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Performance Evaluation of Untreated Sugarcane Bagasse Ash as a Cement Alternative for Sustainable Concrete

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Abstract

Sugarcane bagasse ash (SCBA) is attracting considerable attention as an eco-friendly pozzolanic material for economical and sustainable concrete production. Its high content of amorphous silica makes SCBA an effective pozzolanic material in concrete. This study investigates the use of untreated SCBA (Ut-SCBA) as a partial cement substitute in various mix proportions up to 25%. This paper primarily focuses on fresh and mechanical properties, such as workability, compressive strength, flexural strength, ultrasonic pulse velocity (UPV), and modulus of elasticity (MoE) to determine the mechanical strength of Ut-SCBA mix concrete. The results indicate that substituting up to 15% of cement with Ut-SCBA significantly enhances concrete's mechanical properties compared to the control mix, due to increased pozzolanic activity and pore refinement. In this paper, physical and chemical characterization of raw materials such as ordinary Portland cement (OPC), aggregates, and Ut-SCBA are also evaluated using X-ray diffraction (XRD) and X-ray fluorescence (XRF).

Keywords: Sustainable Concrete; Untreated Sugarcane Bagasse Ash; Mechanical Properties; X-Ray Diffraction (XRD); X-Ray Fluorescence (XRF).

1. Introduction

Concrete is the most widely used material worldwide due to its durability, versatility, and strength. It consists of a cementitious binder matrix and a dispersed aggregate phase. In addition to its core components like cement, sand, and aggregate various supplementary cementitious materials (SCMs) such as fly ash, slag, and silica fume are used to enhance its strength and durability (Juenger et al., 2019). According to the 2023 research and market report, the global cement industry is projected to grow by 3.3% annually. However, this increase in cement production has significantly impacted the global environment due to carbon dioxide emissions (Berenguer et al., 2020). Since producing 1 kg of cement results in 1 kg of CO2, which contributes to the greenhouse effect (Yadav et al., 2020), researchers are focused on developing sustainable and eco-friendly construction materials to minimize CO2 emissions. Several studies (Abdurrahman et al., 2022; Alex et al., 2016; Assiamah et al., 2022; Bahurudeen et al., 2015; Her et al., 2021; Matos et al., 2015) have explored the use of agricultural waste materials like treated sugarcane bagasse ash (T-SCBA), groundnut shell, oyster shell, sawdust, rice husk ash, and cork wastes as cement substitutes. This study focuses on using untreated sugarcane bagasse ash (Ut-SCBA) as a supplementary cementitious material (SCM) due to its high-quality amorphous silica content (Bahurudeen et al., 2015; Praveenkumar et al., 2020). India, the second-largest producer of sugarcane after Brazil, disposes of 44,000 tonnes of Ut-SCBA daily (Singh et al., 2021;

Yogitha et al., 2020). Ut-SCBA is obtained from the controlled burning of bagasse in cogeneration plants linked with sugarcane industries. Notably, CO2 emissions for SCBA are almost eight times lower than those for ordinary Portland cement (Chindaprasirt et al., 2020). Ut-SCBA consists of various particles, including fibrous and burnt particles (Bahurudeen & Santhanam, 2015), which are typically irregular in shape. The chemical composition of agricultural waste materials like sugarcane bagasse ash (SCBA) varies based on factors such as geographical location, crop type, underground water, and soil nature (Quedou et al., 2021; Yogitha et al., 2020). Incorporating more than 10% treated sugarcane bagasse ash (T-SCBA) reduces water requirements while enhancing compressive and flexural strength (Praveenkumar et al., 2020). Additionally, the inclusion of T-SCBA decreases the workability and air content of concrete (Praveenkumar et al., 2020). Ultrasonic pulse velocity (UPV) tests show that T-SCBA geopolymer composites can qualify as cementitious materials (Akbar et al., 2021). Much emphasis has been placed on the mechanical properties of T-SCBA, including compressive strength, flexural strength, split tensile strength, density reduction, strength activity index, and sorptivity tests, as well as its durability. Chemical analyses of T-SCBA using X-ray diffraction (XRD) and thermogravimetric analysis (TGA) reveal the consumption of portlandite and confirm its pozzolanic potential (Berenguer et al., 2020). Concrete grades with target strengths of 20 and 30 MPa can be produced with 10 to 25% T-SCBA replacement for cement (Bahurudeen et al., 2015; Ganesan et al., 2007; Kazmi et al., 2017). Studies on untreated sugarcane bagasse ash (Ut-SCBA) show that substituting 10% Ut-SCBA with cement enhances the mechanical strength of concrete (Batool et al., 2020). Additionally, Ut-SCBA has been studied for use in mortar and bricks (Arenas-Piedrahita et al., 2016; Jiménez-Quero et al., 2013, 2019; Maldonado-García et al., 2018, 2019; Maza-Ignacio et al., 2020).

1.1. Research Significance

Untreated sugarcane bagasse ash (Ut-SCBA) is more economical and eco-friendlier compared to treated sugarcane bagasse ash (T-SCBA), as the existing method for treating sugarcane bagasse ash involves energy-intensive processes like burning, fine sieving (< 90µm), and grinding. Therefore, this study aims to evaluate the fresh and mechanical properties of untreated SCBA sourced from a high-efficiency co-generation boiler to determine its potential as a partial replacement for cement in concrete. The research examines the effects of Ut-SCBA on workability, compressive strength, flexural strength, ultrasonic pulse velocity (UPV), and modulus of elasticity (MoE). The results of this study are compared with control concrete samples to identify the optimal replacement percentage of cement to achieve the target strength of M25-grade concrete. [1-3]

1.2. Raw Materials

This paper explores the partial substitution of cement with untreated sugarcane bagasse ash (Ut-SCBA) in various proportions. This section details the raw materials used in the blended concrete and the specimen preparation process. Ordinary Portland cement (OPC-53 grade), conforming to Indian standards (BIS: 12269 (2013)), is utilized in these experiments with physical properties evaluated as per IS provisions (BIS: 4031 (Part 11) (1988)), as shown in Table 1. Sugarcane bagasse is sourced from the waste disposal area of the Ganpati sugarcane industry in Sangareddy, where it is burned to generate steam during sugar processing. The residual ash, consisting of both fine and coarse particles, is collected, dried, and screened to achieve a particle size of less than 150 µm. The dried ash is then oven-dried at 110°C for 24 hours to eliminate moisture and is used in the production of blended concrete, with its physical properties evaluated as per IS specifications (BIS 1727 (1967)) and listed in Table 1. River sand, obtained from a local plant, conforms to IS 4.75 mm sieve standards, while crushed stones are separated into 20mm and 10mm gradings, with physical properties listed in Table 2, conforming to Indian Standard specification (BIS: 383 (1970)). ECMAPLAST 104 HS, a new generation superplasticizer based on sulphonated naphthalene formaldehyde (SNF), with a specific gravity of 1.26 ± 0.02 @ 27°C, is used to maintain the desired slump with a proper dosage of 1% by the weight of cementitious content in each mix. [4-6]

Table 1 **Physical Characteristics of Cement and UT-SCBA**

Experiments	**Test Results**	**Specification as per IS 12269:2013**
Cement 53 G		
Standard Consistency (%)	29	-
Initial Setting Time (min)	134	30 Min
Final Setting Time (min)	178	600 Max
Soundness (mm)	1.02	10 Max.
Specific Gravity	3.15	-
Fineness Modulus (m^2/kg)	309	370 Max.
Colour	Grey	-
Ut-SCBA		
Specific Gravity	2.05	IS: 1727
Fineness Modulus Passing 45 µm sieve	30	IS: 1727
Density (kg/m^3)	256	-
Colour	Light Grey	-
Mean particle size	< 0.15 mm	-

In this study, M25 grade concrete is designed as per BIS: 10262 (2019) guidelines, with and without untreated sugarcane bagasse ash (Ut-SCBA) as a partial cement replacement. Six different mixtures are prepared, maintaining a constant water-cement ratio of 0.5. The mix without Ut-SCBA is designated as MIX0. Cement is substituted with Ut-SCBA at 5%, 10%, 15%, 20%, and 25%, corresponding to mixes MIX05, MIX10, MIX15, MIX20, and MIX25, respectively. The mix proportions for these concrete mixtures are shown in Table 4.

Table 2 **Physical Properties of Aggregates.**

Experiments		Test Results		
		Fine aggregate	Coarse aggregate	
		IS 4.75 mm sieve retained		
			20mm	10mm
Specific Gravity		2.538	2.658	2.634
Free Moisture Content (%)		5.93	Nil	Nil
Water Absorption (%)		0.903	0.235	0.294
Bulk Density (kg/m^3)	Loose	1422	1469	1427
	Compact	1585	1549	1508
Fineness Modulus		3.04	-	-

2. Method

Various experimental investigations have been conducted to assess the fresh and mechanical properties of concrete incorporating Ut-SCBA as a cementitious material. Chemical and mineralogical analyses of OPC, Ut-SCBA, and fine aggregate were Performed using X-ray diffraction (XRD) and X-ray fluorescence (XRF) to determine mineral phases and elemental compositions. Fresh properties, including workability, are evaluated using slump tests as per BIS 1199 (1959), with three readings taken at different intervals for each mixture. Compressive strength tests are conducted as per BIS: 516 (Part 1/Sec 1) (2021) on three cube specimens for each blend using a 200-ton compression testing machine at 7, 28, 56, and 90 days. The rate of loading is maintained at 14 N/mm²/min, and results were averaged from three specimens. Flexural strength tests are performed according to BIS: 516 (Part 1/Sec 1) (2021) on beam specimens (150mm x 150mm x 700mm) using two-point loading at 7 and 28 days. The results are also averaged from three specimens. Ultrasonic Pulse Velocity (UPV) tests, a non-destructive method, are used to evaluate concrete quality, with values recorded at 7, 28, 56, and 90 days using the direct method on 150x150x150 mm cubes. Based on UPV values, concrete quality is classified according to BIS: 516 (Part 5/Sec 1) (2018). The dynamic modulus of elasticity is also measured as per BIS: 516 (Part 5/Sec 1) (2018).

Table 3 Chemical Composition of Cement, Ut-SCBA and Fine Aggregate

S.No.	Oxides	Cement	Ut-SCBA	Fine Aggregate
1	CaO	72.488 %	6.139 %	4.406 %
2	SiO_2	14.291 %	75.844 %	75.999 %
3	Fe_2O_3	6.148 %	4.822 %	2.039 %
4	SO_3	2.547 %	1.562 %	0.209 %
5	Al_2O_3	2.450 %	3.104 %	10.145 %
6	BaO	0.811 %	-	0.117 %
7	TiO_2	0.639 %	0.775 %	0.339 %
8	K_2O	0.418 %	6.411 %	6.591 %
9	MnO	0.106 %	0.199 %	0.034 %
10	SrO	0.073 %	0.024 %	0.031 %
11	ZrO_2	0.016 %	-	0.029 %
12	CuO	0.013 %	0.034 %	0.012 %
13	P_2O_5	-	0.975 %	-
14	ZnO	-	0.054 %	-
15	V_2O_5	-	0.040 %	-
16	Rb_2O	-	0.011 %	0.037%
17	Br	-	0.006 %	-
18	ThO_2	-	-	0.010 %
19	Y_2O_3	-	-	0.002 %

3. Results and Discussion

3.1. Physical and Chemical Characterization of Materials

The particle size distribution of fine aggregate and Ut-SCBA is performed using a mechanical sieve shaker as shown in Fig. 1. The chemical composition results of OPC, Ut-SCBA, and fine aggregate are displayed in Table 3. The analysis reveals that Ut-SCBA exhibits high silica content, exceeding 70% SiO2, which aligns with (ASTM (C618 − 12a) criteria for pozzolans. Meeting the requirements for class F pozzolans, the Ut-SCBA surpasses the 70% (SiO2 + Al2O3 + Fe2 O3) threshold. Additionally, it contains 6.41% K2O, 6.13% CaO and a notable 1.5% SO3 content, which is within the acceptable limit of 4% for pozzolans (Zaheer & Tabish, 2023). The data also highlights that Ut-SCBA possesses a silica content five times greater than OPC. Interestingly, the fine aggregate demonstrates a similar silica content to Ut-SCBA, as indicated in Table 3. The X-ray diffraction diagrams Fig. 2(a)-(c), reveal the presence of C2S and C3S in OPC, known for favoring the formation of cementitious products like C-S-H and CH during hydration. Additionally, C3A, C4AF and gypsum are observed with less intensity. In the case of Ut-SCBA, the results indicate low crystallinity, signifying the presence of an amorphous silica hump within the 2θ range of 200–35° (Bahurudeen et al., 2015). Principal crystalline components detected include Quartz and Cristobalite. Furthermore, Gibbsite (Al2O3) and Iron Oxide (Fe2O3) are also detected, encouraging the pozzolanic reaction with calcium hydroxide. Traces of phosphorous oxide (P2O5) and other oxides are noted as shown in Table 3, attributed to incomplete Ut-SCBA combustion during burning. Quartz and alumina were observed in higher proportions in fine aggregate.

Table 4 **Mix Proportion of Materials**

Mix ID	Ut-SCBA (%)	OPC (kg)	Ut-SCBA (kg)	F.A (kg)	C.A (kg)		Water (kg)	Admixtures (kg)
					20mm	10mm		
MIX0	00	330	-	780	660	450	165	3.3
MIX05	05	313.5	16.5	780	660	450	165	3.3
MIX10	10	297	33	780	660	450	165	3.3
MIX15	15	280.5	49.5	780	660	450	165	3.3
MIX20	20	264	66	780	660	450	165	3.3
MIX25	25	247.5	82.5	780	660	450	165	3.3

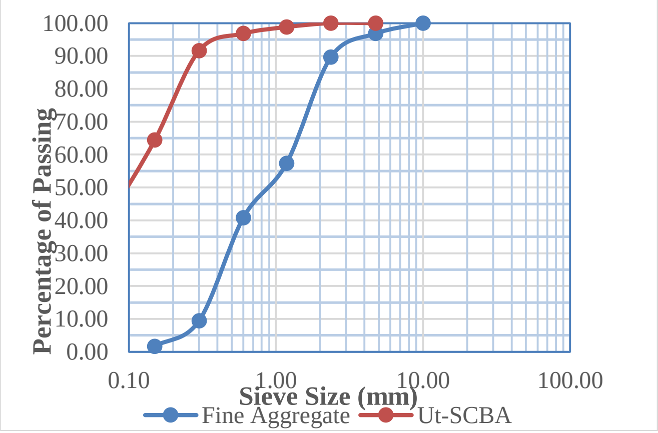
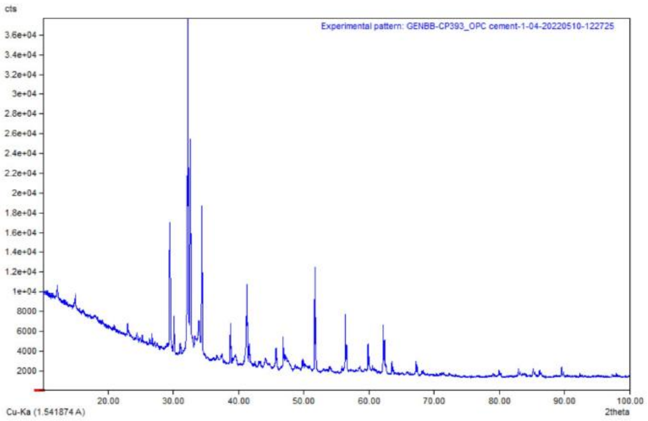


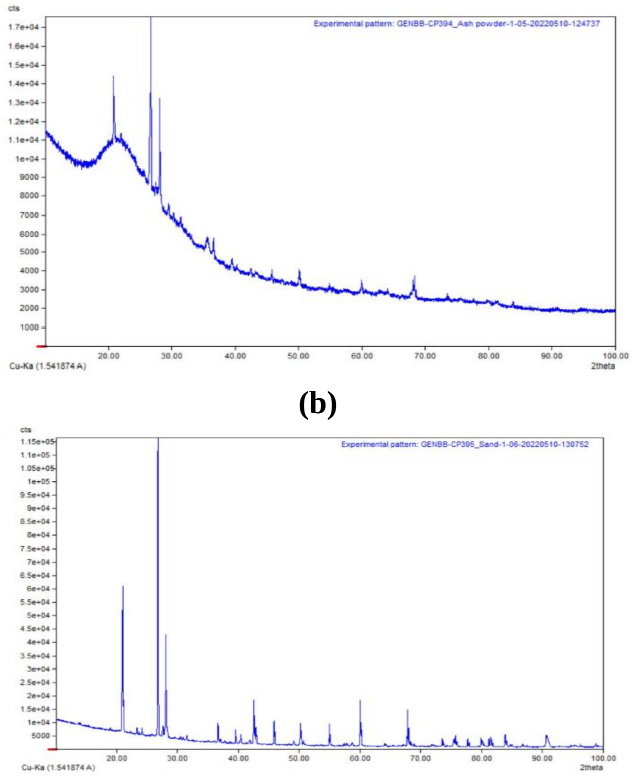
Figure 1 **Particle Size Distribution of Fine Aggregate and Ut-SCBA**

3.2. Fresh Properties – Workability

The workability of fresh concrete is evaluated using a slump cone at various intervals immediately after mixing, 30 minutes, and 60 minutes while maintaining a consistent superplasticizer dose across all blends. This approach aids in quality control, as illustrated in Fig. 3, which shows a notable reduction in slump loss over time with increased Ut-SCBA substitution. The reduced workability with higher Ut-SCB content is attributed to its irregular shape, high specific surface area, porous texture, and absorptive nature (Arif et al., 2016; Kazmi et al., 2017; Vijayalakshmi et al., 2013), necessitating adjustments in water content to achieve desired consistency.



(a)



(b)

(c)

Figure 2(a)-(c) X-Ray Diffraction Spectrum of the (A) OPC (B) Ut-SCBA (C) Fine Aggregate

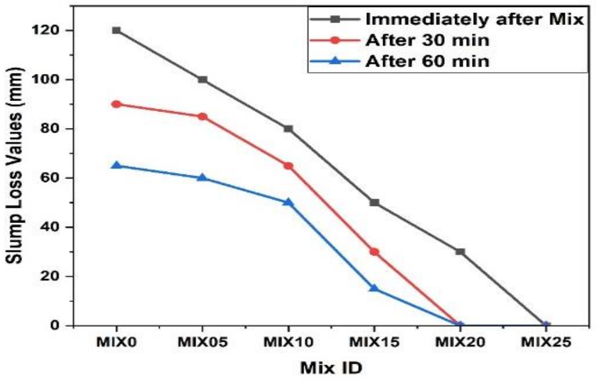


Figure 3 Slump Loss Value of Concrete Versus Duration at Different Substitution Rate of Ut-SCBA By-Product

3.3. Mechanical Properties

3.3.1. Compressive Strength

The compressive strength of concrete with varying Ut-SCBA blends is measured at 7, 28, 56, and 90 days of curing, as detailed in Table 5 and illustrated in Fig. 4. Up to a 20% replacement with Ut-SCBA, compressive strength exceeds that of the control mix, with the highest strength observed at 10% Ut-SCBA (MIX10), reaching 35.92 MPa at 7 days and increasing to 47.88 MPa by 90 days. This enhancement is due to the additional C-S-H gel formation from the reaction between Ut-SCBA's SiO_2 and Al_2O_3 with $Ca(OH)_2$ from cement hydration (Praveenkumar et al., 2020). At 7 days, the compressive strengths for 5%, 15%, and 20% Ut-SCBA blends are 33.04, 30.59, and 29.99 MPa, respectively, representing improvements of 36.69%, 26.56%, and 24.08% over the control mix (24.17 MPa). However, compressive strength diminishes with more than 20% Ut-SCBA replacement due to reduced reactivity, insufficient $Ca(OH)_2$, and dilution effects. Overall, up to 20% Ut-SCBA replacement is effective for maintaining concrete strength, with strength properties improving over time due to increased pozzolanic reactivity. Similar trends are observed after 28, 56 and 90 days of curing.

3.3.2. Flexural Strength

Table 5 and Fig. 5 present the flexural strength results for concrete with various Ut-SCBA proportions. Initially, the flexural strength decreases with Ut-SCBA addition after 7 days but improves after 28 days, reaching up to 15% substitution compared to the control mix (MIX0). The control mix has flexural strengths of 1.74 MPa at 7 days and 2.49 MPa at 28 days. The highest flexural strength, 10.89% greater than MIX0, is achieved with MIX10 after 28 days. This is due to Ut-SCBA's initial dilution effect, which reduces early strength, but enhances long-term strength by forming additional C-S-H gel with lime (Quedou et al., 2021).

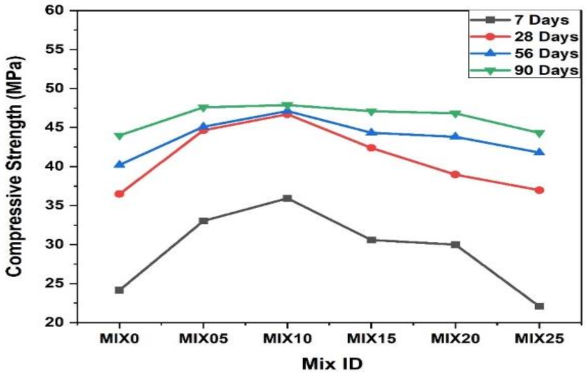


Figure 4 Compressive Strength of Concrete Mixtures at Different Ages-Comparison

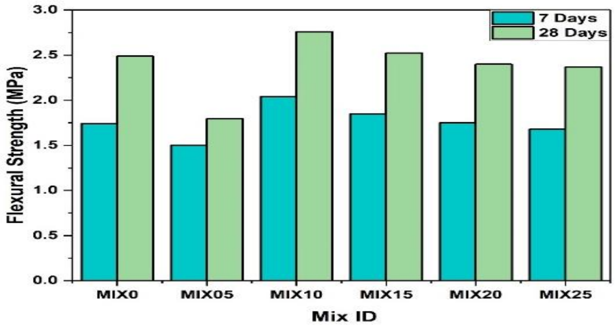


Figure 5 **Flexural Strength of Concrete Mixtures at Different Ages-Comparison**

3.3.3. Ultrasonic Pulse Velocity (UPV)

Table 6 presents the UPV values for concrete mixes with varying Ut-SCBA proportions (MIX0 to MIX25). Pulse velocity increases with Ut-SCBA addition up to 20% compared to the control mix (MIX0) at 7, 28, 56, and 90 days, as shown in Fig. 6. Initially, UPV is lower due to Ut-SCBA's low density and high porosity, but it improves with curing time. At 28 days, velocity increases by 10.14%, 12.85%, 8.94%, and 3.03% for MIX05 to MIX20, respectively, with similar trends at 56 and 90 days. There is a slight decrease in velocity at 25% replacement, with values remaining lower than the control mix until 90 days. The increased UPV indicates greater compactness and is attributed to the filler effect and denser C-S-H formation.

3.3.4. Dynamic Modulus of Elasticity (MOE)

The dynamic modulus of elasticity (MOE) for Ut-SCBA mixes is also compared with the control concrete in Table 6. Previous research indicates that the dynamic modulus of elasticity of concrete generally correlates with its compressive strength and ultrasonic pulse velocity (Praveenkumar & Sankarasubramanian, 2021; Vijayalakshmi et al., 2013). The MOE generally increases with Ut-SCBA addition up to 25%, correlating with improved compressive strength and UPV (Praveenkumar & Sankarasubramanian, 2021). At 28 days, the increments are 24.55%, 37.89%, 22.53%, and 6.02% for MIX05 to MIX20, respectively, with similar patterns at 56 and 90 days, except for MIX25.

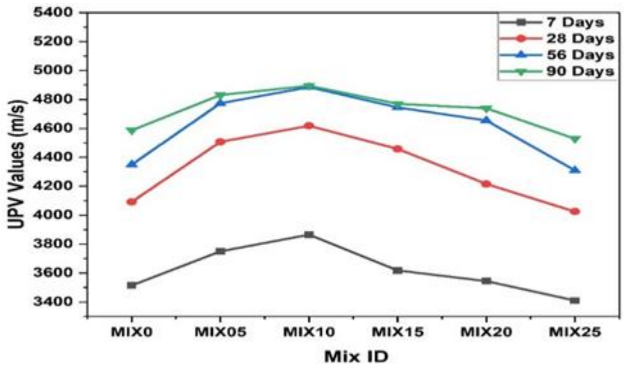


Figure 6 **UPV Values of Concrete Mixtures at Different Ages-Comparison**

Table 5 **Variations in Compressive and Flexural Strength**

Mix ID	Compressive strength (MPa)				Flexural strength (MPa)	
	7 Days	28 Days	56 Days	90 Days	7 Days	28 Days
MIX0	22.86	35.40	38.49	42.59	1.72	2.36
MIX0	24.60	36.19	40.32	43.98	1.73	2.51
MIX0	25.05	37.85	41.85	45.36	1.77	2.61
MIX0 average	**24.17**	**36.48**	**40.22**	**43.98**	**1.74**	**2.49**
MIX05	32.01	43.61	43.14	46.85	1.41	1.67
MIX05	33.07	44.86	45.16	47.75	1.51	1.83
MIX05	34.04	45.45	47.04	48.21	1.58	1.91
MIX05 average	**33.04**	**44.64**	**45.11**	**47.60**	**1.50**	**1.80**

MIX10	34.15	45.09	45.83	46.96	1.98	2.71
MIX10	36.25	47.12	47.56	48.01	2.06	2.74
MIX10	37.35	47.89	47.96	48.66	2.08	2.83
MIX10 average	**35.92**	**46.7**	**47.12**	**47.88**	**2.04**	**2.76**
MIX15	29.14	40.65	43.95	46.05	1.81	2.36
MIX15	30.56	42.54	44.10	47.21	1.84	2.50
MIX15	32.08	43.98	44.92	47.97	1.90	2.71
MIX15 average	**30.59**	**42.39**	**44.32**	**47.08**	**1.85**	**2.52**
MIX20	28.63	37.85	42.31	45.76	1.69	2.29
MIX20	30.05	38.28	43.69	46.8	1.71	2.41
MIX20	31.28	40.78	45.41	47.88	1.85	2.51
MIX20 average	**29.99**	**38.97**	**43.80**	**46.81**	**1.75**	**2.40**
MIX25	20.97	35.91	40.49	43.15	1.64	2.32
MIX25	22.12	36.96	42.31	44.09	1.69	2.38
MIX25	23.15	38.04	42.61	45.68	1.71	2.41
MIX25 average	**22.08**	**36.97**	**41.80**	**44.31**	**1.68**	**2.37**

Table 6 Variations in UPV and MOE at Different Age of Curing

Mix ID	Ultrasonic pulse velocity (m/s)				Concrete quality grading as per IS 516 (Part 5 / Sec I) :2018	Modulus of elasticity (MOE)			
	7 Days	28 Days	56 Days	90 Days	UPV (m/s)	7 Days	28 Days	56 Days	90 Days
MIX0	3515	4092	4350	4587	Above 4400 – Excellent	25.07	34.08	39.12	43.92
MIX05	3750	4507	4773	4830	3750 to 4400 – Good	30.02	42.44	46.23	47.60
MIX10	3865	4618	4885	4895	3000 to 3750 – Doubtful	32.85	46.99	46.63	48.47
MIX15	3618	4458	4745	4770	Below 3000 – Poor	27.24	41.76	45.18	47.00
MIX20	3545	4216	4655	4739		25.51	36.13	44.39	46.36
MIX25	3410	4025	4310	4528		23.58	32.90	37.81	41.95

Conclusion

The study demonstrates that utilizing Ut-SCBA as a supplementary cementitious material (SCM) could effectively address the demand for sustainable concrete. It evaluates the impact of replacing cement with Ut-SCBA in proportions ranging from 5% to 25% on the fresh and mechanical properties of concrete.

- Increasing Ut-SCBA substitution decreases concrete workability due to its high specific surface area and irregular particle characteristics, affecting particle size, packing, and shape.
- Compressive strength improves with Ut-SCBA substitution up to 20% as concrete cures, while flexural strength initially drops but rises after 28 days with up to 15% substitution. The highest strength is observed at 10% replacement due to enhanced C-S-H gel formation from SiO_2 and Al_2O_3 in Ut-SCBA.
- UPV values for up to 20% Ut-SCBA replacement are higher than the control mix, categorizing the concrete as excellent according to BIS 516:2018.

Based on the results from experiments assessing fresh and mechanical properties, the optimal cement substitution with untreated sugarcane bagasse ash (Ut-SCBA) is up to 15%. This level enhances the sustainability of concrete, benefiting both economic and environmental aspects.

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