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CRITICAL REVIEWS

Potential of industrial waste and plastic nanomaterials as a danger or a way to create a sustainable environment: a critical review

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Abstract
The number of studies concerning the adverse effects of industrial waste materials on the environment and human health has risen tremendously across the globe. Besides this, an increase in demand of various types of plastic, i.e., electronic goods, polythene, toys, single used plastic, etc., in the market, the way out of such a waste in the future, more is anticipated. Most of these waste materials including plastics are used to throw by the users in an open environment, water bodies, which affect the environment, animal ecosystems, and the human health up to a greater extent because of the varying size of these plastics, i.e., micro to nanoparticles. Therefore, a detailed review is carried out to identify the potential effects of industrial wastes in the construction sector. Based on the comprehensive survey on the literature, it was observed that industrial waste having cementitious properties may result in the strength enhancement of concrete mix resulting creating a sustainable development in the construction sector. It is also suggested that recycling a higher rate of e-waste leads to industrial reuse of metals, thereby saving the burden on mining of these raw materials. Overall, the plastic waste and e-waste utilization in concrete mix were not found beneficial concerning the compressive strength; however, plastic waste up to 16% and e-waste 0.8% may be recommended from the point of view of tensile and flexural strength.

Keywords Plastic waste · Electronic waste · Construction sector · Sustainable environment · Nonstructural elements

Introduction

The infrastructures such as roads, flyovers, buildings, and containment structures play a vital role in booming a country's economy. The major requirement for the economic rise of a country is its infrastructure development, which is not possible without the use of concrete. Although, the production of cement is an environmental concern due to expulsion of several gases at each manufacturing stage. Also, cement is the most used material in the globe after water [1]. As per Indian Minerals Yearbook, different steel industries are responsible to produce around 12 million ton of steel slag annually [2]. Around 19–20% of CO_2 in India is due to the production of cement and steel [3]. The yearly production of cement has reached 0.83–43.8 million tons (nearly equal to 10%), which poses a serious threat that needs attention [4, 5]. Alex et al. [6] successfully utilized low-calcium fly ash in the construction of geopolymer-reinforced concrete beam (GPC) to lessen carbon release. The different properties of concrete mix, namely load bearing capacity, moment resistance, and crack propagation, were found to be improved in comparison to the conventional concrete mix. In latest research [7], the addition of 10% metakaolin (MK) for cement replacement and ground-granulated blast-furnace slag (GGBS) exhibits highest strength values as compared to other mixes and that is because of the finer particle size as well as the pozzolanic nature of MK and GGBS. Wani and Bhandari [8] proposed 45% of GGBS as the optimum value for cement replacement in concrete. Conversely, 20% of silica fume was identified as an ideal value as the substitution of cement. It is also to note that plastic starts to break down in nanoplastics because of it being subjected to different environmental elements [9–12]. Due to the regular increment in the plastic waste led to the higher risk to human health as the micro- and nanoplastics appear in food chain

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through several ways, i.e., open environment, food packaging, etc. [13–19], as shown in Fig. 1. It is to note that the electronic devices contain mercury, lead, arsenic, etc., inside the equipment, which is dangerous for the environment and health of the different species. Kumar et al. [20] stated that the self-organized companies [21] responsible for e-waste management become a grave threat due to unauthorized recycling practices and lack of specific mechanism and policy, i.e., to check the e-waste flow [21, 22]. The main reason behind e-waste generation are the customers who are engrossed with the latest innovation in the technology (i.e., computer or Smartphone) and will hesitate in replacing the older ones [22–24]. Earlier, some initiation was undertaken by Indian Government and the e-waste management responsibility was assumed to the Ministry of Environment and Forest (MOEF) and it was amended in 2000 and 2003 in the List-A and List-B of Schedule-3 of "Hazardous Wastes (Management & Handling) Rules, 1989" [13, 20]. The Government of India is also encouraging the companies and the people to recycle e-waste and plastic waste however this needs to be done on a larger scale otherwise results will be more dangerous.

Therefore, it is necessary to address the reduction in cement consumption and hazardous gases emission. As the increase of electronic goods and plastic in the market, the e-waste, plastic waste, crumb rubber, various ashes, and GGBS are among the waste materials that may supplant the aggregate or cement to make environment friendly concrete mix, i.e., by converting them into nanoparticles, which will diminish the consumption of cement. Therefore, a detailed literature review is carried out to investigate the feasibility of slag, e-waste, and plastic waste in concrete mix. The influence of e-waste in concrete is studied and discussed in Sect. 2. Also, the influence of plastic waste and recycled concrete aggregate along with utilization of other supplementary waste materials as nanomaterials in the construction sector is discussed in Sects. 3 and 4, respectively.

Classification of nanoparticles and their impact on properties of blend concrete

Nanoparticles are classified as engineered nanoparticles, i.e., which are prepared through bottom-up synthesis (construction of nanoparticles using atoms or molecules to achieve the desired size) or top-down synthesis processes (lowering larger size particles to nanometer proportions) [25], natural nanoparticles (which occur naturally, i.e., volcanic eruptions, etc.) [26], and incidental nanoparticles (occurs in built environment, i.e., tyre material loss, exhaust emissions and many more). Interestingly, Flores et al. [27] concluded that the inclusion of nanosilica particles varying in sizes from 5 to 70 nm (produced by sol–gel method) with the addition of superplasticizer admixture result in the increment in the compressive strength value from 63.9 and 95.9 MPa for 1 and 28 days curing time

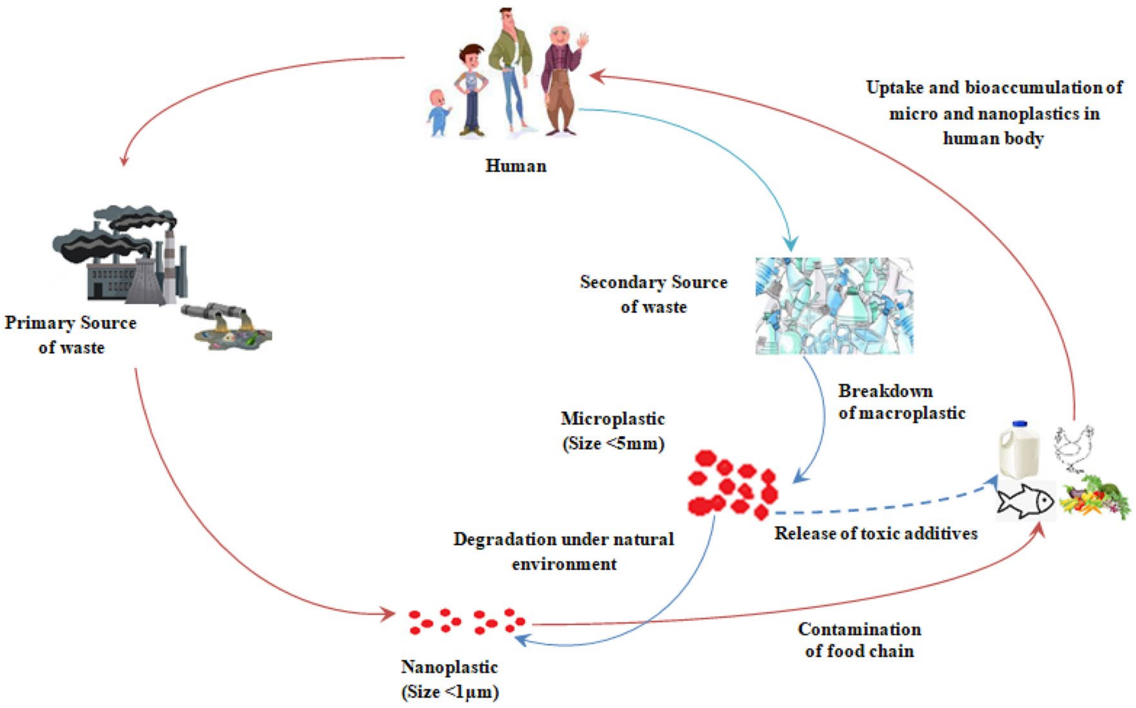


Fig. 1 Micro- and nanoplastic adoption process

period, respectively. Previously [28] it was observed that the cement mortar having higher SiO_2 and Fe_2O_3 nanoparticles exhibits higher compressive and flexural strength in comparison to normal concrete. Addition of nano-SiO_2, fly ash, and silica fume results in achieving good performance especially initial strength of high-volume fly ash concrete (HVFC) and would prove as an economical method to utilize nano-SiO_2 in concrete mix [29]. Earlier [30], it was recommended to use the nano-SiO_2 in concrete mix as the amount of calcium hydroxide crystals was found to decrease while the early strength development of the mix was increasing. In a recent study [31], nano Al_2O_3 (NA) and micro rice husk ash (MRHA) were successfully utilized as substituent of cement as, i.e., 0–2% and 0–20%, respectively, in cement mortar. After a lot of experimental investigation, i.e., individually and in combined form, it was concluded that the use of MRHA and NA will result in compressive and tensile strength enhancement of cement mortar. Combined application of both results in compressive and tensile strength enhancement of up to 26.4 and 48.72%, respectively. Alex et al. [32] pointed out a better crack propagation in geopolymer-reinforced concrete beam as compared to the cement-reinforced concrete beam. Oliveira and Vazquz [33] found that the dry and saturated recycled aggregates are responsible compressive strength reduction of concrete mix. Previously, researchers found increase in water absorption for RCA (ranging 2.15–7.15%) in comparison to NCA [34–36]. Wagih et al. [37] utilized recycled concrete and construction waste aggregate for NA in varying proportions, i.e., 0, 25, 50 up to 100% with different dosage (0–1.3%) of super plasticizer. The properties such as bulk density, absorption, fine content, abrasion index, impact value, compressive, splitting tensile, and modulus of elasticity were evaluated. Based on the findings, the utilization of up to 100% recycled concrete aggregate resulting in reduction in fresh concrete workability and compressive strength. On the other hand, utilization of 75% NA and 25% of RCA was found insignificant in concrete mix properties. Complete replacement of NA led to compressive strength reduction from 18 to 28%. However, previously [38] a reduction of up to 40% in strength using complete RCA in concrete mix was reported. Conclusively, 100% use of RCA will result in lower workability. While using 100% RCA, a reduction in the tensile strength and elasticity modulus up to 25 and 15%, respectively, in comparison to NA was found. A previous study [39] also encouraged using prewetted and saturated recycled aggregate to prevent the reduction in consistency of concrete mix without influencing its mechanical property.

Fleischer et al. [4] concluded that wet processing is not required if the natural wetting of aggregates is considered in concrete mix. Besides this, prespraying all the aggregate homogeneously is rather cumbersome. Huda and Alam [40] utilized 100% RCA of three different generations as NA replacement, i.e., the concrete mix was casted and demolished the hardened concrete for 3 times. Marginal compressive strength reduction was found as compared to control concrete as shown in Fig. 2. Behiry [41] provides a methodology for utilizing the cement-treated RCA as base or subbase layer. Also, it was found that the unconfined compressive strength (UCS) using treated RCA gets improved with increment in the cement content in comparison to LSA as shown in Fig. 3.

Comparable results were found with an increment of fines content in concrete mix using both RCA and LSA. Another important observation was of flexural strength ratio enhancement to UCS with increase in the fine material amount. Silva et al. [42] categorized demolition waste into different categories, which can be used as the replacement of NA in the pavement construction. Topcu and Sengel [43] found reduction in workability of mix for 50% of NA replacement with RA. Huang et al. [44] concluded that utilization of packing density mixes design methodology fixes strength fluctuation problem related to RAC and can achieve the similar strength found in case of NA. Besides these, based on several other studies it was recommend using RCA in concrete mix design [20, 29, 34, 45]. In a recent study [46], applications of nano alumina along with M sand in cement mortar were examined, and it was revealed that the 1% incorporation of nano alumina will result in the increase in strength enhancement of the mortar as shown in Fig. 4.

Influence of E-waste on properties of blend concrete

Gupta et al. [47] utilized e-waste strips having a size of 10 mm as the reinforcement instead of steel and recycled aggregate in M20 mix. It was suggested that 5% of e-waste may be utilized as reinforcement. It was also suggested to

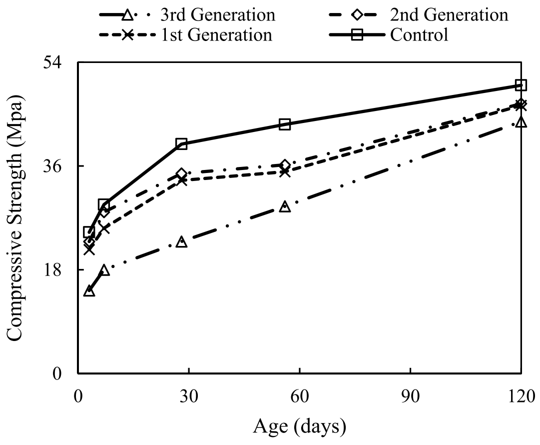
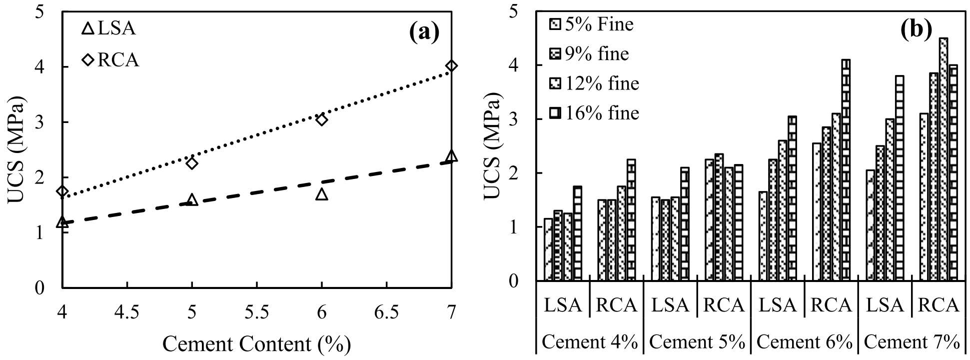


Fig. 2 Compressive strength of various concrete mixes

Fig. 3 Variation in UCS with **a** cement content **b** fine content



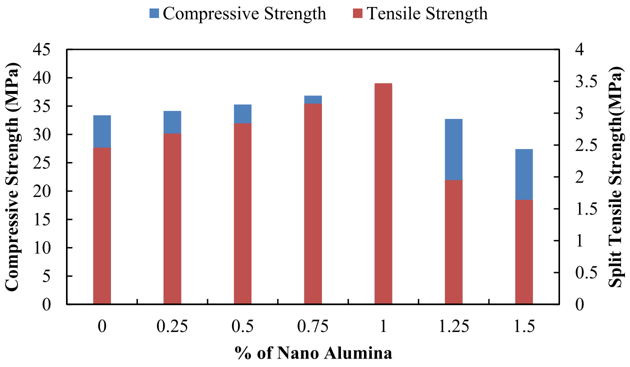


Fig. 4 Variation in Compressive and Splitting Tensile Strength Value with f α-phase Nano Alumina

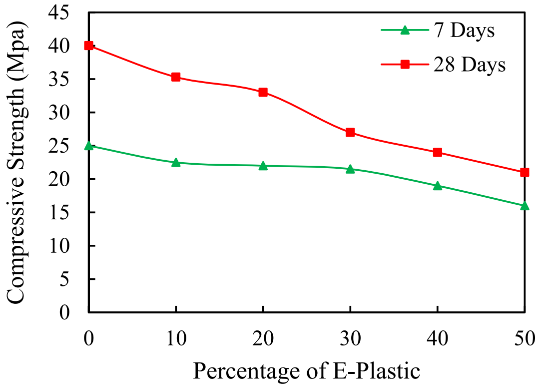


Fig. 5 Variation in compressive strength function of e-plastic content

utilize the e-waste after segregating based on their properties, which can also affect the overall mix performance. Earlier, in [20], the current scenario related to the e-waste management obtained from personal computers and mobile phones in India was evaluated. It was stated that formulation of different guidelines for e-waste management and handling are not sufficient. It was also suggested that there should be a process to modify the equipment by which recycling and reuse of the same can be possible. Direct disposals of e-waste near the working areas may have adverse effects on the human as well as health primitive recycling areas [48, 49]. Consequently, it was recommended to use the e-plastic waste (12.5 mm size) up to 30% substitute for coarse aggregate in structural concrete [14] as shown in Fig. 5. However, use of e-plastic more than 30% and maximum 50% was recommended for nonstructural lightweight concrete elements.

Senthil and Bhaskar [50] utilized e-waste high-impact polystyrene (HIPS) as partial substituent to coarse aggregate in concrete mix. It was observed that the increment in the HIPS was found to reduce the slump, dry density, compressive, flexural, and splitting tensile strength of concrete. It was also suggested 30% of HIPS of 12 mm size as the replacement of coarse aggregate in concrete mix. Also, in [51], it was concluded that concrete mixes using HIPS coarse aggregate of 12 mm size can retain 50% of the strength under all test conditions. Further, the addition of increased content of HIPS found to decrease the strength in the concrete mix. Therefore, it was recommended to use these types of materials where lightweight constructions are required. Kurup and Senthil [52] did the analysis to check the applicability of polyvinyl chloride (PVC) cable e-waste having 4 diameter and 3 mm length by keeping the fiber aspect ratio as 35 in concrete. It was observed that the addition of silica powder along with PVC e-waste found to decrease the shear strength in comparison to fiber concrete (FC). Also, an improvement in the strength was observed due to the inclusion of silica powder, which is due to the small particle size, i.e., nanoparticles responsible to increase the packing density of mix. Another important finding was the improvement in the ductility and reduction in the brittle failure of the concrete. Besides this, it was suggested that the 0.8% value can be adopted as the optimum proportion of PVC e-waste to construct fiber-concrete and silica fiber concrete as it was showing optimum compressive, splitting tensile, and flexural strength values for E-waste percentage [53], see Fig. 6.

Based on the findings of a [54], the inclusion of HIPS more than 50% with respect to various temperatures will result in compressive strength reduction, see Fig. 7. Also, the application of concrete in nonstructural elements such

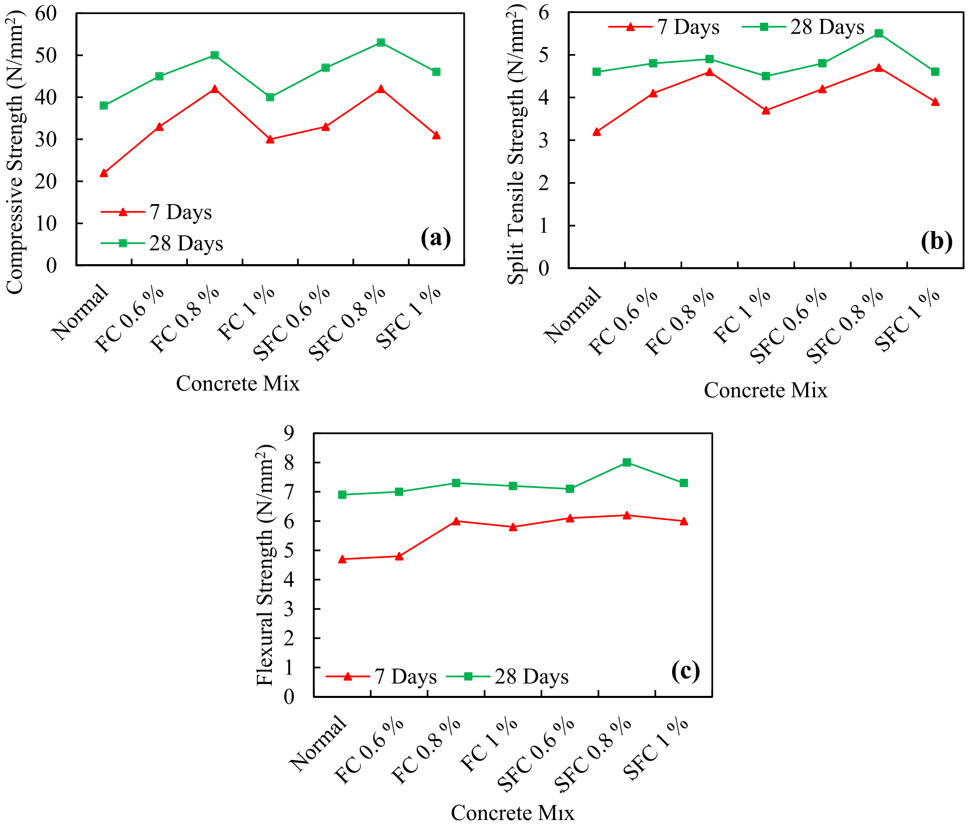


Fig. 6 **a** Compressive strength **b** split tensile strength and (c) flexural strength on various mixes

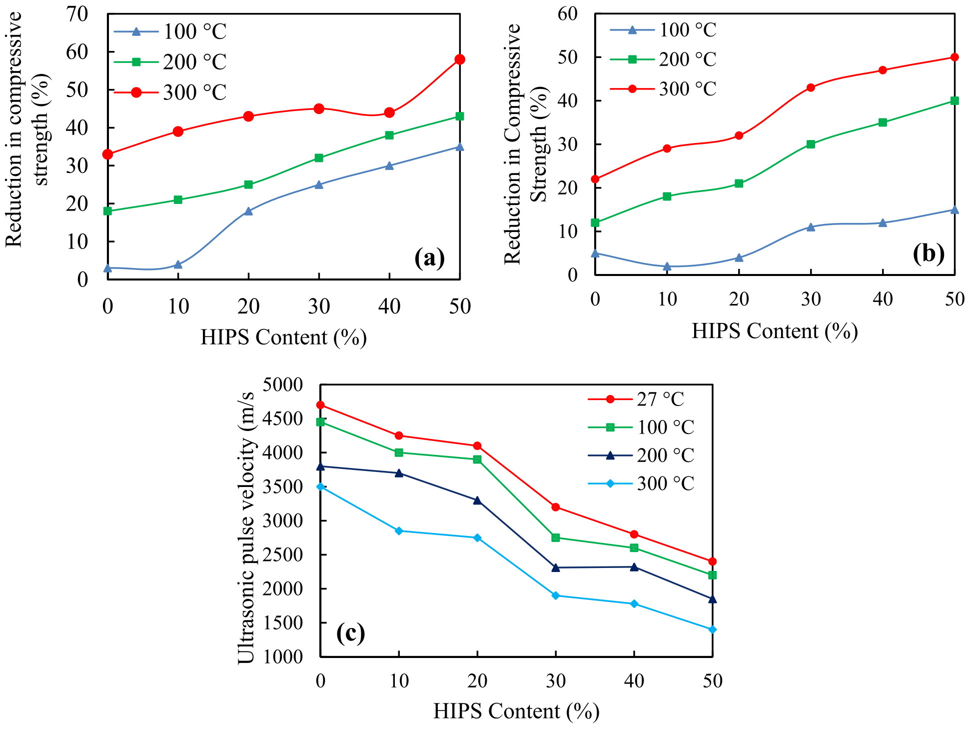


Fig. 7 Reduction in compressive Strength at **a** 7 and **b** 28 days and **c** ultrasonic pulse velocity at 28 days in concrete with HIPS

as partition walls, pavement, etc., was recommended. The ultrasonic pulse velocity test also revealed that using 20% of HIPS was found to be good and acceptable as per the Bureau of Indian Standards (BIS) 13,311 (Part 1) [55]. Based on the findings of the thermal insulation test, it was observed that use of HIPS as the replacement of aggregate will be beneficial from energy perspective as it keeps a serene building interior in comparison to that of outside temperature. Shirodkar and Terkar [5] stated that a stepped recycling approach can deal with issues of e-waste management more efficiently. Also, it was suggested a model, which will take care of the concerns regarding the quantity and consequences of e-waste on the surroundings. Utilization of e-waste plastic aggregate up to 10 and 20% will result in the reduction of overall weight of the concrete [15]. Another observation was the increment in fresh concrete consistency with higher percentage of e-waste due to the ineptitude of plastic to absorb the water. However, the strength of mix was found lesser than the control mix. Needhidasan and Sai [56] utilized discarded e-plastic, i.e., IT equipment and households, etc., as the replacement of aggregate and fly ash to make high-strength concrete (M60). An optimum of 20% of e-waste having 20 mm size and fly ash was found appropriate for producing high-strength concrete as the compressive, flexural, and splitting tensile strength value was found to be higher. Also, Needhidasan and Sai [57] used e-Printed Circuits Boards (PCB) (20 mm size) of as the partial replacement of aggregate up to 12.5% along with manufacturing sand for M20 grade concrete. The compressive and flexural strength was reduced with rise in e-waste proportion, whereas an increment in splitting tensile strength was observed. In a recent study [58], different waste materials (i.e., industrial, agricultural, etc.) used as an admixture considering workability, compressive strength, and other properties. It was concluded that utilizing nanoparticles in green concrete led to achieve higher performance and reduction in carbon emission and preserving natural resources. Findings of the study of Chatterjee and Abraham [59] and Chatterjee and Abraham [60] was found in the agreement of the use of e-waste in the construction practices, which will be very beneficial for environment and human health. Based on the detailed literature, it was observed that the use of e-waste was not found beneficial from the point of view of compressive strength. Conclusively, the waste materials may be utilized in the construction of nonstructural elements where lightweight structures are warranted. Beside this, Cucchiella et al. [61] identified waste from electrical and electronic equipment's (WEEES) as the most growing sector from the point of view of revenue collection, which is found equivalent to 2.15 and 3.67 billion euro in the European market.

Influence of plastic waste on properties of blend concrete

Recently [62], plastic wastes having a size of 3 mm were utilized along with the metakaolin-based geopolymer concrete. It was concluded that the 10% value can be adopted as the optimum f plastic waste supplement as coarse aggregate with marginal decrement in mechanical properties. Though, a 35.27% reduction was observed with the 30% inclusion of plastic as the replacement of aggregate. Similar trend was observed for flexural strength (25.75%) and split tensile strength (50%). Ismail and AL-Hashmi [63] utilized waste plastic possessing 0.15–12 mm length and 0.15–4 mm width for up to 20% in concrete mix. A reduction in compressive as well as flexural strength was observed with increase of waste plastic. It was because of less adhesiveness within the plastic waste and cement. Another reason may be the aquaphobic nature of plastic waste, which averts the seepage of water to concrete structure, which is required for the hydration process. However, compressive strength was observed with different proportions of plastic waste for all the cases at higher sides than the required strength for structural concrete. Similar findings were reported in the previous studies [64, 65]. Recently [66], polyethylene terephthalate (PET) bottles after crushing to a size of 1–1.15 mm were utilized in varying percentage, i.e., 0–50% as the partial replacement of sand in concrete mix. Compressive strength of the mix was marginally decreased at up to 20% of the sand replacement with PET, see Fig. 8; thereafter, the drop was found to be significant. The strength decrement may be due to the reduction in bulk density of the composite or waning of adhesion between PET surface and concrete [16, 67–69]. Same trend for strength reduction with increase in PET proportion was observed for splitting tensile and flexural strength. Also, PET inclusion as partial replacement of sand had adverse

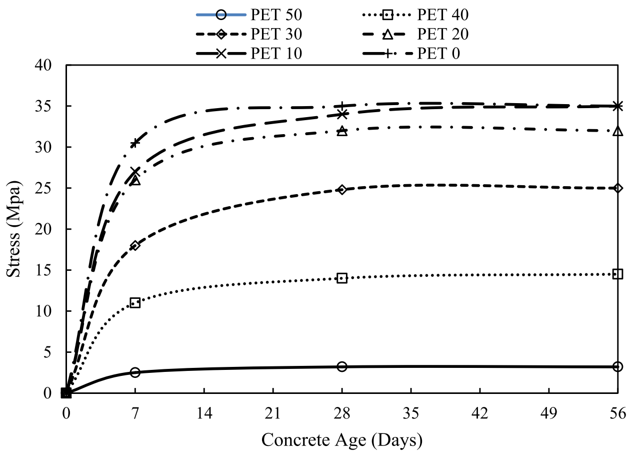


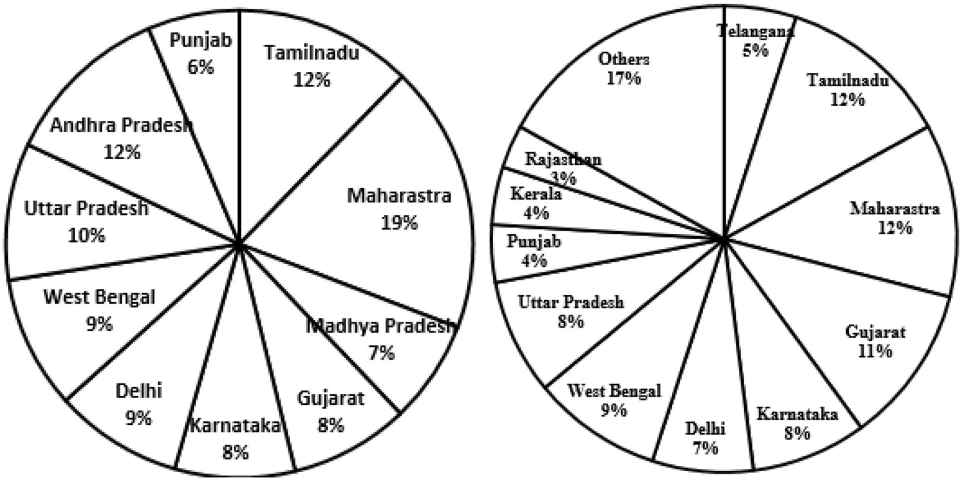
Fig. 8 Effect of recycled PET on concrete compressive strength

effect on fire resistance ability of concrete mix. Kou et al. [70] recommended utilization of PVC granules with a size less than 5 mm as the lightweight aggregate, which improves the ductility, shrinkage, and chloride ion resistance properties of the concrete mix. Though, other mechanical properties, i.e., related to strength of the mix were found to be decreased. Azhdarpour et al. [71] found that the inclusion of PET (size of 2–4.9 mm as coarse and 0.05–2 mm as fine aggregate) up to 10% in concrete mix as the replacement of aggregate found to have increased compressive and flexural strength. However, properties were found to decrease gradually beyond 10% PET. The tensile strength was found to increase up to 15% inclusion of PET in concrete mix. Also, it was observed that the increment in the deformability of concrete and diminishing its elasticity modulus due to the incorporation of PET. Batayneh et al. [72] utilized ground plastics (5 mm size) and glass as the replacement of fine aggregate in concrete mix till 20%. It was revealed that crushed glass insertion till 20%, have no effect on the consistency of concrete mix. Also, superior compressive, splitting tensile, and flexural strength were found than conventional mix. Alternatively, inclusion of plastic waste and crushed recycled concrete up to 20%, results found to have decreased in all the properties of concrete mix. The reason may be due to the significant absorption capacity of crushed concrete and less adhesive strength between plastic surface and concrete.

Choi et al. [73] revealed that waste PET bottles inclusion of 75% in lightweight aggregate concrete (WPLAC) as supplant for coarse aggregate found to have compressive strength reduction up to 21% in comparison with the normal concrete. Also, the mix consistency was increased with higher proportion of WPLAC. Another important finding was to use the PET resin in concrete mix enables cost saving problems, thereby mitigating solid waste management problems and conserving energy [16] without compromising with the other strength properties of mix as the value of compressive strength, flexural strength, splitting tensile strength, and elastic modulus was arrived at 73.7 MPa, 22.4 MPa, 7.85 MPa, and 27.9 GPa, respectively, after 7 days curing time. It was also suggested that the PET resin be mixed. Ishaiba [74] also encouraged the recycled PET aggregates utilization as a substituent for NA. Though, the compressive strength value was found to be varying in between 11 and 24% with the use of 15–45% of PET aggregates. Remadnia et al. [75] identifying that the use of PET aggregates (4 mm size) and animal protein as a foaming agent helps in increasing the flowability of the mortar. Juki et al. [76] studied the influence of PET as the part substituent of FA (0–5 mm size) in concrete mix, while Jassim [77] successfully utilized 60% of polyethylene along with 40% of Portland cement to produce plastic cement. Previously [78] found decrease in tensile strength due to level surface of the PET particles, which has an undesirable effect on bond strength. Recently [79] concluded that the ring-shaped PET waste was found to have better fiber concrete like the commercial synthetic fibers-based concrete. The compressive strength found to have a negative relation with the inclusion of all fiber. While the tensile strength of the concrete having ring-shaped PET fibers with 5 mm diameter was found to be increased with the proportion of fiber, and the optimum content for the same was found around 1%. Rai et al. [80] reported a marginal reduction in the workability and compressive strength due to the waste plastic addition, which can be increased with the application of superplasticizer. Besides this, Siddique et al. [81] and Welle [82] also recommended the use of plastic waste in concrete. Narayana et al. [83] also suggested utilization of GGBFS and polypropylene (PP) fibers (0–0.6% dosage) as an alternative material, which would be helpful in reducing the carbon footprint. Besides this, recent research [84] also recommended the use of plastic aggregate and steel slag to construct lightweight concrete. Further, using 10% of silica fume as a nanomaterial will result in the increase in the strength of the mix.

Current and future challenges

For last few decades, E-waste has become a nuisance contributing to the earth's waste stream. In a latest study [17], yearly global production of this waste was assessed over 50 million tons including India's contribution of 2 million tons in 2020. As per the latest report of Central Pollution Control Board [85], in 2017–2018 around 708,445 tonne e-waste was produced in India, which has been increased up to 32 per cent in 2019–2020. Figure 9a exhibits the existing situation of e-waste production in several Indian states [45]. It is noted that 10% of e-waste was produced in 2018–2019, while only 3.5% was produced in 2017–2018. Only by looking at the statistics can a picture of the seriousness of the situation can be made. However, it was stated that at the internationally e-waste in gold has been recovered to about 10–15 percent. It was also concluded that a higher rate of e-waste recycling leads the industries able to reprocess present metals and materials as a substitute of mining expensive raw metals from the earth. It is to note that most of the studies revealed that the usage of e-waste in concrete mix will consequence in the reduction in the strength of the mix and because of e-waste surface, which is the primary factor accountable for the lack bond between e-waste aggregate and the mix. Though very limited studies, [50, 53, 56] recommended the use of different e-waste types, i.e., HIPS, discarded plastic, and PVC cable as fiber in concrete mix in varying ratio, i.e., 30, 16, and 0.8% dosage, respectively. On the other hand, plastic waste has also become a grave threat



(a) (b)

Fig. 9 Contribution of different state in **a** e-waste **b** plastic waste generation [45]

to environment and human health. However, several measures are undertaken by the state and central government by giving the subsidy to initiate a start-up to reuse the plastic waste or to provide the solution to overcome such an issue.

The latest report of Central Pollution Control Board [86] predicted a yearly generation of 3.3 million metric tonnes of plastic waste in India. Figure 9b is exhibiting the current scenario of plastic waste generation in different states in India. The main issue is related to the management of the plastic waste, which is the tedious process of sorting different plastic waste according to their chemical compositions and its costly recycling process. As per the Centre for Science and Environment [87], in year 2013, 530 million tonnes of C&D waste were produced in India, which is estimated to be 44 times higher than officially recorded and just 1% of C&D waste found to be recycled. This is because of the absence of guidelines and alertness regarding the use of demolished waste in construction practices, which makes it more difficult for successful waste management. However, use of aggregate other than natural ones can be permitted in plain concrete only by following IS 456:2000 [18]. Similar types of challenges were observed in the plastic waste utilization in concrete mix, i.e., reduction in strength due to the improper bonding and the smooth texture of plastic aggregate. However, up to 30% use of plastic aggregate can be permitted as the slight decrease in compressive strength was observed [66, 67, 71, 84]. Though, it was also recommended to add additional additives in the mix to enhance its strength properties, i.e., silica fume. A latest study [88] revealed that the steel slag treated with epoxy acrylic organic-silicone resin (EAOR) in enhancing durability of the pavement. Papayianni et al. [19] also confirmed the positive impact of steel slag on the pavement performance. Another recent study [89] recommended the use of 15% steel slag powder (SSP) along with the active silica, which enhances the overall performance of concrete pavement. Use of SSP also found beneficial to enhance the thermal conductivity for asphalt concrete [90]. Though, a microlevel analysis of the adverse impact of different additives, i.e., activated silica, steel slag, waste plastic on the environment, groundwater quality, and soil properties also warranted.

Discussion

The performance of waste materials in Civil Engineering is a gray area for a couple of decades to maximize the utilization and to avoid the landfilling. Among the series of waste materials, the demand on electronic goods and plastic in the market is rising, the way out of such a waste in the future, more is anticipated. Therefore, a detailed literature review is carried out up to date and following conclusions were drawn;

- Previously, different types of e-waste were utilized as part substituent of coarse aggregate having variation in size also, i.e., 10–12.5 mm. The use of e-waste and plastic waste was not found beneficial from the compressive strength perspective as reduction in strength value was observed up to 62%. However, utilization of these wastes in nonstructural construction applications in earthquake prone areas where lightweight structures are warranted.
- Similar trend was observed for flexural and splitting tensile strength, i.e., maximum reduction for up to 73 and 46%, respectively, with application of e-waste in concrete mix. However, there are some exceptions, which show an enhancement to compressive, flexural, and tensile strength of concrete mix because of 16% inclusion of plastic waste and 0.8% e-waste in the mix by [56] and [53], respectively.

- The studies denied the constructive effects of plastic aggregate inclusion in mix in terms of strength properties, which is due to the smooth texture of plastic aggregate, which prevents the water (required in hydration process) to enter within it.
- It was observed that the 10% use of PET aggregate with a size of 0.05–2 mm was found suitable as FA substituent in concrete mix [71]. While marginal strength decrement was noted with plastic aggregate usage, i.e., at 10 and 20% replacement of sand.
- It was also concluded that the steel slag aggregate (SSA) and RCA can also be utilized in asphalt pavement construction as it has its mechanical and environmental benefits [91–98].
- It is concluded that the investigation on nonstructural concrete with e-waste and plastic waste materials is found limited. Addition of fibers in concrete mix with e-waste and plastic waste may improve the strength and durability properties. It is also suggested that recycling a higher rate of e-waste led to industrial reuse of waste materials while decreasing burden on mining of precious metals.
- Based on findings of previous literature [99–103], it was found that the use of e-waste and plastic waste was found suitable only if used as fiber or reinforcement and as substituent to FA, respectively.

Gaps in the knowledge

Based on detailed review on past studies conducted across the world, lack of evidence was reported on application of different waste materials in a combined approach, which is required to address the optimal percentage of different waste materials (i.e., in different combinations). Besides this, a microlevel study is required to increase the utilization of plastic waste as aggregate without compromising mechanical properties with the inclusion of several types of fiber. An attempt could be made by doing replacement of cement, aggregates, and sand at the same time to check the application of industrial by-products to its optimal usage, which may help in preserving the natural resources and in construction of a sustainable environment by reducing the greenhouse effect.

Additionally, e-waste and plastic waste could be utilized in a mesh structure instead of aggregates, i.e., chip form could provide more promising results in terms of mechanical properties of mix. Another attempt could be made in the direction of geopolymer concrete, i.e., application of e-waste and plastic waste as substituent to aggregate or as reinforcement. Most of the studies were utilizing different processed waste materials, which make it more costly and may result in other hazardous impacts, which need to be addressed. Therefore, it is suggested that the application of different waste materials should be examined as received condition only. There is a significant gap found related to the cost estimation and comparison (while using e-waste, plastic waste, and other industrial waste as mentioned in this study) along with reduction in carbon footprint as compared to conventional concrete, which is not addressed. Therefore, a new treatment technology is required to minimize the overall cost.

Conclusions

Based on the review on past studies conducted across the world, following major conclusions were drawn;

- It is also suggested that recycling a higher rate of e-waste led to industrial reuse of waste materials while decreasing burden on mining of precious metals.
- It is also concluded that industrial waste having cementitious properties may contribute to the increment of strength of concrete mix resulting in a sustainable environment in the construction sector.
- Conclusively, using plastic waste and e-waste were not found beneficial from compressive strength perspective; however, plastic waste up to 16% and e-waste 0.8% may be recommended from the point of view of tensile and flexural strength.

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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