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Properties of Cement Sand Brick Containing Shredded Paper as Partial Sand Replacement

Solahuddin Bin Azuwa [1*]

[1] Faculty of Civil Engineering Technology, Level 1, Chancellery Building, Universiti Malaysia Pahang Al-Sultan Abdullah, Lebuh Persiaran Tun Khalil Yaakob, 26300 Kuantan, Pahang Darul Makmur, Malaysia.

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Abstract

Sand disposal causes significant environmental pollution. Effective sand mining is one of the alternative approaches to reduce sand disposal. Thus, this research investigates the properties of cement sand brick (CSB) containing shredded paper (SP) at various percentages, 0%, 10%, 20%, 30%, 40%, and 50%, as partial sand replacements. This research also investigates the mechanical and durability properties of CSB containing SP. The compressive, flexural, and splitting tensile strengths incline with 10 and 20% sand replacements with SP, respectively. 50% SP replacement shows the maximum influence on water absorption and efflorescence. The scanning electron microscope (SEM) elucidates that the emergence cracks are repaired, which improves the CSB's strength by enhancing the bond connection between sodium hydroxide ($Na(OH)_2$) and potassium-silicate-hydrogen (K-S-H) links. Some cement particles have been hydrated at 20% SP replacement, producing the highest strength. This study indicates that SP can be utilized as partial sand substitution in CSB at 10% and 20%, with significant improvements in strength and engineering properties, especially in building construction. Research on other types of SP that might yield stronger CSB is necessary for future research. Besides that, future studies shall investigate and observe the effects of CSB reactions with different percentages of SP usage.

Keywords: Cement Sand Brick; Shredded Paper; Compressive Strength; Flexural Strength; Splitting Tensile Strength; Efflorescence.

1. Introduction

The widespread use of concrete in infrastructure improvement projects has benefited the lifestyles of regular people. The building construction sector consumes between 600 and 700 million metric tons of cement annually in concrete production [1]. Cement and concrete production harm both the human system and the environmental ecosystem. This production of construction materials significantly contributes to greenhouse gas emissions [2]. Sustainable concrete is being developed using various admixtures. Several mineral admixtures, like fly ash, coal ash, and silica fume, are also employed to produce high-durability concrete. Many supplementary cementitious materials are in high demand to address environmental issues and mitigate problems associated with cement production [3]. In addition, the mills produce around 900 billion metric tons of cement annually. WP generated by paper mills causes severe health and environmental risks to the surrounding community [4]. As we know, a small-scale plant produces around 1 million bricks/year. This production will consume approximately 175 tons of WP annually. Additionally, 1% of global CSB production yields approximately 100 billion bricks per year. If 100 billion bricks adopt SP as either an additive or replacement material, it may save up to 17.5 million tons of WP from landfills. This outcome represents 4% of global WP, notably reducing landfill burden and carbon dioxide and methane gas emissions as well. A combination of experimental investigation and modeling approaches is needed to fully understand the impact of sand mining activities in a complex ecosystem [5].

* Corresponding author: solahuddin.08@yahoo.com

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Although paper can be recycled, practical and economic constraints limit the process's efficiency. Paper fibers degrade with each recycling cycle, reducing their strength and quality. After approximately 5-7 cycles, paper becomes unsuitable for further recycling. Additionally, SP is often excluded from standard recycling streams due to its small size, which complicates the sorting and managing processes. Specialized paper products, such as glossy paper, thermal receipts, and mixed-material packaging, also challenge the conventional recycling system. As a result, a significant volume of paper waste remains unprocessed, contributing to environmental pollution and increasing landfill use. Sand plays a vital role in concrete production by providing bulk, stability, and strength to the material. It acts as a filler that binds with cement and water to form a dense and durable matrix [6]. The quality and gradation of sand significantly influence the mechanical properties, workability, and longevity of concrete structures. However, the high demand for sand, especially in urban development and large-scale infrastructure projects, has led to the exploitation of riverbeds and coastal areas. This not only affects local biodiversity but also increases the carbon footprint associated with transporting sand over long distances. Identifying viable and eco-friendly alternatives to sand is crucial for ensuring the sustainability of the construction industry [7].

The use of SP as partial sand replacement in CSB offers several quantifiable environmental advantages compared to conventional disposal, particularly in landfills. First is waste diversion from landfills. Paper waste constitutes approximately 15-25% of total municipal solid waste in many countries. 1 metric ton of paper in a landfill emits a mere 1.3 metric tons of CO_2, mainly due to methane generation during decomposition. By incorporating 10-20% SP in CSB, around 60-100 m^3 of CSB can be produced. For example, producing a standard size of 1000 CSB using 20% SP can divert 120-150 kg of WP from landfills, potentially avoiding ~0.15-0.2 metric tons of CO_2 emissions. Next is sand extraction decrement. Sand mining has severe ecological impacts, including riverbed erosion, habitat destruction, and groundwater depletion. By replacing even 20% of sand, the demand for river sand is reduced proportionally, which helps to mitigate this effect. Then, lower embodied energy. Using SP in CSB requires dramatically less energy than WP production and recycling processes. Utilizing SP as a filler material avoids energy-intensive incineration and chemical product recycling, thereby lowering the overall embodied energies of construction materials [8, 9].

According to Malik (2023) [10], replacing 5%, 10%, 15%, and 20% of aggregate with WP reduced sludge disposal and improved concrete properties. The fresh concrete slump was at its highest value when the cement was replaced with 5% WP, and further replacement above 5% caused the slump value to decline. The reduction in concrete workability was related to the high-water absorption characteristic of WP particles. In another study, Singh et al. (2015) [11] investigated the concrete properties with 0%, 10%, 15%, and 20% WP addition. The concrete slump increased by 3% with a 10% addition of WP and declined by 6.3% and 12.5% with 20% and 25% WP additions, respectively, compared to the control concrete mixture. This study concluded that the optimal percentage was 10% WP utilization to produce better concrete performance. Shinganmakki et al. (2021) [12] also studied the partial aggregate replacements with WP at 0%, 11%, 21%, 31%, 41%, and 51%. The concrete strength values declined in high-grade concrete specimens and vice versa. WP utilization was successfully applied for low-strength concrete, but it is unsuitable for high-strength concrete. The highest compressive strength was obtained at 10% WP replacement. Hence, 10% was the most suitable WP replacement level in that research investigation. Jung et al. (2022) [13] evaluated the concrete properties by substituting aggregate with 0%, 6%, 11%, 16%, and 21% WP. The results demonstrated that replacing cement mortar with 6% WP resulted in the highest strength compared to 0%, 11%, 16%, and 21% WP substitution because the calcium and silicate bonds in the WP microstructures were enhanced when the WP was replaced at a slight level. Moreover, the highest concrete strength was achieved due to WP's high water absorption rate and the optimal amount of sand used.

The experimental findings indicated that increasing the amount of sodium oxide (Na_2O) improved the concrete's flexural strength [14-17]. The potassium hydroxide (KOH) content also incrementally increased the concrete's tensile strength when the cement was substituted with WP at a percentage ranging from 63 to 111%. The concrete demonstrated superior effectiveness, behavior, and accuracy in forecasting the tensile and flexural strengths across various strength ranges. Another finding revealed significant predictive accuracy in determining the flexural strength of concrete by utilizing an optimum amount of WP addition [18]. Utilizing optimal WP content with an accurate formula equation demonstrated its reliability, especially for researchers and civil engineers who needed to accurately predict and measure the concrete's flexural strength. The formula used in this study depicted superior precision in calculating the WP replacement percentage [19]. Several factors influenced the concrete strength, such as acid ratio, KOH concentration, concrete age, curing state, and molarity. The concrete strength increased with the increasing amounts of these factors. Moreover, it was observed that the load capacity of reinforced concrete beams (RCB) increased as the WP proportion in the concrete mixture increased from 1% to 4%, respectively [20]. It was considered that the increase in RCB's load capacity for 2% WP was optimal and acceptable. Consequently, it could be asserted that WP inclusion in RCB improved the RCB's load amount by up to 20% as well. Moreover, all these materials contained fibers as SP [21-23].

Previous studies had explored the use of cellulose fibers from WP as a reinforcing agent in concrete and mortar. The research findings indicated moderate strength retention at low replacement levels (≤20%) but high porosity and water absorption at high replacement levels (≥20%). Based on microstructural insight, unlike many prior studies, this research investigates the bonding mechanisms between SP, cement hydrates, and K-S-H gels through SEM and XRD analysis. It evaluates mechanical and durability properties, providing a holistic understanding of SP-modified CSB. This research is essential in identifying the ideal mix proportion and SP replacement level to balance the CSB's strength, durability, and insulation properties. Subsequently, it addresses scalability challenges and explores strategies for enhancing long-term durability, making SP a viable alternative for producing eco-friendly construction materials. Many previous studies on the incorporation of WP in concrete and bricks had suggested that low to moderate replacement levels, which were 20% and below, improved the concrete's workability and durability. In contrast, high percentages of SP usage, which were 20% and above, increased the concrete's porosity and reduced its strength. These results were also confirmed by preliminary tests, which showed that ≤20% SP retained good CSB's mechanical properties with insulation improvement, while >30% SP increased the CSB's porosity, leading to higher water absorption and lower strength and performance.

Using WP, either by adding or replacing it with another material, enhanced the concrete strength and properties. Large quantities of WP are readily available in most countries, particularly in western and southern regions. Based on many previous studies, sand had never been replaced with WP in CSB at percentages of 0%-50%. This study investigates the properties of CSB with 0% to 50% sand replacement using SP. As seen from previous studies, WP was not shredded to acquire a smaller size. So, this research shredded the WP in order to get a small size, which would increase the strength and behavior of CSB. This research also aims to investigate whether ordinary CSB can be made more effectively using SP as partial sand replacement. In addition, this research examines the CSB's experimental test results for compressive, flexural, and splitting tensile strengths, including water absorption, by partially replacing sand with WP at 0-50% with water curing. The compressive, flexural, and splitting tensile strength tests are conducted at 7, 14, and 28 days, while the water absorption test is performed at 28 days. On the other hand, neither scanning electron microscopy (SEM) nor x-ray diffraction (XRD) had been conducted in any other research before this. SP microstructures are observed and investigated in this study through SEM and XRD, which is a relatively new approach. Figure 1 delineates the article structure.

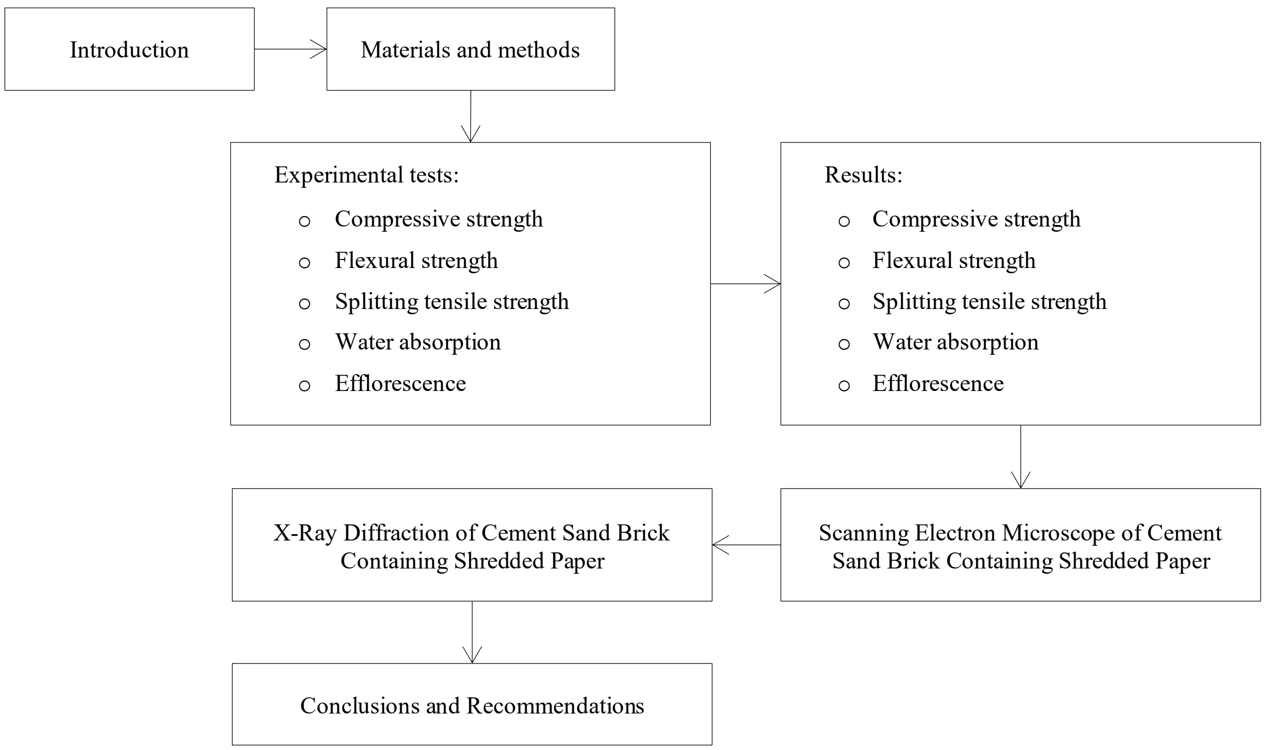

Figure 1. Flowchart of the methodology

2. Materials and Methods

Figure 2 shows the flowchart of research methodology. This research uses Ordinary Portland Cement (OPC) manufactured and produced by the ZUM company. OPC is chosen because of its uniform chemical compositions and characteristics. It is also marketed under the Orang Kuat brand. The OPC used in this product is formulated in accordance with NT 633: Part 2: 2013 [24]. The fine aggregate utilized is river sand from a local source. The fine aggregate has a 1.21 mm maximum size with a 1.33 fineness modulus. Figure 3 shows that the fine aggregate sieve analysis outcome is within the acceptable range for usage as fine aggregate as specified by the BS 812: Part 103 (1985) [25] standard. Granite is selected as the coarse aggregate for this research. The granite was sieved with a 5-20 mm nominal size range as per the BS 882 (1992) [26] standard. The coarse aggregate sieve analysis also falls within the pass range between the lowest and highest cumulative passing percentages defined by the BS 812: Part 103 (1985) standard [25], as delineated in Figure 4. This experiment used ordinary tap water with a pH of 6.5-8.5. Concrete Grade 30 with a water-cement ratio of 0.5 is utilized. The concrete term is used because the mix proportion to produce CSB follows the same standard as concrete production. In conventional CSB production, a W/C ratio of 0.3-0.7 is typically used to ensure workability, hydration, and strength development. The 0.5 ratio aligns with common standards, like CUVO E321 for asphalt mortar and CT FO 883-2 for masonry. For SP, it was collected from an office. The SP was sourced from office waste. A paper shredder machine was utilized to shred the paper in order to acquire the SP with the same and consistent size of 1.6 (*l*) x 0.6 (*w*) x 0.06 cm (*t*), as delineated in Figure 5. The uniformity of SP size was ensured by sieving and secondary shredding. It can be seen that large particles may cause weak bonding with cement matrices, which leads to strength diminishment, while small particles increase surface area, increasing SP bonds and water demand. Not only that, but the fiber orientations in SP structures also contribute to better CSB's crack resistance as well as consistent strength distribution.

Similar fiber size has improved CBS's mechanical properties. Some preliminary tests show that this size optimizes bonding within the cementitious matrices. The specific dimension of SP can be justified based on their effectiveness in both composting and recycling processes. This dimension is correctly aligned with the best practice in each application. Microscopic analysis was conducted to prove that SP had high fiber composition, roughness, and porosity. A standard water absorption capacity test was also performed in order to determine the SP's ability to retain water, which highly impacted the internal curing [15]. Moreover, the ash content was investigated to check for residual organic matter that might affect the hydration process. Shredding paper into smaller pieces increases the surface area available for microbial activity, thereby accelerating the decomposition process. Besides that, appropriately sized shredded paper helps absorb excess moisture in compost piles, maintaining an optimal environment for composting. Smaller paper fragments contribute to better aeration within the compost, facilitating oxygen flow, which is essential for aerobic decomposition. The pH and chemical composition in SP assess the compatibility of SP with the acid and alkaline cement matrices. This study profoundly evaluates the different performance of CSB mixtures containing SP and a control mixture without SP content. All CSB samples were formed in the same size. Cement and SP have specific gravity values of 3.15 and 2.93, respectively. Figure 3 depicts the SP used in this experimental research. Tables 1 and 2 explicate the SP's physical properties and chemical compositions.

Table 3 displays the CSB mix proportions for all CSB samples. The CSB mixtures were designed according to the BS 1881: Part 125 (2013) [26] standard guideline. The selection of the specific mix proportion (0-50%) is justified based on previous research, industry standards, and preliminary experiments. Furthermore, the SP replacement level selection is based on balancing structural performance and sustainability goals.

A 0% (control sample) represents conventional CSB properties for benchmarking. This regular CSB acts as the baseline for comparison with other CSBs that contain various sand replacement percentages with SP in order to investigate SP's impacts. The composition is known as a traditional concrete mixture without SP inclusion. A 10% replacement level is expected to enhance workability and provide minimal strength loss. It is likely to have a moderate internal curing effect due to limited SP water retention. A 20% replacement level, which is optimal, is chosen based on previous research studies and preliminary trials where flexural and compressive strengths peaked. It also offers better fiber interlocking and crack-bridging mechanisms, maximizing structural integrity and enhancing internal curing without excessive porosity. A 30% replacement level is observed at a transition point where excessive SP starts weakening the material. Higher porosity and water absorption are expected, leading to durability concerns. More than 30% substitution level considerably increases the void content, reducing the CSB's strength and performance. In addition, workability issues and poor bonding with cement cause a higher impractical probability for construction works. Similar studies have investigated the effect of adding SP in various applications, like concrete, compost, and insulation materials. Their chosen proportion can serve as a benchmark. For example, research on paper-based additives in concrete, reinforced concrete, and soil stabilization may show that 10-20% inclusion provides optimal performance without compromising structural integrity. The 10% increase allows for a clear comparison of how SP affects the main properties of CSB, such as strength, degradation rate, and insulation effectiveness. It is clearly shown that this method ensures a systematic evaluation, making it easier to determine the optimal mix proportion in order to achieve the best performance of CSB.

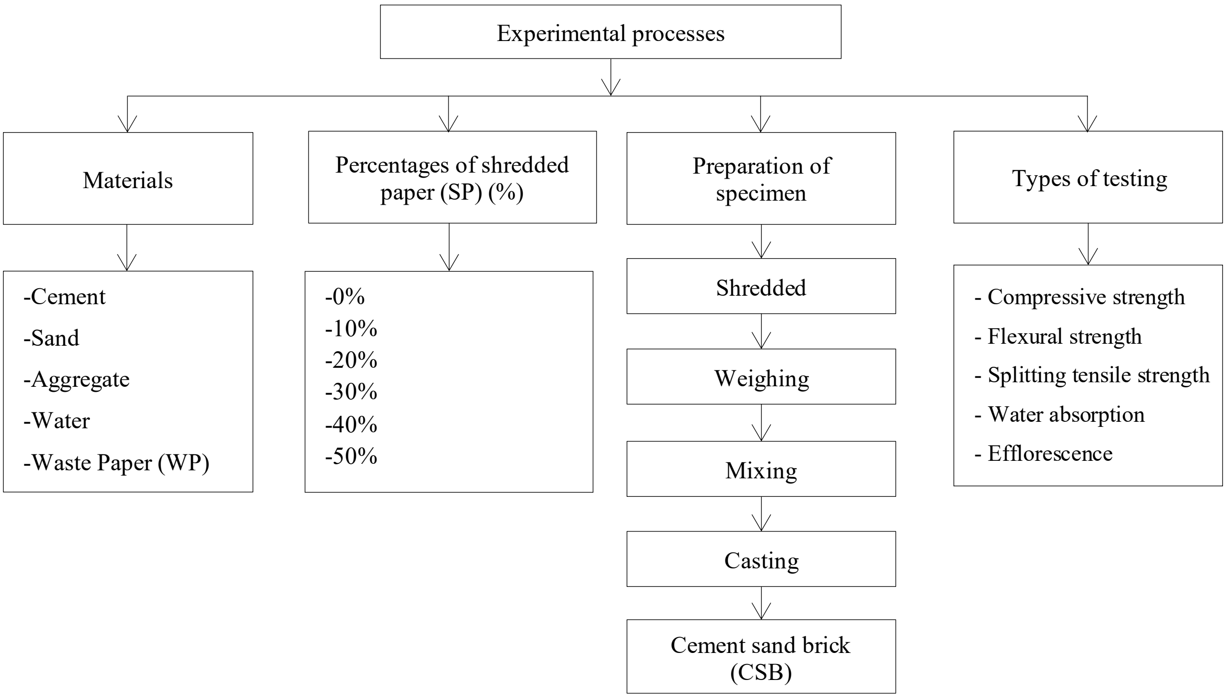

Figure 2. Flowchart of research methodology

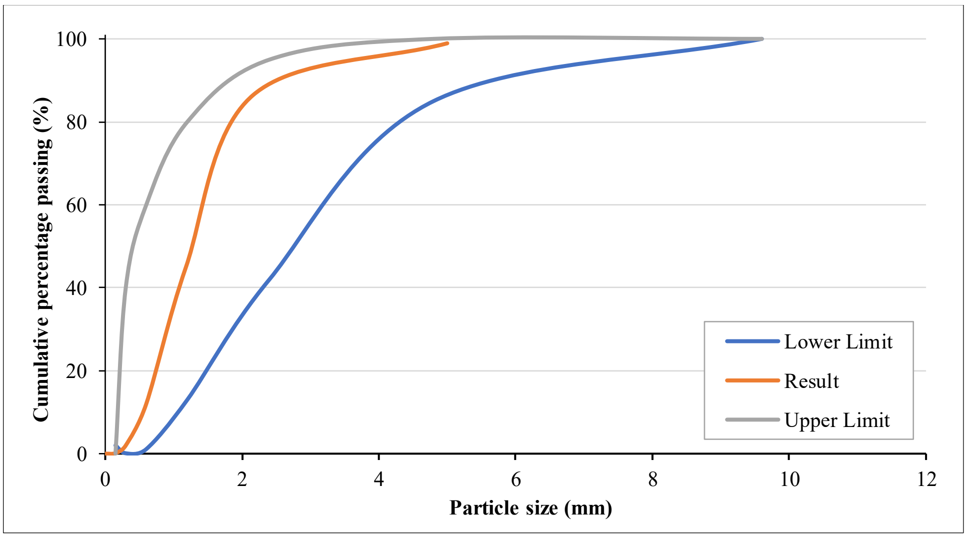

Figure 3. Fine aggregate

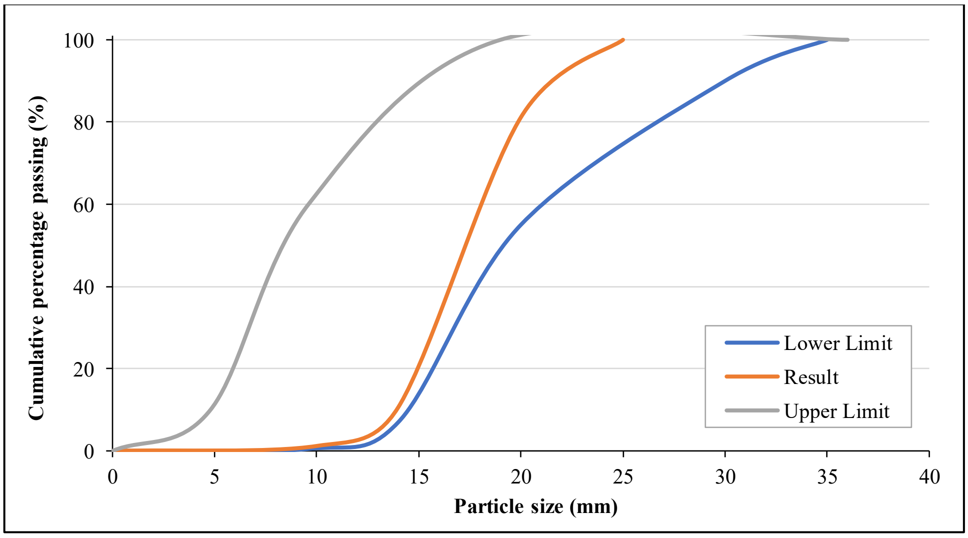

Figure 4. Coarse aggregate

Figure 5. Shredded paper (SP)

Table 1. Physical properties of SP

Physical properties of WP	Data
Inorganic material (%)	30
Organic material (%)	70
Moisture content (%)	2.67
Absorption (%)	89
Density (kg/m3)	800
Specific gravity	0.98
Thickness (μM)	105-110
Moisture (%)	5-5.6
Roughness (N)	211-411
Pressure (kPa)	361-411
Wind load (mN)	611-711
Inertia	1.61-1.76
Momentum	1.46-1.61

Table 2. Chemical composition of SP

Element	Percentage (%)
Carbon dioxide	26.94
Oxygen	25.05
Fiber	71.68
Aluminium	3.17
Calcium	4.61
Sulphur	2.18
Potassium	1.27
Iron	1.03
Sodium	1.33

Table 3. Mix proportion of CSB

Sample	Cement (kg)	Sand (kg)	SP		Water (kg)
			(%)	(kg)	
A	1	5	0	0	0.5
B	1	4.5	10	0.5	
C	1	4	20	1	
D	1	3.5	30	1.5	
E	1	3	40	2	
F	1	2.5	50	2.5	

Several procedures were carried out to produce the concrete mixtures. First, all materials were weighed to the exact quantities needed for the mixing process. The SP was shredded with a paper shredder machine before being mixed. In this study, no chemical modification or special pre-treatment was applied to the SP before it was included in the CSB mix. The SP was used in its natural state after being manually shredded to the targeted size. However, the SP was air-dried to remove any residual moisture and ensure consistency in the water-to-cement ratio across all batches. One of the factors is environmental sustainability. Avoiding chemical pre-treatment aligns with the study's aim in producing low-cost and eco-friendly CSB by repurposing WP. Another factor is baseline performance evaluation. The objective is to evaluate the natural behavior of SP in cementitious matrices to establish a baseline understanding of its performance in terms of strength, water absorption, and durability. A well-cleaned and debris-free concrete mixer was then used to combine all the ingredients until an equal mixture was achieved. The remaining water was added gradually after the initial addition of 75% water and stirring for 2 minutes. After the mixture was well combined, it was poured into molds, followed by compaction using a vibrating table. 300 × 150 × 150 mm CSB brick samples were cast, followed by the conduction of mechanical and durability experimental tests. After compaction, a damp gunny bag was used to cover the mold and left overnight before being demolded. Water curing was utilized for all CSB samples.

After 24 hours, all CSB specimens were removed from the molds and immersed in a bathwater tank for water curing until they reached the matured age for testing. Figure 4 illustrates the CSB preparation process. The compressive, flexural, and splitting tensile strength tests were conducted at 7, 14, and 28 days, while the water absorption and efflorescence tests were performed 28 days after casting and water curing. The curing process is crucial for ensuring the proper development of material properties, particularly in applications like concrete, composites, or biodegradable materials. Here is how the curing environment should be detailed. CSB curing is typically performed at 20-25°C (standard condition) or higher when accelerated curing is applied. Besides that, biodegradable materials may require a controlled temperature to prevent premature degradation. The chosen temperature is based on both ASTM and ACI standards. Furthermore, CSB requires at least 95% relative humidity for the first 7 days to prevent moisture loss and ensure proper hydration. Biodegradable composites may need controlled humidity to balance moisture retention and avoid mold growth. All mechanical properties were tested utilizing a Universal Testing Machine (UTM) with 2500 kN static load capacity at steady and constant rates of 4 kN/s, 0.8 kN/s, and 4.42 kN/s, respectively. In addition, the water absorption test was conducted based on the water absorption formula: $\% = 100\,(W_s - W_d)/(W_d)$, where W_s and W_d were the CSB's saturated and dry weights. The efflorescence test was conducted to determine the state of salt deposits on the CSB surface. Figure 6 depicts the preparation process of CSB.

To address the natural tendency of SP to clump, float, or segregate during mixing, a carefully structured mixing procedure was followed to ensure homogeneous distribution within the CSB mixtures. The mixing procedures are as follows:

1. Dry mixing (Pre-blending)

All dry components, such as cement, sand, and SP, were thoroughly mixed in their dry state for approximately 3-5 minutes to get even distribution and prevent early clumping of the SP in the wet mixes.

2. Gradual addition of water

Water was added gradually and incrementally while the mixture was continuously stirred. This step was essential to prevent the SP from floating or forming lumps due to sudden hydration.

3. Extended Mixing Time

The entire mixing process lasted around 8-10 minutes, slightly longer than the traditional mixing time, to ensure consistency for the fiber dispersion time required for SP.

4. Manual scraping and folding

In smaller batches, manual folding and scraping of the mixing vessel walls were performed in order to ensure that the SP fibers did not stick together or float to the surface.

At lower SP levels (≤20%), fiber distributions are visually uniform and manageable using the above methods. At higher SP levels (≥30%), fiber clumping and reduced mix cohesion are observed, indicating the need to improve the mixing equipment and pre-treatment of SP (e.g. pre-wetting or using dispersing agents).

(a) All materials are mixed up

(b) Concrete compaction

(c) Concrete casting and labelling

(d) Water curing

Figure 6. Preparation process of CSB

3. Experimental Tests

To evaluate the mechanical and durability performance of CSB samples containing SP, standardized testing methods are employed for compressive, flexural, and splitting tensile strengths, water absorption, and efflorescence. All these experimental tests follow ASTM and BS standards to ensure accuracy and comparability.

3.1. Compressive Strength Test

The compressive strength test standard follows ASTM C39 for masonry units. The CSB samples were cast in standard 300×150×150 mm molds. After 24-hour demolding, the specimens were cured for 28 days at 27°C ± 2°C with ~95% relative humidity. A universal testing machine (UTM) with a 3 kN/s load was used. The CSBs were centrally positioned on the compression plate. The load was gradually applied until failure, and the maximum compressive load was recorded. This test is conducted to determine the load-bearing capacity of CSB and identify the optimal SP content that provides the highest strength. The formula used is compressive strength (MPa) = maximum load (N)/cross-sectional area (mm²). Figure 7 shows the compressive strength test.

Figure 7. Compressive strength test

3.2. Flexural Strength Test

The flexural strength test was performed as per ASTM C293, which was the standard test method. Subsequently, the beam-shaped CSB sample size is 300×150×150 mm. All of the specimens were cast and cured under standard conditions. The CSB was placed on two support rollers with a span length of 300 mm. A central point load was applied at a loading rate of 0.05 MPa/s using a UTM. The maximum load at failure was recorded. This test aims to evaluate the bending resistance and crack propagation behavior of CSB and assess the impact of SP interlocking on flexural performance. Figure 8 demonstrates the flexural strength test.

Flexural Strength (MPa)= $3PL/2bd^2$

where: P=Maximum load (N); L=Span length (mm); b=Width of specimen (mm); d=Depth of specimen (mm).

Figure 8. Flexural strength test

3.3. Splitting Tensile Strength Test

The standard test method for CSB's splitting tensile strength is ASTM C496. The CSBs are cylindrical with a 300(h)×150(d) dimension. They were cast and cured in a regular state. The cylinders were horizontally positioned between the UTM's two steel plates. A gradual load was applied along the cylinders' length until they completely failed. This test measures indirect tension resistance, which is essential for crack resistance and durability. Moreover, it helps to analyze the SP's fiber bridging effect in cementitious matrices. Figure 9 illustrates the splitting tensile strength test.

Splitting tensile strength (MPa)= $2P/\pi LD$

where: P=Maximum load (N); L=Length of specimen (mm); D=Diameter of specimen (mm).

Figure 9. Splitting tensile strength test

3.4. Water Absorption Test

The water absorption test was performed in accordance with BS EN 772-11, which was highly suitable for sampling and testing concrete masonry units with dimensions of 300×150×150 mm. The CSB was oven-dried at 105°C for 24 hours to ensure constant masses were acquired. Next, the dry weight obtained was recorded. Another name for this test is water immersion. Then, the CSBs were fully submerged in water for 24 hours at room temperature (~25°C). After that, the CSB's saturated weight (W_2) was recorded after surface drying was completed. It is crucial to keep in mind that this test determines the CSB's porosity and permeability, which is essential to durability assessment and evaluation. As we know, higher SP content typically increases the CSB's water absorption rate, affecting long-term weathering resistance. Figure 10 elucidates the water absorption test.

Water absorption (%)=$[(W_2-W_1)/W_1]\times 100$

where: W_2=Wet mass; W_1=Oven-dried weight.

Figure 10. Water absorption test

3.5. Efflorescence Test

The BS EN 772-5 standard determines a masonry unit's efflorescence. This standard is also utilized for sampling and testing. The CSBs with 300×150×150 mm size were dried in an oven at 105°C for 24 hours. They were partially immersed in tap water and placed vertically in a shallow water tray (25 mm deep) for 7 days. Subsequently, water was allowed to rise by capillary action. The efflorescence test observes salt deposition on the CSB surface, which may degrade aesthetic and structural integrity. It can be seen that this test can also help to determine the suitability of CSB for long-term exposure to moisture. The CSBs were air-dried. Figure 11 explicates the water absorption test. The extent of white salt deposit (efflorescence) is classified based on the following types:

Nil (0%)=No deposits

Slight (≤10% surface covered)=Light patch of white deposit

Moderate (10-50%)=Thin but continuous layer covering part of the surface

Heavy (>50%)=Thick white crystalline deposit over most of the surface

Figure 11. Efflorescence test

4. Results and Discussion

This section discusses all the experimental test results acquired.

4.1. Compressive Strength

Table 4 and Figure 12 show the compressive strengths of CSB at 7, 14, and 28 days of water curing. The compressive strength is the lowest for the control CSB, which is 0% SP content. According to ASTM C129 and BS EN 772-1 standard guidelines, standard non-load-bearing CSBs typically have a compressive strength of 3-7 MPa, while the range of CSB's load-bearing is from 7 to over 15 MPa. Suppose the control CSB (0% SP) falls below both ranges. In that case, it may indicate severe issues with the mix design, possibly due to high porosity, poor compaction, a suboptimal cement-sand ratio, or poor curing conditions. The conventional CSB falls within the theoretical strength range of more than 3 MPa but less than 10 MPa. They may still be usable for non-structural constructions, such as partition walls, paving blocks, and insulation bricks. Besides that, the strength of CSB increases with SP incorporation, which is caused by the fibrous interlocking mechanism and secondary hydration reaction, contributing to CSB's structural properties enhancement as well. At 7 days, 6.08 MPa strength is recorded for the control CSB. The highest value of 8.09 MPa is recorded for the CSB containing 20% SP as partial sand replacement. A 33.31% difference is found compared to regular CSB. The compressive strengths of all CSB mixtures increase with increasing curing time. At 14 days, the compressive strength value for the control CSB is 7.09 MPa. The highest result is 9.12 MPa, containing 20% SP as partial sand replacement. The difference from the control mixture is 28.52%. An 8.32 MPa value is acquired for the control CSB after 28 days. 20% SP records the highest compressive strength value, which is 10.31 MPa. The difference from the reference CSB is around 24.02%. Besides that, a 9.52 MPa compressive strength value is achieved with 30% SP, while the lowest compressive strength value is obtained at 50% SP, which is 8.655 MPa.

The control CSB, which contains 0% SP as partial sand replacement, exhibits the lowest overall compressive strength in the test results. The primary factor is the current form of SP particles, which have been used as partial sand replacement. SP has a filling effect, eliminating air pockets and resulting in a denser and stronger CSB when added to the CSB mixture. It can be seen that well-dispersed fine SP particles fill the voids and microcracks in cement matrices, leading to a denser structure. This dense structure reduces porosity and increases bonding efficiency between cement hydrate and aggregate. Furthermore, SP contains cellulose fibers, which chemically interact with calcium-hydrate (Ca-S-H) and silicon-hydrate (Si-S-H) compounds. These compound formations improve interfacial bond strength, making fiber matrices more cohesive and resilient. Furthermore, SP also has a high interlocking property between particles in its fine form compared to ordinary particles. The CSB's density might be reduced if the SP is used as a substitute material.

According to the experimental test, the compressive strength is positively affected when the sand is replaced with 20% SP. The improvement in compressive strength at 20% SP replacement can be attributed to several key mechanisms that balance the beneficial and detrimental effects of incorporating SP in CSB. Here is a detailed discussion of why this proportion yields the highest compressive strength. One of the factors is the optimal fiber reinforcement effect. It can be seen that at 20% replacement, the SP fibers may have acted as micro-reinforcement, helping to bridge micro-cracks and delay crack propagation under compressive loading. This phenomenon is similar to fiber-reinforced concrete, where tiny, well-distributed fibers improve toughness and load transfer. An SP replacement rate of over 20% may lead to poor bonding and strength reduction due to excessive porosity. The key mechanism is the presence of fibers in SP microstructures, which increases the tensile resistance within the matrices, thereby improving the overall compressive strength by resisting crack formation.

The inclusion of SP in CSB has a notable impact on workability and setting behavior, particularly at higher replacement levels. As SP content increases, the mix becomes less workable and stiffer, especially beyond 20% replacement. This is attributed to the high-water absorption capacity of paper fibers, which reduces the free water available for lubrication in the mix. No plasticizer or water-reducing agent was added in this study. The water-to-cement (w/c) ratio was maintained at 0.5 across all mixes to ensure comparability between all CSB samples and consistency for CSB's mechanical testing. It may have limited the workability of mixes with higher SP content. The presence of SP slightly delays the initial setting time, particularly at a replacement level of 30-50%. This effect can be explained by the slow release of absorbed water from paper fibers, which modifies the hydration rate. The presence of fibers causes the partial hindrance of cement particle contact. Despite these effects, all CSB mixes are set within an acceptable timeframe for manual handling and compaction during brick molding.

Table 4. Compressive strength

Shredded Paper (%)	Compressive Strength (MPa)		
	7 Days	14 Days	28 Days
0	6.08	7.09	8.32
10	7.16	8.13	9.13
20	8.09	9.17	10.31
30	7.51	8.73	9.52
40	7.22	8.32	9.23
50	6.53	7.63	8.66

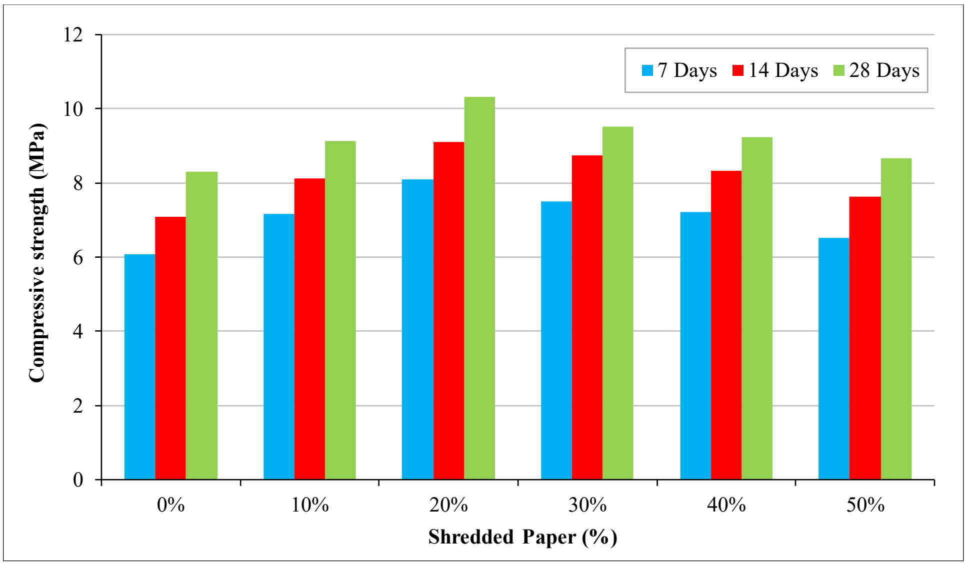

Figure 12. Compressive strength

4.2. Flexural Strength

Table 5 and Figure 13 illuminate the CSB's flexural strength results. The flexural tests were done on six different CSB mixtures: one control mixture and five mixtures with different SP percentages with each other. The sample volume ratios used are 90:10, 80:20, 70:30, 60:40, 50:50, and 100:0. 100:0 acted as the control volume ratio. According to the data obtained, the flexural strength of the control CSB (0% SP) is the lowest for all CSBs tested. The strength value of the control CSB is 0.17 MPa at 7 days. The largest value, 0.22 MPa, is found in the CSB containing 20% SP as partial sand replacement. There is a difference of 29.52% between these two groups. At 14 days, 0.19 MPa flexural strength is acquired for control CSB, while 0.23 MPa is the greatest value obtained for CSB with 20% SP. Both difference is 21.24%. At 28 days, the maximum flexural strength of 0.24 MPa is achieved for 20% SP replacement, while the minimum flexural strength recorded is 0.19 MPa for 50% SP replacement. The value range shows a 25.26% difference. 20% SP delineates the highest strength compared to other mixtures tested. Furthermore, after 7 days of water curing, the results indicate that the CSB with 0% SP yields the same strength value as 50% SP. This same strength value produced depicts that when the proportion of SP is more significant than 50%, the flexural strength drops below the control CSB's strength. SP is used to fill the space within the sand microstructures in order to make the CSB denser and more robust. As a result, the CSB has better flexural strength. The main component of SP is cellulose. Organic fiber is made from carbon-hydrogen bonds.

The oxygen atoms in water molecules strengthen the hydrogen bonds in SP by interacting with hydrogen atoms in cellulose molecules [27]. Flexural strength in CSB is primarily influenced by how well the material resists bending forces. Incorporating SP at an optimal percentage (e.g., 20%) can improve flexural performance through a fiber interlocking mechanism, but excessive SP can weaken the matrix. Here is a deeper insight into how SP affects the CSB's flexural strength. SP fibers act as reinforcement, helping to bridge microcracks that develop under bending stress. Besides that, the interlocking mechanism occurs when fibers are well distributed, allowing them to transfer stress between cracks and slow down crack propagation. This distribution is similar to the effect seen in fiber-reinforced concrete (FRC), where synthetic or natural fibers enhance flexural toughness. SP fibers restrain crack widening, allowing the CSB to sustain a high flexural load before failure occurs. Celluloses slightly tend to interact with calcium hydroxide $Ca(OH)_2$ compounds, possibly leading to surface modification of the fibers. As a result, this incident may influence fiber bonding strength but does not significantly contribute to cementitious reactions. Apart from that, alkaline degradation of cellulose material occurs. The high pH, which is in the range of 12-13, leads to slow degradation of cellulose in a short time. This occurrence causes fiber weakening and reinforcement loss in long-term performance. Nonetheless, a well-cured cementitious system's fiber degradation rate is high and fast.

Table 5. Flexural strength

Shredded Paper (%)	Flexural Strength (MPa)		
	7 Days	14 Days	28 Days
0	0.17	0.19	0.22
10	0.18	0.21	0.23
20	0.22	0.23	0.24
30	0.20	0.21	0.22
40	0.19	0.20	0.21
50	0.18	0.19	0.19

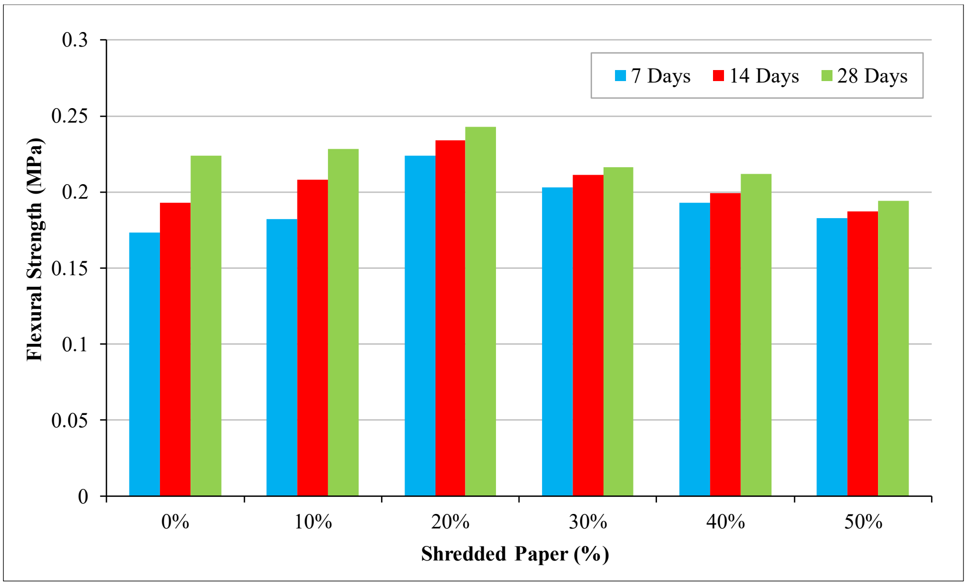

Figure 13. Flexural strength

4.3. Splitting Tensile Strength

Table 6 and Figure 14 illustrate the splitting tensile strength test results conducted on CSB specimens with water curing at 7, 14, and 28 days. When SP is added by 10% and 20%, the strengths rise by 5.7% and 16.12% at 7 days and then drop by 27.7% when added by 30%. At 14 days, the splitting tensile strength required to split the CSB increases by 16.38% at 10%, 11.02% at 20%, and 26.3% at 30% SP as partial sand replacement. Moreover, the strength values rise by 10.6% and 12.34% at 28 days. 40% and 50% increments in SP content lead to 7.65% and 13.76% reductions in splitting tensile strength, respectively. The strength inclines up to 20% sand replacement with SP before beginning to drop at 30% replacement. On the other hand, the optimal percentage of SP that should be used is 20% in order to get the maximum splitting tensile strength for all days. SP contains high alumina and silica contents that are well and perfectly combined with calcium to make it stronger. The alkali in SP exhibits hydraulic and pozzolanic reactions, while the hydration process releases calcium hydroxide ($Ca(OH)_2$), which is also significantly linked to the enhancement of CSB strength. Subsequently, the minor void and porosity of the matrices are reduced when 30%, 40%, and 50% of sand are replaced with SP because of hydration product termination, which does not expose the SP surfaces and microstructures.

The inclusion of SP as partial sand replacement in CSB dramatically affects the mechanical, durability, and thermal properties compared to conventional CSB. 10-20% SP replacement maintains strength and improves flexibility of CSB. Apart from that, SP improves ductility and thermal and acoustic properties as well as porosity and water absorption of CSB. It can be concluded that 10-20% SP substitution offers the best balance between strength, durability, and sustainability. Mix optimization and durability enhancement with sealer and additive substances are needed for a high SP replacement level, which is 30-50%. The celluloses in SP's micro- and macro-structures interact with cement matrices to produce hydrogen bonding and retain water content. It can be seen that cellulose fibers are hydrophilic. That means they absorb and retain water for a long time. This occurrence prolongs the cement hydration process, which enhances CSB's strength development. However, excess cellulose increases porosity, affecting CSB's properties as well. Other factors are physical interlocking and crack-bridging mechanisms. Cellulose microfibers function as reinforcing substances, improving compressive, flexural, and tensile strengths by resisting crack propagation. On the other hand, the fiber matrix bond strength depends on fiber dispersion and interfacial adhesion. The higher the fiber dispersion and interfacial adhesion, the higher the fiber matrix bond strength. High fiber matrix bond strength increases the splitting tensile strength of CSB.

The increase in the strength of CSB with the inclusion of SP, particularly at optimal replacement levels such as 10%-20%, can be explained through a combination of physical and chemical mechanisms. SP has fibrous structures with a high surface area and fine particle size. When properly dispersed, it fills the micro-voids between sand and cement particles. This incident reduces the overall porosity, resulting in denser matrices, which improve the mechanical properties and strength of CSB. The cellulose fibers in SP form mesh-like networks within the cement matrices. These mesh-like network formations enhance the mechanical interlocks between particles, especially in flexural and tensile loading. The rough surfaces of SP fibers allow better adhesion with hydrated cement pastes. Furthermore, SP retains water in high volume because of its natural absorbent material. This water is gradually released during hydration, resulting in a shorter curing period and strength development. It could be seen that the fibrous nature of SP helps in bridging micro-cracks, thus delaying crack propagation. This leads to improved flexural and tensile strengths by dramatically inclining the CSB's ductility and toughness.

The compressive, flexural, and splitting tensile strengths increase when 10% and 20% of sand are replaced with SP. A 50% SP replacement shows the greatest influence on water absorption and efflorescence. Scanning electron microscope (SEM) observations indicate that the formation of cracks is reduced, which improves the strength of CSB by enhancing the bonding interaction between sodium hydroxide (NaOH) and potassium–silicate–hydrogen (K–S–H) links. The results of this study demonstrate that incorporating SP as a partial replacement for sand in CSB can enhance its mechanical properties, particularly at a replacement level of about 20%.

In addition, the absorbent nature of SP contributes to improved flexural performance and promotes an internal curing effect within the CSB matrix. However, higher SP contents also increase water absorption and efflorescence, indicating certain durability trade-offs associated with larger replacement levels. Overall, the findings provide a clearer understanding of the behavior of SP in CSB through the combination of microstructural observations and mechanical performance evaluation. This integrated approach highlights the potential of SP as a sustainable material for construction applications while also identifying the practical limitations associated with higher replacement percentages.

Table 6. Splitting tensile strength

Shredded Paper (%)	Splitting Tensile Strength (MPa)		
	7 Days	14 Days	28 Days
0	0.28	0.31	0.33
10	0.29	0.32	0.34
20	0.33	0.34	0.35
30	0.31	0.32	0.33
40	0.28	0.31	0.32
50	0.19	0.21	0.24

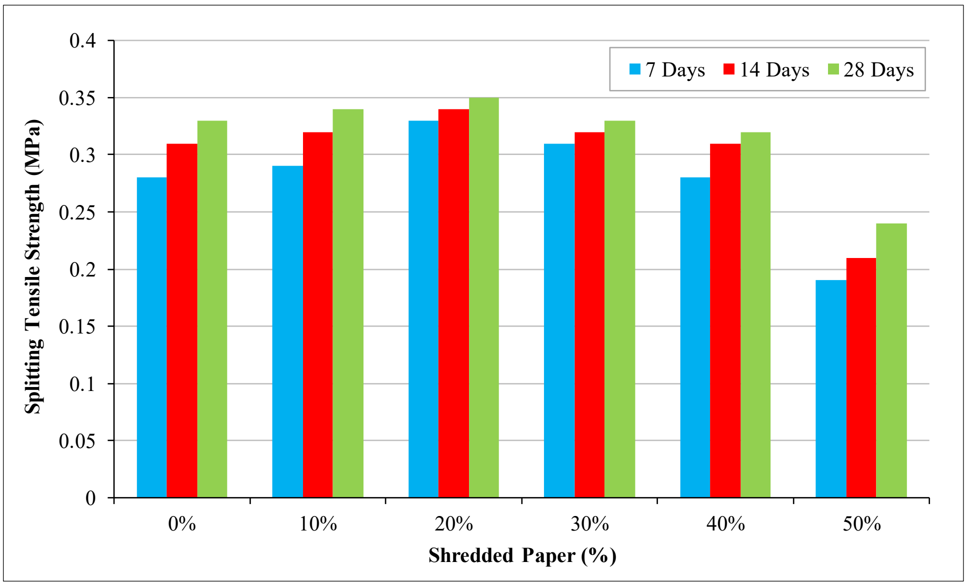

Figure 14. Splitting tensile strength

4.4. Water Absorption

All CSB samples are subjected to water absorption tests to establish their hydration capacity. The CSB is deemed to have lower strength when it absorbs too much water. These test results determine the average water absorption percentage of three CSB for each sample type. The water absorption tests were conducted on one control CSB sample containing 0% SP as partial sand replacement and five CSB specimens containing 10%, 20%, 30%, 40%, and 50% SP as partial sand replacement. The sand-to-SP ratios used are 90:10, 80:20, 70:30, 60:40, 50:50, and 100:0. Table 7 and Figure 15 elucidate the CSB's water absorption results at 28 days of water curing. After 28 days, the results indicate that all CSBs absorb a more significant percentage of water than they had before. The 8.92% water absorption rate produced by the control CSB is the lowest among the other five CSB samples. In comparison, 50% SP replacement reports a maximum water absorption percentage of 13.26%. The water absorption range is 48.65%. CSB can absorb more water if a high SP content is utilized. The higher the SP content, the higher the CSB's capacity to absorb water. SP has unique characteristics that naturally absorb and permit the most water content to pass through compared to other elements. Regular aggregate elimination and its replacement with waste products like SP will benefit and have positive environmental effects.

Long chains of linked sugar molecules are the main components of cellulose formations, as revealed by Zaki et al. (2018) [27]. These sugar molecules expedite and retain the water absorption process for an extended period due to their unique water-absorbent characteristic. The SP absorbent capability comes from the interstitial gaps between cellulose fibers, which seem like tiny air bubbles. The environmental and economic benefits of utilizing this SP material to reduce construction material costs and ecological pollution have been emphasized in earlier studies. Future research studies should investigate different types of SP that might produce better performance of CSB. In addition, future research needs to examine the CSB behavior and performance using other amounts of SP as partial sand replacement. Water absorption is a critical factor affecting the durability, strength, and long-term performance of CSB. As the SP content increases, the CSB tends to absorb more water due to the porous nature of paper fibers. This incident has several implications for durability, including reduced strength, increased porosity, and higher susceptibility to environmental damage.

SP introduces additional voids and microchannels in the cement matrices, improving the overall porosity of the CSB. Furthermore, a higher porosity leads to greater water absorption, weakening the bond strength between cement and aggregate. As SP content increases beyond the optimal threshold (e.g., >20%), the excessive porosity reduces the CSB's density, making them structurally weaker. Higher water absorption reduces the compactness of CSB, leading to weaker inter-particle bonding and lower strength. 0% SP (control CSB) has low water absorption, which is 7-9%, due to dense cementitious matrices with well-hydrated C-S-H phases. In addition, 10-20% SP replacement causes a slight increase in water absorption (9-12%), which is attributed to SP's porous nature. However, SP is well distributed at this level, maintaining good bonding with cement matrices. More than 30% SP replacement leads to a significant increase in water absorption, which ranges from 15-20%. High SP content produces more voids and capillary pores, causing notable strength reduction in CSB. Subsequently, reducing cement paste cohesion leads to higher porosity and permeability, which makes CSB more vulnerable to moisture deterioration.

SP has high porosity due to its fibrous structure, leading to more capillary pores in CSB matrices. The increased void content allows more water to penetrate the CSB over time as well. There are several implications for the long-term durability of CSB. First, prolonged exposure to moisture can weaken cement hydration bonds, leading to gradual strength loss. Next, absorbed water may expand in a cold region upon freezing, causing internal cracking and surface scaling. This occurrence is called freeze-thaw damage. Then, high moisture retention causes algae and fungal growths. Good indoor air quality flow will reduce these algae and fungal growths. After that, excessive moisture can lead to a higher shrinkage rate, causing surface crack occurrence. The best application of SPCSB is indoor use, such as non-load-bearing walls (e.g., partition walls), where moisture exposure is minimal. It is also suitable for low-rise structures in dry climates, where water absorption is less concerning. Moreover, SP is a thermal insulation material that can improve heat retention. SP improves the CSB's structural behavior when used in an optimal amount of 10-20%, acting as a filling effect, hydration enhancement, and crack bridging. These actions considerably diminish the drawbacks of CSB. In addition, an excessive SP amount, which is more than 30%, significantly increases the CSB's water absorption and permeability, leading to weaker mechanical characteristics because of excessive voids and disrupted bonding in SP's micro- and macro-structures. This balance explains why a low SP level enhances CSB's strength, while a high SP level does not.

A paper shredder machine was utilized to shred the paper in order to acquire the SP with the same and consistent size of 1.6 (*l*) x 0.6 (*w*) x 0.06 cm (*t*). Smaller particles (<1 cm²) may disperse more uniformly, providing a better filling effect and improving inter-particle bonding, which contributes to higher strength. Larger particles can create weak zones or non-homogeneous microstructures, reducing mechanical strength due to poor adhesion or stress concentration. Finer SP particles tend to absorb and retain more water, which may increase porosity if not adequately balanced with the mix design. If the particle size is inconsistent and larger, more porous fibers may act like capillaries, increasing water uptake and potentially compromising the CSB's durability performance.

Table 7. Water absorption

Shredded Paper (%)	Water Absorption (%)
	28 Days
0	8.92
10	9.62
20	10.83
30	11.66
40	12.66
50	13.26

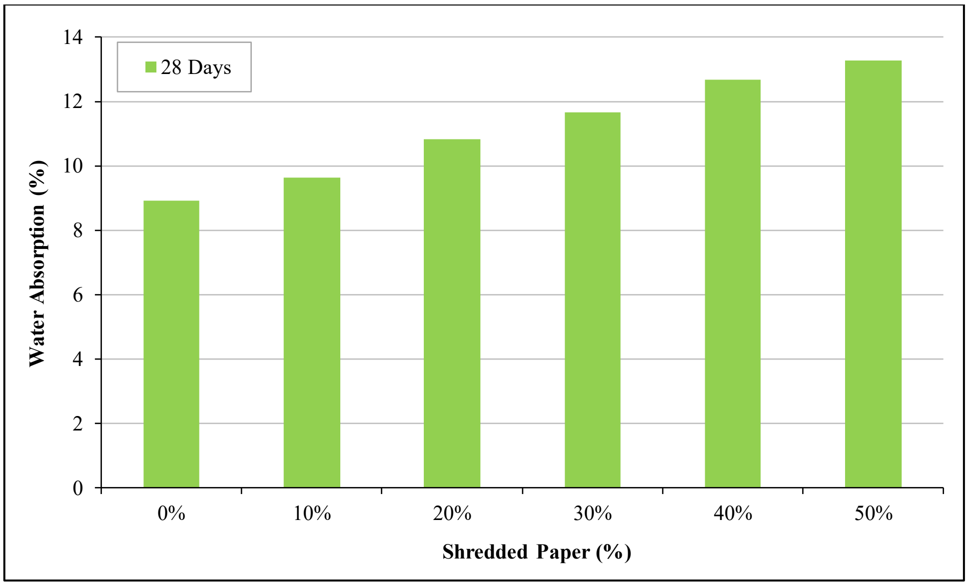

Figure 15. Water absorption

4.5. Efflorescence

The CSB samples are ready for efflorescence testing after water curing for 28 days. Table 8 shows the efflorescence test results. The salt begins to accumulate on the CSB surface. The proportion of SP in each CSB specimen is noted and recorded. This efflorescence test indicates that a heavy condition existed when a heavy salt deposit covers 50% or more of the exposed area of the CSB surface without being included in surface exfoliation. Nevertheless, no efflorescences are detected and observed on the control CSB surface. Hence, the salt deposit is zero. This salt deposit process occurs because of the SP reaction with the salt, which generates various structure formations. One of the chemical properties is the writing ink used on the SP surface. The appearance of salt deposits on the CSB surface can also determine the salt deposit circumstance. 0-10% SP replacement causes minimal efflorescence as the cement hydration process effectively binds acid and alkaline components. Moreover, 20% SP replacement causes slight efflorescence because of high water absorption, which allows soluble positive salt ions like Na^+, K^+, and Ca^{2+} to migrate to the inner CSB surface. Due to several factors, 30-50% SP substitution delineates noticeable efflorescence formation. The factors are high capillary action that facilitates salt transportation and the presence of cellulose fiber retaining moisture inclines, which promotes salt crystallization on the CSB surface.

Another factor is that 50% sand replacement reduces the availability of the $Ca(OH)_2$ compound, which is compulsory to firmly bind acid and alkali components. SPCSB has higher water retention, allowing soluble salt depositions of calcium hydroxide and sodium sulfate on the CSB surface. Both salt types crystallize upon evaporation, forming white deposits on the CSB surface as well. Besides that, efflorescence creates white and powdery deposits, affecting the appearance of CSB, which is called "aesthetic degradation". Salt crystallization causes surface weakening, leading to a surface porosity increment. This surface porosity increment causes harmful effects, which lead to flaking and deterioration. There is also structural risk probability. Prolonged efflorescence can weaken mortar joints, impacting bonding strength in masonry structures. CSB with low thermal conductivity (k) improves insulation and reduces heating and cooling costs. Subsequently, sustainable materials that enhance CSB's thermal performance would contribute to green building production. SP has several potential impacts on the thermal conductivity of CSB. For instance, SP has high density and contains air pockets, which can reduce heat transfer. SP also has high porosity, which reduces CSB's thermal conductivity, making it a better insulator material. Nevertheless, excessive porosity can weaken structural bonds and increase moisture retention, which may negatively affect the CSB's long-term durability performance.

Table 8. Efflorescence

Condition	Explanation
Zero	Salt deposit does not appear at all.
Slight	A thin layer of salt covers less than 30% of CSB's visible surface.
Moderate	Salt deposit is more than slight and cover more than half of the visible CSB surface. If no flaking or powdering occurs, it is considered as surface cracking.
Heavy	A thick layer of salt covers half and more of the exposed CSB surface. If there is no accompanying flaking or powdering, it is determined as surface erosion.
Serious	When exposed, the CSB surface is covered with a thick layer of salt followed by flake or powder formation.

5. Scanning Electron Microscope of Cement Sand Brick Containing Shredded Paper

The scanning electron microscope (SEM) reveals that the microcracks originate from the insufficient binding zone between the SP and the cement paste. The concrete pores close up as a result of this process. Figure 16 shows a fracture in the SP content, while Figure 17 illustrates the same fracture mended at 10% SP replacement. The fracture is repaired, and the concrete strength increases due to strong bonding between silicon dioxide (SiO_2) compounds and beryllium-scandium-hydroxide (Be-Sc-OH) links. The SEM analysis in Figure 18 delineates the presence of scandium particles. These scandium particles appear in amorphous, fibrous, and gel-like structures covering the cement matrices. Additionally, they are highly responsible for the strength and binding properties of cementitious materials. A denser and more compact Be-Sc-OH structure enhances CSB's strength and durability. The hydrated cement particles have a greater tendency to boost CSB performance and properties after being replaced with 10% SP content. Subsequently, the fiber matrices interlock and form hydration products, such as Be-Sc-OH and magnesium-yttrium hydroxide (Mg-Y-OH) compounds, causing the strength of CSB to increase marginally. There is a difference between crack propagation patterns between control and CSB-containing SP. As a result, SP influences the fracture mechanism by reducing crack formation in CSB microstructures. The higher the SP replacement, the less the crack formation in CSB microstructures. SP also reduces crack width, distribution, pore size, and density in CSB because of high fiber dispersion and bonding quality between SP and cement.

In addition, increasing SP content in a concrete mixture influences CSB's porosity and water absorption. This incident can be proved by quantifying the pore size distribution. This SEM also examines the morphology, fiber matrix interface, and hydration products at the microscopic level by analyzing crack emergence and its interaction with SiO_2 and Mg-Y-OH compounds as well. The CSB samples were painted with a thin silver layer to maintain conductivity. A high-resolution SEM was used at 100-micron magnification to analyze and identify the bonding mechanism, crack formation, and porosity distribution of SP. On the other hand, several key findings emerged from the SEM analysis. The presence of SP influences the Be-Sc-OH and Mg-Y-OH bonds, contributing to the enhancement of interlocking bonds. It can also be seen from the crack analysis, where microcrack formations are observed at excessive SP content due to the increment in porosity and weaker fiber-cement adhesion, leading to a notable reduction in CSB's strength. Well-distributed SP fibers at optimal replacement level of 10-20% exhibit strong interfacial bonding with the cementitious phase. High SP content, which is more than 30%, leads to weaker fiber matrix adhesion, resulting in porosity and microcrack formation.

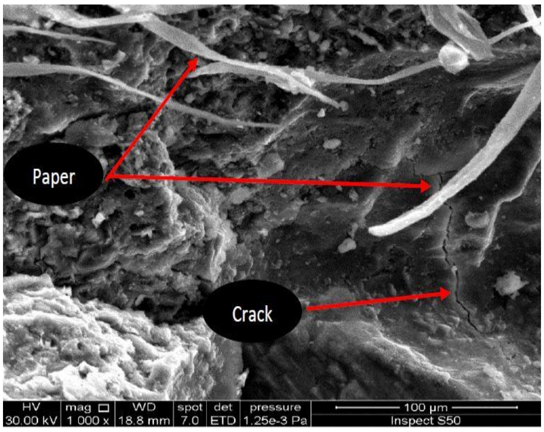

Figure 16. 0% SP

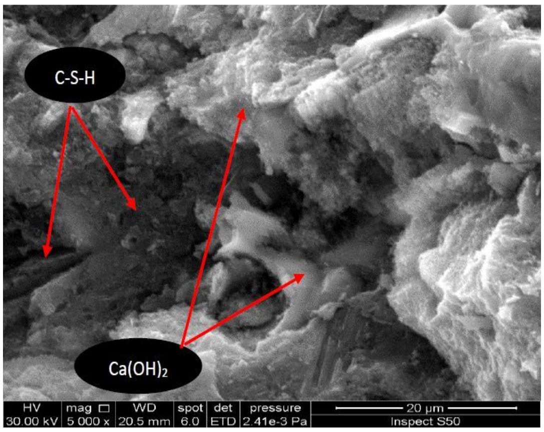

Figure 17. 10% SP

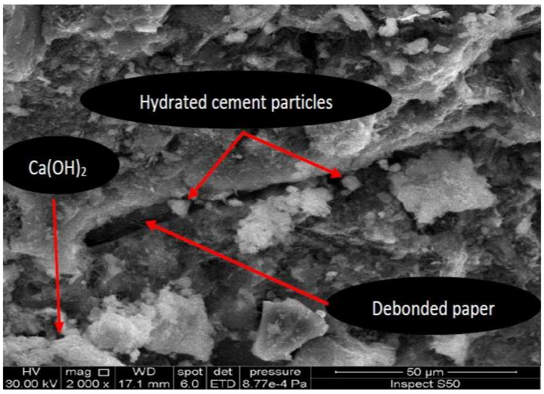

Figure 18. 20% SP

6. X-Ray Diffraction of Cement Sand Brick Containing Shredded Paper

The TG curves in Figure 19 indicate that the CSB samples that have not been thermally pre-treated lose 45% of their weight at temperatures between 300°C and 400°C. Three distinct zones of mass loss are identified along these curves. At 40-2900°C, there is an 8% initial loss of water from the solid pore structures and water surface molecules. The initial loss is due to thermal degradation in the SP material, including the sintering process, which occurs during the second mass loss. CSB made from SP can resist temperatures up to 400 °C. Figure 20 demonstrates the SP diffraction patterns of virgin and binder mixes. The CSB reflection angles are relatively small, with only two peaks, ranging from 30 to 350. Subsequently, the SP material's characteristics and properties remain unchanged regardless of the amount of sand replaced with SP in the concrete mixture. The x-ray diffraction also compares the control and SP-modified CSB. Apart from that, the intensity variations in C-S-H, portlandite, and quartz vary significantly, allowing for the assessment of hydration differences. Broader and less crystalline C-S-H in shredded paper cement sand bricks (SPCSB) also exhibits disorderly hydration products. The formation of a new compound is closely related to K-S-H and $Na(OH)_2$ bonds, indicating the development of the alkali-silicate phase. High C-S-H intensity produces high compressive strength of CSB. The higher the C-S-H intensity, the higher the compressive strength of CSB. From the XRD pattern, a substantial amorphous hump is observed, indicating a good hydration process and a well-bonded matrix. This result is typically correlated with high compressive strength produced. Another finding elucidates that low portlandite produces better CSB durability. If portlandite declines while C-S-H increases, it indicates better long-term stability due to the continuing hydration process. High portlandite may weaken CSB's durability due to potential leaching and carbonation.

In an ordinary Portland cement system, hydration leads to the formation of C-S-H, the primary binding phase (K-S-H), and a minor phase known as "ettringite". SP is rich in cellulose fibers. These cellulose fibers cause the presence of alkali ions (Na^+, K^+), which may lead to secondary effects. K^+ and Na^+ ions slightly modify the structure of C-S-H links, forming K-S-H or N-S-H (potassium/sodium silicate hydrate) links under certain conditions. These alkali-modified gels contribute to additional gel-like bonding networks within cement matrices, although their contribution is limited under regular cement conditions unless under geopolymeric conditions. Subsequently, cellulose fibers themselves interact physically and chemically with cement matrices, contributing to mechanical anchoring within hydrated cement, which produces hydrogen bonding between cellulose hydroxyl groups and hydration products as well. The microstructure observed suggests that SP fibers are physically embedded within cement matrices, contributing to strength improvement through mechanical interlocking. The hydration products, particularly C-S-H, form dense networks around fibers. Alkali ions (Na^+, K^+) from cement modify C-S-H structures. No distinct chemical bonding phases, such as K-S-H, are conclusively identified. Previous studies supported the presence of minor alkali-silicate interactions in such chemical reactions.

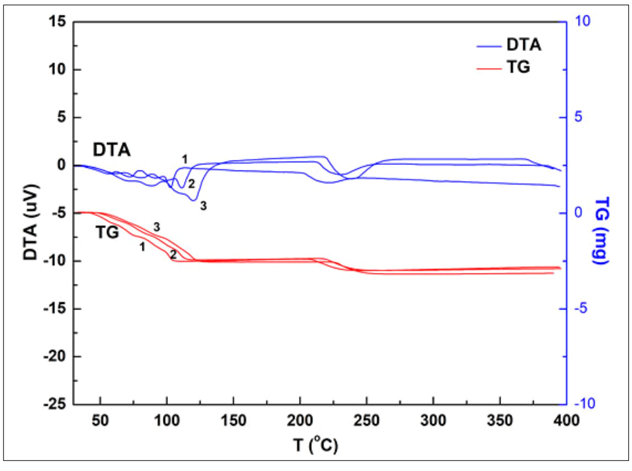

Figure 19. TG-DTA of SP

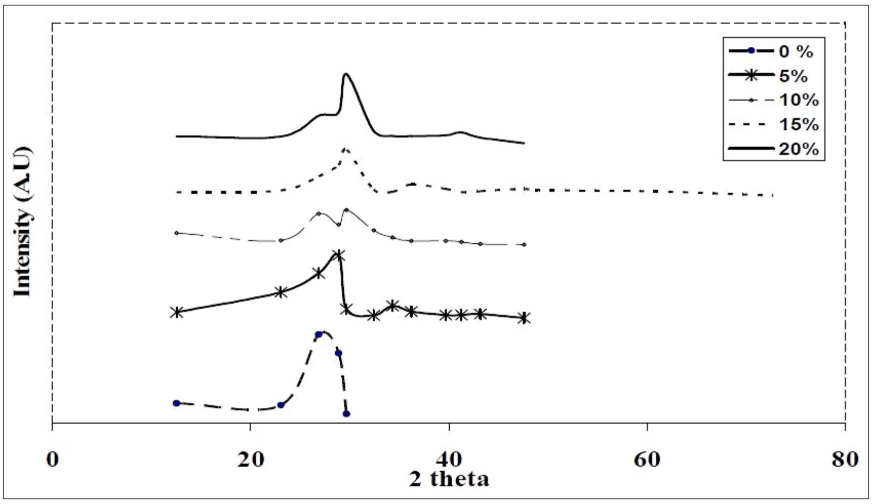

Figure 20. XRD pattern of SP

7. Conclusions

The main conclusions of this study are summarized as follows:

- The compressive strengths of CSB increase at 10% and 20% SP and decrease at more than 20% SP as partial sand replacement.
- The flexural strengths of CSB incline at 10% and 20% SP and decline at more than 20% SP as partial sand replacement.
- The splitting tensile strengths of CSB increase at 10% and 20% SP and diminish at more than 20% SP as partial sand replacement.
- The water absorption of CSB increases with increasing percentage of SP as partial sand replacement. The higher the percentage of SP as partial sand replacement, the higher the water absorption.
- The salt deposit on the CSB surface increases with the inclining percentage of SP as partial sand replacement. The higher the percentage of SP as partial sand replacement, the higher the salt deposit on the CSB surface.
- The majority of SP microstructures are composed of celluloses. The chemical parts of organic fibers consist of carbon and hydrogen atoms. Incorporating water in SP strengthens and enhances hydrogen bond formations due to the interaction between hydrogen atoms in water molecules and those in cellulose molecules.
- The SP particles are in granular form, encompassing a wide range of sizes. Consequently, they serve as a filler, filling the CSB's particle microstructures. SP is proven to be inherited as an element with high water absorption and permeability properties.
- The disposal of WP at landfills will increase environmental pollution. Therefore, the best way to reduce environmental pollution is to utilize WP as a partial replacement for cement, sand, or aggregate in CSB production.

7.1. Recommendations

While incorporating SP in CSB offers sustainability benefits, several challenges, such as increased water absorption, reduced strength at high SP content, and durability concerns, which need further investigation. Future research should focus on optimizing SP utilization by mitigating its drawbacks. The following areas present potential future research opportunities:

- Enhance the mechanical and durability properties of SP-modified CSB through material modifications.
- Investigate hydrophobic treatment, such as silane and silicone coatings, to reduce water absorption and improve long-term durability.
- Explore pre-treated SP fibers like chemical treatment and thermal modification in order to improve bonding with cement matrices.
- Incorporate pozzolanic additives using silica fume, fly ash, and metakaolin in order to refine SP's pore structures and counteract strength loss.
- Enhance moisture resistance, improving durability in humid or freeze-thaw conditions.

8. Declarations

8.1. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

8.3. Conflicts of Interest

The author declares no conflict of interest.

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