

New Generation Waste Material As Sustainable Ingredient In Concrete: An Experimental Approach

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Abstract

E-waste, including devices like phones and computers, poses serious environmental risks. To mitigate these, the construction industry is exploring e-waste as a material to enhance concrete strength and durability. Hence, the present study assesses the performance of M40-grade high-strength concrete by replacing coarse aggregates with 0% to 30% e-waste plastics at various intervals. As the e-waste replacement increased, fresh concrete's workability decreased gradually. The mix containing 30% e-waste experienced the largest reduction in slump value, showing a 10% reduction compared to the control mix. Compressive strength at 28 days declined with increased e-waste content, with the most desirable results observed in mixes containing up to 15% e-waste, which is the recommended substitution level for satisfactory strength. Flexural and tensile strength tests revealed similar trends, with a decline beyond 10-15% e-waste substitution. Throughout the research, a 15% e-waste substitution consistently yielded positive outcomes across all concrete grades, enhancing workability, strength, and resistance to acid attack while controlling water absorption.

Keywords: E-waste, concrete, flexural strength, tensile strength, compressive strength

INTRODUCTION

The construction industry faces significant challenges, notably its environmental impact and dwindling resources, especially in concrete production [1-3]. Concrete heavily relies on depleting natural resources like gravel and sand, and its manufacturing emits substantial carbon dioxide, exacerbating climate change [4]. Given the depletion of natural resources, it is essential to find sustainable alternatives, leading many researchers to explore the use of several wastes. This study

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focuses on utilizing electronic waste (e-waste) to create sustainable concrete, aiming to enhance the environmental friendliness and resource efficiency of the construction industry. This approach also addresses the growing global challenge of e-waste, which currently contributes significantly to landfill waste [5-9]. E-waste comprises heavy elements viz. cadmium, lead, mercury, and persistent organic pollutants, posing environmental and health risks [10,11]. Figure 1 illustrates E-waste's negative environmental impact, showing the release of toxins [12].

E-waste represents a rapidly growing segment of manufactured waste worldwide, with an annual increase rate of approximately 3 to 4% [10,13-15]. [16] A comprehensive report of 2007 revealed alarming E-waste volumes, totaling approximately 3,35,00 metric tons (MT) that year. Notably,

computers (~56,000 MT), mobile phones (~1,650 MT), and televisions (~275,000 MT) contributed significantly to this fig. emphasizing the magnitude of the issue [17]. Projections suggest a troubling trend, with E-waste production expected to approach nearly 1 million MT by 2015 and a forecasted escalation to a staggering 2 million MT by 2025, as shown in Figure 2.

Addressing the global issue of electronic waste recycling and reuse is urgent. Recycling strategies must be technically and economically viable and garner societal support [18].

Repurposing end-of-life electronic products in construction offers an environmentally friendly solution [19, 20]. Incorporating waste materials into concrete manufacturing can alleviate environmental burdens and reduce natural resource extraction, aligning with the principles of a circular economy [21,22].

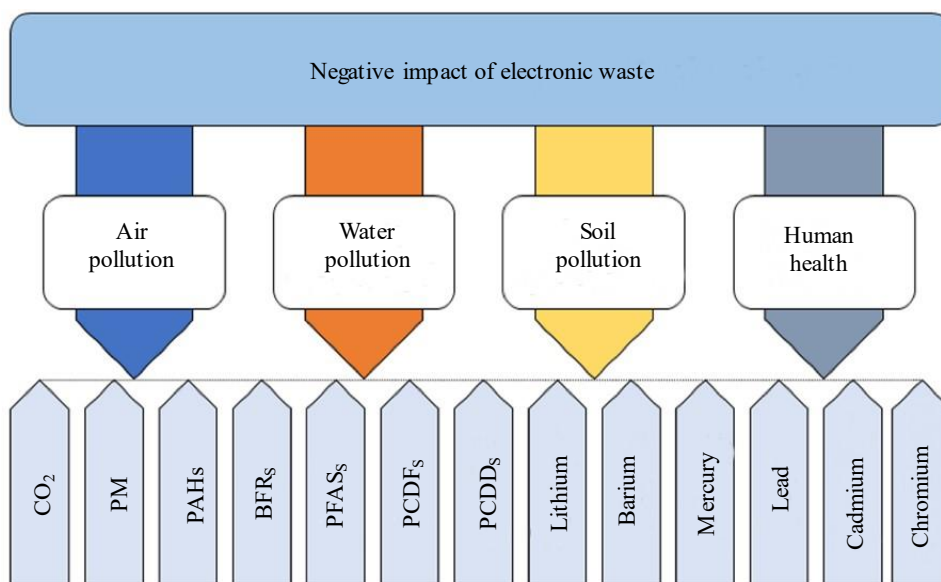


Figure 1. Harmful effects of e-waste on environment.

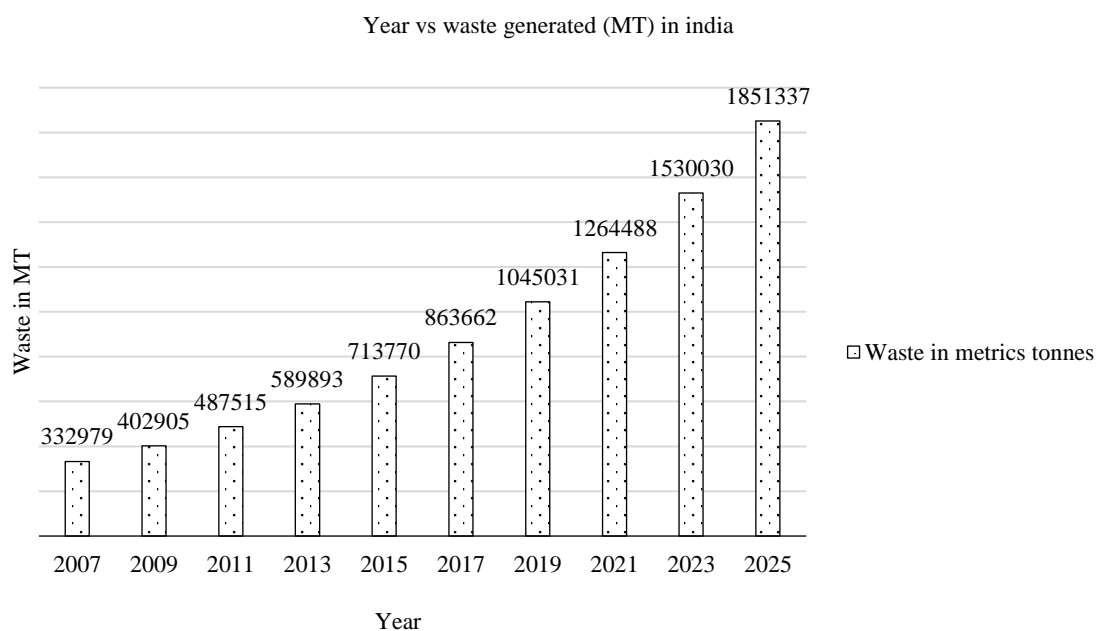


Figure 2. E-waste generation in india [12-16].

E-waste materials can be assessed for compatibility with concrete and their impact on desired properties evaluated [23-25]. Mechanical property assessments, including strength and durability, provide insights into the sustainability benefits of waste material-modified concrete [26]. Integrating these methodologies in construction can mitigate environmental degradation and conserve natural resources [27,28]. This study aims to develop sustainable concrete with improved properties compared to conventional concrete, reducing the dependence on natural resources and enhancing solid waste management. It evaluates the use of e-waste plastic as a substitute for coarse aggregate in M-40 grade concrete, with proportions of 0%, 5%, 10%, 15%, 20%, 25%, and 30%, using OPC 53 grade cement as per IS 8112 standards. The developed concrete is tested according to IS specifications. Compressive strength will be assessed on days 7, 14, and 28, while tensile and flexural strengths will be measured on day 28. The study indicates that using crushed E-waste plastic as a substitute material in construction could reduce the costs associated with concrete production.

MATERIALS

E-Plastic

The e-waste analyzed for this research comes from obsolete electronic devices and domestic appliances. These materials, once cut into 10 mm fragments, include discarded circuit boards and chips, serving as substitutes for coarse aggregates in varying proportions.

Table 1 details the characteristics of the e-waste material investigated.

Table 1. Categorization of E-waste.

Combinations	P.C.B.(gm)	Kit material.(gm)	Steel.(gm)	Plastic.(gm)	Other combined materials	TotalWt (kg)
1 st	1360 gm	439 gm	78gm	105 gm	18 gm	2
2 nd	1540 gm	390 gm	30 gm	33 gm	7 gm	2
3 rd	1460 gm	408 gm	62 gm	60 gm	10 gm	2
4 th	1520 gm	410 gm	42 gm	22 gm	6 gm	2
Total (%)	73.5%	20.5875%	2.65%	2.755%	0.512%	100%

Cement

The properties of OPC grade 53 [29] were evaluated based on IS 2386 (Part-1) 1963, and the test outcomes are presented in Table 2.

Table 2. Test outcomes for cement.

S N.	Characteristics	Value
1	Consistency of Cement	31 %
2	IS Time	87 min
3	FS Time	350 min
4	FC	94 %
5	Soundness of Cement	2 mm

Fine Aggregate

A 4.75 mm mesh sieve removes debris from aggregates, classifying the material that passes through as fine aggregate. Its properties are defined by IS-2386 (Part-1) 1963.

Coarse Aggregate

The experiment employed 20 mm coarse aggregates, tested according to the criteria specified in IS 2386 (Part-1) 1963 [30].

Testing of Material

Experiments were conducted to demonstrate compliance with the appropriate rules of Information Systems (IS) in the context of electronic waste (e-waste). Table 3 contains a comprehensive presentation of the pertinent data and information derived from these experiments.

Table 3. Properties of ingredients.

Sr.N.	Characteristics	Fine aggregate	Course aggregate	E-waste
1	Fineness Modulus	4.96	8.69	--
2	Bulking	3%	--	--
3	Water absorption	1.2%	--	--
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

METHODOLOGY

Mix Design

The high-strength concrete mix design for M40 utilized the following criteria: OPC 53 grade cement, aggregates having an MSA of 20 mm, along with water-cement ratio capped at 0.45. Cement has a relative density of 3.15, while both coarse and fine aggregates exhibit a relative density of 2.74 each. Various tests on the concrete were conducted after casting, curing, and initial testing, following Indian standards.

The high-strength concrete mix design for M40 was formulated following the guidelines of IS-10262-2009, utilizing the specified data [31]. Table 4 presents the details of proportioning for 1 kg/m³ concrete.

Table 4. Details of Proportioning: For 1 kg/ m³.

Material	Substitution ratio in kg/m ³						
	0 %	05%	10 %	15 %	20 %	25 %	30 %
Cement (Actual OPC)	437	437	437	437	437	437	437
Water	197	197	197	197	197	197	197
Fine aggregate	693	693	693	693	693	693	693
Coarse aggregate of 20 mm size	565	565	565	565	565	565	565
Coarse aggregate of 10 mm size	565	528.4	510	473.7	455.5	423.63	400.8
E-waste	0	18.24	36.48	54.73	72.97	91.22	100.46
Revised w/c ratio	0.45	0.45	0.45	0.45	0.45	0.45	0.45

Replacement

Coarse aggregates are replaced with E-waste material at substitution levels ranging from 5% to 30%, with the E-waste being subjected to various tests as described in the subsequent sections.

Casting

Concrete cubes, cylinders, and beam specimens incorporating e-waste material ranging from 5% to 30% were cast (Table 5) and cured according to IS specifications to evaluate their mechanical properties. Cubes with a dimension of 150 mm were used to assess the CS of different concrete specimens at different curing ages. Cylinders of dimension 15 × 30 cm were further used for testing the tensile strength, while beams sized 10 × 10 × 50 cm were prepared to assess the FS. Figure 3 shows the casting process for these molds, which will be cured and tested accordingly.

Table 5. Details of specimens casted.

S N.	Specimen name	Details
1	M401	Control Mix
2	M402	5% replacement
3	M403	10% replacement
4	M404	15% replacement
5	M405	20% replacement
6	M406	25% replacement
7	M407	30% replacement

Curing

The samples were cured by immersing them in a tank under controlled conditions, as outlined in Indian standards, and evaluated at designated curing intervals. Figure 3 depicts the curing process for these samples.



Figure 3. Photographs of a) casting of moulds and b) curing of moulds.

Tests Conducted on Concrete Mix

Slump cone test

This test assesses how different replacement percentages affect concrete's workability. This test assesses concrete's consistency in its freshly mixed state, offering insights into its workability and flowability before hardening. In the case of M-40 grade concrete, slump values were investigated by substituting coarse aggregates with e-waste at proportions varying from 0-30%. Figure 4 illustrates the slump cone test visually. The test consists of filling a cone with concrete in three layers, with each layer being compacted, and lifting the cone to measure the concrete's slump, indicating its workability [32].



Figure 4. Illustration of slump cone test.

Compressive strength test

After curing, CS tests were carried out on the cubes at 7, 14, and 28 days. The arrangement for this test is depicted in Figure 5, which visually represents the findings. The test involves applying a load on concrete specimens in a compression testing machine (CTM) until failure [33].

The CS of the specimens was calculated by:

$$F_{ck} = \frac{P_c}{A}$$

P_c - Failure load

A - Area of the cube

Flexural strength test

This test is measured by determining the stress at which the material yields. In this study, flexural testing employed specimens measuring 500 millimeters in length, 100 millimeters in width, and 100 millimeters in depth. Figure 6 shows the arrangement for the FS test. The beams are placed in the machine and loaded at specific points as per IS until failure occurs. The maximum load applied is recorded, and the flexural strength is calculated based on this load and the beam's dimensions, including span length, width, and depth [33].

The FS was found using the following formula.

$$F_b = \frac{P \times L}{b \times d^2}$$

Where, P - Maximum Load, b & d – Width and failure point depth of specimen, L - Supported length,

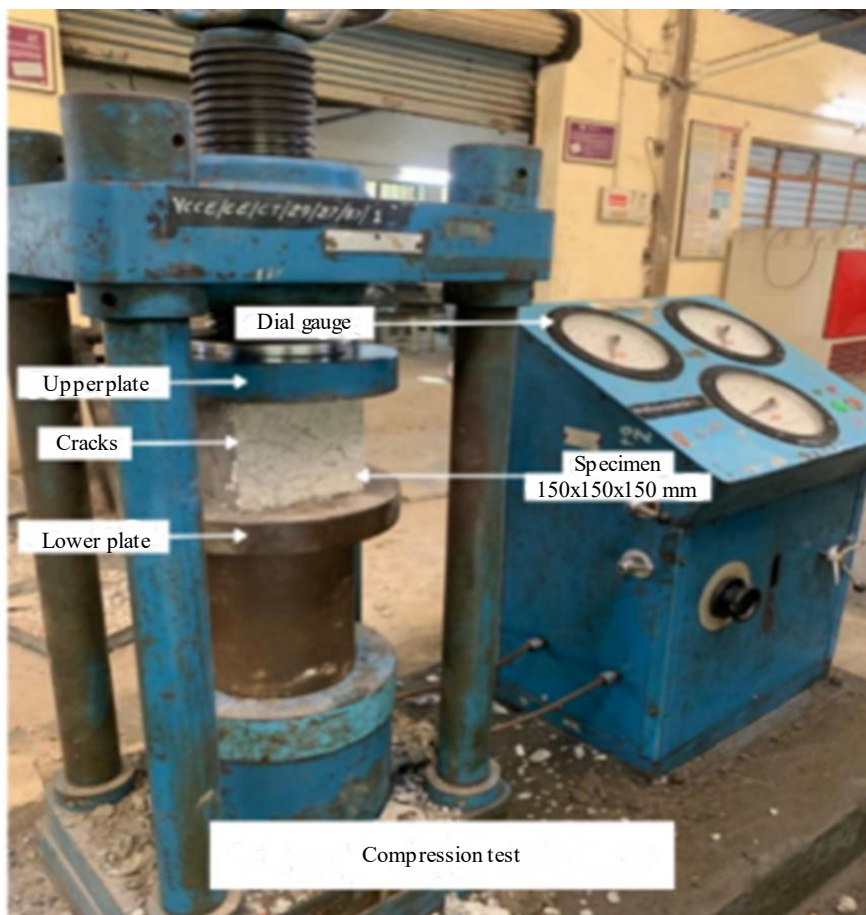


Figure 5. Performance of CS test on concrete specimen.



Figure 6. Concrete beam subjected to flexural strength test.

Each specimen had its observations carefully recorded, and Figure 15 depicts the distribution of those results across a range of replacement percentages, including 0%, 5%, 10%, 15%, 20%, 25%, and 30%.

Split tensile test

Typically, concrete tends to display a lesser tensile strength when contrasted with its compressive strength. The STS test involves applying a lateral force to 300 mm by 150 mm concrete cylinders in a testing machine. The highest load at failure is recorded, and the tensile strength is determined using this load and the dimensions of the cylinder [34]. Figure 7 illustrates the procedure for this test.

Calculation of Split tensile strength using:

$$F = \frac{2P}{\pi D L}$$

Where, P – Maximum load,

L & D – Length and depth of specimens

RESULTS AND DISCUSSION

Coarse aggregates were substituted with E-waste at varying levels of 0%, 5%, 10%, 15%, 20%, 25%, and 30%. Tests were performed to assess different concrete properties after specified curing periods, and the results are analyzed below.

Slump Cone Test

The slump test evaluated the workability of M-40 concrete mixes, following IS 1199 (1959) guidelines, shedding light on e-waste's impact. Initially, the control mix (M401) had excellent workability, with a significant 100 mm slump. Up to 10% e-waste replacement (M402 to M403) showed no notable deviation. However, beyond this, workability gradually decreased. For instance, M404 saw a modest 4% slump decrease. This trend continued, with M405 experiencing a 5% reduction and M406 showing a 6% decline. The most significant decline was in mix M407, with a notable 10% slump reduction. E-waste inclusion likely altered concrete characteristics, affecting flowability and placement ease.



Figure 7. STS on cylindrical specimens.

E-waste materials often have irregular shapes and rough surface textures compared to natural aggregates. This increases the friction between particles, leading to less fluidity and decreased workability of the concrete mix. Also, the volume of coarse aggregate is decreased with an increase in the percentage of e-waste hence affecting the workability.

Overall, workability analysis provides insights into e-waste incorporation's practical implications, emphasizing the need for sustainability and practicality balance in construction projects. Figure 8 illustrates slump values for all M-40 concrete.

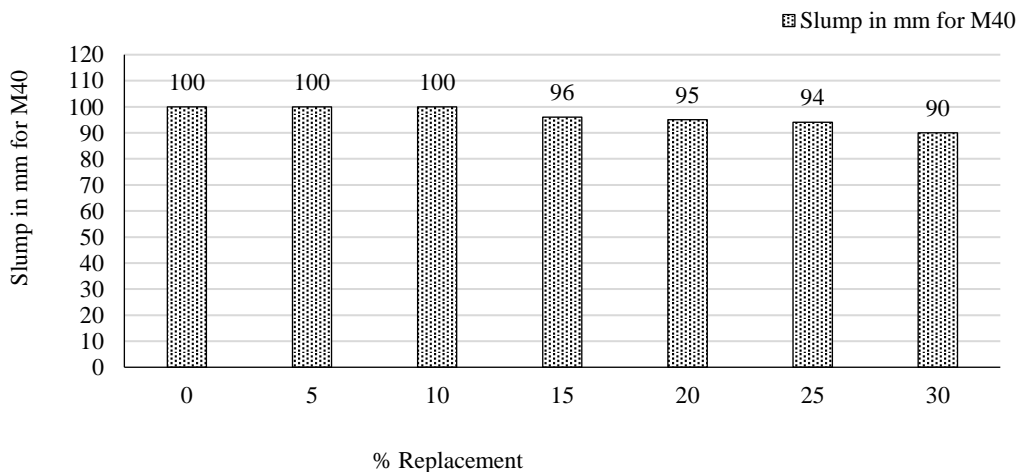


Figure 8. Comparison of slump for M-40 concrete mixes.

Compressive Strength Test

The CST analysis for M40 mixes was conducted according to IS 516 (IS 516, 2021), utilizing concrete cubes of dimension 150 mm. Testing procedures were diligently executed post-curing at 28 and 90 days, with each mix subjected to a thorough examination. Compressive strength testing, crucial for evaluating concrete performance, was conducted on three specimens per mix, and the average strength was calculated. The outcomes demonstrated a significant variation in compressive strength between the mixtures, indicating the impact of integrating e-waste.

28-Day CST analysis: Higher E-waste replacements led to reduced strengths. Control mix strengths were 41.92 MPa and 42.96 MPa at 28 and 90 days. Mixes M402 to M407 showed varying degrees of strength reduction, with M406 and M407 displaying the most significant decreases at 29.63 MPa and 27.259 MPa, respectively.

90-Day CST analysis: Similar declines were observed at 90 days. M406 and M407 showed notable decreases at 29.481 MPa and 26.963 MPa, respectively. Relative percentage decreases were approximately 30.16% for M406 and 39.17% for M407 when compared with the standard mix.

The average CS for M-40 mixes, with percentage changes when compared with the standard mix. Figure 9 and 10 depict comparative graphical representations of CST results for M40 mixes at various intervals.

E-waste materials do not bond as effectively with the cement paste as natural aggregates. The weaker bond between e-waste and the cement composite leads to reduced strength. This is because strong bonding is essential for transferring stresses and maintaining the integrity of the concrete under compression.

Flexural Strength Test

Following IS 516 (2021) standards, FST was performed on concrete beams (100 mm x 100 mm x 500 mm) after 28 and 90 days of curing. Two-point loading flexural testing aimed to assess flexural characteristics vital for resilience against bending and tensile forces [35].

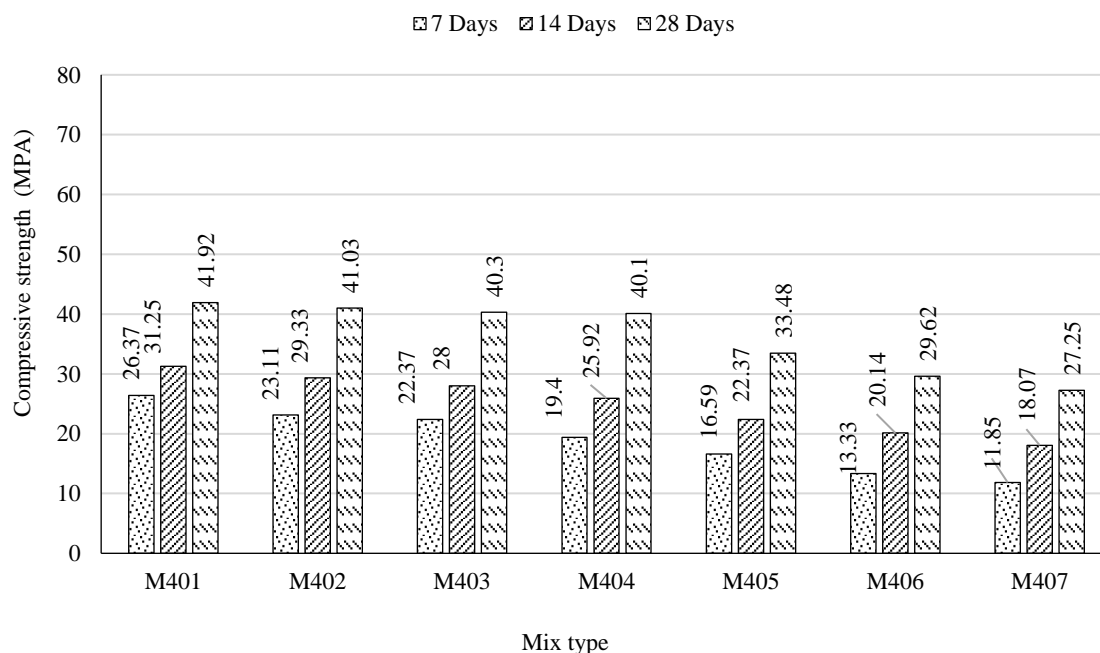


Figure 9. Variation of CST results of M40 mixes after 7,14,28 days of curing.

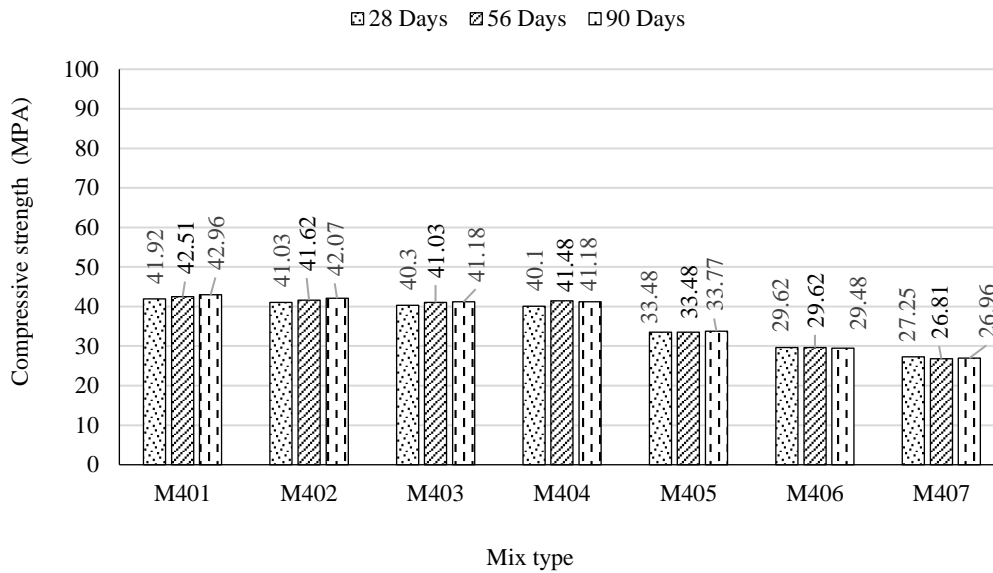


Figure 10. Variation of CST results of M40 mixes after 28,56,90 days of curing.

28-Day analysis: Control mix (M401) showed robust flexural strength at 4.33 MPa, close to IS 456 (2000) requirements [36]. Mixes M402 to M405 experienced varying reductions, with M406 and M407 showing notable declines of around 32.53% and 49.95%, respectively.

90-Day analysis: The control mix maintained consistent flexural strength at 5.42 MPa, surpassing prescribed minimums. However, M402 to M405 exhibited declines, with M406 and M407 recording significant decreases of approximately 52.39% and 61.73%, respectively, compared to the standard mix's strength. Thus, FS of M-40 mixes declined with increasing E-waste proportion. Figure 11 and 12 offer comparative charts of FST results for M40 mixes at various intervals.

Similar to the effect on CST results, the poor bonding of e-waste and the cement composite significantly affects the flexural strength. Flexural strength relies heavily on the ability of the concrete to resist tensile stresses, which requires a strong bond between the aggregates and the cement paste. E-waste materials generally do not bond as effectively as natural aggregates, leading to weaker tensile strength under bending or flexural loads.

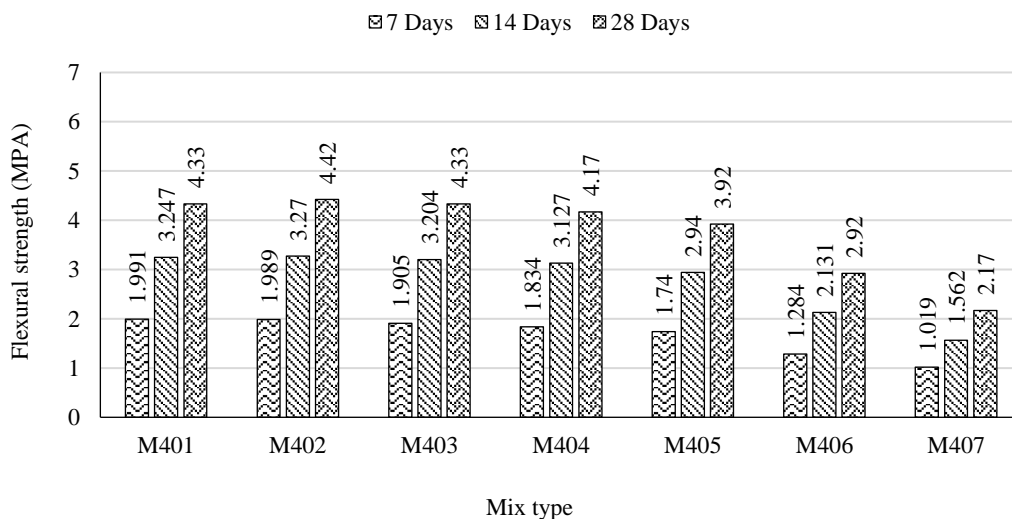


Figure 11. Variation of FST results of M40 mixes after 7,14,28 days of curing.

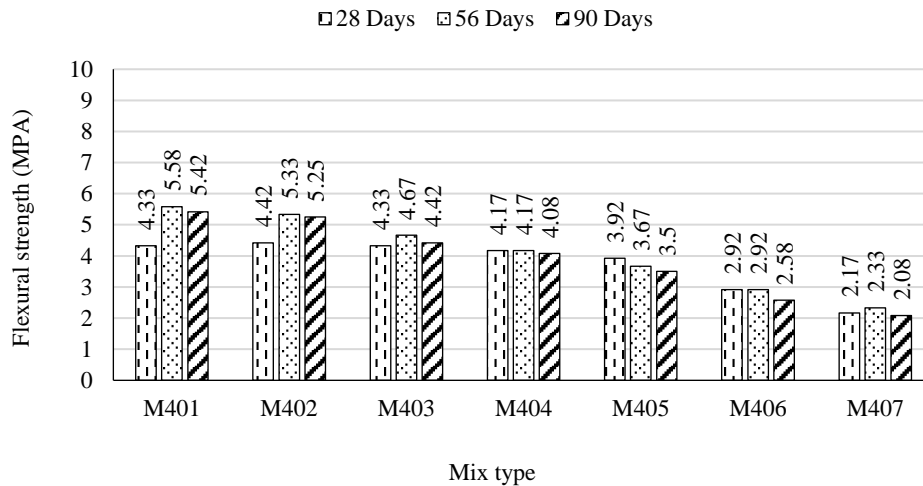


Figure 12. Variation of FST Results of M40 mixes after 28,56,90 days of curing.

Split Tensile Test

The STS test was conducted according to IS 516:2021 and IS 5816:1999 standards, using cylindrical specimens (length:300mm and Diameter:150 mm).

28-Day tensile strength analysis: Control mix M401 met IS 456 (2000) standards with a tensile strength of 4.38 MPa. However, mixes with E-waste replacements showed varied strengths: M402, M403, and M404 at 4.19 MPa, 4.01 MPa, and 3.17 MPa, respectively, falling short by approximately 4.08%, 9.70%, and 37.71%. M406 and M407 exhibited significant declines of approximately 43.13% and 55.88%, respectively.

90-Day tensile strength analysis: At 90 days, M401 maintained a strength of 4.51 MPa, exceeding IS 456 (2000) requirements. Mixes M406 and M407 showed reductions of 22.62% and 34.15%, respectively, when compared with the standard mix, indicating the long-term effects of E-waste integration. Figure 13 and 14 compare tensile strength results for M40 mixes at various curing durations.

The STS relies on the ability of the aggregates to transfer tensile loads through the concrete. E-waste particles may not have the same stiffness or load-bearing capacity as natural aggregates, which results in inefficient load transfer and weaker resistance to tensile forces. This leads to a decline in the STS of the concrete.

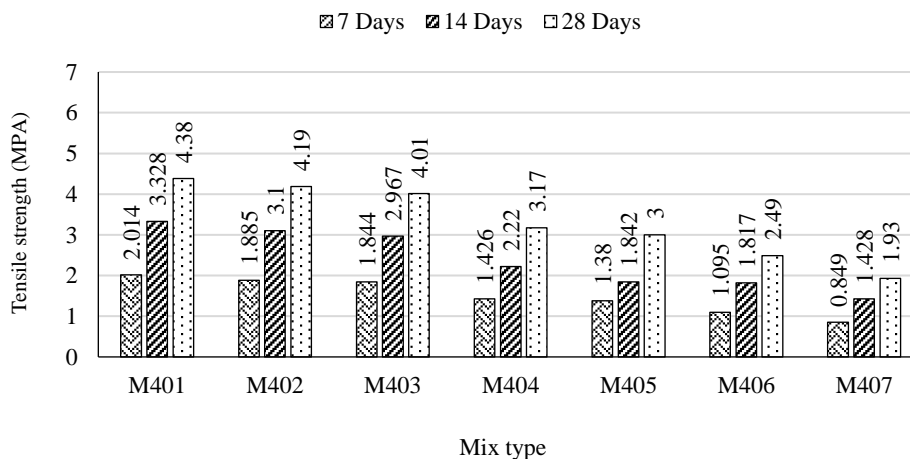


Figure 13. Variation of STS test results after 7,14,28 days of curing for M40 mixes

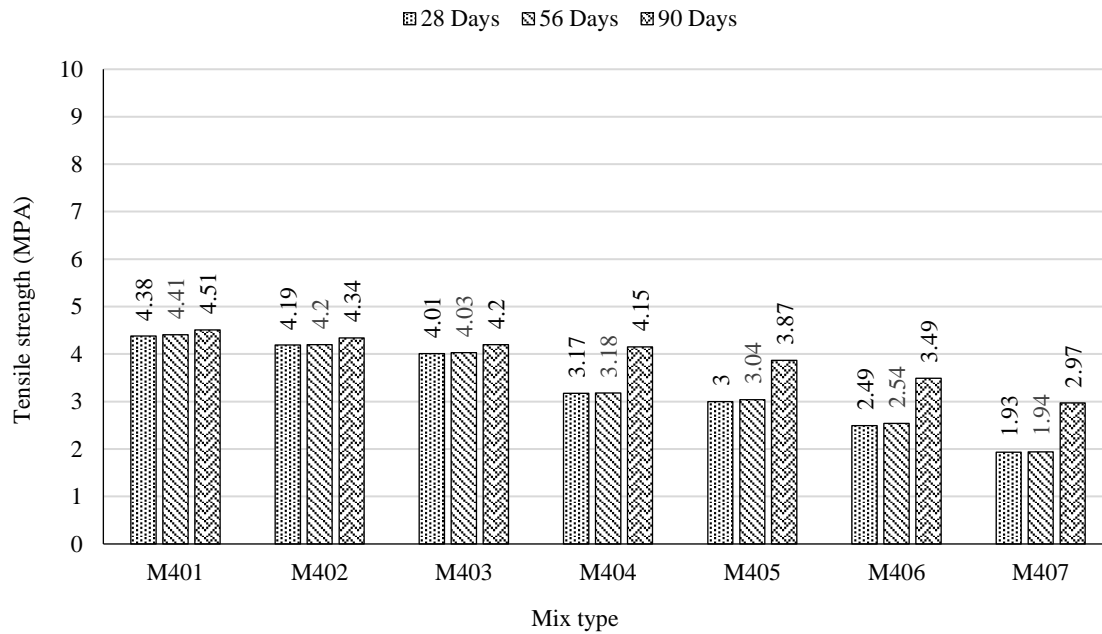


Figure 14. Variation of STS test results after 28,56,90 days of curing for M40 mixes.

Water absorption test

Water absorption, an important indicator of concrete durability, was examined across various mixes with different percentages of E-waste replacement, following BS 1881-122:2011.

The results revealed a linear increase in absorption of water with a rise in the proportion of E-waste replacement. Notably, the control mix (M401) exhibited a water absorption value of 2.27% at 28 days. As E-waste content increased, a corresponding elevation in water absorption was observed. The trends align with the overall pattern observed in this research, reflecting the effect of increased E-waste content over the permeability of concrete. Notably, the sharp increase in water absorption for mixes beyond 10% E-waste replacement emphasizes a critical threshold beyond which the substitution with E-waste negatively influences the durability of the concrete.

Figure 15 demonstrates the changes in water absorption for all mixes considered in this part of the study.

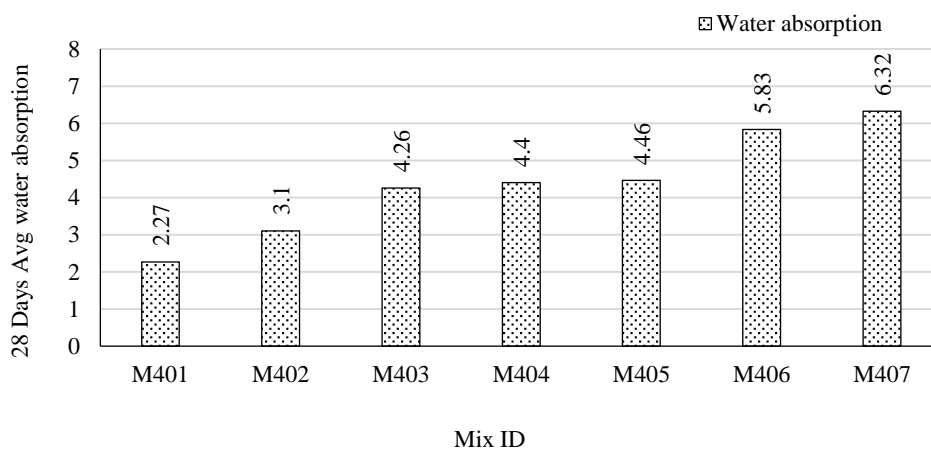


Figure 15. Variation in water absorption for M-40 grade concrete.

E-waste materials, due to their irregular shapes, sizes, and poor packing characteristics, create more voids within the concrete mix. These voids increase the overall porosity of the concrete, allowing more water to penetrate and be absorbed. Higher porosity means that there are more capillary pores and void spaces that can hold water, leading to an increase in water absorption.

Acid Attack Test on Concrete

Concrete specimens' resistance to acid attack was evaluated in compliance with ASTM standards (ASTM C1898-20, 2020). After 56 days in an acidic medium, cubes were evaluated for compressive strength, weight loss, and appearance alterations. Mix M401, the control, exhibited a significant loss of 38.60% in compressive strength, with a 5.26% weight loss. Mixes M402 to M407 also experienced compressive strength reductions, with percentage losses ranging from 22.64% to 33.59%, and weight losses from 3.09% to 4.91%, indicating improved acid attack resistance with higher E-waste content.

Table 6. illustrates the findings derived from subjecting the concrete specimens to an acid attack examination. The alterations in cube appearance following 56 days in the H₂SO₄ solution are depicted in Figure 16. Figure 17 illustrates the acid attack resistance, represented as the % loss in CS, observed in the M-40 concrete mixes analyzed in this section of the study.

Table 6. Effect of Acid Attack on Concrete Mixes.

S.N.	Mix	28 days Compressive strength(MPa)	Compressive Strength after acid attack(MPa)	% Loss in weight	% Loss in compressive strength
1	M401	41.92	25.74	5.26	38.60
2	M402	41.03	27.25	4.91	33.59
3	M403	40.30	28.55	4.46	29.16
4	M404	40.10	29.66	5.33	26.03
5	M405	33.48	25.25	3.52	24.58
6	M406	29.63	22.83	4.27	22.95
7	M407	27.25	21.08	3.09	22.64

Due to increased porosity and the existence of hydrophilic substances in e-waste, the concrete is more likely to absorb and retain acidic solutions. This prolonged contact time between the acid and the concrete matrix leads to a greater extent of chemical attack, as acids have more time to react with the cement paste and other components.



Figure 16. Surface texture of cubes after immersion in H₂SO₄ solution for 56 days.

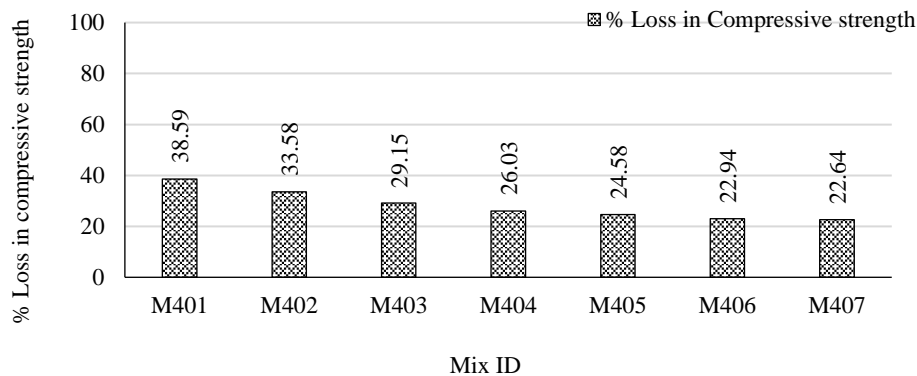


Figure 17. % loss in CS due to acid attack for M-40 grade concrete.

CONCLUSION

The experimental work of M-40 concrete is summarized with the following conclusions.

1. The workability of M40-grade concrete decreased with higher E-waste replacement. The M407 mix showed a significant 10% reduction in slump compared to the control, but workability remained stable with 10-15% E-waste substitution.
2. Compressive strength test results exhibited that strength followed a declining path with an increase in the E-waste content of mixes. Mixes M403 and M404 had the best results, with up to 15% E-waste substitution recommended for satisfactory strength.
3. Flexural strength initially improved or stayed stable with up to 10-15% E-waste substitution but declined beyond this point. Mixes M403 and M404 showed good performance, similar to the control specimen, while M407 had the lowest strength at 2.17 MPa, a 50% drop from the control. A 15% E-waste substitution was optimal for maintaining flexural strength.
4. Water absorption in concrete increased linearly with higher E-waste content. Mix M404 had the lowest increase, while M407 had the highest. Water absorption rose steadily up to 20% E-waste substitution, then increased sharply. An optimal substitution of up to 20% is recommended for managing water absorption.
5. The acid attack test results indicate that while the control mix and mixes with lower E-waste content experienced greater losses in compressive strength, the impact was reduced with higher E-waste content. Control mix exhibited a higher percentage loss of 38.60% in compressive strength after acid attack compared to mixes with E-waste replacement, with M407 flaunting a % loss of 22.64%. A superior acid attack resistance was observed in mixes with an increase in E-waste content.

LIST OF NOMENCLATURES

E-waste - Electronic waste

MT - Million tonnes

OPC - Ordinary Portland cement

IS time - Initial setting time

FS time - Final setting time

IS - Indian Standards

MSA - Mean size of aggregate

CS - Compressive strength

STS - Split tensile strength

CST - Compressive strength test

FST - Flexural strength test

STS - Split tensile strength

BS - British standards

ASTM - American Society for testing and materials

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