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Research Article

Evaluating the use of eggshell powder and sawdust ash as cement replacements in sustainable concrete development

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ABSTRACT

Concrete, the most widely utilized material in construction worldwide, contributes significantly to the consumption of natural resources and energy. The construction sector is a major source of waste and greenhouse gas (GHG) emissions, making it essential to improve the environmental impact of concrete to address climate change and pollution concerns. Evaluating the environmental footprint of concrete is crucial for advancing sustainable building practices. Cement, a key binder in concrete, is particularly responsible for GHG emissions due to its energy-intensive production process. This study applies the Life Cycle Assessment (LCA) methodology, using SimaPro software and the Ecoinvent database, to assess the environmental impact of concrete. A modified concrete mix was developed by replacing Portland Composite Cement with Eggshell Powder (ESP) (60% by weight) and Sawdust Ash (SDA) (40% by weight) at varying replacement rates of 10%, 20%, 30%, and 40%. The results showed up to 20% for replacement cement with ESP and SDA improved compressive strength in a 28-56 day period, with the highest strength growth rate of 29.58% observed for the mixes with replacement. However, higher replacement levels of 30% and 40% showed limited strength improvement during the same period. The enhanced compressive Strength and higher strength growth (compared to traditional concrete) are observed withare0-20 % replacement of cement s. This suggests that this blend of materials could be used in projects with significant budget constraints, directly decreasing carbon emissions associated with concrete production. This aligns with global sustainability goals and can be used in projects aiming for green certifications like LEED (Leadership in Energy and Environmental Design). The study indicates that substituting cement with ESP and SDA reduces costs. This can significantly benefit low-budget housing projects or areas with high cement prices, providing a direct economic advantage. The environmental performance of the modified concrete was analyzed through LCA following the ISO 14040:2006 framework, focusing on the cradle-to-grave impacts, including raw material extraction, energy consumption, and water usage. One cubic meter of concrete was chosen as the functional unit. The analysis revealed significant reductions in the endpoint impact categories, including a 59% reduction in ecosystem impacts, 60% in human health, 61% in resource depletion, 59.79% in ozone depletion, and 54.32% in fossil fuel depletion. These results highlight the potential of ESP and SDA as sustainable alternatives for improving concrete's mechanical properties and environmental performance, supporting the development of more sustainable construction practices.

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1. INTRODUCTION

Concrete is a fundamental material in construction and is recognized as the most widely used composite material for infrastructure projects [1]. Traditionally, it is made from a precisely proportioned blend of cement, sand, and aggregates, all essential for its production. The construction sector relies heavily on these raw materials [2]. Numerous studies [3] have highlighted that cement, a primary component of concrete, emits large quantities of carbon dioxide (CO_2) during production [4]. CO_2 is a significant greenhouse gas (GHG), and the rapid expansion of the construction industry has dramatically exacerbated global warming and climate change [5]. As one of the most significant contributors to GHG emissions, the construction sector negatively affects the atmosphere and the environment [6]. Consequently, concrete production has become a key environmental issue, contributing to several challenges the construction industry faces [7–10]. The rising demand for concrete, driven by rapid urbanization, has led the construction industry to explore alternative waste materials that can replace part of the cement content. This approach seeks to lower cement consumption and reduce construction costs since cement production is responsible for 10% to 30% of global CO_2 emissions [11]. As a result, the concrete industry is becoming more interested in alternative aggregates, which offer benefits like social acceptance, economic savings, and sustainability [12]. Utilizing these materials can reduce environmental carbon footprints and foster sustainable development, minimizing environmental damage [13].

The increasing demand for natural resources driven by rapid urbanization and the challenge of agricultural waste disposal in developed countries has opened up opportunities to utilize agrarian waste in construction applications [14]. Farming by-products typically include includes such as rice husks, Sugarcane bagasse residue, wild reed, wood chips, groundnut husks, coconut husks, shellfish shells, tobacco byproducts, palm ash, and similar by-products [15]. Studies have highlighted the significance of Farming by-products substituting 10-30% of cement with Farming by-products can produce durable, high-performance concrete [16]. Even with these replacements, cement incorporating farming by-product ash has demonstrated remarkable resistance in mortar and concrete, even when exposed to hydrochloric acid solutions [17]. Recently, driven by socio-economic development and scientific progress, agro-waste was agreed upon due to its viability and cost-effectiveness. Agro-wastes, rich in fibers, provide a favorable balance of stiffness and toughness, along with high efficiency in thermal insulation, tensile Strength, and unique biomass ash characteristics [18]. While agro-waste is often considered a by-product of agriculture, it presents significant potential as an additive in construction, helping reduce energy demand throughout the construction and operational phases. Additionally, agro-cement offers strong thermal insulation, effectively addressing agricultural waste disposal and urban construction's thermal challenges [19].

This study uses eggshell powder and sawdust ash as alternative materials to replace traditional cement components. Typically considered waste, these materials are readily available, with sawdust originating as a by-product of wood carving industries and eggshells as the discarded outer shell of eggs after consumption. Assessing these waste materials based on their performance, quality, cost, and societal and ecological effects is essential. To accomplish this, Life Cycle Assessment (LCA), a widely recognized methodology, is an effective tool for evaluating the environmental performance of a product or process across its entire life cycle [20–22]. LCA helps optimize the use of materials and energy while quantifying the total environmental impacts [23, 24]. It is regarded as an ideal method for evaluating the environmental footprint of construction materials [25–31]. This study presents a novel approach by investigating the feasibility of combining two waste materials in concrete mixtures, followed by an impact assessment using SimaPro software to evaluate the environmental implications of four concrete mixtures where cement is replaced by a blend of eggshell powder and sawdust ash at varying proportions. Unlike previous studies that have focused on using eggshell powder (ESP) or sawdust ash (SDA) individually as supplementary cementitious materials, this research examines the combined use of 60% ESP and 40% SDA in various proportions (10%, 20%, 30%, and 40%) as replacements for traditional cement in concrete along with the introduction of a thorough Life Cycle Assessment (LCA) using SimaPro software to evaluate the environmental impacts, an approach that has been scarce in studies involving these two materials together. The study further delves into the strength growth of concrete at multiple curing intervals (7, 28, and 56 days), providing valuable insights into the long-term performance of concrete made with these alternative materials. Overall, this research offers fresh data on the dual use of ESP and SDA, their strength development, and their environmental advantages, with a strong emphasis on their potential for sustainable concrete applications. The findings are analyzed, and conclusions and recommendations are provided to inform future research in alignment with ISO 14040:2006 guidelines.

2. LITERATURE REVIEW

Eggshell powder (ESP), an agricultural and domestic waste primarily composed of limestone, is known for accelerating setting times and improving the characteristics of concrete and mortar in their plastic and solidified forms. The combination of SDA and ESP has the potential to form a unique cement mixture with improved properties. However, studies investigating ternary cement blends incorporating SDA and ESP to enhance cement quality are limited. According to [32], increased SDA content leads to prolonged setting times, influencing the material's properties. This delay in setting time can be advantageous for preserving workability, particularly under high-temperature conditions.

On the other hand, incorporating eggshell powder (ESP) has been shown to enhance the fineness of cement by increasing its surface area, which helps accelerate the setting process. When both SDA and ESP are used together, they have opposite effects on the setting time, with SDA tending to extend it, while ESP reduces the setting time as their replacement levels rise. Various industrial, agricultural, and domestic waste by-products—such as fly ash, bottom ash, rice husk ash, SDA, ESP, and metakaolin—have been explored as supplementary cementitious materials (SCMs), showing varying effectiveness. Research suggests that cement blends containing ESP often achieve strength levels equal to or surpass those of ordinary Portland cement [33–37]. Additionally, incorporating SDA into ESP-based cement blends as an SCM can enhance concrete properties, as SDA's high amorphous silica content makes it a highly reactive pozzolanic material [38].

Eggshell powder has been employed as a partial replacement for cement in varying amounts of 5%, 10%, 15%, and 20%. The impact of these replacements has been evaluated by testing the concrete's mechanical properties, including compressive Strength, flexural Strength, and tensile Strength. Eggshells exhibit good water absorption and concrete permeability, with 15% replacement yielding optimal results [39]. Concrete incorporating up to 15% eggshell as a binder replacement showed improved Strength at 10% replacement compared to control concrete. When combined with fly ash, Strength significantly surpasses conventional concrete [40]. Eggshell powder replacements of 6%, 12%, 18%, and 24% were tested, showing comparable workability, permeability, and Strength to control concrete at the highest replacement rate [41].

Sawdust was used as a partial substitute for fine aggregate, with replacement levels reaching up to 50%. However, the results showed a decline in concrete performance when the sawdust content exceeded 10%, compared to conventional concrete [42]. On the other hand, a mixture of sawdust and rice husk as partial replacements for cement up to 45% led to improvements in both the strength and durability of traditional concrete [43, 44].

When adding an agent to concrete, eggshell enhances its strength beyond conventional concrete, with up to 20% replacement yielding optimal results. The fine texture of sawdust aids in filling voids, improving both permeability and compaction properties. As a result, these materials are efficiently utilized as substitutes in concrete manufacturing [45].

Cement is a widely used binding material in concrete [46], but its production requires substantial natural resources such as shale, clay, gypsum, water, and fossil fuels [47]. Cement manufacturing also generates significant greenhouse gas emissions, contributing to climate change. Research has shown that producing one ton of cement releases an amount of CO_2 equivalent to the cement's weight, causing no environmental harm [48]. This process is highly resource-intensive and results in considerable pollution [49]. In response to these issues, researchers worldwide are exploring industrial and waste by-products as more sustainable alternatives for cement-based materials [50–52].

Given the environmental concerns related to cement-based materials in concrete, this study investigates the potential of using eggshell powder and sawdust ash as alternatives. The ecological impact of these materials was assessed using SimaPro 9.6 software and the Ecoinvent 3 database to develop a Life Cycle Assessment (LCA) model, comparing the effects of these alternatives on concrete production. To fully understand the environmental implications of concrete, it is essential to consider its entire life cycle—from production to disposal—and to evaluate the broader environmental impact beyond the project's immediate boundaries [53]. This life cycle encompasses all stages, from raw material extraction to the final disposal of waste [54]. Achieving environmental sustainability is crucial from a conservation standpoint, and by partially replacing cement with alternative materials, it is possible to reduce environmental impacts while maintaining concrete's functional performance [55].

Research on using waste materials as partial replacements for cement, fine aggregates, coarse aggregates, and conducting life cycle assessments (LCA) remains limited. Fly ash (FA) and copper tailings (CT), both by-products of industrial activities, have been explored as substitutes for cement in concrete mixes. An LCA conducted by ISO 14040:2006 standards revealed notable reductions in several environmental impact categories. These include climate change (up to 38%), human toxicity (up to 32.6%), ozone depletion (up to 33.6%), agricultural land use (up to 31.9%), water consumption (up to 34.3%), fossil fuel depletion (up to 34.8%), particulate matter (up to 35.4%), and metal depletion (up to 25.2%) [56]. Additionally, Gursel and Ostertag [57] found that the environmental impact of aggregates decreases as the substitution of natural sand with copper slag increases. For instance, substituting sand with 40% and 100% copper slag led to reductions in embodied energy (8% and 40%), global warming potential (12% and 30%), acidification (8% and 41%), and particulate matter formation (7% and 35%), respectively. Colangelo et al. [58] proposed using "green" recycled aggregates to minimize concrete's environmental and energy impacts. SimaPro© analysis of these aggregates revealed a lower environmental footprint than traditional concrete. Manjunatha et al. [50] prepared concrete using three types of binders: Ordinary Portland Cement (OPC), Ground Granulated Blast Furnace Slag (GGBS), and Portland Pozzolana Cement (PPC) are commonly used in concrete production. An LCA model developed using SimaPro 9.1 and the Ecoinvent database revealed that PPC and GGBS have a greater environmental impact than OPC. Manjunatha et al. [59] examine the fresh, mechanical, and microstructural properties of M40 grade concrete in which polyvinyl chloride (PVC) waste powder (PWP) partially replaces cement, with 8% silica fume kept constant. Concrete samples were tested with varying PWP percentages from 0% to 30%. The findings suggest that up to 15% PWP can be incorporated without negatively affecting the fresh and mechanical properties, such as compressive, split-tensile, and flexural Strength at 7, 14, 28, and 90 days of curing. The microstructural analysis also reveals enhanced calcium-silicate-hydrate gel formation at 15% PWP, in contrast to the mix with 20% PWP. This research presents a viable approach to addressing the increasing demand for cement and the growing issue of plastic waste. Manjunatha et al. [60] evaluate the environmental impact and energy consumption of concrete incorporating industrial waste materials, specifically polyvinyl chloride (PVC) waste powder (PWP) and ground granulated blast furnace slag (GGBS), compared to conventional concrete. Focusing on both experimental and environmental aspects, the research applies the Life Cycle Assessment (LCA) approach, using a constant 30% GGBS and varying PWP content (0%-30%) as cement replacements. LCA models, created with SimaPro software and the Ecoinvent database, demonstrate that using 15-20% PWP in combination with GGBS enhances structural performance while significantly reducing environmental impacts. This study offers important insights into the feasibility of sustainable concrete alternatives. Tangadagi et al. [61] investigate the influence of mineral admixtures, alccofine and GGBS, on the Strength and durability of self-compacting concrete (SCC) to reduce cement consumption. Nine M60, M80, and M100 grade SCC mixes were evaluated for their fresh properties, mechanical strengths, and durability characteristics, including creep and shrinkage. The findings demonstrate that incorporating GGBS and alccofine improves fresh and hardened properties, lowers cement consumption, and reduces construction costs. Additionally, this research fills existing gaps in the literature, particularly concerning the behavior of high-grade SCC concerning creep and shrinkage. Manjunatha et al. [62] examine the effects of engineered fibers, polyvinyl chloride (PVC) waste powder, and ground granulated blast furnace slag (GGBS) on the fresh and mechanical properties of M50-grade concrete. Fourteen concrete mixes, including those with and without fibers, were prepared with varying PVC waste powder content (0%–30%) and 0.6% SNF superplasticizer. The findings indicate that incorporating up to 20% PVC waste powder along with 30% GGBS and engineered fibers enhances the strength properties and reduces cement consumption, providing a sustainable and cost-effective alternative for concrete production. Pradhan et al. [63] examined the environmental effects of using recycled coarse aggregate (RCA) and the Particle Packing Method (PPM) for mix design, comparing them with concrete made from natural coarse aggregate (NCA) according to the IS code method. Teixeira et al. [64] explored the environmental advantages of incorporating various percentages of two types of fly ash as partial substitutes for cement in concrete mixes. These ashes, by-products from coal or biomass-fueled power plants, were found to reduce environmental impact and improve environmental performance as their replacement levels increased in concrete production.

Manjunatha et al. [65] investigate the incorporation of industrial polyvinyl chloride (PVC) waste powder (PWP) as a partial replacement for cement in M60 grade self-compacting concrete (SCC). Several mixes with PWP content ranging from 0% to 30% were evaluated for their fresh properties, mechanical Strength, microstructural characteristics, and environmental impacts using life cycle assessment. The findings indicate that replacing 5–10% of cement with PWP improves environmental sustainability and lowers costs while maintaining the concrete's Strength and durability.

These fly ashes are by-products from coal or biomass-fueled power and heat production sectors. The findings indicated that both types of ash contribute to reduced environmental impact and enhanced environmental performance as cement replacement levels increase in concrete production. Dharek et al. [66] investigate the engineering properties and life cycle assessment (LCA) of hybrid fiber reinforced concrete (HFRC) incorporating equal proportions of glass and polypropylene fibers (ranging from 0% to 2%). The findings indicate that a 1% fiber content significantly improves Strength, durability, and impact resistance, although workability decreases. LCA results demonstrate that HFRC provides environmental and economic advantages over conventional concrete, highlighting its viability for sustainable construction applications. Maddikeari et al. [67] explore the potential of using wastewater as a substitute for potable water in concrete production, focusing on its effects on concrete properties such as Strength, durability, and microstructure. It outlines the advantages of wastewater recycling, including resource conservation, cost reduction, and increased sustainability. The paper also highlights the challenges and the necessity for developing effective methods to incorporate treated wastewater into concrete production, particularly emphasizing the superior performance of reclaimed and tertiary-treated wastewater compared to secondary-treated wastewater.

While existing studies have investigated the environmental benefits of using various waste materials—such as fly ash, copper tailings, recycled aggregates, and copper slag—as partial substitutes for cement and aggregates in concrete, there has been limited research specifically focusing on the strength development, including properties like slump, compressive Strength, and tensile Strength, when cement is replaced with eggshell powder and sawdust ash in varying proportions. Furthermore, there is a lack of detailed life cycle analysis (LCA) conducted using SimaPro software to assess the environmental impact of substituting these materials for cement. This gap highlights the need for further research into using eggshell powder and sawdust ash as viable, sustainable alternatives in concrete production to enhance environmental sustainability in the construction sector.

3. METHODOLOGY

3.1. Materials

➢ Egg-shell powder

Bangladesh ranks 18th globally in annual egg production, resulting in substantial eggshell waste yearly. Disposing these eggshells presents a significant challenge, as landfill disposal attracts pests and poses health and environmental risks [35]. Eggshells are commonly collected from poultry farms, chick hatcheries, bakeries, and restaurants. Structurally, eggshells

Figure 1. Crushed Eggshell.

Figure 2. Sawdust ash.

Table 1. Mix proportions of materials

Specimen	Proportion of substituted components (%)	Water (Liter)	Cement (kg)	Fine Aggregate (FA) (kg)	Coarse Aggregate (CA) (kg)
Cylinder	0	6.8	14	25.6	28
	10	6.8	12.6	25.6	28
	20	6.8	11.2	25.6	28
	30	6.8	9.8	25.6	28
	40	6.8	8.4	25.6	28

consist of multiple layers of $CaCO_3$, with the innermost layer attached to the egg membrane. The structure of an eggshell includes a foundational layer that supports a thick palisade layer, which is the most substantial part of the shell. The outermost layer, which is oriented vertically, is coated with an organic cuticle [68]. As noted by Okonkwo, eggshells are primarily composed of approximately 93.7% calcium carbonate, 4.2% organic substances, 1.3% magnesium carbonate, and 0.8% calcium phosphate [69]. This calcium-rich waste closely resembles limestone in chemical composition, making eggshells a viable alternative to natural lime for cement replacement in concrete, offering benefits such as reduced cement consumption, conservation, and waste utilization [35]. When calcium carbonate is incinerated at 500°C, it produces calcium oxide, which enhances setting time—an asset in construction, especially under unpredictable weather conditions like those in the rainy season (Fig. 1) [70].

- Saw dust Ash

Sawdust, a by-product of wood processing such as cutting, grinding, drilling, and sanding, consists of fine wood particles. It can adversely affect the setting and hardening of cement due to its tannin and soluble carbohydrate content. Sawdust, commonly used as a household fuel, produces ash known as sawdust ash (SDA), which is classified as a pozzolanic material. When sawdust is burned, the resulting ash can be used in concrete. Dry sawdust-based concrete has a density of only about 30% of conventional concrete and offers insulation comparable to wood. With the correct cement-to-wood ratio, it is also non-flammable (Fig. 2).

- Cement- PCC (Type 2/ CEM II), Grade 42.5N
- Sand- Sylhet Sand, Durgapur (FM > 2.50)
- Crushed stone- Gabbro, UAE

Material and apparatus used for testing can be seen on Figure 3 and Figure 4.

3.1.1. Mix Proportion

- Grade of Concrete: M 40

On the Table 1, mix proportion is given for 90 cylinders. Of these, 45 cylinders are subjected to a compression test and a split tensile strength test at 45. The cement, fine aggregate, and coarse aggregate were mixed in a ratio of 1:1.83:2 for the 0% cement replacement. The mix design fixed the ratio using the ACI Concrete Mix Design Method.

3.1.2. Physical Characteristics of the Material

Physical characteristics of the material can be seen on Table 2 and Table 3.

3.1.3. Chemical Composition of Material

A comprehensive analysis of the chemical compounds in cement, eggshell powder, and saw dust ash is provided below on Table 4.

3.2. Experimental Work

In the experimental setup, 90 specimens were created, consisting of 45 cubes for testing compressive Strength and 45 cylinders for evaluating tensile Strength. The compressive and tensile strengths were calculated by averaging the results from three cubes for each curing duration. A com-

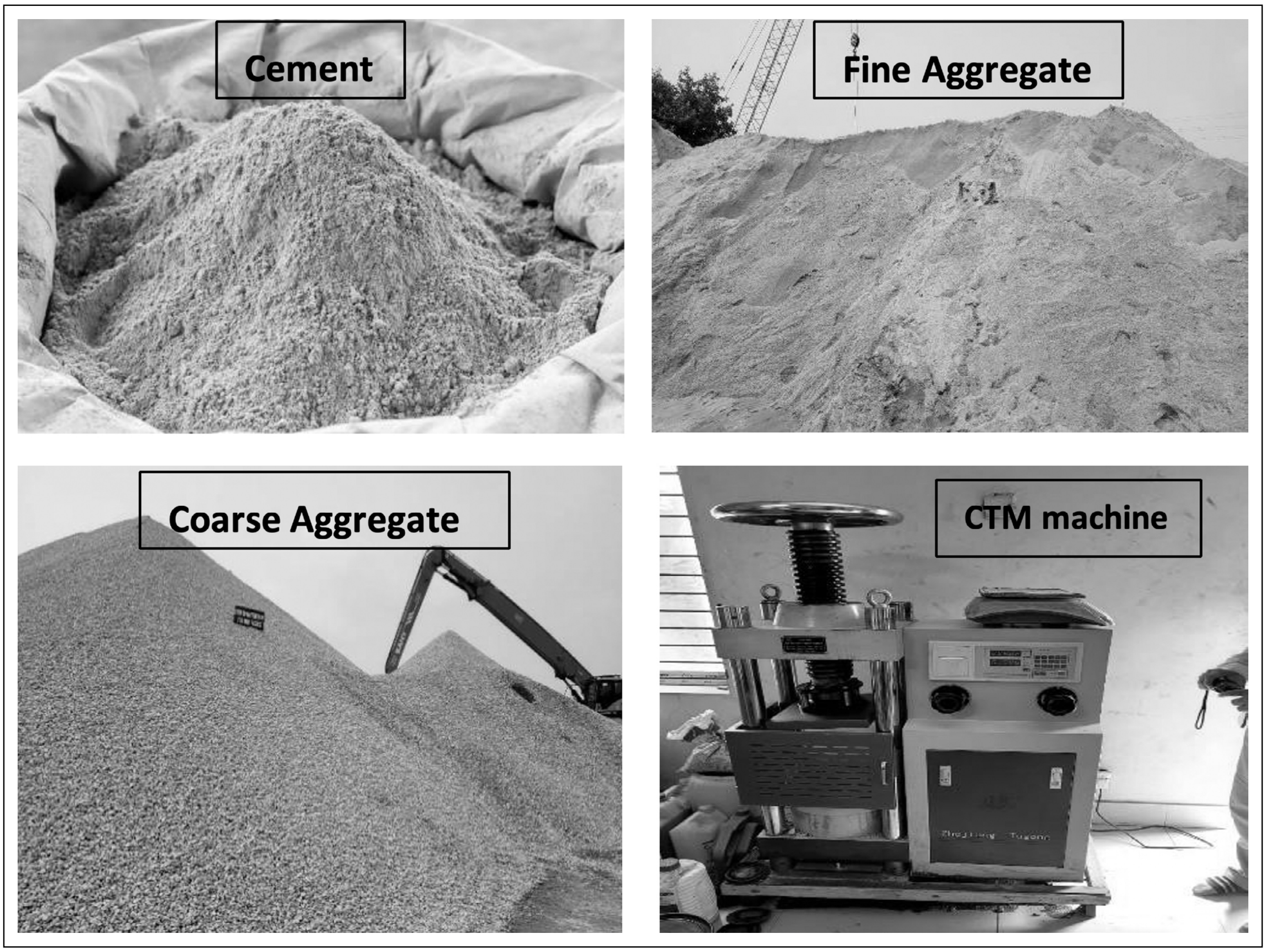

Figure 3. Material and apparatus used for testing.

prehensive list of the specimens and their corresponding proportions is provided below (Table 5):

Due to the higher availability of eggshell powder (ESP) as a waste material compared to sawdust ash (SDA), the percentage of ESP used as a substitute for cement is higher than that of SDA in the concrete mixes (Table 6).

3.2.1. Concrete Compressive Strength with Partial Cement Substitution

A laboratory test was performed following ASTM C39/C39M standards to assess the compressive Strength of the cylindrical samples, depicted in Figure 5, which was measured on specimens with a diameter of 150 mm and a height of 300 mm. All specimens were tested in a saturated surface-dry state, with moisture carefully removed. Three identical specimens for each variation in percentage and the control group were tested under the same loading rate. The compressive Strength was assessed at 7, 14, and 28-day intervals.

3.2.2. Split Tensile Strength Test

The test was performed on concrete to evaluate its tensile strength characteristics. A cylindrical sample was placed horizontally and exposed to a steadily increasing tensile load, as depicted in Figure 6. The specimen was positioned horizontally under the CTM machine, which applied the load until splitting or cracking occurred, as shown in the figure. Cylindrical samples measuring 150 mm in diameter and 300 mm in height were fabricated for this analysis.

3.2.3. Slump Test

The slump test is performed to evaluate the workability of the concrete mix, measuring how readily the concrete flows under its weight by assessing its resistance to deformation. The procedure follows the guidelines specified in ASTM standard C143/C143M. The slump values for various specimens are provided in Table 7.

3.3. Environmental Impact Evaluation of Cement and Cement-Substituted Concrete Mixes Using Life Cycle Assessment (LCA)

There is no universally accepted "golden standard" for environmental assessment, as each methodology has strengths and limitations [71]. The ISO 14040 standard offers a structured Life Cycle Assessment (LCA) approach through four phases. The process begins with the goal definition phase, which establishes the scope and objectives of the study. In the second phase, known as the life cycle inventory (LCI) analysis, the raw materials required for the system are identified. The third phase, the impact assessment, focuses on evaluating the potential environmental effects. The final phase, interpretation, involves analyzing and drawing conclusions from the data collected in the pre-

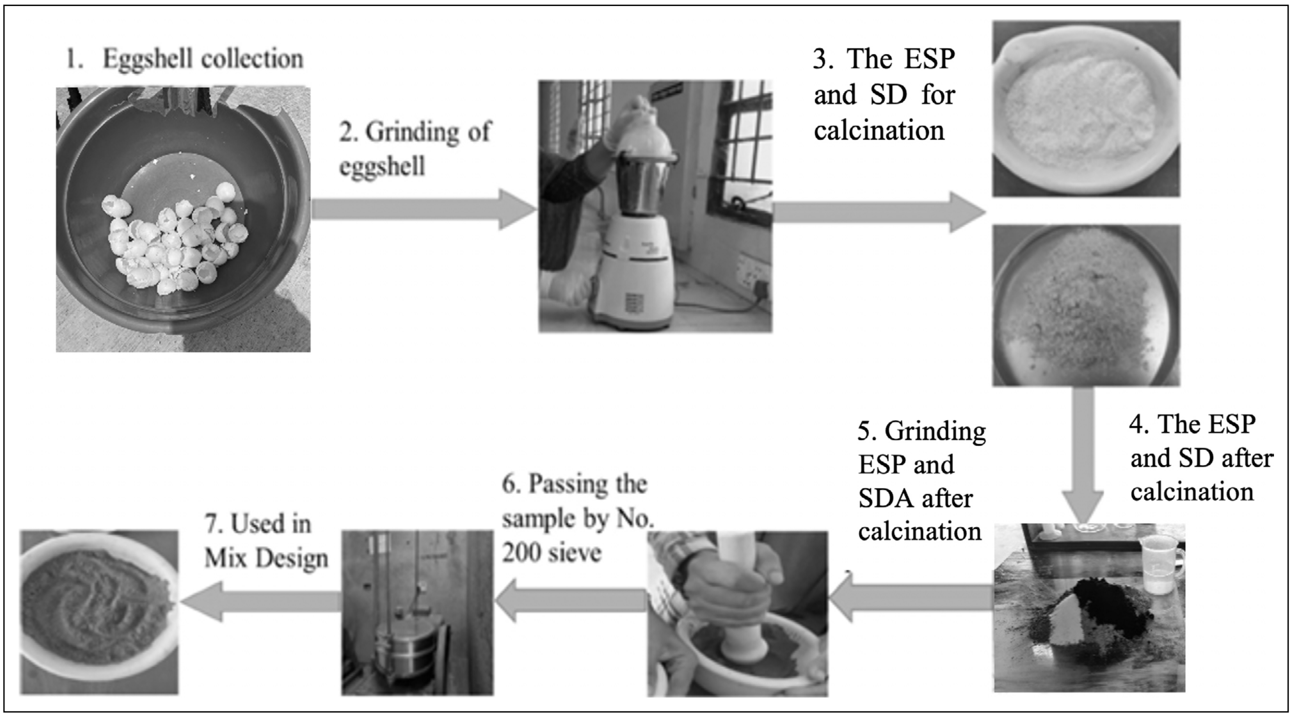

Figure 4. Processing of ESP and SDA.

Table 2. Physical characteristics of the material

Property	Egg-shell powder	Saw dust ash	Fine aggregate (FA)	Coarse aggregate
Sp. Gravity	2.21	2.58	2.44	2.49
FM	4.34	1.88	3.0	7.55
Moisture Content	–	–	2.3%	1.4%
Water Absorption (%)			2.85	1.1
Unit Weight (kg/m^3)	1068	1224	1660.4	1473.87
Dry Rodded Unit Weight	–	–	–	0.84

Table 3. Cement's Physical Properties

Sl No.	Property	Cement
1.	Standard consistency (ASTM C187-11)	25%
2.	Initial Setting Time (ASTM C595-19)	148 mins.
3.	Final Setting Time (ASTM C595-19)	280 mins.
4.	Compressive Strength at 28 days (ASTM 109-11b)	45.1 MPa

Table 4. Chemical composition of cement (%)

Element	Cement	Egg shell powder	Saw dust ash
SiO_2	21.85	87.60	65.1
Al_2O_3	6.87	0.21	3.8
Fe_2O_3	3.58	0.23	2.22
CaO	64.83	0.36	9.4
Na_2O	0.21	0.27	0.05
K_2O	0.64	1.06	0.10
SO_3	2.67	2.84	0.42
LOI (Loss of Ignition)	4.2	–	–

vious stages [72, 73]. The LCA framework applied in this study is depicted in Figure 6. The methodology followed for this analysis, using SimaPro 9.6 software and the Ecoinvent 3 database, is presented in Figure 7 and Figure 8, following Bangladeshi standards.

3.3.1. Defining Goal and Scope

Five distinct concrete mixtures incorporating eggshell powder and sawdust ash were analyzed in this study. It is noteworthy to mention here that this research primarily examines the effects of cement and the subsequent changes observed when it is partially replaced with eggshell powder and sawdust ash. The mix compositions used in the study were as follows (Table 8):

Mix 1: Concrete cylinder with no cement replacement.
Mix 2: Concrete cylinder with 10% of the cement replaced.
Mix 3: Concrete cylinder with 20% of the cement replaced.
Mix 4: Concrete cylinder with 30% of the cement replaced.
Mix 5: Concrete cylinder with 40% of the cement replaced.

Figure 5. Applying the load to the cylinder specimen to measure its load-bearing capacity.

Figure 6. Application of load to the cylindrical specimen to evaluate the split tensile strength and the specimen's failure behavior.

3.3.2. Functional Unit

In this research, the functional unit was defined as one cubic meter (m^3) of concrete, with a density of approximately 2400 kg/m^3, to simplify data analysis and enhance practical applicability. This approach aligns with the recommendation of Marinković et al. [74], as 1 m^3 of concrete provides a more accurate and meaningful reference than 1 kg. The study offers a comprehensive evaluation of the environmental impacts associated with cement production, use, and disposal, using 1 m^3 of concrete as the baseline for analysis.

3.3.3. System Boundaries

This research focuses on the production phase of concrete, intentionally excluding the treatment and disposal stages. Several studies [75–77] support this decision, highlighting that the production phase generally contributes the most to environmental impacts. The study encompasses the processing of raw materials, transportation, and concrete production, including the energy required for these processes. The exact transportation distances were applied to ensure consistency in impact comparisons across different mixtures: 70 km from the concrete mixing plant to the production site and 20 km from the production site to the delivery location. The system boundaries are shown in Figure 9.

Table 5. Proportion of cement and composite waste

Specimen	Cement (%)	ESP (%)	SDA (%)
SDA 0+ ESP 0	100	0	0
ESP 6+ SDA 4	90	6	4
ESP 12+ SDA 8	80	12	8
ESP 18+ SDA 12	70	18	12
ESP 24+ SDA 16	60	24	16

ESP: Egg shell powder; SDA: Saw dust ash.

Table 6. Fixed parameters

Type of cement	Portland Composite Cement (PCC)
Water cement ratio	0.42
Cement Fine & Coarse aggregate	1: 1.84:2.02
Sample type (cylinder)	4-inch x 8-inch
Curing days	7, 14 and 28 days

Table 7. Proportion of cement and composite waste

Replacement of Cement	Slump Value (Split Tensile)	Slump Value (Compressive Strength)
0%	2.5 inch (62.5 mm)	1 inch (25 mm)
10%	1.6 inch (40 mm)	2.5 inch (62.5 mm)
20%	1.8 inch (45 mm)	1.8 inch (45 mm)
30%	2 i nch (50 mm)	2.5 inch (62.5 mm)
40%	1.8 inch (45 mm)	2.8 inch (70.5 mm)

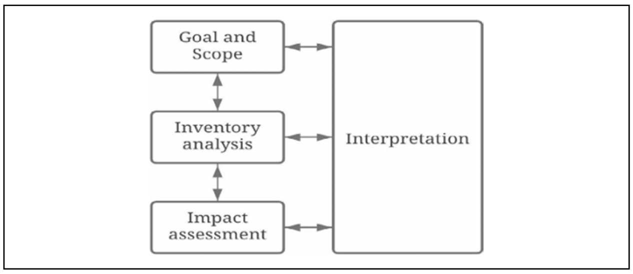

Figure 7. Comprehensive Structure of Life Cycle Assessment (LCA).

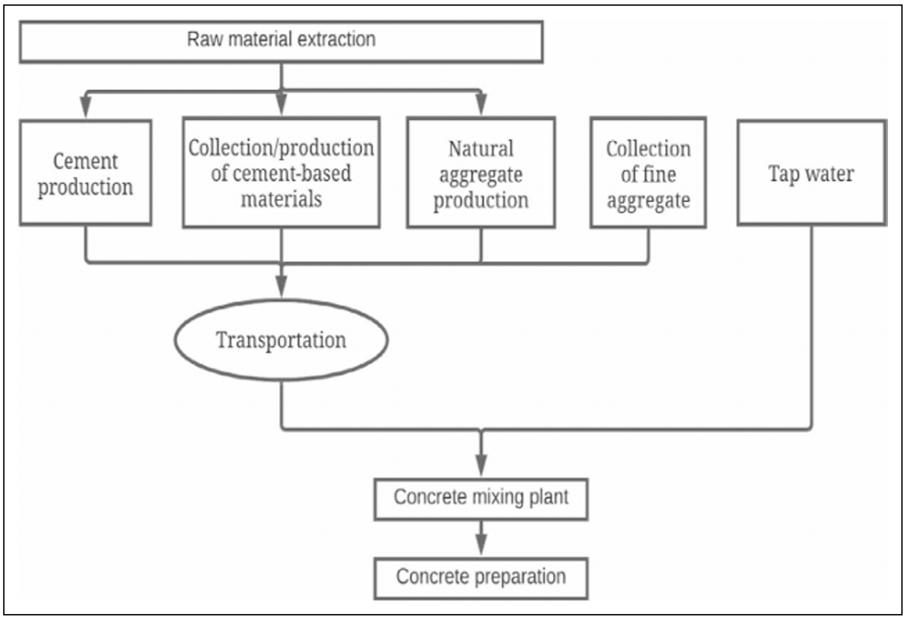

Figure 8. Simulation process for concrete preparation in SimaPro.

Table 8. Concrete mix design

Replacement (%)	Water (L/m³)	Cement (kg/m³)	Fine Aggregate (FA) (kg/m³)	Coarse Aggregate (CA) (kg/m³)	ESP (kg/m³)	SDA (kg/m³)
0%	6.8	14	25.6	28	0	0
10%	6.8	12.6	25.6	28	0.84	0.56
20%	6.8	11.2	25.6	28	1.68	1.12
30%	6.8	9.8	25.6	28	2.52	1.68
40%	6.8	8.4	25.6	28	3.36	2.24

3.3.4. Method of Evaluation

The impact assessment process evaluated the potential environmental effects through a four-step procedure. The initial step, classification, entailed organizing the various impact types for each item in the inventory. In the subsequent step, characterization, each item was linked to its relevant environmental impact category. The following phase, normalization, evaluated the scope of ecological effects locally and globally. In the final step, weighting, the significance of each impact category was assessed and prioritized based on its relative importance.

For the assessment, the Eco-indicator 99 method, which is incorporated into the SimaPro software, was utilized to analyze environmental impacts throughout the entire life cycle of products or systems. This approach streamlines the comparison and decision-making process by consolidating various impacts into a single score. The Eco-indicator 99 uses a damage-oriented endpoint methodology, focusing on three main impact categories:

1. Human health is measured in disability-adjusted life years (DALY).
2. Resource Depletion focuses on the reduction of natural resources.
3. Ecosystem Quality measures damage to ecosystems and biodiversity loss (Eco-indicator 99 Manual for designers).

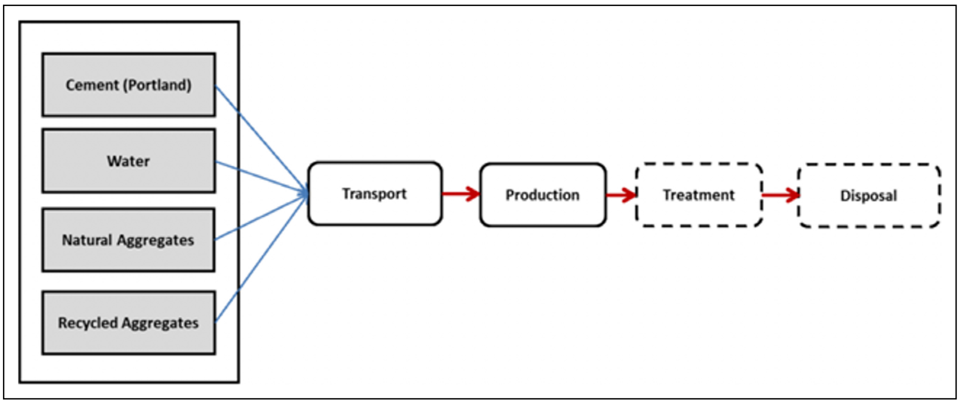

Figure 9. System boundary.

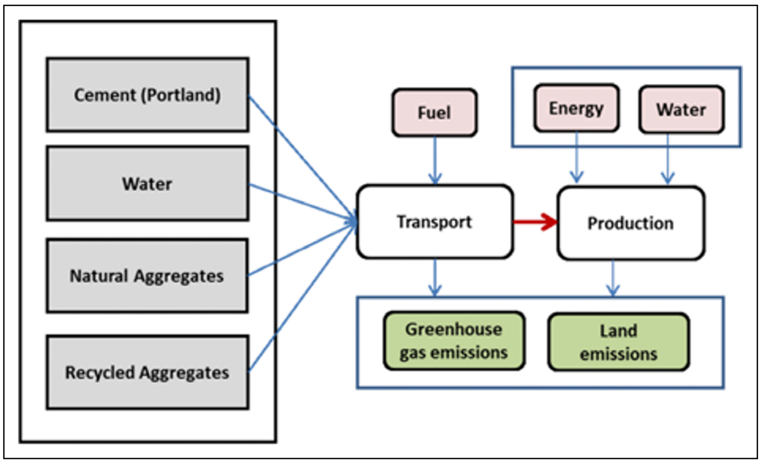

Figure 10. Process of producing mixed concrete.

The impact estimates from these categories were consolidated into a single value known as the Eco-indicator, which is represented in Points (Pt) or Milli Points (MPt). One Point (Pt) corresponds to 1/1000 of a year of life lost for a healthy European citizen. Additionally, this study employed the ReCiPe 2016 endpoint method in SimaPro for the Life Cycle Assessment (LCA). This method was selected for its capacity to generate a single score that facilitates the comparison of various concrete mixes. The ReCiPe framework includes both midpoint and endpoint levels of impact. Midpoint impacts, which rely on robust empirical data, cover categories such as climate change, human toxicity, ozone depletion, acidification, and abiotic resource depletion. In contrast, endpoint impacts address broader environmental harm related to material production [50]. This research evaluated endpoint impacts to assess the effects of conventional concrete (100% cement) and concrete with partial cement replacements at 10%, 20%, 30%, and 40%.

The mixes evaluated were:
- Mix-1: Conventional mix (100% cement)
- Mix-2: 6% ESP and 4% SDA
- Mix-3: 12% ESP and 8% SDA
- Mix-4: 18% ESP and 12% SDA
- Mix-5: 24% ESP and 16% SDA

The environmental impacts of all five mixes were compared comprehensively using the ReCiPe 2016 Endpoint (H) method.

3.3.5. Analysis of Inventory

For a valid comparison of different methodologies, it is crucial to have precise, controlled data on emissions and resource extraction during the production of commodities. The ecoinvent database v3 was employed to meet this requirement, along with updated inventory data from the European Plastics Industry [78–81]. The ecoinvent database offers a dependable framework that ensures consistent system boundaries and coherent background processes for all materials and commodities, including transportation, electricity, heat, and infrastructure. Furthermore, it offers a thorough range of environmental impact data [78]. In this stage of the Life Cycle Assessment (LCA), all inputs and outputs from each life cycle phase were considered. The LCA model was developed using the ecoinvent v3 database, and the life cycle inventory (LCI) data for each process is shown in Figure 10.

4. RESULT AND DISCUSSION

4.1. Concrete Compressive Strength with Partial Cement Substitution

Forty-five concrete cylinders were cast to evaluate compressive Strength at 7,28, and 56 days. Nine cylinders were made with standard concrete, while 36 cylinders were created with different proportions of cement replaced by

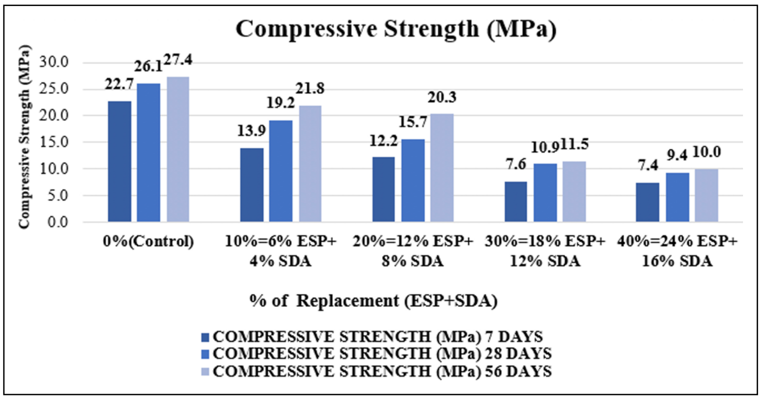

Figure 11. Concrete cylinder strength at 7, 28, and 56 days of curing.

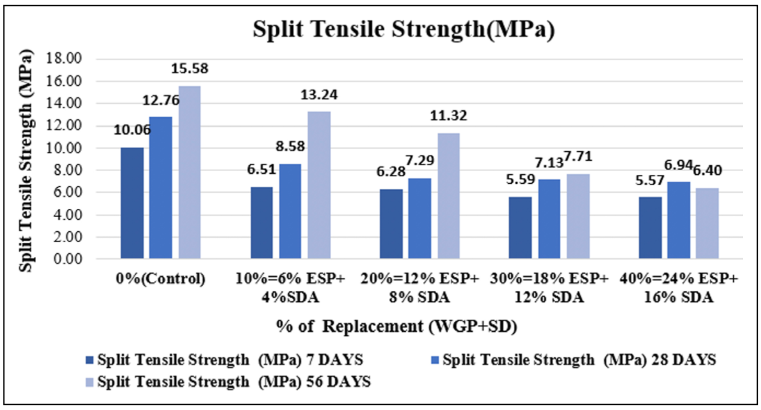

Figure 12. Split tensile strength of concrete cylinders at 7, 28, and 56 days.

Table 9. Data table of growth rate from 7 to 28 and 28 to 56 days

Cement Replacement (%)	7-Day Strength (psi)	28-Day Strength (psi)	56-Day Strength (psi)	Growth Rate (7 to 28 Days) (%)	Growth Rate (28 to 56 Days) (%)
0% (Control)	3295	3783	3966	14.80	4.83
ESP 6% +SDA 4%	2012	2780	3164	38.15	13.81
ESP 12% +SDA 8%	1764	2275	2948	28.94	**29.58**
ESP 18% + SDA 12%	1101	1582	1661	**43.60**	5.00
ESP 24% + SDA 16%	1071	1358	1455	26.80	7.15

eggshell powder (ESP) and sawdust ash (SDA). For each replacement level, three cylinders were tested to obtain average compressive Strength. In Figure 11, the results show that the control sample (0% replacement) achieved the highest strength values across all curing periods, reaching 27.4 MPa at 56 days. As the replacement percentage increased, compressive Strength progressively decreased; for example, 10% replacement (6% ESP + 4% SDA) achieved 21.8 MPa at 56 days, while 40% replacement (24% ESP + 16% SDA) dropped to 10.0 MPa. It was observed that higher replacement levels, especially those exceeding 20%, led to a decrease in long-term Strength. This is because, in Table 4, it is observed that cement contains 64.83% calcium oxide (CaO), whereas ESP and SDA contain only 0.36% and 9.46% CaO, respectively. CaO, commonly known as lime, is crucial in cement production. When hydrated, CaO reacts with water to form calcium hydroxide, a key component in the setting process of cement. This reaction contributes to the binding and solidification of the mixture, forming a gel-like substance that imparts the structural integrity and Strength of hardened concrete. As the proportion of composite waste increases, the amount of CaO does not increase proportionally, which may influence the strength properties of the resulting concrete. Additionally, there was little to no improvement in Strength between 28 and 56 days, suggesting that concrete's Strength does not significantly increase after 28 days when higher amounts of ESP and SDA are used as replacements.

4.2. Strength Growth Analysis of Concrete Replaced with ESP & SDA

Table 9 presents the compressive Strength (measured in psi) of concrete at curing intervals of 7, 28, and 56 days for various cement replacement levels utilizing egg-

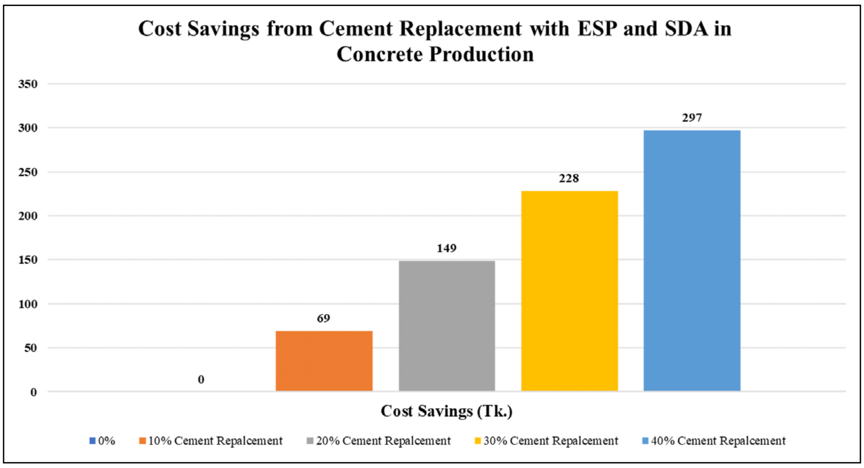

Figure 13. Cost savings achieved through varying levels of cement replacement in concrete.

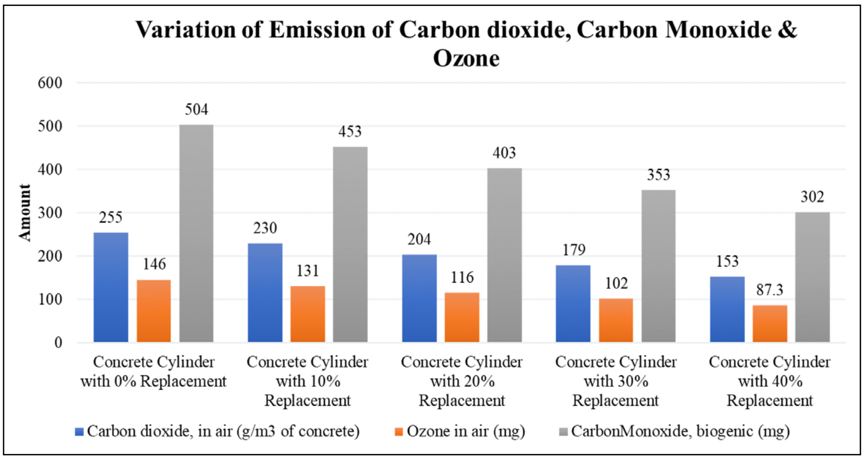

Figure 14. Changes in greenhouse gas emissions and ozone depletion with varying cement replacement levels.

shell powder (ESP) and sawdust ash (SDA), along with the associated strength development rates. The control sample (0% replacement) exhibits the highest Strength across all curing periods, with moderate growth rates of 14.8% from 7 to 28 days and 4.83% from 28 to 56 days. At 10% replacement, compressive Strength reaches 3164 psi at 56 days, with a substantial 38.15% growth from 7 to 28 days. The 20% replacement mix demonstrates robust growth, particularly from 28 to 56 days (29.58%), achieving a final strength of 2948 psi. Higher replacement levels (30% and 40%) yield significantly lower compressive strengths; although the 30% replacement mix shows the highest early-stage growth rate (43.6% from 7 to 28 days), strength development slows between 28 and 56 days. In summary, moderate replacement levels (10-20%) provide a balanced combination of initial and long-term strength development, while higher replacement levels (30-40%) result in reduced overall Strength and limited gains in later stages. This strength growth analysis focuses on the compressive strength data, as concrete is inherently more resistant to compression than tension. As a result, only the compressive Strength is examined, while split tensile Strength is not included in the analysis.

4.3. Tensile Strength Analysis of Concrete with Partial Cement Substitution

Figure 12 shows the split tensile Strength of concrete at 7, 28, and 56 days with different cement replacement levels utilizing eggshell powder (ESP) and sawdust ash (SDA). The control mix (0% replacement) achieved the highest tensile Strength, measuring 10.06 MPa at 7 days and 15.58 MPa at 56 days. As replacement levels increase, tensile Strength generally decreases; for example, 10% replacement reaches 13.24 MPa at 56 days, while 40% replacement drops to 6.40 MPa. This suggests that higher ESP and SDA replacement ratios reduce tensile strength, while lower replacement levels better preserve concrete's tensile performance. When comparing the results with a similar combination of waste glass powder (WGP) and sawdust ash (SDA) mixed in a 50-50 ratio (by weight) conducted by Fahad et al. [82], the tensile strength values obtained at 7 and 14 days are significantly lower than those of the ESP and SDA combination. This highlights the superior performance of the ESP and SDA blend in terms of tensile Strength.

4.4. Cost Analysis

Cost savings are based on local market prices, and estimations focus on the prevalent market prices of the material during the study.

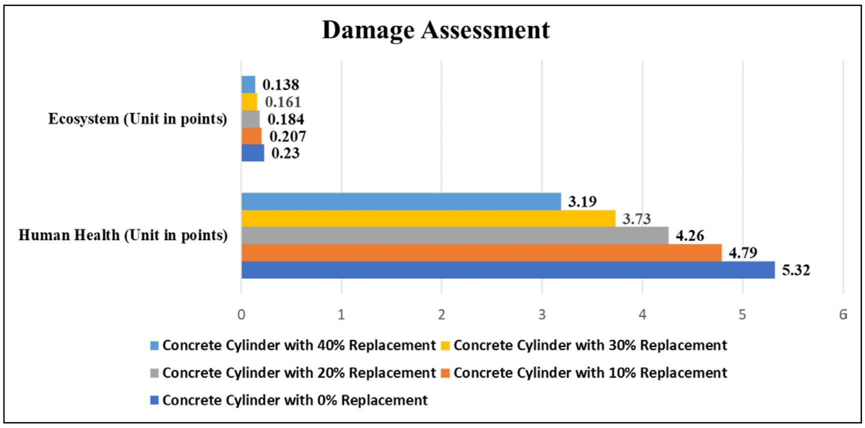

Figure 15. Comparative damage assessment of concrete cylinders with varying levels of SDA & ESP replacement (based on weightage).

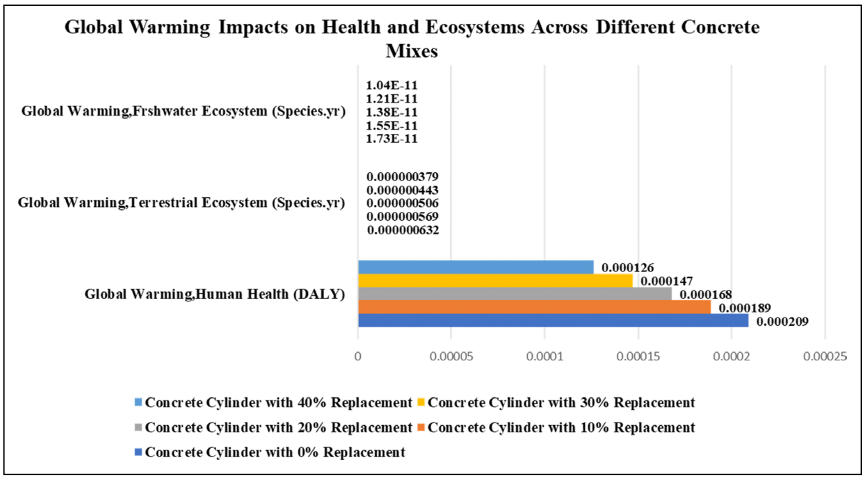

Figure 16. Comparative analysis of global warming impacts across concrete mixes with varying cement replacement levels.

Cost Reductions Compared to 0% Replacement:

- 10% Replacement: 69.30 TK savings
- 20% Replacement: 148.50 TK savings
- 30% Replacement: 227.70 TK savings
- 40% Replacement: 297.00 TK savings

4.5. Assessment of Environmental Impacts Throughout the Life Cycle

After defining the processes for all materials needed to produce 1 m^3 of concrete, assemblies for each mix were created using SimaPro 9.6 software alongside the Ecoinvent database. The Life Cycle Impact Assessment (LCIA) was carried out using the ReCiPe 2016 endpoint method (H), which evaluates environmental impacts in points (Pt). The environmental impact analysis was done using general, global data about energy use depending on the local resource availability of ESP and SDA. This study adopted an international approach for the environmental assessment, utilizing generic data from the Ecoinvent database, which reflects standard conditions for raw material production, transportation, and energy consumption across different regions. The local availability of waste materials like ESP and SDA can significantly alter the environmental impact. The results of the LCIA for each mix are shown in Figures 11–14.

In contrast, Figure 15 presents a comparative life cycle assessment of all the mixtures. The results demonstrate a significant decrease as the replacement percentage increases from 0% to 40%, highlighting the environmental advantages of using ESP and SDA as partial substitutes for cement in concrete production. The data were derived through the Life Cycle Assessment (LCA) methodology and analyzed using SimaPro software.

Figure 14 depicts the emissions of carbon dioxide (CO_2), ozone, and biogenic carbon monoxide (CO) from concrete cylinders with different levels of cement replacement utilizing Eggshell powder (ESP) and Sawdust ash (SDA). As the replacement percentage increases from 0% to 40%, there is a notable reduction in emissions across all three pollutants. For instance, CO_2 emissions decrease from 255 g/m^3 in the control sample (0% replacement) to 153 g/m^3 at 40% replacement. Similarly, ozone emissions decline from 146 mg in control to 87.3 mg at 40% replacement, and biogenic CO emissions drop from 504 mg to 302 mg over the same range. This pattern indicates that higher levels of ESP and SDA substitution in concrete contribute to lower emissions of these pollutants, highlighting the environmental benefits of increased replacement levels.

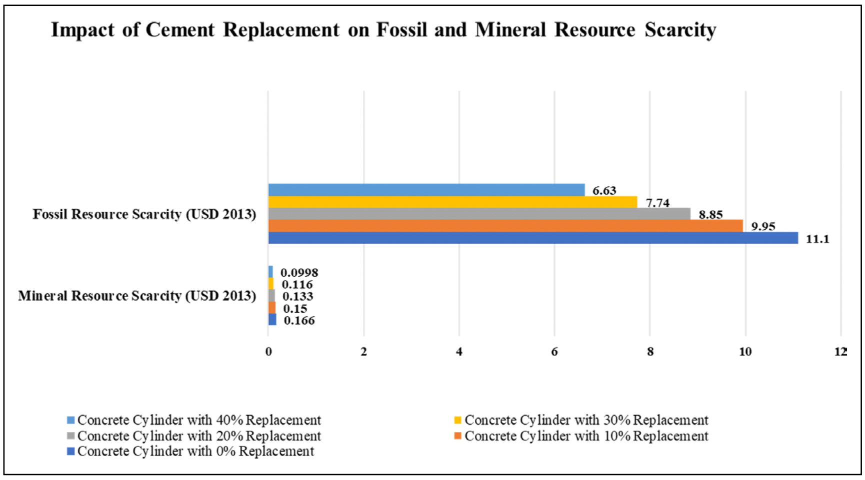

Figure 17. Resource scarcity analysis of concrete mixes with varying cement content.

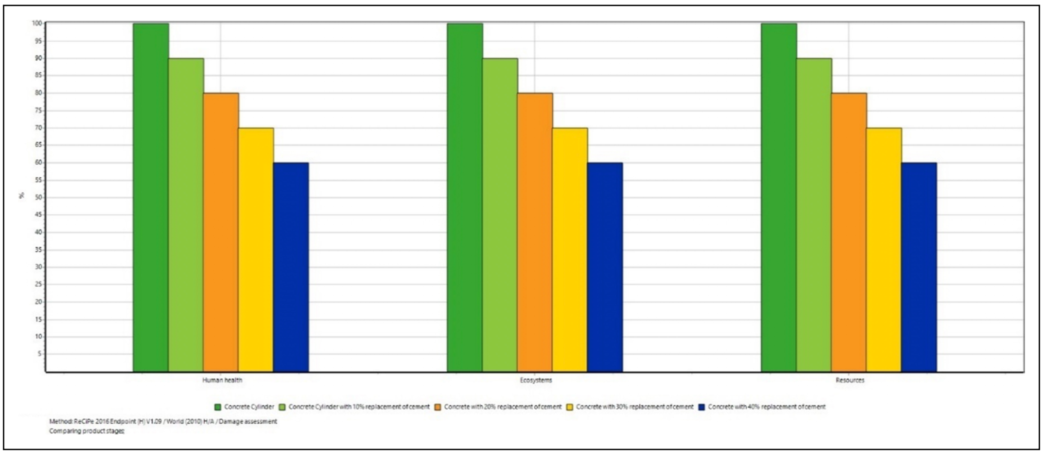

Figure 18. Presents the damage evaluation outcomes for various cement replacement percentages (0%, 10%, 20%, 30%, and 40%) on three key indicators: Human Health, Ecosystems, and Resources, assessed using the ReCiPe 2016 Endpoint method.

The graph of Figure 15 presents the damage assessment of concrete cylinders with varying cement replacement levels using a combination of eggshell powder (ESP) and sawdust ash (SDA), focusing on impacts on Human Health and the Ecosystem. The human health impact, measured in points, decreases as cement replacement increases, with the control sample (0% replacement) showing the highest impact at 5.32 points and the 40% replacement sample at the lowest at 3.19 points. Similarly, ecosystem impacts decline with increasing replacement, from 0.23 points in the control sample to 0.138 points at 40% replacement. Notably, the reduction of cement has a minimal impact on the ecosystem compared to human health, as the effect on the ecosystem for conventional and partially replaced concrete mixes is less than 1 point. These findings indicate that higher levels of ESP and SDA replacement in concrete significantly mitigate environmental damage, with a more pronounced benefit to human health than the ecosystem, making higher replacement levels environmentally advantageous.

The graph of Figure 16 demonstrates the impacts of global warming on health and ecosystems across various concrete mixes with replacement levels of 0%, 10%, 20%, 30%, and 40%. Impacts are categorized into Freshwater Ecosystem (species lost per year), Terrestrial Ecosystem (species lost per year), and Human well-being (quantified in DALY - Disability-Adjusted Life Years). The data indicates that higher replacement levels in concrete mixes reduce global warming impacts, as shown by lower DALY values and species loss rates. Notably, concrete with a 40% replacement level shows the lowest impact on human health and ecosystems, followed by 30%, 20%, and 10% replacements, while the 0% replacement has the highest impact. Interestingly, global warming has a very negligible impact on freshwater and terrestrial ecosystems, as the number of species lost yearly is extremely low compared to the effect on human health. This trend highlights that increasing replacement levels in concrete can mitigate global warming effects, promoting sustainability in construction materials.

In Figure 17, the impact of USD 2013 refers to the environmental impact being expressed in terms of U.S. Dollars (USD) equivalent, adjusted to the value of the dollar in the year 2013. This unit is commonly utilized in Life Cycle Assessment (LCA) to evaluate the economic consequences associated with the depletion of resources, such as fossil fuels and minerals. Fossil Resource Scarcity (USD2013) measures the economic cost arising from the exhaustion of fos-

Table 10. Environmental impact assessment of different concrete mixes with varying cement replacement levels

Impact category	Unit	Concrete Cylinder with 0% Replacement	Concrete Cylinder with 10% Replacement	Concrete Cylinder with 20% Replacement	Concrete Cylinder with 30% Replacement	Concrete Cylinder with 40% Replacement
Global Warming, Human Health	DALY	0.000209	0.000189	0.000168	0.000147	0.000126
Global warming, Terrestrial	species. yr	0.000000632	0.000000569	0.000000506	0.000000443	0.000000379
Global warming, Freshwater	species. yr	1.73×10^{-11}	1.55×10^{-11}	1.38×10^{-11}	1.21×10^{-11}	1.04×10^{-11}
Stratospheric ozone depletion	DALY	5.94×10^{-09}	5.35×10^{-09}	4.75×10^{-09}	4.16×10^{-09}	3.56×10^{-09}
Ionizing radiation	DALY	1.98×10^{-09}	1.79×10^{-09}	1.59×10^{-09}	1.39×10^{-09}	1.19×10^{-09}
Ozone Formation, Human Health	DALY	0.00000083	0.000000747	0.000000664	0.000000581	0.000000498
Fine particulate matter formation	DALY	0.000087	0.0000783	0.0000696	0.0000609	0.0000522
Ozone formation, Terrestrial	species. yr	0.000000119	0.000000107	9.56E-08	8.36E-08	7.17E-08
Terrestrial acidification	species. yr	8.08E-08	7.27E-08	6.46E-08	5.65E-08	4.85E-08
Freshwater eutrophication	species. yr	1.99×10^{-09}	1.79×10^{-09}	1.59×10^{-09}	1.39×10^{-09}	1.22×10^{-09}
Marine eutrophication	species. yr	1.07E-09	9.89E-10	8.53E-10	7.46E-10	6.4E-10
Terrestrial ecotoxicity	species. yr	3.29×10^{-09}	3.29×10^{-09}	2.92×10^{-09}	2.56×10^{-09}	2.19×10^{-09}
Freshwater ecotoxicity	species. yr	6.39E-10	6.39E-10	5.68E-10	4.97E-10	4.26E-10
Marine ecotoxicity	species. yr	0.0000177	0.0000165	0.0000142	0.0000124	0.0000106
Human carcinogenic toxicity	DALY	0.00000396	0.00000357	0.00000316	0.00000277	0.00000238
Human non-carcinogenic toxicity	DALY	0.00000396	0.00000357	0.00000316	0.00000277	0.00000238
Land use	species. yr	8.08×10^{-09}	7.27×10^{-09}	6.47×10^{-09}	5.66×10^{-09}	4.85×10^{-09}
Mineral resource scarcity	USD2013	0.166	0.15	0.133	0.116	0.0998
Fossil resource scarcity	USD2013	11.1	9.95	8.85	7.74	6.63
Water consumption, Human Health	DALY	0.000000154	0.000000138	0.000000122	0.000000112	0.000000103
Water consumption, Terrestrial	species. yr	1.76×10^{-09}	1.58×10^{-09}	1.41×10^{-09}	1.23×10^{-09}	1.06×10^{-09}
Water consumption, Aquatic	species. yr	1.74×10^{-13}	1.57×10^{-13}	1.39×10^{-13}	1.22×10^{-13}	1.04×10^{-13}

sil fuels. It estimates how much it would cost in 2013 USD to replace the depleted resources or to mitigate the impacts caused by their extraction and use. Mineral Resource Scarcity (USD2013) estimates the economic impact of depleting mineral resources, expressed in how much it would cost in 2013 USD to replace or mitigate the effects of extracting these minerals. The graph of Figure 17 demonstrates how different cement replacement levels affect the scarcity of fossil and mineral resources across various concrete mixes, with replacement levels ranging from 0% to 40%. The scarcity costs, measured in USD 2013, are presented for fossil and mineral resources. The data reveals that as the percentage of cement replacement rises, the scarcity costs for fossil resources generally decrease, highlighting a reduc-

Table 11. Environmental Impact of Chemical Substances Across Different Concrete Mixes with Varying Cement Replacement Levels

Substance	Compartment	Unit	Concrete Cylinder with 0% Replacement	Concrete Cylinder with 10% Replacement	Concrete Cylinder with 20% Replacement	Concrete Cylinder with 30% Replacement	Concrete Cylinder with 40% Replacement
1-Butanol	Air	ng	154	139	123	108	92.4
1-Butanol	Water	µg	142	127	113	99.2	85
1-Pentanol	Air	ng	32.7	29.4	26.1	22.9	19.6
1-Pentanol	Water	µg	78.4	70.5	62.7	54.9	47
1-Pentene	Air	ng	427	385	347	299	256
1-Pentene	Water	µg	59.2	53.3	47.4	41.5	35.5
1-Propanol	Air	ng	142	127	113	99.2	84.9
1-Propanol	Water	µg	142	127	113	99.2	84.9
1,1,1-Trichloroethane	Air	µg	1.84	1.66	1.47	1.29	1.11
1,1,1-Trichloroethane	Water	µg	83.1	74.8	66.5	58.1	49.8
1,3-Dioxolan-2-one	Air	ng	427	385	347	299	256
1,4-Butanediol	Air	ng	351	316	281	246	201
1,4-Butanediol	Water	µg	315	193	172	150	129
2-Aminopropanol	Air	ng	33.4	30.1	26.7	23.4	20.1
2-Aminopropanol	Water	µg	30.4	26.7	23.4	20.3	17.3
2-Butene, 2-methyl-	Air	ng	2.39	2.15	1.91	1.67	1.44
2-Butene, 2-methyl-	Water	pg	106	95	84.4	73.9	63.3
2-Methyl-1-propanol	Air	ng	253	228	203	177	152
2-Methyl-1-propanol	Water	pg	7.16	6.45	5.73	5.01	4.3
2-Methyl-2-butanol	Air	ng	0.891	0.802	0.701	0.624	0.535
2-Methyl-4-chlorophenoxyacetic acid	Soil	pg	8.5	8.1	6.6	5.8	4.7
2-Methyl-4-chlorophenoxyacetic acid	Soil	pg	8.5	8.1	6.6	5.8	4.7
2-Nitrobenzoic acid	Soil	pg	79.4	71.4	55.6	47.6	39.6
2-Propanol	Air	mg	1.98	1.79	1.59	1.39	1.19
2-Propanol	Water	µg	23.9	21.5	19.6	18.4	16.7
2,4-D	Air	mg	255	229	203	178	152
2,4-D	Soil	µg	5.36	4.83	4.29	3.85	3.25
2,4-D ester	Air	mg	2.4	2.15	2.05	1.86	1.7
2,4-D ester	Soil	pg	0.0000589	0.000053	0.0000471	0.0000412	0.0000353
2,4-D dimethylamine salt	Air	pg	0.0000432	0.0000434	0.0000345	0.0000325	0.0000295

tion in fossil fuel dependency. For example, concrete with 40% replacement has the lowest fossil resource scarcity cost at USD 6.63, while concrete with 0% replacement is the highest at USD 11.1. Mineral resource scarcity costs are comparatively lower but slightly reduced with increased replacement, ranging from USD 0.0998 for 40% replacement to USD 0.166 for 0% replacement. By comparing Fossil and Mineral resources, it is very clear that cement production is greatly dependent on Fossil resources compared to mineral resources, and that's why the economic cost associated with the depletion of fossil fuels is more than that of fuel obtained from mineral resources.

Figure 18 presents the damage evaluation outcomes for various cement replacement percentages (0%, 10%, 20%, 30%, and 40%) on three key indicators: Human Health, Ecosystems, and Resources, assessed using the ReCiPe 2016 Endpoint method. The results reveal a consistent pattern where increasing the proportion of cement replacement significantly reduces environmental impacts across all categories. Concrete with 40% replacement shows the lowest impact, followed by 30%, 20%, and 10%, while the conventional mix (0% replacement) exhibits the highest impact. The most notable reduction is observed in the "Resources" category, highlighting the substantial conservation of raw materials achieved with higher replacement levels. This trend emphasizes the environmental benefits of increased cement replacement, including reduced resource depletion and minimized harm to human health and ecosystems, thereby promoting greater sustainability.

Table 10 highlights the environmental impacts of concrete mixes with varying cement replacement levels (0% to 40%) across various impact categories, including human health (measured in DALY), ecosystem degradation (species. yr), and resource depletion (USD2013). Increasing cement replacement significantly reduces environmental impacts, indicating improved sustainability. The table reveals a significant decline in fossil resource scarcity (USD2013) with increasing cement replacement levels, decreasing from USD 11.1 at 0% replacement to USD 6.63 at 40% replacement, indicating substantial conservation of fossil fuels. This shows the heavy reliance of cement production on fossil resources and demonstrates how higher replacement levels effectively reduce this dependency. Furthermore, the global warming impact on human health (measured in DALY) shows a steady reduction, from 0.000209 at 0% replacement to 0.000126 at 40% replacement, highlighting the environmental advantages of reduced CO_2 emissions. These findings collectively demonstrate that higher cement replacement levels conserve critical resources and mitigate the adverse effects of global warming on ecosystems and human health.

Table 11 presents the concentrations of various chemical substances in air, water, and soil compartments for concrete mixes with varying cement replacement levels (0% to 40%), measured in units such as ng, µg, pg, or mg, depending on the substance. The data demonstrates that emissions of these substances decrease consistently with higher cement replacement, highlighting the environmental advantages of this approach. Substances such as 1-Butanol, 1-Pentanol, 1-Pentene, and 2-Propanol exhibit the highest emissions in the air, with 1-Butanol reducing from 154 ng for 0% replacement to 92.4 ng for 40% replacement. Elevated concentrations of these airborne chemicals harm human health, potentially causing respiratory and other health issues [83, 84]. Similarly, 1,1,1-Trichloroethane and 2-Methyl-4-chlorophenoxyacetic acid show significant concentrations in water, with 1,1,1-Trichloroethane decreasing from 83.1 µg to 49.8 µg as replacement increases, reducing toxicity to aquatic ecosystems, disrupting the reproductive cycles of marine organisms and contaminating water supplies [85]. In the soil compartment, chemicals such as 2-nitrobenzoic acid and 2,4-D pose risks of long-term contamination and bioaccumulation, with 2-nitrobenzoic acid emissions dropping from 79.4 pg to 39.6 pg as cement replacement levels rise. These substances can lead to long-term soil contamination, impacting plant growth and entering the food chain [86]. The high air emissions of chemicals like 1-Butanol are particularly concerning due to their widespread exposure risks. Still, their reduction with increased cement replacement offers dual benefits of mitigating environmental harm and improving public health. The table highlights the significant reduction in toxic emissions to air, water, and soil achieved by higher cement replacement levels, thereby substantially lowering concrete production's environmental and health effects.

5. CONCLUSION

1. The study highlights that replacing up to 20% of cement with eggshell powder (ESP) and sawdust ash (SDA) offers both environmental advantages and satisfactory mechanical performance, making it a cost-effective option for large-scale concrete production. This mix significantly reduces CO_2 emissions, resource depletion, and human health impacts, showcasing its potential for promoting sustainable construction practices. Additionally, the 13% cost savings achieved by substituting cement with ESP and SDA provide a practical solution for addressing budget constraints, especially in low-income housing projects or regions with high cement prices. The scalability of this approach is supported by the widespread availability of ESP and SDA as waste materials, and their incorporation into concrete production can be easily implemented with minimal infrastructure changes, making it a viable solution for both small and large-scale applications, thereby enhancing the long-term sustainability of the construction industry.
2. Considering potential trade-offs, an optimal balance between environmental performance and mechanical Strength can be attained by carefully adjusting the cement replacement levels. Thus, a 10-20% cement replacement offers a practical compromise, providing both environmental advantages and adequate mechanical properties, suitable for many standard construction applications. This trade-off arises from the limited presence of calcium oxide (CaO) in ESP and SDA, which impairs the pozzolanic reaction essential for the ongoing strength development as the concrete matures.
3. Carbon dioxide emissions are the primary contributor to global warming associated with cement production, driven by the high energy consumption and extensive use of natural resources required for its manufacturing process. These emissions can be effectively mitigated by incorporating Eggshell Powder (ESP) and Sawdust Ash (SDA) as sustainable cement-based materials in concrete production. Significantly, in residential or commercial building projects where environmental certifications (like LEED) are essential, using the 10% replacement mix would contribute to sustainability goals because, for projects that prioritize sustainability without significantly compromising on performance, the 10% replacement level offers a strong balance. The growth rate from 7 to 28 days (38.15%) is higher than that of normal concrete (14.80%), and the subsequent growth from 28 to 56 days (13.81%) is moderate but sufficient for many standard applications as per strength requirements for different codes.

4. By comparing Fossil and Mineral resources, it is very clear that the production of cement is greatly dependent on Fossil fuel, so partially replacing cement with ESP and SDA at an optimal level, depletion of fossil resources can be avoided, and ecological balance can be conserved along with promoting sustainability in construction materials.
5. From the compressive strength graph, we have not observed any significant difference between 28 and 56 days except for 20 % replacement, which shows an increase of 4.6 MPa concrete strength from 28 to 56 days. So, in low-income housing projects where budget constraints are significant, using the 20% replacement mix can reduce material costs while still providing a durable structure that gains Strength over time because in regions where the price of cement is high or there is an abundance of ESP and SDA, replacing cement with 20% SDA and ESP can be cost-effective while maintaining acceptable performance. The significant gain from 28 to 56 days (29.58%) with 20% replacement suggests that, while the early Strength may not match normal concrete, the long-term performance could be superior.
6. The strength growth analysis of Table 9 highlights the significant interaction between curing time and replacement levels in compressive Strength development. Between 7 and 28 days, mixes with lower replacement levels (10% and 20%) show considerable strength improvement due to higher early hydration rates. In contrast, mixes with higher replacement levels (30% and 40%) exhibit faster Strength gain initially, but the growth slows considerably after 28 days, suggesting limited long-term strength development. This pattern is likely due to the lower availability of calcium oxide (CaO) in these mixes, which hinders the pozzolanic reaction essential for sustained strength growth. The findings emphasize the need to balance curing time and replacement levels to achieve optimal early and long-term Strength in concrete mixes containing ESP and SDA.
7. The cost of producing concrete can be lowered by up to 13% by substituting cement with these waste materials.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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