

RESEARCH ARTICLE

The Influence of Sugarcane Bagasse Ash and Superplasticizer on the Compressive Strength of Concrete

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ABSTRACT

This study investigates the effect of sugarcane bagasse ash (SBA) and superplasticizer on the compressive strength of Portland cement concrete to support sustainable concrete development. In contrast to previous studies that mainly focused on SBA as a partial cement replacement, this study highlights the combined use of SBA with a fixed superplasticizer dosage to identify an optimum mixture proportion for strength improvement. Concrete mixtures were prepared using Portland cement as the primary binder with SBA replacement levels of 5%, 10%, 15%, and 20% by weight of cement. A fixed dosage of 1% superplasticizer was added based on workability requirements, while the mixtures were designed using controlled proportions and a constant water-cement ratio. Control concrete and concrete containing only superplasticizer were also tested for comparison. Cylindrical specimens of 150 mm × 300 mm were cast and tested under uniaxial compression after 28 days of curing. The results showed a non-linear effect of SBA on compressive strength. The control concrete achieved 28.99 MPa, while the superplasticizer-only mixture reached 28.31 MPa. SBA-modified concretes achieved 28.65 MPa, 31.48 MPa, 30.12 MPa, and 21.06 MPa at 5%, 10%, 15%, and 20% replacement, respectively. The optimum strength of 31.48 MPa was obtained at 10% SBA with 1% superplasticizer. This improvement was attributed to the combined effect of pozzolanic activity and particle packing at moderate SBA content. However, excessive SBA reduced strength due to cement dilution and limited reactivity. These findings confirm that optimized SBA with superplasticizer can be used as a viable supplementary cementitious material for sustainable concrete production.

Keywords: Sugarcane Bagasse Ash, Compressive Strength, Cement Concrete, Superplasticizer, Sustainable

INTRODUCTION

The rapid expansion of infrastructure development has led to a continuous increase in global concrete demand, as concrete remains the most widely used construction material due to its mechanical performance, durability, and cost efficiency. However, Portland cement production is highly energy-intensive and contributes significantly to global CO₂ emissions, accounting for a substantial share of anthropogenic greenhouse gas emissions in the construction sector [1, 2]. This environmental concern has encouraged the development of sustainable concrete through the use of alternative cementitious materials that can reduce cement consumption without compromising mechanical performance [1, 3]. One of the most effective strategies to reduce cement-related emissions is the partial replacement of Portland cement with supplementary cementitious materials (SCMs) derived from industrial and agricultural by-products [1, 2]. Among agricultural wastes, sugarcane bagasse ash (SBA), a by-product of sugar industry combustion, has attracted increasing attention due to its high silica content and latent pozzolanic reactivity after controlled burning and grinding processes [1, 4]. Recent studies have confirmed that SBA can contribute to the formation of additional calcium silicate hydrate (C-S-H) gel, thereby improving microstructure densification and compressive strength when used at appropriate replacement levels [5-7]. Experimental evidence shows that SBA incorporation can enhance hydration processes and mechanical performance through filler and pozzolanic effects, particularly at moderate replacement levels [5, 7, 8]. Its application has also been successfully extended to ultra-high-performance concrete (UHPC), where SBA contributes to strength enhancement and microstructural refinement [5]. However, the performance of SBA is highly dependent on combustion conditions, particle fineness, and replacement ratio [1, 7]. While moderate substitution improves mechanical properties, excessive replacement leads to clinker dilution and reduced hydration activity, resulting in strength reduction [6, 9]. This indicates that SBA cannot simply be applied as a general cement substitute without identifying the optimum replacement level for a specific concrete mixture.

Furthermore, recent studies indicate that SBA can be effectively combined with other supplementary materials such as metakaolin, fly ash, and fibers to achieve synergistic improvements in mechanical and durability performance. Nevertheless, such multi-component systems often introduce variability in mix design and complicate practical implementation in conventional construction practice [10, 11]. In addition to SCMs, chemical admixtures such as superplasticizers play a crucial role in modern concrete technology by enhancing workability and reducing water demand without compromising strength. When used with fine pozzolanic materials such as SBA, superplasticizer may improve particle dispersion and fresh concrete flow, while also influencing hydration and compressive strength development. The interaction between superplasticizers and fine pozzolanic materials significantly influences particle dispersion, rheological behavior, hydration kinetics, and microstructural development of cement-based systems [7, 9]. Therefore, the combined use of SBA and superplasticizer requires further evaluation, particularly to determine whether improved workability can be achieved while maintaining or enhancing compressive strength in normal-strength concrete. Despite extensive research on

SBA-based cementitious materials, most existing studies focus on high-performance systems such as UHPC, self-compacting concrete, or engineered cementitious composites [5, 9, 10]. Although these studies demonstrate the potential of SBA, they do not fully represent the behavior of SBA in conventional normal-strength Portland cement concrete, which is more commonly used in practical construction. Limited attention has been given to the behavior of SBA in normal-strength Portland cement concrete under practical mix design conditions. Moreover, the combined effect of SBA replacement and superplasticizer dosage on compressive strength optimization in conventional concrete systems remains insufficiently investigated in the literature [2, 12]. This research gap justifies the need for a focused experimental study on normal-strength concrete incorporating SBA with a fixed 1% superplasticizer dosage. Therefore, this study investigates the compressive strength behavior of Portland cement concrete incorporating sugarcane bagasse ash (SBA) at replacement levels of 5%, 10%, 15%, and 20%, combined with a fixed 1% superplasticizer dosage. This study aims to determine the optimum sugarcane bagasse ash (SBA) replacement level that maximizes the 28-day compressive strength of normal-strength Portland cement concrete incorporating a constant 1% superplasticizer dosage. Through experimental testing and regression-based analysis, this research specifically evaluates the combined influence of SBA and superplasticizer on strength development under conventional concrete mix conditions. The novelty of this study lies in its focused assessment of SBA as a partial cement replacement in normal-strength concrete with a fixed superplasticizer dosage, providing practical evidence for the utilization of agricultural waste in sustainable and low-carbon concrete production.

LITERATURE REVIEW

CONCRETE AS A COMPOSITE MATERIAL

Concrete is a heterogeneous composite material composed of cement, fine aggregates, coarse aggregates, and water, forming a hardened matrix through hydration reactions. Its extensive use in civil engineering is attributed to its mechanical strength, durability, and versatility for structural applications. From a fundamental perspective, concrete behavior is governed by interactions between its constituent phases, particularly cement paste and aggregates, which control its overall mechanical and durability performance [13, 14]. Modern cement-based materials are considered multi-phase systems in which hydration kinetics, particle packing, and microstructural evolution determine macroscopic properties. Therefore, concrete should not be regarded as a simple mixture but as a chemically active composite system [13].

CEMENT AND PORTLAND CEMENT SYSTEM

Cement is a hydraulic binder that reacts chemically with water to form hydration products responsible for the hardening and strength development of concrete. When water is added to cement, a hydration reaction occurs, producing compounds that gradually fill the voids between particles and bind the aggregates into a solid mass. Unlike aggregates, which primarily function as filler materials and contribute to volume stability, cement plays a more active role by governing the binding mechanism, cohesion, and structural integrity of concrete [13, 14]. The quality, fineness, chemical composition, and proportion of cement in a concrete

mixture significantly influence workability, setting time, early-age strength, long-term strength, and durability. Portland cement is the most commonly used type of cement in structural concrete. It consists mainly of calcium silicate compounds, particularly tricalcium silicate and dicalcium silicate, which react with water to produce calcium silicate hydrate (C-S-H) and calcium hydroxide. Among these hydration products, C-S-H is considered the primary strength-giving phase because it forms a dense gel-like structure that binds the aggregate particles together and contributes to the hardened concrete matrix. The continuous formation of C-S-H during hydration explains why concrete strength increases with age, especially when adequate moisture and curing conditions are maintained. Portland cement is widely used in construction because of its predictable engineering performance, availability, compatibility with various aggregates and admixtures, and suitability for a wide range of mix designs and structural applications [14].

SUPPLEMENTARY CEMENTITIOUS MATERIALS AND SUGARCANE BAGASSE ASH

The use of supplementary cementitious materials (SCMs) has become a key strategy for reducing cement consumption and environmental impact. Among agricultural waste materials, sugarcane bagasse ash (SBA) has gained significant attention due to its high silica content and pozzolanic potential [1, 2]. SBA is produced by the combustion of sugarcane bagasse and contains reactive silica capable of reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), improving strength and microstructure [7]. Recent studies have confirmed the effectiveness of SBA in various cementitious systems, including ultra-high-performance concrete (UHPC), where it contributes to mechanical enhancement and microstructural densification [4, 5]. However, its performance strongly depends on combustion conditions, fineness, and replacement level [1, 7]. Excessive replacement of cement with SBA may reduce mechanical performance due to clinker dilution effects, while moderate replacement levels generally improve compressive strength and durability [6, 9]. Advanced studies also show that SBA can be combined with other SCMs, such as fly ash or fibers, to enhance performance synergistically [10, 11].

CHEMICAL ADMIXTURES AND SUPERPLASTICIZER

Chemical admixtures are materials added to concrete to modify fresh and hardened properties without significantly altering the base composition [13]. Superplasticizers are high-range water-reducing agents that improve workability and reduce water demand while maintaining or enhancing strength. Their mechanism involves dispersion of cement particles, reducing flocculation and improving hydration efficiency. The interaction between superplasticizers and fine pozzolanic materials such as SBA plays a critical role in determining rheological behavior, particle dispersion, and microstructural development of concrete [7, 9].

MIX DESIGN AND FRESH CONCRETE BEHAVIOR

Concrete mix design is a systematic procedure used to determine optimal proportions of cement, aggregates, water, and admixtures to achieve desired performance. It aims to ensure strength, workability, and economic efficiency in construction applications. Fresh concrete properties are commonly evaluated

using slump tests, which indicate consistency and workability. Slump behavior is influenced by water content, particle interaction, and admixture efficiency [14].

COMPRESSIVE STRENGTH AND DATA ANALYSIS

Compressive strength is the most important mechanical property of concrete, defined as the maximum load per unit area before failure. It is typically measured at 28 days as the standard reference for structural design [14]. Recent studies indicate that SBA incorporation can influence both mechanical strength and durability performance depending on mix composition and curing conditions [2, 12]. Improvements are generally associated with optimized replacement levels and proper material processing.

MATERIALS AND METHODS

RESEARCH DESIGN

The study was designed as a controlled laboratory experimental investigation to quantify the influence of sugarcane bagasse ash (SBA) as a partial cement replacement in normal concrete. The methodology was structured based on conventional cement composite principles [13, 14] and previous findings indicating that agricultural waste ashes can significantly modify hydration behavior and mechanical performance of cement-based materials [1,2]. The experimental program consisted of five sequential stages: literature review, material characterization, mix design, specimen fabrication, and mechanical testing. Cylindrical specimens with dimensions of 150 mm × 300 mm were used in accordance with standard concrete testing procedures. Six mixture groups were prepared, including a control mix, a superplasticizer-only mix, and four SBA replacement levels (5%, 10%, 15%, and 20%), while maintaining a constant superplasticizer dosage of 1% by cement weight. All specimens were tested at 28 days curing age, which is widely recognized as the standard benchmark for evaluating compressive strength development in Portland cement systems [14].

MIX DESIGN AND SPECIMEN PREPARATION

The experimental preparation began with the conditioning of all materials, calibration of testing equipment, and preliminary characterization of aggregates to ensure consistency before concrete mixing. The sugarcane bagasse ash (SBA) used in this study was obtained from the controlled combustion of agricultural waste, so that the resulting ash had a more uniform physical condition. Before being incorporated into the concrete mixture, the SBA was air-dried for 24 hours to reduce and stabilize its moisture content. This step was carried out to minimize variations in water demand during mixing and to ensure that the SBA could be used under relatively consistent conditions throughout the experimental process.

Aggregate grading and moisture condition adjustments were conducted to ensure consistency in mix design input parameters. This step is critical because aggregate characteristics significantly influence concrete strength and workability behavior [14]. The materials used in this study were selected in accordance with standard concrete mix design requirements and prior research on SBA-based cement systems [2,8,10]. The materials include Ordinary Portland Cement Type I, natural river sand from Krueng Aceh River as fine aggregate, crushed coarse aggregate with a maximum size of 19.1 mm, potable water from the laboratory supply, sugarcane bagasse ash (SBA) as supplementary cementitious material, and

a commercial polycarboxylate-based superplasticizer (Sika). Cement and aggregates were visually and physically verified prior to use to ensure compliance with SNI and ASTM standards. SBA was used as received after drying without further chemical modification, consistent with previous studies reporting its pozzolanic potential after combustion [2,5].

Concrete mix design was developed using the ACI 211.1-91 method for normal strength concrete with a target compressive strength of 25 MPa. A constant water-to-cement ratio (w/c) of 0.30 was maintained to isolate the effect of SBA incorporation. The experimental matrix consisted of six mix groups, as presented in Table 1, including a control mix, a superplasticizer-only mix, and SBA-modified mixes at 5%, 10%, 15%, and 20% replacement levels. This range was selected based on previous studies indicating that SBA typically exhibits optimal performance at low-to-medium replacement levels due to its pozzolanic activity and filler effect [4,7,10].

EXPERIMENTAL PROCEDURE

The experimental program was carried out using a systematic laboratory-based methodology encompassing aggregate characterization, mix design, mixing procedure, specimen fabrication, curing regime, compressive strength testing, and statistical evaluation. Physical properties of fine and coarse aggregates were determined in accordance with ASTM standards, including specific gravity, water absorption, bulk density, and sieve analysis. These parameters play a crucial role in controlling mix proportioning and significantly influence concrete workability, density, and mechanical performance [14]. The mix design was developed using the ACI 211.1-91 method for normal-strength concrete, targeting a compressive strength of 25 MPa while ensuring adequate workability. The incorporation of sugarcane bagasse ash (SBA) as a partial cement replacement follows previous studies reporting its effectiveness in improving sustainability and reducing Portland cement consumption in cement-based materials [2,8,10].

Table 1. Experimental matrix of cylindrical concrete specimens

Specimen Code	Number of Specimens	Sugarcane Bagasse Ash (SBA)	Superplasticizer (SP)
PC, SBA 0%, SP 0%	5	0%	0.00%
PC, SBA 0%, SP 1%	5	0%	1.00%
PC, SBA 5%, SP 1%	5	5%	1.00%
PC, SBA 10%, SP 1%	5	10%	1.00%
PC, SBA 15%, SP 1%	5	15%	1.00%
PC, SBA 20%, SP 1%	5	20%	1.00%

All constituent materials, including cement, fine aggregate, coarse aggregate, and SBA, were dry-mixed in a mechanical mixer to ensure uniform distribution prior to water addition. Water combined with superplasticizer was then gradually introduced into the mixture, followed by continued mixing for approximately two minutes until a homogeneous and workable concrete was achieved. The use of superplasticizer was essential to improve particle dispersion, enhance workability, and reduce water demand in mixtures containing fine pozzolanic materials [12]. Fresh concrete was subsequently cast into cylindrical molds (150 mm × 300 mm) in three layers, each compacted using 25 rodding strokes to minimize entrapped air and ensure uniform density. After casting, specimen

surfaces were leveled and properly labeled for identification. The experimental setup and specimen arrangement during compressive strength testing are shown in Figure 1.

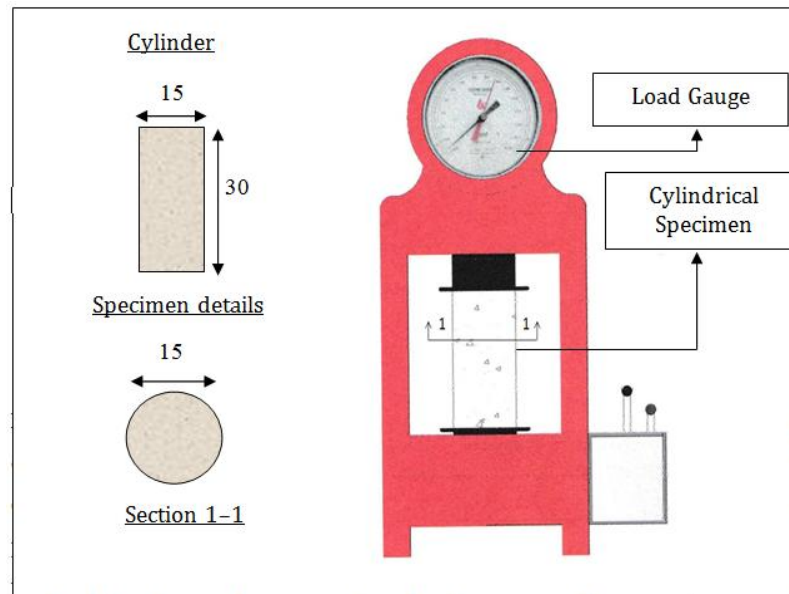


Figure 1. Experimental setup and arrangement of cylindrical specimens

Specimens were demolded after 24 hours and cured in water until reaching 28 days of age to ensure continuous hydration and full strength development. Proper curing conditions are recognized as a critical factor governing the long-term mechanical performance of cementitious composites [14]. Compressive strength testing was conducted at 28 days using a standard compression testing machine. Prior to testing, each specimen was weighed and dimensionally verified to ensure measurement accuracy. Axial loading was applied continuously until failure, and the maximum load was recorded for compressive strength calculation using standard formulations. Experimental results were subjected to statistical analysis to evaluate the influence of SBA and superplasticizer on compressive strength behavior. The performance of modified mixtures was compared against the control concrete to identify strength enhancement or reduction trends. Regression analysis was further applied to establish the relationship between SBA content and compressive strength, and to determine the optimum replacement level for maximum mechanical performance. This analytical framework aligns with current developments in sustainable concrete research, where experimental investigation is integrated with statistical modeling to optimize material efficiency and environmental performance [13].

TESTING PROCEDURES

Compressive strength testing was performed using an unconfined compressive strength (UCS) testing machine, in which axial load was applied continuously at a controlled rate until specimen failure occurred. The compressive strength was calculated using Equation (1):

$$F'c = \frac{P}{A} \quad (1)$$

where $f'c$ is the compressive strength (N/mm^2), P is the maximum applied load (N), and A is the cross-sectional area of the specimen (mm^2).

Workability of fresh concrete was assessed using the slump test to evaluate consistency and flow characteristics prior to hardening. This test was selected as it represents a key parameter governing placement performance and compaction quality of normal concrete mixtures.

DATA ANALYSIS

The compressive strength data were analyzed using statistical parameters to evaluate variability and consistency. The standard deviation was calculated using Equation 2, the mean compressive strength was determined using Equation 3 and the coefficient of variation (Cv) was calculated using Equation 4.

$$S = \sqrt{\frac{\sum_{i=1}^n (X_i - X)^2}{n-1}} \quad (2)$$

$$X = \frac{\sum_{i=1}^n X_i}{n} \quad (3)$$

$$Cv = \frac{S}{X} \times 100\% \quad (4)$$

where S is the standard deviation, X_i is the compressive strength of each specimen (N/mm^2), X is the average compressive strength (N/mm^2), and n is the number of specimens. The influence of SBA content on compressive strength was evaluated based on observed experimental trends. Each mixture was compared with the control concrete to assess strength enhancement or reduction, and the results were used to determine the optimum SBA replacement level that yields the highest mechanical performance under the specified mix conditions.

RESULTS AND DISCUSSION

PHYSICAL PROPERTIES OF AGGREGATES

The physical properties of fine and coarse aggregates were evaluated prior to concrete mixing to ensure their suitability as constituent materials. The tests included bulk density, specific gravity (SSD and OD conditions), water absorption, and fineness modulus. The results indicate that all aggregates used in this study generally satisfy the standard requirements for normal concrete production.

Table 2. Physical properties of aggregates used in the study

Property	Coarse Aggregate (19.1 mm)	Coarse Sand	Fine Sand
Specific Gravity (SSD)	2.463	–	2.199
Specific Gravity (OD)	2.439	–	2.153
Absorption (%)	2.650	1.794	2.028
Bulk Density (kg/L)	1.858	2.107	1.733
Fineness Modulus	6.382	3.713	2.850

Table 2 showed the coarse aggregate exhibited a specific gravity (SSD) of 2.463 and an absorption value of 2.650%. Although the absorption is slightly higher than the ideal range for coarse aggregate, the overall values still indicate acceptable quality for structural concrete applications with proper mix adjustment. The fineness modulus (FM) of coarse sand (3.713) and fine sand (2.850) falls within the recommended ranges for concrete production, indicating proper grading suitability.

AGGREGATE GRADATION

The aggregate gradation was examined using sieve analysis with standard sieves ranging from 3/4 inch to No. 200. This analysis was carried out to determine the particle size distribution of the aggregate used in the concrete mixture. Aggregate gradation is an important factor in concrete mix design because it influences workability, particle packing, void content, cement paste demand, and the strength development of hardened concrete. The resulting gradation curve for a maximum aggregate size of 19.1 mm is presented in Figure 2. This curve provides a visual representation of the aggregate distribution and is used to assess whether the selected aggregate falls within the acceptable grading limits for normal concrete production.

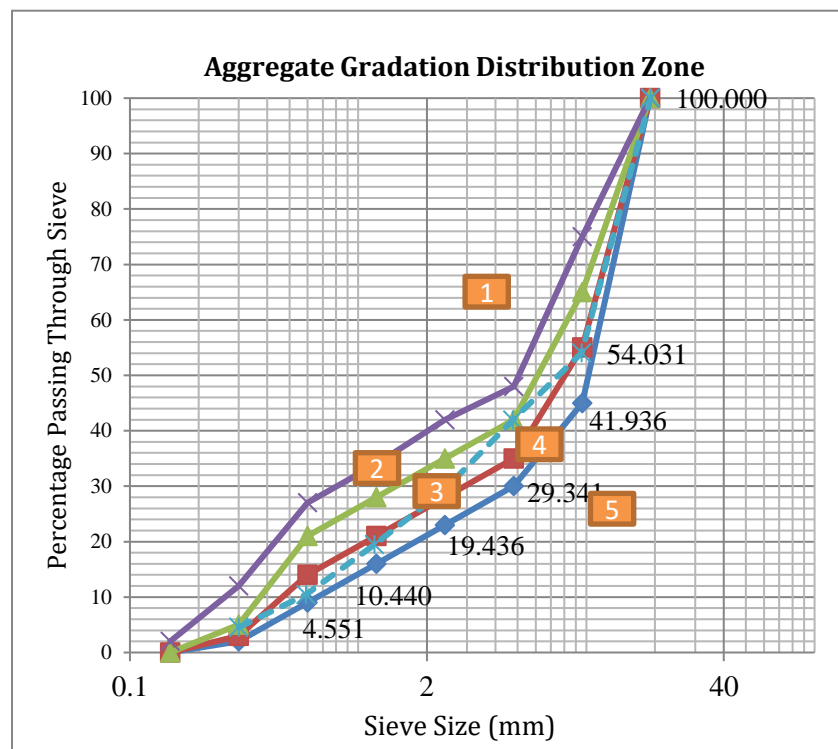


Figure 2. Aggregate Gradation Curve for Maximum Aggregate Size of 19.1 mm

The test results presented in Figure 2 indicate that the aggregate particle distribution remains within the acceptable grading limits for concrete production. The gradation curve shows a continuous distribution from coarse to fine particles, suggesting that the aggregate has adequate particle packing characteristics. Although the curve slightly shifts toward the finer side compared with the median grading line between Zone 2 and Zone 3, this deviation is not significant and remains within the recommended envelope. This condition indicates that the aggregate is still suitable for normal concrete mixtures. The tendency of the curve to fall within Zone 3 also suggests that the aggregate may improve mixture cohesiveness and support workable fresh concrete, provided that the water content and cement paste volume are properly controlled. Therefore, based on the sieve analysis results, the selected aggregate gradation can be considered appropriate for producing concrete with acceptable fresh and hardened properties.

SLUMP TEST

Slump testing was conducted using a water–cement ratio (w/c) of 0.30 with Ordinary Portland Cement (OPC). Sugarcane Bagasse Ash (SBA) was incorporated at 5%, 10%, 15%, and 20%, while the superplasticizer (SP) dosage was maintained at 1% of cement weight for all modified mixtures. The slump results for all mixes are presented in Figure 3.

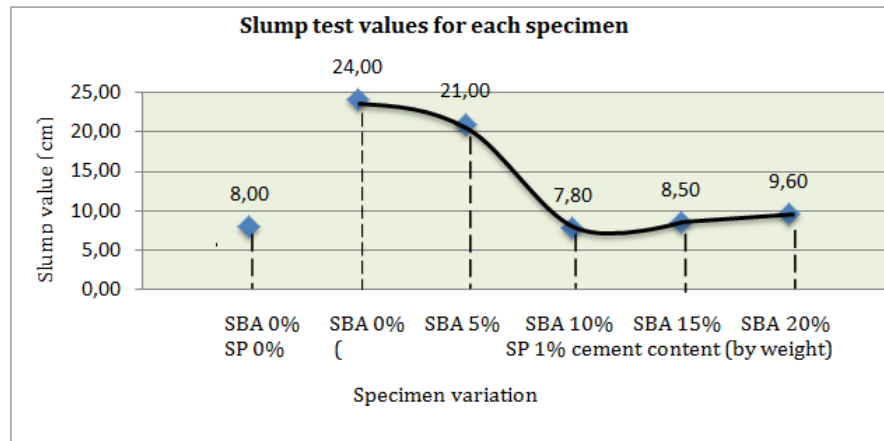


Figure 3. Effect of Sugarcane Bagasse Ash and Superplasticizer on Slump Value

The control concrete (0% SBA without SP) showed a slump value of 8.00 cm. The addition of only 1% superplasticizer resulted in a sharp increase in slump to 24.00 cm, indicating a significantly higher workability than the designed range. A similar behavior was observed for the 5% SBA mixture with 1% SP, which recorded a slump of 21.00 cm. As the SBA content increased to 10%, 15%, and 20% with 1% SP, the slump values gradually stabilized at 7.80 cm, 8.50 cm, and 9.60 cm, respectively, aligning more closely with the target workability range specified in the mix design. These results suggest that the presence of SBA contributes to improving the stability of fresh concrete consistency when used alongside superplasticizer, particularly in controlling excessive fluidity in the mixture.

COMPRESSIVE STRENGTH TESTING

After the specimen casting process was completed, compressive strength testing was conducted at 28 days of curing age. For each mixture variation, sugarcane bagasse ash (SBA) was added at 5%, 10%, 15%, and 20%, while the superplasticizer (SP) dosage was kept constant at 1% of cement weight. Prior to testing, each specimen was weighed and its dimensions were verified to ensure accuracy of results, followed by axial loading until failure to determine the compressive strength. The detailed test results are presented in Table 3.

Table 3. Compressive Strength Test Results of Cylindrical Specimens (28 Days)

Treatment	Specimen	Compressive Strength (MPa)	Average Strength (MPa)	Standard Deviation (S)	Compressive Strength Range $f'_{ck} = f'_c \pm 1.6S$ (MPa)
Control (0% SBA, 0% SP)	PC, SBA 0% SP 0% - 1	25.48	28.99	3.162	23.93–34.05
	PC, SBA 0% SP 0% - 2	33.40			
	PC, SBA 0% SP 0% - 3	26.61			
	PC, SBA 0% SP 0% - 4	30.57			
	PC, SBA 0% SP 0% - 5	28.87			
With 1% SP only	PC, SBA 0% SP 1% - 1	20.38	28.31	6.899	17.27–39.35
	PC, SBA 0% SP 1% - 2	36.80			
	PC, SBA 0% SP 1% - 3	26.61			
	PC, SBA 0% SP 1% - 4	33.97			
	PC, SBA 0% SP 1% - 5	23.78			
SBA 5% + 1% SP	PC, SBA 5% SP 1% - 1	26.61	28.65	3.340	23.30–33.99
	PC, SBA 5% SP 1% - 2	23.78			
	PC, SBA 5% SP 1% - 3	30.57			
	PC, SBA 5% SP 1% - 4	31.71			
	PC, SBA 5% SP 1% - 5	30.57			
SBA 10% + 1% SP	PC, SBA 10% SP 1% - 1	31.71	31.48	4.114	24.90–38.06
	PC, SBA 10% SP 1% - 2	28.31			
	PC, SBA 10% SP 1% - 3	29.44			
	PC, SBA 10% SP 1% - 4	38.50			
	PC, SBA 10% SP 1% - 5	29.44			
SBA 15% + 1% SP	PC, SBA 15% SP 1% - 1	28.87	30.13	1.410	27.86–32.38
	PC, SBA 15% SP 1% - 2	28.87			
	PC, SBA 15% SP 1% - 3	30.01			
	PC, SBA 15% SP 1% - 4	30.57			
	PC, SBA 15% SP 1% - 5	32.27			
SBA 20% + 1% SP	PC, SBA 20% SP 1% - 1	22.08	21.06	2.258	16.56–25.56
	PC, SBA 20% SP 1% - 2	17.55			
	PC, SBA 20% SP 1% - 3	19.25			
	PC, SBA 20% SP 1% - 4	21.51			
	PC, SBA 20% SP 1% - 5	24.91			

Based on the compressive strength results presented in Table 3, the strength range expressed as $f'_c \pm 1.6S$ was used as an indicator of data dispersion within each mixture group, where f'_c denotes the average compressive strength and S represents the standard deviation. This parameter was not used to define the design compressive strength, but rather to evaluate the consistency and uniformity of the test results among specimens in the same mixture variation. For the mixture containing 10% SBA and 1% superplasticizer, the average compressive strength reached 31.48 MPa, with a standard deviation of 4.114 MPa and a calculated strength range of 24.90–38.06 MPa. Although one specimen recorded a compressive strength of 38.50 MPa, which was slightly above the upper limit of the calculated range, the deviation was not considered sufficient to exclude

the data from the analysis. Therefore, all specimen results were retained, and the average compressive strength remained 31.48 MPa. This result clearly indicates that the optimum compressive strength was achieved at 10% SBA replacement with the addition of 1% superplasticizer, demonstrating the most favorable balance between cement replacement and strength development among the tested mixtures.

The mixture containing 20% SBA and 1% superplasticizer showed a decrease in average compressive strength to 21.06 MPa, with a standard deviation of 2.258 MPa and a calculated strength range of 17.45–24.67 MPa. The individual test results generally remained within this range, indicating that the reduction in strength was not caused by a single abnormal specimen, but reflected the overall behavior of the mixture at a higher SBA replacement level. Compared with the mixtures containing 10% and 15% SBA, the 20% SBA mixture exhibited a more pronounced decline in compressive strength. This result suggests that excessive SBA replacement may reduce the availability of cementitious material required for effective bonding and strength development. Therefore, although SBA can contribute positively to concrete strength at an appropriate replacement level [15], its use at higher proportions may negatively affect the mechanical performance and uniformity of concrete.

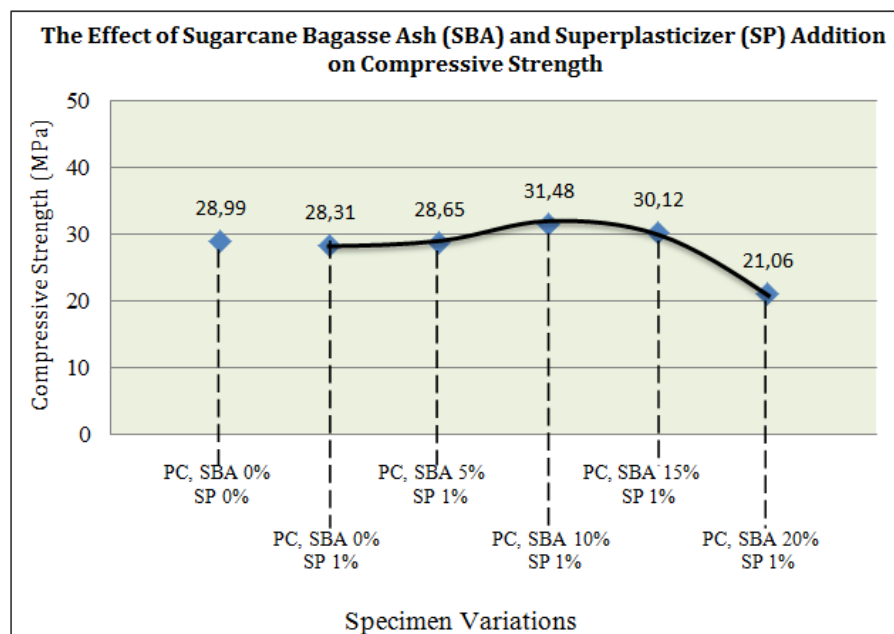


Figure 4. Comparison of Average Compressive Strength of Concrete Mixtures

As shown in Figure 4, the control concrete without SBA and superplasticizer (SP) achieved a compressive strength of 28.99 MPa. The addition of 1% SP resulted in a slightly lower value of 28.31 MPa. With SBA incorporation, the compressive strength increased at 5% SBA (28.65 MPa), reached a peak at 10% SBA (31.48 MPa), and then gradually decreased at 15% SBA (30.12 MPa), followed by a significant reduction at 20% SBA (21.06 MPa). This trend indicates that SBA improves compressive strength at moderate replacement levels but becomes detrimental at higher percentages due to cement dilution and increased water demand.

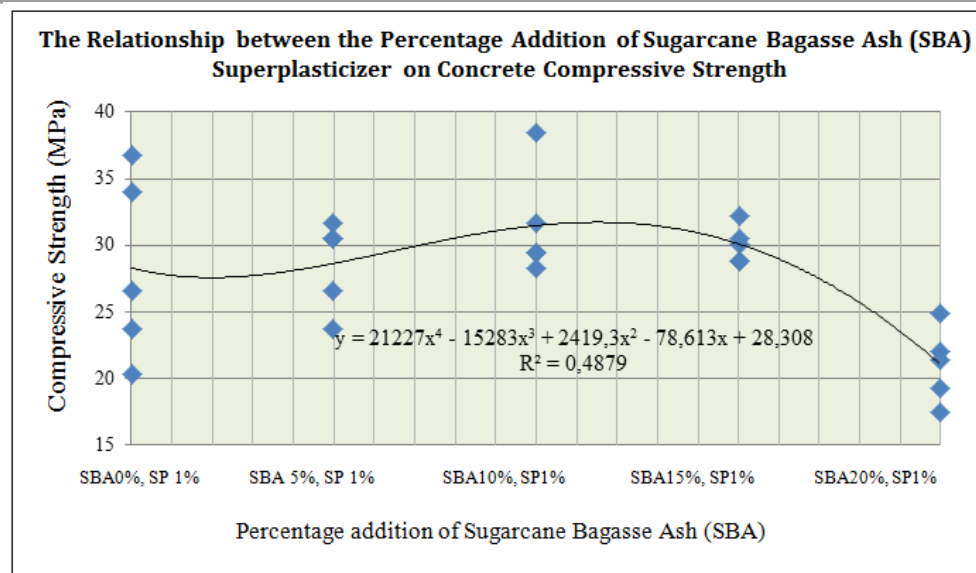


Figure 5. The relationship between the percentage addition of Sugarcane Bagasse Ash (SBA) and 1% Superplasticizer (SP) by weight of cement

Figure 5 presents the relationship between the percentage of Sugarcane Bagasse Ash (SBA) replacement and the compressive strength of concrete mixtures containing 1% superplasticizer. The normal concrete mixture was not included in this regression analysis because the model was specifically developed to evaluate the effect of SBA addition in concrete mixtures incorporating superplasticizer. Therefore, the analysis focused on the modified mixtures to obtain a clearer trend regarding the influence of SBA replacement on compressive strength development.

The relationship between SBA replacement level and compressive strength of cylindrical specimens was modeled using a fourth-order polynomial regression equation $y = 21227x^4 - 15283x^3 + 2419x^2 - 78.61x + 28.30$, where y represents the predicted compressive strength and x represents the SBA replacement level. The coefficient of determination obtained from the model was $R^2 = 0.487$, indicating that the regression equation explains part of the variation in the compressive strength data. The correlation coefficient, calculated as the square root of R^2 , was $R = 0.822$, suggesting a relatively strong relationship between SBA replacement level and the compressive strength trend. However, the moderate R^2 value indicates that the regression model should be interpreted as a trend estimation rather than a fully predictive model.

Based on this equation, the compressive strength of concrete incorporating 10% SBA and 1% superplasticizer can be estimated and compared with the experimental results to evaluate the optimum replacement level. This interpretation is important because the experimental data showed that the 10% SBA mixture produced the highest compressive strength among the tested variations. Thus, Figure 5 provides an initial regression-based indication that moderate SBA replacement contributes positively to compressive strength, while higher replacement levels may reduce mechanical performance.

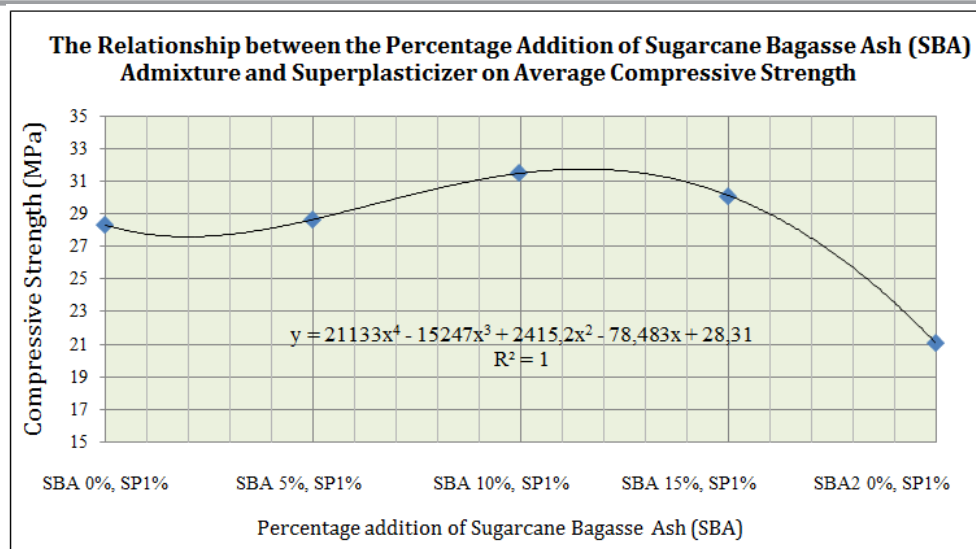


Figure 6. Regression graph of the relationship between the percentage addition of Sugarcane Bagasse Ash (SBA) and Superplasticizer (SP) on average compressive strength

From Figure 6, the same data distribution is also modeled using a 6th-order polynomial regression equation for cylindrical specimens. The resulting regression equation is: $y=21133x^4-15247x^3+2415x^2-78.48x+28.31$ with a coefficient of determination $R^2=1$. The coefficient of determination ranges between 0 and 1, and the model is considered better when R^2 approaches 1. Using this regression equation, the compressive strength can be determined for the use of 10% Sugarcane Bagasse Ash (SBA) and 15% Superplasticizer (SP) by weight of cement. During concrete casting, increasing the percentage of Sugarcane Bagasse Ash (SBA) and 1% Superplasticizer (SP) by weight of cement leads to material agglomeration. As a result, compaction of the concrete mixture into the specimens becomes difficult because it sets more quickly due to reduced available water caused by higher water absorption of the increasing SBA content. During casting of fresh concrete into the mold, the mixture hardens rapidly while the cement water is evenly distributed, resulting in an uneven concrete surface. Therefore, capping is required approximately 3–4 hours after casting. The data processing results, both individual and average values, indicates the optimum compressive strength obtained at 10% Sugarcane Bagasse Ash (SBA) addition.

CONCLUSION

Based on the experimental results, the aggregates used in this study met ASTM standards and ACI requirements, indicating their suitability for concrete production. The control concrete without sugarcane bagasse ash (SBA) and superplasticizer produced a slump value of 8.00 cm, which was within the acceptable ACI range of 7.5–10 cm. The addition of 1% superplasticizer increased the workability of fresh concrete, while the incorporation of SBA helped regulate the slump values, particularly at 10%, 15%, and 20% SBA replacement levels, which produced slump values closer to the target workability range. The compressive strength results showed that the control concrete achieved 28.99 MPa, while the mixture with 1% superplasticizer without SBA reached 28.31 MPa. The mixtures containing 5%, 10%, 15%, and 20% SBA with 1% superplasticizer produced compressive strengths of 28.65 MPa, 31.48 MPa, 30.12 MPa, and 21.06

MPa, respectively. These findings indicate that SBA can improve the compressive strength of concrete when used at an appropriate replacement level. The optimum performance was achieved by the mixture containing 10% SBA and 1% superplasticizer, with a compressive strength of 31.48 MPa. Therefore, the use of 10% SBA combined with 1% superplasticizer provides the most effective balance between workability, cement replacement, and compressive strength development, while higher SBA content may reduce mechanical performance.

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CONFLICTS OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Meillyta: conceptualization, methodology and supervision; **Munawir:** methodology and supervision; **Riski Rudiansyah:** data curation, writing-original draft preparation; **Aldina Fatimah** and **Haris Saputra:** visualization, investigation, software, validation, writing- reviewing and editing.

DATA AVAILABILITY STATEMENT

The data used to support the findings of this study are included within the article.

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