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Experimental investigation on the utilization of e-waste, plastic waste, and crushed coconut shell as partial replacements for natural aggregates in concrete

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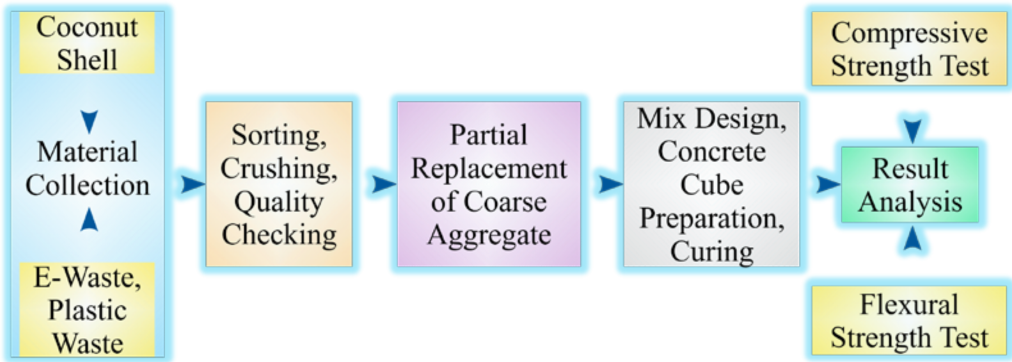

ABSTRACT

In a rapidly urbanizing world, achieving sustainable and ethical development requires the close integration of buildings with the surrounding environment. This research explores the findings from experiments investigating the impacts of substituting a portion of the coarse aggregate (CA) with e-waste, plastic waste, and crushed coconut shell (CCS) within the concrete mix. The experimental results in this research show that including 5-10% by weight of plastic, e-waste, and CCS as partial replacements for CA in concrete mix brings significant and considerable compressive and flexural strength on the 3rd, 7th, 14th, and 28th days. Specifically, the compressive strength reaches 21.8 MPa after 5% replacement of CA and 19.4 MPa after 10% substitution of CA on the 28th day. However, it is noted that increasing the amount of this waste material beyond 10% results in a decline in the compressive and flexural strength of concrete. Therefore, as per experimental outcomes, the compressive strength is higher at 5% replacement; however, for 10% replacement, the compressive strength is at a satisfactory and acceptable level, so 10% is the considerable proportion found for partial replacement of CA with CCS, e-waste and plastic waste in the concrete mix. The combination of these wastes in suitable ratios can be applied as possible and workable alternative substitutes for ordinary construction materials while maintaining environmental friendliness and affordability.

Keywords: E-Waste, Plastic Waste, Crushed Coconut Shell, Compressive Strength, Flexural Strength

INTRODUCTION

With global sustainable growth in building construction, there is a deep exploration of using eco-friendly materials such as by-products, natural resources and waste materials in concrete and mortar for both structural and non-structural purposes. A promising avenue of innovation lies in incorporating waste materials such as agricultural waste and household waste (plastic and e-waste) into concrete mixes for building construction.[1,2,3] In this research, crushed coconut shell (CCS) as agricultural waste and plastic and e-waste as household waste are partially used in concrete mix.

The concrete industry is continuously providing the base materials for construction and infrastructural development. However, usual concrete production highly depends on the utilization of natural resources, especially aggregates, which leads to significant environmental impacts and the depletion of natural resources.[4,5] Researchers are continuously exploring alternative materials (usually discarded materials) and methods by which household, agricultural, and industrial waste can be reused in concrete to mitigate growing issues and challenges regarding waste management and environmental sustainability. In this modern digital world, electronic waste (e-waste) and household plastic waste management are crucial environmental issues.[6] The growth of discarded household electronic devices and plastic products is presenting hazardous threats to human health and ecosystems.[7]

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These wastes represent opportunities for sustainable utilization by partially mixing with construction materials.

The discarded household e-waste, plastic waste, and some agricultural waste can be utilized as a partial substitution for coarse aggregate (CA) in the concrete mixtures for building construction. For partially replacing ordinary CA, researchers have now investigated the relevancy and applicability of including these wastes in concrete mix.[8] By reusing and utilizing these waste materials, it controls environmental pollution and also minimizes the demand for natural aggregates, which will mitigate the environmental degradation related to their mining.[9]

Furthermore, the exploration of other alternative aggregates, such as CCS, can enhance the sustainability of concrete production. In India, waste coconut shells are abundantly available in temples and in homes on religious festivals, and these shells have desirable properties such as being lightweight, having a high strength-to-weight ratio, and having thermal insulation, which makes them a potentially valuable substitute for concrete mixtures.[10]

The discarded plastic and e-waste from houses, offices, and industries are hazardous in nature and have limited reusability and fewer recycling options.[11] These wastes, including discarded plastics from various electronic devices such as computers, TVs, toys, electronic equipment, and home appliances, are usually non-biodegradable substitutes for CA.[12,13] The coconut shell waste is usually used as charcoal and for other applications like handicrafts and handmade decoration items. Now, reusing these waste materials in concrete mixes can provide a partial solution to environmental issues and reduce reliance on landfills.[14,15]

This research mainly aims at sustainability in construction materials by investigating the performance of concrete mixed with CCS, e-waste, and plastic waste as partial replacements for CA. The experimental analyses, mainly compressive and flexural strength tests are performed in this research to assess the impact of the concrete formulations. This research has the potential to lead concrete industry practices by examining the effectiveness and feasibility of utilizing discarded e-waste, plastic waste, and CCS as alternatives to CA. Adopting such innovative approaches contributes to the advancement of environmentally responsible construction practices.

Soundness test is conducted for cement only, in this research cement has not been replace, so soundness test is not required for this research. In this research, cement has not been replaced, and a soundness test is conducted for cement only, so soundness tests are not required for this research. The workability and slump test value were in the normal range, so there was no need to highlight it in this research. The split test was not conducted in this research.

Research Challenges

This research addresses an innovative approach to sustainable construction materials using discarded waste plastic, e-waste, and coconut shell waste from temples. However, various challenges encountered in conducting and implementing this research include:

- **Material Properties Variability:** E-waste, plastic waste, and CCS may exhibit significant variations in their physical and chemical properties, depending on their sources and processing methods. Ensuring consistent and reliable properties across different batches of these materials can be challenging.[16]
- **Compatibility with Concrete Matrix:** Incorporating unconventional materials like e-waste, plastic waste, and coconut shell into concrete mixtures may affect compatibility with the cementitious matrix, potentially leading to issues such as reduced workability, setting time alteration, or compromised mechanical strength.
- **Durability Concerns:** The long-term durability of concrete mix having e-waste, plastic waste, and coconut shell aggregates needs to be thoroughly evaluated. Factors such as chemical reactions, moisture absorption, and resistance to environmental degradation could affect the structural stability and service life of the concrete.
- **Optimization of Mix Proportions:** Achieving the desired performance characteristics while using e-waste, plastic waste, and coconut shell as partial replacements for natural aggregates requires meticulous optimization of mix proportions. Balancing factors such as strength, workability, and durability pose a significant challenge.
- **Environmental Impact Assessment:** While the utilization of coconut shell, plastic and e-waste in concrete has positive environmental benefits in terms of waste reduction and resource conservation, comprehensive environmental impact assessments are necessary to evaluate the overall sustainability of the concrete mixtures, including considerations such as embodied energy and greenhouse gas emissions.
- **Regulatory and Standards Compliance:** Concrete mixtures containing unconventional aggregates must comply with relevant regulatory requirements and industry standards to ensure safety, performance, and compatibility with existing construction practices. Adhering to these standards while using non-traditional materials can be complex and may require extensive testing and documentation.
- **Cost-Effectiveness and Economic Viability:** Assessing the economic feasibility of incorporating plastic, e-waste, and coconut shell aggregates in concrete is essential for their practical implementation. Factors such as material acquisition costs, processing expenses, and potential savings or additional expenses associated with concrete production need to be carefully analyzed.[17]
- **Public Perceptual Experience and Acceptance:** Introducing novel materials into construction practices may encounter doubtfulness and resistance from stakeholders due to concerns regarding performance, safety, or aesthetics. Addressing these perceptions through effective communication and demonstration of the benefits is crucial for the acceptance and adoption of sustainable construction practices.

Addressing these challenges requires a multidisciplinary approach integrating materials science, civil engineering, environmental science, and sustainability principles to develop innovative and practical solutions for advancing the utilization of alternative aggregates in concrete production.[18]

Objectives of the Research

In this research work, the objectives are as follows:

- To evaluate and examine the possibility and workability of partially substituting the natural aggregates in the concrete mixes with CCS, household, e-waste, and plastic waste.

- To investigate the effects of including (partially) these alternative (plastic waste, e-waste, and CCS) aggregates on the physical properties of the concrete, such as flexural, and compressive strength.
- To analyze the environmental impact and sustainability effects of applying these alternative aggregates in concrete by considering pollution generated by those wastes.

The rest of this article is structured as follows: The related work section provides the challenges highlighted in previous research related to this work. The material and methodology section explains the samples and methods applied with equipment and apparatus details for this research. The result and discussion section presents the outcomes from the experimental analysis, discussion, contributions, and limitations of the research, and the article concludes with a conclusion and future work section.

RELATED WORK

Concrete is an essential construction material utilized worldwide, playing a vital role in building development. It is widely acknowledged for its significance in advancing human progress. This section examines alternative materials that can partially substitute traditional aggregates in concrete, supplementing cement in construction applications.

Supit *et al.*[19] present experimental investigations regarding the impact of replacing a portion of the CA with plastic waste, specifically “Polyethylene Terephthalate (PET)”, in pervious concrete. They suggest that when incorporated at appropriate proportions using well-established methods, these plastic waste materials contain the potential to work as a viable alternative construction material, particularly benefiting environmental conservation, energy efficiency, and cost-effectiveness.

Needhidasan *et al.*[20] replaced traditional CA with plastic of e-waste in the range of 0 to 12.5% for M-20-grade concrete incorporating manufactured sand. Results indicated higher flexural and compressive strength in the concrete with e-waste replacement compared to ordinary traditional concrete with 10% partial substitution. Additionally, the split tensile strength result was higher in concrete with 12.5% e-waste substitution compared to ordinary traditional concrete.

Gradinaru *et al.*[21] conducted an analysis to assess the impact of substituting part of the cement with silica fume and fly ash, as well as incorporating air entraining additives and liquid sodium silicate, on the mechanical characteristics and density of two variants of vegetal concrete. In one variant, 50% of mineral aggregates were substituted by corn cob, while in the other, sunflower granules were used. Their findings suggest that natural plant-based aggregates can be utilized to produce a construction material that is enhanced through partial cement substutution with silica fume, fly ash or by incorporating additives such as air entrainers and sodium silicate. These improvements can have potential applications in various construction contexts, including closures and finishes.

Sau *et al.*[22] investigated the durability and mechanical characteristics of the concrete integrating waste “polyethylene-terephthalate (PET)” and recycled waste “polyethylene (PE)” based aggregates as substitutes for natural coarse and fine aggregates, respectively. Their study involved assessing various properties, containg water permeability, compressive strength, sorptivity, resistance to aggressive environments such as acid, base, marine water, and wastewater, that affect gas permeability, resistance, rapid chloride penetration (RCPT), abrasion loss (surface and Cantabro), leachability of microplastics, and elevated temperature effects. The experiments were conducted with different levels of volumetric replacement (ranging from 0% to 40%) of ordinary fine and CA with PE and PET-based aggregates, respectively, over various curing times. Their findings indicated that the sorptiveness of PE-based concrete is the minimum among the tested materials.

Yehia *et al.*[23] chemically transformed shrimp shell wastes into chitosan. When incorporating this natural polymer into concrete, they observed an interactive effect on the properties and performance of the concrete mix. The chitosan produced was analyzed using thermogravimetric analysis (TGA), X-ray diffraction (XRD), Fourier transform infrared spectroscopy (FT-IR), and scanning electron microscopy (SEM). To accomplish the research objectives, five concrete mixtures were formulated. In specific concrete formulations, additives like superplasticizer (chemical) and chitosan (natural polymer) were included at a dosage of 0.05% relative to the cement weight. These additives were incorporated to assess their impact on concrete properties and to contrast the findings with those from standard concrete formulations. Their findings demonstrated that chitosan-incorporated concrete exhibited significant improvements in mechanical properties.

Palanisamy *et al.*[24] employed PCB (Printed Circuit Board) derived from e-waste to replace CA in concrete. The highest compressive strength was achieved with a partial substitution of 12% of plastic and e-waste. Similarly, the flexural and tensile strength also peaked at 12%. The study noted that the concrete incorporating PCB from e-waste, using and without using plasticizer, attained its highest strength when replaced about 12% of CA.

Hammad *et al.*[25] investigated the viability of integrating textile sludge, plastic waste, and demolition and construction waste into concrete, which works as a sustainable alternative substitute to conventional construction materials. They assessed the durability and mechanical properties, and cost implications associated with various processes of the project. The study specifically examines the substitution of fine aggregate with plastic waste and textile sludge and CA with demolition and construction waste. Consequently, four concrete mixes incorporating textile sludge and plastic waste were formulated, with replacement levels of 0%, 10%, 25%, and 40%. Concrete containing 10% plastic waste as a substitution for fine aggregate (FA) exhibited 32.49 N/mm^2 compressive strength, surpassing the results obtained with textile sludge.

Resende *et al.*[26] produced and evaluated lightweight concrete compositions composed solely of lightweight aggregates, predominantly recycled plastic aggregates. They first introduced an optimized dosage method for lightweight concrete. Based on the mortar’s performance, the formulation of lightweight concrete was determined, utilizing entirely recycled PET aggregates as a replacement for natural aggregates. The PET aggregates exhibited affecting production, irregular shapes, and lightweight concrete with approximately 21% void index and 18% water absorption.

Shah *et al.*[27] used the "multi-expression programming (MEP)" machine learning approach to investigate the compressive strength and tensile strength of concrete made with e-waste aggregate. Krishnaswami *et al.*[28] used industrial residues as supplementary filler aggregate in concrete manufacturing. By-products such as silica fume, glass cullet, GBF slag, and fly ash have seen utilization in civil engineering projects in recent years. The experiment utilized 53-grade OPC. CA in the concrete mix served as a substitute for electronic waste to some extent.

Parsons and Nwaubani[29] assessed an evaluation of concrete made with acrylonitrile butadiene styrene plastic sourced from e-waste as a substitute for natural CA. Different proportions of granulated waste acrylonitrile butadiene styrene were used to replace the natural aggregate at 5%, 10%, 25%, 50%, 75%, and 100% by volume. To enhance the early-age performance of concrete, all mixtures underwent curing through precarbonation in addition to conventional water curing. This assessment included examining mechanical strength, durability, and microstructure.

Frahat *et al.*[30] presented an innovative method for crafting eco-friendly lightweight concrete by integrating a distinct variety of lightweight aggregate known as popcorn aggregate, which boasts complete environmental friendliness. Their approach involved exploring fourteen combinations of coarse and fine aggregate ratios by volume (25%, 50%, and 100%) to supplant natural aggregates. They conducted assessments on flexural, compressive, and splitting tensile strength, and workability; X-ray spectrometry of energy dispersion and strength; and microstructure analysis. The findings presented that as the substitution ratio of ordinary conventional aggregates with popcorn aggregates increased, so did the slump value.

Hama *et al.*[31] investigated the utilization of plastic water bottle caps as a partial substitute for CA in the concrete. They evaluated both compressive and flexural strengths, along with crack width, mode of failure, and midspan deflection of a verified reinforced slab of concrete under a centralized load. Their findings indicated that optimal strength was achieved with a 10% inclusion of PWC.

Saha *et al.*[32] used PET and PE waste-derived aggregates to partially substitute natural aggregates in concrete, resulting in decreased overall costs while maintaining mechanical strength. This occurs particularly when factoring in the monetized environmental and social advantages of the approach alongside aggregate requirements.

To gain deeper insights into how waste plastic influences the properties of geopolymer concrete, which is an eco-friendly substitute for traditional concrete, Zia-ul-haq *et al.*[33] proposed a series of experiments. These research experiments aim to analyze the effects of integrating recycled plastic into geopolymer concretes. Their study synthesizes previous research on utilizing waste plastic in concrete. The experimental methods encompass the selection and description of plastics, the preparation of samples, and the testing procedures.

Jawaid *et al.*[34] demonstrated that integrating recycled plastic waste into cementitious composites is highly beneficial as it has the potential to substitute all solid components of the composite. Their qualitative examination of different plastic waste management approaches, emphasizing key aspects, indicates that newer methods prioritize environmental and sustainability benefits but often lack economic viability.

The researchers are finding alternative materials that can be partially used up to a certain limit with CA and that can be successfully applied in construction. According to the literature study, the challenges are that an integrated mix of other natural, agricultural, household, and industrial waste can be partially used in concrete.

Table 1 Literature and Waste Replacement in their Research

Literature	Waste Replacement in their Research
Supit *et al.*[19], Resende *et al.*[26]	Polyethylene-Terephthalate (PET)
Needhidasan *et al.*[20]	E-waste, plastic
Gradinaru *et al.*[21]	Fly ash, silica fume, corn cob, sunflower granules
Sau *et al.*[22], Saha *et al.*[32]	Polyethylene (PE), Polyethylene-Terephthalate (PET)
Yehia *et al.*[23]	Shrimp shell, chitosan, superplasticizer
Palanisamy *et al.*[24]	Printed circuit board (PCB)
Hammad *et al.*[25]	Textile sludge, Plastic waste, demolition and construction waste
Shah *et al.*[27]	E-waste
Krishnaswami *et al.*[28]	Industrial residues
Parsons and Nwaubani[29]	Acrylonitrile butadiene styrene (ABS)
Frahat *et al.*[30]	Popcorn aggregate
Hama *et al.*[31]	Plastic water bottle caps
Zia-ul-haq *et al.*[33], Jawaid *et al.*[34]	Plastic
Proposed Work	E-waste, plastic, crushed coconut shell

The use of crushed coconut shells with small amounts of plastic and e-waste as a partial substitution of CA is an innovative approach, and experimentally verifying their applicability is the novelty of this research. The Table 1 represents the unique aspects of this research work in comparison to the existing literature mentioned in the related work section. This summarized table also specifies the research gap in sustainable concrete research.

MATERIALS AND METHODOLOGY

Reusing e-waste, plastic waste, and CCS partially in concrete mix for construction is an innovative step to solve the problems of waste management, and it also promotes sustainable construction methods. The discarded wastes of electronic devices (e-waste), household hard plastics, and CCS collected from temples can be processed and mixed in concrete to partially replace CA such as crushed stone and gravel.

The essential steps (as presented in Figure 1) to use this waste in concrete are as follows:

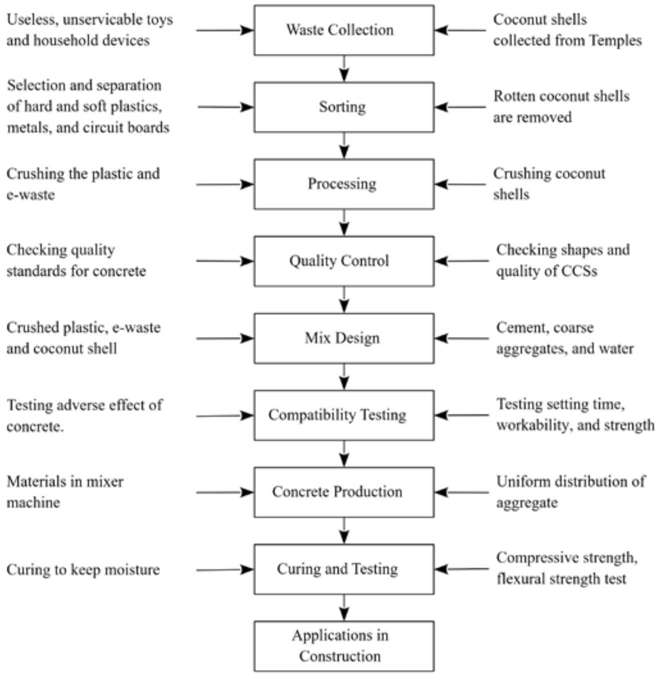

Figure 1 Proposed Methodology

- **Waste Collection:** E-waste and plastic waste are collected from useless and unserviceable toys and household electronic devices such as computers, smart phones, laptops, and other electronic gadgets. The majority of coconut shells are collected from temples.
- **Sorting:** The hard matters are selected and separated, and the soft matters are discarded (soft plastics are processed to make them hard). Sort the e-waste to separate materials like plastics, metals, and circuit boards. Rotten and weak coconut shells are removed, the goal is to isolate the components that can be used as aggregates.
- **Processing:** Crush and grind the e-waste components into coarse particles resembling traditional aggregates. This can be achieved using mechanical processes or specialized equipment.
- **Quality Control:** Conduct tests to ensure that the processed e-waste aggregates meet the required quality standards for concrete production. This may include assessing particle size distribution, shape, and other mechanical properties.
- **Mix Design:** Develop a concrete mix design that incorporates the plastic, e-waste and CCS aggregates while maintaining the required structural and durability properties. Adjust the proportions of other concrete components (cement, CA, water, and additives) accordingly.
- **Compatibility Testing:** Perform compatibility tests to ensure that the e-waste aggregates do not adversely affect the concrete's setting time, workability, or strength development.
- **Concrete Production:** Mix the concrete components, including the processed e-waste aggregates, in a concrete batching on-site mixer or plant. Ensure that the mixing process is thorough to achieve a uniform distribution of aggregates.
- **Curing and Testing:** Cure the concrete properly to promote strength, development, and durability. Conduct standard concrete tests, such as durability, flexural, and compressive strength tests, to assess the performance of the plastic, e-waste, and CCS based concrete.
- **Applications in Construction:** The plastic, e-waste, and CCS partially mixed with concrete can be applied in construction applications where pure CA are employed, such as in the production of concrete blocks, or structural elements.

The coconut shell sample, depicted in Figure 2, weighing around 100 kg, gathered mainly from Maa Kali Temple in Jahangirabad, and other temples in Bhopal. The collected coconut shells underwent sun-drying to eliminate moisture content completely. The dried coconut shell was processed further after a week. The dried coconut shell was fed into the crusher. Post-crushing, the coconut shell underwent sieving using "Indian Standard Sieve Analysis," followed by quality control and testing to ascertain material properties. The crushed is situated at Research Lab, RKDF University in Bhopal. The day after crushing, the crushed coconut shells (CCSs), weighing up to 90 kg, were collected. This material was gathered and utilized for a subsequent investigation.

Figure 2 Coconut Shell Collected from Temple

Similarly, household e-waste and plastic waste are collected collaboratively by researchers, faculty members, staff, students, shops, and laboratories. The waste that is to be substituted is 60% of CCS, 20-20% of e-waste, and plastic waste, as shown in Figure 3.

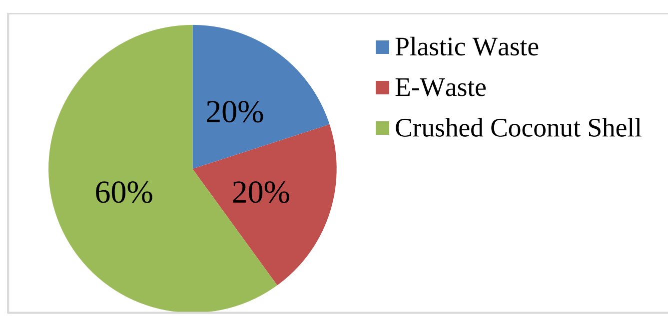

Figure 3 Ratio of CCS, Plastic and E-waste

The advantages of using plastic waste, e-waste, and coconut shell in concrete mix may be the solution for e-waste and soil pollution control, minimizing the environmental impact related to disposal of waste into the ground, and promoting reusing waste materials.

Characteristics of the Waste Materials

Table 2 summarizes the physical characteristics of waste materials used as partial substitution in concrete. The physical characteristics such as size, density, porosity, percentage of water absorption, impact on compressive strength, thermal conductivity, and their workability in the concrete mix affect the characteristics of the construction.

Table 2 Physical Characteristics of Waste Materials Used in Concrete Mix

Property	CCS	Plastic Waste	E-Waste
Particle Size	5-20 mm	2-10 mm	1-8 mm
Shape	Irregular, flaky, rough texture	Irregular, elongated, smooth	Irregular, sharp-edged
Bulk Density (kg/m³)	500-600	850-950	1000-1500
Water Absorption	15-24%	0.1-0.5%	0.5-1%
Porosity	High	Low	Medium
Surface Texture	Rough, fibrous	Smooth, hydrophobic	Glassy, rough
Compressive Strength Impact	Reduces strength but acceptable up to 10% replacement	Reduces strength but improves durability	Can maintain strength with proper grading
Thermal Conductivity	Moderate	Low (insulating properties)	High (due to metallic content)
Workability in Concrete	Moderate	Low (needs chemical treatment)	Good

Similarly, Table 3 represents the physical characteristics of waste materials utilized as partial substitution in concrete. The main chemical characteristics, such as their compositions, percentage of silica content, thermal and chemical stability, toxic content, etc., affect the characteristics of the concrete mix.

Table 3 Chemical Characteristics of Waste Materials Used in Concrete Mix

Property	CCS	Plastic Waste	E-Waste
Main Components	Cellulose, hemicellulose, lignin, silica	Carbon (C), Hydrogen (H), Oxygen (O), Plasticizers	Silica (SiO_2), Aluminum (Al), Copper (Cu), Lead (Pb)
Silica Content	40-50 %	Negligible	50-70 %
Pozzolanic Activity	Low to moderate	None	Moderate
Thermal Stability	Decomposes above 200°C	Decomposes at 250-300°C	Decomposes at 300-400°C
Alkaline Resistance	Moderate (can affect cement hydration)	High (non-reactive)	High (resistant to cement reactions)
Chemical Stability	May degrade over time if not treated	Highly stable, non-degradable	Chemically stable, potential heavy metal leaching
Chloride & Sulfate Content	Low	None	Potential presence of heavy metals (Pb, Hg, Cd)
Toxic Emissions Risk	Non-toxic	Potential volatile organic compound emissions	Heavy metal leaching risk

CCS is usually a lightweight substitute, but it is highly porous, which needs some water adjustment in the concrete mix. CCSs are organic compounds that can interfere with hydration, but they have some silica content. Plastic wastes are non-reactive and hydrophobic, which improves the durability but reduces strength and bonding. E-waste usually contains high silica content, which contributes to strength retention, but it usually has potentially heavy metals, such as Cd, Hg, and Pb, which are highly toxic to the environment, eco-system and health.

Equipment and Apparatus Details

Table 4 represents the specified apparatus and equipment applied for conducting physical experiments and tests, it includes test methods, procedures, standards, and parameters. This research explores the partially substitution of CA with CCS, plastic, and e-waste across varying proportions: 0%, 5%, 10%, 15%, and 20%. Physical tests adhere to the procedures outlined in the IS code, as delineated in Table 4. Conforming to IS Code 4031 (Part 5) - 1988, four specimens were fabricated for each curing period (3rd, 7th, 14th, and 28th days) to determine compressive and flexural strength. The mean value of these specimens is considered for the compressive and flexural strength assessments. For the experimental investigation, a total of 30 samples were prepared with tests conducted under standard laboratory safety precautions.

Table 4 List of Applied Apparatus and Equipment

Testing/Process	Testing Parameters/Processing	Testing Methods/Procedures	Apparatus and Equipment
Crushing coconut shell	Max. 10 cm, moisture 4-5%	Crushing	Crusher machine
Ordinary Portland Cement (43-grade), Physical Test	Compressive strength test	IS:4031 (Part 5)-1988	Natural sand, vibrating machine,
	Flexural strength test	IS:4031 (Part 5)-1988	50 Hz Bennewart flex tester
	Initial setting and final setting test	IS:4031 (Part 5)-1988	Gauging trowel, stop watch Vicat's apparatus,

Safety measures include wearing gloves to shield hands from chemical exposure during material handling, employing respirators and dust masks, adhering to fire protection protocols. The identified materials can potentially enhance the utilization of substitute materials in practical applications within the realm of concrete research. If a particular substitution ratio demonstrates notable enhancements in properties such as strength or durability, its implementation could lead to strengthened structures, reduced costs, enhanced performance, or diminished environmental impact in construction material practices.

RESULT AND DISCUSSION

In this research, the compressive and flexural strength test were conducted to assess the test results.

Compressive Strength Test

In this critical research, the most significant properties – compressive strength should be assessed through experiments. However, measuring the strength of concrete mix may be challenging due to excessive shrinkage and subsequent cracking. To determine compressive strength, a 150 × 150 × 150 mm^3 cube is created using a mixture of standard FA, CA, a proportion of partially substituted waste materials (household plastic, e-waste, CCS) cement, and water. Compressive strength is then tested after incorporating 0%, 5%, 10%, 15%, and 20% of certain additives (substituted waste materials). The tests are conducted at 3^{rd}, 7^{th}, 14^{th}, and 28^{th} days post-curing, following standards such as IS:4031 (part 6) (1988), IS:650 (1966), IS:10080 (1982), and IS:269 (1976). Results are shown in Figure 4 and Table 5.

The compressive strength (in N/mm^2) is basically evaluated as:

$$\text{Compressive Strength} = \frac{L_m}{A_c} \qquad (1)$$

Where L_m denotes the highest applied load and A_c denotes the area of the cube.

Based on this research, it is inferred that incorporating 5-10% of waste (CCS, plastic, and e-waste) gives considerable compressive strength. However, the result of the strength assessment is enhanced by extending it to 28 days and 45 days to ascertain the complete cement strength. Substituting 5-10% of the waste results in considerable compressive strength.

The strength gain from 3rd to 7th days is merely around 10% for a standard concrete mix. However, in the case of various additive mixtures incorporating plastic, e-waste, and CCS, the average strength escalation from 3rd to 7th days is heightened to 58%, presented in Figure 4.

Based on the investigation of this experimental result, it is concluded that the inclusion of 5-10% additives (plastic, e-waste, and CCS) can yield a considerable and satisfactory compressive strength level, a finding corroborated by other researchers as well. This research limitation lies in its evaluation period, which is extended to the 28th and 45th days to ascertain the complete strength potential of the concrete. Ultimately, the compressive strength is workable through the substitution of up to 5-10%.

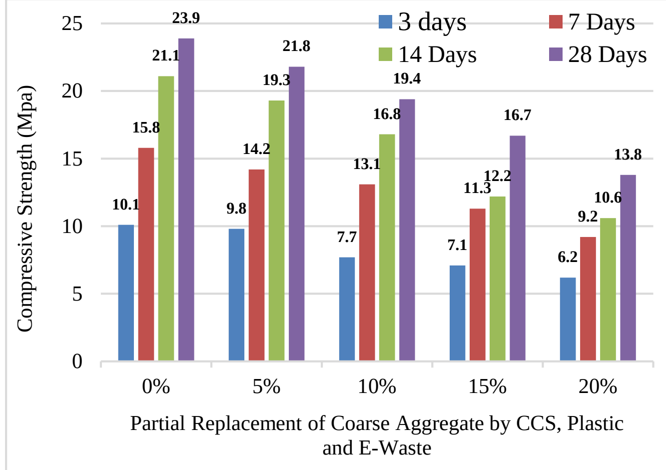

Figure 4 Compressive Strength Test Result

Table 5 Compressive Strength Test Result

Coarse Aggregate	CCS	Plastic Waste	E-Waste	Total Waste	Compressive Strength in MPa			
					3^{rd} Day	7^{th} Day	14^{th} Day	28^{th} Day
100%	0%	0%	0%	0%	10.1	15.8	21.1	23.9
95%	3%	1%	1%	5%	9.8	14.2	19.3	21.8
90%	6%	2%	2%	10%	7.7	13.1	16.8	19.4
85%	9%	3%	3%	15%	7.1	11.3	12.2	16.7
80%	12%	4%	4%	20%	6.2	9.2	10.6	13.8

Table 6 Flexural Strength Test Result

Coarse Aggregate	CCS	Plastic Waste	E-Waste	Total Waste	Flexural Strength in MPa		
					7^{th} Day	21^{st} Day	28^{th} Day
100%	0%	0%	0%	0%	2.7	2.9	3.38
90%	6%	2%	2%	10%	2.5	2.7	3.1
80%	12%	4%	4%	20%	2	2.2	2.8

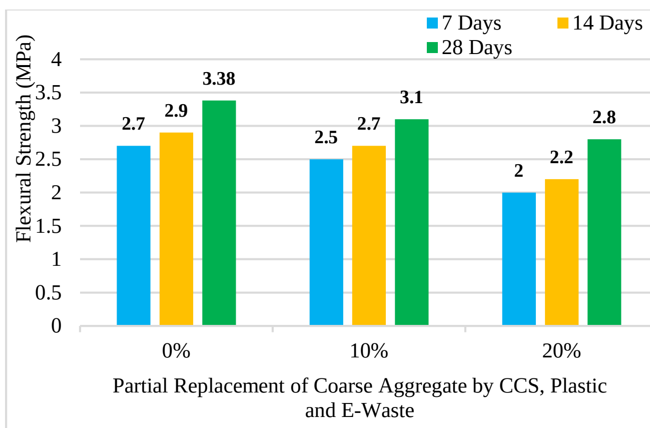

Figure 5 Flexural Strength Test Result

Flexural Strength Test

The ASTM standard for flexural strength is generally measured using this equation:

$$\text{Flexural Strength} = \frac{3PL}{2bd^2}\,(\text{MPa}) \qquad (2)$$

where, P is the highest load (in Newton) applied to the sample.
L denotes an effective span sample depth.
b denotes the sample width.
d denotes the sample depth.

The test result of flexural strength is presented in Figure 5 and Table 6. The testing of flexural strength is very important, as it evaluates the capability of the concrete to respond bending load. It is very crucial for structures like beams and slabs.

It ensures the safety, reliability, and performance of concrete structures, quality control in production, durability, and compliance with building construction. The considerable flexural strength (3.1 MPa) achieved at 28 days in this experiment was achieved by 10% replacement of CA with CSS, plastic, and e-waste.

Setting Time

For ordinary Portland cement, the setting time is important property as it evaluates the time taken for the concrete to change from a plastic into a solid state. It also helps in quality control to achieve considerable and satisfactory strength and durability properties in the structure. The initial setting time is found to be around 29 minutes after 10% replacement of waste for CA.

Result Discussion in Relation to Previous Studies

The results in this article indicate that incorporating 5-10% of CCS, plastic, and e-waste represents a considerable, acceptable, and satisfactory level of compressive strength. This result aligns with previous results in the literature[20,25] that reported use of plastic waste as a partial substitution in the concrete. Furthermore, researchers in[19,22,26,32] mostly reused a common thermoplastic polymer called "polyethylene terephthalate (PET)" as a partial substitution in concrete. Studies in[20,24,25,27,31,33,34] show mainly the reuse of plastic and e-waste in construction. The survey conducted in the literature shows that beyond the uncertain portion of replacement, compressive strength tends to decline due to weak bonding between plastic and cement; this trend is also corroborated in the results of this article.

Environmental Impact and Sustainability

By integrating 10% of natural aggregates such as CCS with a small amount of e-waste and plastic waste as partial replacements for CA, the dependability on natural stone aggregates can significantly be reduced, which means reduced mining, processing, and CO_2 emissions. Moreover, reusing e-waste and plastic waste components helps in the mitigation of the hazardous emissions and reduced environmental pollution and health risks, which are directly associated with the improper disposal, such as toxic fumes generated from plastic incineration, and it diverts non-biodegradable materials from landfills. So, the integration of these waste materials into concrete production supports sustainable waste management policies. The incorporation of up to 10% waste materials does not significantly compromise strength, which makes it a feasible and considerable application for eco-friendly construction. Comparative analysis with conventional disposal methods such as incineration and landfilling highlights reduced environmental hazards associated with toxic emissions.

Efficiency of the Result

The efficiency of the result can be calculated, and the efficiency percentage can be incorporated for both compressive and flexural strength relative to the control mix (0% waste).

Efficiency Percentage Calculation:

The efficiency percentage of waste material mix as compared to conventional concrete is calculated using the equation below:

$$\text{Efficiency} = \frac{\text{Strength of Waste Incorporated Mix}}{\text{Strength of Conventional Concrete}} \times 100\%$$

Compressive Strength Efficiency (at 28 Days):

Table 7 represents the efficiency of compressive strength, which shows that up to 5-10% waste substitution maintains over 80% efficiency, which makes it an acceptable and viable sustainable alternative. A significant reduction is observed beyond 10% due to weaker bonding between waste materials and concrete mix.

Table 7 Efficiency of Compressive Strength

Waste Percentage	Compressive Strength (MPa)	Efficiency (%)
0% (control)	**23.9**	**100%**
5% waste	21.8	91.2%
10% waste	19.4	81.2%
15% waste	16.7	69.9%
20% waste	13.8	57.7%

Flexural Strength Efficiency (at 28 Days):

Similarly, the Table 8 represents the efficiency of flexural strength, which shows that up to 10% waste substitution maintains over 90% efficiency, which also makes it an acceptable and viable sustainable alternative.

The variations in compressive and flexural strength depend on the properties of the waste materials (CCS, plastic, and e-waste), which have been used as partial substitutes in concrete. Due to the hydrophobic nature of plastic and e-waste, they usually show lower bonding with cement, which leads to the reduction in strength. However, CCS (a natural substitute) provides better particle interlocking, which contributes to considerable and sustained compressive and flexural strength, so as a substitute material, the proportion of CCS was kept higher than plastic and e-waste.

Table 8 Efficiency of Flexural Strength

Waste Percentage	Flexural Strength (MPa)	Efficiency (%)
0% (control)	**3.38**	**100%**
10% waste	3.1	91.7%
20% waste	2.8	82.8%

Limitation of the Research

In this experimental research, the aggregate, including more than 10% replacement of plastic, e-waste, and CCS for CA, did not demonstrate a significant and noteworthy compressive or flexural strength. The smooth and glossy nature of the plastic material prevents good bonding with concrete components, so more than 10% of this waste results in a lack of strength improvement. This study validates the viability of using synthetic CA made from plastic waste as building materials, particularly when making composite cement and concrete for use in pavements, roads, and highways.

Conclusion and Future Work

This research explores the potential of utilizing household e-waste, plastic waste, and CCS as partial replacements for CA in concrete to address sustainable development challenges. The experimental results show that mixing 5-10% by weight of these waste materials as CA in the concrete mix maintains ideal and considerable compressive and flexural strength for M25-grade concrete materials. These experimental results suggest that combined plastic, e-waste, and CCS can effectively contribute to the mechanical characteristics of the concrete, thereby maintaining its structural integrity and durability. However, it is observed that exceeding 10% of waste into concrete (optimal replacement ratio) may compromise the compressive and flexural strengths of the concrete, and in the waste material, the ratio of CCS must be higher because plastics have bad characteristic bonding with concrete materials. In this research, among the waste materials, CCS was included at 60%, and plastic and e-waste were included at 20-20%.

Future research endeavors focus on further exploring the feasibility and performance of alternative waste materials in the concrete mixtures beyond the scope of this study. This includes investigating the shrinkage, long-term durability, and permeability properties of concrete integrating e-waste, plastic waste, and CCS to assess their suitability for diverse construction applications. Moreover, efforts should be directed towards optimizing the processing techniques and treatment methods for incorporating these waste materials into concrete, ensuring compatibility with existing construction practices and standards. Additionally, holistic life cycle assessments should be conducted to assess the environmental consequences and sustainability benefits associated with the utilization of alternative aggregates in concrete production. By addressing these research gaps and challenges, stakeholders in the construction industry can harness the full potential of e-waste, plastic waste, and CCS as eco-friendly and cost-effective substitutes for natural aggregates, thereby advancing the paradigm of sustainable construction practices and mitigating the environmental footprint of infrastructure development.

Extensive research at nano-scale and testing are necessary to ensure that the e-waste concrete meets the required structural and durability standards for specific construction applications. Collaboration between researchers, engineers, and regulatory bodies is crucial to advancing and implementing sustainable practices in the construction industry.

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Conflict of Interest Statement

The authors state that there is no conflict of interest in the paper.

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