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Compressive strength performance of sustainable concrete incorporating rice husk ash and sugarcane bagasse ash as agricultural waste-based supplementary cementitious materials

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Abstract

Background: The growing environmental concerns associated with Portland cement production have encouraged the utilization of agricultural waste as supplementary cementitious materials for sustainable concrete. Rice husk ash (RHA) and sugarcane bagasse ash (SCBA) are silica-rich by-products with pozzolanic potential that can reduce cement consumption while promoting environmentally responsible construction.
Aim: This study aimed to evaluate the compressive strength performance of sustainable concrete incorporating RHA and SCBA and to determine the most effective mixture proportion for structural concrete applications.
Method: A pure experimental approach was employed using concrete with a target compressive strength of 21 MPa at 28 days. RHA was used as a constant 10% cement replacement by weight, while SCBA was incorporated at 1%, 3%, 5%, 7%, and 9% of the binder content. Superplasticizer was added to maintain workability within a slump range of 6–18 cm, and compressive strength was evaluated after 7, 14, and 28 days of curing.
Results: Increasing SCBA content progressively reduced compressive strength because of its porous structure and high water demand, which limited cement hydration. The mixture containing 10% RHA and 1% SCBA exhibited the highest compressive strength among the modified concretes, although it remained below the control concrete (25.51 MPa) and the targeted structural strength.
Conclusion: RHA and SCBA have potential as agricultural waste-based supplementary cementitious materials for sustainable concrete, particularly for non-structural applications. Further optimization of ash processing and mixture proportions is required to enhance their mechanical performance and broaden their structural applicability.

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INTRODUCTION

The construction sector serves as one of the primary drivers of economic growth by providing the physical infrastructure required to support urbanization, industrial expansion, and population development. Concrete remains the most extensively utilized construction material because of its excellent mechanical properties, versatility, durability, and cost-effectiveness across a wide range of engineering applications (Afsoosbiria & Machowska, 2025; Alnadish, 2026; Behera et al., 2025; Odeh et al., 2025). The continuous increase in global infrastructure demand has consequently led to a substantial rise in cement consumption, making the construction industry one

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of the largest consumers of natural resources. Although Portland cement provides the essential binding properties required for concrete production, its manufacturing process is highly energy-intensive and generates considerable greenhouse gas emissions throughout clinker production. The calcination of limestone and the combustion of fossil fuels during cement manufacturing have become major contributors to environmental degradation and climate change. As environmental regulations become increasingly stringent, reducing the carbon footprint associated with cement production has emerged as a critical priority for both researchers and industry practitioners (Habert et al., 2020; Hosen & Bărbulescu, 2026; Mishra et al., 2022). In response to these challenges, sustainable construction has evolved from an optional concept into a fundamental objective for modern infrastructure development. One practical strategy to achieve this objective involves reducing the proportion of Portland cement by incorporating supplementary cementitious materials capable of maintaining or enhancing concrete performance. Such materials not only decrease cement consumption but also promote resource efficiency through the beneficial utilization of industrial and agricultural by-products that would otherwise become environmental burdens. Similarly, previous studies on modified construction materials have demonstrated that optimizing the composition of alternative modifiers can significantly influence mechanical performance while simultaneously supporting more sustainable infrastructure development, emphasizing the importance of appropriate material proportioning in engineering applications (Karami et al., 2020). Consequently, the development of sustainable concrete incorporating environmentally friendly cementitious materials has become an increasingly important research focus in contemporary construction engineering.

Among the numerous alternative cementitious materials that have been investigated, agricultural waste has attracted considerable attention because of its abundance, renewability, and potential to contribute to sustainable resource management. The utilization of agricultural residues in concrete production simultaneously addresses two important environmental concerns, namely reducing waste accumulation and decreasing dependence on conventional Portland cement. Rice husk ash (RHA) has emerged as one of the most promising agricultural waste-derived supplementary cementitious materials because of its exceptionally high silica content and significant pozzolanic reactivity (Frahat et al., 2026; Mohamed & Tayeh, 2026; Olaiya et al., 2025; Sadoon et al., 2025; Yin et al., 2025). Produced through the controlled combustion of rice husks generated during rice milling operations, RHA contains amorphous silica capable of reacting with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate gel. The formation of this secondary hydration product contributes to the densification of the cement matrix and may improve the mechanical and durability characteristics of concrete. Previous investigations have consistently demonstrated that appropriate incorporation of RHA can enhance compressive strength, reduce permeability, refine pore structure, and improve long-term durability when suitable replacement levels are adopted (Amran et al., 2021; Endale et al., 2022; Öztürk et al., 2025; Ullah et al., 2025). Beyond its engineering advantages, the utilization of RHA also supports circular economy principles by converting abundant agricultural waste into value-added construction materials with practical engineering applications. This approach is particularly relevant for agricultural countries where rice production generates substantial quantities of rice husks every year that remain insufficiently utilized. Transforming these residues into supplementary cementitious materials therefore provides both environmental and economic benefits while promoting more efficient resource utilization. As a result, RHA has become one of the most extensively investigated agricultural waste materials for the development of sustainable concrete technology.

In addition to rice husk ash, sugarcane bagasse ash (SCBA) has gained increasing attention as another promising agricultural waste-derived supplementary cementitious material with considerable potential for concrete applications. Sugarcane bagasse is generated in large quantities as a fibrous by-product following sugar extraction, and it is commonly combusted as a biomass fuel in sugar processing industries, producing significant volumes of ash as a secondary residue (Hiranobe et al., 2024; Quereshi et al., 2022; Ungureanu et al., 2022). Similar to RHA, properly processed SCBA contains silica-rich compounds capable of participating in pozzolanic reactions that contribute to the improvement of cementitious matrices (Gayathri & Salman, 2026; Okeke et al., 2025). The incorporation of SCBA into concrete has been reported to reduce cement consumption while simultaneously providing an environmentally responsible solution for managing agricultural waste generated by the sugar industry. However, the engineering performance of SCBA is strongly influenced by several processing variables, including combustion conditions, particle fineness, mineralogical composition, and replacement percentage, resulting in considerable variability in its effectiveness as a supplementary cementitious material (Ganpule et al., 2026; Mohan et al., 2021; Zaheer & Tabish, 2023). Unlike RHA, SCBA generally exhibits a more porous particle structure and higher water absorption characteristics, which may adversely influence workability and compressive strength when excessive replacement levels are employed. These differences indicate that the interaction between RHA and SCBA within the same cementitious system is considerably more complex than the behavior of either material used individually. Although both agricultural ashes possess significant potential for sustainable concrete production, studies investigating their combined utilization remain relatively limited compared with the extensive body of research devoted to individual supplementary cementitious materials. Furthermore, available investigations have not yet established a comprehensive understanding of how different proportions of SCBA influence concrete performance when combined with a fixed amount of RHA in the same mixture. Therefore, further experimental research is required to determine the optimum combination of these agricultural waste-based cementitious materials capable of balancing environmental sustainability with satisfactory mechanical performance for practical concrete applications.

Although extensive research has established the potential of agricultural waste-derived supplementary cementitious materials (SCMs) for reducing cement consumption and improving the sustainability of concrete production, previous studies have predominantly focused on comprehensive reviews of agricultural waste utilization or on the individual performance of specific materials such as rice husk ash (RHA) and sugarcane bagasse ash (SCBA) as cement substitutes (He et al., 2020; Nicoara et al., 2020; Siddika et al., 2021; Singh et al., 2025; Thomas et al., 2021). More recently, research has expanded towards binary and ternary SCM systems to enhance the mechanical and durability performance of concrete; however, these studies have primarily investigated combinations of industrial by-products, including fly ash, ground granulated blast furnace slag, silica fume, metakaolin, and limestone powder rather than agricultural waste ashes (Alyousef et al., 2023; Bheel et al., 2020; Lee et al., 2021; Nasr et al., 2021; Weng & Liao, 2021). Furthermore, although a limited number of studies have explored the combined use of RHA and SCBA, the investigations have mainly emphasized material characterization, pozzolanic reactivity, durability assessment, or short-term concrete performance, while systematic evaluation of compressive strength development under controlled replacement strategies remains scarce (Tabish et al., 2025; Yaseen, 2024). In particular, little attention has been devoted to determining the optimum proportion of concrete produced using a constant RHA replacement combined with progressively varied SCBA contents under a normal-strength concrete design, despite the substantial differences in particle morphology, water demand, and pozzolanic activity between the two agricultural waste ashes that may significantly influence hydration behaviour and compressive strength. Therefore, further experimental investigation is required to clarify the synergistic interaction between RHA and SCBA and to establish an optimum mixture composition that supports both sustainable agricultural waste utilization and satisfactory mechanical performance for concrete applications.

This study aims to evaluate the compressive strength performance of sustainable concrete incorporating rice husk ash and sugarcane bagasse ash as agricultural waste-based supplementary cementitious materials. The research investigates the feasibility of utilizing these agricultural by-products as partial cement replacements while maintaining acceptable mechanical performance for concrete applications. A constant replacement level of 10% rice husk ash is employed to establish a stable pozzolanic contribution, whereas the proportion of sugarcane bagasse ash is systematically varied to examine its influence on compressive strength development. The investigation evaluates the compressive strength of concrete specimens at different curing ages to observe the evolution of mechanical properties throughout the hydration process. Particular emphasis is placed on identifying the optimum mixture composition capable of producing the highest compressive strength among the modified concrete mixtures. The study also examines whether the incorporation of combined agricultural waste ashes can satisfy the targeted compressive strength requirements for normal structural concrete. In addition, the research seeks to improve understanding of the interaction between rice husk ash and sugarcane bagasse ash within a blended supplementary cementitious system. The findings are expected to provide scientific evidence supporting the practical utilization of agricultural waste as sustainable cementitious materials in concrete production. From an environmental perspective, the study contributes to ongoing efforts to reduce cement consumption, minimize agricultural waste disposal, and promote circular resource utilization within the construction sector. Ultimately, this research is intended to support the advancement of sustainable concrete technology by providing experimental information that can guide the future development of environmentally responsible construction materials.

LITERATURE REVIEW

Sustainable concrete has become one of the most important innovations in modern construction engineering because it addresses the dual challenge of maintaining structural performance while minimizing environmental impacts associated with conventional concrete production. The concept of sustainable concrete emphasizes the efficient utilization of natural resources, reduction of greenhouse gas emissions, and incorporation of environmentally friendly materials throughout the concrete life cycle (Akbulut et al., 2024; Alibeigibeni et al., 2025; Rusnak, 2025). Among various sustainability strategies, the partial replacement of Portland cement with supplementary cementitious materials (SCMs) has received considerable attention due to its potential to reduce carbon emissions without significantly compromising mechanical properties. Supplementary cementitious materials consist of natural, industrial, or agricultural materials possessing pozzolanic or latent hydraulic properties that contribute to cement hydration reactions. These materials react with calcium hydroxide produced during cement hydration to generate additional calcium silicate hydrate (C–S–H), thereby improving the density and integrity of the cementitious matrix. The formation of secondary hydration products generally contributes to enhanced compressive strength, lower permeability, and improved long-term durability under appropriate replacement levels. In addition to improving engineering performance, SCMs significantly reduce the clinker content of concrete, thereby lowering energy consumption and carbon dioxide emissions associated with cement production. Recent developments in sustainable construction have encouraged the exploration of locally available waste materials as alternative SCMs because they simultaneously address environmental pollution and resource depletion. Agricultural waste-derived ashes have emerged as particularly attractive alternatives because they are renewable, inexpensive, and widely available in many developing countries with large agricultural sectors (Ahmed et al., 2024; Mawthoh et al., 2026; Sadoon et al., 2025). Consequently, the integration of agricultural waste-based supplementary cementitious materials has become an increasingly important approach for developing environmentally responsible concrete technology.

Rice husk ash (RHA) is widely recognized as one of the most effective agricultural waste-derived supplementary cementitious materials because of its high silica content and remarkable pozzolanic activity. Rice husks are generated in substantial quantities during rice milling operations and are commonly disposed of through uncontrolled burning or landfill disposal, creating environmental concerns in many rice-producing countries (Gowlla et al., 2025; Kariyawasam & Semananda, 2025; Miah et al., 2025; Rihan & S. Alahmari, 2025). Controlled combustion of rice husks produces ash containing a high proportion of amorphous silica, which serves as the primary source of pozzolanic reactivity in cementitious systems. When incorporated into concrete, the reactive silica in RHA reacts with calcium hydroxide released during cement hydration to form additional calcium silicate hydrate gel that strengthens the internal microstructure. This secondary hydration process contributes to pore refinement, reduced permeability, and improved bonding within the hardened cement matrix. Numerous experimental studies have reported that moderate replacement levels of RHA improve compressive strength by enhancing particle packing density and promoting continued hydration reactions during curing. The effectiveness of RHA, however, is strongly influenced by several factors, including combustion temperature, grinding process, particle fineness, silica crystallinity, and replacement percentage (Amran et al., 2021; Endale et al., 2022; Mohamed et al., 2025; Thiedeitz et al., 2020). Excessive replacement levels may reduce concrete strength because the available cement content becomes insufficient to sustain adequate hydration and early strength development. Beyond its engineering advantages, the utilization of RHA contributes to sustainable waste management by transforming agricultural residues into valuable construction materials while reducing environmental pollution associated with rice production. Consequently, RHA has become one of the most extensively investigated agricultural supplementary cementitious materials for improving both the environmental and mechanical performance of concrete.

Sugarcane bagasse ash (SCBA) has attracted increasing research interest as another promising agricultural waste-derived supplementary cementitious material because of its abundance in sugar-producing regions and its significant silica content. Sugarcane bagasse is produced after juice extraction and is commonly utilized as biomass fuel in sugar mills, generating substantial quantities of ash as a combustion by-product. Properly processed SCBA contains reactive silica capable of participating in pozzolanic reactions that contribute to the formation of additional cementitious products within the concrete matrix. Similar to other pozzolanic materials, SCBA can reduce the consumption of Portland cement while simultaneously improving resource efficiency and supporting sustainable construction practices (Goyal & Murmu, 2026; Hasan et al., 2026; Mirzaei et al., 2025). Several studies have reported improvements in compressive strength, durability, and resistance to aggressive environmental conditions when SCBA is incorporated at appropriate replacement levels. Nevertheless, the engineering performance of SCBA is highly dependent on ash quality, combustion conditions, particle fineness, mineralogical composition, and replacement proportion. Compared with rice husk ash, SCBA generally exhibits higher porosity and greater water absorption capacity, characteristics that may adversely influence workability and mechanical performance when excessive quantities are introduced into concrete mixtures (Azzam et al., 2025; Ganpule et al., 2026; Goyal & Murmu, 2026; M. A. Khan et al., 2025; Santhosh et al., 2026). The variability of SCBA properties among different production sources has also contributed to inconsistent findings regarding its optimum replacement level in previous experimental investigations. These variations indicate that careful mixture design and quality control are essential to maximize the pozzolanic contribution of SCBA while minimizing potential reductions in concrete performance. Therefore, continued investigation into the engineering behavior of SCBA remains essential for expanding its practical application as a sustainable supplementary cementitious material in concrete technology.

Binary supplementary cementitious material (binary SCM) systems have emerged as an effective approach to improve the engineering performance of sustainable concrete while simultaneously reducing the environmental impact associated with Portland cement consumption. Unlike single-material replacement systems, binary SCMs combine two supplementary cementitious materials with complementary physical and chemical characteristics to produce synergistic effects during cement hydration. The incorporation of multiple SCMs can enhance particle packing density, optimize pore structure, increase the availability of reactive silica, and improve the long-term hydration process within the cementitious matrix. Previous studies have demonstrated that binary SCM systems composed of fly ash, ground granulated blast furnace slag, silica fume, metakaolin, or limestone powder frequently exhibit superior mechanical and durability properties compared with concrete containing only one supplementary cementitious material (Akintayo et al., 2025; Anderson & Adesina, 2026; Nassiri et al., 2025; Prakash et al., 2021; Sathiparan et al., 2024). These improvements are attributed to the combined filler effect, pozzolanic reaction, and microstructural refinement generated by the interaction between different SCMs. In recent years, researchers have begun exploring the feasibility of replacing industrial by-products with agricultural waste-derived SCMs to further improve the environmental sustainability of concrete production. Among the agricultural waste materials investigated, rice husk ash and sugarcane bagasse ash have demonstrated promising pozzolanic characteristics that may complement one another when incorporated into the same cementitious system. Rice husk ash generally provides high silica reactivity and finer particle distribution, whereas sugarcane bagasse ash contributes additional reactive minerals but exhibits relatively higher porosity and water absorption characteristics. These contrasting properties indicate that an appropriate combination of RHA and SCBA may produce synergistic hydration behavior capable of improving concrete performance while reducing cement consumption. Nevertheless, comprehensive studies evaluating the interaction between these two agricultural waste-derived supplementary cementitious materials remain relatively limited, particularly with respect to optimizing mixture proportions for normal-strength concrete.

Compressive strength is widely recognized as the primary mechanical property used to evaluate the structural performance and engineering quality of concrete because it directly reflects the ability of hardened concrete to resist applied compressive loads. The development of compressive strength is influenced by numerous interrelated factors, including cement composition, water-to-binder ratio, curing conditions, aggregate characteristics, and the physical and chemical properties of supplementary cementitious materials (Aziz et al., 2024; Duchesne, 2021; M. I. Khan et al., 2024; Mo et al., 2026; Yaseen, 2024). When pozzolanic materials are incorporated into concrete, strength development depends largely on the balance between cement dilution and the formation of additional calcium silicate hydrate produced through secondary hydration reactions. Moderate incorporation of highly reactive SCMs often improves compressive strength by refining pore structure, reducing internal voids, and strengthening the interfacial transition zone between cement paste and aggregates. Conversely, excessive replacement levels may reduce compressive strength because the reduction in cement content exceeds the contribution provided by pozzolanic reactions, particularly during the early stages of curing. The combined use of rice husk ash and sugarcane bagasse ash therefore requires careful proportioning to maximize their complementary characteristics while minimizing adverse effects associated with increased water demand and particle porosity. Despite the increasing number of studies investigating agricultural waste-derived supplementary cementitious materials, relatively few investigations have systematically examined concrete mixtures employing a constant rice husk ash replacement together with progressively varied sugarcane bagasse ash contents under identical experimental conditions. Furthermore, limited information is available regarding the compressive strength development of these binary agricultural waste systems at different curing ages, making it difficult to establish the optimum replacement strategy for practical concrete production. A systematic investigation of compressive strength development is therefore essential to improve understanding of the interaction between rice husk ash and sugarcane bagasse ash throughout the hydration process and to identify mixture compositions capable of maintaining satisfactory structural performance. Such knowledge will contribute to the broader development of sustainable concrete technology by providing scientific evidence supporting the effective utilization of agricultural waste as environmentally responsible supplementary cementitious materials.

METHOD

Research Design

This study employed a laboratory-based experimental design to investigate the influence of incorporating rice husk ash (RHA) and sugarcane bagasse ash (SCBA) on the compressive strength performance of sustainable concrete. Ordinary Portland Composite Cement (PCC) concrete served as the control mixture, while modified concretes were prepared by replacing 10% of the cement with RHA and incorporating SCBA as an additional filler at five dosage levels (1%, 3%, 5%, 7%, and 9% of the total binder weight). Concrete specimens were cast, water-cured, and tested for compressive strength at curing ages of 7, 14, and 28 days. The experimental procedure followed the Indonesian National Standards (SNI) for concrete mix design, specimen preparation, curing, and compressive strength testing.

Study Area

All laboratory activities were conducted at the Civil Engineering Laboratory, Politeknik Negeri Pontianak, Indonesia. The experimental program, including material characterization, concrete mixing, specimen preparation, curing, and compressive strength testing, was completed over approximately two months under controlled laboratory conditions.

Materials

The concrete mixtures were produced using Portland Composite Cement (PCC), natural fine aggregate, crushed coarse aggregate, PDAM (municipal) water, rice husk ash (RHA), sugarcane bagasse ash (SCBA), and a superplasticizer admixture. PCC functioned as the primary cementitious binder, while RHA served as a supplementary cementitious material replacing 10% of the cement content in all modified mixtures. SCBA was incorporated as an additional filler material to investigate its influence on concrete performance. Fine and coarse aggregates were used as conventional concrete aggregates, whereas municipal water was utilized for both concrete mixing and curing. A superplasticizer was added to improve the workability of concrete mixtures containing agricultural ash materials. Prior to concrete production, aggregate properties including moisture content, specific gravity, water absorption, bulk density, gradation, and abrasion resistance were evaluated in accordance with the relevant SNI standards to ensure compliance with concrete production requirements.

Concrete Mix Proportions and Specimen Preparation

Six concrete mixtures were prepared. The control mixture (BN) contained 100% Portland Composite Cement without RHA or SCBA. The modified mixtures maintained a constant binder composition consisting of 90% cement and 10% rice husk ash, while sugarcane bagasse ash was incorporated at 1%, 3%, 5%, 7%, and 9% of the total binder weight. These mixtures were designated as BPT1, BPT3, BPT5, BPT7, and BPT9, respectively. Cylindrical concrete specimens with dimensions of 150 mm in diameter and 300 mm in height were cast for each mixture. Five specimens were prepared for each curing age (7, 14, and 28 days), resulting in 15 specimens for every mixture and a total of 90 concrete cylinders. After casting, the specimens were cured using clean municipal water until the designated testing ages.

Experimental Procedures and Data Analysis

The experimental program consisted of two main stages: material characterization and concrete performance evaluation. Aggregate testing included moisture content, specific gravity, water absorption, bulk density, particle size distribution, and abrasion resistance using standardized laboratory procedures specified in the Indonesian National Standards (SNI). Following material characterization, concrete mixtures were proportioned according to the planned mix design and mixed using identical procedures for all mixtures. Fresh concrete workability was evaluated using the slump test before casting. Cylindrical specimens were then compacted in steel molds, demolded after initial setting, and cured in water until testing ages of 7, 14, and 28 days. Compressive strength tests were performed using a compression testing machine following SNI 1974:2024. The resulting compressive strength values were analyzed descriptively and comparatively to evaluate the influence of different SCBA incorporation levels on the mechanical performance of concrete relative to the control mixture and the target design strength of 21 MPa.

Concrete Mix Design

The concrete mix was designed to achieve a target compressive strength (f'c) of 21 MPa using the procedures specified in SNI 7656:2012 for normal concrete mix proportioning. Prior to mixture preparation, the physical properties of the aggregates, including moisture content, specific gravity, water absorption, bulk density, particle size distribution, and abrasion resistance, were determined to establish the required mix proportions. The control mixture (BN) consisted of 100% Portland Composite Cement (PCC) as the sole binder. In the modified mixtures, 10% of the cement was consistently replaced with rice husk ash (RHA), while sugarcane bagasse ash (SCBA) was incorporated as an additional filler at levels of 1%, 3%, 5%, 7%, and 9% relative to the total binder mass. Accordingly, six concrete mixtures were evaluated, namely BN, BPT1, BPT3, BPT5, BPT7, and BPT9. This experimental design enabled the effect of increasing SCBA content to be evaluated while maintaining a constant RHA replacement level throughout the investigation.

Table 1. Concrete Mix Design

Mix ID	Cement (%)	Rice Husk Ash (%)	Sugarcane Bagasse Ash (%)
BN	100	0	0
BPT1	90	10	1
BPT3	90	10	3
BPT5	90	10	5
BPT7	90	10	7
BPT9	90	10	9

Concrete Specimen Preparation

Concrete production began with the preparation and weighing of all constituent materials according to the predetermined mix proportions. Fine aggregate, coarse aggregate, cement, rice husk ash, and sugarcane bagasse ash were mixed until a homogeneous dry mixture was obtained. Water and superplasticizer were subsequently introduced into the mixture while continuous mixing was maintained to produce fresh concrete with adequate consistency and uniformity. Immediately after mixing, the workability of the fresh concrete was evaluated through a slump test before casting. The concrete was then placed into cylindrical steel molds with dimensions of 150 mm in diameter and 300 mm in height. Each specimen was compacted using a standard tamping rod to eliminate entrapped air and ensure uniform density throughout the concrete. Following casting, the specimens were allowed to set before being removed from the molds and subsequently cured in clean PDAM water until the designated testing ages of 7, 14, and 28 days. Five specimens were prepared for each curing age in every mixture, resulting in a total of ninety cylindrical concrete specimens for the entire experimental program.

Slump Test

The workability of fresh concrete was evaluated using the slump test in accordance with SNI 1972:2024 before specimen casting. Fresh concrete was placed into a standard Abrams cone in three equal layers, with each layer compacted using a tamping rod to achieve consistent consolidation. After the cone had been completely filled and the upper surface leveled, the mold was lifted vertically at a steady rate without disturbing the concrete mass. The decrease in concrete height was then measured using a ruler and recorded as the slump value. The slump test was performed to evaluate the influence of rice husk ash and sugarcane bagasse ash on the consistency and workability of fresh concrete, as these agricultural ash materials may alter water demand because of their particle characteristics and specific surface area. The measured slump values were used to verify that all concrete mixtures exhibited acceptable workability before the casting process proceeded.

Compressive Strength Test

The compressive strength of hardened concrete was determined in accordance with SNI 1974:2024 using cylindrical specimens measuring 150 mm in diameter and 300 mm in height. After curing in water for 7, 14, and 28 days, the specimens were removed from the curing tank, surface-dried, and positioned concentrically in a compression testing machine. A continuously increasing compressive load was applied until specimen failure occurred, and the maximum load sustained by each specimen was recorded. The compressive strength was subsequently calculated by dividing the maximum failure load by the cross-sectional area of the specimen. Five specimens were tested for each mixture at every curing age, and the average compressive strength was calculated to represent the performance of each concrete mixture. The resulting data were compared among all mixtures to evaluate the effect of increasing sugarcane bagasse ash content on the compressive strength development of concrete incorporating a constant 10% rice husk ash replacement. Furthermore, the measured compressive strengths were compared with the target design strength of 21 MPa to assess the structural feasibility of each mixture.

Compressive Strength Test

The research methodology began with a laboratory-based experimental design conducted at the Civil Engineering Laboratory of Politeknik Negeri Pontianak, Indonesia. The study utilized Portland Composite Cement (PCC), fine and coarse aggregates, rice husk ash (RHA), sugarcane bagasse ash (SCBA), water, and a superplasticizer as the primary materials. Six concrete mixtures were prepared, consisting of one control mixture and five modified mixtures containing a constant 10% RHA replacement with SCBA contents ranging from 1% to 9%, targeting a compressive strength of 21 MPa. Concrete specimens were produced through material weighing, dry mixing, water and superplasticizer addition, slump testing, casting, compaction, and water curing, resulting in a total of 90 cylindrical specimens (150 × 300 mm). Fresh concrete workability was evaluated using the slump test in accordance with SNI 1972:2024, while compressive strength was determined at curing ages of 7, 14, and 28 days following SNI 1974:2024. Finally, the experimental data were analyzed by comparing the slump and compressive strength of all concrete mixtures to identify the optimum SCBA content capable of producing the most favorable mechanical performance for sustainable concrete.

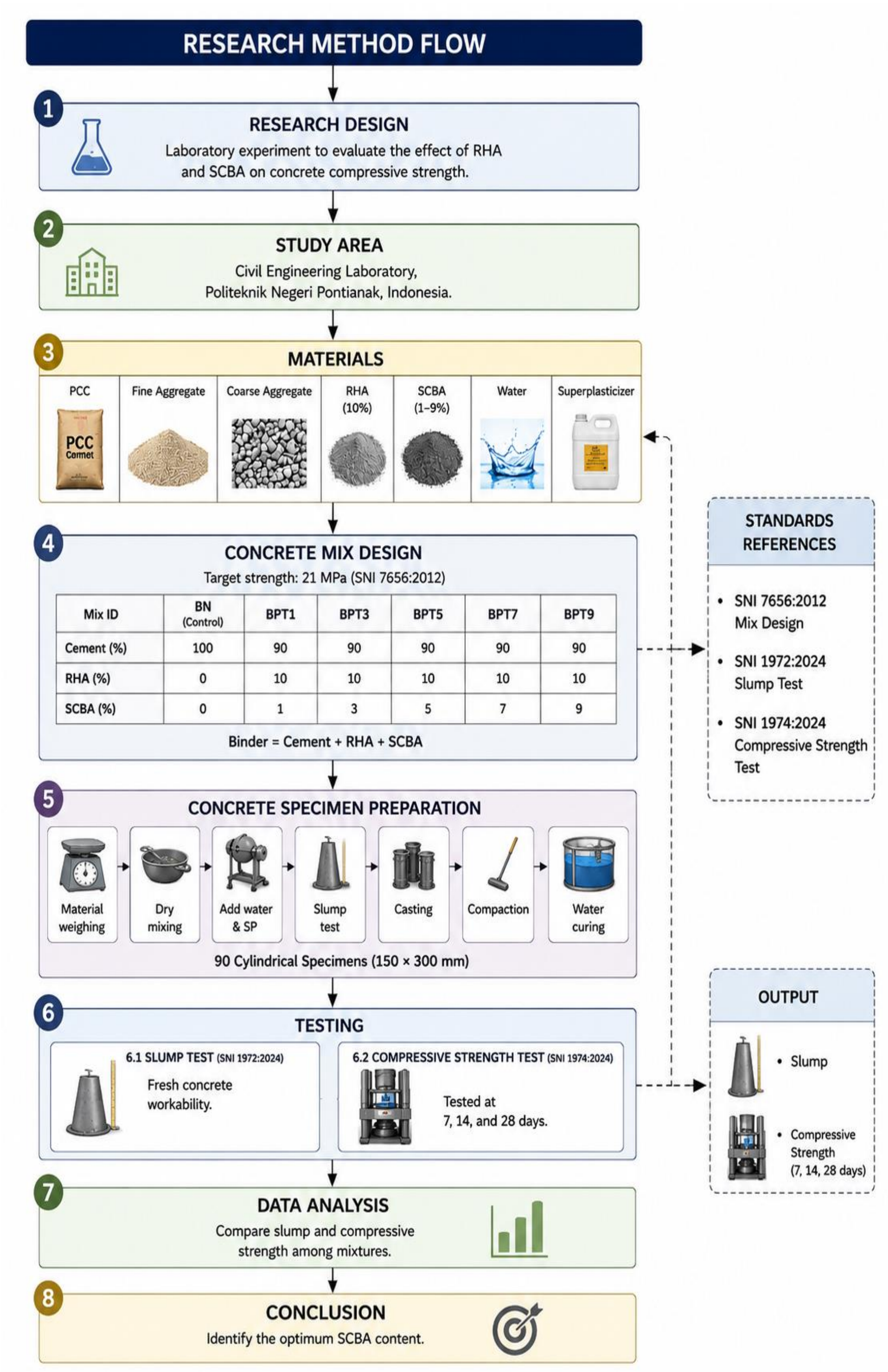


Figure 1. Research Method Flow

RESULTS AND DISCUSSION

Results

Physical Properties of Constituent Materials

Prior to concrete production, all constituent materials were characterized to verify their compliance with the physical property requirements specified in the relevant Indonesian National Standards (SNI). The laboratory characterization included moisture content, specific gravity, water absorption, bulk density, particle size distribution, and abrasion resistance tests for both fine and coarse aggregates. These preliminary evaluations were conducted to ensure that the aggregates possessed appropriate physical characteristics for concrete production and to provide the necessary parameters for concrete mix proportioning. The measured aggregate properties were subsequently used to determine water correction factors and establish the concrete mix design employed throughout the experimental program. The summarized physical properties of the aggregates are presented in Table 1.

Table 1. Physical properties of constituent aggregates.

Property	Fine Aggregate	Coarse Aggregate	Standard/Classification
Moisture content (%)	4.985	0.260	SNI requirement
Bulk specific gravity	2.570	2.685	Normal-weight aggregate
SSD specific gravity	2.580	2.695	—
Apparent specific gravity	2.610	2.720	—
Water absorption (%)	0.655	0.460	Acceptable
Bulk density (kg/dm^3)	1.538	1.482	SNI ASTM C29/C29M
Gradation	Zone II	Maximum size 40 mm	SNI grading

The laboratory results indicate that both fine and coarse aggregates satisfied the physical property requirements for concrete production. Fine aggregate exhibited a higher average moisture content than coarse aggregate, with values of 4.985% and 0.260%, respectively. The relatively higher moisture retained by the fine aggregate reflects its larger specific surface area and finer particle distribution. Nevertheless, both aggregates exhibited stable moisture conditions that could be accommodated through water correction during concrete batching. The measured water absorption values remained below the acceptable limits, indicating that only a limited quantity of mixing water would be absorbed during concrete production. The specific gravity values confirmed that both aggregates belonged to the normal-weight aggregate category commonly used for structural concrete. Furthermore, the measured bulk density values indicated satisfactory aggregate packing characteristics that support accurate volumetric proportioning during mix preparation. The aggregate characterization therefore confirmed that all constituent materials were suitable for the subsequent concrete production process.

Moisture Content

The moisture content test was performed to determine the amount of free water contained within the aggregates prior to concrete mixing. As presented in Table 2, the fine aggregate produced moisture contents of 5.670% and 4.300%, resulting in an average value of 4.985%. Although one measurement exceeded the upper limit because of local variations in stockpile moisture, the average value remained acceptable for concrete production after applying water correction during batching. Conversely, the coarse aggregate exhibited considerably lower moisture contents of 0.280% and 0.240%, with an average value of 0.260%. These results indicate that the coarse aggregate remained relatively dry and stable during the testing period. The substantial difference in moisture content between the two aggregates demonstrates the greater water retention capacity of the finer particles. Consequently, the measured moisture contents were incorporated into the concrete mix calculation to maintain the designed water-to-binder ratio throughout the experimental program.

Table 2. Moisture content of aggregates.

Aggregate	Test 1 (%)	Test 2 (%)	Average (%)
Fine aggregate	5.670	4.300	**4.985**
Coarse aggregate	0.280	0.240	**0.260**

Specific Gravity and Water Absorption

The specific gravity and water absorption tests were conducted to evaluate the density characteristics and water uptake capacity of the aggregates. The fine aggregate exhibited average bulk, saturated surface-dry (SSD), and apparent specific gravities of 2.570, 2.580, and 2.610, respectively, while the corresponding water absorption was 0.655%. Similarly, the coarse aggregate produced bulk, SSD, and apparent specific gravities of 2.685, 2.695, and 2.720, respectively, with an average water absorption of 0.460%. These values indicate that both aggregates possess relatively low porosity and stable density characteristics suitable for normal concrete production. In addition, the lower water absorption observed in the coarse aggregate suggests that it absorbs less mixing water than the fine aggregate during concrete preparation. The measured physical properties therefore provided reliable input parameters for concrete mix proportioning and water correction calculations.

Table 3. Specific gravity and water absorption of aggregates.

Property	Fine Aggregate	Coarse Aggregate
Bulk specific gravity	2.570	2.685
SSD specific gravity	2.580	2.695
Apparent specific gravity	2.610	2.720
Water absorption (%)	0.655	0.460

Bulk Density

Bulk density testing was performed to evaluate the packing characteristics of the aggregates used in this study. The fine aggregate exhibited an average bulk density of 1.538 kg/dm^3, while the coarse aggregate produced an average bulk density of 1.482 kg/dm^3. Both aggregates demonstrated consistent compacted and loose bulk densities, indicating stable particle packing during volumetric measurement. The measured values comply with the applicable SNI requirements and confirm that the aggregates possess appropriate volumetric characteristics for concrete production. The relatively small difference between the bulk densities of the two aggregates further indicates that the selected aggregate combination is capable of producing a stable concrete skeleton during mixing and compaction.

Table 4. Bulk density of aggregates.

Aggregate	Bulk density (kg/dm^3)
Fine aggregate	**1.538**
Coarse aggregate	**1.482**

Aggregate Gradation and Abrasion Resistance

The sieve analysis results demonstrated that the fine aggregate satisfied the grading requirements for Zone II (medium-coarse sand) according to the applicable Indonesian standard. The grading curve remained within the specified upper and lower limits, indicating an appropriate particle size distribution capable of providing satisfactory workability and particle packing. Likewise, the coarse aggregate exhibited a continuous gradation with a nominal maximum particle size of 40 mm, satisfying the required grading specification for normal concrete production. In addition to particle size distribution, the abrasion resistance of the coarse aggregate was evaluated to assess its mechanical durability. The abrasion test confirmed that the coarse aggregate complied with the specified quality requirements, indicating satisfactory resistance to mechanical wear during service.

Overall, the gradation and abrasion test results verified that both aggregates fulfilled the necessary quality criteria and were appropriate for use in the experimental concrete mixtures.

Concrete Mix Design

Six concrete mixtures were prepared to evaluate the influence of incorporating rice husk ash (RHA) and sugarcane bagasse ash (SCBA) on the compressive strength of sustainable concrete. One mixture was produced as the control concrete (BN), consisting entirely of Portland Composite Cement (PCC), while five modified mixtures were prepared by replacing 10% of the cement with rice husk ash and incorporating sugarcane bagasse ash as an additional filler at different proportions. The percentage of sugarcane bagasse ash was varied from 1% to 9% relative to the total binder weight, whereas the replacement level of rice husk ash was maintained constant throughout the experimental program. This experimental arrangement enabled the effect of increasing SCBA content to be evaluated while minimizing the influence of other mixture parameters. The concrete mix compositions adopted in this study are presented in Table 5.

Table 5. Concrete mixture compositions adopted in this study

Mix ID	Portland Composite Cement (PCC)	Rice Husk Ash (RHA)	Sugarcane Bagasse Ash (SCBA)*	Description
BN	100%	0%	0%	Control concrete
BPT1	90%	10%	1%	RHA + SCBA
BPT3	90%	10%	3%	RHA + SCBA
BPT5	90%	10%	5%	RHA + SCBA
BPT7	90%	10%	7%	RHA + SCBA
BPT9	90%	10%	9%	RHA + SCBA

To ensure a consistent comparison among mixtures, all specimens were designed to achieve a target compressive strength of 21 MPa using the mix design procedure specified in SNI 7656:2012. Except for the binder composition, all other mixture variables, including aggregate type, aggregate grading, water source, superplasticizer dosage, curing procedure, and specimen dimensions, were maintained constant throughout the investigation. Consequently, the binder composition represented the primary experimental variable affecting the fresh and hardened properties of concrete. A total of 90 cylindrical concrete specimens with dimensions of 150 mm × 300 mm were produced for laboratory testing. Each concrete mixture consisted of 15 specimens, comprising five specimens tested at 7 days, five specimens tested at 14 days, and five specimens tested at 28 days. This experimental design ensured equal sample sizes for every mixture and testing age, thereby providing a consistent basis for evaluating compressive strength development across all concrete mixtures. The distribution of concrete specimens is summarized in Table 6.

Table 6. Distribution of concrete specimens.

Mix ID	7 Days	14 Days	28 Days	Total Specimens
BN	5	5	5	15
BPT1	5	5	5	15
BPT3	5	5	5	15
BPT5	5	5	5	15
BPT7	5	5	5	15
BPT9	5	5	5	15
Total	**30**	**30**	**30**	**90**

The adopted mixture configuration establishes a systematic framework for evaluating the influence of progressively increasing SCBA content while maintaining a constant RHA replacement level. The control mixture provides the baseline performance of conventional concrete, whereas the modified mixtures facilitate comparison of the mechanical response resulting from the incorporation of agricultural waste-derived supplementary cementitious materials. The identical specimen dimensions, curing conditions, testing schedule, and sample allocation across all mixtures ensure that subsequent comparisons of compressive strength are attributable primarily to differences in binder composition rather than variations in specimen preparation or testing conditions. This experimental arrangement provides a consistent foundation for the compressive strength results presented in the following section.

Compressive Strength Development of Concrete

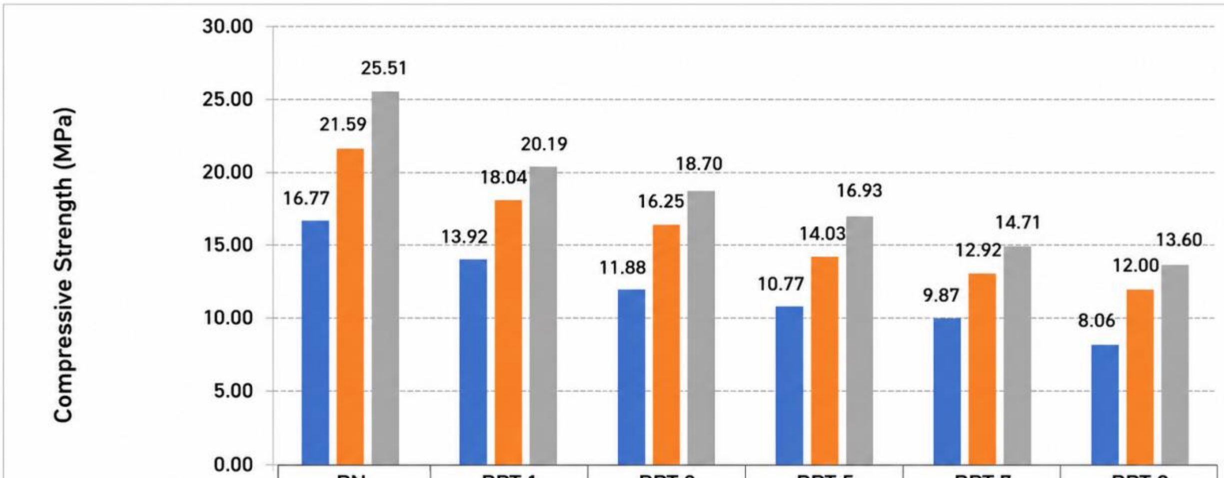
The compressive strength test was performed to evaluate the mechanical performance of concrete containing rice husk ash (RHA) and sugarcane bagasse ash (SCBA) at different curing ages. Six concrete mixtures were investigated, consisting of one control mixture (BN) and five modified mixtures containing a constant replacement of 10% rice husk ash with varying proportions of sugarcane bagasse ash ranging from 1% to 9%. For each curing age (7, 14, and 28 days), five cylindrical specimens were tested, and the average compressive strength was calculated. The summarized compressive strength results are presented in Table 7.

Table 7. Average compressive strength of concrete mixtures at different curing ages.

Mix ID	Binder Composition	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)	Increase 7–28 Days (%)
BN	100% PCC (Control)	**16.77**	**21.59**	**25.51**	**52.12**
BPT1	90% PCC + 10% RHA + 1% SCBA	**13.92**	**18.04**	**20.19**	**45.04**
BPT3	90% PCC + 10% RHA + 3% SCBA	**11.88**	**16.25**	**18.70**	**57.41**
BPT5	90% PCC + 10% RHA + 5% SCBA	**10.77**	**14.03**	**16.90**	**56.92**
BPT7	90% PCC + 10% RHA + 7% SCBA	**9.87**	**12.92**	**14.71**	**49.04**
BPT9	90% PCC + 10% RHA + 9% SCBA	**8.06**	**12.00**	**13.60**	**68.73**

The compressive strength results demonstrate a continuous increase in strength with curing age for all concrete mixtures. Regardless of the binder composition, the average compressive strength measured at 14 days exceeded that obtained at 7 days, while the highest values were consistently achieved after 28 days of curing. This trend indicates that strength development progressed throughout the hydration period in every concrete mixture evaluated in this study. The control concrete (BN) consistently exhibited the highest compressive strength at all curing ages, recording average strengths of 16.77 MPa, 21.59 MPa, and 25.51 MPa at 7, 14, and 28 days, respectively. Among the modified mixtures, BPT1 produced the highest compressive strength throughout the testing period, reaching 20.19 MPa after 28 days of curing. Conversely, the lowest compressive strengths were consistently observed in BPT9, which recorded average strengths of 8.06 MPa, 12.00 MPa, and 13.60 MPa at the respective curing ages.

A gradual decline in compressive strength was observed as the percentage of sugarcane bagasse ash increased from 1% to 9%, while the rice husk ash replacement level remained constant at 10%. At 28 days, the compressive strength decreased from 20.19 MPa for BPT1 to 18.70 MPa, 16.90 MPa, 14.71 MPa, and 13.60 MPa for BPT3, BPT5, BPT7, and BPT9, respectively. The same pattern was evident at both 7 and 14 days, indicating a consistent ranking of concrete mixtures throughout the curing period. The relative increase in compressive strength between 7 and 28 days differed among the concrete mixtures. The control concrete exhibited a strength increase of 52.12%, while the modified mixtures showed increases ranging from 45.04% to 68.73%. The highest percentage increase was recorded by BPT9, although this mixture still exhibited the lowest absolute compressive strength among all mixtures. This finding indicates that mixtures with lower early-age strength experienced greater relative strength development during prolonged curing.



	BN	BPT 1	BPT 3	BPT 5	BPT 7	BPT 9
7-Day Compressive Strength	16.77	13.92	11.88	10.77	9.87	8.06
14-Day Compressive Strength	21.59	18.04	16.25	14.03	12.92	12.00
28-Day Compressive Strength	25.51	20,19	18,70	16.93	14.71	13.60

Concrete Mixtures

Figure 2. Developent of the Average Compressive Strength of Concrete Mixtures at Curing Ages of 7, 14, and 28 days.

Figure 2 illustrates the development of compressive strength for all concrete mixtures at curing ages of 7, 14, and 28 days. Regardless of the binder composition, all mixtures exhibited a continuous increase in compressive strength with prolonged curing time. The control concrete (BN) consistently achieved the highest compressive strength throughout the testing period, while the modified concrete mixtures exhibited lower strength values than the control mixture at every curing age. At the age of 7 days, the control concrete (BN) reached an average compressive strength of 16.77 MPa, whereas the modified mixtures recorded strengths ranging from 8.06 MPa to 13.92 MPa. Among the modified mixtures, BPT1 produced the highest early-age compressive strength (13.92 MPa), followed by BPT3 (11.88 MPa), BPT5 (10.77 MPa), BPT7 (9.87 MPa), and BPT9 (8.06 MPa). The results indicate that increasing the proportion of sugarcane bagasse ash was associated with progressively lower compressive strength during the initial curing stage. A similar trend was observed after 14 days of curing. The average compressive strength of the control concrete increased to 21.59 MPa, while the modified mixtures achieved strengths of 18.04 MPa, 16.25 MPa, 14.03 MPa, 12.92 MPa, and 12.00 MPa for BPT1, BPT3, BPT5, BPT7, and BPT9, respectively. Compared with the 7-day results, all mixtures demonstrated continued strength development, indicating ongoing hydration during the intermediate curing period.

After 28 days of curing, all concrete mixtures reached their maximum measured compressive strength. The control concrete achieved 25.51 MPa, followed by 20.19 MPa for BPT1, 18.70 MPa for BPT3, 16.93 MPa for BPT5, 14.71 MPa for BPT7, and 13.60 MPa for BPT9. Although all modified mixtures continued to gain strength with curing time, none exceeded the compressive strength of the control concrete. The ranking of compressive strength remained unchanged throughout the curing period, with BN consistently producing the highest strength and BPT9 producing the lowest.

The percentage reduction in compressive strength relative to the control concrete is summarized in Table 8. At the age of 7 days, the strength reductions ranged from 16.99% for BPT1 to 51.82% for BPT9. After 14 days, the reductions ranged from 16.44% to 44.42%, while at 28 days, the reductions varied between 20.85% and 46.69%. Across all curing ages, greater SCBA incorporation was associated with larger reductions in compressive strength compared with the control mixture. Nevertheless, all concrete mixtures exhibited continuous strength development between 7 and 28 days, confirming that compressive strength increased progressively throughout the curing period.

Table 8. Compressive Strength and Percentage Reduction Relative to the Control Concrete

No.	Mix ID	Compressive Strength (MPa)			Strength Reduction (%)		
		7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
1	BN	16.77	21.59	25.51	0.00	0.00	0.00
2	BPT1	13.92	18.04	20.19	16.99	16.44	20.85
3	BPT3	11.88	16.25	18.70	29.16	24.73	26.77
4	BPT5	10.77	14.03	16.93	35.78	35.02	33.63
5	BPT7	9.87	12.92	14.71	41.14	40.16	42.34
6	BPT9	8.08	12.00	13.60	51.82	44.42	46.69

Table 8 summarizes the compressive strength and percentage reduction of all concrete mixtures relative to the control concrete at curing ages of 7, 14, and 28 days. The control mixture (BN) consistently achieved the highest compressive strength throughout the testing period, whereas all modified mixtures exhibited lower strength values. The magnitude of strength reduction increased with the increasing proportion of sugarcane bagasse ash, with BPT1 showing the smallest reduction and BPT9 the largest at each curing age. Despite these differences, all mixtures demonstrated continuous strength development during curing, indicating progressive increases in compressive strength from 7 to 28 days. These results provide a comparative overview of the mechanical performance of the control and modified concrete mixtures before further interpretation of the influence of agricultural waste incorporation.

Discussion

The compressive strength results demonstrate that the incorporation of agricultural waste-derived supplementary cementitious materials significantly influenced the mechanical performance of concrete throughout the curing period. All concrete mixtures exhibited a continuous increase in compressive strength from 7 to 28 days, confirming that strength development progressed consistently during hydration. Nevertheless, the control concrete consistently produced higher compressive strength than all modified mixtures at every curing age, indicating that replacing a portion of Portland Composite Cement with rice husk ash and sugarcane bagasse ash altered the early and later-age mechanical response of the concrete. Among the modified mixtures, BPT1 exhibited the highest compressive strength, whereas BPT9 consistently recorded the lowest values, suggesting that increasing the proportion of sugarcane bagasse ash was associated with a gradual reduction in compressive strength. This trend became evident not only in the absolute compressive strength values but also in the percentage reduction relative to the control concrete, which increased as the SCBA content increased from 1% to 9%. Although the modified concretes exhibited lower strength than the control mixture, all mixtures continued to gain strength during curing, indicating that hydration and cementitious reactions remained active throughout the testing period. The progressive increase in compressive strength across all curing ages also suggests that the incorporation of agricultural waste materials did not prevent the normal development of hardened concrete, although it affected the magnitude of strength achieved. These findings indicate that the binder composition plays an important role in determining the balance between sustainability objectives and mechanical performance in concrete production (Aziz et al., 2024; Hossain et al., 2022; M. A. Khan et al., 2025). Consequently, the observed variations in compressive strength provide a basis for evaluating the effectiveness of combining rice husk ash and sugarcane bagasse ash as supplementary cementitious materials in sustainable concrete systems. Overall, the experimental results demonstrate a clear relationship between binder modification and compressive strength development, highlighting the sensitivity of concrete performance to variations in agricultural waste incorporation.

The gradual reduction in compressive strength observed with increasing sugarcane bagasse ash content is consistent with numerous previous studies investigating agricultural waste as supplementary cementitious materials. Previous researchers have reported that moderate replacement levels of pozzolanic materials generally maintain acceptable mechanical performance (Derrouiche et al., 2025; Samadi et al., 2025), whereas excessive replacement levels often reduce compressive strength because the amount of available hydraulic cement becomes insufficient to sustain the formation of cementitious products during the early stages of hydration. Similar findings were reported by studies evaluating rice husk ash, where limited replacement levels enhanced particle packing and long-term pozzolanic activity, but excessive replacement resulted in reduced early-age strength owing to slower reaction kinetics (Albadrani, 2025; Gu et al., 2026; Meerapillai Sainulabdeen & Sathyan, 2026; Miah et al., 2025; Parvez et al., 2026). Investigations involving sugarcane bagasse ash have likewise demonstrated that the mechanical performance of concrete depends strongly on replacement percentage, ash fineness, combustion quality, and silica content. The present study follows a comparable trend, as the lowest SCBA incorporation (BPT1) produced considerably higher compressive strength than mixtures containing larger SCBA proportions. This indicates that increasing SCBA content beyond a certain level may reduce the contribution of Portland cement during the early hydration process while the pozzolanic reaction has not yet fully developed. Similar observations have also been reported for binary and ternary blended cement systems, where the interaction between multiple supplementary cementitious materials influences the balance between filler effects and cement dilution. Therefore, the decrease in compressive strength observed in BPT3, BPT5, BPT7, and BPT9 appears to be consistent with previously established behaviour of blended cement concrete incorporating agricultural ashes. Despite this reduction, the continuous increase in compressive strength up to 28 days indicates that hydration and secondary reactions remained active during curing, although the overall strength level remained below that of the control concrete. These similarities with previous investigations strengthen the reliability of the present findings and demonstrate that the observed mechanical behaviour follows the general characteristics of concrete containing agricultural waste-based supplementary cementitious materials.

An important observation from this study is that all modified concrete mixtures continued to exhibit substantial strength development between 7 and 28 days despite their lower initial compressive strength. The increase in compressive strength over time suggests that the cementitious matrix continued to densify throughout the curing period as hydration progressed and additional reaction products were gradually formed. Earlier investigations have consistently shown that pozzolanic materials such as rice husk ash contribute more significantly to later-age strength than to early-age strength because their reaction depends on calcium hydroxide released during cement hydration. Consequently, strength development in blended concrete generally becomes more pronounced after extended curing periods compared with ordinary Portland cement concrete. The present results demonstrate this behaviour, as every modified mixture experienced continuous compressive strength gains between successive testing ages, although the rate of improvement differed among mixtures. In particular, mixtures containing higher SCBA proportions exhibited relatively greater percentage increases from 7 to 28 days despite maintaining lower absolute compressive strength values than the control mixture. This behaviour indicates that relative strength development and absolute strength performance should be interpreted as complementary indicators when evaluating blended concrete systems. Previous studies on ternary blended concrete have similarly reported that mixtures with lower early-age strength may continue to gain strength at later ages owing to the prolonged pozzolanic reaction and gradual refinement of the pore structure (Anderson & Adesina, 2026; Yehualaw et al., 2025; Zhang et al., 2026). Accordingly, the curing period becomes an important factor influencing the mechanical performance of concrete incorporating agricultural waste materials, particularly when supplementary cementitious materials partially replace conventional cement. These findings suggest that evaluating concrete performance solely at early ages may underestimate the long-term contribution of agricultural waste-based binders to strength development, although the ultimate compressive strength remains dependent on the proportion and characteristics of the supplementary materials incorporated.

The mechanical performance observed in this study also reflects the combined influence of material composition and curing duration on concrete behaviour. Although all modified mixtures exhibited lower compressive strength than the control concrete, the progressive strength development observed throughout the curing period indicates that the blended binder system remained chemically active during hydration. The relatively better performance of BPT1 suggests that a lower proportion of sugarcane bagasse ash was more compatible with the constant 10% rice husk ash replacement adopted in this investigation. This finding supports previous studies reporting that optimum proportions of supplementary cementitious materials can partially compensate for cement reduction by improving particle packing and contributing to secondary cementitious reactions without substantially compromising mechanical properties (Benjeddou & Aldahdooh, 2026; Robalo et al., 2021; Zhang et al., 2026). Conversely, higher SCBA contents in BPT5, BPT7, and BPT9 were associated with progressively lower compressive strengths, indicating that the increase in ash proportion exceeded the level at which the beneficial filler and pozzolanic effects could adequately compensate for cement dilution. Similar trends have been documented in studies involving ternary blended concrete incorporating rice husk ash, fly ash, silica fume, and other agricultural ashes, where excessive replacement levels consistently resulted in reduced compressive strength despite continued hydration (Ahmed et al., 2024; Fapohunda et al., 2023; R. A. Khan & Haq, 2020; Mohamed & Tayeh, 2026; Ullah et al., 2025). Variations in ash fineness, silica content, combustion temperature, and particle morphology have also been identified as important factors governing the efficiency of pozzolanic reactions and the resulting mechanical performance. Consequently, differences in compressive strength among published studies often reflect differences in material processing and replacement ratios rather than inconsistencies in the fundamental behaviour of supplementary cementitious materials. The findings of the present study therefore reinforce the importance of optimizing the dosage of agricultural waste materials to achieve an appropriate balance between environmental sustainability and structural performance. Overall, the experimental evidence demonstrates that the proportion of sugarcane bagasse ash is a critical variable influencing the compressive strength of concrete when used together with rice husk ash as a supplementary cementitious material.

From a practical perspective, the results indicate that agricultural waste materials can be incorporated into concrete production while maintaining measurable strength development throughout the curing period, although careful proportioning is required to preserve mechanical performance. The use of rice husk ash and sugarcane bagasse ash offers an alternative approach for reducing cement consumption and promoting the utilization of renewable industrial by-products that would otherwise contribute to environmental waste accumulation. Previous investigations have highlighted that replacing a portion of cement with well-processed agricultural ashes can reduce greenhouse gas emissions associated with cement production while simultaneously improving resource efficiency within the construction sector. The present study supports these broader sustainability objectives by demonstrating that concrete containing agricultural waste-derived supplementary cementitious materials continued to develop compressive strength up to 28 days despite exhibiting lower absolute strength than the control mixture. Among the modified mixtures, BPT1 achieved the highest compressive strength, suggesting that relatively low SCBA incorporation provided the most favourable balance between cement replacement and mechanical performance under the conditions investigated. This observation is consistent with previous reports indicating that the optimum replacement level of supplementary cementitious materials is generally limited and should be determined experimentally for each material source because of variations in chemical composition and physical characteristics. Accordingly, the results emphasize that the engineering application of agricultural waste-based binders should prioritize optimized mixture proportions rather than maximizing the replacement percentage alone. The findings also contribute to the growing body of evidence supporting the feasibility of integrating agricultural waste into sustainable concrete technology while recognizing the need to maintain adequate structural performance. Future improvements in ash processing techniques, including controlled combustion and finer particle grinding, may further enhance the reactivity of rice husk ash and sugarcane bagasse ash, thereby improving the mechanical properties of blended concrete. Collectively, these findings demonstrate that optimizing the interaction between binder composition and curing conditions is essential for maximizing the engineering potential of agricultural waste-based supplementary cementitious materials in sustainable concrete applications.

Implications

The findings of this study provide important implications for both sustainable concrete technology and the broader utilization of agricultural waste in the construction industry. The experimental results demonstrate that incorporating rice husk ash and sugarcane bagasse ash as supplementary cementitious materials can contribute to reducing the dependence on Portland cement while maintaining continuous compressive strength development throughout the curing period. From an environmental perspective, this approach promotes the beneficial reuse of abundant agricultural by-products that are commonly disposed of through open burning or landfilling, thereby supporting waste valorization and circular economy principles. From an engineering perspective, the results indicate that the proportion of supplementary cementitious materials should be carefully optimized to achieve an appropriate balance between sustainability objectives and structural performance. Among the investigated mixtures, the combination containing 10% rice husk ash and 1% sugarcane bagasse ash exhibited the most favourable mechanical performance, suggesting that relatively low levels of sugarcane bagasse ash are more suitable for maintaining compressive strength under the investigated conditions. These findings provide practical guidance for engineers and concrete producers in selecting replacement levels that minimize cement consumption without causing excessive reductions in mechanical properties. The study also highlights that evaluating blended concrete solely on the basis of early-age strength may underestimate its overall performance because all mixtures continued to gain strength during prolonged curing. Consequently, the curing period should be considered an essential factor when assessing the structural feasibility of concrete incorporating agricultural waste-derived binders. Furthermore, the experimental evidence supports the integration of agricultural waste materials into sustainable construction practices as a viable strategy for lowering the environmental footprint associated with cement production while promoting resource efficiency. The findings may also serve as a scientific reference for future standards and technical guidelines concerning the application of rice husk ash and sugarcane bagasse ash in blended cement concrete. In addition, the results provide a valuable foundation for further material optimization through improvements in ash processing techniques, particle fineness, and binder proportioning to enhance both sustainability and mechanical performance. Overall, this study contributes to the advancement of environmentally responsible concrete technology by demonstrating that appropriately proportioned agricultural waste-based supplementary cementitious materials can support the development of more sustainable construction materials while maintaining acceptable engineering performance.

Limitations and Suggestions for Future Research

This study has several limitations that should be acknowledged. First, the evaluation focused only on compressive strength, without investigating other mechanical and durability properties of concrete. Second, the experimental program was limited to a fixed 10% rice husk ash replacement combined with sugarcane bagasse ash contents ranging from 1% to 9%, which may not represent the optimum binder composition. Third, the compressive strength was assessed only up to 28 days, limiting the understanding of long-term performance. Future research should investigate a wider range of replacement levels and longer curing periods to identify the optimum proportion of agricultural waste-based supplementary cementitious materials. Further studies are also recommended to evaluate durability characteristics, including water absorption, chloride penetration, sulfate resistance, and carbonation, to better assess long-term serviceability. In addition, microstructural analyses using techniques such as SEM, XRD, and FTIR are needed to explain the mechanisms underlying strength development. The influence of ash fineness and different processing methods should also be explored to improve pozzolanic reactivity. Furthermore, future studies should include environmental and economic assessments to evaluate the practical feasibility of large-scale implementation. These improvements would provide a more comprehensive understanding of the engineering performance and sustainability benefits of agricultural waste-based concrete. Overall, expanding the experimental scope will strengthen the scientific evidence supporting the application of rice husk ash and sugarcane bagasse ash in sustainable concrete technology.

CONCLUSION

This study demonstrated that incorporating rice husk ash (RHA) and sugarcane bagasse ash (SCBA) as supplementary cementitious materials influenced the compressive strength of sustainable concrete. All concrete mixtures exhibited continuous strength development from 7 to 28 days, indicating ongoing hydration during curing. However, increasing the SCBA content progressively reduced the compressive strength compared with the control mixture. The mixture containing 10% RHA and 1% SCBA (BPT1) achieved the best mechanical performance among the modified concretes. These findings indicate that the proportion of agricultural waste-based binders plays a critical role in determining concrete strength. Therefore, optimizing the replacement level is essential to balance structural performance with environmental sustainability. Overall, the study confirms that appropriately proportioned RHA and SCBA have strong potential as sustainable supplementary cementitious materials for reducing cement consumption while maintaining acceptable compressive strength.

AUTHOR CONTRIBUTIONS STATEMENT

Arifurrahman contributed to the conceptualization of the study, research design, experimental investigation, data collection, formal analysis, interpretation of the results, visualization, and preparation of the original manuscript draft. Agil Dwi Cahyadi contributed to the research methodology, laboratory supervision, data validation, statistical analysis, and critical revision of the manuscript. Pramudya Kurniawan contributed to the development of the experimental framework, investigation, data interpretation, and manuscript review and editing.

Randy Setiawan contributed to the supervision of the research, validation of the research process, interpretation of the findings, and critical review of the manuscript. Wattini contributed to data verification, laboratory coordination, methodological evaluation, and manuscript revision. Qalbi Hafiyyan contributed to data curation, visualization, final manuscript editing, and quality assurance of the research outputs. All authors reviewed, approved, and agreed to the final version of the manuscript prior to submission.

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