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Article

The Mechanical Behavior of Sustainable Concrete Using Raw and Processed Sugarcane Bagasse Ash

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Abstract: Sugarcane Bagasse Ash (SCBA) is one of the most common types of agricultural waste. By its availability and pozzolanic properties, sugarcane bagasse ash can be utilized as a partial replacement for cement in the production of sustainable concrete. This study experimentally investigated the impact of employing two types of sugarcane bagasse ash as a partial substitute for cement up to 30% on the compressive strength, flexural strength, and Young's modulus of the concrete mixture. The first type of bagasse ash used was raw SCBA, which was used as it arrived from the plant, with the same characteristics, considering that it was exposed to a temperature of 600 °C in the boilers to generate energy. The second type of bagasse ash utilized, called processed SCBA, was produced by regrinding raw SCBA for an hour and then burning it again for two hours at a temperature of 600 °C. This was done to improve the pozzolanic activity and consequently the mechanical properties of the concrete mixture. The findings indicated that employing raw sugarcane bagasse ash had a detrimental effect on the mechanical characteristics of the concrete mixture but using processed sugarcane bagasse ash at a proportion of no more than 10% had a considerable effect on improving the properties of the concrete mixture. The utilization of processed SCBA up to 10% into the concrete mixture resulted in a 12%, 8%, and 8% increase in compressive strength, flexural strength, and Young's modulus, respectively, compared to the normal concrete specimen. On the contrary, the inclusion of raw SCBA with varying content into the concrete mixture decreased compressive strength, flexural strength, and Young's modulus by up to 50%, 30%, and 29%, respectively, compared to the normal concrete specimen. The experimental findings were validated by comparison with ACI predictions. ACI overestimated the flexural strength of SCBA concrete specimens, with a mean coefficient of difference between the ACI equation and experimental results of 22%, however, ACI underestimated the Young's modulus of SCBA concrete specimens, with a mean coefficient of difference between the ACI equation and experimental results of −6%.

Keywords: sustainable concrete; sugarcane; bagasse ash; compressive strength; flexural strength; Young's modulus



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1. Introduction

Waste disposal is considered a crucial area in terms of ecological and environmental considerations in evolving countries, such as Egypt. Furthermore, due to the rapid destruction of the environment, the sustainability of natural resources is a prominent challenge. The primary focus of investigators is on reducing the use of raw materials and increasing the use of renewable alternatives. The use of alternative materials will aid in the reduction

of natural resource depletion. Alternative materials should be evaluated for their ability to replace natural resources based on their physical and chemical characteristics [1,2]. Alternative materials might be created intentionally or from industrial waste. Iron and steel, as well as agro-based industries, can produce industrial side products. The usage of industrial side products can ultimately aid in the reduction of environmental issues, such as carbon dioxide emissions and landfill disposal issues.

Sugarcane bagasse ash is one of the available side products in Egypt, and it is produced by burning bagasse in boilers to generate energy. Sugar factories in Egypt produce over 16 million tons of sugarcane waste annually [3]. Besides being widely available, earlier studies demonstrated the remarkable impact of partially replacing cement weight with sugarcane bagasse ash on enhancing the mechanical characteristics of the concrete mixture [4–10].

Cement manufacturing is the second-largest source of carbon dioxide emissions. A ton of cement manufacturing causes a considerable amount of carbon dioxide emission in the environment, accounting for 8% of total output [11]. Furthermore, each ton of cement manufacturing requires 1.6 tons of natural materials to produce [12]. Employing blended Pozzolans, such as sugarcane bagasse ash, as a substitute for cement in the concrete mixture is one method for lowering carbon dioxide emissions. Pozzolan is a finely separated siliceous or aluminous substance that, in the hydration process and at room temperature, interacts with further lime to create secondary calcium silicate hydrate gel [13]. Original sugarcane bagasse ash has a greater carbon content and consists of more crystalline silica, which might cause problems when used as a pozzolan [14]. Heating or grinding, for example, could be other ways to increase the activation of silica in sugarcane bagasse ash [15–19]; on the other hand, it requires more energy to grind or burn into finer particles.

Several studies have focused on using SCBA as a cement substitute in concrete. Bahrudeen A., et al. [20] investigated the efficiency of sugarcane bagasse ash concrete mixtures, showing that using sugarcane bagasse ash in concrete significantly improved its performance. When compared to control concrete, bagasse ash blended concrete showed lower heat of hydration, extra strength gain due to pozzolanic activity, a considerable reduction in permeability due to pore refining, and identical drying shrinkage behavior. According to the findings, sugarcane bagasse ash can be utilized to substitute cement up to 25% in the production of concrete with high mechanical and durability properties. To partially substitute cement, Quedou P. et al. [21] studied the mechanical and durability characteristics of concrete utilizing sugarcane bagasse ash. Sugarcane bagasse ash was replaced in percentages of 5%, 10%, 15%, and 20% by weight of cement for an average compressive strength of 27 MPa. The results showed that after 120 days of curing, the compressive strength increased by 2.6% and 1.7% for concrete specimens with sugarcane bagasse ash content of 5% and 10%, respectively, when compared to the control specimen. Additionally, water absorption improved by 255%, 390%, 438%, and 488% for concrete specimens with sugarcane bagasse ash content of 5%, 10%, 15%, and 20%, respectively. Other experiments demonstrated lower flexural strength and ultrasonic pulse velocity, as well as higher water penetration and carbonation depth. According to the findings, replacing 10% of cement with SCBA provided promising outcomes and can be regarded as a suitable concrete mixture for use in the building industry. P. Jagadesh et al. [22] explored the mechanical characteristics of concrete mixtures with up to a 30% weight substitution of ordinary Portland cement weight by sugarcane bagasse ash. The most significant improvement in cylindrical compressive strength was obtained for concrete specimens containing original sugarcane bagasse ash of 10% or processed sugarcane bagasse ash of 20% as a partial replacement cement weight, while concrete specimens with 10% partial replacement cement by original or processed sugarcane bagasse ash had the highest flexural strength gain. Original sugarcane bagasse ash concrete specimens exhibited lower compressive strength, flexural strength, and Young's modulus than processed sugarcane bagasse ash concrete specimens. P. Jagadesh et al. [23] also investigated the fracture properties of processed sugarcane bagasse ash concrete. Based on experimental results, the optimal replacement percentage of

cement by processed sugarcane bagasse ash is found to be 10% based on density, strength, and fracture energy properties. Microscopic studies revealed an improvement in calcium silicate hydrate and a reduction in calcium hydroxide at a 10% replacement percentage of cement by processed sugarcane bagasse ash, resulting in a higher density of cementitious material and higher strength. J. Neto et al. [24] investigated the effects of replacing cement with 5%, 10%, and 15% sugarcane bagasse ash on the characteristics and durability of concrete. The investigated sugarcane bagasse ash had a significant pozzolanic activity, which decreased porosity and water absorption by capillarity, while also increasing the concrete's mechanical strength. The presence of granular silica and alumina in sugarcane bagasse ash calcined at 600 °C provided it with significant pozzolanic activity. Because of the physical impact, improved filling, and pozzolanic reaction, the inclusion of approximately 15% sugarcane bagasse ash contributed to high porosity and increased compressive strength. S. Loganayagan et al. [25] studied the properties of sugarcane bagasse ash as extra material in concrete mixtures. Sugarcane bagasse ash concrete had a higher compressive strength than normal concrete. The maximum compressive strength was achieved by incorporating 10% sugarcane bagasse ash into the concrete mixture.

Despite various studies that have been published on improving SCBA characteristics [26–32], the techniques of processing SCBA in terms of burning degrees, grinding time, and particle size are unclear. Besides this, there are very few studies on the impact of employing locally produced sugarcane bagasse ash on the characteristics of concrete mixtures. Therefore, the novelty of the current research is in examining how locally produced sugarcane bagasse ash affects the behavior of the concrete mixture, in addition to examining how re-milling and re-burning sugarcane bagasse ash affects the pozzolanic activity and subsequently the characteristics of the concrete mixture. Another important goal of the current study is to determine the ideal proportion of sugarcane bagasse ash to utilize as a substitute for a percentage of the cement weight in the concrete mixture. The mechanical properties that were experimentally evaluated in this paper were compressive strength, flexural strength, and Young's modulus.

2. Experimental Program

2.1. Materials

Raw sugarcane bagasse ash specimen was obtained from Egyptian Sugar & Integrated Industries (ESIIC), which produces sugar, alcohol, and softwood. Sugarcane bagasse is used as fuel instead of diesel for steam boilers to generate the energy needed to run machinery and industrial processes. To obtain the required steam, the sugarcane bagasse is burned in a boiler at temperatures up to 600 °C. On the basis of past research, the raw sugarcane bagasse ash was sieved with a 75 µm sieve to remove undesired brittle particles, such as incompletely burned sugarcane bagasse, and to enhance pozzolanic reactivity [21,23,33]. Only those particles getting passed through the 75 µm size were picked up and used as raw sugarcane bagasse ash (RSCBA) in this study. The processed sugarcane bagasse ash used in this study was made by grinding raw sugarcane bagasse ash for one hour at 300 rpm in a laboratory grinding machine. After grinding, sugarcane bagasse ash is placed in a muffle furnace at 600 °C for two hours to increase silica content. Only those particles that passed through the 40µm size were picked up and used as processed sugarcane bagasse ash (PSCBA) in this study. Table 1 summarizes the physical properties of raw and processed sugarcane bagasse ash as well as ordinary Portland cement, while Table 2 summarizes the chemical composition of raw and processed sugarcane bagasse ash as well as ordinary Portland cement. Figure 1 illustrates the raw and processed sugarcane bagasse ash used in this study. Table 3 shows the physical properties of the fine and coarse aggregate. In the current study, raw and processed sugarcane bagasse ash was used in concrete as a partial replacement for cement, with the objective of delivering a compressive strength of approximately 22 MPa.

Table 1. Physical properties of cement, raw, and processed SCBA.

Properties	Specific Gravity	Retained on Sieve 75 μm (%)	Bulk Density (kg/m^3)	Average Particle Size (μm)
OPC	3.15	-	1440	25
RSCBA	1.91	30	1410	75
PSCBA	2.23	9.5	1480	40

Table 2. Chemical properties of cement, raw, and processed SCBA per weight (%).

Properties	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO
OPC	22.14	5.50	2.83	63.50	-	0.4	3.2
RSCBA	50.80	3.40	0.40	4.91	0.90	4.10	5.03
PSCBA	63.10	4.65	4.01	3.90	0.43	3.82	2.90

**Figure 1.** The shape of raw and processed SCBA. (a)—Raw SCBA. (b)—Processed SCBA.**Table 3.** Physical properties of fine and coarse aggregates.

Properties	Specific Gravity	Water Absorption (%)	Moisture Content (%)
Fine Aggregate	2.732	2.41	1.72
Coarse Aggregate	2.751	0.51	0.31
	2.742	0.75	0.36

2.2. Mixture Proportions

The experimental work included 12 sugarcane bagasse ash blended concrete mixtures with varying sugarcane bagasse ash content, classified into 2 groups, and 1 normal concrete mixture with no sugarcane bagasse ash content. Group one consists of six raw sugarcane bagasse ash blended concrete mixtures with varying raw sugarcane bagasse ash contents of 5%, 10%, 15%, 20%, 25%, and 30% as a partial replacement for cement weight. Group two consists of six processed sugarcane bagasse ash blended concrete mixtures with varying raw sugarcane bagasse ash contents of 5%, 10%, 15%, 20%, 25%, and 30% as a partial replacement for cement weight. All concrete specimens were tested for compressive strength, flexural strength, and Young's modulus. Table 4 presents the various quantities for all concrete mixtures.

Table 4. Mix properties.

KERRYPNX	MIX ID	OPC (kg/m ³)	RSCBA %	PSCBA %	Coarse Aggregate (kg/m ³)		Fine Aggregate (kg/m ³)	W/C Ratio	
					20 mm	10 mm			
	NM	360	-	-	800	350	715	0.5	
Group 1	RSCBA	RM1	342	5	-	800	350	715	0.5
		RM2	324	10	-	800	350	715	0.5
		RM3	306	15	-	800	350	715	0.5
		RM4	288	20	-	800	350	715	0.5
		RM5	270	25	-	800	350	715	0.5
		RM6	252	30	-	800	350	715	0.5
Group 2	PSCBA	PM1	342	-	5	800	350	715	0.5
		PM2	324	-	10	800	350	715	0.5
		PM3	306	-	15	800	350	715	0.5
		PM4	288	-	20	800	350	715	0.5
		PM5	270	-	25	800	350	715	0.5
		PM6	252	-	30	800	350	715	0.5

2.3. Method of Casting and Curing

Dried sugarcane bagasse ash is blended with cement for two minutes in the required proportions in the mechanical dry mixer and then kept in an airtight container. Fine sand and crushed granite were first mixed for 2–3 min in a mechanical dry mixer. After that, the blended types of cement were mixed in the needed proportions for another two minutes in a dried state. Once the dry mix looks to have an appropriate distribution of coarse aggregates, fine aggregates, and binders, the needed amount of water was progressively applied and mixing was kept going for another 4–6 min until a uniform mixture was achieved. The moulds for the different samples were filled with three equal layers of concrete; each concrete layer was thoroughly compacted to reduce voids in the mixture.

In order to determine the compressive strength, six concrete cubes with dimensions of 15 cm width, 15 cm breadth, and 15 cm height, were formed for every mixture. Three concrete cubes were examined after seven days, with three more after twenty-eight days. Additionally, the concrete's Young's modulus was evaluated for every concrete mixture through testing three cylindrical concrete samples after seven days and three more after twenty-eight days. All cylindrical samples had dimensions of 15 cm in diameter and 30 cm in height. While every concrete mixture's flexural strength was assessed by testing three concrete beam samples after seven days and three more after twenty-eight days. All concrete beams were 70 cm in length, 15 cm wide, and had a 15 cm thickness. Thereafter, the moulds remained stored at an ambient condition. After 24 h of placing, the concrete specimens were thoroughly withdrawn and then immersed in water and exposed to ambient temperature until the examination date. The Egyptian code provisions were followed in the preparation and testing of all concrete specimens.

2.4. Test Methods

2.4.1. Compression Test

Concrete cube specimens were placed in the center of the machine's base plate, as seen in Figure 2a. Up until the specimen failed, the compression load was continually applied at a rate of 10 Mpa/min. Both the maximum load and the specimen's failure mode were reported. At each chosen age, a minimum of three cubes should be examined. The findings of these cubes should be disregarded if the strength of a certain cube differs by much more exceeding 10% of the average strength. Compressive strength is determined by taking the average of three cubes. The cubic compressive strength for each cube specimen (f_{cu}) was calculated as follows:

$$f_{cu} = \frac{P}{A} \quad (1)$$

where P represents the failure compressive load.



Figure 2. Test setup for all concrete specimens. (a) Compression test. (b) Young's modulus test. (c) Flexural strength test.

A represents the cross-section area of the cube, ($150 \text{ mm} \times 150 \text{ mm}$).

2.4.2. Young's Modulus Test

As illustrated in Figure 2b, the cylinders were installed with a compressometer to determine the static Young's modulus in accordance with Egyptian requirements. Two steel rings for holding the specimen, two-gauge length bars, and a dial gauge with a 0–12.7 mm range comprised the compressometer. The specimens were placed on the compression testing machine platform with the compressometer set up. The compression load was applied gradually with an increase of 10 Mpa/min. The measurement of the dial gauge inserted between the two steel rings was used to determine the length difference. According to Egyptian standards, the Young's modulus can be used with a working compressive stress range of approximately 0 to 40% of the ultimate compressive strength of concrete cylindrical specimens. Young's modulus E was calculated according to the following equation:

$$E = \frac{\text{Interval stress}}{\text{Interval strain}} \quad (2)$$

where the interval stress was calculated by dividing 40% of the ultimate compressive load by the cylinder cross-section area. Whereas the interval strain was calculated as the average of the two dial gauge readings at 40% of the ultimate load divided by the distance between the two steel rings (165 mm).

2.4.3. Flexural Test

The concrete beams were appropriately positioned throughout the flexural machine test with a center-point loading, as shown in Figure 2c. The beam was supported by two rollers that are 300 mm apart from the central load. The load was subjected to a constant rate of approximately 1 Mpa/min until the specimen failed. The failure load was recorded. The flexural strength of each beam specimen f_r is calculated as follows:

$$f_r = \frac{3 PL}{2 bd^2} \quad (3)$$

where

P represents the failure flexure load.

L represents the effective span, (600 mm).

b represents the width of the beam, (150 mm).

d represents the breadth of the beam, (150 mm).

3. Results and Discussion

The values in our findings are based on the average value of three standard-cured specimens, which were tested at the same time. Those specimens were produced from the same concrete mixture, with the same mixing and curing conditions. Tables 5 and 6 show the mechanical properties of all tested concrete specimens, including density, cubic compressive strength, flexural strength, and Young's modulus at 7 days and 28 days, respectively. To ensure that the maximum coefficient of variation did not exceed 10%, as required by the Egyptian code, the coefficient of variance between the average value and the value of each specimen was also presented. Tables 5 and 6 include statistics about the highest coefficient of variation.

Table 5. Compressive strength, flexural strength, and Young's modulus results for all concrete specimens at 7 days.

MIX ID	Compressive Strength (MPa) 7 Days			Flexural Strength (MPa) 7 Days			Young's Modulus (GPa) 7 Days		
	Average	Max Coeff of Variance %		Average	Max Coeff of Variance %		Average	Max Coeff of Variance %	
NM	14.44			2.30			13.50		
	13.90	14.31	1.96	2.24	2.31	3.46	13.77	13.88	3.54
	14.59			2.39			14.37		
RM1	14.20			2.11			13.70		
	13.84	13.89	2.23	2.25	2.21	2.71	13.31	13.64	1.99
	13.63			2.27			13.91		
RM2	14.00			2.00			13.40		
	14.02	13.10	7.02	2.20	2.11	4.27	13.10	13.56	4.57
	11.28			2.13			14.18		
RM3	10.80			2.00			12.50		
	11.24	11.10	1.44	2.11	2.00	5.50	12.00	12.13	3.08
	11.26			1.89			11.88		
RM4	9.01			1.80			11.00		
	9.55	9.68	8.26	1.85	1.85	2.70	11.51	11.64	6.66
	10.48			1.90			12.42		
RM5	8.60			1.80			11.19		
	9.02	8.71	3.56	1.71	1.72	4.65	11.00	11.10	0.81
	8.51			1.65			11.11		

Table 5. Cont.

MIX ID	Compressive Strength (MPa) 7 Days			Flexural Strength (MPa) 7 Days			Young's Modulus (GPa) 7 Days		
	Average	Max Coeff of Variance %		Average	Max Coeff of Variance %		Average	Max Coeff of Variance %	
RM6	7.90			1.45			10.45		
	8.00	7.70	3.90	1.60	1.50	6.67	10.31	10.07	3.83
	7.20			1.45			9.44		
PM1	14.21			2.35			13.55		
	15.20	15.05	4.58	2.40	2.37	1.27	14.82	14.32	3.53
	15.74			2.36			14.58		
PM2	16.00			2.35			14.30		
	16.11	16.80	8.87	2.26	2.40	7.92	14.99	14.94	3.99
	18.29			2.59			15.54		
PM3	13.66			2.20			13.00		
	14.00	13.72	2.04	2.30	2.25	2.22	13.80	13.76	5.23
	13.50			2.25			14.48		
PM4	14.00			2.19			13.20		
	14.32	14.02	2.14	2.10	2.23	7.62	13.61	13.42	1.39
	13.74			2.40			13.46		
PM5	12.30			2.00			12.45		
	12.10	12.11	1.57	2.15	2.01	6.97	12.70	12.75	2.81
	11.93			1.88			13.11		
PM6	10.05			1.80			12.00		
	10.20	10.50	7.14	1.91	1.90	4.74	12.10	12.11	0.97
	11.25			1.99			12.23		

Table 6. Density, Compressive strength, flexural strength, and Young's modulus results for all concrete specimens at 28 days.

MIX ID	Density (kg/m ³) 28 Days			Compressive Strength (MPa) 28 Days			Flexural Strength (MPa) 28 Days			Young's Modulus (GPa) 28 Days		
	Average	Max Coeff of Variance %		Average	Max Coeff of Variance %		Average	Max Coeff of Variance %		Average	Max Coeff of Variance %	
NM	2570			23.20			3.32			19.80		
	2400	2440	5.33	21.30	22.20	4.50	3.20	3.21	3.43	20.11	19.83	1.41
	2350			22.10			3.11			19.58		
RM1	2390			22.00			3.00			19.50		
	2300	2431	7.08	20.90	21.90	4.11	3.22	3.12	3.21	20.33	19.79	2.75
	2603			22.80			3.14			19.53		
RM2	2350			20.00			2.80			20.00		
	2500	2415	3.52	21.80	20.82	4.71	3.15	3.01	4.65	20.11	19.37	3.81
	2395			20.66			3.08			18.00		
RM3	2390			18.40			2.91			17.99		
	2320	2361	1.23	17.50	18.01	2.17	2.90	2.85	2.11	18.00	17.83	0.94
	2373			18.13			2.74			17.51		
RM4	2390			15.67			2.59			17.00		
	2200	2332	3.17	14.20	15.30	4.77	2.75	2.70	2.22	16.21	16.88	3.29
	2406			16.03			2.76			17.44		

Table 6. Cont.

MIX ID	Density (kg/m ³) 28 Days			Compressive Strength (MPa) 28 Days			Flexural Strength (MPa) 28 Days			Young's Modulus (GPa) 28 Days		
	Average		Max Coeff of Variance %	Average		Max Coeff of Variance %	Average		Max Coeff of Variance %	Average		Max Coeff of Variance %
RM5	2450			13.90			2.68			15.06		
	2167	2323	5.47	12.50	13.40	3.73	2.40	2.53	5.93	15.60	15.12	3.20
	2352			13.80			2.51			14.69		
RM6	2233.1			10.71			2.30			15.06		
	2350	2304	2.00	11.10	11.05	2.62	2.20	2.23	3.14	14.51	14.04	7.29
	2329			11.34			2.19			12.54		
PM1	2409			24.05			3.25			19.00		
	2500	2461	1.58	23.00	23.10	4.11	3.30	3.38	6.21	20.53	20.69	8.92
	2474			22.25			3.59			22.53		
PM2	2322			23.22			3.38			21.50		
	2450	2490	8.35	24.91	24.90	6.71	3.50	3.47	1.73	20.95	21.54	2.93
	2698			26.57			3.53			22.17		
PM3	2590			23.90			3.30			19.33		
	2338.1	2439	6.19	21.09	22.00	8.64	3.25	3.20	3.12	20.10	19.78	1.62
	2389			21.01			3.05			19.91		
PM4	2380			20.90			3.26			18.56		
	2371.4	2429	4.39	21.00	21.51	5.21	3.07	3.11	4.82	19.90	19.32	3.01
	2536			22.63			3.00			19.50		
PM5	2300			18.81			2.80			18.42		
	2427	2391	2.30	20.25	19.95	4.21	2.99	2.98	5.70	18.00	18.26	0.87
	2446			20.79			3.15			18.36		
PM6	2350			18.11			2.88			17.50		
	2304.6	2360	2.77	17.04	17.45	3.78	2.73	2.78	3.60	17.82	17.65	0.95
	2425			17.20			2.73			17.64		

3.1. Unit Weight

As shown in Figure 3, the 28 days density for specimens in group 1 showed a slight decrease of 0.4%, 1%, 3.2%, 4.4%, 4.8%, and 5.5%, compared to the control specimen when raw sugarcane bagasse ash content was 5%, 10%, 15%, 20%, 25%, and 30%, respectively. On the other hand, the 28 days density for specimens in group 2 showed a slight increase of 0.9% and 2%, compared to the control specimen when processed sugarcane bagasse ash content was 5%, and 10%, respectively. However, increasing the processed sugarcane bagasse ash concentration to 15%, 20%, 25%, and 30% resulted in a 0.04%, 0.5%, 2%, and 3.3% reduction in density, respectively.

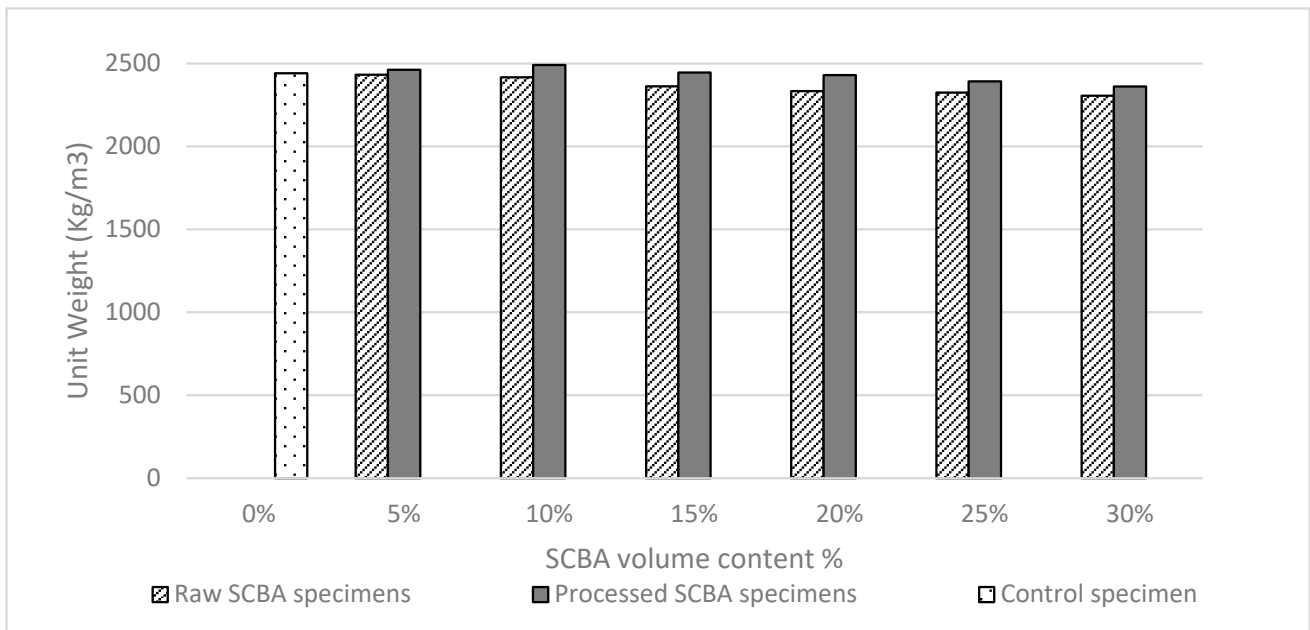


Figure 3. Relation between raw and processed SCBA volume content versus unit weight for all concrete specimens.

3.2. Compressive Strength

The compressive strength of concrete was determined after 7 and 28 days for various bagasse ash blended concretes. All raw and processed SCBA concrete specimens, as well as the control specimen, displayed the same failure mode under the compression test. Cracks first appeared vertically in the center of the concrete cubes and then spread to the edges. As the compressive load increased, the cracks increased and continued to widen, resulting in concrete spalling. Figure 4 shows a typical compressive failure mode for raw and processed SCBA concrete specimens.



Figure 4. A typical compressive failure mode for raw and processed SCBA concrete specimens.

Figure 5 shows the relation between raw and processed SCBA volume content versus compressive strength for all concrete specimens. Test results of concrete specimens for group one showed that the 7 days compressive strength decreased by 3%, 8.5%, 22%, 32%, 39%, and 46%, compared to the control specimen when raw sugarcane bagasse ash content was 5%, 10%, 15%, 20%, 25%, and 30%, respectively. In addition, the 28 days compressive strength decreased by 1.4%, 6%, 19%, 31%, 39%, and 50%, compared to the control specimen when raw sugarcane bagasse ash content was 5%, 10%, 15%, 20%, 25%, and 30%, respectively.

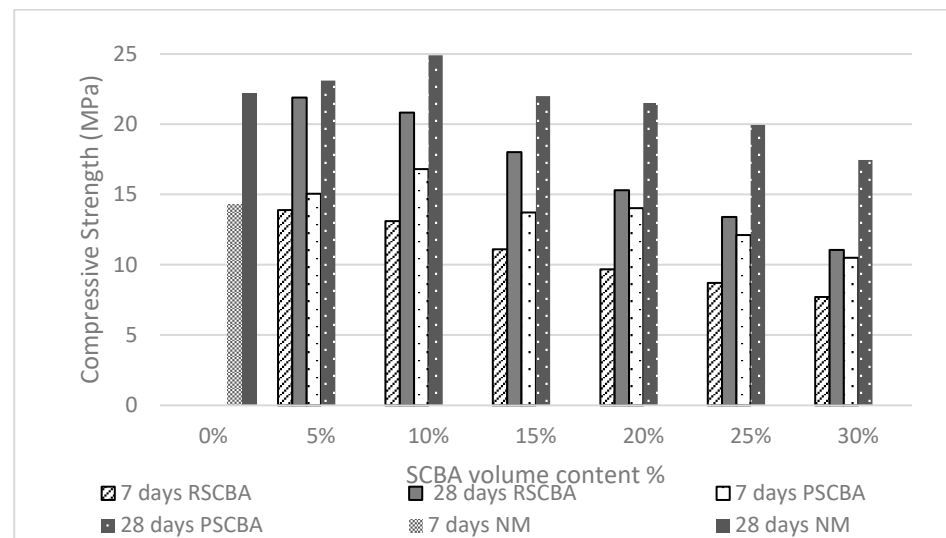


Figure 5. Relation between raw and processed SCBA volume content versus compressive strength for all concrete specimens.

Analysis of concrete specimens for group two showed that when processed sugarcane bagasse ash content was 15%, 20%, 25%, and 30%, the 7 days compressive strength for specimens in group 2 decreased by 4%, 2%, 15%, and 26%, respectively, compared to the control specimen. Furthermore, when processed sugarcane bagasse ash content was 15%, 20%, 25%, and 30%, the 28 days compressive strength decreased by 1%, 3%, 10%, and 21%, respectively, compared to the control specimen. However, when processed sugarcane bagasse ash content was 5%, and 10%, the compressive strength increased by 5% and 17%, respectively, compared to the control specimen after 7 days. Additionally, the compressive strength at 28 days increased by 4%, and 12%, compared to the control specimen when processed sugarcane bagasse ash content was 5% and 10%, respectively.

3.3. Flexural Strength

The flexural strength can be evaluated by performing a flexural strength test on the specimens. Even so, flexural strength is generally more valuable than indirect split tensile strength. Figure 6 shows the failure pattern for all raw and processed SCBA concrete specimens, as well as control specimens, which was typical of brittle failure in the middle of the beam attributed to the generation of a flexural crack, resulting in extensive splitting. As shown in Figure 7, the 7 days flexural strength for specimens in group 1 showed a decrease of 4.3%, 8.6%, 13%, 20%, 25%, and 35%, compared to the control specimen when raw sugarcane bagasse ash content was 5%, 10%, 15%, 20%, 25%, and 30%, respectively. In addition, the 28 days flexural strength for specimens in group 1 showed a decrease of 3%, 6%, 11%, 16%, 21%, and 30%, compared to the control specimen when raw sugarcane bagasse ash content was 5%, 10%, 15%, 20%, 25%, and 30%, respectively. Furthermore, the 7 days flexural strength for specimens in group 2 showed a decrease of 2.6%, 3.5%, 13%, and 18%, compared to the control specimen when processed sugarcane bagasse ash content was 15%, 20%, 25%, and 30%, respectively. Additionally, the 28 days flexural strength for specimens in group 2 showed a decrease of 0.3%, 3.1%, 7.1%, and 13%, compared to the control specimen when processed sugarcane bagasse ash content was 15%, 20%, 25%, and 30%, respectively. On the contrary, the flexural strength at 7 days increased by 2.6% and 4%, compared to the control specimen when processed sugarcane bagasse ash content was 5% and 10%, respectively. In addition, the flexural strength at 28 days increased by 5.3% and 8%, compared to the control specimen when processed sugarcane bagasse ash content was 5% and 10%, respectively.



Figure 6. A typical flexure failure mode for raw and processed SCBA concrete specimens.

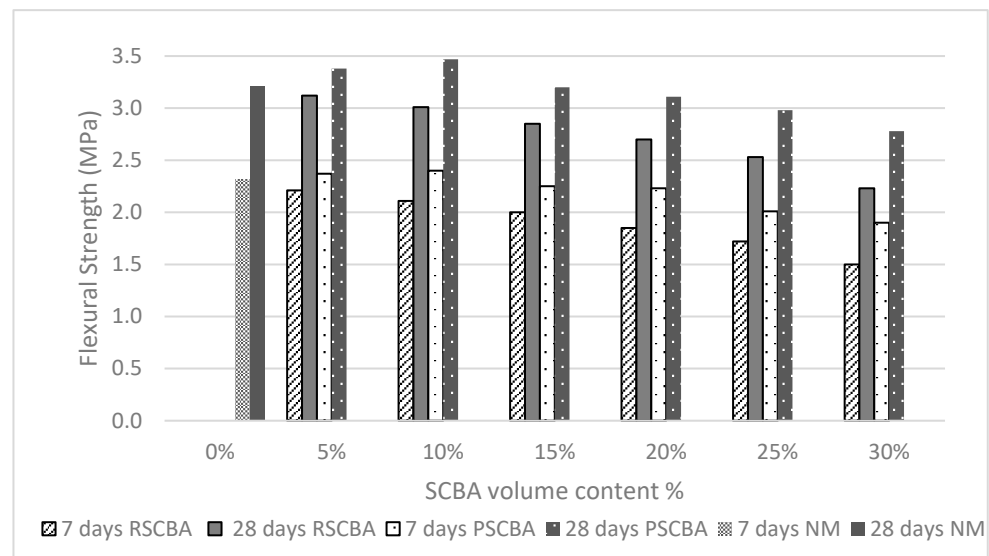


Figure 7. Relation between raw and processed SCBA volume content versus flexural strength for all concrete specimens.

3.4. Young's Modulus

Young's modulus measures a material's response to elastic deformation under subjected stress. It seems to be one of the most crucial factors to consider while designing a structure. As shown in Figure 8, When raw sugarcane bagasse ash content was 5%, 10%, 15%, 20%, 25%, and 30%, the 7-day Young's modulus for specimens in group 1 decreased by 1.7%, 2.3%, 13%, 16%, 20%, and 27%, respectively, compared to the control specimen. Furthermore, when raw sugarcane bagasse ash content was 5%, 10%, 15%, 20%, 25%, and 30%, the 28-day Young's modulus for specimens in group 1 decreased by 0.2%, 2.3%, 10%, 15%, 24%, and 29%, respectively, compared to the control specimen. For specimens in group 2, the 7 days Young's modulus showed a decrease of 0.8%, 3.2%, 8%, and 13%, compared to the control specimen when processed sugarcane bagasse ash content was 15%, 20%, 25%, and 30%, respectively. Furthermore, the 28 days Young's modulus for specimens in group 2 showed a decrease of 0.2%, 2.5%, 7.8%, and 11%, compared to the control specimen when processed sugarcane bagasse ash content was 15%, 20%, 25%, and 30%, respectively. On the contrary, the Young's modulus at 7 days increased by 3.2% and 8%, compared to the control specimen when processed sugarcane bagasse ash content was 5% and 10%, respectively. Additionally, the Young's modulus at 28 days increased by 2.5% and 8%, compared to the control specimen when processed sugarcane bagasse ash content was 5% and 10%, respectively.

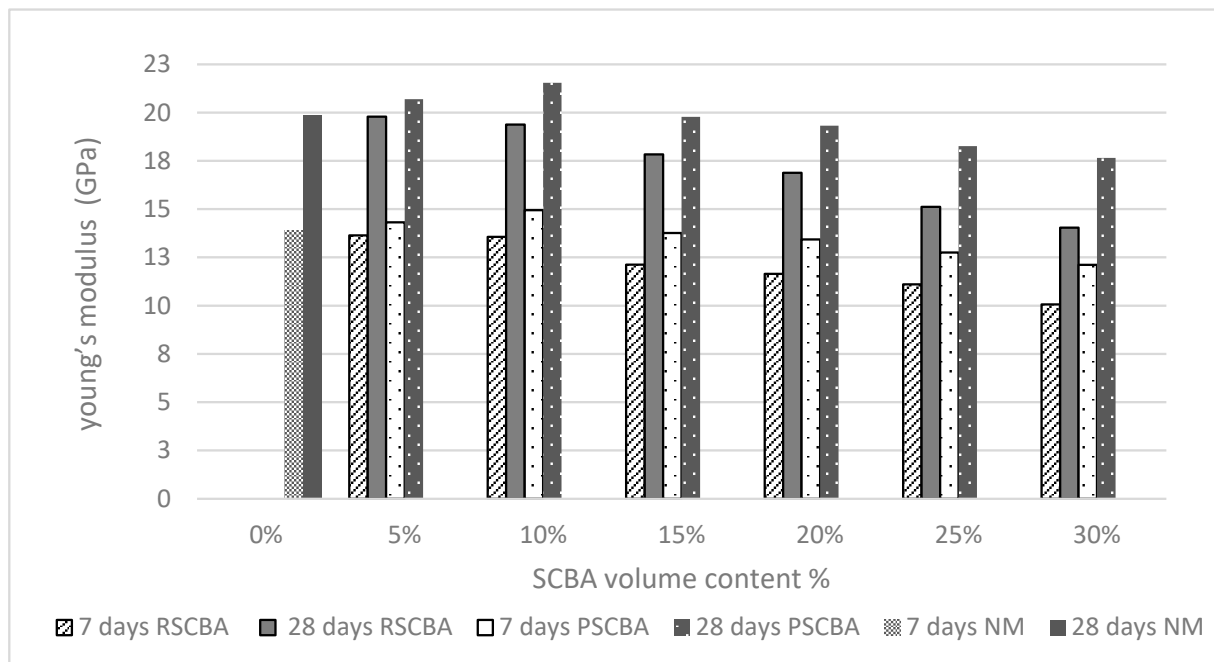


Figure 8. Relation between raw and processed SCBA volume content versus Young's modulus for all concrete specimens.

4. Discussion

4.1. Unit Weight

The density of RSCBA blended concrete specimens at 28 days ranged between 2304 and 2431 kg/m³, while the 28 days density of PSCBA blended concrete specimens varied between 2360 and 2490 kg/m³. Because of the large size of the particles and their porous nature, the density of the concrete specimens reduced as the RSCBA content in the mixture increased [22,24,34,35]. RSCBA concrete specimens had a lower density than PSCBA concrete specimens at the same sugarcane bagasse ash percentage for the same reason. When PSCBA content was increased to 10%, the density of the concrete mixture improved slightly, compared to control concrete. This could be a reference to the PSCBA's high silica content, which aids in the development of a silica calcium hydrate matrix. The development of a silica calcium hydrate matrix reduces voids, improves compaction, and enhances the interfacial transition zone as a result [36–38]. Using more than 10% processed SCBA in the concrete mixture resulted in a slight decrease in unit weight when compared to the normal concrete specimen. This is due to a reduction in cement content, which increases porous and voids inside the concrete mixture as these processed SCBA particles are larger than cement particles, leading to a reduction in strength and density [13,22,36].

4.2. Compressive Strength

Compressive strength decreased for all specimens in group one, which contained RSCBA, compared to the control concrete specimen. The larger particle size of RSCBA causes inappropriate compaction, extra voids, and subsequent decomposition of the hydration process. On the other hand, the use of PSCBA up to 10% as a partial replacement for cement resulted in a significant increase in compressive strength. The incorporation of PSCBA helps the hydration process since they contain a considerable amount of silica, which combines with calcium hydroxide to generate the calcium silica hydrate CSH matrix, which is principally responsible for the strength of concrete [39,40]. Furthermore, the appropriate particle size distribution of PSCBA may result in void filling and increased strength. The specimen with the maximum compressive strength was M.P2, which contains 10% PSCBA. The compressive strength decreased as the PSCBA volume concentration exceeded

the optimal. Prior research [21,22,24,41–43] demonstrated that compressive strength was negatively impacted by increasing the concentration of PSCBA inside the concrete mixture. This is due to the low alumina content in sugarcane bagasse ash, which slows the hydration of calcium aluminate and, as a result, reduces the strength. The current study's findings agree with previous research findings regarding the effect of percentage, reprocessing, and physical properties of sugarcane bagasse ash on compressive strength. Previous results showed that replacing cement weight with a percentage of processed sugarcane bagasse ash ranging from 5–15% increased compressive strength by approximately 20–37%, as reported in Table 7, while using raw sugarcane bagasse ash with content ranging from 5–10% improved the compressive strength by a maximum of 15%. This demonstrates how crucial reprocessing sugarcane bagasse ash is for enhancing concrete strength.

Table 7. Effect of SCBA on compressive strength at 28 days from previous studies.

Author	SCBA Reprocessing Operation	SCBA Max. PARTICLE Size μm	SCBA Optimum Percentage %	* The Ratio of Compressive Strength Increases %	Maximum Compressive Strength at 28 Days MPa
Current study	600 °C for 2 h + grinding	25	10	12	24.9
Jagadesh et al. [22]	400 °C for 4 h + grinding	30	10	28	23.24
Neto et al. [24]	600 °C for 8 h + grinding	36	15	21	36.95
Hussien et al. [27]	600 °C for 2 h + grinding	-	10	20	32.54
Ganesan et al. [4]	600 °C for 1 h + grinding	5.4	10	20	23.5
Srinivasan et al. [28]	600 °C–800 °C + grinding	-	5	37	29.5
Buyapureddy et al. [26]	600 °C for 2 h + grinding	30	15	20	50
Kiran et al. [29]	as it brought from the factory	150	5	15	45.54
Priya et al. [30]	as it brought from the factory	-	10	14	38.07

* ratio of compressive strength increases % = ((SCBA specimen results/control specimen results) – 1) \times 100.

4.3. Flexural Strength

In comparison to using RSCBA, adding PSCBA to the concrete mixture significantly increased flexural strength. Furthermore, increasing the PSCBA content by up to 10% improved the flexural strength slightly more than the control specimen. This is due to the high silica content of PSCBA, which aids in the formation of silica calcium hydrate matrix and thus improves the hydration process. The silica calcium hydrate matrix reduces voids, improves the interfacial transition zone and thus prevents crack formation and expansion. Prior research has shown that incorporating SCBA into concrete with less than 20% volume content improves hydration and increases flexure strength [20–22]. The specimen with the highest flexural strength was PM2, which has a PSCBA content of 10%. The results showed that increasing the PSCBA concentration above 10% reduced the flexure strength of the concrete specimens. That was because the bagasse ash of numerous sugarcanes had been added to the concrete mix, which lowered the amount of alumina in the mixture and thus decomposed the formation of calcium aluminate. This results in poor compaction, additional voids, and eventually decomposition in the interfacial transition zone. Table 8 displays the results for flexural strength and the recommended amount of sugarcane bagasse ash in concrete. Between 5 and 10% of sugarcane bagasse ash should be used, according to studies. Utilizing processed sugarcane bagasse ash increased flexural strength by up to 14%, whereas using raw sugarcane bagasse ash increased the strength by up to 13%. The comparison with prior research demonstrates that the current research's observations of the flexural behavior of concrete containing sugarcane bagasse ash are consistent with those observations in earlier studies.

Table 8. Effect of SCBA on flexural strength at 28 days from previous studies.

Author	SCBA Reprocessing Operation	SCBA Max. Particle Size μm	SCBA Optimum Percentage %	The Ratio of Flexural Strength Increases	Maximum Flexural Strength at 28 Days MPa
Current study	600 °C for 2 h + grinding	25	10	8	3.47
Jagadesh et al. [22]	400 °C for 4 h + grinding	30	10	14	3.62
Srinivasan et al. [28]	600 °C–800 °C + grinding	-	5	8	3.74
Kiran et al. [29]	as it brought from the factory	150	5	12	4.38
Priya et al. [30]	as it brought from the factory	-	10	13	6.82

4.4. Young's Modulus

The addition of up to 10% PSCBA to concrete specimens enhanced the Young's modulus marginally more than the control specimens. This is owing to the PSCBA's high silica content, which optimizes the hydration process of silica calcium hydrate, resulting in minimal voids, optimum compaction, and a strong interfacial transition zone. The Young's modulus of concrete specimens was reduced when RSCBA with varying volume content was used. This is due to RSCBA's large particle size, which results in more voids, a breakdown of the interfacial transition zone, as well as a disruption of the hydration process. Increasing the PSCBA above 10% lowered the Young's modulus of concrete specimens, just as it did with compressive strength and flexural strength. The reason for this is a reduction in cement content, which corresponds to lower alumina content and leads calcium aluminate to decompose during the hydration process, resulting in a lower Young's modulus. As demonstrated in Table 9, prior research revealed that adding sugarcane bagasse to concrete at a proportion of between 5 and 10% could enhance the concrete's Young's modulus. The findings of the current study are consistent with earlier studies in terms of the Young's modulus of the concrete mixture and the optimal bagasse ratio. Priya et al. [30] acknowledged that using 10% raw sugarcane bagasse ash enhanced the Young's modulus of concrete by 8%, whereas Jagadesh et al. [22] demonstrated that using 10% processed sugarcane bagasse ash in concrete increased the Young's modulus by roughly 14%. On the contrary, Srinivasan et al. [28] demonstrated that the use of bagasse reduces the Young's modulus of concrete, possibly due to an increase in the size of bagasse ash particles, which was not reported in the article and thus an increase in voids within the concrete as well as a reduction in stiffness.

Table 9. Effect of SCBA on Young's modulus at 28 days from previous studies.

Author	SCBA Reprocessing Operation	SCBA Max. Particle size μm	SCBA Optimum Percentage %	* Variation of Young's Modulus %	Maximum Young's Modulus at 28 Days GPa
Current study	600 °C for 2 h + grinding	25	10	8	21.54
Jagadesh et al. [22]	400 °C for 4 h + grinding	30	10	13	22.17
Srinivasan et al. [28]	600 °C–800 °C + grinding	-	5	−3	29.2
Priya et al. [30]	as it brought from the factory	-	10	8	51.2

* variation of Young's modulus % = ((SCBA specimen results/control specimen results) − 1) × 100.

5. Validation of Experimental Results Using ACI Predictions

5.1. Validation of Experimental Flexural Strength Results for SCBA-Blend Concrete

The flexural strength for sugarcane bagasse ash blended concrete was calculated in this section using ACI provisions. The validation of code equations is demonstrated by comparing code analyses to experimental results.

The following formula is provided by ACI318 [44] for predicting the concrete flexural strength:

$$f_r = 0.62 \sqrt{f'_c} \quad (4)$$

where

f_r is the flexural strength of concrete.

f'_c is the cylindrical compressive strength of concrete.

The correction factor for obtaining the equivalent compressive strength of the standard cube is given by ECP203 [45] as follows:

$$f_{cu} = 1.25f'_c \quad (5)$$

where f_{cu} is the cubic ultimate compressive strength of concrete.

Table 10 shows a comparison between the experimental and the ACI predicted values of flexural strength for sugarcane bagasse ash blended concrete specimens. The experimental flexural strength values were higher than the ACI predicted flexural strength, as seen in the data. This indicates that the flexural strength of raw and processed sugarcane bagasse ash blended concrete specimens predicted by ACI is appropriate. The mean coefficient of variance between the ACI equation and experimental results was 22%, indicating that ACI underestimated the flexural strength of sugarcane bagasse ash blended concrete specimens. Figure 9 shows that the experimental result of 28-day flexural strength was higher than the ACI predicted flexural strength by 20%, 19%, 21%, 24%, 25%, and 21% for raw sugarcane bagasse ash concrete specimens RM1, RM2, RM3, RM4, RM5, and RM6, respectively. Additionally, for processed sugarcane bagasse ash concrete specimens PM1, PM2, PM3, PM4, PM5, and PM6, the experimental result of 28-day flexural strength was 27%, 25%, 23%, 21%, 20%, and 20% greater than the ACI predicted flexural strength, respectively.

Table 10. Experimental, and ACI results of flexural strength for all concrete specimens.

MIX ID	Flexural Strength (MPa)		* Coeff of Variance %
	28 Days Exp	ACI	
NM	3.21	2.61	23
RM1	3.12	2.60	20
RM2	3.01	2.53	19
RM3	2.85	2.35	21
RM4	2.70	2.17	24
RM5	2.53	2.03	25
RM6	2.23	1.84	21
PM1	3.38	2.67	27
PM2	3.47	2.77	25
PM3	3.20	2.60	23
PM4	3.11	2.57	21
PM5	2.98	2.48	20
PM6	2.78	2.32	20

* coefficient of variance % = ((Exp results/ACI results) - 1) × 100.

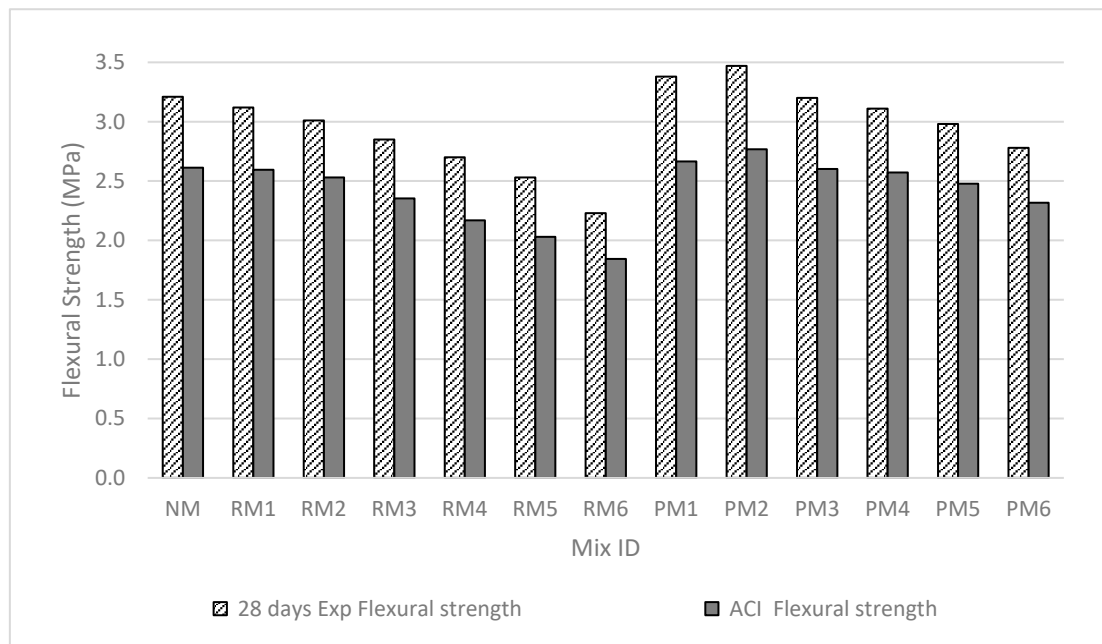


Figure 9. Comparison between the experimental and the ACI results of flexural strength for all concrete specimens.

5.2. Validation of Experimental Young's Modulus Results for SCBA Blended Concrete

The Young's modulus for sugarcane bagasse ash blended concrete was computed in this part using ACI specifications. By comparing code predictions to experimental data, the reliability and validity of code formulas can be confirmed.

The ACI standard provides the following formula for calculating the concrete Young's modulus:

$$E_c = w_c^{1.5} 0.043 \sqrt{f'_c} \quad (6)$$

where

E_c is the Young's modulus of concrete, MPa.

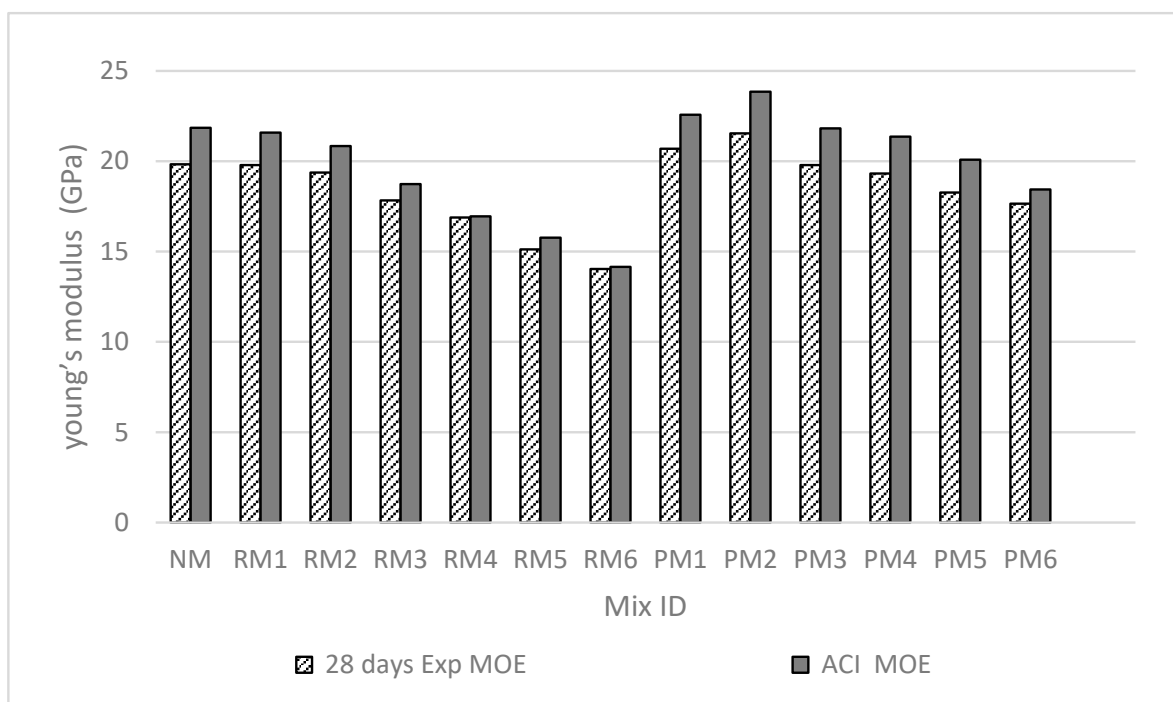
w_c is the density or unit weight of concrete, kg/m^3 .

f'_c is the cylindrical compressive strength of concrete, MPa.

Table 11, compares the experimental and ACI predicted Young's modulus results for raw and processed sugarcane bagasse ash blended concrete specimens. The findings show that the Young's modulus values in the experimental test were less than the ACI predictions. This means that the Young's modulus of raw and processed sugarcane bagasse ash blended concrete specimens was overestimated by ACI, however, the difference is not significant. The mean coefficient of variation between the ACI equation and the experimental results was -6% . As seen in Figure 10, the experimental 28-day Young's modulus was 8%, 7%, 5%, 0.4%, 4%, and 1% lower than the ACI predicted Young's modulus for raw sugarcane bagasse ash concrete specimens RM1, RM2, RM3, RM4, RM5, and RM6, respectively. Moreover, the experimental result of 28-day Young's modulus was less than the ACI predicted Young's modulus by 8%, 10%, 9%, 10%, 9%, and 9% for processed sugarcane bagasse ash concrete specimens PM1, PM2, PM3, PM4, PM5, and PM6, respectively.

Table 11. Experimental, and ACI results of Young's modulus for all concrete specimens.

MIX ID	Young's Modulus (MPa)		Coeff of Variance %
	28 Days Exp	ACI	
NM	19,830	21,844	−9
RM1	19,786	21,578	−8
RM2	19,371	20,836	−7
RM3	17,832	18,734	−5
RM4	16,883	16,946	−0.4
RM5	15,116	15,769	−4.
RM6	14,037	14,148	−0.8
PM1	20,688	22,568	−8
PM2	21,541	23,846	−10
PM3	19,779	21,811	−9
PM4	19,319	21,359	−10
PM5	18,261	20,087	−9
PM6	17,652	18,429	−9

**Figure 10.** Comparison between the experimental and ACI results of Young's modulus for all concrete specimens.

6. Conclusions

The objective of this study was to investigate the mechanical properties of raw and processed sugarcane bagasse ash blended concrete, which includes unit weight, compressive strength, flexural strength, and Young's modulus. The experimental and theoretical investigations could achieve the respective meaningful conclusions:

1. Despite the addition of sugarcane bagasse ash has proved to be beneficial in improving the studied mechanical properties of the concrete mix, such as compressive strength, flexure strength, and Young's modulus, further processing is required to attain the intended results because using samples directly from the plant (raw SCBA) revealed that they were ineffective at improving the characteristics of the concrete mix.
2. Raw SCBA concrete specimens had lower density, compressive strength, flexural strength, and Young's modulus than processed SCBA concrete specimens at the same

sugarcane bagasse ash proportion because raw SCBA has significantly larger particle sizes and lower silica content, resulting in much more porosity and voids in the concrete mixture and, ultimately, lower density and strength.

3. Re-grinding for an hour, as well as re-burning raw sugarcane bagasse ash at 600 °C for two hours (processed SCBA), resulted in a significant improvement in the studied mechanical properties of the concrete mixture, with compressive strength, flexural strength, and Young's modulus increasing up to 12%, 8%, and 8%, respectively, more than the normal concrete mixture. This is because the SCBA recycling process increased the amount of silica, which combines with calcium hydroxide to generate the calcium silica hydrate CSH matrix, which is primarily responsible for the strength of concrete.
4. The optimal amount of processed SCBA to apply as a partial substitute for cement weight was 10%; however, adding more than this resulted in a deterioration in the concrete mixture's density, compressive strength, flexural strength, and Young's modulus. This is due to reducing the proportion of cement and thus the alumina content in the concrete mixture, which leads to the decay of the hydration of calcium aluminate and, as a result, reduces the strength.
5. The flexural strength of sugarcane bagasse ash blended concrete specimens was measured experimentally and compared to ACI predictions. The comparison revealed that ACI underestimated the flexural strength of SCBA concrete specimens, with a mean coefficient of variation of 22% between the ACI equation and experimental results.
6. Young's modulus experimental results for raw and processed SCBA blended concrete specimens were slightly close and significantly consistent with ACI predictions; however, ACI overestimated Young's modulus, with a mean coefficient of variance between the ACI equation and experimental results of −6%.

7. Future Studies

Although the use of sugarcane bagasse ash has demonstrated its effectiveness in increasing the mechanical properties of the concrete mix, reprocessing is necessary to achieve the desired outcomes as the usage of samples directly from the factory revealed that they were ineffective at enhancing the properties of the concrete mix. The reprocessing of sugarcane bagasse ash in the current study is limited to regrinding for only one hour, as well as to re-burning at 600 °C for only two hours. Furthermore, the curing process is limited to 28 days at room temperature. As a result, it is possible to carry out further research on a variety of aspects of the sugarcane bagasse ash recycling process or to improve the pozzolanic activity by incorporating other waste materials, such as fly ash, and to investigate how these reflect the characteristics of the concrete mixture in the aspects that are outlined below:

1. Sugarcane bagasse ash blended concrete's durability and mechanical characteristics subjected to different curing regimes;
2. Sugarcane bagasse ash blended concrete's durability and mechanical characteristics subjected to different calcination temperatures;
3. Effect of different recycling processes of sugarcane bagasse ash on the mechanical properties of the concrete mixture;
4. Mechanical behavior of hybrid fly ash-sugarcane bagasse ash blended concrete.

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