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Review Paper

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

Sanjeet Kumar† and Sanjay Kumar

Department of Civil Engineering, National Institute of Technology Patna, (Bihar), India

†Corresponding author: Sanjeet Kumar; sanjeetk.phd19.ce@nitp.ac.in

ORCID ID: 0009-0001-4932-6728

ORCID ID: 0000-0001-6497-9519

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ABSTRACT

Around the world, 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 drive global concrete production, causing pollution and depleting natural resources. To address the challenges of electronic waste plastic and concrete production, using e-waste plastic as a natural aggregate presents a novel way to conserve resources. This article discusses different e-waste plastic types, techniques for producing e-plastic aggregate, and its application in traditional concrete. Additionally, this article examines the behavior of e-waste plastic aggregate, which affects various concrete characteristics. These include fresh properties like workability, as well as hardened characteristics such as density (both fresh and dried), splitting tension strength, flexural strength, compressive strength, and durability aspects like chloride attack and thermal resistance. Reusing electronic waste plastic as aggregate is also identified as 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-plastic waste disposal challenges and its uses 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 defenses in a way that has resulted in notable advancements over time (Danish et al., 2023; Hamsavathi et al., 2020; S. Ullah et al., 2022; Wang & Xu, 2014; Wath et al., 2011). Technological companies always 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 & K, 2015; Tipre et al., 2021; Xu et al., 2012). Modern society relies on electrical and electronic systems that are creatively and newly designed. 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 & K, 2015). Increased demand from people utilizing new products more frequently causes massive production of electrical as well as electronic equipment, which further shortens device lifespans and generates an extensive amount of e-waste (Babu et al., 2007; Yong et al., 2019). Electronic 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 like 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 Abdolmajid, 2022; Wath et al., 2011). The main categories of electronic 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; J. Gupta, 2023; Ilankoon et al., 2018; Liu et al., 2023; Tipre et al., 2021; Tuncuk et al., 2012; Van Yken et al., 2021). Electronic waste is composed of one thousand diverse kinds of materials, both toxic and non-toxic, all of which pollute the environment. If toxic materials like mercury, arsenic, cadmium, and lead are not properly managed, they will lead to health issues. Nontoxic resources like platinum, gold, copper, and silver are recycled (Brindhadevi et al., 2023; Kurup & Senthil Kumar, 2017; Needhidasan et al., 2014; Wath et al., 2011). In the year 2019, only 17.4% of the total 53.6 million metric tons of e-waste produced worldwide were recycled appropriately. The balance of 82.6 percent was not officially reported or recycled. There were 50 million metric tons of electronic waste created in Asia, America, and Europe in 2019, 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 electronic 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 garbage (Fadaei Abdolmajid, 2022). Plastic is one of the most important and essential elements of electrical waste in this instance. Tackling e-plastic waste management is the world's most significant challenge. Due to the presence of flame retardants, it significantly hinders their recycling despite several technological advancements (Danish et al., 2023; Hamsavathi et al., 2020; Sahajwalla & Gaikwad, 2018). Many researchers employ diverse approaches to manage the e-waste plastics, with one strategy being the use of electronic waste plastics in the construction industry. Electronic waste like 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, 2017). On the other hand, concrete is the most widely utilized construction material globally, right after water (Nilimaa, 2023). Conventional concrete is widely utilized because of its excellent mechanical properties, such as higher compressive strength, long-lasting durability, and the capability to be molded into the favorite shape during casting (Kumar et al., 2025). The increasing need for infrastructure development is evident in the rising amount of concrete being produced daily. The rising requirement for concrete and its associated effects have led to the possibility that the exploitation of natural aggregate is depleting natural resources globally, hence endangering the needs of future generations. Aggregate, which makes up more than 70% of the material's volume, is one of the most crucial ingredients used in the formation of concrete. Focusing on the conservation of natural materials is vital for minimizing the impacts of resource depletion and climate change (Padmanaban et al., 2020; Z. Ullah et al., 2021). To reduce the use of natural aggregate as much as possible, many researchers are always trying to replace it, either entirely or partially, with waste materials such as e-waste, recycled natural aggregate, granite, marble, regular plastic, refractory brick, ceramic tile, etc. Nevertheless, recycled natural aggregate, granite, marble, regular plastic, refractory brick, ceramic tile, and other waste materials cannot be produced in sufficient quantities to meet the requirements of the rising building sector. In this case, the abundant generation of e-waste will be directed toward the substitution of natural aggregate to encourage the use of green concrete and, as a result, preserve natural resources. Nearly all researchers have worked on e-waste recycling, management, usage in concrete, and consequences on humans and the environment after analyzing several research articles. Rare research has been done to enhance the concrete's strength 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 aggregate in traditional concrete, in addition to the challenges of using electronic waste plastic in lieu of natural aggregate. Additionally, it provides an in-depth exploration of issues related to e-waste plastic, such as recycling, toxic materials, environmental harm, and health concerns.

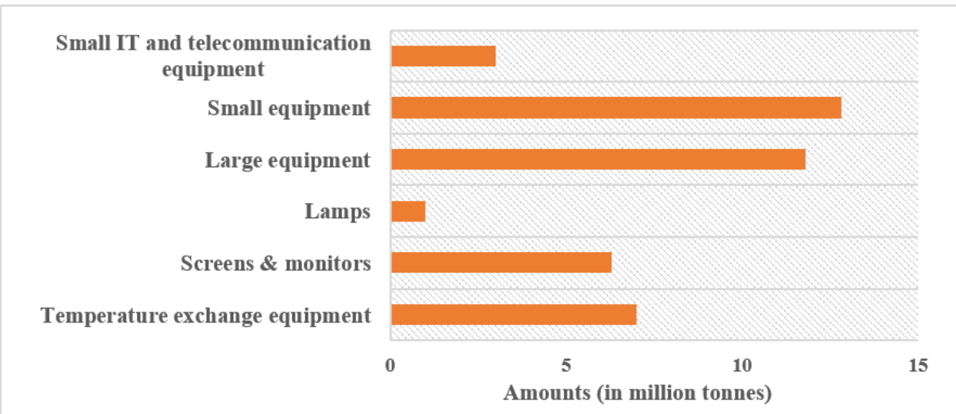

Fig. 1: Classification of e-waste (Kumar et al., 2017).

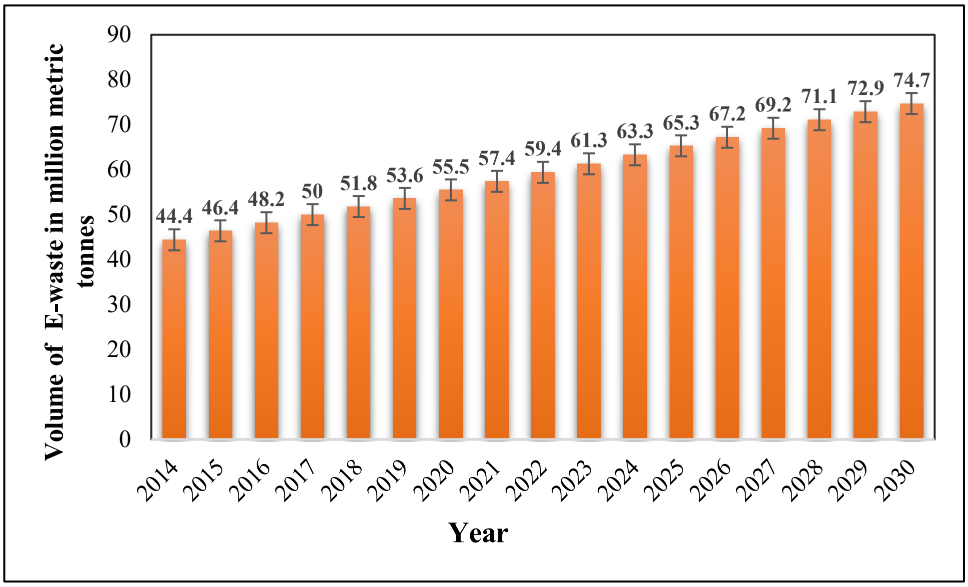

Fig. 2: Electronic waste production from year 2014 to 2024 (Forti et al., 2020).

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

2. RESEARCH METHODOLOGY

The growing requirement for concrete and its byproducts, combined with the mounting problem of electrical waste, has prompted investigations for the viability of replacing natural aggregates in concrete with electronic waste materials. This study primarily looks at the behavior of e-plastic waste as a traditional aggregate in regular concrete and how that affects the mechanical as well as durability characteristics of the material. The most innovative research articles on e-waste plastic are taken into consideration in this review. A variety of sources, including Google Scholar, Science Direct, Springer, Taylor & Francis, and other notable works that were accessible as open resources, were used to conduct the literature survey. Specialized keywords like "electronic waste," "e-plastic aggregate," "e-waste plastic," and "e-waste aggregate" are typically utilized for review.

The information was gathered in such a way 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 aggregate in conventional concrete. A comprehensive review has been carried out, drawing on a range of papers, to study the impacts of waste e-plastic aggregate on the unique characteristics of ordinary concrete. Moreover, a quantitative evaluation of fragmented information has been employed to examine the suitability of e-plastic aggregates as a sustainable and safe replacement for fine or coarse aggregate in concrete.

2.1. E-Waste Composition

Electronic trash 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 both human health and the environment. 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, or PCBs, 12% CRT and LCD displays, 2% cables, 5% metal-plastic blend, 15% plastics, and 1% miscellaneous goods. Issues like the kinds of electronic devices, their model, producer, age, and date of production significantly affect the formation of e-waste (Tipre et al., 2021; Yong et al., 2019). Various e-waste components and their environmental impacts are depicted in Table 1. Compared to regular municipal waste, e-waste contains thousands of harmful components and metals like 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. There are substances that are partially neurotoxic and carcinogenic (Yadav & Upadhyay, 2015). These contaminated ingredients existing in e-waste are also illustrated in Table 2.

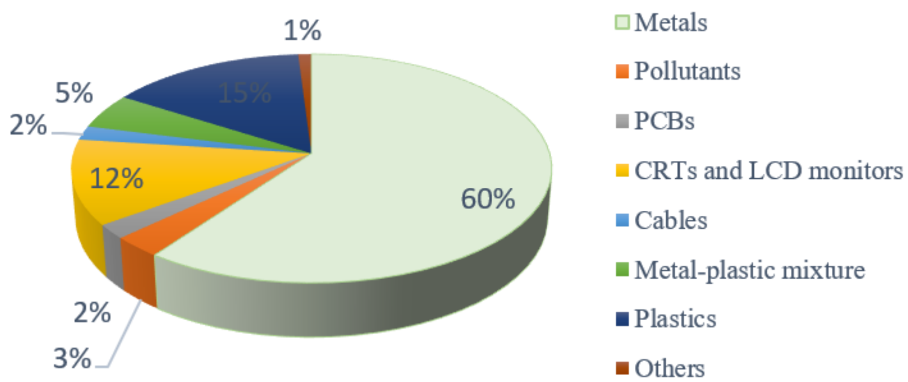

Fig. 4: Composition of e-waste (Chakraborty et al., 2022; Mtibe et al., 2023; Tipre et al., 2021).

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 re quires eliminating soldering, outdoor fire, and an acid bath.	Gas leaks, air, surface, and subsurface water pollution, glass dust
Chips and a couple of au-plated components.	A chemical stripping procedure using HNO3 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 gasses, 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 gasses 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.

2.2. Techniques for Recycling Plastic from used Electronics

The first stage of plastic recycling from electronic trash is to collect, physically select, disassemble, and shred electronic devices. (Ceballos & Dong, 2016). Materials both metallic and non-metallic (plastics, glass, and ceramics) are mechanically detached from the shredded electronic waste (Patil & Ramakrishna, 2020; Shahabuddin et al., 2023). Polyethylene, acrylonitrile-butadiene styrene, polycarbonate, polyesters, polyamides, polypropylene, and high-impact polystyrene are among the polymers that may be recovered from electronic waste (Ilankoon et al., 2018; Wang & Xu, 2014). Prior to being recycled into goods or transformed into energy, these need to be graded. Although e-waste offers valuable engineering plastics like ABS, recycling remains a challenge due to 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 strip, as shown in Fig. 5., for which a well-established recycling process requires appropriate recycling infrastructure. The manufactured or processed e-waste plastic aggregate is as seen in Fig. 6.

Fig. 5: Shredded e-waste plastic strip.

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

2.3. 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, while in secondary recycling, the retrieved plastic is repurposed to produce new goods with lower functionality requirements than the original materials. The process of size reduction begins with the separation of the plastic fractions from the electronic waste. This involves breaking the plastic waste into tiny pellets or pieces, sorting, and cleaning (based on the desired product, either optical sorting, magnetic sorting, 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). The flow diagram of primary and secondary recycling is shown in Fig. 7.

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 non-magnetics, 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.

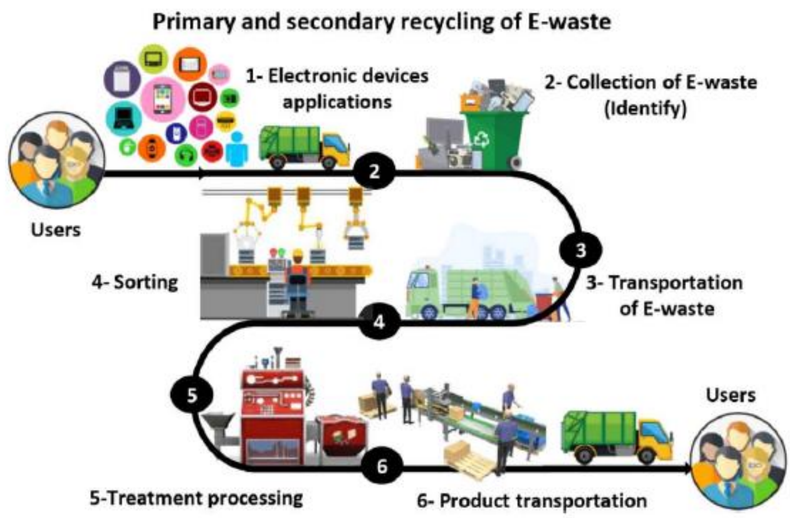

Fig. 7: Primary and secondary recycling diagram of e-waste (Elgarahy et al., 2024).

2.4. Tertiary Recycling

The third step of chemical and thermal recycling uses 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 enables polluted polymers to be processed without requiring laborious pretreatment steps. Subsequently, the plastic portions are repurposed to create valuable items. Catalytic cracking, pyrolysis, hydrogenation, dissolution, and gasification are examples of common processes. The sample is heated to high temperatures (400–800 degrees Celsius under inert conditions) during the pyrolysis process to produce products like char, oil, and combustible gases; pyrolysis produces fewer contaminants than conventional thermal treatment (Charitopoulou et al., 2021). The optimal processing parameters, including temperature, feedstock composition, heating rate, and time, determine the products that are produced during pyrolysis. Utilizing catalytic pyrolysis, which lowers temperature and shortens residence time, can yield high-value compounds. The flow diagram of the tertiary recycling approach to electronic waste is depicted in Fig. 8.

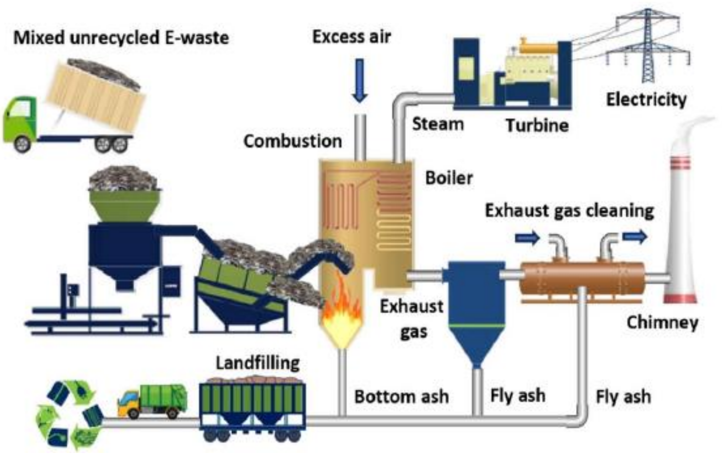

Fig. 8: Tertiary recycling diagram of e-waste (Elgarahy et al., 2024).

3. Incorporating E-Plastic Waste into Concrete Production

Various research studies have been performed on the use of electronic waste plastic in the manufacturing of concrete. These discarded components go through a recycling procedure before being used to make concrete, as can be seen in Fig. 9, where the raw plastic components from e-waste are crushed and processed into various aggregate sizes, much like regular aggregates, for the creation of concrete. Processed e-waste, particularly electronic waste plastic particles, is frequently utilized as an alternative for either fine or coarse aggregate in concrete mixes. Novel research highlights 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% to 50% of conventional aggregates. The mechanical, physical, and long-lasting characteristics of concrete with these substitutions were compared with regular concrete by earlier reviewers.

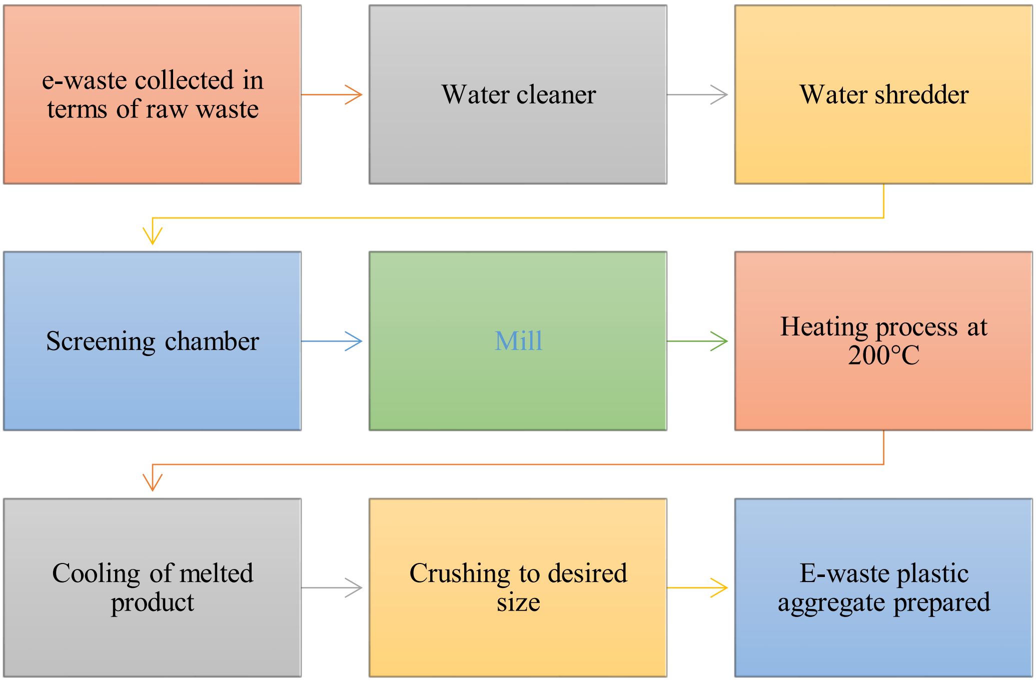

Fig. 9: Manufacturing procedure of e-waste aggregate (Bamigboye et al., 2024; Z. Ullah et al., 2021).

4. 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 some of the primary characteristics. Multiple studies have analyzed the efficiency of e-waste plastic in enhancing the physical characteristics of concrete. Here are some of the e-waste plastic aggregate's physical characteristics, shown in **Error! Reference source not found.**. The following sections will critically explore how e-plastic aggregates impact concrete's properties.

4.1. 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-plastic can lead to reduced workability. Like Kumar and Baskar (2015b) demonstrated, the addition of 10%–50% e-plastic in concrete led to a reduction of slump of 25%–65% compared to standard mixes, as the plastic obstructs other ingredients and reduces workability. A related remark was quantified by Kumar and Baskar (2015a) 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 a 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. A study by Manjunath (2016) also noted that the use of 10-30% e-plastic waste in concrete exhibited a slump decrease ranging from 10.93% to 41.40% with respect 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.

Table 4: Properties of e-waste plastic aggregate (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%

4.2. Dry Density and Fresh Density

The qualities of fresh concrete have an impact on important prepared concrete properties. For instance, concrete's slump, fluidity, and consistency are influenced by its fresh density, whereas its hardened properties are influenced by its dry density. Research on the unique properties of e-waste plastics is lacking. Kumar and 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 decreases because the e-plastic waste aggregate has a lesser density than the coarse aggregate. A similar study was done by Kumar and Baskar (2015a), who used 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 ranging from 0.93% to 14.41% and 0.77% to 13.58%, respectively, with respect to the control sample.

5. Structural Properties of E-Waste Concrete

5.1. Mechanical Properties

5.1.1 Compressive Strength

The material's capacity to resist loads that try to compress or shorten its dimensions, rather than those that stretch it, is known as compression strength. Kumar and 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. On the other hand, Ahirwar et al. (2016) replaced coarse aggregate by 0% to 30% with e-waste and the cement by 10% to 30% with fly ash, observing a minor drop in compressive strength with respect to the reference concrete. An innovative idea by

Rohini and Padmapriya (2021) was focused on the addition of microbiologically induced calcite precipitation to electronic waste-treated concrete for strength enhancement. Their conclusions showed that the compressive strength of 15% e-waste plastic concrete improved by 6.26%, 8.41%, and 5.95%, respectively, with the addition of 0%, 1%, and 2% bacteria compared to the control mix. The improvement in compressive strength of e-waste plastic concrete with the addition of bacteria is connected to the production of calcium carbonate and its inherent self-healing properties.

5.1.2 ***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 since concrete is naturally prone to tensile weakness due to its brittle characteristics. Research consistently shows that increasing the proportion of e-waste aggregates tends to diminish the concrete's splitting tensile strength. For example, Kumar and 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, they showed that the samples containing e-waste plastic aggregates exhibited a different failure mode in their splitting behavior, unlike the typical brittle failure seen in the reference specimen. A similar remark was conveyed by Kumar and Baskar (2015a), who assessed how high-impact polystyrene electronic waste affected the concrete's ability to split tensile strength. 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 before fully breaking down, e-waste plastic aggregates can tolerate significant elastic deformation. A similar study by Manjunath (2016) incorporated e-waste plastic aggregates at replacement levels ranging from 10 to 30 percent for coarse aggregate in the concrete mix. The inclusion of 20% e-waste plastic aggregates was found to improve the 28-day splitting tensile strength of concrete by 10.20% compared to the reference sample. Ganesh et al. (2021) conducted a 28-day split tensile test of concrete (M20 grade) contained crushed printed circuit board as fine aggregate replacement level 3% to 25% wt. The split tensile strength reached 1.51 MPa, reflecting an 11.85% increase with 15% fine aggregate replacement using PCB, as compared to the control mix's strength of 1.35 MPa.

5.1.3 ***Flexural Strength***

It is the measure of the capability of the material to withstand distortion under increasing load, and numerous studies have explored this property. For instance, Kumar and Baskar (2015b) prepared concrete by replacing coarse aggregate (CA) with variable proportions (10% to 50%) of e-plastic by volume and assessed the 7 and 28-days flexural strength. As the proportion of e-plastic increased, a decline in the concrete's flexural strength was noted. The 10% replacement of coarse aggregate yielded the highest values of flexural strength 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 in comparison 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) made concrete with nano graphite platelets (doses of 1%, 3%, and 5% by weight of cement) and e-waste plastic coarse aggregates substituted partially by a percentage level of 25% to explore the flexural strength. It was observed that specimens with 25% plastic aggregate 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. It was indicated that the strength dropped by as much as 15.18%, 15.10%, and 16.01% at a 25% replacement level for 7, 14, and 28 days, respectively. Observations indicated that a replacement level of up to 10% e-waste plastic was viable.

5.1.4 *Shear Strength*

Kurup and 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. The incorporation of silica powder into fiber-reinforced concrete improves its shear strength in comparison to conventional fiber-reinforced concrete. Silica fiber-reinforced concrete showed 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 conventional concrete. The Summary of effects of e-waste on various concrete properties are shown in Table 5.

Table 5: Summary of effects of e-waste on various 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

6. Durability Characteristics of Concrete Incorporating Electronic Waste

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

6.1. Water Absorption Properties

To evaluate if e-waste concrete is suitable for construction applications, it is essential to conduct additional studies on the water absorption capabilities of this plastic-based concrete. Durability in concrete is associated with lower water absorption values, yet this property has not been widely investigated. In their study, Ullah et al. (2021) conducted tests to assess the water absorption characteristics of concrete incorporating e-waste as a coarse aggregate. It was observed that as the replacement of natural coarse aggregate 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 aggregate was replaced with e-waste at levels of 10%, 15%, and 20%, the concrete's sorptivity coefficient decreased by 12.2%, 14.5%, and 29.0%, respectively.

6.2. Alternate Wetting And Drying

Concrete's ability to endure weathering in various wet and dry environments is assessed using sea tidal waves as stress factors. Structural durability diminishes when cracks from stress develop and reinforcement becomes weathered. Ullah et al. (2021) created that 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 contrast to concrete with natural coarse aggregates.

6.3. Abrasion Resistance

It has been investigated in several studies, which have improved the material's viability. However, there is very limited research available on this topic. Like Ullah et al. (2021), noted that a higher electronic waste percentage improves abrasion resistance. The experimental findings indicated that substituting 10%, 15%, and 20%

of natural coarse aggregate with e-waste enhanced abrasion resistance by 39.8%, 44.3%, and 46.4%, respectively. This was because of e-plastic aggregates' increased toughness and abrasion resistance over those of natural aggregates.

6.4. Ultrasonic Pulse Velocity (UPV)

This examination of durability is essential for evaluating the homogeneity and consistency of concrete. With the use of this test, the concrete's compactness and flaws like pores and cracks are found. In connection to this, Kurup, and 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. The specimen with e-waste fibers demonstrated a declining UPV value, attributed to the fibers' ability to absorb pulse waves. A similar study by Ullah et al. (2021) found that as the content of e-waste aggregate rises, the UPV value of the concrete declines, which is due to an increased air void content and the irregular distribution of the plastic aggregate. With the replacement of natural coarse aggregate by 10%, 15%, and 20%, the UPV value of e-waste concrete declined 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 between 3660 and 4575 m/s.

6.5. Chloride Penetration

Chloride attack must be considered when evaluating concrete's long-term resilience, as it is a primary cause of reinforcement corrosion, which is of great importance. For instance, Kumar and 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 was found to have modest levels of chloride ion penetration, while the fine and coarse aggregate replacement made from e-waste showed moderate levels of chloride ion penetration, with charges passing between 3271 and 3966 coulombs.

6.6. Temperature Resistance of Electronic Waste Concrete

It is important to understand the effect of temperature on material strength for the construction of fire-resistant structures. This test evaluates the material's response to fire and its tendency to ignite. For instance, Lakshmi and Nagan (2010) revealed that as the amount of electronic waste plastic aggregate increases, concrete's compressive strength 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°C to 350°C, applying e-waste at various replacement percentages for coarse aggregate. 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 depicted in Fig. 10. However, this reduction is minor with respect to the strength losses observed in the standard mix. Further investigation is required to confirm that electronic waste plastic performs adequately as a construction material at high temperatures.

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

6.7. 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. The 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, 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, as well as crystal phases at 28.16° and 81.72°, associated with calcite. Low-intensity peaks at 18.48° and 80.38° were also detected, which are associated with calcium hydroxide. Conversely, the introduction of 20% e-waste plastic resulted in a new peak for hatrurite, and it was found that the most intense crystal phases of dellaite occur at 18.15° and 47.17°, respectively. However, it was reported that the matrix's strength characteristics were reduced due to the expansion and fissures caused by the presence of water. Strength reduction occurred due to a lower formation of dicalcium silicate (Ca2SiO4). The XRD pattern of the composite concrete matrix can be seen in Fig. 12.

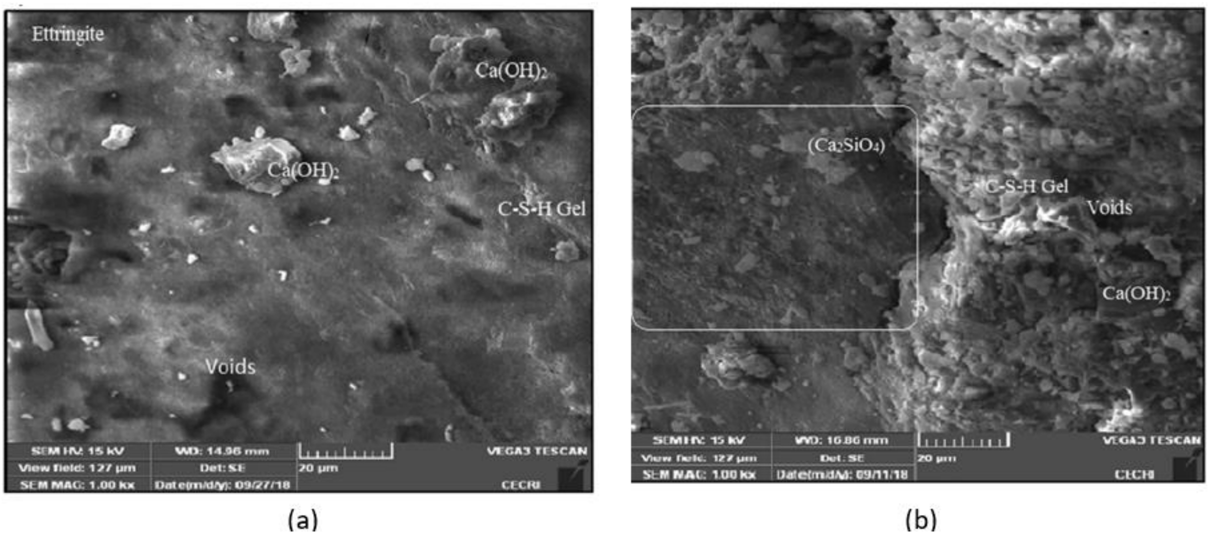

Fig. 11: SEM view of (a) Normal concrete (b) E -waste concrete (Balasubramanian et al., 2021).

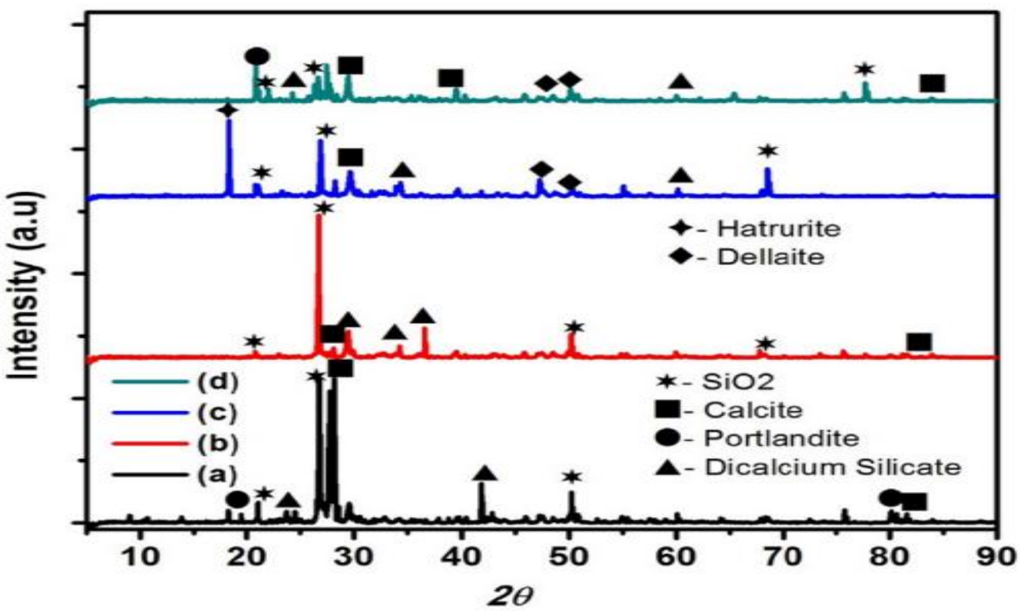

Fig. 12: XRD pattern of (a) control concrete (c) E-waste concrete (Balasubramanian et al., 2021).

7. 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 concrete's density, 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, a 44.07% decrease in axial compressive strength, and a 25.76% drop in elastic modulus. Conversely, the splitting tensile strength improved by 46.29%, and the impact resistance increased by 181.3 joules. Based on these findings, it can be concluded that a 10% to 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.

8. 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 that has been altered with e-waste useful as a building material. The following are the crucial strategies for enhancing the electronic waste concrete characteristics:

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 show that these changes can significantly enhance its overall strength.
2. Incorporating Admixtures: To improve the workability and mechanical strength of fresh e-waste concrete, incorporating superplasticizers and mineral admixtures like fly ash, silica fume, and slag is recommended. Previous research has shown that superplasticizers improve both 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 greatly improves the density and hardness of cementitious composites by reducing porosity and reinforcing the microstructure. Consequently, incorporating GO could 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. Adopting these strategies will help address the issues related to e-waste concrete, supporting resource conservation and broader application in the construction industry.

9. Prospects and Recommendations for Further Research

Even with the difficulties in using e-waste concrete, there are several methods for investigation that should be pursued to overcome the material's limitations.

1. There are several ways that 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 to conventional concrete, e-waste aggregate concrete demonstrates adequate sound absorption. Its UPV values fall within the range of 3660 to 4575 m/s, suggesting elevated quality, 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 increases its resistance to abrasion.
4. It is essential to recognize that 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 due to e-waste's low water absorption.

Further investigation is essential to fully comprehending the role of electronic waste aggregate concrete in construction practices. The literature review could uncover various gaps in current knowledge. Below are some suggestions for additional research.

1. Mechanical properties such as hardness (measured by aggregate abrasion), strength (assessed through the aggregate crushing value), and toughness (evaluated by the aggregate impact value) should be utilized in the classification of electronic 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 plastic into reinforced concrete remain scarce. In 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 reaction, 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 in e-waste aggregate concrete because e-waste has poor bonding with cement mortar.

10. CONCLUSIONS

This review paper seeks to highlight the incorporation of e-waste in construction and infrastructure while adhering to a sustainable framework. To accomplish this, it evaluates 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 are made:

1. The physical concrete's properties containing e-waste aggregates are largely influenced by the sizes and shapes of the aggregates. Finer electronic waste aggregates usually exhibit higher density, lower absorbency, and a lower fineness modulus compared to 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 non-absorbent.
2. Lead, antimony, mercury, brominated flame retardants, and cadmium (Cd) not only contaminate soil, water, and air and destabilize the ecosystem 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 enhances the workability of concrete. Research indicates that incorporating shredded e-waste particles of different sizes influences the concrete's workability.
4. Based on a review of multiple literature sources, it is suggested that replacing e-waste with coarse or fine aggregate up to 15% of the original amount is the ideal replacement ratio in terms of strength.
5. An increased e-waste content in the concrete matrix reduces both the UPV value and sorptivity coefficient while improving abrasion resistance.
6. High temperatures cause e-waste concrete to compress more readily, according to thermal exposure testing.
7. According to literature, its strength is reduced by 39% at high temperatures (300°C). Research on boosting strength at elevated temperatures is still lacking, though.

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

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