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Performance Assessment of E-Waste Plastic as a Sustainable Natural Aggregate Substitute in Traditional Concrete: A Comprehensive Review

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ABSTRACT

Globally, e-waste plastic recycling has emerged as a more popular and creative way to manage electronic waste, which is also being accepted since this resource is available in enormous amounts, comprises many kinds of hazardous components, and possesses a very low recycling rate. Growing urbanization, industrialization, and economic expansion are driving global concrete production, causing pollution and depleting natural resources. Using e-waste plastic as a natural aggregate presents a novel method for conserving resources and addressing the challenges of electronic waste, plastic, and concrete production. This article discusses different e-waste plastic types, techniques for producing e-plastic aggregates, and their application in traditional concrete. Additionally, this study examined the behavior of e-waste plastic aggregates, which affect various concrete characteristics. These include fresh properties such as workability, as well as hardened characteristics such as density (both fresh and dried), splitting tension strength, flexural strength, compressive strength, and durability aspects such as chloride attack and thermal resistance. Reusing electronic waste plastic as aggregates is also a new hope for protecting the environment and guaranteeing the secure disposal of the enormous amount of e-plastic waste generated. However, additional research is needed to address e-waste disposal challenges and its use in conventional concrete.

INTRODUCTION

Advances in science and technology have driven the rapid expansion of the electronics and electrical systems sector, now the fastest-developing sector across the globe (Ilankoon et al. 2018, Wang & Xu 2014, Yadav & Upadhyay 2015). These sectors have changed how people live and influenced communication, healthcare, and defense in a way that has resulted in notable advancements over time (Danish et al. 2023, Hamsavathi et al. 2020, Ullah et al. 2022, Wang & Xu 2014, Wath et al. 2011). Technology companies constantly introduce new, eye-catching products to dominate the stable market. For instance, in 2019, the central processing unit's (CPU) life expectancy in personal computers (PCs) dropped from 6 to 4 years and from 3 to 2 years in 2005, respectively, while the lifespan of cell phones is less than 2 years (Akram et al. 2019, Babu et al. 2007, Ilankoon et al. 2018, Islam et al. 2020, Kang & Schoenung 2005, Needhidasan et al. 2014, Shamim 2015, Tipre et al. 2021, Xu et al. 2012). Modern society relies on creatively and newly designed electrical and electronic systems. Additionally, its effects reduce the price of electrical and electronic products and assist many people in developing and impoverished nations in improving their standard of living (Babu et al. 2007, Shamim, 2015). Increased demand from people utilizing new products more frequently causes massive production of electrical and electronic equipment, which further shortens device lifespans and generates an extensive amount of e-waste (Babu et al. 2007, Yong et al. 2019). E-waste, often recognized as "E-waste," is a shorthand form of unwanted electrical and electronic devices, including copper, glass, steel, plastic, and other components, as well as electronic devices that present difficulties in recycling (Luhar & Luhar 2019). Specifically, electronic waste (e-waste) comprises items such as PCBs, televisions, DVD players, refrigerators, freezers, cell phones, MP3 players, and other electronic devices that are discarded after a relatively short period of use (Fadaei 2022, Wath et al. 2011). The main categories of e-waste are illustrated in Fig. 1. The European Union (EU) states that electronic waste is escalating annually at a rate of between 3% and 5% (Akram et al. 2019, Babu et al. 2007, Gaidajis et al. 2010, Gupta 2023, Ilankoon et al. 2018, Liu et al. 2023, Tipre et al. 2021, Tuncuk et al. 2012, Van Yken et al. 2021). E-waste is composed of 1000 diverse kinds of materials, both toxic and non-toxic, all of which pollute the environment. If toxic materials such as mercury, arsenic, cadmium, and lead are not properly managed, they will lead to health issues. Nontoxic resources such as platinum, gold, copper, and silver are recycled (Brindhadevi et al. 2023, Kurup & Kumar 2017a, Needhidasan et al. 2014, Wath et al. 2011). In 2019, only 17.4% of the total 53.6 million metric tons of e-waste produced worldwide was recycled appropriately. The balance of 82.6 percent was not officially reported or recycled. In 2019, 50 million metric tons of electronic waste were created in Asia, America, and Europe, as opposed to 0.7 and 2.9 million metric tons in Oceania and Asia, respectively. Globally, e-waste is predicted to attain 74.7 million metric tons by the year 2030 and 110 million metric tons by the year 2050 (Baldé et al. 2022, Elgarahy et al. 2024, Liu et al. 2023, Rajesh et al. 2022, Shahabuddin et al. 2023, Van Yken et al. 2021). Forecasts of global e-waste generation around the world are typically shown in Fig. 2. The total volume of electrical and electronic equipment (WEEE) constitutes approximately 8% of all municipal solid waste (Fadaei 2022). Plastic is one of the most essential components of e-waste. Tackling e-plastic waste management is the most significant challenge worldwide. The presence of flame retardants significantly hinders the recycling of these materials, despite several technological advancements (Danish et al. 2023, Hamsavathi et al. 2020, Sahajwalla & Gaikwad 2018). Many researchers have employed diverse approaches to manage e-waste plastics, one of which is their use of electronic waste plastics in the construction industry. Electronic waste, such as printed circuit boards, as illustrated in Fig. 3, recovered acrylonitrile butadiene styrene, high-impact polystyrene wastes, and other varieties of electronic waste can be utilized to create sustainable concrete (Kurup & Kumar 2017b). Concrete is the second most widely utilized construction material globally, after water (Nilimaa 2023). Conventional concrete is widely utilized because of its excellent mechanical properties, such as high compressive strength, long-lasting durability, and capability to be molded into the desired shape during casting (Kumar et al. 2025). The increasing need for infrastructure development is evident in the increasing amount of concrete produced daily. The rising requirement for concrete and its associated effects have led to the possibility that the exploitation of natural aggregates is depleting natural resources globally, hence endangering the needs of future generations. Aggregate, which constitutes more than 70% of the material's volume, is one of the most crucial ingredients used in concrete. Focusing on the conservation of natural materials is vital for minimizing the impacts of resource depletion and climate change (Padmanaban et al. 2020, Ullah et al. 2021). To reduce the use of natural aggregates as much as possible, many researchers are attempting to replace them, either entirely or partially, with waste materials such as e-waste, recycled natural aggregates, granite, marble, regular plastic, refractory bricks, and ceramic tiles. Nevertheless, recycled natural aggregates, granite, marble, regular plastic, refractory bricks, ceramic tiles, and other waste materials cannot be produced in sufficient quantities to meet the requirements of the growing building sector. In this case, the abundant generation of e-waste will be directed toward the substitution of natural aggregates to encourage the use of green concrete and preserve natural resources. After analyzing several research articles, we found that nearly all researchers have worked on e-waste recycling, management, usage in concrete, and the consequences for humans and the environment. Little research has been conducted to enhance the strength of concrete composites composed of e-plastic waste. The major aim of this detailed analysis is to scrutinize the behavior of e-waste plastic as a sustainable substitute for natural aggregates in traditional concrete, in addition to the challenges of using electronic waste plastic in lieu of natural aggregates. Additionally, it provides an in-depth exploration of issues related to e-waste plastics, such as recycling, toxic materials, environmental harm, and health concerns.

MATERIALS AND METHODS

The growing requirement for concrete and its byproducts, combined with the mounting problem of electrical waste, has prompted investigations into the viability of replacing natural aggregates in concrete with e-waste materials. This study primarily examines the behavior of e-plastic waste as a traditional aggregate in regular concrete and its effect on the mechanical and durability characteristics of the material. The most innovative research articles on e-waste plastics were considered in this review. A variety of sources, including Google Scholar, Science Direct, Springer, Taylor

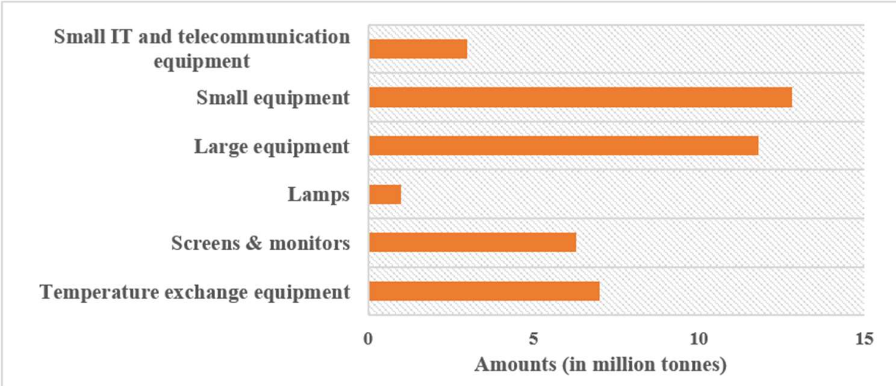

Fig. 1: Classification of e-waste (Kumar et al. 2017).

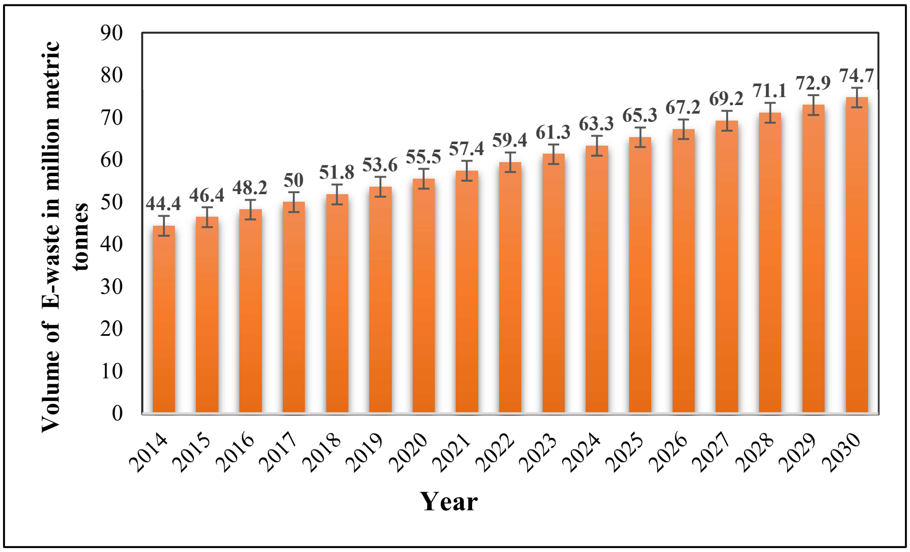

Fig. 2: E-waste production from 2014 to 2030 (Forti et al. 2020).

Fig. 3: Raw printed circuit boards (Gupta & Singh 2021).

& Francis, and other notable works that were accessible as open resources, were used to conduct the literature survey. Specialized keywords such as "electronic waste," "e-plastic aggregate," "e-waste plastic," and "e-waste aggregate" are typically used for reviews. The information was gathered such that the work reports included the major discoveries of the previous few years, including the formation technique, recycling procedure, and usage of rejected plastic as both fine and coarse aggregates in conventional concrete. A comprehensive review was conducted, drawing on a range

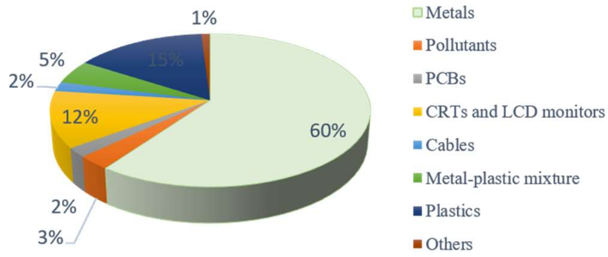

Fig. 4: Composition of e-waste (Chakraborty et al. 2022, Mtibe et al. 2023, Tipre et al. 2021).

Table 1: Environmental impacts of e-waste (Luhar & Luhar 2019, Manjunath 2016).

Component category of E-waste	Procedure used for	Possible Effects on Groundwater, Soils, Health, and Environmental Hazards
Computers, TVs with CRT screens, monitors, ATMs, cameras, and so forth.	Removal and disposal of items following a breakup	The leaching of heavy metals like lead, barium, and others introduces toxic phosphorus into underground water.
PCBs are thin, plate-like structures and a few e-constituents for mechanical support and electrical connection.	Recovering the best metal items requires eliminating soldering, outdoor fire, and an acid bath.	Gas leaks, air, surface, and subsurface water pollution, and glass dust
Chips and a couple of au-plated components.	A chemical stripping procedure using HNO_3 and HCl, along with setting the chips on fire	Fish and plants are acidified when hydrocarbons, dense metals and materials exposed to bromination, such as dioxin, seep directly into surface and subterranean waters.
Computer cords	Cu is extracted by chemical and fire stripping outside.	Discharge of hydrocarbon ash into the atmosphere, soils, and water vapor.

Table 2: Contaminates in e-waste (Akram et al. 2019, Gaidajis et al. 2010, Rao et al. 2017).

Elements	Occurrence in electronic waste	Associated health and environmental factors
Polychlorinated biphenyls	Old-fashioned light fluorescent ballasts with transformers, condensers, and capacitors.	It causes cancer, which affects the endocrine, neurological, immunological, and reproductive systems of humans.
Chlorofluorocarbon	Insulation foam and refrigerants are used.	Combustion of halogenated compounds may produce dangerous fumes.
Arsenic	They are present in trace amounts as gallium arsenide in light-emitting diodes.	Long-term exposure to it is extremely harmful to health.
Polyvinyl chloride	Cable insulation	Processes using high temperatures and wires that convert chlorine into dioxins and furans may release
Barium	Computer screens and plasma displays.	Moisture can cause combustible gases, such as hydrogen.
Beryllium	Exist in wires, power supply boxes, including silicon-controlled rectifiers, and heat sinks for computer chips.	harmful if consumed
Cadmium	Present in plastics, printer ink, and cell phones	It is extremely harmful and can ruin your health over time.
Chromium VI	Floppy disks and data tapes	Highly poisonous and detrimental to health over an extended period. Additionally, it causes allergic reactions.
Lithium	Present in Li-batteries	Capable of releasing explosive hydrogen gases when wet.
Mercury	Useful for mercury-wetted switches and fluorescent lights.	Highly toxic and detrimental to health over time.
Nickel	Like electron guns and rechargeable nickel-cadmium batteries.	It is possible to experience allergic reactions.
Zinc sulfide	Used in CRT screens in conjunction with rare earth elements.	Harmful if breathed in
Residue from toner	Printer and copier cartridges for laser devices.	Inhaling dust raises the chance of explosion.

of papers, to study the impact of waste e-plastic aggregates on the unique characteristics of ordinary concrete. Moreover, a quantitative evaluation of fragmented information was employed to examine the suitability of e-plastic aggregates as a sustainable and safe replacement for fine or coarse aggregates in concrete**.**

E-Waste Composition

E-waste is a complex mixture of potentially dangerous and helpful materials. The complex components that make up e-waste comprise a wide spectrum of both "hazardous" and "non-hazardous" substances. Inadequate handling of these materials may result in significant damage to human health and the environment. The electronic waste plastic can be categorized into eight distinct classes based on its composition, as depicted in Fig. 4. E-waste usually consists of the following materials: 60% metals, 3% contaminants, 2% printed circuit boards (PCBs), 12% cathode ray tubes (CRTs) and liquid crystal displays (LCDs), 2% cables, 5% metal-plastic blend, 15% plastics, and 1% miscellaneous goods. Factors such as the types of electronic devices, their models, producers, ages, and production dates significantly affect the formation of e-waste (Tipre et al. 2021, Yong et al. 2019). The various e-waste components and their environmental impacts are listed in Table 1. Compared to regular municipal waste, e-waste contains thousands of harmful components and metals, such as lead, phthalates, beryllium, antimony, cadmium (Cd), chromium, mercury, polyvinyl chlorides, and brominated flame retardants, making it significantly more hazardous (Elgarahy et al. 2024, Luhar & Luhar 2019). Extended exposure to the reproductive and endocrine systems, joints, organs, and brain circuits is detrimental. Some of these substances are partially neurotoxic and carcinogenic (Yadav & Upadhyay 2015). The contaminated ingredients present in e-waste are listed in Table 2.

Techniques for Recycling Plastic from Used Electronics

The first stage of plastic recycling from electronic waste is the collection, physical selection, disassembly, and shredding of electronic devices. (Ceballos & Dong 2016). Materials, both metallic and non-metallic (plastics, glass, and ceramics), are mechanically detached from shredded electronic waste (Patil & Ramakrishna 2020, Shahabuddin et al. 2023). Polyethylene, acrylonitrile-butadiene-styrene,

Fig. 5: Shredded plastic strip of e-waste.

Fig. 6: Formation of e-waste plastic aggregates (Senthil Kumar & Baskar 2015a, 2015b).

Table 3: Physical techniques for extracting metals from WEEE (Tuncuk et al. 2012).

Techniques	Criteria for separation	Sorting metals
Separation by gravity	Specific gravity	Metals derived from polymers
Separation using a magnetic	Vulnerability to magnetic fields	Ferromagnetic from a non-magnetic, ferrous substance
Coronal electrostatic separation	Conductivity of electricity	Costly metals derived from materials that are not metallic
Spread of eddy currents	Density and conductivity of electricity	Switching from non-metals to non-ferrous metals.

polycarbonate, polyesters, polyamides, polypropylene, and high-impact polystyrene are among the polymers that can be recovered from e-waste (Ilankoon et al. 2018, Wang & Xu 2014). Prior to being recycled into goods or transformed into energy, these must be graded. Although e-waste offers valuable engineering plastics such as ABS, recycling remains a challenge because of the presence of numerous polymers, BFRs, and plasticizers, and the limited understanding of the compatibility between plastics during the melt extrusion process (Mtibe et al. 2023). Large amounts of sorted e-waste plastic strips, as shown in Fig. 5, require appropriate recycling infrastructure for a well-established recycling process. The manufactured or processed e-waste plastic aggregate is shown in Fig. 6.

Primary and Secondary Recycling

Melting plastics from e-waste and forming them into new products is a frequently used technique called mechanical recycling (Sugumar & Nayak 2014). In the first recycling, recycled plastic is utilized to produce items that closely resemble virgin plastic products in appearance and performance, whereas in secondary recycling, the retrieved plastic is repurposed to produce new goods with lower functionality requirements than the original materials. The size reduction process begins with the separation of plastic fractions from electronic waste. This involves breaking the plastic waste into tiny pellets or pieces, sorting, and cleaning (based on the desired product, either optical, magnetic, or manual sorting utilizing eddy current separators, as illustrated in Table 3). After sorting, the plastics are put through various melt processing procedures, including injection molding, hot pressing, and melt extrusion (Charitopoulou et al. 2021, Das et al. 2021, Jaidev et al. 2021, Mtibe et al. 2021). A flow diagram of primary and secondary recycling is shown in Fig. 7.

Tertiary Recycling

The third step of chemical and thermal recycling involves the use of depolymerization techniques to separate chemicals and fuels from polymers made from electronic waste through thermal and chemical treatments (Sugumar & Nayak 2014). For e-plastic waste, recycling chemicals enable the processing of polluted polymers without requiring laborious pretreatment steps. Subsequently, plastic portions are repurposed to create valuable items. Catalytic cracking, pyrolysis, hydrogenation, dissolution, and gasification are common processes. The sample is heated to high temperatures (400–800°C under inert conditions) during pyrolysis to produce products such as char, oil, and combustible gases. Pyrolysis produces fewer contaminants than conventional thermal treatments (Charitopoulou et al. 2021). The optimal processing parameters, including temperature, feedstock

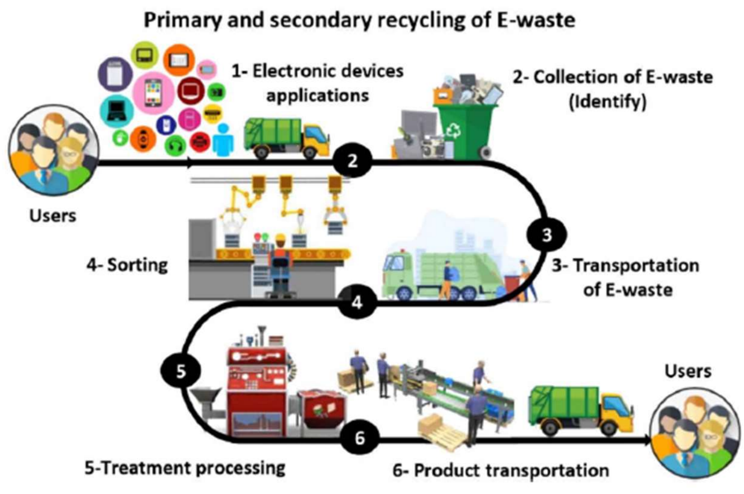

Fig. 7: Primary and secondary recycling of e-waste (Elgarahy et al. 2024).

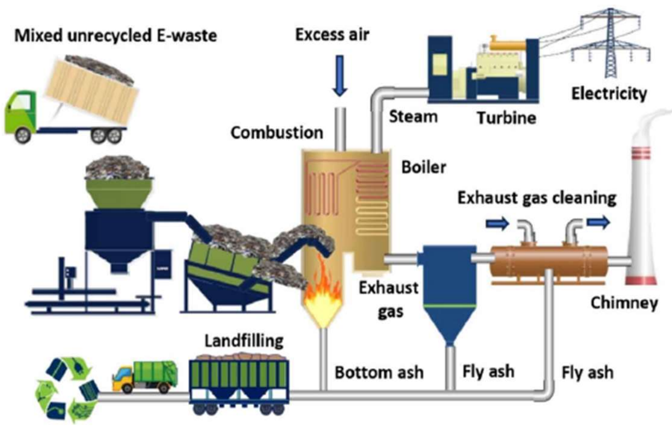

Fig. 8: Tertiary recycling diagram of e-waste (Elgarahy et al. 2024).

composition, heating rate, and time, determine the products produced during pyrolysis. Utilizing catalytic pyrolysis, which lowers the temperature and shortens the residence time, can yield high-value compounds. A flow diagram of the tertiary recycling approach for e-waste is shown in Fig. 8.

Incorporating E-Plastic Waste into Concrete Production

Various studies have been conducted on the use of plastic electronic waste in concrete manufacturing. These discarded components undergo a recycling procedure before being used to make concrete, as shown in Fig. 9, where the raw plastic components from e-waste are crushed and processed into various aggregate sizes, similar to regular aggregates, for the creation of concrete. Processed e-waste, particularly electronic waste plastic particles, is frequently utilized as an alternative to fine or coarse aggregates in concrete mixes. Novel research has highlighted that the materials were organized according to their weight, with e-plastic aggregates replacing natural coarse and fine aggregates based on weight (Arun Kumar & Senthamizh Selvan 2017, Manjunath 2016). According to past studies, e-plastic aggregates were used to substitute 5%–50% of conventional aggregates. The mechanical, physical, and long-lasting characteristics of concrete with these substitutions have been compared with those of regular concrete by previous researchers.

Characteristics of Concrete with E-Waste

Concrete's properties, both fresh and hardened, are evaluated by the physical and mechanical characteristics of its components. Durability, workability, strength, hardness, and water absorption are the primary characteristics of concrete. Multiple studies have analyzed the efficiency of e-waste plastics in enhancing the physical characteristics of

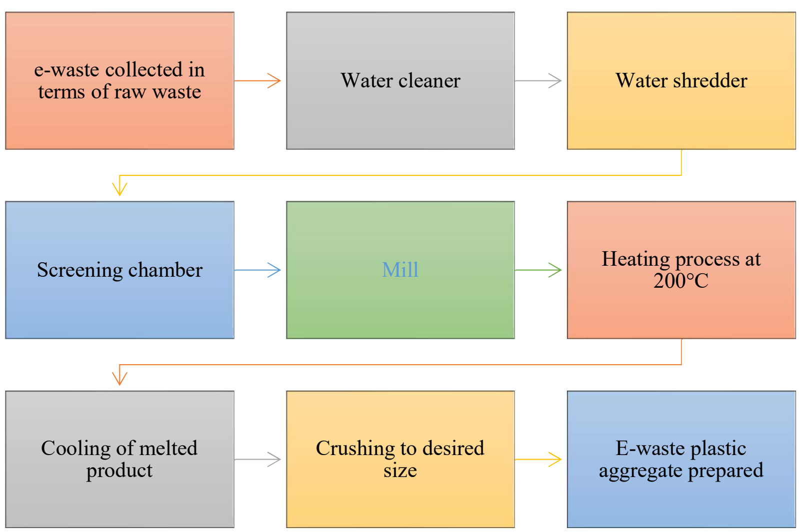

Fig. 9: Manufacturing procedure for e-waste aggregate (Bamigboye et al. 2024, Z. Ullah et al. 2021).

Table 4: Properties of e-waste plastic aggregates (Danish et al. 2023, Lakshmi & Nagan 2011).

Description of Properties	Test data
Color	White and dark
Shape	Irregular
size	4.5 mm-20mm
Specific gravity	1-1.25
Aggregate crushing value	< 2%

concrete. The physical characteristics of the e-waste plastic aggregates are shown in Table 4. The following sections critically explore the impact of e-plastic aggregates on the properties of concrete.

Workability

Published literature shows that the viability of concrete adapted with e-waste varies based on the size and form of the used e-waste. Few studies suggest that substituting coarse aggregates (CA) in concrete with e-plastics can lead to reduced workability. Kumar & Baskar (2015b) demonstrated that the addition of 10%–50% e-plastic in concrete led to a reduction in slump of 25%–65% compared to standard mixes, as the plastic obstructs other ingredients and reduces workability. Kumar & Baskar (2015a) quantified a related remark and observed that concrete mixtures with 10-50% e-plastic waste and water-to-cement ratios of 0.45, 0.49, and 0.53 showed slump reduction of 10-61%, 23-67%, and 31-73%, respectively, with respect to the control mix, with minimal change noted at 50% coarse aggregate replacement. Manjunath (2016) also noted that the use of 10-30% e-plastic waste in concrete resulted in a slump decrease of 10.93% to 41.40% compared to the standard specimen. Rohini & Padmapriya (2021) revealed that the slump value of the bacteria- and e-waste-based concrete was 50% higher at 20% e-waste and 0% to 2% bacteria compared to the control concrete.

Dry Density and Fresh Density

The quality of fresh concrete affects the properties of the prepared concrete. For instance, the slump, fluidity, and consistency of concrete are influenced by its fresh density, whereas its dry density influences its hardened properties. Research on the unique properties of e-waste plastics is limited. Kumar & Baskar (2015b) showed that adding electronic waste plastic to concrete reduced its initial density. According to their research, replacing 10-50% of the coarse particles with e-plastic waste reduced the new concrete density by 1.10-13.58% as compared to the standard mix. The fresh density decreased because the e-plastic waste aggregate had a lower density than the coarse aggregate. Kumar & Baskar (2015a) conducted a similar study using high-impact polystyrene (HIPS) electronic waste aggregates at varying weight-to-cement ratios to produce ecologically friendly concrete. In comparison to the reference specimen, investigators found that at a w/c of 0.53, adding 10-50% e-waste decreased density by 0.61-14.64%. At water-to-cement ratios of 0.45 and 0.59, incorporating similar amounts of e-waste plastic resulted in a fresh density reduction of 0.93–14.41% and 0.77–13.58%, respectively, with respect to the control sample.

Structural Properties of E-Waste Concrete

Mechanical Properties

Compressive strength: The capacity of a material to resist loads that attempt to compress or shorten its dimensions, rather than those that stretch it, is known as compression strength. Kumar & Baskar (2015b) observed that the compressive strength (CS) value drops as the proportion of e-plastic in the mixture rises (10% to 50%), and it exhibited a maximum loss of 47.41% at 50% e-plastic replacement because of one of the causes, namely, insufficient adherence of e-plastic to cement mortar. Another similar study by Manjunath (2016) utilized coarse e-waste plastic (0% to 30%) as aggregate and observed that the compressive strength dropped by 53.05% at 30% e-waste content. In contrast, Ahirwar et al. (2016) replaced 0–30% coarse aggregate with e-waste and 10–30% cement with fly ash, observing a minor drop in compressive strength with respect to the reference concrete. Rohini & Padmapriya (2021) proposed an innovative idea that focused on the addition of microbiologically induced calcite precipitation to electronic waste-treated concrete for strength enhancement. Their results showed that the compressive strength of 15% e-waste plastic concrete improved by 6.26%, 8.41%, and 5.95% with the addition of 0%, 1%, and 2% bacteria, respectively, compared with the control mix. The improvement in the compressive strength of e-waste plastic concrete with the addition of bacteria is attributed to the production of calcium carbonate and its inherent self-healing properties.

Splitting tensile strength: Analyzing the splitting tensile strength of concrete containing varying levels of e-waste plastic aggregates is vital for understanding its performance under tensile loads, particularly because concrete is naturally prone to tensile weakness owing to its brittle characteristics. Research consistently shows that increasing the proportion of e-waste aggregates tends to diminish the splitting tensile strength of concrete. For example, Kumar & Baskar (2015b) indicated that incorporating 10-50% e-waste led to a decrease in the splitting tensile strength of concrete, reducing it by 8.06% to 47.89% compared to the control sample. Additionally, the samples containing e-waste plastic aggregates exhibited a different failure mode in their splitting behavior, unlike the typical brittle failure observed in the reference specimen. A similar remark was conveyed by Kumar & Baskar (2015a) assessed the effect of high-impact polystyrene electronic waste on the splitting tensile strength of concrete. Their results demonstrated that concrete containing e-waste plastic aggregates exhibited ductile behavior, preventing complete separation into two parts, whereas the control specimen experienced brittle failure, splitting into two distinct halves under the ultimate load. This implies that e-waste plastic aggregates can tolerate significant elastic deformation before fully breaking down. A similar study by Manjunath (2016) incorporated e-waste plastic aggregates at replacement levels ranging from 10 to 30 percent for coarse aggregates in the concrete mix. The inclusion of 20% e-waste plastic aggregates improved the 28-day splitting tensile strength of concrete by 10.20% compared to that of the reference sample. Ganesh et al. (2021) conducted a 28-day split tensile test of concrete (M20 grade) containing crushed printed circuit board as fine aggregate replacement at levels of 3% to 25% wt. The split tensile strength reached 1.51 MPa, reflecting an 11.85% increase with 15% fine aggregate replacement using PCB, compared to the control mix strength of 1.35 MPa.

Flexural strength: It measures the capability of a material

Table 5: Summary of effects of e-waste on concrete properties.

Author and Date	Percentage replacement (%)	Replacement method	Grade of Concrete	Strength after 28 days in MPa		
				CS	TS	FS
Manjunath (2016)	0%	E-plastic with FA or CA	M20	44.81	4.90	5.76
	10%			41.25	4.80	4.92
	20%			17.95	5.40	5.28
	30%			19.03	3.80	6.84
Alagusankareswari et al. (2016)	0%	Printed circuit boards with FA	M30	33.11	3.31	5.60
	10%			30.59	3.26	4.67
	20%			25.99	2.62	3.33
	30%			24.46	2.02	3.20
Needhidasan et al. (2020)	0%	E-plastic with CA	M20	45.05	3.90	4.10
	12%			41.95	3.50	4.30
	17%			44.93	4.90	4.80
	22%			41.95	6.70	5.20
Mary Treasa Shinu & Needhidasan (2020)	0%	E-plastic with CA	M40	46.25	4.63	4.54
	12%			44.85	4.09	4.20
	17%			38.24	3.82	4.01
	22%			35.15	3.01	3.84
Rajkumar et al. (2021)	Control	E-plastic with CA	M20	27.83	1.98	4.40
	5%			31.60	2.55	5.07
	10%			33.20	3.10	6.00
	15%			35.50	2.85	6.38
	20%			25.50	2.65	5.09
Ullah et al. (2021)	0%	ABS with CA	M20	34.40	2.68	4.35
	10%			32.20	2.05	4.40
	15%			31.20	1.85	4.30
	20%			28.00	1.81	2.50
Arivalagan (2020)	0%	E-plastic with CA	M30	31.00	4.90	4.40
	10%			32.73	4.40	4.40
	20%			37.50	5.50	4.50
	30%			35.00	3.75	2.90

[5] CS-Compressive strength, TS-Tensile strength, FS- Flexural strength, ABS-Acrylonitrile butadiene styrene plastic, CA-Coarse aggregate, FA-Fine aggregate

to withstand distortion under an increasing load, and numerous studies have explored this property. For instance, Kumar & Baskar (2015b) prepared concrete by replacing coarse aggregates (CA) with variable proportions (10% to 50%) of e-plastic by volume and assessed the 7 and 28-day flexural strength. As the proportion of e-plastic increased, a decline in the flexural strength of concrete was noted. The 10% replacement of coarse aggregate yielded the highest flexural strength values at 7 and 28 days compared to all other replacement percentages. Similarly, Manjunath (2016) noted a 1.14% enhancement in the 28-day flexural strength of concrete with 10% e-waste plastic aggregate compared to the control specimen.

Additionally, their results showed that concrete containing 20% e-waste plastic aggregates exhibited a flexural load capacity comparable to that of the control mix. Ahmad et al. (2022) prepared concrete with nano graphite platelets (doses of 1%, 3%, and 5% by weight of cement) and e-waste plastic coarse aggregates substituted partially at a percentage level of 25% to explore the flexural strength. The specimens with 25% plastic aggregates and 5% nano-graphite platelets exhibited a 31.42% increase in flexural strength. Sharma et al. (2022) developed M30 concrete by using HIPS electronic waste as a replacement for natural fine aggregate at levels of 5% to 25% and conducted a flexural test. The strength decreased by as much as 15.18%, 15.10%, and 16.01% at a 25% replacement level for 7, 14, and 28 days, respectively. The observations indicated that a replacement level of up to 10% e-waste plastic was viable.

Shear strength: Kurup & Kumar (2017) added e-waste fibers to the concrete mix in proportions of 0.6%, 0.8%, and 1% by OPC weight, and silica powder replaced 10% of the cement content to produce silica fiber-reinforced concrete (SFRC). The incorporation of silica powder into fiber-reinforced concrete improves its shear strength compared to that of conventional fiber-reinforced concrete. Silica fiber-reinforced concrete exhibited a 21.5% decrease in shear strength, whereas fiber-reinforced concrete experienced a 25.6% reduction compared to conventional concrete with the inclusion of 1% fiber. Although there was a decline in strength, the addition of e-waste fibers significantly minimized the brittleness of the conventional concrete. A Summary of the effects of e-waste on various concrete properties is presented in Table 5.

Durability Characteristics of Concrete Incorporating Electronic Waste

This attribute is vital for practical applications in the industry. Consequently, assessing the durability of e-waste concrete to determine its long-term performance and suitability is essential for its application. There is still a shortage of studies on the long-term behavior of e-waste concrete, as mentioned below.

Water Absorption Properties

To evaluate the suitability of e-waste concrete for construction applications, it is essential to conduct additional studies on the water absorption capabilities of this plastic-based concrete. Concrete durability is associated with lower water absorption values; however, this property has not been widely investigated. Ullah et al. (2022) conducted tests to assess the water absorption characteristics of concrete incorporating e-waste as a coarse aggregate. As the replacement of natural coarse aggregates with e-waste increased from 0% to 20%, the reduction in water absorption became more pronounced, which was linked to a decrease in the sorptivity coefficient. When coarse aggregates were replaced with e-waste at levels of 10%, 15%, and 20%, the sorptivity coefficient of the concrete decreased by 12.2%, 14.5%, and 29.0%, respectively.

Alternate Wetting and Drying

The ability of concrete to endure weathering in various wet and dry environments is assessed using sea tidal waves as stress factors. Structural durability diminishes when cracks develop due to stress and the reinforcement becomes weathered. Ullah et al. (2022) created concrete with electronic waste, demonstrating improved resistance to compressive strength deterioration after cycles of wetting and drying, with resistance increasing as electronic waste content rose, in contra st to concrete with natural coarse aggregates.

Abrasion Resistance

This has been investigated in several studies, which have improved the viability of the material. However, research on this topic is limited. Ullah et al. (2021) noted that a higher percentage of e-waste improves the abrasion resistance. The experimental findings indicated that substituting 10%, 15%, and 20% of natural coarse aggregates with e-waste enhanced the abrasion resistance by 39.8%, 44.3%, and 46.4%, respectively. This was because of the increased toughness and abrasion resistance of the e-plastic aggregates compared to those of the natural aggregates.

Ultrasonic Pulse Velocity (UPV)

This durability examination is essential for evaluating the homogeneity and consistency of concrete. Using this test, the compactness of the concrete and flaws such as pores and cracks were identified. In this context, Kurup & Kumar (2017) created fiber-reinforced concrete using PVC waste at 0.6%, 0.8%, and 1% by weight of cement and silica-reinforced concrete with 10% of the cement weight replaced by silica. It was discovered that the various concrete mix types had values above 4.2 km.s.$^{-1}$ The specimen with e-waste fibers demonstrated a declining UPV value, which was attributed to the ability of the fibers to absorb pulse waves. A similar study by Ullah et al. (2021) found that as the content of the e-waste aggregate increased, the UPV of the concrete decreased, which was due to an increased air void content and irregular distribution of the plastic aggregate. When the natural coarse aggregate was replaced by 10%, 15%, and 20%, the UPV of the e-waste concrete decreased by 1.2%, 1.9%, and 3.3%, respectively. The incorporation of e-waste plastic as a coarse aggregate had a minimal impact on concrete quality, with UPV values ranging from 3660 to 4575 m.s^{-1}.

Chloride Penetration

Chloride attack must be considered when evaluating the long-term resilience of concrete, as it is a primary cause of reinforcement corrosion, which is of great importance. For instance, Kumar & Selvan (2017) conducted a rapid chloride ion penetration test using e-waste, where coarse aggregates (5%, 10%, and 15%) and fine aggregates (10%, 20%, and 30%) in fiber-reinforced green concrete were replaced with 30% GGBS instead of cement. The control concrete exhibited modest levels of chloride ion penetration, whereas the fine and coarse aggregate replacements made from e-waste showed moderate levels of chloride ion penetration, with charges passing between 3271 and 3966 coulombs.

Temperature Resistance of Electronic Waste Concrete

It is important to understand the effect of temperature on the material strength for the construction of fire-resistant structures. This test evaluates the response of a material to fire and its tendency to ignite. For instance, Lakshmi & Nagan (2010) revealed that as the amount of electronic waste plastic aggregates increases, the compressive strength of concrete decreases at elevated temperatures. Another observation by Ullah et al. (2021) developed e-plastic waste-based concrete to assess its performance at elevated temperatures ranging from 150 to 350 °C, applying e-waste at various replacement percentages for coarse aggregates. They reported a compressive strength decrease of 21-26% at 150 °C and 39% at 300 °C. The appearance of e-waste plastic concrete before and after thermal exposure is shown in Fig. 10. However, this reduction is minor compared to the strength losses observed in the standard mix. Further investigation is required to confirm that electronic waste plastics perform adequately as construction materials at high temperatures.

SEM and XRD Analysis of Electronic Waste Concrete

Balasubramanian et al. (2021) utilized e-waste plastic to replace 5% to 20% of the coarse aggregate volume in the concrete matrix for SEM and XRD analysis. SEM analysis identified darker regions associated with denser packing and lower porosity of calcium hydroxide (CH) in conventional concrete. It also revealed large hexagonal CH plates, a small fibrous crystalline C-S-H gel, and needle-like crystalline ettringite. Conversely, the bond between the waste plastic aggregates and the concrete matrix was found to be weaker, as shown in Fig. 11. In the X-ray diffraction analysis, the control specimen demonstrated prominent crystal phases at 21°, 26.7°, and 50.08°, linked to silicon dioxide and crystal phases at 28.16° and 81.72°, associated with calcite. Low-intensity peaks at 18.48° and 80.38° were also detected,

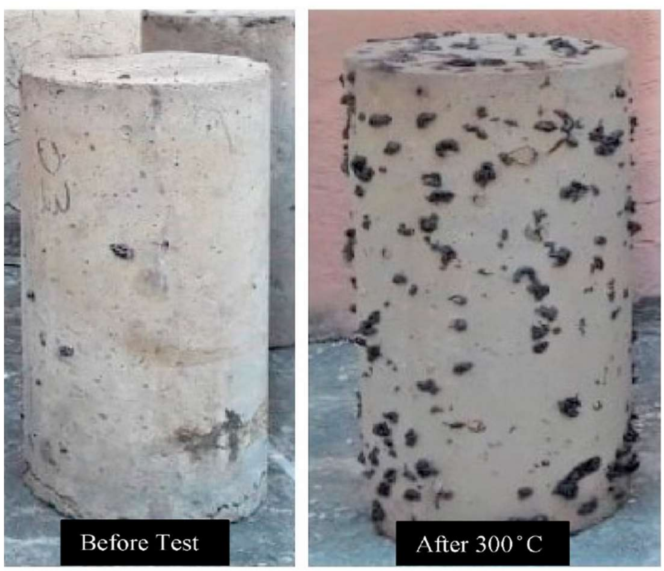

Fig. 10: Photographic view of e-waste concrete before and after exposure to high temperature (Ullah et al. 2021).

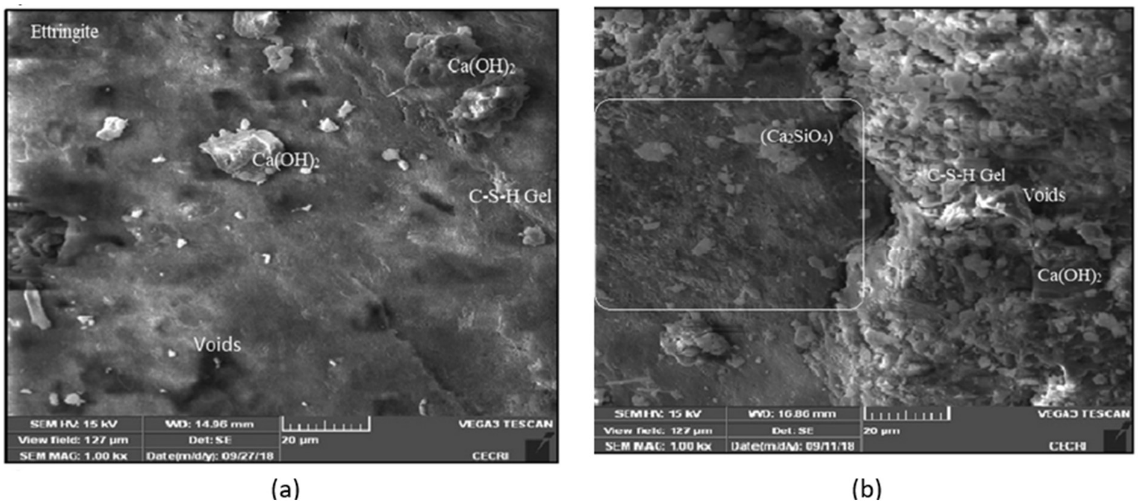

Fig. 11: SEM images of (a) normal concrete and (b) E-waste concrete (Balasubramanian et al. 2021).

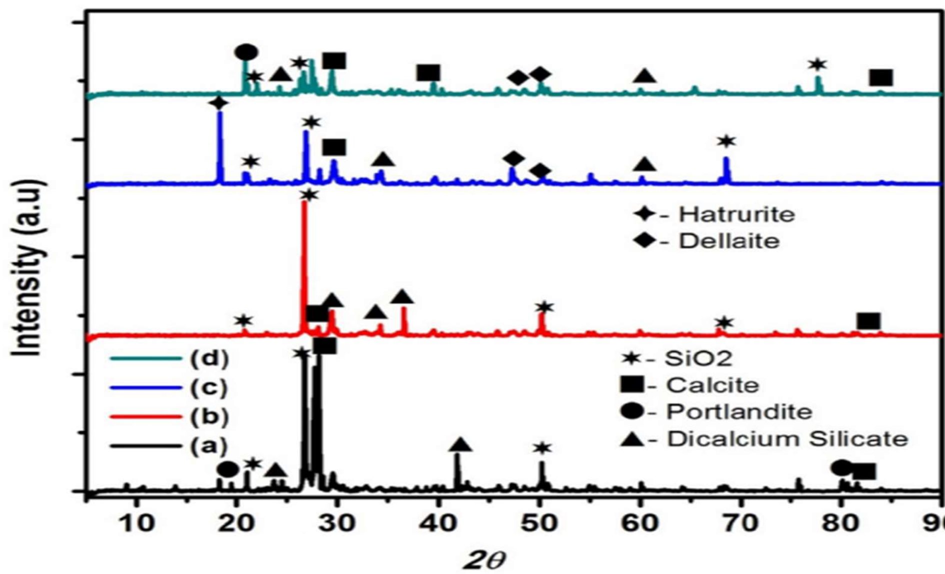

Fig. 12: XRD patterns of (a) control concrete and (c) E-waste concrete (Balasubramanian et al. 2021).

which were associated with calcium hydroxide. Conversely, the introduction of 20 % e-waste plastic resulted in a new peak for hatrurite, and the most intense crystal phases of dellaite occurred at 18.15° and 47.17°, respectively. However, the strength characteristics of the matrix were reduced owing to the expansion and fissures caused by the presence of water. Strength reduction occurred owing to the lower formation of dicalcium silicate ($Ca2SiO4$). The XRD pattern of the composite concrete matrix is shown in Fig. 12.

Comparison of E-Waste Concrete with Other Alternative Aggregate Concretes

Islam et al. (2025) investigated the use of e-waste as a partial replacement for natural coarse aggregate in concrete, with substitution levels varying from 10% to 20% by mass. After 28 days of curing, the study observed a decline in compressive strength by 13.41% to 25.50% and in tensile strength by 11% to 19.26% relative to conventional concrete. Afshinnia & Rangaraju (2016) observed that replacing natural coarse aggregate with coarse waste glass notably decreased both compressive and splitting tensile strengths, with a 38% drop in compressive strength. Nováková & Mikulica (2016) produced sustainable concrete by substituting natural aggregates with recycled concrete aggregates (RCA) and found that replacing raw aggregates with up to 20% RCA did not adversely affect the concrete's physical or mechanical properties. Alaud et al. (2023) created sustainable concrete by substituting gravel with recycled rubber particles at 10%, 15%, and 20% by volume. The inclusion of rubber reduced the density of concrete, resulting in a compressive strength drop of over 26% at 20% replacement. Li et al. (2025) investigated the effects of varying rubber replacement ratios (0%, 5%, 10%, and 15%) on the fundamental mechanical, dynamic, and frost resistance properties of rubber recycled aggregate concrete. At a 15% replacement level, the results showed a 36.86% reduction in compressive strength, 44.07% decrease in axial compressive strength, and 25.76% drop in elastic modulus. Conversely, the splitting tensile strength improved by 46.29% and the impact resistance increased by 181.3 J. Based on these findings, it can be concluded that a 10–15% replacement level of alternative aggregates, such as rubber, glass, or recycled aggregates, may offer an optimal balance between mechanical performance and sustainability, making it a promising range for producing eco-friendly concrete without significantly compromising structural integrity.

Potential Strategies for Enhancing the Characteristics of E-Waste Concrete

When e-waste is mixed with concrete, the peculiar properties of the e-waste components may result in diminished strength. Researchers have proposed several solutions to overcome this issue and make concrete altered with e-waste useful as a building material. The following are crucial strategies for enhancing the characteristics of concrete containing e-waste:

1. Optimizing the Design of Concrete Mix: Researchers have suggested adjusting the water-to-cement ratio, choosing suitable e-waste aggregates, and incorporating chemical admixtures to enhance the workability and strength of e-waste concrete. Studies have shown that these changes can significantly enhance the overall strength.
2. Incorporating Admixtures: To improve the workability and mechanical strength of fresh e-waste concrete, incorporating superplasticizers and mineral admixtures such as fly ash, silica fume, and slag is recommended. Previous research has shown that superplasticizers improve the strength and fluidity of e-waste concrete.
3. Fiber reinforcement: It has been suggested that strengthening concrete treated with e-waste with fibers that are synthetic or natural could enhance the material's mechanical properties.
4. Microbial Additives in Concrete: Strength improvements in e-waste concrete can be achieved through an innovative approach that facilitates calcium carbonate precipitation, and microorganisms help reduce the negative impacts associated with e-waste aggregates.
5. Incorporating graphene oxide into concrete: Graphene oxide (GO) is a novel nanofiller that significantly improves the density and hardness of cementitious composites by reducing porosity and reinforcing the microstructure. Consequently, incorporating GO can improve the hardened characteristics of e-plastic waste concrete.

Combining these techniques will allow for improvements in e-plastic waste-modified concrete, transforming it into a more valuable and eco-friendly building material for the construction industry. Adopting these strategies will help address issues related to e-waste concrete, supporting resource conservation and broader applications in the construction industry.

Prospects and Recommendations for Further Research

Despite the difficulties in using e-waste concrete, several methods should be investigated to overcome the limitations of the material.

1. There are several ways in which e-waste integration into concrete will benefit the environment: it will produce more sustainable concrete, manage e-waste more effectively, and conserve natural aggregate resources.
2. Compared with conventional concrete, e-waste aggregate concrete demonstrated adequate sound absorption. The UPV values of the concrete specimens ranged from 3660 to 4575 $m.s^{-1}$, suggesting elevated quality and making e-waste concrete a suitable alternative, as these values are within the acceptable range.
3. Incorporating electronic waste aggregates as a 20% replacement for natural coarse aggregates in concrete increased its resistance to abrasion.
4. It is essential to recognize that the inclusion of e-waste aggregates can enhance the workability of concrete. However, using shredded e-waste components of non-uniform size should be avoided, as this can negatively affect workability, largely because of the low water absorption of e-waste.

Further investigation is essential to fully comprehend the role of E-waste aggregate concrete in construction practices. The literature review uncovered various gaps in the current knowledge. The following are suggestions for future research.

1. Mechanical properties, such as hardness (measured by aggregate abrasion), strength (assessed using the aggregate crushing value), and toughness (evaluated using the aggregate impact value), should be considered in the classification of e-waste aggregates.
2. There is insufficient data on the elastic modulus, bond

strength, Poisson's ratio, stress-strain behavior, and flexural strength of concrete using e-waste aggregates.

3. Studies on incorporating e-waste plastics into reinforced concrete remain scarce. When constructing columns, beams, and slabs, e-waste should be considered as an alternative aggregate with different substitution rates and mix compositions.
4. Additional research is necessary to explore the impacts of alkali aggregate reactions, color changes, thermal resistance beyond 300°C, post-fire characteristics, slip resistance, carbonation, chloride penetration, freeze-thaw stability, seawater and chemical resistance, shrinkage, and swelling. It is necessary to investigate the durability-related behavior of e-waste aggregate concrete because e-waste has poor bonding with cement mortar.

CONCLUSIONS

This review highlights the incorporation of e-waste in construction and infrastructure while adhering to a sustainable framework. To accomplish this, we evaluated the essential features of green concrete containing e-waste, focusing on its physical properties (both fresh and hardened), strength, durability, and thermal performance. Based on this evaluation, the following conclusions were drawn:

1. The size and shape of the aggregates largely influence the properties of the concrete containing e-waste aggregates. Finer electronic waste aggregates usually exhibit higher density, lower absorbability, and lower fineness modulus than coarser aggregates. Additionally, e-waste aggregates often have lower bulk densities and specific gravities than conventional aggregates, and they tend to absorb less water because many e-waste materials, particularly plastics, are nonabsorbent.
2. Lead, antimony, mercury, brominated flame retardants, and cadmium (Cd) not only contaminate soil, water, and air and destabilize ecosystems but also present potential health hazards to humans. Consequently, careful consideration is required when choosing e-waste for concrete manufacturing.
3. A higher proportion of e-waste in the aggregate mix enhanced the workability of the concrete. Research indicates that incorporating shredded e-waste particles of different sizes influences the workability of concrete.
4. Based on a review of multiple literature sources, it is suggested that replacing up to 15% of the original amount of coarse or fine aggregates with e-waste is the ideal replacement ratio in terms of strength.
5. An increased e-waste content in the concrete matrix reduced both the UPV value and sorptivity coefficient while improving the abrasion resistance.
6. According to thermal exposure testing, high temperatures cause e-waste concrete to compress more readily.
7. According to the literature, its strength is reduced by 39% at high temperatures (300°C). However, research on boosting strength at elevated temperatures is still lacking.

Recycled plastic aggregates sourced from e-waste provide an eco-friendly alternative, helping manage excessive e-waste, preserve the environment, and reduce traditional concrete expenses.

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