strength. The experiment includes both fresh concrete testing, such as workability assessments, and hardened concrete testing, such as compressive strength measurements. The reference standards used for this study are based on the Indonesian National Standard (SNI) and ASTM guidelines to ensure the validity and reproducibility of the results.

The concrete mixtures in this research were composed of five primary materials: cement, fine aggregate, coarse aggregate, bamboo charcoal powder, and water. Figure 1 shows the material inspection.

i. Cement: The type of cement used was Portland Composite Cement (PCC), specifically Tiga Roda brand. PCC is widely used in construction due to its reliable compressive strength development and workability properties.
ii. Fine Aggregate: Fine aggregate was sourced from natural sand, with a gradation conforming to SNI standards. Only sand particles passing through sieve No.8 (2.36 mm) were selected to ensure uniformity and consistency in the mix.
iii. Coarse Aggregate: Coarse aggregate used in this study was crushed gravel. The aggregates passed through a 15 mm sieve and were retained on a 4.75 mm sieve to comply with standard concrete mix design recommendations for optimal particle size distribution.
iv. Bamboo Charcoal Powder (Figure 2): The bamboo powder used was derived from *Petung* bamboo (*Dendrocalamus asper*), a commonly available bamboo species in Indonesia. The bamboo waste was combusted into charcoal and ground into a fine powder. It was sieved to ensure particles passed through sieve No.200 (0.075 mm), which aligns with pozzolanic material criteria to facilitate proper reaction in the concrete matrix.
v. Water: Clean tap water from the laboratory was used for mixing and curing. The water was ensured to be free from harmful substances like acids, alkalis, or organic impurities that could affect the concrete quality, in accordance with SNI 2847:2013.

**Fig. 1.** Material inspection (Source: Authors' documentation)

**Fig. 2.** Bamboo powder (Source: Authors' documentation)

Concrete mix design was developed with a target compressive strength of 30 MPa (f'c 30 MPa) at 28 days of curing, following the guidelines of SNI 03-2834-2000 (mix design). Bamboo charcoal powder was used as a partial replacement of cement at three different levels: 6%, 10%, and 12% by volume of the fine aggregate. A control mixture containing 0% bamboo charcoal powder (normal concrete) was prepared for comparison.
The mixing process involved the following steps:

i. Weighing all materials accurately based on the mix design calculation, considering the specific gravity and moisture content of the aggregates.
ii. Dry mixing the coarse aggregate, fine aggregate, and bamboo charcoal powder (for the respective variation) to ensure homogeneous distribution of materials.
iii. Wet mixing, where cement and water were added gradually into the dry mixture while continuously stirring using a portable concrete mixer until a consistent and workable mix was achieved.

Concrete specimens were cast in cylindrical molds measuring 150 mm in diameter and 300 mm in height (Figure 3). For each mix variation, a total of six specimens were prepared, three for testing at 7 days of curing and three for 28 days, resulting in 24 cylindrical specimens in total. The freshly mixed concrete was poured into the molds in layers, each layer compacted with a tamping rod to minimize air voids and ensure uniform density.

**Fig. 3.** Fresh concrete (Source: Authors' documentation)

After casting, the molds were covered to prevent early moisture loss. Specimens were removed from the molds after 24 hours and then cured using water immersion (SNI 4810:2013) to maintain consistent curing conditions (Figure 4).

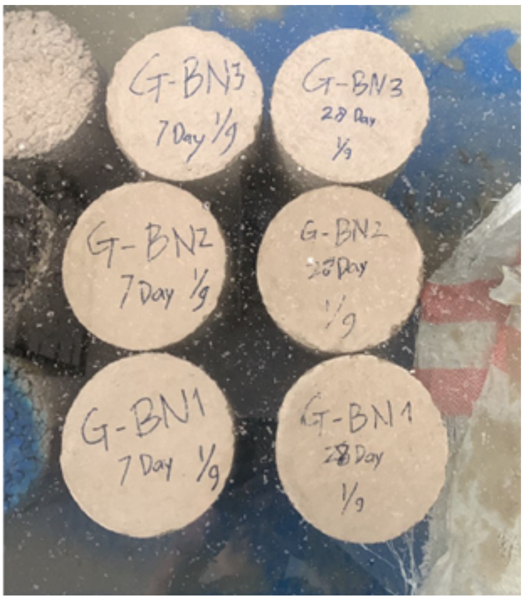


**Fig. 4.** Fresh concrete (Source: Authors' documentation)

This study conducted several tests. First, a slump test was performed immediately after mixing to assess the workability of fresh concrete. The procedure followed the SNI 03-1972-1990 standard using the Abrams cone method. The slump value indicates the ease of placement and workability of the mix, which is critical for evaluating the effects of bamboo charcoal powder on the mix's fluidity.

The compressive strength test was conducted using a Universal Testing Machine (UTM) at curing ages of 7 and 28 days. Testing adhered to SNI 1974:2011 and ASTM C39 standards, using cylindrical specimens (Figure 5). The compressive strength (f'c) was calculated by dividing the maximum load applied during failure by the cross-sectional area of the specimen. This test is fundamental to determine the mechanical performance of concrete with bamboo charcoal powder compared to standard concrete.

**Fig. 5.** Compressive strength test (Source: Authors' documentation)

Prior to concrete mixing, various tests were conducted on the aggregates to ensure compliance with the mix design requirements:

i. Specific Gravity and Absorption Test (SNI 1970:2008 for fine aggregate, SNI 1969:2008 for coarse aggregate): To determine the weight-volume relationship and water absorption capacity of the aggregates.
ii. Gradation Test (SNI 03-1968-1990): To evaluate the particle size distribution of both fine and coarse aggregates, ensuring proper gradation for optimal mix compactness.
iii. Mud Content Test (SNI 03-4142-1996): To measure the amount of silt and clay in the aggregates, which can affect concrete bonding.
iv. Moisture Content Test: To calculate the correction factor for water in the mix design, ensuring precise water-cement ratio control.

Through these comprehensive laboratory procedures, this study aimed to systematically analyze the influence of bamboo charcoal powder on the physical and mechanical properties of concrete, particularly its compressive strength development over time.

## 3. Results and Discussion

### *3.1 Slump Test Results*

The slump test was conducted to assess the workability of the fresh concrete mix immediately after preparation [16]. Workability is a critical property of fresh concrete as it affects the ease of mixing, transporting, placing, and compacting the material without segregation [17]. The test results (Table 1) show a clear trend of decreasing slump value as the proportion of bamboo charcoal powder in the mix increases.

**Table 1**
Slump test results

| Bamboo charcoal (%) | Slump (mm) |
|---|---|
| 0% (Normal concrete) | 73 |
| 6% | 67 |
| 10% | 65 |
| 12% | 61 |

The control mix (0% bamboo powder) produced a slump of 73 mm, indicating good workability suitable for typical construction applications. However, when 6% bamboo charcoal powder was added, the slump reduced to 67 mm. Further increasing the bamboo powder to 10% and 12% led to slump values of 65 mm and 61 mm, respectively.

This reduction in slump can be attributed to the high porosity and absorptive nature of bamboo charcoal powder. Bamboo charcoal has a large surface area with micro- and nano-sized pores, which tend to absorb more water from the mix [18]. As a result, the free water available for lubricating the aggregates decreases, leading to lower workability. This behavior suggests that when bamboo charcoal powder is used as a cement replacement, adjustments in water content or the use of superplasticizers may be required to maintain desired workability levels without compromising concrete quality.

### *3.2 Compressive Strength Test Results*

The compressive strength test was performed at 7 days and 28 days of curing to evaluate the mechanical performance of the concrete mixtures. The results are summarized in Table 2 and Table 3.

**Table 2**
Compressive strength test results (7 days)

| Bamboo charcoal (%) | Compressive strength (MPa) |
|---|---|
| 0% (Normal concrete) | 18.30 |
| 6% | 20.47 |
| 10% | 21.88 |
| 12% | 21.60 |

At 7 days, the concrete mixture with 10% bamboo charcoal powder achieved the highest compressive strength of 21.88 MPa, surpassing both the control sample (18.30 MPa) and the other variations. The mix with 6% bamboo powder also showed a slight increase to 20.47 MPa, indicating early strength improvement due to pozzolanic activity. However, the 12% bamboo powder mix exhibited a slight reduction in strength to 21.60 MPa, suggesting diminishing returns or negative effects when the replacement level becomes too high at early ages.

**Table 3**
Compressive strength test results (28 days)

| Bamboo charcoal (%) | Compressive strength (MPa) |
|---|---|
| 0% (Normal Concrete) | 28.95 |
| 6% | 32.73 |
| 10% | 34.05 |
| 12% | 33.86 |

At 28 days, the strength development trend became more pronounced. The concrete with 10% bamboo charcoal powder reached a compressive strength of 34.05 MPa, representing an improvement of approximately 17.6% over the control concrete. The 6% bamboo powder mix also performed better than the control, achieving 32.73 MPa, while the 12% bamboo powder mix fell to 33.86 MPa.

These results indicate that the inclusion of bamboo charcoal powder, particularly at 10%, enhances the long-term compressive strength of concrete. The pozzolanic reaction between bamboo ash silica and calcium hydroxide from cement hydration leads to additional formation of calcium silicate hydrate (C-S-H), which fills voids and strengthens the concrete matrix over time [19]. However, excessive replacement at 12% leads to a reduction in strength, likely because the bamboo powder, despite its pozzolanic properties, cannot fully compensate for the reduced cement content beyond a certain threshold.

*3.3 Discussion and Implications*

The experimental results confirm that bamboo charcoal powder has a beneficial effect on concrete compressive strength when used in optimal proportions. The 10% replacement level was found to be the most effective, producing the highest strength at both 7 and 28 days of curing. This enhancement can be attributed to several factors:

i. Pozzolanic Activity: The silica ($SiO_2$) content in bamboo charcoal reacts with calcium hydroxide (Ca $(OH)_2$), a by-product of cement hydration, forming additional calcium silicate hydrate (C-S-H), which contributes to strength gain.
ii. Micro-filler Effect: The fine particles of bamboo charcoal powder act as micro-fillers, reducing porosity and improving the density of the concrete matrix.
iii. Improved Microstructure: The bamboo powder fills microvoids, reducing internal weaknesses and enhancing the overall mechanical performance of the concrete.

However, the data also indicates that exceeding a 10% replacement rate leads to a decline in performance. At 12% substitution, the compressive strength at 28 days decreased to 33.86 MPa, slightly below the concrete with 10% substitution. This reduction is likely due to the dilution effect, where the replacement of too much cement reduces the available clinker content responsible for early strength development [20]. Additionally, excessive bamboo powder may introduce more porous zones within the matrix if not adequately compacted or if water demand is not properly adjusted.

The decrease in slump values further highlights the need to balance workability with mechanical performance. While bamboo charcoal powder improves strength due to its pozzolanic properties, it also increases water absorption, which can adversely affect the fresh concrete's flowability [21]. This must be addressed in practical applications by incorporating admixtures or adjusting mix proportions.

The findings of this study provide important implications for both academic research and the construction industry, particularly in the fields of sustainable materials and green construction practices. One of the most significant implications of this research is its contribution to reducing the environmental footprint of the construction industry. Cement production is responsible for substantial $CO_2$ emissions globally, contributing to climate change and environmental degradation [4]. By partially replacing cement with bamboo charcoal powder, the construction industry can reduce its reliance on cement, subsequently lowering carbon emissions. Since bamboo is a renewable and fast-growing resource, its use promotes carbon sequestration during growth and offers a sustainable lifecycle solution when its by-products are recycled into construction materials. This approach aligns with the global shift toward circular economy practices, where waste is repurposed rather than discarded.

This research highlights the potential of bamboo waste valorization. Bamboo is widely cultivated in many developing countries, but large volumes of bamboo waste, especially from construction, furniture industries, and agricultural activities, often remain underutilized. Converting bamboo waste into bamboo charcoal powder for concrete applications provides a practical solution for managing this waste stream. It creates an opportunity for local industries to transform what would otherwise be biomass waste into a valuable construction material, promoting zero-waste manufacturing systems and supporting regional economic development.

From a practical standpoint, the research suggests that bamboo charcoal powder can be effectively used as a partial cement substitute in general concrete applications, particularly in non-prestressed and low-to-medium load-bearing structures. The study identifies 10% replacement as the optimal level, offering improved compressive strength without significant compromises in workability. This insight provides clear guidance for concrete mix designers and contractors aiming to develop more sustainable concrete formulations while maintaining structural integrity.

However, the reduction in workability observed in the slump test implies that adjustments in mix design are necessary when incorporating bamboo charcoal powder. Contractors may need to increase water content, use water-reducing admixtures, or apply other mix optimization techniques to ensure the concrete remains workable on-site. Understanding these trade-offs is critical for successful field implementation.

The research adds to the growing body of knowledge on green concrete and eco-friendly construction materials. The use of alternative pozzolanic materials, like bamboo charcoal powder, helps meet sustainability targets set by green building certifications (e.g., LEED, Indonesian Greenship). It opens opportunities for the development of localized, low-carbon concrete production systems, especially in regions where bamboo is abundant, but conventional supplementary cementitious materials (SCMs) such as fly ash or silica fume are scarce or expensive.

The use of bamboo charcoal powder in concrete has the potential to generate new economic activities, particularly in rural areas where bamboo is plentiful. It could create job opportunities in bamboo waste processing industries, including charcoal production, grinding, and packaging, thus supporting community-based economies. Additionally, adopting green construction materials can enhance the social image of construction companies by demonstrating corporate social responsibility and commitment to environmental stewardship.

## 4. Conclusions

This research has demonstrated that the addition of bamboo charcoal powder as a partial cement replacement has a significant effect on the compressive strength and workability of concrete. The experimental results showed that using 10% bamboo charcoal powder yields the most favorable outcome, achieving higher compressive strength than the control concrete at both 7 and 28 days. This improvement is attributed to the pozzolanic properties of bamboo charcoal, which react with calcium hydroxide to produce additional calcium silicate hydrate (C-S-H), enhancing the concrete's microstructure and filling voids in the matrix. However, the study also found that increasing the replacement level to 12% led to a decrease in compressive strength, likely due to reduced cement content surpassing the optimal threshold, resulting in insufficient binder availability.

The findings of this research suggest that bamboo charcoal powder has strong potential as a sustainable supplementary material in concrete production, particularly in regions where bamboo is abundant. While the strength of concrete can be enhanced with proper substitution levels, careful attention must be given to the mix design, especially regarding workability, which decreases with higher bamboo content due to the material's high water absorption capacity. This study holds significant value in addressing pressing environmental challenges posed by conventional construction practices, particularly the high carbon emissions associated with cement production. By investigating the incorporation of bamboo charcoal powder as a partial cement replacement, the research introduces an innovative and sustainable approach to concrete formulation. Cement manufacturing is responsible for global $CO_2$ emissions, and finding viable alternatives is critical for achieving global sustainability targets.

The research contributes to the body of knowledge by empirically demonstrating that bamboo charcoal powder, when used optimally at a 10% replacement level, can enhance the compressive strength of concrete while simultaneously reducing cement usage. This not only supports the circular economy by valorizing bamboo waste, but also promotes local, low-carbon construction solutions, especially in regions where traditional supplementary cementitious materials are scarce or expensive. Further studies are recommended to explore long-term durability, environmental impact analysis, and the economic feasibility of large-scale implementation of bamboo charcoal powder in concrete mixtures.

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