EVALUATION OF THE EFFECTIVENESS OF THE STEEL FIBER-RINFORCED CONCRETE INCORPORATING SUGARCANE BAGASSE ASH

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ABSTRACT

The use of agro-industrial waste material-based sustainable concrete has presented an alternative to conventional concrete. Conventional concrete exhibits relatively low tensile resistance and often eventually develops early cracking. Tensile strength can be enhanced by fiber reinforcement and supplemented with cementitious materials. This paper reports the rheological and mechanical performance of concrete modified with sugarcane bagasse ash as a partial cement replacement (0%, 10%, 15%) and waste steel fibers at 0.5% and 1.0% by volume. Rheological performance was analyzed through slump, compacting factor, ball penetration, and density tests, while the mechanical behavior of the mixes was assessed through 7 and 28-day compressive strength tests. The results have shown that the addition of SCBA and WSF reduces the workability of mixes significantly, such that the slump decreased in the range of 25-35%, the compacting factor dropped by up to 15%, and the ball penetration depth decreased by 31% over the control mixture. Yield stress was increased by about 19% which supports the reduced flowability of hybrid mixtures. The mechanical test results indicated that the addition of WSF and low dosages of SCBA improves compressive strength. The highest 28-day strength was registered in mix W1S0, with a strength gain of 15.86% over the control. Mixes with 0.5% WSF combined with SCBA showed moderate strength gains of 1-6%. Increased dosage of SCBA at 15% resulted in strength reduction, although mixes were still above the control, with strength increase in the range of 1.56-9.82% depending on the dosage of the fibers. The overall trend from this work illustrates how optimized inclusion of WSF and limited contents of SCBA improve sustainability and enhance mechanical performance.

Keywords: *Sugarcane Bagasse Ash, Waste Steel Fiber, Sustainable Concrete, Rheological Properties, Compressive Strength*

1. INTRODUCTION

Concrete is one of the most common materials in the modern construction industry for its satisfactory compressive strength and long-term durability. On the other hand, the concrete industry is also one of the most resource-intensive sectors in the field of construction, which significantly contributes to global energy consumption and CO_2 emissions. OPC releases almost 0.9 t CO_2 per ton of cement and accounts for about 7-8% of global anthropogenic CO_2 emissions (He, Zhu, Wang, Mu, & Wang, 2019). The environmental impact of cement has recently encouraged the construction industry toward sustainable usages, such as "green concrete," in which some amount of cement is replaced with SCMs derived from industrial or agricultural waste (Zareei, Ameri, & Bahrami, 2018).

In this context, SCMs and fiber reinforcements obtained from various industrial and agricultural by-products have recently attracted considerable attention (Arshad, Sharif, Irfan-ul-Hassan, Khan, & Zhang, 2020). Among these SCMs, sugarcane bagasse ash (SCBA), a by-product of sugar industries, is rich in amorphous silica and alumina and can exhibit significant pozzolanic reactivity when finely ground Hamcumpai et al. (2025). Studies have shown that OPC replacement with 5-15% SCBA enhances long-term strength and reduces permeability, due to the refinement of the pore structure induced by the additional formation of C-S-H gel (Tipraj, Athira, & Priya, 2025). Mahmud, Islam, Rubieyat, Islam, and Hasan (2018) and Ganesan, Rajagopal, and Thangavel (2007) separately found that a partial replacement of cement with SCBA within 5 to 10 % can improve the compressive strength and workability of M20-M30 concretes, while higher proportions were burdened by dilution effects. Similarly, Raghuram, Manoharan, Gayathri, and Thilahar (2024) recently found that the addition of 5% SCBA along with steel fibers significantly improves the compressive and flexural strengths, thanks to the improvement in matrix densification and fiber-matrix bonding. Despite being strong under compression, conventional concrete is brittle and weak in tension. Adding discrete steel fibers has been widely demonstrated to effectively enhance ductility, crack control, and impact resistance (Guan, Too, Teh, & Kum, 2023). Indeed, fibers are bridging micro-cracks, delaying crack propagation, and enhancing the post-peak load-carrying capacity. However, excessive fiber content may lead to poor workability and fiber clustering (which would adversely impact rheology) (Aziz & Mohammed, 2022). Much research has demonstrated that the addition of Waste Steel Fibers (WSF) between 0.5 and 2.0% of volume increases compressive, tensile, and flexural strengths while keeping costs low. For instance, Elrefaei, Alsaadawi, Abdolwahab, Adly, and Elshahat (2025) also reported improved toughness and reduced permeability in concrete containing tire-derived WSF combined with fly ash or bagasse ash. Recent sustainable construction research has combined agro-industrial SCMs, such as SCBA, with recycled steel fibers (from machining or blacksmith waste), yielding a hybrid composite capable of reducing the carbon footprint while maintaining superior strength (Rihan, Onchiri, Gathimba, & Sabuni, 2024). Yet, the literature reveals a limited understanding of the rheological behaviour, specifically the flowability, viscosity, and cohesiveness of such hybrid concretes, and their correlation with hardened mechanical performance.

In the current study, seven concrete mixes were prepared to investigate the combined effect of waste steel fibers (WSF) and sugarcane bagasse ash (SCBA) on the mechanical and rheological behaviour of sustainable concrete. Sugarcane bagasse ash was partially replaced by cement at levels of 0%, 10%, and 15%, while waste steel fibers were added at 0.5% and 1.0% by volume of concrete. It is hoped that this study will contribute to the advancement of eco-friendly concrete technology by providing practical insights into the use of agro-industrial and metallic wastes in structural applications for a sustainable built environment.

2. METHODOLOGY

2.1 Materials

In this study, Ordinary Portland Cement (OPC) Type I, which is in conforming with ASTM C150 (C. ASTM, 2020), was used as the main binder and was purchased in a single batch to maintain consistency. Table 1 represents its specific gravity, setting times, and physical composition. Natural river sand received from the Sylhet region of Bangladesh (max size 4.75 mm) was washed and graded according to ASTM C33/C33M-18 (Kasulanati & Pancharathi, 2024) and was used as fine aggregate. Crushed stone with a maximum size of 20 mm was used as coarse aggregate, with physical properties detailed according to the ASTM C136 / C136M-19 (C. Astm, 2006). Potable tap water with free from impurities, was used for mixing and curing, conforming to ASTM C1602 (C. ASTM, 2018). Sugarcane bagasse ash (SCBA) was produced by burning sugarcane bagasse at 600 °C in southern Bangladesh, then sieved through a 75 µm mesh. The chemical composition of SCBA, determined by X-ray fluorescence (XRF), is shown in Table 2 and Figure 1. Waste steel fibers (WSF) were sourced from Bangladesh Cable Shilpa Limited, Khulna, cleaned, and cut to 30 mm lengths with a 1 mm diameter (aspect ratio 50). The fibers, with a density of 7800 kg/m³, were incorporated into concrete mixes at 0.5% and 1.0% by volume. The physical properties of the WSF are provided in Table 3, and their morphology is shown in Figure 2.

Table 1: Physical properties of ordinary Portland cement

Setting times (minutes)	Initial-30
	Final- 600
Specific Gravity	3.15
Standard Consistency	30-35
Compressive Strength 28 days (N/mm^2)	53
Unit Weight (Kg/m^3)	1440

Table 2: Physical properties of SCBA

Property	Value
Fineness modulus	2.12
Specific gravity	1.78

Table 3: Physical properties of waste steel fiber

Property	Value
Length	35 mm
Cross-sectional diameter	0.6 mm
Undulation width	2 mm
Aspect ratio	50

Figure 1: Sugarcane bagasse ash

Figure 2: Waste steel fiber

2.2 Experimental program

2.2.1 Mix proportion and concrete mixing

A concrete mix ratio of 1:1.85:2.55 by the weight of ordinary Portland cement, Sylhet sand, and crushed stone chips was used to mix the concrete. A water-to-cement ratio of 0.39 was maintained throughout the mix, without the use of water-reducing admixtures. The concrete was prepared by mixing all the materials in their calculated proportions using the laboratory's mixing machine. SCBA replaced cement at 0%, 10%, and 15% by weight, while waste steel fibers (WSF) were incorporated at 0.5% and 1.0% by volume of concrete. According to the literature review, these percentages of both materials are responsible for improving sustainability and potential strength. The mixes were designated as W0S0, W0.5S0, W0.5S10, W0.5S15, W1S0, W1S10, and W1S15. Table 4 shows the proportion of mix for 1 m3 of concrete. Mixing was conducted in a pan mixer following ASTM C192/C192M. Coarse aggregate, Sylhet sand, and cement (or cement-SCBA blend) were dry mixed for 1 minute. Water was then added gradually and mixed for 4 minutes. WSF was introduced slowly to avoid balling and to ensure uniform dispersion.

Table 4: Mix proportion

Mix ID	Cement (kg/m³)	SCBA (kg/m³)	Water (kg/m³)	Coarse Agg (kg/m³)	Sand (kg/m³)	W (%)
W0S0	412.50	0.00	194.00	1052.00	761.50	0.0%
W0.5S0	412.50	0.00	194.00	1052.00	761.50	0.5%
W0.5S10	371.25	41.25	194.00	1052.00	761.50	0.5%
W0.5S15	350.63	61.88	194.00	1052.00	761.50	0.5%
W1S0	412.50	0.00	194.00	1052.00	761.50	1.0%
W1S10	371.25	41.25	194.00	1052.00	761.50	1.0%
W1S15	350.63	61.88	194.00	1052.00	761.50	1.0%

2.3 Sample preparation and curing

Cylindrical specimens of 100 mm × 200 mm were cast for compressive strength testing. A total of 28 cylinders were prepared to evaluate compressive strength at 7 and 28 days. Moulds were cleaned, lubricated, and filled in three layers, each compacted with 25 blows using a tamping rod. Fresh concrete was also used to determine its rheological properties, including slump, compacting factor, Kelly ball penetration, and fresh density before casting. Specimens were kept for 24 ± 2 hours in the laboratory (30 °C, 82 % RH), then demolded and cured in water until the designated testing ages, in accordance with ASTM C192/C192M-19.

2.3.1 Rheological and mechanical properties testing

The slump cone test was performed to measure the workability of freshly mixed concrete in accordance with the ASTM C143/C143M-15a test method (A. ASTM, 2015). Slump measurements were taken for all mixes to evaluate the influence of fibers and the combined effect of fibers and SCBA on the workability of concrete. Slump is closely related to the rheological parameters of a mixture, specifically yield stress and plastic viscosity. Based on a finite element model of the slump test, Hu et al. (Hu et al., 1996) proposed an expression for estimating yield stress as a function of concrete density and slump, as presented in Equation (1). Their finite element simulations covered concretes with slump values ranging from 0 to 25 cm. Nevertheless, this equation is not applicable for concretes exhibiting a plastic viscosity greater than 300 Pa·s (Ede & Agbede, 2015).

$$\tau_0 = \frac{\rho}{270}(300 - s) \qquad (1)$$

Where τ_0 = yield stress in Pa, s = slump in mm, ρ = density in kg/m³. The ball penetration test is a simplified field test used in measuring the workability of concrete. The tests were conducted according to ASTM C360. The compacting factor test was also conducted in conformity with BS 1881-103 to further investigate the workability of freshly mixed concrete. The fresh concrete density test was performed according to ASTM C138. Figures 3(a), 3(b), and 3(c) illustrate the setup for slump testing, the ball penetration method, and the compaction factor test setup, respectively. The compressive strength of the concrete specimens was identified using cylindrical samples of 100 × 200 mm after curing at 7 and 28 days, following ASTM C39/C39M-20.

(a)

(b)

(c) (d)

Figure 3: Fresh and mechanical properties test.

3. RESULTS AND DISCUSSION

3.1 Rheological properties

3.1.1 Slump and compacting factor

Figure 4 illustrates the slump value and compacting factor of fresh concrete containing different percentages of SCBA and WSF. A consistent reduction in workability was clearly seen upon the addition of these green materials.

The highest slump value of 105.40 mm was recorded for the control mix W0S0, which gradually decreased to 90.25, 87.00, and 81.90 mm for mixes W0.5S0, W0.5S10, and W0.5S15, respectively, with the addition of 0.5% WSF and 10-15% SCBA. Again reduction in slump values was observed for mixes containing an increased dosage of fiber up to 1%, with slump values of 84.98, 71.25, and 68.36 mm for W1S0, W1S10, and W1S15 concrete mixes, respectively. On the whole, concrete containing SCBA and WSF demonstrated an average slump reduction of 25-35% compared to the control mix. This reduction in slump can be attributed to the high fineness as well as the porous nature of SCBA, which enhances water absorption and reduces free water available for lubrication.

In other words, the mechanical interlocking introduced by WSF increases internal friction and restricts aggregate movement. At higher dosages of fiber, localized fiber clustering further limits flowability, although all mixes produced a true slump, indicating good cohesiveness without signs of shear slump.

The same trend was followed when it came to the compacting factor. A value of control mix was 0.95, and the compaction efficiency of the SCBA-WSF modified mixes was lower: the compacting factor dropped to 0.909, 0.900, and 0.870 with mix W0.5S0, W0.5S10, and W0.5S15, respectively, and lower to 0.89, 0.85, and 0.806 with 1% fiber mixes. As an example, mixes W1S10 and W1S15 showed the reductions of 10.5 and 15.1 percent compared to the control, which showed the growing difficulty of attaining full compaction as hybrid constituents were added. This decreasing trend confirms that increased doses of fiber and pozzolanic SCBA particles hinder internal rearrangement of aggregates during compaction. The mechanical interlocking and more surface area demand more energy for compaction, leading to a lower compacting factor. Such results are in agreement with the reported behaviors of fiber-reinforced and SCM-modified concretes, where improved internal resistance decreases workability (Rudraswamy, Patagundi, & Prakash, 2018).

The correlation between slump value and yield stress is illustrated in Figure 5. A strong inverse linear relationship ($R^2 = 0.9997$) was obtained from the regression analysis, which confirmed that the yield stress increases as the slump decreases. This is expected; mixtures with higher stiffness and fiber content offer greater internal resistance to flow and, therefore, require higher yield stress to initiate deformation. Mix W1S15, the stiffest mixture, recorded the highest yield stress of 2099.3 Pa, whereas the control mix had the lowest value of 1766.36 Pa. These results show an excellent relation with the classical rheological interpretations reported by Tattersall and Banfill (Tattersall & Banfill, 1983).

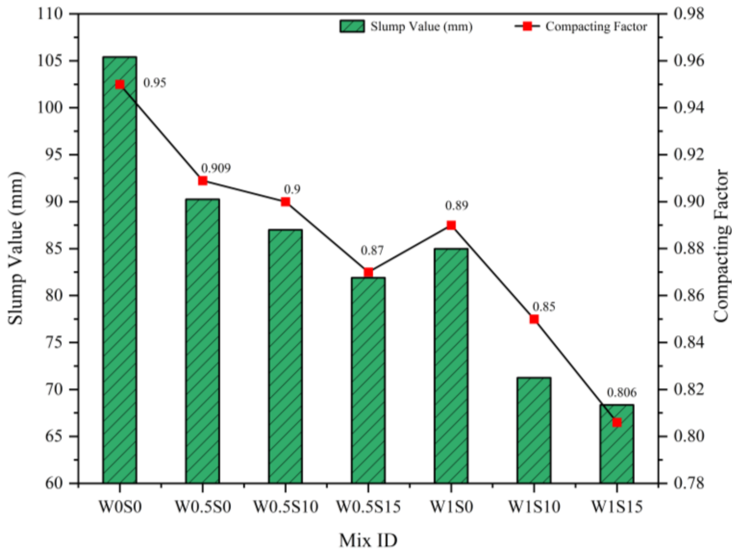

Figure 4: Compacting factor and slump values for all mixes

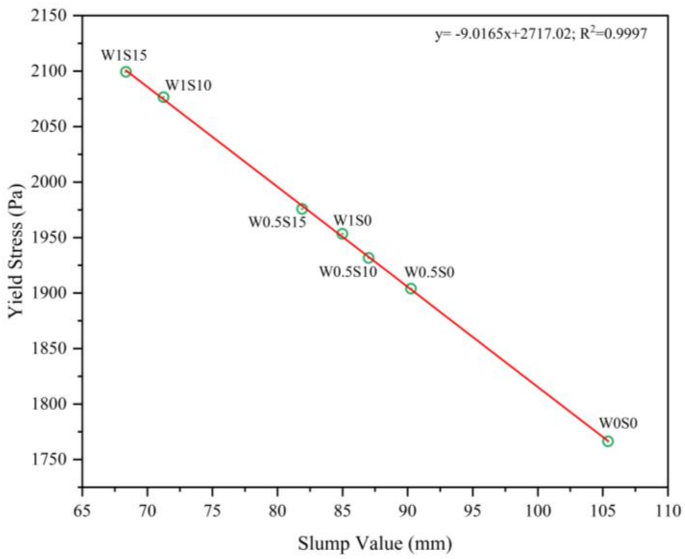

Figure 5: Variations of yield stress with slump values for fresh concrete

3.1.2 Density and ball penetration value

The results for the density of SCBA-WSF concrete mixtures (Figure 6) were quite consistent, fluctuating between 2445-2453 kg/m³, although the addition of fibers and SCBA caused minor variations. The control mixture reached a value of 2450.75 kg/m³, while the highest value was obtained in W1S0 (2452.97 kg/m³) due to the presence of denser steel fibers in the absence of SCBA. A slight decrease at higher contents of SCBA (2446.95 kg/m³ in the case of W1S15) is most likely due to the ability of bagasse ash to make the mixture porous during particle packing.

A similar decreasing trend was observed for the ball penetration test, where the depth of penetration decreased from 49.2 mm for W0S0 to 33.7 mm for W1S15, representing a 31% decrease in penetrability. This reduction reflects the enhancement of mixture stiffness with greater fiber and SCBA content. Interactions between the effects of fiber bridging and the increased viscosity due to SCBA lead to a decrease in the available free water, thus creating a less workable and more resistant fresh matrix. These observations align with previous studies by Dopko and Najimi (Dopko et al., 2018), who reported decreasing ball penetration depth in fiber-reinforced systems due to enhanced internal resistance. Additionally, the slump value in this study averaged about 1.5 times the ball penetration value, suggesting that slump could be reliably estimated using penetration data.

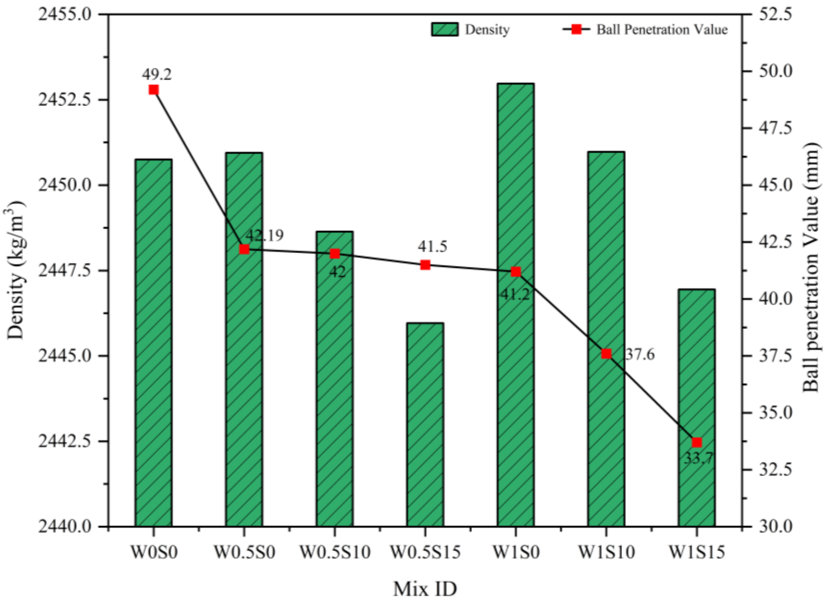

Figure 6: Density and ball penetration values for mixes

3.2 Hardened properties

3.2.1 Effects of sugarcane bagasse ash and waste steel fibres on compressive strength

The compressive strength results of all concrete mixtures are summarized in Table 5. The values presented correspond to the mean compressive strength of two specimens tested for each mix at 7 and 28 days. The table also includes the percentage change in strength relative to the control mix (W0S0) to evaluate the influence of varying SCBA and WSF contents.

Figure 7 illustrates the compressive strength of every mix after 7 and 28 days. The trends indicate that there is a strong influence on the strength development because of introducing SCBA along with WSF. In the case of control mix (W0S0), the compressive strengths of the 7-day compressive strength and 28-day compressive strength were 15.83 MPa and 24.45 MPa, respectively. A combination of 0.5% steel fibre without SCBA (W0.5S0) indicated a 6.45% and 6.09% increase in compressive strength at 7 and 28 days, respectively, showing that the addition of steel fibre is beneficial in early and later development of strength.

The mixtures W0.5S10 and W0.5S15, WSF combined with 10% and 15% SCBA, respectively, showed further improvements compared to the control mix. Thus, at 7 days, the increase in strength was 3.09% and 1.83%, while at 28 days, the increase was 3.15% and 1.56%, respectively. A significant change in performance occurred when WSF content was increased to 1% (W1S0). W1S0 mixture had the best compressive strength of all mixtures; it peaked at 22.01 MPa and 28.32 MPa in 7 and 28 days, respectively. These compressive strengths are equivalent to 39.02% and 15.86% significant gains over the control mixture. These findings suggest that this addition of WSF maximizes the mechanical response of the composite by enabling the bridging of cracks and a better post-cracking behaviour, and the absence of SCBA prevents any dilution and breakage of the cementitious matrix.

Further incorporation of SCBA as partial cement replacement into the 1% WSF mixes (W1S10 and W1S20) produced compressive strengths that remained higher than the control, although slightly lower than the fibre-only mix (W1S0). At 7 days, the strength increases for W1S10 and W1S20 were

33.29% and 23.83%, respectively; at 28 days, the increases were 12.37% and 9.82%, respectively. This suggests that while moderate SCBA replacement contributes pozzolanic refinement of the matrix, increasing SCBA content can marginally reduce early and later-age compressive strength compared with the 1% WSF-only optimum, likely because higher SCBA replacement decreases the available clinker content and may alter early hydration kinetics.

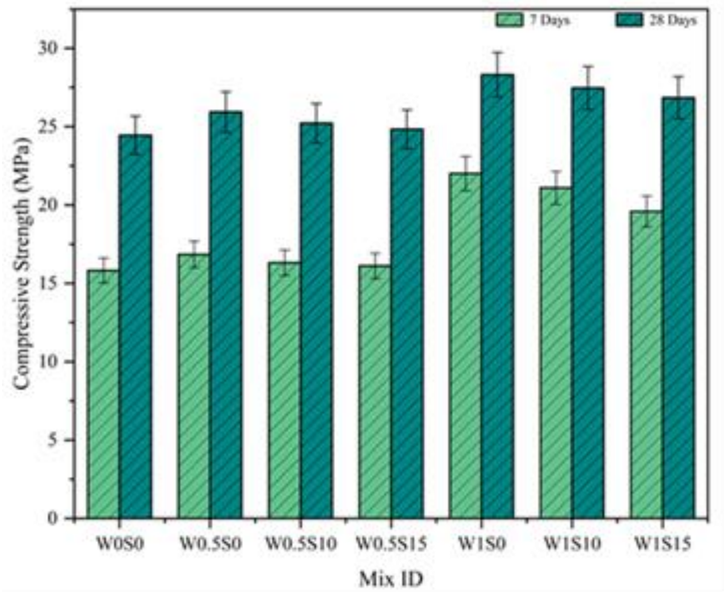

Figure 7: Compressive strength values for all mixtures at 7 and 28 days

Figure 8, which shows the percentage change in strength relative to the control concrete, confirms this trend: the largest improvement corresponds to W1S0, while mixes with increasing SCBA replacement (S10, S20) show progressively reduced strength gains. This pattern agrees with reported outcomes that the benefits of fibre addition and SCMs are both dosage-dependent, such as excessive SCM replacement or improper proportions can offset fibre benefits by affecting workability, compaction, and packing density.

Overall, the results indicate that a 1% addition of WSF without SCBA (W1S0) produced the optimum compressive strength, whereas introducing SCBA at 10% and 20% into the 1% WSF mixes (W1S10, W1S20) still enhanced strength relative to the control but slightly reduced the peak performance due to the trade-offs described above.

Table 5: Compressive strength results

Mix ID	7-day (MPa)	% Change-7	28-day (MPa)	% Change-28
W0S0	15.83	0.00%	24.45	0.00%
W0.5S0	16.85	6.45%	25.94	6.09%
W0.5S10	16.32	3.10%	25.22	3.15%
W0.5S15	16.12	1.83%	24.83	1.56%
W1S0	22.01	39.07%	28.32	15.83%
W1S10	21.10	33.31%	27.47	12.36%
W1S15	19.60	23.81%	26.85	9.82%

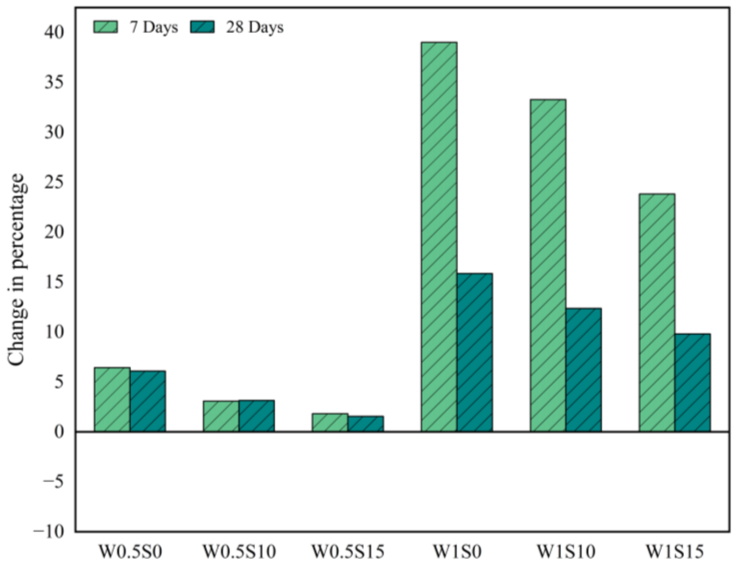

Figure 8: Percentage change in compressive strength of mixtures compared to W0S0

4. CONCLUSIONS

The test results support the following conclusions:

- SCBA and WSF maintain a good potential for recycling agricultural and industrial wastes, decrease the usage of cement, lessen environmental pollution, and support sustainable concrete production.
- Workability decreased with the increase of fibre and SCBA content due to higher water demand and internal friction.
- Yield stress increased as slump decreased, indicating reduced flowability with combined SCBA–WSF mixes.
- Fresh density of mixtures remained practically constant, with minor reductions at the highest levels of SCBA.
- The highest compressive strength was achieved in W1S0, which contained 1% fibre and 0% SCBA; it reflects the fact that the optimum fiber content without SCBA gave maximum compaction and strength.
- The mixtures containing both WSF and SCBA have still demonstrated strength improvement compared to the control; however, more SCBA content reduced the compressive strength due to dilution effects and less matrix densification.
- On the whole, the combined use of SCBA and waste steel fibers can result in sustainable concrete with improved mechanical behavior, provided it is used in proper proportions.

Declaration of Use of AI

The authors declare that no AI tools were used in the preparation of this manuscript, including the research methodology, data analysis, or writing process. All aspects of the manuscript were created without the assistance of AI technologies.

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