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RESEARCH **Open Access**

An assessment of workability, mechanical and durability properties of high-strength concrete incorporating nano-silica and recycled E-waste materials

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Abstract

Background Presently, the proper disposal of E-waste is a major challenge for all nations. Portland cement and aggregates continue to play a major role in the construction industry's operations. Meanwhile, natural resources like gravel (aggregates) are becoming scarce. Thus, E-waste is now offering the building industry a chance to replace traditional aggregates. The main goal of the current study is to determine the highest amount of E-waste that may be replaced with 10-mm coarse aggregates with a nano-silica associated ternary blend in M-60 grade high-strength concrete while still maintaining the designed concrete's mechanical, durability, microstructural and workability characteristics.

Results When compared to normal concrete, concrete with 15% E-waste replacement maintained the design-required compressive, flexural and tensile strength properties. When the E-waste plastic component percentage is considerably high (15–30%), there is a significant decremental performance regarding the mechanical properties and the decremental rate is found to be in the range of 13–23%. Even the microstructure characteristics of concrete validate the mechanical performance of concrete. Nevertheless, the durability characteristics of E-waste incorporated concrete were found to be promising.

Conclusions The overall outcome of the study recommends 15% as the optimal replacement percentage of E-waste for conventional concrete, and it is recommended to adopt for real-time practices.

Keywords E-waste aggregates, Acid attack test, Nano-silica, Workability

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1 Background

Research on incorporating E-waste into concrete, a common building material, is encouraging. It has the potential to enhance the material's strength, workability and durability [3, 9, 15, 35, 36]. Moreover, one key tactic for lowering pollution and advancing sustainability is the utilization of different wastes, such as mining and agricultural outputs, in the production of new materials [35–38]. It is feasible to improve the qualities of the final products while simultaneously reducing the detrimental effects on the environment by incorporating waste materials into construction [26]. Human society has reaped significant benefits because of the exponential growth and expansion of the electronic-based industrial sector, particularly in the areas of communication, healthcare and security. These fields have developed because of the requirements of the modern era, adapting to the dynamic shifts that have occurred in creative practices [6, 7]. There is a discernible decrease in the lifespan of electronic materials, which is being driven by the changing needs and trends of consumers, which has in turn led to an increase in the demand for products that are technologically advanced [16]. In 2019, the worldwide generation of electronic waste amounted to 53.6 million, with a projected increase to 74.7 million tones (MT) by the year 2030 [11, 13, 25]. The relentless consumer demand for electronic devices and their rapid turnover strain the already limited pool of available resources, particularly the rare and expensive components used in their production. Figure 1 depicts country-by-country E-waste generation [6, 14, 16], while Fig. 2 demonstrates region-wise E-waste generation v/s recycling data. Specifically in Asia

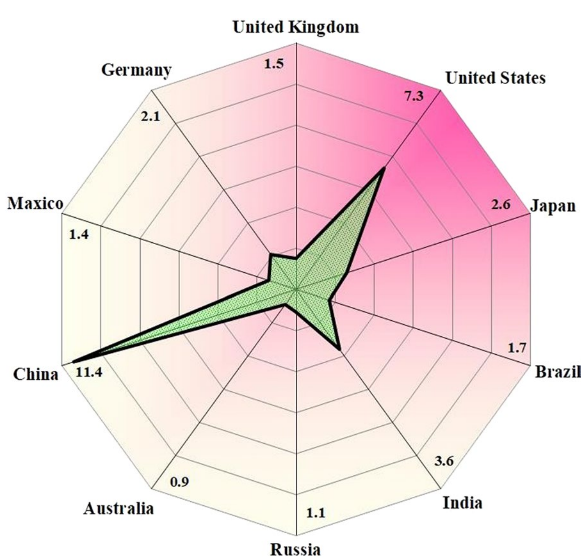


Fig. 1 Generation of E-waste from 10 countries in Million Metric Tones (Source:[3])

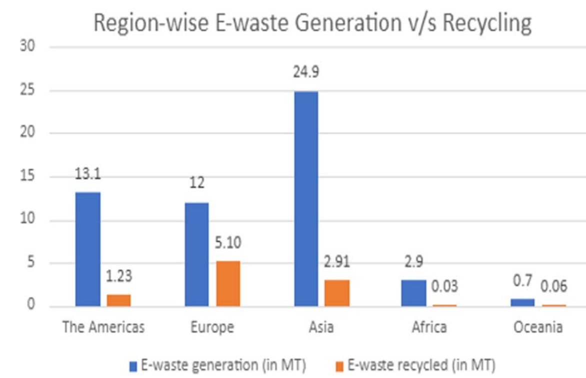


Fig. 2 Amount of E-waste generated and recycled across different regions globally (Source: [3, 26])

it needs a solid solution because the difference between E-waste generation v/s recycling is about 22 MT, and it confirms recycling percentage not even reached 1%. So, it creates research opportunity in the question of "what technology can do?".

Electronic waste is a category of artificial waste that is rapidly expanding on a global scale, with an annual growth rate ranging from 3 to 4% for the growth rate of the category [2, 6, 14, 16]. Currently, recycling electronic waste for specific alternative applications accounts for only 15% of all electronic waste. The complexity of electronic waste, which is composed of a wide variety of components that fall into different categories based on their materials and may include metals, toxins, PCBs, cables, plastics, CRT or LED monitors, and various accessories loaded with hazardous chemicals and rare earth elements, poses a significant challenge to recycling efforts. These components include monitors that use either CRT or LED technology and various accessories that are loaded with hazardous chemicals and it is crucial to highlight that the inclusion of flame retardants further complicates the recycling of electronic waste [29]. Figure 3 depicts the most common E-waste composition breakdown.

The unquenchable thirst for adopting the newest technologies in step with the latest developments in the world market has resulted in the unfortunate practice of throwing away older devices that are still functional into the environment. Due to inefficient disposal and recycling practices, electronic waste, also known as E-waste, has recently come to the forefront as a primary factor in the deterioration of the environment [17]. This has far-reaching implications, as it not only affects the well-being of the current population but also the well-being of future generations and the ecosystem. In developing countries such as India, which ranks as the third-largest generator of electronic waste globally with an estimated 3.3 million

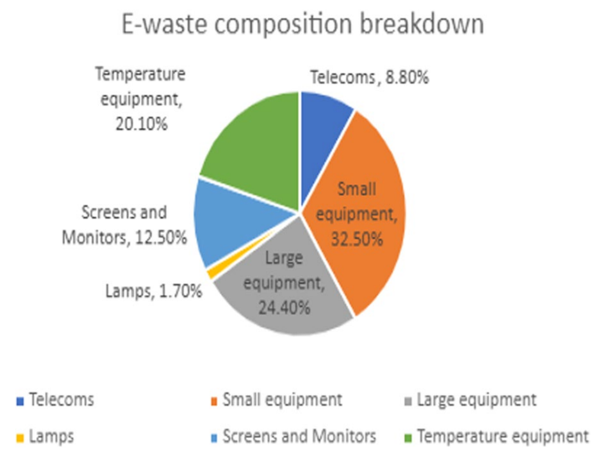


Fig. 3 Global E-waste composition breakdown (Source: [10, 26])

Table 1 E-waste generation in India since 2017–2018. *Source*: Epa et al. [10], Reena and Verinder [26]

Financial year	E-waste generation (tons) in India
2017–2018	7,08,445.00
2018–2019	7,71,215.00
2019–2020	10,14,961.21
2020–2021	13,46,496.31
2021–2022	16,01,155.36

metric tons in 2022, improper electronic waste disposal represents a significant environmental threat because it releases hazardous materials into the environment [29]. Taking cognizance of this threat, the government of India has taken steps to regulate E-waste management through the E-waste (Management) Rules, 2016. However, challenges like informal recycling practices, lack of awareness, insufficient infrastructure, and inadequate enforcement are a matter of concern at present. Based on the data from annual report of Central Pollution Control Board (CPCB), Table 1 represents the statistical data for generation of e-waste in India. Figure 4 highlights the critical need for improving recycling practices in India as well as globally.

The utilization of electronic waste (electronic waste) in concrete, either as fine or coarse, offers a potential solution that could alleviate the demand for raw materials and address the challenges that are associated with the disposal of E-waste [29]. The proper disposal of electronic waste can have significant positive effects on the natural environment, but improper disposal can also have significant negative effects. The incorporation of recycled plastic and other types of electronic waste into concrete presents a potentially useful approach to addressing a variety of environmental and ecological concerns (Karthikeyan 2017, [4, 23, 24, 27, 28, 31–34]).

India is currently experiencing a significant increase in urbanization, which is leading to an increased demand for construction materials. India is the fourth largest construction market in the world, with an estimated annualized construction spending of approximately 427 billion dollars. The growth of smart cities and the development of urban infrastructure have been the primary drivers behind this increased demand for construction [1]. Because of this, the perspective of the researchers reflects global efforts to incorporate components of electronic waste (electronic waste) utilized as a partial replacement for coarse aggregates in the construction sector [29]. Notably, studies carried out by Dawande [8] showed that after a period of 28 days, the results of experiment demonstrated that utilizing 10% E-waste as coarse aggregate yielded optimal results. Furthermore, in an independent study [6, 14, 16] the researchers concluded that utilizing electronic waste as a partial substitute for fine aggregate

Fig. 4 Recycling of E-waste in India and globally (2021–2022) (Source: [10, 26])

and coarse aggregates is viable for achieving an equivalent level of concrete strength. In subsequent research [2, 29], investigated the possibility of utilizing E-waste as a significant substitute for coarse aggregate in concrete. According to the researchers, using 10% and 12.5% electronic waste in place of coarse aggregate led to improvements in the material's compressive, tensile, and flexural strengths, respectively. This experiment builds upon existing research but employs novel methodologies to investigate the effects of fly ash and nano-silica, both individually and in combination with cement (binary and ternary blends). One can successfully replace 10-mm-sized coarse aggregates in high-strength concrete (M-60 grade) with non-biodegradable components of electronic waste that have combinations of Printed Circuit Board (P.C.B.) + Kit material + Steel + Plastic + Other combined materials.

2 Materials

2.1 E- waste aggregate procuring procedure.

The phrase "electronic waste," frequently shortened as "E-waste," encompasses any discarded or outdated electrical or electronic devices, electronics, home electronics, and other products. Circuit boards and chips that are no longer in use can be used in place of coarse aggregates after being reduced in size through crushing and cutting to pieces no larger than 10 mm as illustrated in Fig. 5. The characteristics of the electronic waste that was utilized in this study are detailed in Table 2, and an illustration of the electronic waste that was utilized in this study is to be found as in Fig. 6. It validates the variety in the contents of E-waste, such as the dominant Printed Circuit Board (P.C.B), which was determined to be between 68 and 77%, kit material, which was between 19 and 21%, steel-plastic variations, which were between 1 and 5%, and other combination materials, which were less than 1%. Chemical properties of E-waste confirm the presence of 1.31 mg/l of lead, 0.44 mg/l cadmium, 0.22 mg/l chromium, 4.33 mg/l copper, 1.51 mg/l iron, 9.88 mg/l nickel and 5.55 mg/l zinc.

Table 2 Variation of E-waste material constituents

Identified variation of combination no.	P.C.B. (%)	Kit material. (%)	Steel. (%)	Plastic. (%)	Other combined materials
1st	68	22	4	5	1
2nd	77	19	2	1	1
3rd	73	20	3	3	1
4th	76	21	2	1	0

2.2 Binders

The Ordinary Portland Cement (OPC) grade 53 assessment was conducted in accordance with the parameters outlined in IS standards [18, 19]. The general features of cement that were taken into consideration for the study are confirmed in Table 3, which was created by compiling the results of the examination of numerous criteria. Furthermore, Class F Fly Ash serves as a secondary supplementary cementitious material, while nano-silica functions as a ternary supplementary cementitious material. Overall, its features support quality assurances.

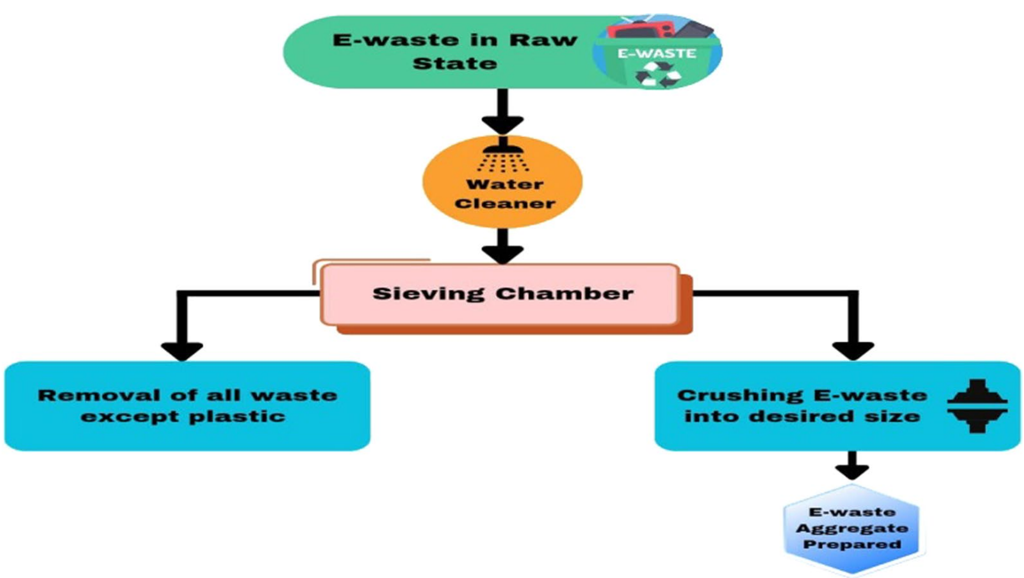
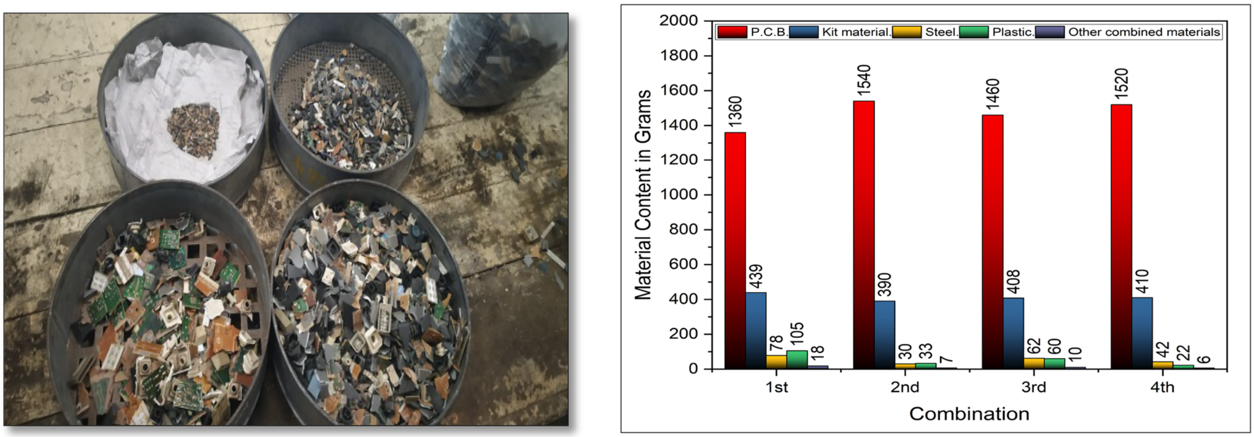


Fig. 5 Flow chart of E-waste emerging from raw state to aggregate phase



(a) (b)

Fig. 6 **a** Crushed E-waste material and **b** possible variation of combination

Table 3 Binder characteristics

Sr. no.	Characteristics	Cement	Fly ash (Class F)	Nano-silica
1	Fineness	5.98%	4.81%	–
2	Setting time (initial)	87 min	–	–
3	Setting time (final)	350 min	–	–
4	Consistency	31%	–	–
5	Specific gravity	3.15	2.91	2.31
6	Specific surface area (m^2/g)	0.371	0.452	202
7	Particle size			
	d_{10}	3.8 (μm)	2.01 (μm)	179.00 (nm)
	d_{50}	14.31 (μm)	8.31 (μm)	208.11 (nm)
	d_{90}	32.14 (μm)	28.14 (μm)	228.13 (nm)

2.3 Aggregates characteristics

The fine aggregates undergo a sieving process with a fineness of 4.75 mm to efficiently remove unwanted stones and contaminants. The term "fine aggregate" is used to describe aggregate particles that have been able to pass through a screen with a thickness of 4.75 mm. The attributes of fine aggregate are defined using the established standard as per IS: 2366 (Part IV)—1963 [20], and it is confirming Zone II. Table 4 presents a comprehensive compilation of numerical data pertaining to different characteristics of the fine aggregate. The study utilized coarse aggregates that had a particle size of 20 mm, in accordance with the specifications provided in the IS 2386 [20]. The results derived from the examination of diverse attributes of coarse aggregate carried out within the scope of this study, as well as confirming the minimum quality assurance of materials. Meanwhile E-waste aggregates also confirm the minimal considerable characteristics by achieving equivalent crushing and impact values as of natural aggregates (IS: 2366 (Part IV)—1963) [20]. Here by this crushing value confirms sustainable characteristics of E-waste aggregates against static loads as well as impact value confirms sustainable

Table 4 E-waste aggregates and conventional aggregates characteristics

Sr. no.	Characteristics	Fine aggregate	Coarse aggregate	E-waste
1	Fineness modulus	4.96	8.69	–
2	Bulking (%)	3	–	–
3	Water absorption (%)	1.2	–	0.001
4	Specific gravity	2.74	2.74	1.77
5	Impact value (%)	–	10.52	12.03
6	Crushing value (%)	–	16.90	17.74
7	Abrasion value (%)	–	16.76	2.258

Sand utilized as fine aggregates and granite as coarse aggregates characteristics of E-waste aggregates against dynamic loads. Meanwhile, the abrasion value of E-waste aggregates is being compromised and it is about 14.502% lower than natural aggregates.

3 Methodology

3.1 Mix design

The mix design was carefully carried out as per IS 456:2000 [11] to achieve high-strength concrete with a desired compressive strength of M60 as presented in Table 5. The cement used in this study was OPC 53, a distinct grade of cement, followed by secondary & ternary binder be the Class F Fly-Ash and nano-silica. Furthermore, aggregates were limited to a maximum nominal size of 20 mm and followed 10 mm with E-waste replacement from 5 to 30% with an 5% incremental range, while the water/cement ratio was constrained to a maximum value of 0.45 as per I.S. 10262: 2009 [11, 21] guidelines.

3.2 Tests generalization

Further the processes of casting, curing and testing of concrete specimens were subjected to a sequence of evaluations, encompassing compressive, flexural and split tensile tests as per I.S 516: 1959 [12] which are detailed in sections from 3.3 to 3.5.

3.3 Casting

Casting 63 (each set of 3 replicates) cubes of concrete measuring 15 cm on each side were carried out for successive tests at the intervals of 7, 14 and 28 days as showcased in Fig. 7. In a similar manner, 63 (each set of 3 replicates) beams measuring 10 × 10 × 50 cm were cast to determine the flexural strength of the concrete, and 63 (each set of 3 replicates) cylinders measuring 15 × 30 cm were prepared to determine the tensile strength of the concrete. Furthermore 21 (each set of 3 replicates) cubes and cylinders were cast to subject under acid attack tests.

Table 5 Mix design characteristics of concrete

	Replacement proportion in kg/m^3						
Material	**0%**	**05%**	**10%**	**15%**	**20%**	**25%**	**30%**
Mix	**M601**	**M602**	**M603**	**M604**	**M605**	**M606**	**M607**
Cement (actual OPC) (kg/m^3)	413.6	413.66	413.66	413.64	413.6	413.66	413.66
Water (kg/m^3)	162	162	162	161	162	162	162
Fine aggregate (kg/m^3)	481	481	481	481	481	481	481
Coarse aggregate 20 mm (kg/m^3)	491.23	491.23	491.23	491.23	491.23	491.23	491.23
Coarse aggregate 10 mm (kg/m^3)	491.23	466.7	442.1	417.25	392.10	368.42	343.90
Nano-silica (%)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fly ash (kg/m^3)	191	191	191	191	191	191	191
Super plasticizer (kg/m^3)	6.36	6.36	6.36	6.36	6.36	6.36	6.36
E waste (kg/m^3)	0	16	31.73	46.83	63.10	79.33	95.20
Revised water to cement (*w/c*) ratio	0.255	0.255	0.255	0.255	0.255	0.255	0.255

The revised *w/c* ratio is the actual *w/c* ratio used to compensate for the influence of nano-silica (high surface area) and super plasticizer through practical observation to ensure suitable workability and strength

Fig. 7 **a** Concrete cubes and **b** concrete cylinders

3.4 Curing

Before being evaluated on specific days like 7, 14 and 28 days, the cubes, cylinders and beams that were designated for testing went through a painstaking curing process in water tanks as showcased in Fig. 8. This was done to ensure that the components were exposed to the appropriate conditions for hydration process before subjecting them to testing protocols.

3.5 Workability and mechanical properties

3.5.1 Slump cone test

The slump cone test was carried out as per IS 7320 [22] as visualized in Fig. 9, so that an analysis is carried out to determine the effect that various replacement percentages have on the workability of the concrete. This test is used to determine the consistency of concrete in its freshly mixed state. The results of this test provide information regarding the concrete's workability and flowability before it begins to harden. In the case of concrete grade M-60, the slump value assurance is a significant factor regarding deciding of its workability characteristics.

Fig. 9 Slump cone test

3.5.2 Compressive strength test

The compression test was a fundamental test as detailed in Fig. 10, which was conducted on standard cubes sized 150 mm×150 mm×150 mm at intervals of 7, 14 and

Fig. 8 Curing process

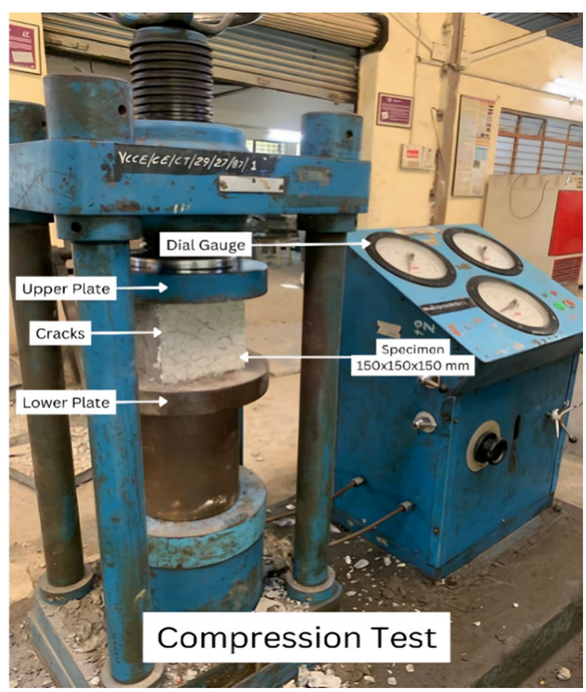


Fig. 10 Compressive strength test

28 days as per IS 516 specifications [12]. Further, the compressive strength of concrete is measured through Eq. 1.

$$F_{ck} = \frac{P_c}{A} \quad (1)$$

where P_c—failure load, A—area of the cube.

3.5.3 Flexural strength test

The flexural strength of a concrete is determined by measuring stress at the point just before the material yields in a flexural test as detailed in Fig. 11, which is also known as the rupture modulus [42–47]. Further, the flexural strength of concrete is measured through Eq. 2.

$$F_b = P \times L/(bd^2) \quad (2)$$

where P—maximum load, L—supported length, b—width of specimen, d—failure point depth.

3.5.4 Split tensile test

In comparison with its strength under compression, concrete's tensile strength is not particularly noteworthy. The splitting tensile strength test, conducted on concrete cylinders, is a method that can be employed to assess the concrete's tensile strength level as per previous studies [44–50]. The results of putting cylinders with dimensions of 300 mm in length and 150 mm in diameter through the testing machine with loads applied to opposing sides of the cylinders are presented in Fig. 12. Further, the split tensile strength of concrete is measured through Eq. 3.

$$F = (2P)/\pi DL \quad (3)$$

Fig. 12 Tensile strength test

where P—(maximum load), L—(length of the specimen), D—(cross sectional dimension).

3.5.5 Water absorption test

When determining the concrete specimens' durability through acid attack test as detailed in 3.5.6, it is essential to conduct tests to determine how well they absorb water. The formation of voids in concrete mixes can be a consequence of insufficient bonding between the E-waste particles and the cement paste, which in turn reduces the overall durability of the concrete. In accordance with the British standard BS 1881-122, 2011 [5], the water absorption test was carried out. The experimental specimens that were used in this investigation were cylindrical samples of concrete, each of which had a diameter of 75 mm. These specimens went through a drying process in an oven for exactly seventy-two and a half hours. After taking it out of the oven, there was a waiting period of precisely twenty-four and a half hours for it to cool down. After the cooling phase, we immediately recorded the weight of each specimen. After this, the specimens were submerged completely in water for a period of 30 min plus or minus half a minute as showcased in Fig. 13. After being submerged, the samples were carefully dried with cloths to remove any trace of surface water before their weight was determined once more.

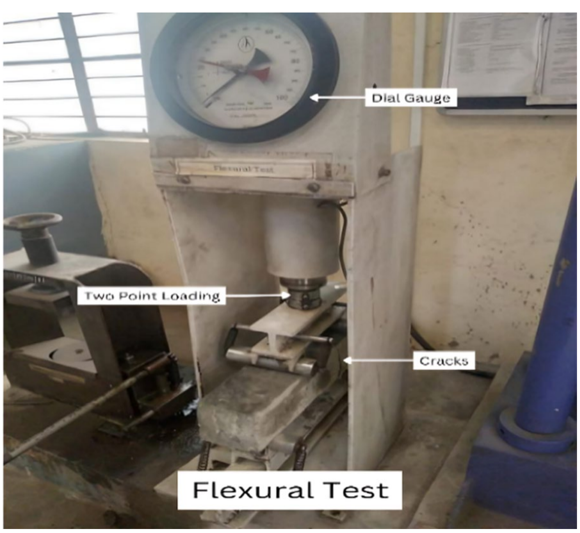


Fig. 11 Flexural strength test

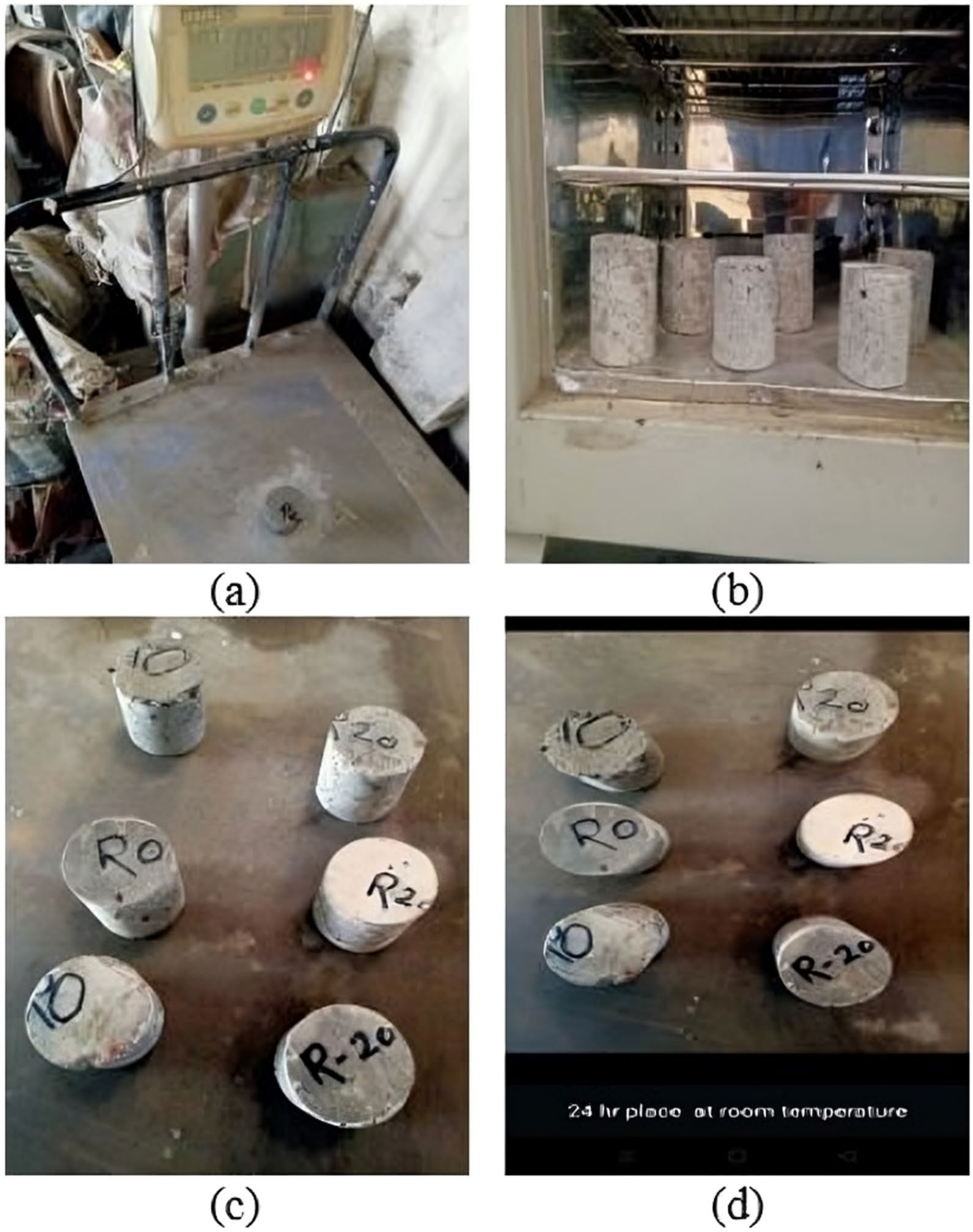


Fig. 13 Water absorption sample

3.5.6 Acid attack test

The acid attack test was conducted on all concrete samples following the protocols specified by the American Society for Testing and Materials (ASTM) in accordance with ASTM C1898-20 [30]. The evaluation was conducted using cube specimens measuring 150 mm on each side. After being cast, the concrete cubes were allowed to remain in their molds for a period of 24 h before undergoing a curing process that lasted for 28 days. Following the curing phase that lasted for 28 days, the specimens went through a drying phase that lasted for 24 h. After determining the initial weight of each specimen, it was determined that concrete samples should be submerged in an acidic solution made with sulfuric acid (H_2SO_4) and kept at a pH level of 2 as showcased in Fig. 14. This procedure was repeated three times. Following the completion of each 7-day interval, the specimens were transferred to a container made of inert materials, and

Fig. 14 Acid attack test

the pH level of the acidic solution was measured, after which it was adjusted to a pH level of 2. After a period of 56 days, the cubes were extracted from the acidic solution and then subjected to quantitative analysis. Following this procedure, the weight that was recorded was the definitive weight of the specimens. Testing for compressive strength was carried out with the assistance of a compressive testing machine as detailed in 3.5.2, and an analysis was carried out to determine the degree to which compressive strength had been diminished.

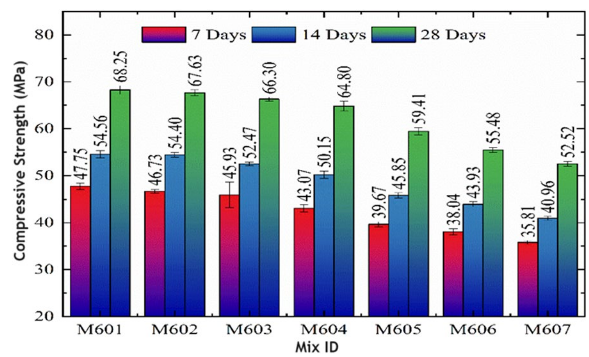


Fig. 16 Graphical representation of compressive strength test results

3.5.7 SEM examination

This investigation was specifically performed optimal and associated mixes. In the wake of the Field Emission Scanning Electron Microscope (FE-SEM) analysis, an energy-dispersive X-ray (EDX) analysis was carried out to ascertain the phase composition of the materials.

4 Results

See Figs. 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25 and 26.

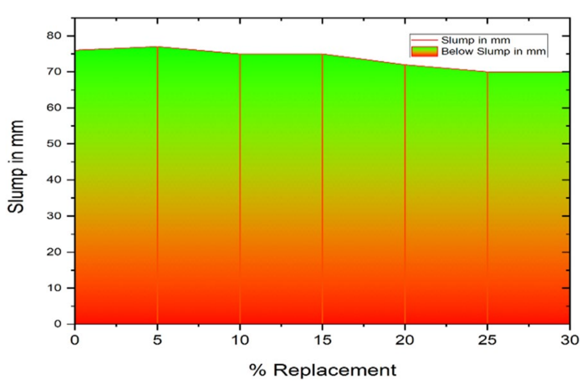


Fig. 15 Graphical representation of slump cone test results

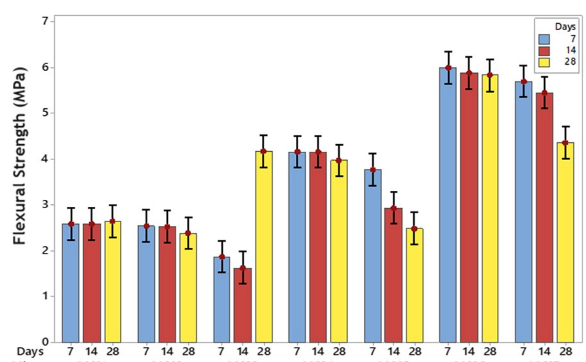


Fig. 17 Graphical representation of flexural strength test results

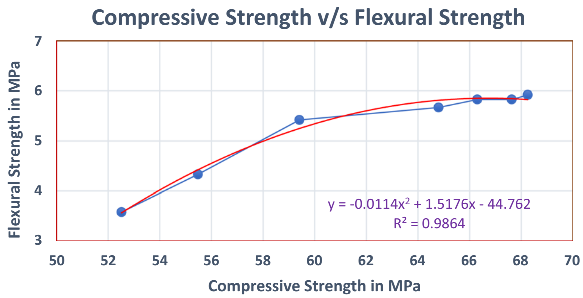


Fig. 18 Relationship between compressive strength and flexural strength

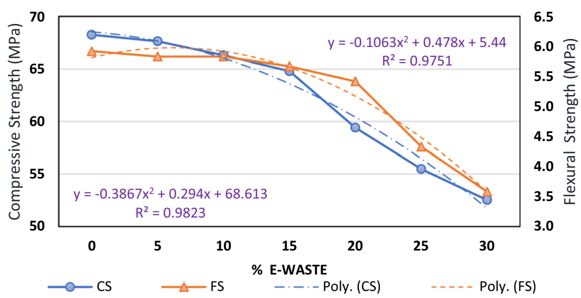


Fig. 19 Correlation between % E-waste, compressive and flexural strength of E-waste concrete

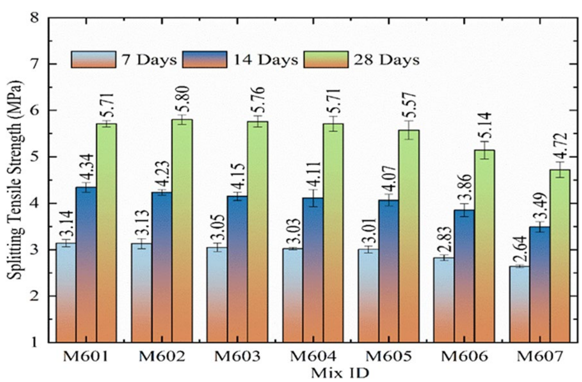


Fig. 20 Graphical representation of tensile strength test results

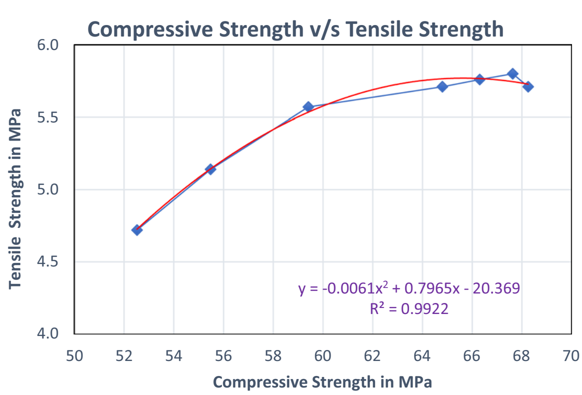


Fig. 21 Relationship between compressive strength and flexural strength of E-waste concrete

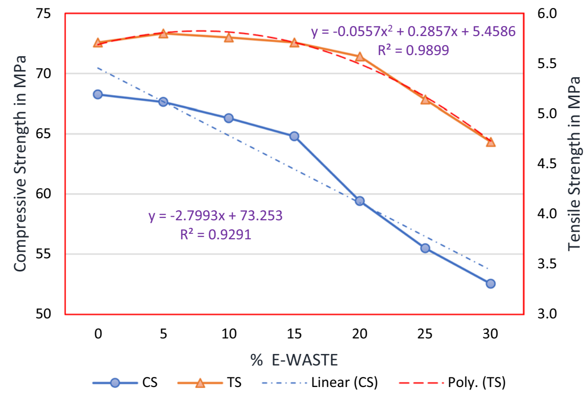


Fig. 22 Correlation between % E-waste, compressive and tensile strength of E-waste concrete

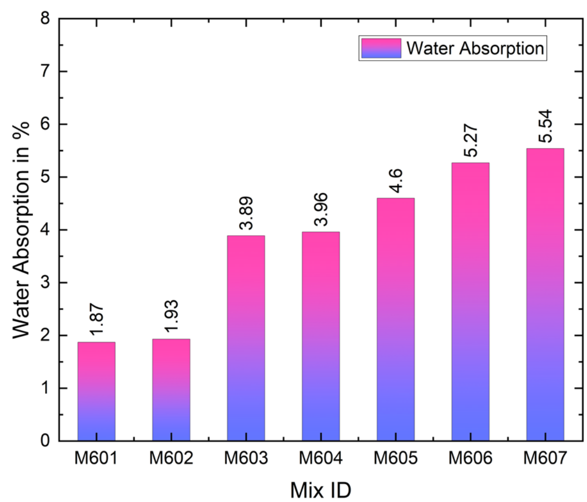


Fig. 23 Graphical representation of water absorption test result

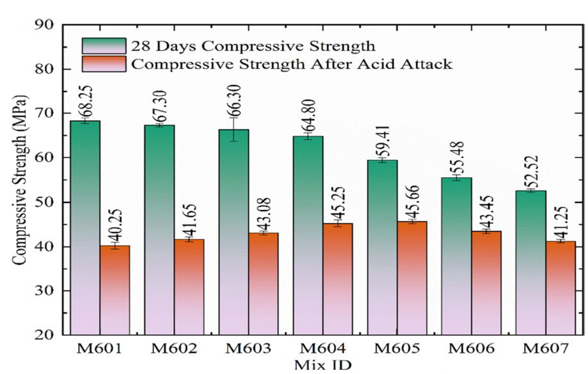


Fig. 24 Graphical representation of acid attack test result

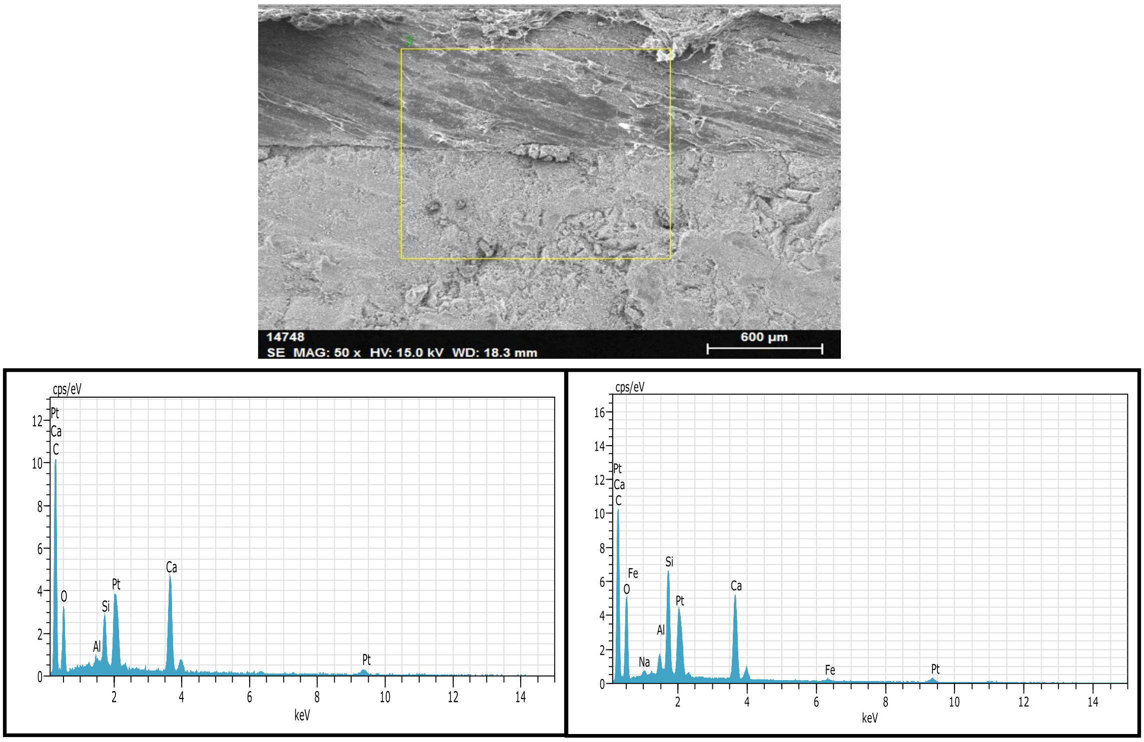


Fig. 25 Representation of EDS result for 15% and 20% replacement

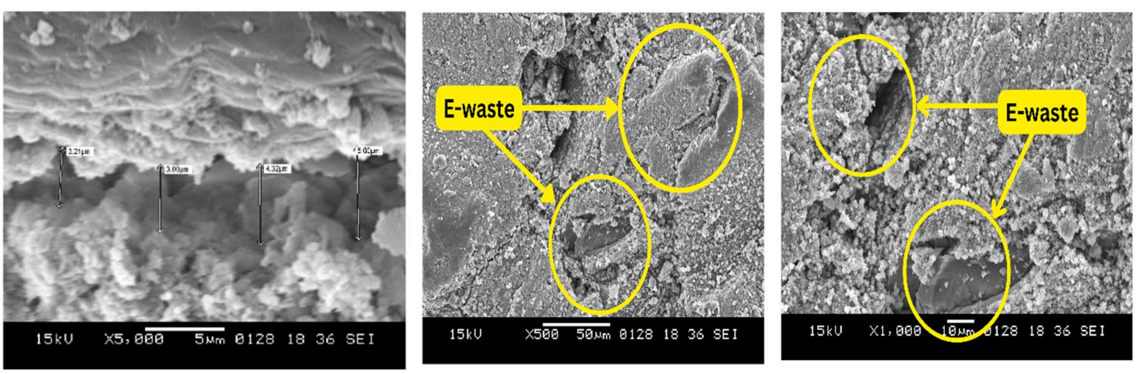


Fig. 26 Representation of FE-SEM results

5 Discussion

5.1 The slump cone examination

The results of the slump cone test were based on the testing of mixtures with replacement percentages of 0%, 5%, 10%, 15%, 20%, 25% and 30%, respectively. These findings shed light on the various aspects of the feasibility of the mix, including the E-waste replacement rate and the slump value. Figure 15 is a graph that shows the correlation between the slump value and the percentage of waste e-plastic. The slump values remain consistent from 0 to 15% E-waste replacement. Beyond the 15% replacement (M604 mix), there is a gradual decrease in slump values. It clearly validates that more 15% replacement of E-waste demands the compromise of workability characteristics of concrete of about 5mm.

5.2 Test of compressive strength

At the 28-day mark, the results showed that up to 15% E-waste replacement, concrete mixes represent compressive strength as same as control mix and it is about 64.80–68.25 MPa at 28 days of curing. Beyond 15% replacement, a more significant decrease was found. The mix M607 showed the maximum decrease of 23% in compressive strength compared to M601. Even these findings are in line with workability characteristics of concrete. Reason being poor compaction of concrete achieved due to varied irregularity texture, least specific gravity and least abrasion characteristics (Refer Table 4) of E-waste which results in more voids and poor density. Figure 16 presents a comparison of the compressive strength of the material after 7, 14, and 28 days. Even the same decreasing pattern of compressive strength can be observed at initial days (7 and 14 days) of curing period as expected.

5.3 Test of flexural strength

Figure 17 shows the flexural strength of the material after 7, 14 and 28 days, with varying percentages of coarse aggregate (CA) replaced by electronic waste. The results of the flexural tests illustrate the resiliency of mixtures that contain varying degrees (0–30%) of electronic waste in their composition. It is important to point out that although there is a decrease in consistency, the sudden drop by 0.5 to 0.6 MPa is in flexural strength once the proportion of E-waste replacement reaches more than 15%. M601 (control mix) has the highest flexural strength of about 5.92 MPa. Flexural strength for 15% E-waste replacement mix (M604) was 5.83 MPa, while for 30% replacement mix (M607) it was 3.58 MPa. This exhibits that M607's flexural strength was 38.59–39.47% lower than that of the M604 & M601. Overall, these findings are in line with compressive strength characteristics of concrete and replacement percent of E-waste as detailed in Figs. 18 and 19, which validates through linear regression relationship by having R^2 value of about 0.98. It even makes clear that, in terms of high-strength concrete, the 15% replacement percentage of E waste renders the presence of nano-silica, which was anticipated to result in increased CSH production and tough bond formation between E-waste and other parts of concrete, meaningless.

5.4 Test of tensile splitting strength

Figure 20 illustrates a comparison of the results from split tensile tests conducted at 7, 14, and 28 days, involving different percentages of E-waste plastic replacements. As expected, the tensile strength of the control mixture closely resembles that of the 15% replacement. However, it progressively diminishes as the E-waste percentage in the replacement rises. Overall, there was a 17.34% reduction in tensile strength at 30% replacement of E-waste. Figures 21 and 22 validate the linear relationship of tensile characteristics with compressive strength and E-waste replacement percentage by achieving $R2$ value of about 0.99 and 0.92. Overall, it is in line with other workability and mechanical characteristics of concrete.

5.5 Water absorption test

The experimental findings indicated a direct linear correlation between the quantity of e-waste incorporated into the concrete mixes and their water absorption capacity. The different rates of water absorption that were found in the various concrete mixes that were investigated during this stage of the research are depicted in Fig. 23. The water absorption rate of the control mix (M601) was 1.87%, while the water absorption rate of the M607 mix was 5.54%. This represents an almost fourfold increase in comparison with the water absorption rate of the control mix. Overall, 15% is the compromising limits with volumetric characteristics of concrete.

5.6 Acid attack test

Acid attack test reveals that compressive strength of the control mix decreased by 41.03% because of the decrease in volume as in Fig. 24. In contrast, the M607 mix demonstrated the least amount of reduction, with only a slight decrease of 21.46%. The reduction in compressive strength was equal to control mix characteristics which was approximately 30.17% when 15% of the coarse aggregates was replaced with E-waste. Higher proportions of E-waste particle replacement, particularly in the form of fibers, promote to mitigate the decrease in compressive strength that occurred. The incorporation of these E-waste fibers up to 20% proved to be an effective barrier against the development of cracks even better than control mix performances. Reason being P.C.B percent of E-waste is 68–76% so it is the strongest resistor to dilute of concrete which results in better performance regards strength characteristics of concrete. Overall, it proves that E-waste-incorporated concrete has significant benefits regards durability characteristics of concrete.

5.7 SEM results

Following the favorable outcomes in strength parameters with a maximum of 15% replacement of coarse aggregate with E-waste and associated mix having 20% E-waste was chosen because the first mix (M604) is the optimum performed mix and other (M605) exhibited the sudden drop-down workability, and mechanical characteristics, so these are chosen for examination using a scanning electron microscope (SEM) to understand microstructural challenges. According to the findings, the two mixtures share a common presence of carbon and oxygen as their primary constituents as in Fig. 25. When compared to the M605 mixture, the atomic weight percentages of carbon and oxygen in the M604 mixture were 33.11% and 21.74%, respectively, while in the M605 mixture, these percentages were 33.01% and 16.81%. In addition, calcium and silica were found to be other prominent elements present in both mixes. In the M605 mix, the percentages of calcium and silica were 10.59% and 1.86%, respectively, whereas in the M604 mix, those percentages accounted for 10.05% and 4.58%, respectively. Along with this Fig. 26 represents CSH, CC & E-coated E-waste particles which result in voids formation. It is evident that the physical characteristics of E-waste, specifically specific gravity of about 1.77 as detailed in Table 4, is the culprit for improper bonding and its texture is the ultimate limitations for its poor microstructure characteristics. Overall, these findings validate the mechanical characteristics of concrete.

6 Conclusions

Testing on M-60 grade concrete with E-waste as a partial substitute for coarse aggregates indicated restrictions up to 15% substitutions. It was found that the concrete mixture containing 15% E-waste replacement achieved workability and mechanical properties that were nearly equivalent to that of concrete containing no replacement at all. In contrast, once the replacement proportion exceeded 15%, the concrete's mechanical properties began to suddenly drop down and the reason being its specific gravity or porosity as validated by FE-SEM and EDS observations. Resistance against acid attack was found to be significantly favorable when observed in all E-waste-incorporated concrete compared to the control mix. Overall, 15% E-waste-incorporated M60 grade concrete can be utilized for real time practices, specifically in the context of durability demand.

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Author contributions
The authors confirm contribution to the paper as follows: PH, TS, RR, BN, SR helped in study conception and design; PH, TS collected the data; MK, AT, SRN were involved in analysis and interpretation of results; PH, TS, RR, BN, SR, MK, AT, SRN helped in draft manuscript preparation. All authors reviewed the results and approved.

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Not applicable.

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