

Toward Low-Carbon Cement: Comparative Assessment of Industrial and Plant-Based SCMs for Cleaner Cement Production

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Abstract: The environmental impact of cement production has to be lowered since normal Portland cement generates approximately 0.8 kg CO₂ per kilogram and produces approximately 10% of all emissions worldwide. This paper explores the effect of partial replacement of cement by addition of cementitious materials (SCM) which are fly ash, bagasse, silica fume, quartz powder and calcium carbonate on performance as well as sustainability. Water to binder ratios of 0.30 and 0.40 were used to prepare cement pastes with dosage of 5% to 25% by mass of SCM. Indirect tensile strength were conducted and estimated CO₂ savings. The dominance patterns globally are indicated by the slope graphs of the winners at each W/C. The global dominance patterns are captured by the heatmaps with isocontours. The findings indicate that when quartz and bagasse ash content in low to moderate amounts (10–15percent) were replaced, tensile strength rose by 23–88 percent than in controls and clinker demand was minimized by as much as 15 percent. Silica fume showed the greatest uplift of +58% at 5–10 per cent mixes of high water-to-cement but showed no improvement at low W/C. Calcium carbonate showed more modest and broader, with maxims of 15–20 per cent replacement. Fly ash has always had a low performance on early age controls because of the slow pozzolanic reaction. The calculated sustainability indices showed that a 15 percent cement replacement will reduce CO₂ emissions by approximately 0.12 per tonne of binder, which depicts significant environmental advantages. Results show that quartz powder (10–15%) and bagasse ash (10–15 %) significantly enhance early age tensile strength (up to 88%), while a 15% cement replacement reduces embodied CO₂ by approximately 0.12 t per tonne of binder, demonstrating a direct performance sustainability synergy. This work shows that the direct correlation of mechanical performance with embodied CO₂ reductions can be used to generate cleaner and sustainable binders through optimized use of agro-industrial wastes and filler type SCMs to promote both performance objectives and cleaner production strategies.

Keywords: Fly ash; Bagasse ash; Silica fume; Quartz powder; Calcium carbonate; Sustainability; Mechanical properties; Cement



1. Introduction

Cement is the most manufactured/used material in the world after water in construction but it has a huge environmental cost of production. Production of Portland cement causes high levels of greenhouse gases mainly CO₂ because of the decarbonation of limestone as well as the burning of fossil fuels to heat kilns. The production of 1 kg of cement emits around 0.8 kg of CO₂ (Pisciotta *et al.*, 2023), (Suman *et al.*, 2025) and the cement industry in the world accounts 10 percent of the anthropogenic carbon dioxide emissions. These gases are added to other environmental effects, such as dust, NO_x, SO₂ and dioxin emissions, noise and vibration due to quarrying activities (Sun *et al.*, 2019), (Al-Habaibeh *et al.*, 2025). Since the International Energy Agency estimates that cement demand will keep growing in order to sustain the world population, it is necessary to decrease the clinker amount of cement in order to meet the global climate objectives. This necessity is the basis of a significant research agenda to find the feasible additional cementitious materials (SCMs) that can partially substitute Portland cement and, through doing so, reduce embodied CO₂ without compromising or degrading mechanical performance (Kezembayeva *et al.*, 2025). Industrial derived by products, agricultural residues or naturally found materials can be used as a source of SCMs and each category introduces varying chemical and physical characteristics to a binder system. The main mode on which SCMs enhance cementitious materials is through pozzolanic action and /or filler effect. The Pozzolanic SCM comprises of reactive silica and alumina, which reacts with calcium hydroxide (Ca(OH)₂) emitted during hydration of cement to produce more calcium silicate hydrate (C-S-H) to enhance the strength and density of the micro structure. By comparison, inert fillers are unaffected by chemical reactions and serve to fill openings in the cement matrix and they may offer a site of nucleation to hydrating products, leading to rapid hydration (John and Lothenbach, 2023). The tendency of the material to be a pozzolan or filler usually relies on mineralogy, particle size, specific surface area as well as calcium content of the material. This becomes complicated when several SCMs are used together or when the replacement levels are changed in different water cement ratios (W/C). These interactions must be studied through systematic experimentation because individual SCMs can affect workability, kinetics of early hydration, shrinkage, long term strength and durability in one way or another (Zhang and Scherer, 2011). The SCM environmental case is strong. Cement production does not only produce CO₂ it also uses huge quantities of raw materials, water and energy (Miller, 2018). Addition of SCMs to clinker decreases quantity of limestone consumed and also the amount of thermal energy to break down limestone, thus cutting down on the emissions in the processes directly. Most SCM products are industrial, e.g., fly ash leading to the burning of coal, blast furnace slag resulting in the production of steel, silica fume during the smelting of ferrosilicon and silicon. These wastes are normally dumped in landfills or stocks which are hazardous to the environment. By recycling them into cementitious products, the embodiment of the principles of the circular economy allows using waste as a valuable resource and eliminates the necessity to use virgin raw materials and lessen the environmental consequences of waste disposal (Mohammadi and Ramezani-pour, 2023), Hasila *et al.*, in 2025 investigated controllable supercooling in phase change material advances in triggering methods (JARIMI *et al.*, 2025), Jamil and his fellow researchers came up with the research of conversion of organic wastes to electricity (Arun *et al.*, 2024). While numerous studies investigate individual SCMs, direct cross comparisons under identical mix designs and water to cement ratios particularly for early age tensile strength remain scarce and sustainability metrics are rarely integrated into mechanical assessments.

Within the agricultural context, such wastes as sugarcane bagasse ash can also be used to valorize the waste. The cellulose (45–55%), hemicellulose (20–25%) and lignin (18–24%), though, are the cellulose based by-product that is leftover after juicing the sugarcane it is composed of a small ash fraction. On burning as fuel in sugar mills, bagasse produces ash with high amorphous silica composition that is capable of serving as a pozzolanic SCM. The utilization of bagasse ash will help lessen the demands on landfill disposal, reduce the use of more energy-intensive materials, and promote rural circular economies. Also, the substitution of clinker with agro-industrial residues is consistent with the United Nations Sustainable Development Goals on responsible consumption and climate action, as it manages waste at the same time as it reduces the embodied CO₂ (Hiranobe *et al.*, 2024). Cleaner production in cement does not only entail the reduction of the emissions but also the efficiency of the resources and performance of the products. The addition of SCMs has the ability to optimize pore structures to reduce shrinkage and increase resistance to the attack of chemicals. The incorporation of SCMs however can tend to affect fresh properties (workability, setting time) and the optimum dose may depend on the mix design, particularly the water-cement ratio. The multi-dimensional nature of these effects justifies the necessity of integrated approaches to mechanical and sustainability evaluation that would look at performance and environmental impact (Gbadeyan *et al.*, 2023).

Fly ash (FA) is a fine particulate matter of the electric precipitated flue gases of power plants that burn coal. It is approximately 60 percent of all waste due to combustion of coal and is the most popular

SCM in concrete (Liu *et al.*, 2025). ASTM C618 Class F fly ash, which is produced by burning of bituminous or anthracitic coal, is mainly composed of silica and alumina and is mainly pozzolanic. Class C fly ash, which is produced by burning of lignite or sub bituminous coal, is actually composed of higher content of calcium (>20% CaO) and also exhibits some self cementing behaviour (Islam *et al.*, 2025). They both contain large proportions of amorphous glassy silica (SiO₂) and crystalline silica such as quartz and mullite. The fly ash particles are usually spherical with a diameter ranging between 0.5 μ m and 300 μ m in diameter (Shakouri, Ahmed and Teymouri, 2024), which enables them to enhance workability and decrease the demand of water. Pozzolanic reaction of fly ash is comparatively slow at the initial ages (e.g., 7–28 days), fly ash blends can suffer compared to control mixes in strength, and long term advantages can be significant provided that there is adequate curing. Besides substituting cement in the concrete, fly ash is applied in the base of roads, soil stabilization, bricks and as filler in plastics (Helmy and Fakher, 2024). This is in line with the sluggish reactions of fly ash pozzolana. Fly ash can be detrimental due to their low initial strength increase although it is necessary to achieve long term sustainability and durability benefits; hence where rapid development of strength is required, it cannot be used except by using activators or heat curing. Bagasse burning to produce a power source produces an ash that contains amorphous silica in high concentrations, as a result of sugarcane bagasse as a solid residue of the juice extraction process. The bagasse itself consists mostly of cellulose, hemicellulose, and lignin, and of an ash content, approximately, 1–4%. Bagasse ash can be prepared through calcinations or controlled combustion to be of pozzolanic activity. The chemical composition of bagasse ash varies depending on the cane variety, the temperature and conditions of burning, although amorphous silica is normally the most common and this can react with calcium hydroxide in cement paste. Ash of bagasse has been studied as an SCM in mortar and concrete and some of its studies have reported similar or even better performance with respect to rice husk ash owing to its high silica content. It can also have a large portion of unburnt carbon, which can influence water demand and strength development (Iro *et al.*, 2025a). In the experiments conducted nowadays, bagasse ash showed serious early age strength gains compared to cement at 10–15 percent of the mass. Replacing 15 percent at W/C = 0.30 gave a 26 percent tensile strength increase over the control and replacing 10 percent at W/C = 0.40 gave an approximate 44 percent tensile strength increase over control (Tabish, Zaheer and Baqi, 2025a). These results indicate that bagasse ash was found to be a reactive filler with moderate concentrations to increase particle packing, and also to supply reactive silica which promotes early hydration. Strength started to decrease beyond 15, which signifies binder dilution. The difference between the performance of water and cement ratios indicates that there is an interaction between the porosity of the paste and the reactivity of the SCM (Alvarenga and Cordeiro, 2024a). Silica fume (SF) is an amorphous silica of ultrafine grade which is a by-product of the production of silicon and ferrosilicon alloys. Its particles are spherical, whose average diameters are approximately 150 nm and the specific surface areas of 15 000–30 000 m² kg⁻¹ are approximately 100 times lower than those of the cement grains (Iro *et al.*, 2025b). Silica fume is a highly reactive pozzolan due to its high specific surface area and amorphous character because it can absorb calcium hydroxide quickly and form more C-S-H, which makes it a micro filler, which packs between cement particles at a rate that drastically lowers permeability of concrete (Tabish, Zaheer and Baqi, 2025b). Silica fume in high performance concrete improves compressive strength, bond strength and abrasion resistance. Silica fume, however, has a very large surface area, thus, it is likely to result in water demand increase and decreased slump unless superplasticizers are applied. The silica fume used in this experiment enhanced tensile strength in mixes with W/C = 0.40, in which silica fume provided a 58 percent improvement especially at 5–10 percent replacement. However, silica fume was not greater than the control strength at W/C = 0.30 (Alvarenga and Cordeiro, 2024b). These findings suggest that silica fume is most effective in cases where adequate water and paste volume is present in denser mixes so that the high surface area of the ultrafine particles can be absorbed and where the ultrafine particles can also pose hydration difficulties and lead to workability problems. This subtle behaviour underscores the significance of aligning SCM type and SCM dosage with the mix design in question. Inert fillers include quartz powder (QP) and calcium carbonate (CaCO₃). Quartz powder refers to a fine crystalline silica powder that is mostly predominantly physical in its effect on cement hydration. Quartz particles that are finely ground occupy the voids, enhance the packing density and serve as a nucleation site of hydration products, which enhances cement hydration at the initial hours. Nevertheless, at particle sizes longer than about 20–25 μ m (Khan and Siddique, 2011a), the pozzolanic activity of quartz powder is insignificant, and the effect is largely due to the filler effect. Calcium carbonate, combined with limestone, is a filler that is also ground and works as a filler, although, to a small extent, some reaction may occur to produce carboaluminate hydrates that dense the microstructure. Although both the quartz powder and the calcium carbonate are inert materials, it is possible to enhance the mechanical properties by their judicious use (Khedr and Abou-Zeid, 1994a). The good tensile strength improvements of 10–15% replacement were observed in quartz powder and 15–20% replacement in calcium carbonate in the current work. These

benefits may be attributed to better packing and lesser porosity but over replacement causes dilution of cementitious part and subsequent loss of strength. Also, the inert fillers are usually characterized by low embodied energy and CO₂, which is appealing to decarbonization initiatives (Mazloom, Ramezani-pour and Brooks, 2004a).

Water cement ratio is a very important factor that determines how the SCMs will perform. Increased W/C ratios result in less dense pastes that can be enhanced using filler type SCMs, which enhances packing and early hydration. On the other hand, smaller W/C mixes are denser and thus they are better in reactive SCMs which can boost later age strength but it might not give immediate gains. This experiment noted that optimum replacement level of quartz and bagasse ash reduced a little with an increase in W/C. As an example, quartz was optimum at 10 percent substitution of W/C = 0.40 and at 15 percent substitution of W/C = 0.30. Silica fume was most effective at 5–10% replacement in W/C = 0.40 mixes, and nonexistent in W/C = 0.30 mixes. Calcium carbonate provided small increases over larger dosage range with a high optimum at W/C = 0.40. Replacements of 20% or higher in all cases led to a loss of strength, suggesting that the effect of the binder was greater than the filler effect. These results highlight the importance of adjusting the dosage of SCM in order to combine porosity and the chosen performance age. Tensile ability in early age is especially sensitive to the dilution of binder hence moderate replacement levels (15%) should be used in the SCMs with weak or moderate pozzolanic activity. When mixes are used where the long-term durability or strength is a priority, the replacement levels can be tolerated provided that adequate curing is allowed. The originality of this study lies in its unified experimental framework that directly compares industrial and agro-based SCMs under identical conditions, with a specific focus on early age tensile strength and quantified embodied CO₂ reduction an approach rarely reported in existing literature.

2. Significance and Motivation

Even though the empirical research on SCM has been conducted on a one-on-one basis, there are still several critical gaps that prompted the study. First, most of the studies are done on compressive or flexural strength in concrete, less of which are on indirect tensile strength at young ages (Xu *et al.*, 2025a). Tensile strength is an important parameter in cracking and failure analysis, but it does not get much attention. Second, the literature researching one SCM is very extensive, and cross material comparison cannot be conducted because of the diversity of methods, curing regimes, and mix designs. Systematic tests which utilize many SCMs in an experimental framework which is worked out and repeated at constant W/C ratios and replacement levels are lacking. Third, mechanical assessments are rarely combined with environmental measurements like a decrease in CO₂, although the importance of sustainability gains more and more. In order to fill these gaps, the present study aims to present a detailed assessment of five SCMs (fly ash, bagasse ash, silica fume, quartz powder and calcium carbonate) in case of 5–25 percent replacement, two W/C ratios, and the evaluation of the indirect tensile strength and corresponding physical properties. Through the application of homogeneous materials, mixing, and test processes, the work provides a direct comparison of contributions exerted by SCM on early strength, shrinkage, density and porosity. The definition of sustainability indices has measured the CO₂ savings per replacement level in each level and correlated material performance with environmental gains. Further the systematic data permits determination of optimum dosages of each SCM and indicate changes in optimum with water cement ratio.

The importance of the research is that he/she measures the performance and sustainability simultaneously. The study offers viable information on the best replacement levels to use in order to realize early tensile strength benefits and at the same time durability is not jeopardized by the replacement levels. An example is the quartz and bagasse ash, which indicates that a replacement of 10–15% balances the filler effect and the contribution of pozzolana, and silica fume, which has a significant effect and needs only 5–10 percent replacement to accomplish the same. Although fly ash is beneficial to the environment, it was revealed to have poor performance, which implies that its application must be accompanied by prolonged curing or activator in case of early strength. These observations can be used to guide mix design of precast elements, repair mortars and any other precast where tensile capacity is important at an early age. Concerning sustainability, the research illustrates the above percentage under replacement of clinker by 25 percent translates to huge CO₂ savings of up to 0.2 t CO₂ per tonne of binder without compromising or deteriorating mechanical properties. Agro/industrial -residues use such as bagasse ash is according to the principles of the circular economy and promotes the efficiency of the sugar industry resources. A mixture of performance indices and environmental indices is a comprehensive approach to choosing SCMs in response to calls to make the cement industry cleaner. Lastly, the work preconditions future studies. Increasing the test to longer periods will show the role of fly ash and other slow pozzolanic materials in the enhancement of strength when tested at 28–90 days. Microstructural studies (SEM, XRD) might explain the mechanism of filler-pozzolan interaction,

especially of mixed SCM systems. Multi-dimensional correlations between the type of SCM, dosage, water cement ratio and performance results could be further optimized using response-surface techniques or machine learning programs. The use of mechanical, physical and environmental evaluations assists in steering cleaner, stronger and sustainable concrete by incorporating additional cementitious material in this study. [Figure 1](#) indicates a typical flow chart of this study.

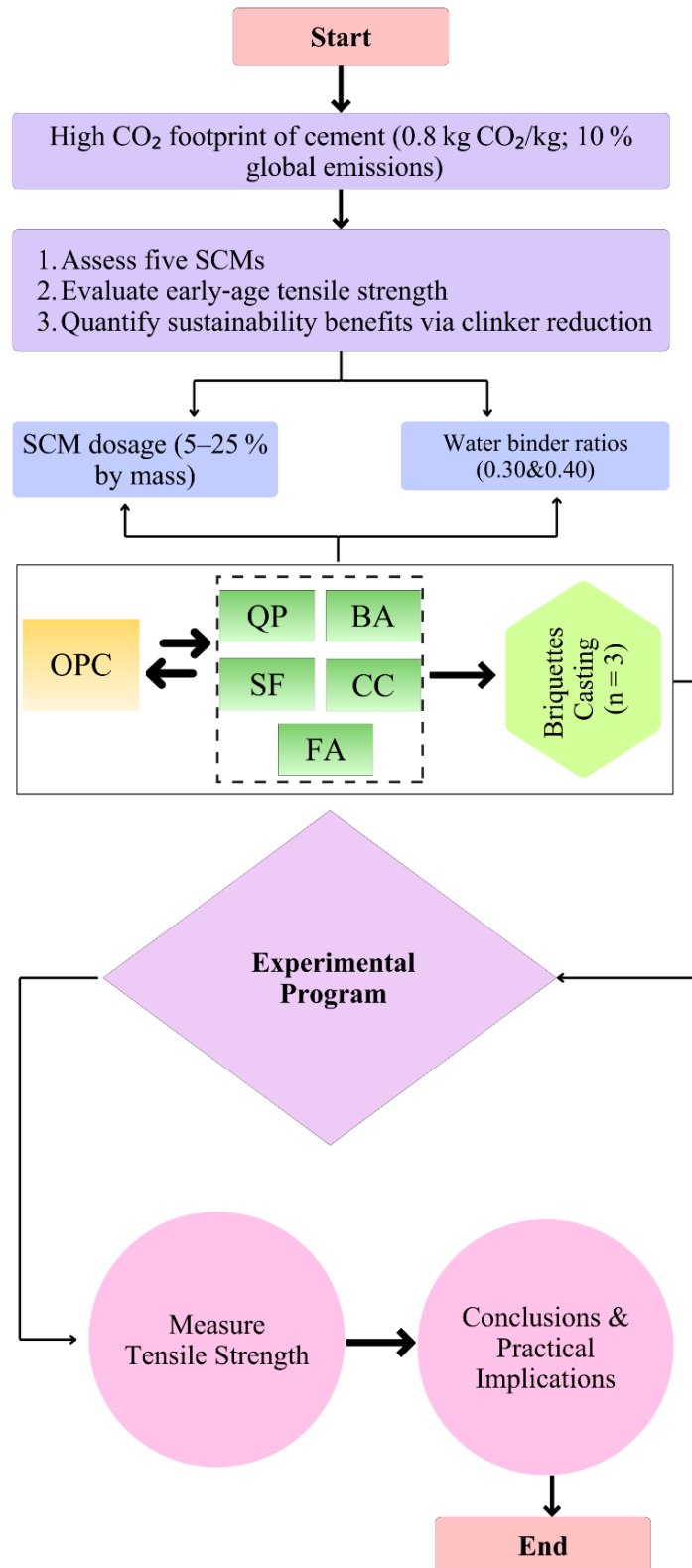


Figure 1. Workflow of proposed study.

3. Materials and methods

3.1. Materials

Every cement paste and hybrid briquette mixtures in the present study were made using Siam Cement Group (SCG) Hybrid Innovative Eco-Friendly Cement a product that is meant to reduce the environmental footprint relative to that of an ordinary Portland cement (OPC). Its chemical make up is characteristic of OPC containing calcium oxide ($\text{CaO}=67\%$) and silicon dioxide ($\text{SiO}_2=19\%$), traces of alumina, iron oxide and alkalis (Hansu and Etl, 2025). The cement meets the applicable ASTM standards in the preparation of paste. A commercial supplier of quartz powder, CERNIC INTERNATIONAL CO., LTD., based in Thailand, was used. Laboratory analysis, certificate of analysis issued by the supplier, showed a bulk density of 1.04 g/cm^3 and a specific gravity of 2.46. Quartz was used as an inert filler at a percentage of 5-25 mass of cement. It is predominantly acting as a filler effect since it has silica content that is over 99, which enhances the packing of particles and minimizes the voids (Liu *et al.*, 2019). A pozzolanic SCM of class F (ASTM C618-12a) was introduced as a replacement ranging 5–25% in mass of cement. It also had 50-60% SiO_2 , 20–30% Al_2O_3 , and low CaO (2-6%), which was expected considering its classification. The specific gravity measured was 2.26. Its pozzolanic potential adds to the long-term strength but generally adds porosity and retards premature hydration (Piasta and Zarzycki, 2017). Agro-waste SCM was bagasse ash, a by product of sugar industry, used at replacement percentages of 5–25 mass. The sieving and crushing were followed by a specific gravity of the final product of approximately 2.20. BA is found in literature to be an excellent fine pozzolanic material with 55–65% SiO_2 and moderate level of CaO (5–10) and Fe_2O_3 (5-8), however porous morphology of the material could negatively affect density (Win *et al.*, 2023a), (Bragança, Bergmann and Hübner, 2006). Silica fume was utilized as a by-product of silicon/ferrosilicon alloy manufacturing in compliance with ASTM C1240-14 at the replacement of 5–25 percent. Amorphous silica (85–95%), SF has a specific gravity of 2.20 and it is highly reactive and is known to refine pore structure, strengthen and also increase durability (Win *et al.*, 2023b). A filler and a partial replacement of cement were the finely ground calcium carbonate at 5–25% mass. Its specific gravity was 2.71. It has 95–99 percent CaCO_3 content and very little impurities, which enhances early-age strength by filling and helps in densifying (Golewski, 2022). The common materials are illustrated in Figure 2.

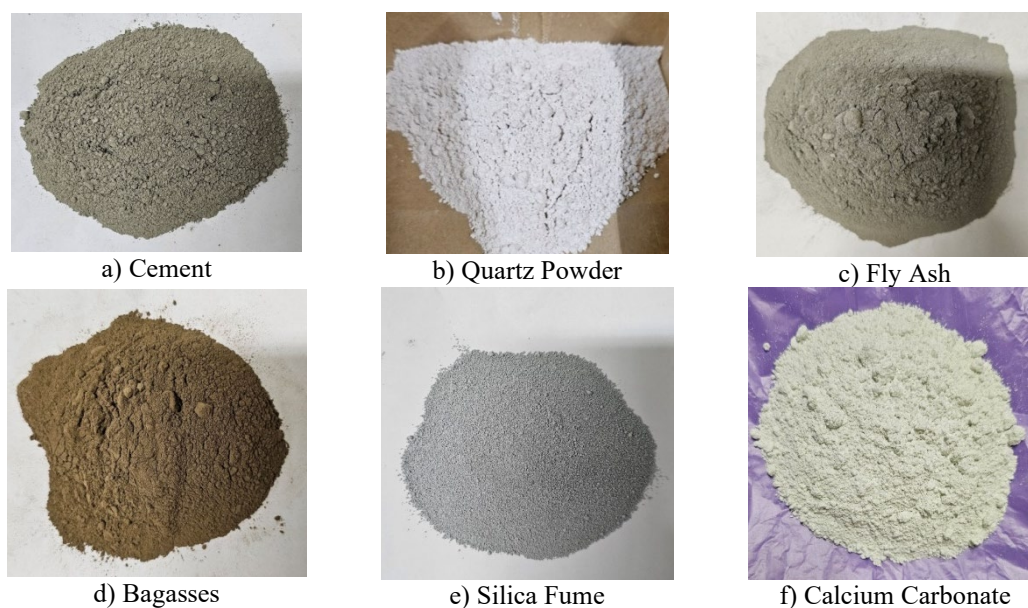


Figure 2. Materials used in this study.

3.2. Mix Details

There were 26 mixes that were designed and developed in this work (Table 1). The mix designs had been designed to examine the impact of various additional cementitious materials (SCMs) on the cement paste briquette performance. Quartz powder (QP), fly ash (FA), bagasse ash (BA) and silica fume (SF) were used to partially replace ordinary Portland cement (OPC, ASTM C150 Type I) at substitution levels of 0, 5, 10, 15, 20 and 25 percent mass of cement. To examine how the water content affects the behavior of hydration and durability in the composites, two water-to-cement (w/c) ratios of 0.30 and 0.40 were

taken. Two water cement ratios (0.30 & 0.40) were selected to represent dense, low porosity paste systems and relatively porous paste systems commonly used in precast and repair applications. This range enables evaluation of SCM performance under contrasting hydration environments and allows investigation of filler, nucleation, and pozzolanic mechanisms as a function of paste porosity. In each of the mixtures the overall binder content was kept at 1000 g, and the SCM content was varied based on the replacement percentage. The w/c ratio chosen as a selection criterion was fixed throughout the series to make the mixing water comparable. At each w/c level 100% cement control mixes were made too. Figure 2 represents 5 SCM adopted in this study and Table 1 represents the mix proportions that have been adopted in this research. Replacement levels of 5–25% were selected based on commonly reported SCM dosage ranges in the literature, capturing low (5–10%), moderate (10–15%), and high ($\geq 20\%$) replacement regimes to identify optimum performance and dilution thresholds.

Table 1. Mix proportions for cement paste.

Mix No.	Cement (g)	SCM Type	SCM (g)	Replacement (%)	W/C ratio	
1	950	Quartz	50	5	0.3	0.4
2	900	Quartz	100	10	0.3	0.4
3	850	Quartz	150	15	0.3	0.4
4	800	Quartz	200	20	0.3	0.4
5	750	Quartz	250	25	0.3	0.4
6	950	Fly Ash	50	5	0.3	0.4
7	900	Fly Ash	100	10	0.3	0.4
8	850	Fly Ash	150	15	0.3	0.4
9	800	Fly Ash	200	20	0.3	0.4
10	750	Fly Ash	250	25	0.3	0.4
11	950	Bagasse	50	5	0.3	0.4
12	900	Bagasse	100	10	0.3	0.4
13	850	Bagasse	150	15	0.3	0.4
14	800	Bagasse	200	20	0.3	0.4
15	750	Bagasse	250	25	0.3	0.4
16	950	Silica Fume	50	5	0.3	0.4
17	900	Silica Fume	100	10	0.3	0.4
18	850	Silica Fume	150	15	0.3	0.4
19	800	Silica Fume	200	20	0.3	0.4
20	750	Silica Fume	250	25	0.3	0.4
21	950	Calcium Carbonate	50	5	0.3	0.4
22	900	Calcium Carbonate	100	10	0.3	0.4
23	850	Calcium Carbonate	150	15	0.3	0.4
24	800	Calcium Carbonate	200	20	0.3	0.4
25	750	Calcium Carbonate	250	25	0.3	0.4
26	1000	None	0	0	0.3	0.4

Test Specimens

Water to cement (w/c) ratio ratio 0.30 and 0.40 were applied as two water contents on the direct tensile performance of cement based composites. Measurement of all materials was taken by weight to ensure consistency in batches and the mixing process was done according to the established laboratory guidelines. All mixes used Ordinary Portland Cement (OPC), which was used as the primary binder and met the requirements of type I of the ASTM C150 standards. The mixing was done with portable water that was of the quality of ASTM C1602. To attain homogenous/uniform OPC and SCM mixture, the dry cement was initially blended individually within one minute. Gradually the addition of water was carried out and the mixing was further done in another three minutes with the help of a normal laboratory mixer to create a homogenous paste. The fresh paste was poured in briquette molds, having a 75 mm x 25 mm x 25 mm neck size. They were filled with molds in two layers with the second layer slightly tamped and compacted due to mild vibration to remove air trapped in the molds and allow them to be well packed (Figure 3a). Polyethylene sheets were used to cover the filled molds to prevent the loss of moisture in the early setting period. The specimens were then taken out of the molds and exposed to a curing room with temperature of 23 +/- 2degC and relative humidity of almost 100 percent which was in line with the procedure in ASTM C192/C192M (Figure 3b). For each mix, three briquette specimens were tested and the reported tensile strength represents the average value. Testing was conducted in accordance with

ASTM C307 using a universal testing machine under controlled displacement loading. After conventional water curing, direct tensile strength was measured on briquette-shaped specimens in accordance with ASTM C307. Each sample was mounted in a universal testing machine and loaded under a constant displacement rate until failure. Three specimens were tested for each mix, and the average tensile strength was calculated by dividing the maximum load by the briquette neck area.



Figure 3. a) test specimens b) curing after 24 hrs, c) typical test specimens and d) test setup.

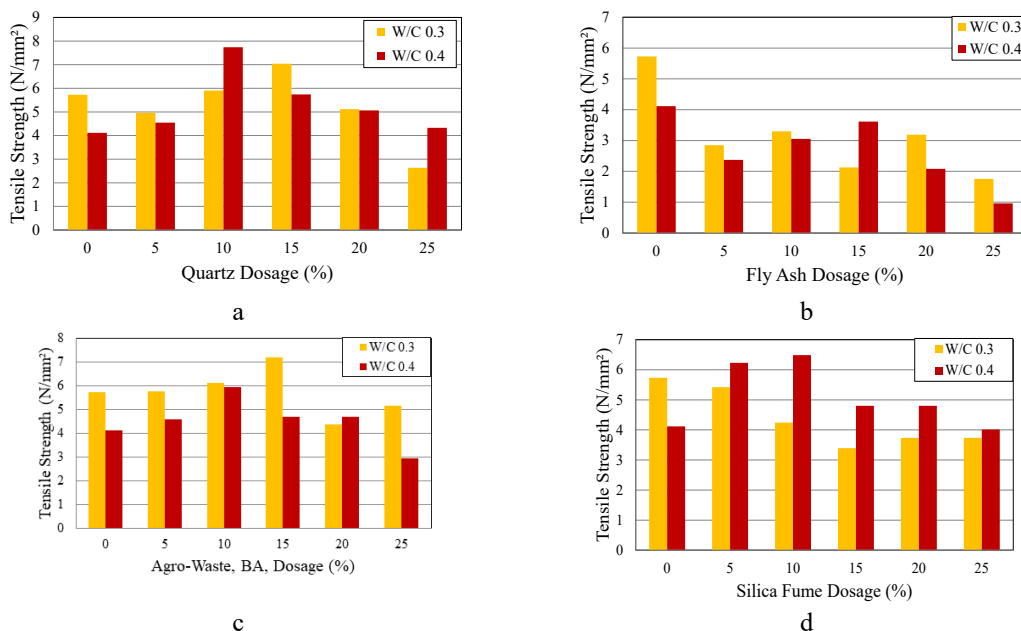
4. Results

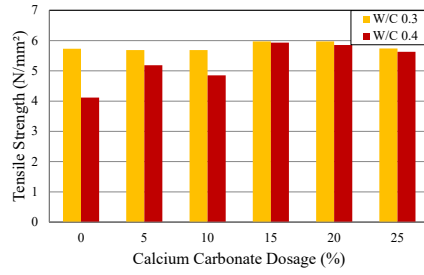
4.1. Tensile Strength

Figure 4(a) exhibits the Quartz powder mainly acts as a physical filler and does not take part in cement hydration. Because it is not chemically active, large amounts usually lower strength by diluting the cement. In this study, small dosages produced mixed results. At $W/C = 0.30$, 5% quartz reduced tensile strength, while 15% gave the best gain (+22.9%). At $W/C = 0.40$, 10% quartz gave the highest increase (+88.0%), which can be explained by better particle packing and reduced voids in the slightly wetter mix [23]. Higher replacements (20–25%) caused strength losses, especially at $W/C = 0.30$. Overall, quartz performed best at 10–15% depending on W/C ratio, with stronger benefits at 0.40. Figure 4(b) shows the clear comparison between control and BA incorporated early tensile strength. Bagasse ash

is rich in reactive silica that combines with calcium hydroxide to form extra binding gel, which strengthens the concrete. At W/C = 0.30, the best result came from 15% SCBA (+25.8%), while at W/C = 0.40 the optimum was 10% (+44.3%). Smaller additions gave modest gains, and higher levels (20–25%) reduced strength due to unreacted ash particles and lack of cement. The results align with earlier studies showing that 10-15% SCBA can improve tensile strength, but excessive replacement limits hydration (Khedr and Abou-Zeid, 1994b).

Silica fume is an ultrafine, highly reactive material that improves strength by filling tiny voids and forming more gel. At W/C = 0.40, 5–10% silica fume gave strong gains (51–58%), while 15–20% still added moderate benefits Figure 4(d) represents the strength comparison between different w/c and dosage of BA in cement paste . However, at W/C = 0.30, all replacements reduced strength. This is because the very fine particles increased water demand and reduced workability, leading to incomplete hydration without chemical admixtures. The findings confirm that silica fume works best at 5-10% under higher water conditions, as also reported in past studies (Khan and Siddique, 2011b). Figure 4(b) represents the decreasing trend of the fly ash at the early age. Fly ash reacts slowly and often lowers early strength. In this dataset, all fly-ash mixes showed reduced tensile strength. At W/C = 0.30, strength losses were large (up to -63%), while at W/C = 0.40 the reductions were less severe (around -12% at 15%) (Mazloom, Ramezani-pour and Brooks, 2004b). These results suggest the tests were at early age, before fly ash could fully react. Literature shows that at longer curing times, 15-30% fly ash can improve strength, especially when combined with more reactive materials. Calcium carbonate (limestone powder) is a fine filler that also provides sites for hydration. In Figure 4(e) at W/C = 0.30, it had little effect at low dosages, but 15–20% gave small gains. At W/C = 0.40, the effect was much stronger: 15–20% replacement raised tensile strength by 42–44%, and even 25% gave a 37% increase. This shows that limestone can be very effective in improving strength when water availability supports proper dispersion (Xu et al., 2025b). Table 2 summarizes all the recorded tensile strengths during testing for each SCM and W/C. Lower W/C ratios (0.30) gave higher absolute tensile strength in control mixes because of their denser structure. However, many SCMs performed better at W/C = 0.40 in terms of percentage improvement. The extra water allowed finer materials like silica fume and quartz to disperse and react more effectively. Bagasse ash and calcium carbonate improved strength at both ratios, while fly ash showed weak early-age performance in all cases. The observed strength gain at moderate quartz replacement is attributed to enhanced particle packing and nucleation of hydration products, whereas higher replacement levels result in binder dilution and reduced load bearing capacity.





e

Figure 4. Test results a) quartz b) fly Ash c) agro-waste d) silica Fume and e) calcium carbonate.

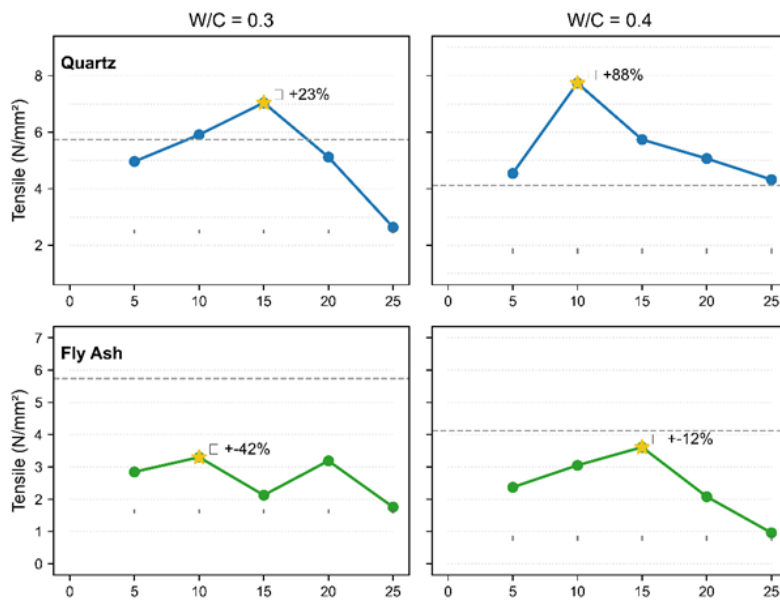
Table 2. Summary Tensile strength recorded for each mix.

Mix No.	Dosage (%)	0.3		0.4	
		Tensile Strength (N/mm ²)	% Change vs Control	Tensile Strength (N/mm ²)	% Change vs Control
1	0	5.739	0	4.117	0
2	5	4.962	-13.5	4.544	10.4
3	10	5.909	3	7.739	87.9
4	15	7.043	22.7	5.739	39.4
5	20	5.12	-10.8	5.067	23.1
6	25	2.637	-54.1	4.324	5
7	5	2.847	-50.4	2.371	-42.4
8	10	3.301	-42.5	3.051	-25.9
9	15	2.126	-63	3.612	-12.3
10	20	3.189	-44.4	2.08	-49.5
11	25	1.757	-69.4	0.96	-76.7
12	5	5.76	0.4	4.601	11.7
13	10	6.137	6.9	5.941	44.3
14	15	7.211	25.7	4.695	14
15	20	4.363	-24	4.695	14
16	25	5.163	-10	2.933	-28.8
17	5	5.419	-5.6	6.229	51.3
18	10	4.245	-26	6.485	57.5
19	15	3.392	-40.9	4.8	16.6
20	20	3.733	-34.9	4.8	16.6
21	25	3.733	-34.9	4.011	-2.6
22	5	5.685	-0.9	5.184	25.9
23	10	5.685	-0.9	4.853	17.9
24	15	5.973	4.1	5.933	44.1
25	20	5.973	4.1	5.856	42.2
26	25	5.739	0	5.632	36.8

4.2. Dose-response trend by SCMs

The trends of strength of the different supplementary cementitious materials portray a distinct increase to an optimum dosage, and then, decrease as replacement levels become excessive, indicated in Figure 5, a balance between packing of the particles and reduction of the binder. The higher water to cement ratio mix (W/C = 0.40) showed the best performance of quartz at 10 percent replacement with the tensile strength of 7.739 Nmm^{-2} increased by 88 percent over the control. The optimum of the denser mix (W/C = 0.30) was at 15%, and the value was 7.043 N mm^{-2} and it increased by 23%. The same trend was observed with bagasse ash where the highest strengths were found at 10–15% replacement at W/C = 0.40 a 10% dosage produced 5.941 N mm^{-2} (approximately 44% gain) and at W/C = 0.30 a 15% replacement produced 7.211 N mm^{-2} (26% gain). Based on these results, the two materials are effective nucleation sites, as well as fillers at low doses; however, overreplacement reduces the quantity of cement that can be used to bind. As demonstrated in the Figure 5 silica fume was more complex. Low dosages (5–10%) at W/C= 0.40 gave significant gains a 10 % replacement produced 6.485 N mm^{-2} in tensile, approximately

58% greater than the control, but with increased dosage, strength decreased even below the control. With the lower W/C however, even the highest best result of 5% (5.419 N mm⁻²) still failed to beat the control, meaning that in dense pastes the ultrafine particles are of no early-age advantage and even worse still, they are detrimental to strength. Calcium carbonate was used as a filler with little meaningful results and generated a consistent but low level of gains. The W/C = 0.40 mixes showed a rise in strengths since at 5 percent replacement, the strengths were at 5.184 N mm⁻² and at 15 percent, the strengths topped 5.933 N mm⁻², which is approximately 44 per cent higher than the control. In the case of W/C = 0.30 the improvements were less, and a wide optimum in the range of 15–20% provided some percentage increase of improvement over control. In comparison, fly ash could not compete with the control strength in any dosage and even W/C level. At W/C= 0.40 with the highest result 3.612 Nmm⁻² at 15 per cent still lagged by approximately 12 per cent in comparison with the control, and at higher replacements the strengths decreased more steeply. Even worse the W/C = 0.30 mixes, and a 10 percent dosage provided only 3.301 N mm⁻², about 43 percent of the control. These losses indicate the gradual pozzolanic reaction of fly ash that are of major strength benefits do not generally manifest till 28–56 days or with chemical action. No chemical addition takes place in this case.



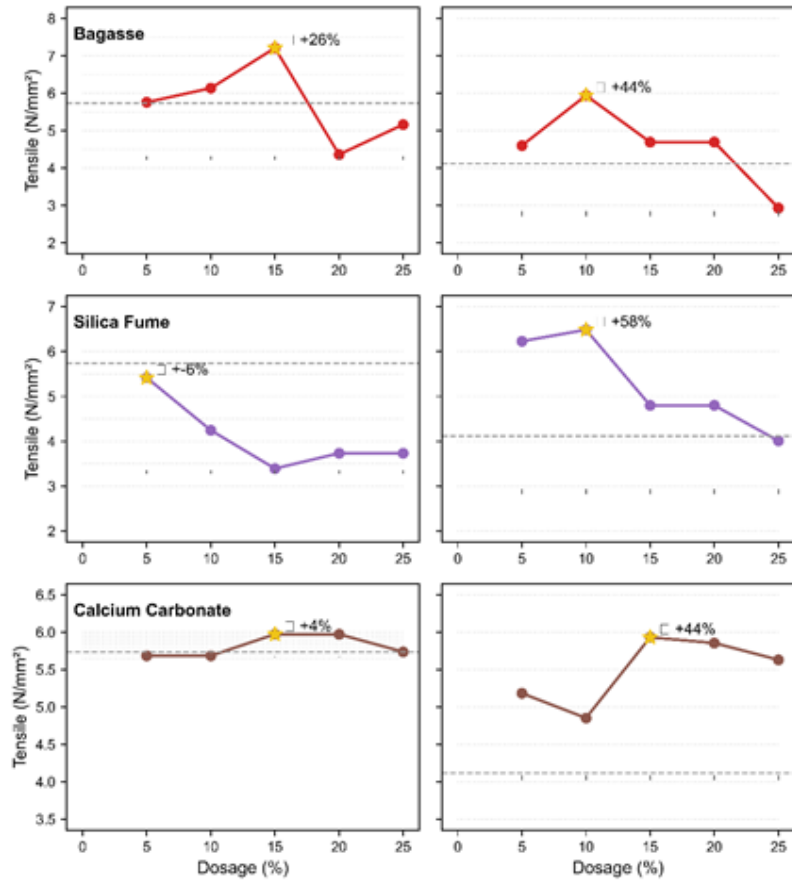
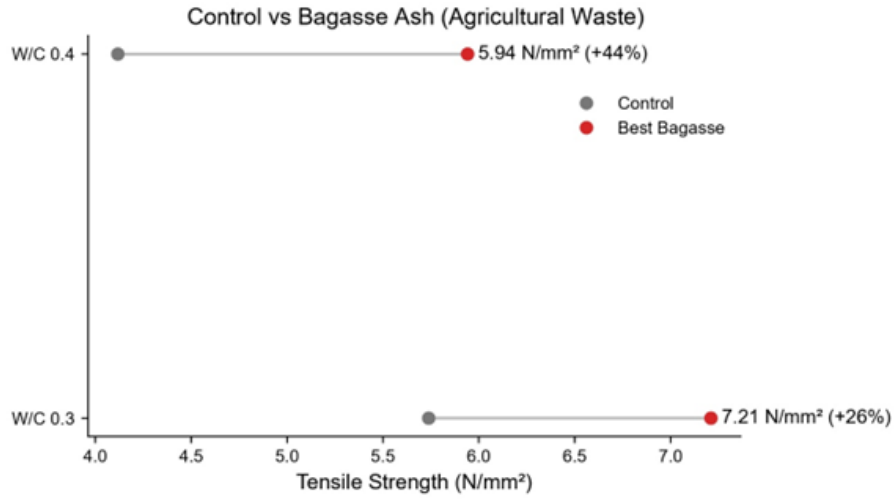


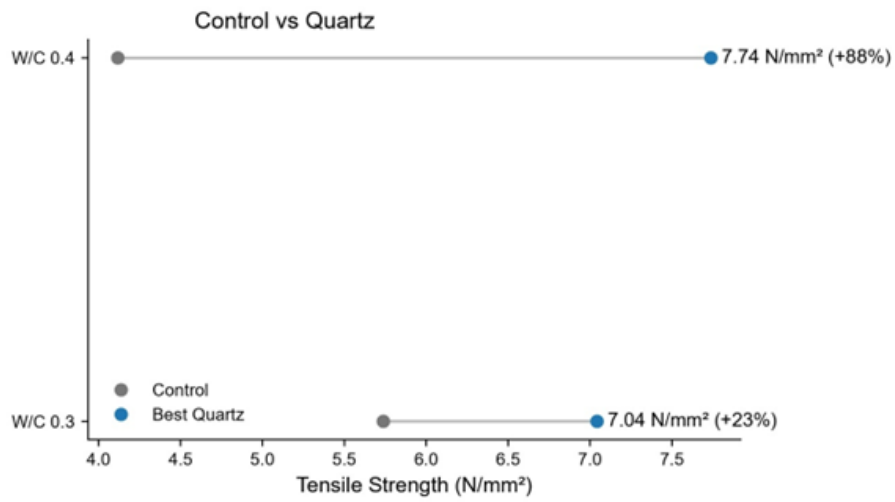
Figure 5. Response Trends by SCM.

4.3. Performance Relative to Control

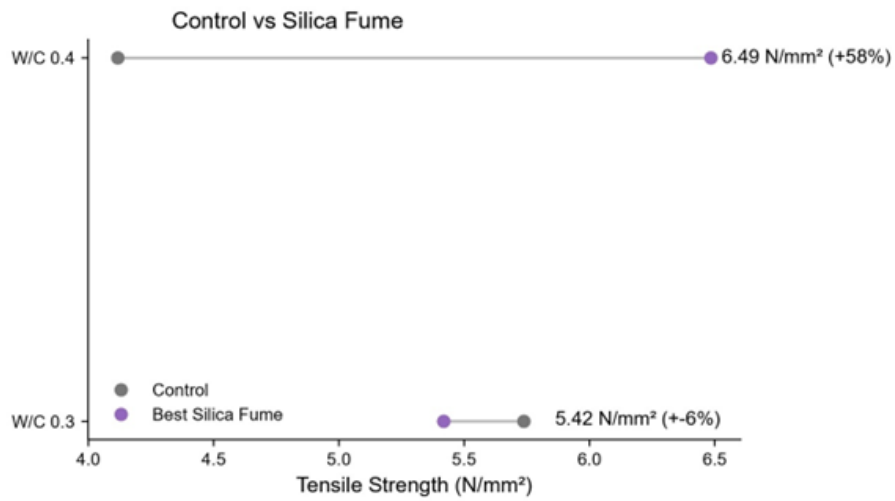
Performance relative to control refers to the percentage change in tensile strength of SCM modified mixes compared to the corresponding 100% cement paste at the same water to cement ratio. When compared to the control mixes in terms of increase, only some of the mixes provided meaningful gains/increase. Shown in Figure 6. At lower water cement ratio ($W/C = 0.30$), bagasse ash and quartz showed the most notable improvements a 15 per cent replacement of bagasse ash has improved to approximately 7.211 N mm^{-2} , or approximately 26 per cent compared to the 7.043 N mm^{-2} or approximately 23 per cent improvement with the other mixes, as shown in the Figure 6(b), which depicts the higher dose of bagasse ash resulting in the same gain or less than the control. With a W/C of 0.40 the hierarchy changed slightly a 10% replacement of quartz gave a striking 7.739 N mm^{-2} or almost 88 percent more than control and silica fume at 10 percent and 5 percent gave significant but lesser increases at about 58 percent and 51 percent, respectively. The direct label curves reveal that quartz, Figure 6(b) and bagasse ash, Figure 6(c) can only maintain above control strengths within the 10–15% replacement and silica fume is only useful at 5–10% at the higher W/C . Figure 6(d) shows that Calcium carbonate provides consistent yet slight gains below varying dosages and fly ash does not surpass the control at any dose, implying that it has minimal contribution to the tensile strength. Demonstrated in Figure 6(d) and 6(e) respectively.



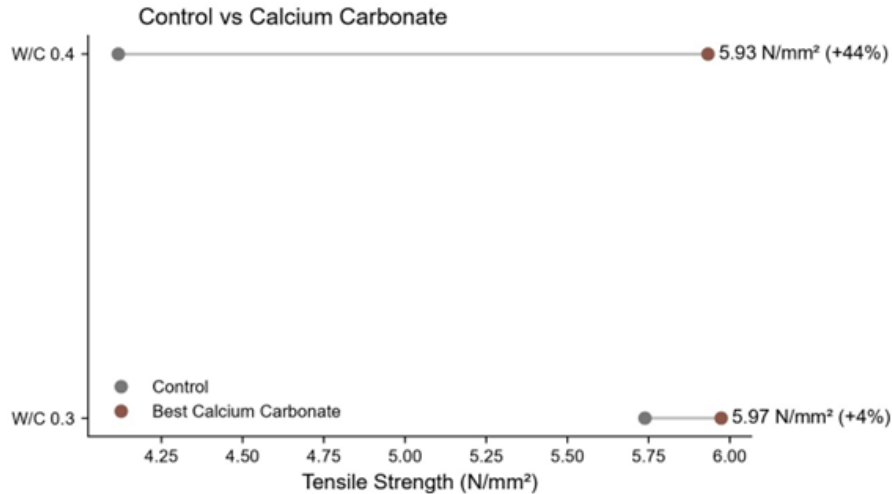
(a)



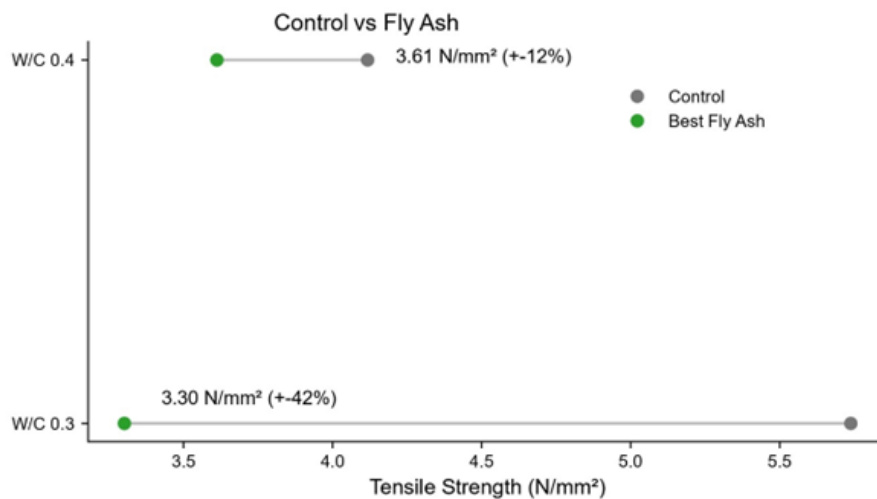
(b)



(c)



(d)



(e)

Figure 6. Control vs SCMs for a) agricultural waste, b) quartz, c) silica fume, d) calcium carbonate and e) fly ash.

4.4. SCM and W/C Interaction

The effect of the water-to-cement ratio on the optimum replacement level and the heatmaps represented below in Figure 7(a,b), 8 show highest tensile strength at a lower dosage when the mix is wetter and the optimum level shifts to 15 a 100 percent when the mix is drier: W/C = 0.40 W/C = 0.30. The behavior of bagasse ash is in a similar vein that the highest performance is at 10 percent in the more porous mix and at 15 percent in the leaner again demonstrating that excessive replacement will rapidly diminish strength, heatmap and the isocontours presented in Figure 7(a) and 7(b). Silica fume does not act the same way. at W/C = 0.40 it gives a broad, high plateau with around 5% to 10% giving the highest value of about 6.5 N mm^{-2} though there is no benefit at all at 0.30 which indicates that only when a substantial volume of paste is present the extremely fine particles are effective. Calcium carbonate, in its turn, attains its peak at 15-20% of both W/C, the absolute strength being a bit higher in the moister mix. In all materials, replacement of more than approximately 20 percent causes a decrease in tensile strength since the cementitious binder is being lost rather than having a filler effect. Combined, these results indicate that the optimum dosage decreases with an increase in W/C, and the strength of the improvement is a function of the nature of SCM as well as the original porosity of the paste. Figure 8 shows heatmap of tensile strength across the space of W/C dosage of each SCM. The optimum replacement range of 10-15% for bagasse ash observed here aligns with previous reports indicating enhanced tensile

and compressive performance at moderate dosages (Li *et al.*, 2022a), (Harish, Madupu and Satyanarayana, 2024).

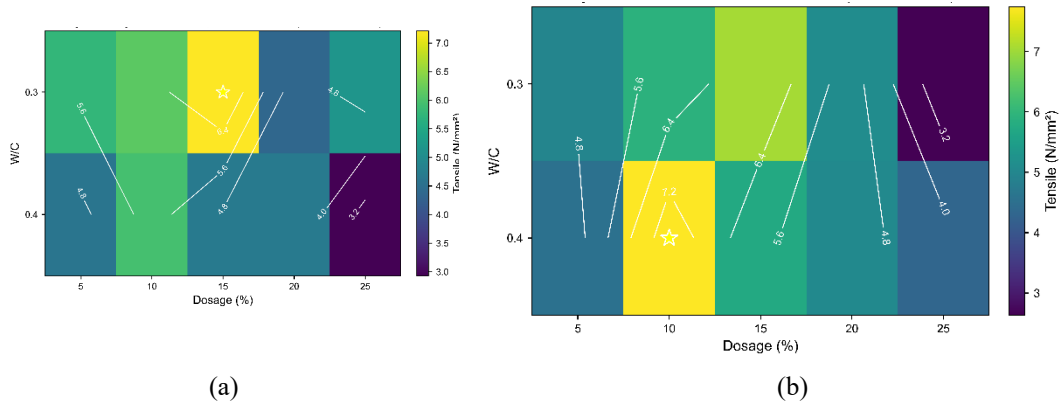


Figure 7. (a) Bagasse Ash 10 (b) Quartz, Heatmap & Isocontours.

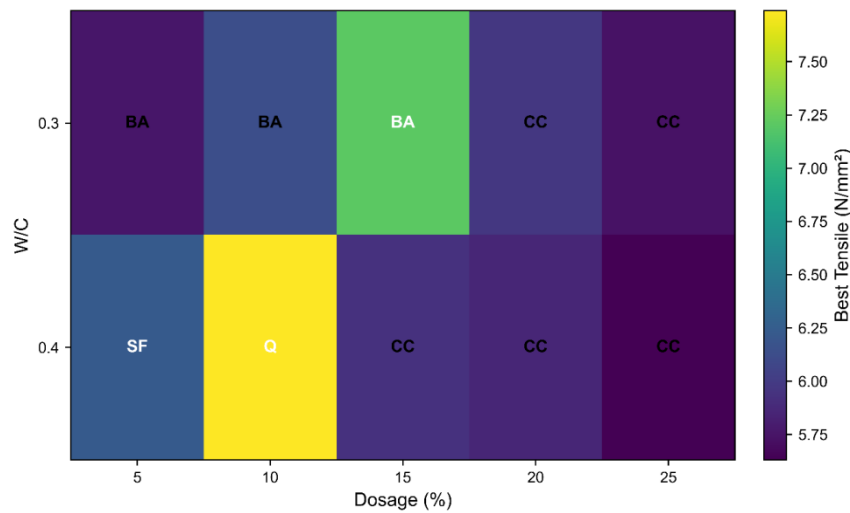


Figure 8. Heatmap showing tensile strength across the W/C–dosage space for each SCM Strength Slope graphs with its microtrend.

Figures 9, 10(a,b) indicates the slope graph podium and microtrend chart of the performing mixes (Outperforming). All these point out to the dominant mixes in terms of absolute tensile strength as well as the dosage response mechanisms through which the strengths were obtained. The slope-graph podium at W/C = 0.30 indicates that the top performers are Bagasse Ash 15% (7.211 N/mm², +25.7%), Quartz 15% (7.043 N/mm², +22.7%) and Bagasse Ash 10% (6.137 N/mm², +6.9%). The microtrend curves used to show these improvements do not show them as one-off effects but as components of a steady upward trend that climaxed at the 10-15 percent range. In addition to these levels, the performance of both SCMs decreased, which proved that during overdose, cement is diluted and an unreacted residue is present. The slope graph at W/C = 0.40 shows that Quartz 10% (7.739 N/mm², +87.9%), Silica Fume 10% (6.485 N/mm², +57.5%), and Silica Fume 5% (6.229 N/mm², +51.3%) are the podium mixes in this case. The plots of the microtrend further reveal that Quartz has a sharp peak of 10 percent replacement beyond which the strength becomes progressively less. Silica Fume, in its turn, demonstrates a wider effective range, with 5 and 10 percent substitutes giving significant benefits, but larger concentrations resulting in a decrease in tensile strength as a consequence of water requirement and dispersal problems at low W/C ratios. Figure 8 is a heatmap that helps to place the performance in the (W/C, dosage) space in its entirety. At W/C = 0.30 Quartz and Bagasse Ash are dominant and at W/C = 0.40 Quartz and Silica Fume are dominant. Calcium Carbonate offers consistent yet moderate effects in both ratios whereas Fly Ash is unlikely to dominate in any cell although its microtrend profiles are very flat or downward sloping indicating its slower pozzolanic kinetics at young ages. The triangulation highlights the importance of

critical interaction between the SCM type, the ratio of water to cement and dosage in terms of tensile performance control. The acquired insights validate the notion that no single SCM is necessarily superior and instead, its efficacy heavily relies on mix porosity, water availability as well as the relative balance between the effects of filler, nucleation, and pozzolana.

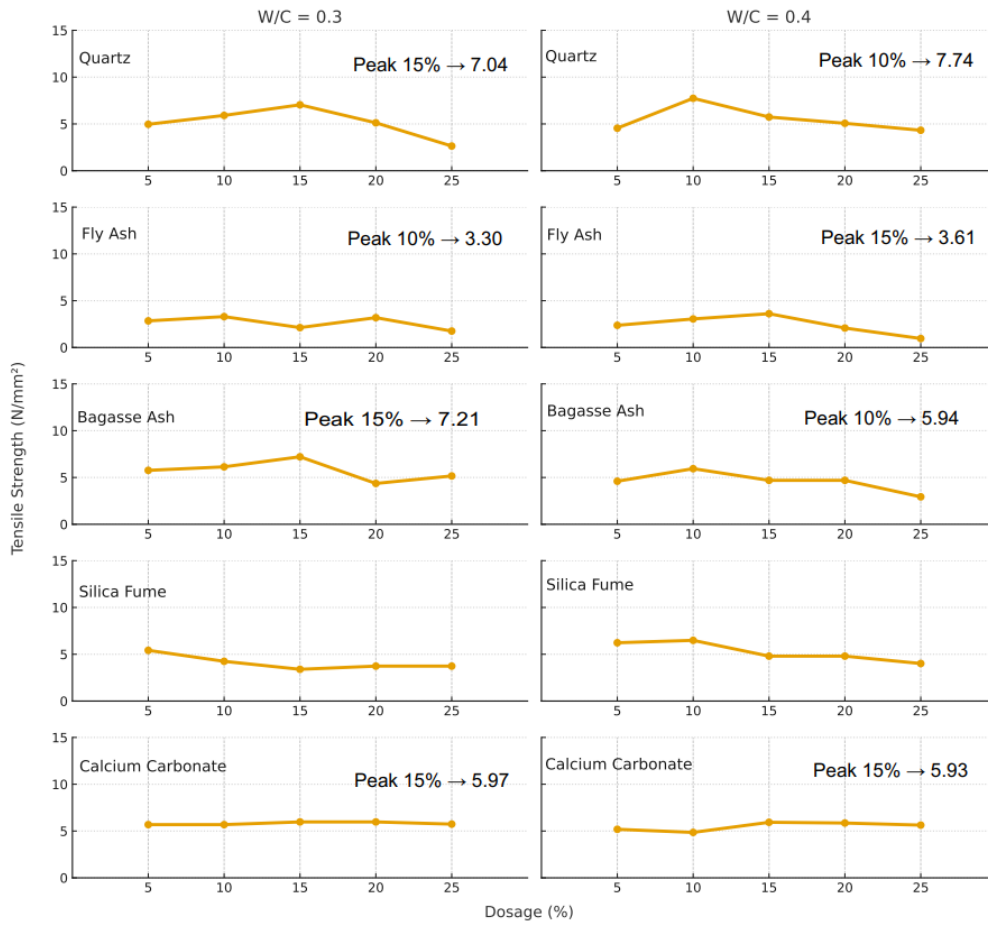
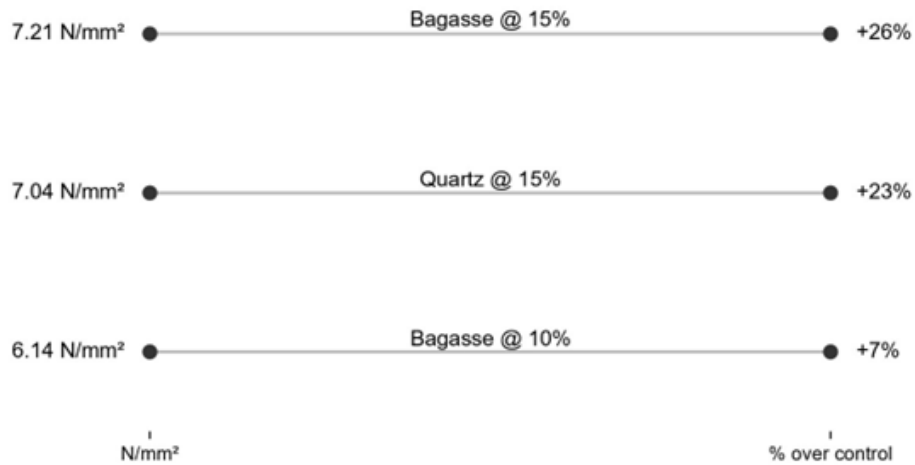
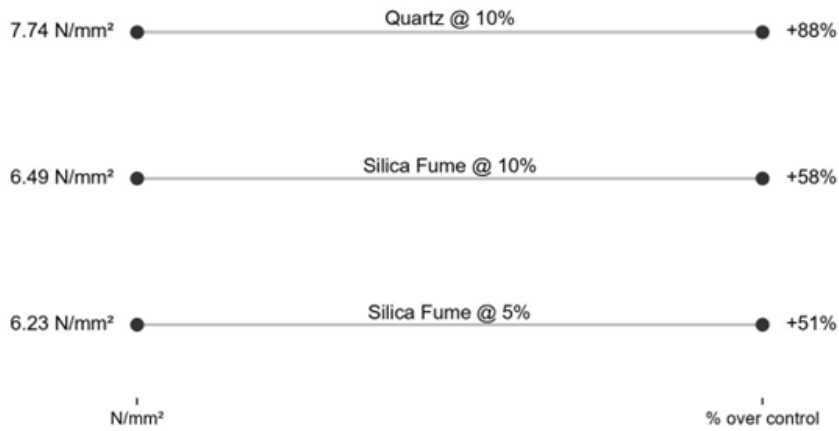


Figure 9. Microtrend of SCM and its performance for each W/C.

W/C = 0.3 (Top 3 mixes)



W/C = 0.4 (Top 3 mixes)



(a)

Figure 10. (a) Slope graph w/c 0.3, 10 (b) Slope graph w/c 0.4.

5. Discussion

There is an evident trend in the interaction of each supplementary cementitious material (SCM) with the water cement ratio and dosage to affect early tensile strength. Overall, low and moderate replacements increase the strength by increasing the strength of the particle packing and forming nucleation of the hydration products, whereas high replacements reduce the strength of the binder and dilute it. The outstanding performance of SCM at varying level of W/C is presented in Figure 11. The optimum replacement level shifts more towards higher percentages as the mix grows denser (W/C = 0.30) since the paste will carry more filler to high degree of dilution before becoming critical but even then it grows plateau soon as the fraction of cement is decreased excessively. Quartz and bagasse ash are used as an example of the advantages of finely ground fillers. At W/C = 0.40, quartz achieved its maximum strength at approximately 10 per cent replacement providing a radical uplift of approximately 88 per cent compared to the control. At the leaner mix (W/C = 0.30) the optimum went to 15% and a less impressive but still a significant 23% increase was achieved. The behaviour of bagasse ash was also similar but with a rather lower ceiling with the best behaviour at 10% of W/C = 0.40 and 15% of W/C = 0.30, which supports the notion that a small proportion of reactive silica in combination with filler effects can significantly enhance early tensile capacity. The two materials are only useful in the short-term at a percentage of approximately 15 as the loss of cementitious binder exceeds they offer in the microstructure.

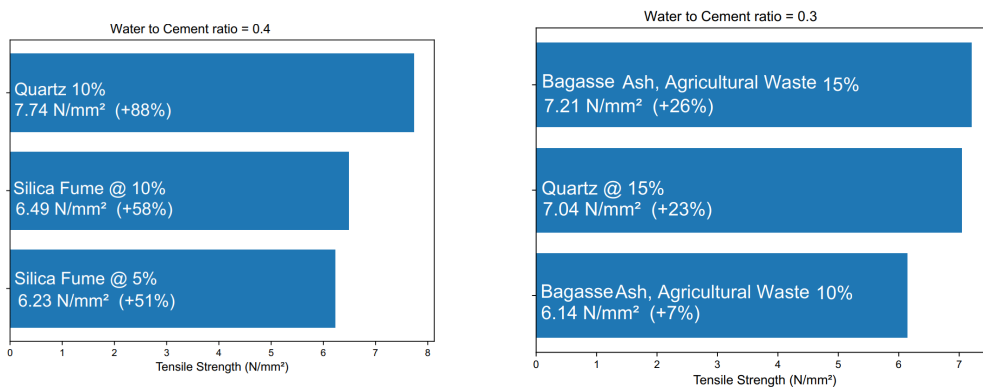


Figure 11. Performance of SCM with different W/C.

There was a other dependency of mix porosity with silica fume. Between 5 and 10 percent the replacements at W/C = 0.40 resulted in a broad plateau of enhanced strength with the greatest improvement of about 60 percent being at 10 percent. But, even at the highest W/C = 0.30 the best result was a little lower than the control. This indicates that the fineness of silica fume can only be advantageous in cases where water and paste volume is sufficient to make silica fume disperse and react; when silica fume is in a dense matrix it can be counterproductive since it may excessively refine the pore structure, preventing early strength. Calcium carbonate served as a rather inert filler. Replacements in the 15-20 percent gave modest and consistent returns especially at the higher W/C, which shows that better particle grading can raise the tensile strength without much contribution of pozzolana. Fly ash was different to the rest of the SCMs. At the water-cement ratios as well as at all the dosages used the fly ash mixes performed poorly as compared to the controls. This is in line with the slow pozzolanic reaction of unactivated fly ash that is well known and does not add much strength at the early ages. The findings are an important reminder that one cannot utilize fly ash in cases with tensile capacity being important unless an intervention like chemical activation or extended curing is taken. However, its long term advantages of durability and strength at later age still suggest that it may still be useful in mixtures where tensile strength at the early age is not the design criterion. The other significant observation is that all the materials exhibited a sharp deterioration in strength at a replacement value of 20 percent and more. In spite of the type of SCM and W/C, tensile capacity was lost with high cement replacement, which resulted in a dilution of the binder. This supports the necessity of balancing sustainability objectives (by cement reduction) and mechanical performance and emphasizes the fact that SCM dosage must be customized to the desired water cement ratio and the early age properties. Precast elements and early-loaded structural members Quartz and Bagasse Ash are the most promising SCMs when high tensile capacity is required as in the case of repair mortars, precast elements and early-loaded structural members. The replacement values of between 10–15 percent sit well between the strength gain and cement loss, and the optimum value of this replacement varies with the water cement ratio (10% at W/C = 0.40, 15% at W/C = 0.30). Silica Fume works well at 5–10% in higher W/C mixes but will not do any good in a firmer mix its application should only be used in the pastes that are more porous. The Calcium Carbonate may be used as a benign filler at a percentage of 15–20 to gain modest returns especially when water cement ratio is high. Fly Ash, however, cannot be counted on early days tensile strength pozzolanic response is slow, and there should be considerable increase at later ages or chemical activation. These are suggestions to indicate that SCM type and dosage must be matched with water cement ratio and the intended age at which the loading is desired. The present study is limited to early days tensile strength and does not capture longer-term pozzolanic reactions, especially for fly ash, nor does it encompass other key properties such as compressive strength, modulus of rupture, or durability indicators. To build a more comprehensive understanding, future work should extend the testing program to additional ages 7, 28, 56, and 90 days and include a broader suite of mechanical and durability tests. At higher W/C ratios, increased pore volume allows finer SCM particles to act as effective fillers and nucleation sites, whereas at lower W/C ratios, excessive fineness increases water demand and limits early hydration. The findings are particularly relevant for precast components, repair mortars, and early loaded structural elements where early tensile capacity is critical.

6. Environmental and Cleaner-Production Implications

6.1 Embodied CO₂ reduction

The direct substitution of Portland cement by the SCMs has a direct effect of diminishing the embodied carbon of the binder since every kilogram of cement substituted by the SCMs eradicates a value of about 0.80 kg CO₂ in the calcification and burning of fossil fuel. The approximate CO₂ saving of all mixes, including the insignificant agro-industrial by-products (fly ash, bagasse ash, silica fume), low values of embodied CO₂ of the inert fillers (quartz = 0.05 kg CO₂ kg⁻¹; calcium carbonate = 0.07 kg CO₂ kg⁻¹), are presented in Table 3. The formula used to obtain the avoided emissions (ΔCO₂) was as follows where R_c is replacement ratio (fractional per cent), E_{cement}=0.80kg CO₂ kg⁻¹ and E_{SCM}the embodied CO₂ of each supplementary material. Replacement levels of 15 percent gave a mean reduction of CO₂ of 0.10–0.13 t CO₂ per t binder across all SCMs which is a reduction in total emissions of 13-16%.

$$\Delta\text{CO}_2 = R_c \times (E_{\text{cement}} - E_{\text{SCM}}) \quad (1)$$

6.2. Performance–Sustainability Synergy

Quartz powder and bagasse ash are better in regards to the embodied-carbon ratio to mechanical gains to savings. Quartz (10 percent) powder +88 percent tensile strength -12 percent CO₂ = Sustainability Index 7.3 Bagasse ash (15 percent)- +26 percent strength/ -12 percent CO₂= Index 2.2. Silica fume (10

percent) +58 percent strength/ -12 percent CO₂ = Index 4.8. CaCO₃ (20 percent)+42 percent strength -14 percent CO₂ = Index 3.0 Fly ash (15 percent) -12 percent strength -12 percent CO₂ = Index < 0. The discussion of this demonstrates that the moderate additions of 10–15 percent are ideally the best mechanical payoff per unit prohibition CO₂, and that small, carefully selected SCM additions would be far-reaching to the cleaner-production goals. The five SCMs in question are either by-products of industries that are rich (fly ash, silica fume), agro-residue (bagasse ash), or readily available fillers (quartz, CaCO₃). Their adoption therefore perpetuates, Waste valorization, utilization of by-products, that would otherwise be taking space in landfills or providing air pollution. Energy saving, elimination of the kiln energy requirement of the replaced part of clinker. Close supply, bagasse ash and quartz powder can be sourced locally in south east Asia, which reduces the amount of emissions made in the transportation process. The SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action) should be taken into consideration with the help of the construction materials turned into the waste flows in the agricultural and metallurgical sector. By using these materials as part of the normal production of cement, the industry can cut overall CO₂ emissions without necessarily incurring new capital-intensive technologies, and by 10–20 percent which constitutes an almost-term cleaner-production pathway.

Table 3. Estimated Embodied CO₂ Reductions and Sustainability Indices.

SCM Type	Optimum Dosage (%)	W/C	Tensile Strength (MPa)	% Change vs Control	ΔCO ₂ (t binder) ⁻¹	Sustainability Index (% ΔStrength / % ΔCO ₂)
Quartz Powder	10	0.40	7.74	+88	0.12	7.3
Bagasse Ash	15	0.30	7.21	+26	0.12	2.2
Silica Fume	10	0.40	6.49	+58	0.12	4.8
Calcium Carbonate	20	0.40	5.86	+42	0.14	3.0
Fly Ash	15	0.40	3.61	-12	0.12	-1.0

The combination of the above measurements, the most effective mixes may be Quartz (10 %), Bagasse Ash (15 %), and Silica Fume (10%) and they are capable of saving = 0.12 t of CO₂ per tonne binder and improve tensile capacity with a 26-88 percentage. Industrial-scale replacement of 15% of world cement production by these optimized SCM blends would avert in excess of > 400 Mt CO₂ yr⁻¹, which is equal to the annual emissions of Thailand and Malaysia combined.

Table 4. Performance Sustainability Dataset.

SCM Type	Replacement (%)	W/C	Day Tensile (MPa)	% Change vs Control	Estimated ΔCO ₂ (t binder) ⁻¹	Sustainability Index (%ΔStrength %ΔCO ₂)
Control	0	0.30	5.74	0	0	0
Quartz Powder	10	0.40	7.74	88	0.12	7.3
Bagasse Ash	15	0.30	7.21	26	0.12	2.2
Silica Fume	10	0.40	6.49	58	0.12	4.8
Calcium Carbonate	20	0.40	5.86	42	0.14	3.0
Fly Ash	15	0.40	3.61	-12	0.12	-1.0

7. Conclusions

The tensile weakness is inherent to concrete, although its tensile performance during early age can be enhanced through the partial substitution of Portland cement with supplementary cementitious materials (SCMs). The degree of improvement however depends upon the nature of the SCM applied in addition to the water cement (w/c) or water binder (W/B) ratio of the mix therefore there is no ideal replacement level. The SCMs act via different physical and chemical processes including the action of microfiltration, nucleation, or pozzolana reaction and each possesses a dosage range wherein benefits become optimum and afterwards, level off or even fall.

1. Quartz powder is mostly used as a non-reactive microfiller, which enhances the strength of concrete by physical action rather than by chemically. Combined with cementitious mixes, it reduces the binder concentration, raising the local water-to-cement ratio, and provides additional nucleation sites to hydration. This increases the speed of hydration, less porosity and a more compact microstructure, particularly whereby the quartz powder is finely ground. Experiments with ultra-high-performance concrete indicate that cement can be substituted with fine particles of quartz to a level of 30 per cent without affecting compressive strength, but tensile strength generally reduces with a replacement of up to 10–15 per cent. In this range, microfiller effect is effective in densifying interfacial transition zone. Quartz powder should have a good supply of water to become well dispersed- mixes with very low W/C ratios may lead to decreased workability, therefore particle fineness and gradation needs to be optimized to give uniform packing (Li et al., 2022b),
2. Sugarcane Bagasse Ash is a pozzolan and microfiller which is attributed to its high levels of amorphous silica. It combines with the calcium hydroxide to bring more C-S-H gel which densifies the matrix and enhances the paste-aggregate bond. The replacement is optimum at about 10% and increases tensile strength by approximately 20–23 and an extreme (>15) does not increase the gains due to unreacted ash. SCBA works well with low W/B ratios (~ 0.37) having good curing so that the pozzolanic activity is maintained and shrinkage is reduced. (Li et al., 2022b; Harish, Madupu and Satyanarayana, 2024b)
3. Silica Fume (SF) is an ultrafine and extremely reactive pozzolan that enhances pore structure and strengthens interfacial transition zone. It can increase tensile strength in splitting by up to 86 percent and compressive strength to almost 96 Mpa (when W/C = 0.26) at the replacement levels of 5–15 percent. It is sensitive to the content of water-moderate to high W/C ratios give it strong gains in strength, but very low ratios do not permit further increases (Yang, Liu and Wang, 2024).
4. Calcium Carbonate (CaCO₃) works primarily as an inert filler and nucleation promoter, which enhances the early-age strength by increasing the packing density and hydration development. Its effect on tensile strength is small and impermanent. Its best results are at 5-15 percent substitution, where dilution negates advantage. It can be used in high and low W/C systems to stabilize mixtures and helps to speed up early hydration (Silva et al., 2024).
5. Fly Ash (FA) is a sluggishly reactive pozzolan, and can result in premature loss of strength (up to 60 per cent loss in 28 days at high replacement). However, with time, secondary C-S-H formation increases durability and subsequent strength. Mechanical grinding or chemical activation (e.g. sodium sulfate) enhances reactivity, which boosts early compressive strength by 8–12 percent and 3-day strength by 34-64 percent compared to unactivated FA (Ullah et al., 2025) , (Shah et al., 2022)
6. To conclude, supplementary cementitious materials (SCM) of a particular type can be chosen and dosed to enhance the tensile performance of concrete in its early age. Quartz powder and sugarcane bagasse ash have shown to be the most effective with a replacement level of about 10-15% when they improve the particle packing and exhibit pozzolanic activity without over working the solution. Silica fume gives the best strength benefits when combined with appropriate water-cement ratio and in particular, the mixes that demand high density. Calcium carbonate is primarily a filler, with a small but consistent effect, but unactivated fly ash is likely to decrease early strength unless mechanically or chemically activated. Finally, optimal performance results should be achieved based on a customized mix design achieving the balance between performance requirements and sustainability objectives.

Author Contributions

Conceptualization, A.M.K, A.N, Q.H, H.M, P.C, P.T, A.J and SB.; methodology, A.M.K, A.N, Q.H, H.M, P.C, P.T, A.J and SB.; software, A.M.K, A.N, Q.H, H.M, P.C, P.T, A.J and SB.; data curation, A.M.K, A.N, Q.H, H.M, P.C, P.T, A.J and SB.; writing—original draft preparation, A.M.K, A.N, Q.H, H.M, P.C, P.T, A.J and SB.; writing—review and editing, A.M.K, A.N, Q.H, H.M, P.C, P.T, A.J and SB. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest Statement

Author declares no conflict of interest.

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