Experimental Evaluation of Sugarcane Bagasse Ash as a Sustainable Supplementary Cementitious Material in Concrete

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Abstract

This study investigates the use of Sugarcane Bagasse Ash (SBA) as a partial replacement for Ordinary Portland Cement (OPC) in concrete to improve sustainability and mechanical performance. The research addresses the environmental impact of cement production, a major source of global CO_2 emissions, by exploring the potential of an agricultural waste product as a supplementary cementitious material (SCM). Concrete mixes were prepared with varying percentages of SBA (0%, 5%, 10%, 15%, and 20%) replacing cement, and specimens were tested for compressive and tensile strength after 7, 14, and 28 days of curing. The results show that substituting cement with SBA at a 5–10% replacement level significantly enhances both compressive and tensile strengths, particularly at later curing ages. This improvement is attributed to the pozzolanic reaction, where the amorphous silica in SBA reacts with calcium hydroxide from cement hydration, forming additional calcium silicate hydrate (C–S–H) gel. This process densifies the microstructure and strengthens the concrete. In contrast, higher replacement percentages (15% and 20%) led to a reduction in strength, indicating a dilution effect at excessive levels. The findings suggest that using SBA at an optimal level is a viable, eco-friendly method to create durable concrete while simultaneously reducing agricultural waste and the carbon footprint of the construction industry. Unprocessed sugarcane bagasse ash used in this research offers a sustainable, low-cost alternative to cement, reducing construction expenses while promoting effective waste management.

Key Words: Sustainable Development, Sugarcane Bagasse Ash, Concrete Strength, Ordinary Portland Cement, SDG

Introduction

Buildings have been constructed from a variety of materials since the dawn of human history. Concrete, the world's most common construction material, has advanced from a basic mix of cement, water, and aggregates to a composite incorporating mineral additives, chemical admixtures, and fibers [1, 2]. Beginning with the Industrial Revolution, structures were more robust and long-lasting due to the increasing usage of cement binder [3]. Cement is a vital constituent in the production of concrete and mortar [4, 5]. The necessity of cement rises day by day with the advancement of the society. Ordinary Portland cement is considered as a main component in building construction world widely [6, 7, 8]. The production of cement has scaled up in the 20th century. Ten year ago, the cement production was 3 billion tons globally with an annual growth rate of 6.3 % [9]. The production of each metric ton of Portland cement requires about 4–5 GJ of energy [10]. Around 60–130 kg of fuel oil or its equivalent and about 110 KW-h of electricity are required to produce one metric ton of cement, depending on the cement type and the processes used [11]. Approximately, 800–1000 kg of CO_2 emissions occurs during the production of each ton of cement [9, 12, 13] . About 5%–8% of the global man-made emissions of CO_2 is caused by cement production [9, 13, 14, 15].

At present, researchers worldwide are concentrating on finding methods to use agricultural or industrial waste as a source of raw materials for manufacturing. From this angle, it can be beneficial to use cementitious and pozzolanic wastes and by-products as partial substitutes for cement [16]. The correct disposal of the large amounts of waste produced by municipal and agricultural operations as well as by many industrial processes is a major concern. Because these materials have pozzolanic and cementitious qualities, they can be used in cementitious composites to partially replace cement, reducing the high production costs and environmental pollution linked to cement factories [16]. Different Supplementary Cementous Materials (SCMs) have different effects on cement-based materials because of their different chemical and physical characteristics. Additionally, the production of a particular SCMs is dependent on a particular industrial, agricultural, or municipal process [16, 17, 18]. A lot of bagasse ash, the leftovers from an in-line sugar industry, and bagasse-biomass fuel have been tried to be used in the electric generation sector [19]. Numerous waste products, such as those from industry, municipalities, agriculture, and even natural waste, can be used to create supplemental cementitious materials (SCMs) [16, 20, 21]. A variety of SCMs are derived from both industrial and agro-industrial waste. Fly ash, ground granulated blast furnace slag, bottom ash, silica fume, limestone powder, and other industrial waste-based SCMs are used extensively in construction research, as are SCMs derived from agricultural waste, such as palm oil fuel ash (POFA), rice husk ash (RHA), sugarcane bagasse ash (BA), etc. [16, 19].

Many nations, including Bangladesh and India, cultivate sugarcane to make sugar; in 2019 alone, Bangladesh produced about 3.2 million tons of sugarcane [22]. Since the amount of carbon dioxide (CO_2) released is offset by the CO_2 ingested during the growth of sugarcane plants, burning dried bagasse will not release CO_2 into the atmosphere [16, 23, 24].

Extensive research has been conducted to assess the mechanical properties and pozzolanic activity of concrete incorporating Sugarcane Bagasse Ash (SBA) as a partial replacement for cement. The calcination temperature of sugarcane bagasse and the particle fineness of the resulting ash significantly affect the pozzolanic reactivity of SBA, and consequently influence the mechanical performance of concrete [25, 26]. This study focused on the investigation physical and chemical properties of SBA, assessment of the mechanical properties of SBA mixed concrete and through this transforming Sugarcane Waste into Construction Materials.

Methodology

This study involves the utilization of Sugarcane Bagasse Ash (SBA) as a SCMs for partial replacement of Ordinary Portland Cement (OPC) in concrete. OPC, natural Domar sand with specification ASTM C128 as fine aggregate, and Stones with specification ASTM C33 as coarse aggregates were the main ingredients used in this study, while SBA was collected from locally incinerated Sugarcane Bagasse, dried to a temperature of approximately 110°C and sieved through 0.075 mm sieve. Concrete mixing was prepared with a constant ratio of 1:2:4 and a water-cement ratio of 0.5 in which OPC is partially replaced by Sugarcane Bagasse Ash (SBA) with varying percentages (0%, 5%, 10%, 15% and 20%), alongside a control mix without SBA. The mix designs with varying SBA percentages are shown in Table 1 and Table 2 respectively.

Table 1: Mix proportion of SBA Reinforced Cement Concrete for five type Cubic Specimen

Mix Designation	Quantities						
	SBA (%)	Cement (gm)	Sand (gm)	Stone (gm)	SBA in Replacement of cement (gm)	W/C ratio	Water (ml)
Cy 1	0%	512	1177.52	2121.58	0	0.5	256
Cy 2	5%	486.4	1177.52	2121.58	25.6	0.5	256
Cy 3	10%	460.8	1177.52	2121.58	51.2	0.5	256
Cy 4	15%	435.2	1177.52	2121.58	76.8	0.5	256
Cy 5	20%	409.6	1177.52	2121.58	102.4	0.5	256

Table 2: Mix proportion of SBA Reinforced Cement Concrete for five type Cylindrical Specimen

Mix Designation	Quantities						
	SBA(%)	Cement (gm)	Sand (gm)	Stone (gm)	SBA in Replacement of cement (gm)	W/C	Water (ml)
Cu 1	0%	326	749.63	1350.64	0	0.5	163
Cu 2	5%	309.7	749.63	1350.64	16.3	0.5	163
Cu 3	10%	293.4	749.63	1350.64	32.6	0.5	163
Cu 4	15%	277.1	749.63	1350.64	48.9	0.5	163
Cu 5	20%	260.8	749.63	1350.64	65.2	0.5	163

Standard cube specimens of size 4 inch × 4 inch were cast and cylindrical specimen of diameter 4 inch and height 8 inch were cast for compressive strength test and tensile strength test respectively. After casting, both the specimens were cured in water for 7, 14, and 28 days. Casting, molding, and curing of specimens are shown in the Figure 1.

Figure 1: Preparation for Casting and Curing of Specimens

Mechanical performance was assessed through compressive (figure 2) and split tensile strength (figure 3) tests in accordance with ASTM C39 and ASTM C496, respectively.

Figure 2: Compressive Strength Test

Figure 3: Tensile Strength Test

Furthermore, in accordance with ASTM C1365, C114, and C1723-16 (2022), X-ray diffraction (XRD) and scanning electron microscopy (SEM) were used to examine the chemical and microstructural properties of SBA. After 28 days of curing, slab sample were used to assess the strength of the pavement. The objective of this thorough technique was to evaluate the durability and mechanical performance of SBA-incorporated concrete under various circumstances.

The water absorption test was performed by exposing a single surface of the concrete specimen to water and monitoring the increase in mass with time, thereby quantifying the rate of capillary absorption. ASTM C1585 serves as a standard guideline for this assessment, as it provides an indication of the concrete's vulnerability to water ingress, a key parameter in evaluating durability under potential deterioration mechanisms such as freeze, thaw damage, surface scaling, and corrosion of embedded reinforcement. The permeability test was executed in accordance with ASTM C1202. Furthermore, the workability of fresh concrete was assessed using the slump test, conducted following the provisions of ASTM C143/C143M.

Result and Discussions

Concrete's compressive strength is essential to secure the safety, stability, and durability of structures by determining its load-bearing capacity. It indicates the capability of a material to handle compressive stress before failing or deforming. In case of concrete, compressive strength is determined by applying load to a cubical or cylindrical specimen until it fails. Here, the primary object of the compressive strength test was to evaluate the effect of use Sugarcane Bagasse Ash (SBA) as a replacement of Ordinary Portland Cement (OPC) where four levels of SBA substitution were incorporated into the design of the concrete mixes: 5%, 10%, 15%, and 20%, alongside a control mix without SBA. The results shown in Figure 4 illustrate the compressive strength development at each curing interval (7, 14, and 28 days of curing).

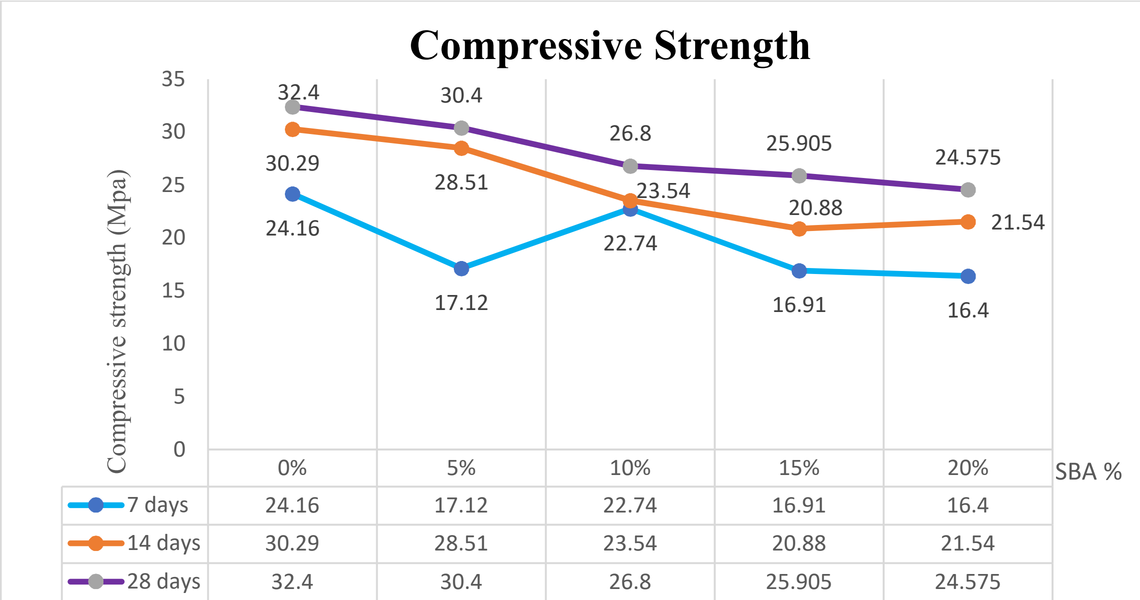
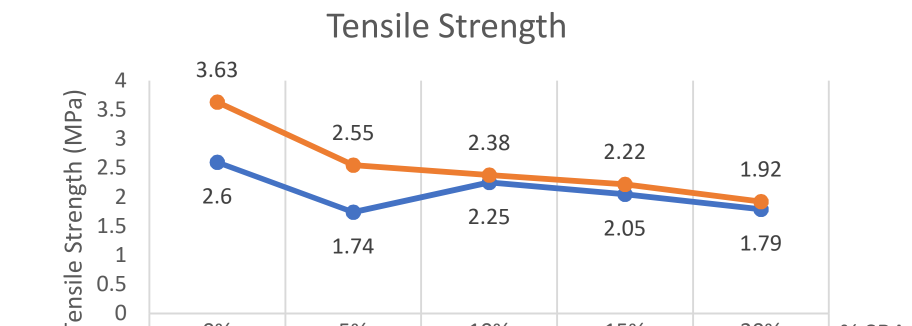


Figure 4: Average Compressive Strength (at 7, 14, 28 days) at different percentage of SBA.

From Figure 4, it is evident that the control mix (0% SBA) exhibited the highest compressive strength across all curing periods. Among the SBA-incorporated mixes, the 10% SBA mix showed the highest strength at 7 days, whereas the 5% SBA mix achieved the maximum strength at 14 and 28 days, indicating a progressive increase in strength with curing age. In contrast, the 15% and 20% SBA mixes showed notable reductions in compressive strength, suggesting a decline in effectiveness at higher replacement levels.

The results suggest that partial replacement of cement with SBA at 5–10% enhances long-term compressive strength, while higher levels (15–20%) reduce performance reflecting the diminishing pozzolanic contribution and potential dilution of cementitious material. These findings suggest that an SBA replacement of 5–10% optimally balances mechanical performance and sustainability benefits in concrete.

Tensile strength is a fundamental mechanical property that represents the maximum stress a material can withstand while being stretched or pulled before failure. It reflects the material's resistance to cracking, elongation, or rupture under tensile loads. Tensile strength is critical for evaluating structural performance, particularly in elements subjected to bending, tension, or flexural stresses. Determining tensile strength of concrete is essential to assess its durability, serviceability, and suitability for construction applications. In this study, the tensile behavior of concrete incorporating different proportions of Sugarcane Bagasse Ash (SBA) as a partial cement replacement was investigated to understand its effect on the mechanical integrity and long-term performance of the material. Mixtures containing 0% (control), 5%, 10%, 15%, and 20% SBA were tested at curing ages of 7 and 28 days. The results are shown in figure 5.



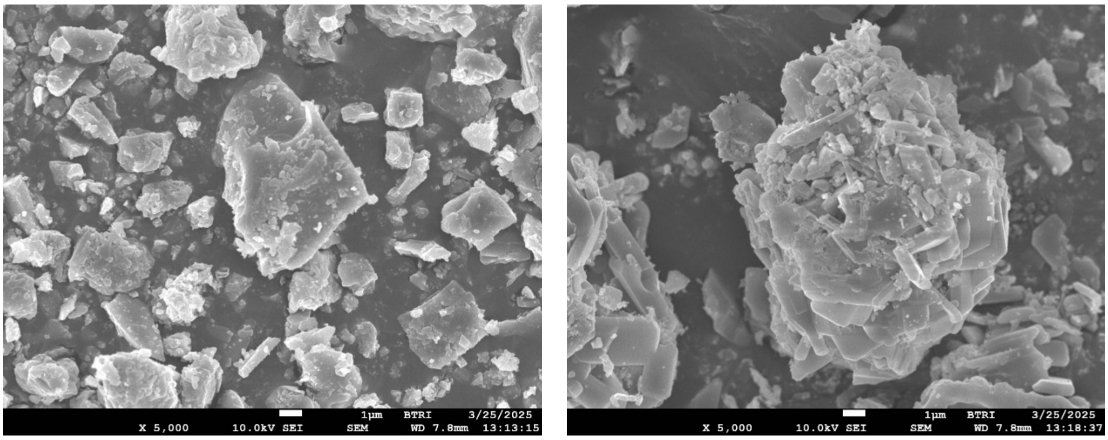
	0%	5%	10%	15%	20%
7 Days	2.6	1.74	2.25	2.05	1.79
28 Days	3.63	2.55	2.38	2.22	1.92

Figure 5: Tensile Strength at 7 days and 28 days

The tensile strength of concrete mixes incorporating varying percentages of SBA is presented in Figure 5. The control mix (0% SBA) exhibited the highest tensile strength at both 7 days (2.6 MPa) and 28 days (3.63 MPa), indicating the baseline performance of ordinary concrete without SBA. For the SBA-incorporated mixes, the 10% SBA replacement achieved higher tensile strength at 7 days (2.25 MPa) compared to the 5% mix (1.74 MPa), while at 28 days, the 5% SBA mix reached 2.55 MPa, slightly higher than the 10% mix (2.38 MPa). This suggests that lower replacement levels of SBA contribute positively to long-term tensile strength, likely due to optimal pozzolanic activity and better cementitious matrix densification.

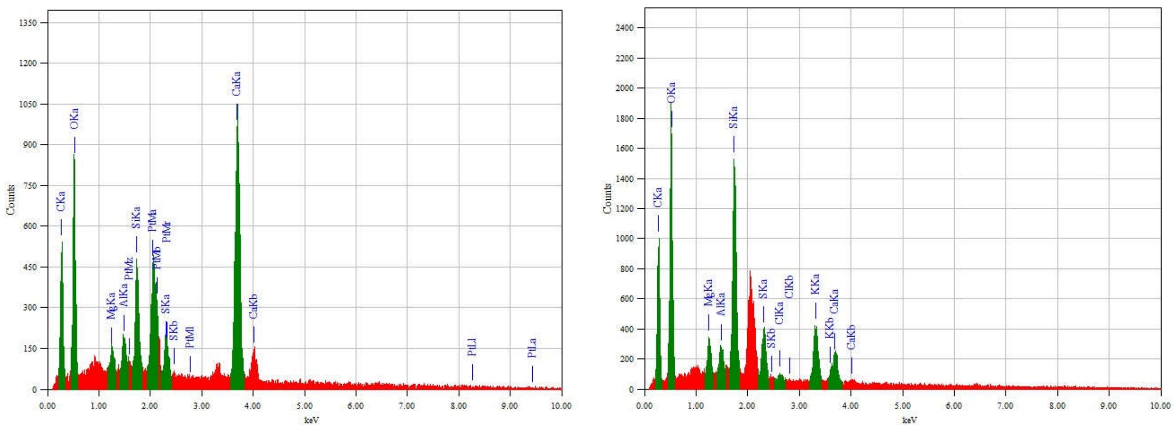
In contrast, higher replacement levels (15% and 20% SBA) led to notable reductions in tensile strength at both ages, with the 20% mix showing the lowest values (1.79 MPa at 7 days and 1.92 MPa at 28 days). This decline can be attributed to dilution of cement content and insufficient pozzolanic contribution at elevated SBA percentages. Overall, these results indicate that a 5–10% SBA replacement provides an optimal balance between sustainability and mechanical performance, enhancing tensile properties without compromising structural integrity.

Based on the provided SEM and EDX analyses, sugarcane bagasse ash (SBA) and cement exhibit distinct differences in both particle morphology and elemental composition. The SEM images reveal that SBA consists of highly porous, irregular, and often spherical particles, while the cement particles are more dense, angular, and crystalline. This morphological distinction is a direct result of their different origins and production processes. Physical properties of cement and SBA shown in figure 6, and chemical composition of cement and SBA shown in figure 7.



(1) (2)

Figure 6: Physical Properties of Cement (1) and SBA (2)



(1) (2)

Figure 7: Chemical Composition of Cement (1) and SBA (2)

The most critical difference lies in their chemical makeup, as shown by the EDS data. Cement is a calcareous material, with a dominant presence of Calcium (Ca) and Oxygen (O). This high calcium content is essential for its function as a hydraulic binder. In contrast, SBA is a siliceous material, characterized by its high concentration of Silicon (Si) and Oxygen (O), which is indicative of its high silicon dioxide (SiO_2) content.

Microstructural analysis of the raw materials revealed significant differences. The scanning electron micrograph of sugarcane bagasse ash (SBA) displays a predominantly porous and highly irregular particle morphology. The associated EDS analysis confirmed that this material is rich in silicon (Si) and oxygen (O), consistent with a high concentration of amorphous SiO_2, which is known to provide pozzolanic reactivity. Conversely, the SEM image of the cement sample shows a microcrystalline structure composed of dense, blocky particles. Elemental analysis confirmed a high concentration of Calcium (Ca), indicating its primary composition of calcium silicates.

The distinct chemical composition and morphology of SBA are fundamental to its function as a supplementary cementitious material (SCM). The primary binding mechanism in cement involves a hydration reaction that produces calcium silicate hydrate (C-S-H) gel, which is responsible for strength, and calcium hydroxide ($Ca(OH)_2$) as a byproduct. The presence of $Ca(OH)_2$ can be detrimental to the long-term durability of concrete, as it is soluble and can create pathways for chemical ingress.

SBA's role as an SCM is defined by the pozzolanic reaction. The amorphous silica in SBA reacts with the calcium hydroxide byproduct of cement hydration, as shown in the following simplified reaction:
SiO_2 (from SBA) + $Ca(OH)_2$ (from cement hydration) → C−S−H gel

This reaction serves two critical functions:

1. It consumes the soluble calcium hydroxide, improving the long-term chemical resistance and durability of the concrete.
2. It produces additional C-S-H gel, which densifies the microstructure, refines the pore structure, and leads to a continued increase in strength over time, particularly at later curing ages.

The porous, high-surface-area morphology observed in the SBA particles further facilitates this reaction by providing numerous sites for the $Ca(OH)_2$ to interact with the amorphous silica. This increases the efficiency of the pozzolanic reaction and contributes to the superior performance of blended cements [27, 28]. Therefore, while cement provides the initial strength, SBA enhances long-term performance by transforming a weak, undesirable byproduct into a strong, microstructural component. This demonstrates that SBA is not merely a filler but an active SCM that improves both the mechanical and durability properties of cementitious systems. The findings of this study demonstrate that partial replacement of Ordinary Portland Cement (OPC) with Sugarcane Bagasse Ash (SBA) in the range of 5–10% offers the most favorable balance between mechanical performance, durability, and sustainability. The enhanced compressive and tensile strengths observed at these substitution levels are attributed to the pozzolanic reactivity of SBA, which promotes additional calcium silicate hydrate (C–S–H) formation while consuming calcium hydroxide, thereby refining the microstructure and improving long-term performance. In contrast, higher replacement levels (15–20%) led to reductions in strength, reflecting the dilution of cementitious phases and diminished pozzolanic efficiency. These trends are in close agreement with previous studies that have similarly reported performance improvements at lower substitution levels and strength penalties at higher replacements [29, 30, 31].

From a broader perspective, the incorporation of SBA as a supplementary cementitious material aligns directly with several United Nations Sustainable Development Goals (SDGs). Specifically, it advances SDG 9

(Industry, Innovation, and Infrastructure) by fostering the development of resource-efficient construction materials, supports SDG 11 (Sustainable Cities and Communities) through the promotion of durable and resilient infrastructure, and contributes to SDG 12 (Responsible Consumption and Production) by valorizing agricultural residues into high-value construction inputs [32, 33, 34]. Moreover, by reducing clinker demand and associated CO_2 emissions, the approach contributes to SDG 13 (Climate Action) [35]. Collectively, these outcomes highlight that the judicious use of SBA at optimal levels not only enhances concrete performance but also offers a viable pathway toward greener, more sustainable construction practices. Cement represents the most costly ingredient in concrete production. Substituting a portion of it with an economical, naturally occurring, and locally sourced material such as sugarcane bagasse ash (SBA) offers dual benefits: it promotes sustainable waste utilization and lowers the overall expense of concrete and housing construction [36, 37, 38]. Numerous studies have examined the incorporation of sugarcane bagasse ash (SBA) in concrete; however, these investigations predominantly employed.

Conclusions

The present study highlights the potential of Sugarcane Bagasse Ash (SBA), an agro-industrial residue, as a sustainable partial replacement for Ordinary Portland Cement (OPC) in concrete. Experimental results reveal that substituting 5–10% of cement with SBA significantly improves both compressive and tensile strengths. This is primarily due to the pozzolanic reaction, where the amorphous silica in the SBA reacts with the calcium hydroxide byproduct of cement hydration to form additional calcium silicate hydrate (C-S-H) gel. This process strengthens the concrete's internal structure and enhances its resistance to deterioration. Especially at extended curing periods, due to the pozzolanic interaction between the amorphous silica in SBA and calcium hydroxide produced during cement hydration.

Higher replacement levels (15-20%) were found to reduce strength, indicating that there is an optimal balance between utilizing the waste material and maintaining the structural integrity of the concrete. Overall, incorporating SBA at optimal levels offers an environmentally friendly approach to reduce cement consumption, lower carbon emissions, and repurpose agricultural waste, contributing to stronger, more durable concrete while supporting sustainable construction practices and climate-conscious infrastructure development. This approach not only provides a beneficial use for agricultural waste but also reduces the environmental impact of cement production, which is a major source of CO_2 emissions. This study highlights unprocessed sugarcane bagasse ash (SBA) as a sustainable and cost-effective partial replacement for cement. Its use not only reduces concrete and housing costs but also promotes efficient waste management, offering a practical pathway toward greener construction practices.

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