

Sorption and Thermal Conductivity of Concrete Containing Aggregates of E-Waste

Rakesh Kumar Saini

Ph.D. Scholar, Structural Engineering, Rajasthan Technical University (RTU), Rawatbhata Road, Kota, 324010, India, rksaini.phd19@rtu.ac.in

Praveen Kumar

Ex. Professor, RTU, Kota, 324010, India

Follow this and additional works at: <https://commons.yildiz.edu.tr/jscmt>



Part of the [Biomaterials Commons](#), [Chemical Engineering Commons](#), [Civil and Environmental Engineering Commons](#), [Engineering Science and Materials Commons](#), [Materials Science and Engineering Commons](#), [Mechanical Engineering Commons](#), and the [Molecular, Cellular, and Tissue Engineering Commons](#)

Recommended Citation

Saini, Rakesh Kumar and Kumar, Praveen (2026) "Sorption and Thermal Conductivity of Concrete Containing Aggregates of E-Waste," *Journal of Sustainable Construction Materials and Technologies*: Vol. 11: Iss. 2, Article 3. <https://doi.org/10.29187/2458-973X.1219>

Available at: <https://commons.yildiz.edu.tr/jscmt/vol11/iss2/3>

This Research Article is brought to you for free and open access by YTU Press. It has been accepted for inclusion in Journal of Sustainable Construction Materials and Technologies by an authorized editor of YTU Press.



RESEARCH ARTICLE

Sorption and Thermal Conductivity of Concrete Containing Aggregates of E-Waste

Rakesh Kumar Saini^{a,*}, Praveen Kumar^b

^a Ph.D. Scholar, Structural Engineering, Rajasthan Technical University (RTU), Rawatbhata Road, Kota, 324010, India

^b Ex. Professor, RTU, Kota, 324010, India

ABSTRACT

In many parts of the world, substantial energy is used to maintain comfortable temperatures in inner parts of the buildings for living and working. Construction materials with low thermal conductivity, if used in the exterior walls and façade etc. in such structures can be useful in lowering the energy demand. On the other hand, moisture ingress through sorption is a common factor contributing in degradation of concrete structures with time. Constituents of concrete may be engineered to some extent to get both the desired attributes, lower thermal conductivity and sorption than normal concrete.

The rapid increase in electronic waste, or e-waste, presents a major environmental challenge in today's world, with plastic components comprising a substantial portion of this waste. Utilizing e-waste plastic in concrete presents a sustainable solution with waste utilisation while conserving natural resources for aggregates. The experimental work presented in the paper explored the use of E-waste scrap (PA) comprising of discarded computers, printers, and mobile phone as coarse aggregates. The waste sized to 4.75–20 mm was used in concrete mixes. It replaced NA at levels of 0%, 33%, 66%, and 100%. Test results presented in the paper illustrates progressive reduction in thermal conductivity and sorptivity with increasing percentage replacement of the crushed rock aggregates by E-waste aggregates. Paper also presents that thermal conductivity follows a multilinear relationship with water-cement ratio and percentage replacement of the aggregates in concrete.

Keywords: Thermal conductivity, Sorptivity, E-waste, Plastics, Concrete

1. Introduction

In 2023, building sector consumed 32% of global energy and contributed to 34 % of global CO₂ emissions [1]. The CO₂ emissions from building sector have been reported to have risen by five percent since 2015 [1]. Air-conditioners and other appliances used to maintain comfortable temperatures in the inner parts of the buildings for living and working contribute significantly to power demand, whose generation mostly involves CO₂ emission. Proper selection of materials used in exterior parts of buildings, can reduce heat transmission thus aiding in checking the rate of rise in CO₂ emissions. Use of lightweight

concrete may be one of the ways to reduce thermal conductivity [2]. Density of concrete can be reduced through various means; use of lightweight aggregates has been the most common among them [3].

On the other hand, rapid increase in electronic waste has become a major environmental problem, requiring creative approaches for effective management. E-waste contains primarily plastics, predominantly in the form of insulating components, casings, and circuit boards [4]. This, if not properly managed, poses substantial environmental risks. Recycling and repurposing of e-waste plastic may either mitigate environmental hazards or provide an opportunity to develop sustainable construction materials.

Received 8 September 2025; revised 2 May 2026; accepted 3 May 2026.
Available online 12 May 2026

* Corresponding author.
E-mail address: rksaini.phd19@rtu.ac.in (R. K. Saini).

<https://doi.org/10.29187/2458-973X.1219>

2458-973X/© 2026 Published by Yıldız Technical University Press, İstanbul, Türkiye. This is an open access article under the CC BY-NC 4.0 Licence (<https://creativecommons.org/licenses/by-nc/4.0/>).

Construction involves substantial use of natural resources; however investigators have been exploring alternative materials to improve sustainability. One such alternative can be the use of waste plastic. It has the potential of decreasing the consumption of natural aggregates, thus conserving natural resources and reducing environmental impact [5].

Various studies have investigated PET, LDPE, HDPE, PP, and PVC to improve or at least maintain concrete performance while enhancing sustainability. Sau et al. (2024) investigated polyethylene (PE) and polyethylene terephthalate (PET) as aggregates in M30 concrete with a 0.37 water-cement ratio. They replaced natural aggregates at levels ranging from 10% to 40%. The study found that replacements up to 30% PE and 20% PET yielded acceptable mechanical performance with improved resistance to impact, abrasion, and chloride penetration [6]. Similarly, Basha et al. (2020) used recycled plastic aggregates (RPAs) composed of mixed plastic types in varying sizes. At 100% replacement, a compressive strength reduction of 51% was noted; however, at 25% replacement, the mix achieved 35 MPa strength, along with improved thermal insulation and reduced flexural strength, suggesting potential for non-structural applications [5].

Several studies explored specific plastic types. Mahmoud et al. (2021) examined PET, HDPE, and PP (≤ 14 mm) used as coarse aggregates at 10–20% replacement. Although compressive strength was not quantified, all mixes met kerb strength requirements, with PET and PP enhancing abrasion resistance and reducing drying shrinkage [7]. Khalil and Khalaf (2017) used shredded PET (2.6 mm, 11.4 mm, or mixed) in OPC with silica fume, noting a 40–50% reduction in compressive strength but improved slump and the production of lightweight concrete [8].

Sorptivity, which represents the rate of capillary water absorption in unsaturated concrete, is a critical parameter in assessing durability, particularly for lightweight concrete where aggregate properties significantly influence moisture transport. Choi et al. investigated the use of pulverized fuel ash in lightweight concrete. They reported a notable reduction in sorptivity, achieving values as low as 0.45%, attributed to the pore-filling effect of these by-products which reduced the connectivity of capillary pores [9]. Earlier studies on the penetrability of lightweight aggregate concrete (LWAC) have shown that lightweight aggregates (LWAs), due to their highly porous and cellular structures, tend to absorb 8–13% of their weight in water within the first 30 minutes of exposure, with most absorption occurring in the first two minutes. Surface roughness, aggregate moisture, and pore size distribution affects initial sorptivity [10].

In terms of durability, Silva et al. (2013) analyzed PET plastic aggregates (1–11.2 mm) at 7.5% and 15% replacement with water-cement ratios of 0.52–0.61. Results showed that PET led to increased shrinkage and water absorption, but durability under dry curing conditions surpassed conventional concrete [11]. Focusing on non-structural applications, Vanitha et al. (2015) investigated inclusion of unspecified plastic scrap in M20 concrete blocks. Replacement levels between 0–10% showed slight strength increases (2–4%) in paver blocks at 4%, though the use was deemed unsuitable for structural purposes [12]. Patil et al. (2014) used industrial plastic waste (PP and PET) to partially replace coarse aggregates at 10–50% levels. While strength data were limited, the study reported decreased density and highlighted the material's viability in reducing costs and environmental impact [13]. Pirzada et al. (2018) further examined PET coarse aggregates in M25 concrete combined with a polycarboxylate ether-based superplasticizer. Between a w/c 0.42 to 0.57, compressive strength improved up to 15% replacement, along with enhanced workability and reduced thermal conductivity [14]. Aldahdooh et al. (2018) optimized concrete mixes containing mixed PWAs (≤ 5 mm) using response surface methodology (RSM), replacing 30% of the total aggregate. The study reported acceptable mechanical properties and emphasized the importance of statistical optimization in designing durable and sustainable mixes [15].

Beyond aggregates, recent studies have assessed the influence of plastic fibers in concrete. Artid Poonyakan et al. investigated various recycled plastic fibers (LDPE, HDPE, PP, and PET) in concrete. They observed decreased workability due to fiber entanglement, but the inclusion of LDPE at 30% volume showed the most promising results, significantly reducing thermal conductivity while maintaining acceptable mechanical strength [16]. Durability aspects such as sorptivity—a measure of water absorption through capillaries—have also been explored. According to Abu-Saleem et al., the inclusion of plastics as partial aggregates can influence sorptivity depending on plastic type, replacement ratio, and bond quality with cement paste. PET generally improved resistance to water absorption, while HDPE and PP had mixed results. Overall, plastic waste aggregates tend to reduce sorptivity, contributing to enhanced concrete durability.

While many studies evaluated compressive strength, density, and rheology-literature remains limited regarding properties like thermal conductivity and sorptivity, especially when using E-waste



Fig. 1. E-waste aggregate (PA).

plastic aggregates. Objective of this study to examine the incorporation of e-waste into concrete and effect on its thermal conductivity and sorptivity. By investigating these properties, the research intends to advance the development sustainable and durable materials.

2. Research methodology

The present study investigates E-waste aggregate (PA) obtained from scrap of E-waste, i.e., scrap of computers, printers and mobile phones, etc; which was procured from a ragman. Fig. 1 shows photograph of its state at that time. As can be seen, it consisted scrap of miscellaneous sizes (mostly in the range 5-40 mm) and shapes. Firstly, dirt and miscellaneous other materials in it were removed through sieving with 1 mm size sieve. Then, only E waste scrap remained. Larger pieces among these were sorted

Table 1. Characteristics of coarse aggregate.

Parameter	Normal Aggregate (NA)	E-waste Aggregate(PA)
Relative Density	2.65	1.09
Water Absorption (%)	1.00	1.76
Density (Kg/m ³)	1726	533

manually and were broken by hand hammer. The resulting mix was sieved on 4.75 mm sieve, the passing out portion was rejected and the mass retained on the sieve was used directed as coarse aggregate in concrete. Such aggregate was checked for flakiness and elongation index as per IS 2386 Part 1 [43], and was found to meet the specifications for use in concrete. Its physical properties were assessed for aggregate as displayed in Table 1.

Quantities for concrete mixes were calculated following Indian standards, with w/c: 0.53, 0.47 and 0.43. Thermal conductivity and sorptivity were

Table 2. Parametric variations.

Property	Specimen Type & Size (mm)	Age of Testing in Days	Number of Specimens			
			NA	33PA	66PA	100PA
Thermal Conductivity	Cylinder (50 × 100)	28	4	4	4	4
Sorptivity	Cylinder(50 × 100)	28	4	4	4	4

assessed through experimental testing of cast specimens. The specific details of these properties and the number of samples tested are presented in Table 2. The replacement of normal aggregates (NA) was 0, 33%, 66% and 100% by PA for each water-cement ratio. Thermal conductivity and sorptivity of concrete were evaluated and specimens were cast and tested accordingly.

3. Materials

In this study, OPC-43 Grade having the relative density 3.12 and a consistency of 30%, crushed rock aggregate (NA), and E-waste plastics as coarse aggregates (PA) were used. Grading of fine aggregate conformed to Zone II of IS383:2016. High range water reducing admixture (Naphthalene-based) having a relative density of 1.14 was employed. It is observed that the relative density of the E-waste plastic aggregate (PA) is lower than that of the normal aggregate (NA). The Elemental analysis of PA is presented below (Table 3). Energy Dispersive X-Ray Fluorescence (ED-XRF) Spectrometry was used to perform this analysis. The testing was done on the request of the authors in an external Institute's (CIPET) laboratory, in solid state of the sample with 60-second measurement. The

wt% values excludes the organic matrix (C, H, O, N), and are normalised to the inorganic fraction.

4. Mix proportioning

Four types of concrete mix proportions: Concrete with NA (Natural aggregate), Concrete with 33% replacement of NA by PA, Concrete with 66% replacement of NA by PA and concrete with only PA (E-waste plastic aggregate), with each water-cement ratio (0.53, 0.47, and 0.43) was made in this study. A consistent amount of 158 kg water in 1 m³ concrete was used in all the mix types and water-cement ratios. The superplasticiser dosage was slightly adjusted along with the water-cement ratio to achieve similar workability. This compensated for changes in paste volume and internal friction due to varying w/c ratios and E-waste aggregate (PA) content, maintaining a consistent slump range of 75–100 mm for all mixes. Uniform workability ensured that variations in thermal conductivity and sorptivity were mainly due to aggregate replacement level and w/c ratio, rather than differences in fresh concrete consistency. This workability range also helped in full compaction of concrete easily in laboratory conditions with minimum effort. Fine Aggregate (FA) was added in an SSD condition.

Table 3. Elemental analysis of E-waste aggregate.

Atomic Number	Element	Percentage Concentration
12	Mg	3.275
13	Al	3.551
14	Si	11.719
15	P	0.071
16	S	0.964
17	Cl	19.481
20	Ca	14.173
26	Fe	6.352
19	K	0.069
22	Ti	1.496
52	Te	34.381
82	Pb	0.714
25	Mn	0.254
24	Cr	0.099
30	Zn	0.956
27	Co	0.014
29	Cu	0.254
23	V	0.113

5. Experimental program

The workability of fresh concrete was assessed by conducting slump tests on all mixes in accordance with IS: IS 1199: Part 2: 2018. To evaluate the compressive strength, cube specimens of 150 × 150 × 150 mm were cast and water-cured until testing. Strength was determined at multiple curing ages (7, 28, and 56 days) as per IS: 516. For flexural strength, prismatic specimens of 100 × 100 × 500 mm were tested at 28 days under a two-point loading configuration, ensuring uniform stress distribution. Splitting tensile strength and static modulus of elasticity were determined at 28 days on cylindrical specimens of 100 × 200 mm, following IS: 5816 and IS: 516 respectively.

An experimental study was conducted with a focus on two essential properties: thermal conductivity and sorptivity. The concrete proportions and sample

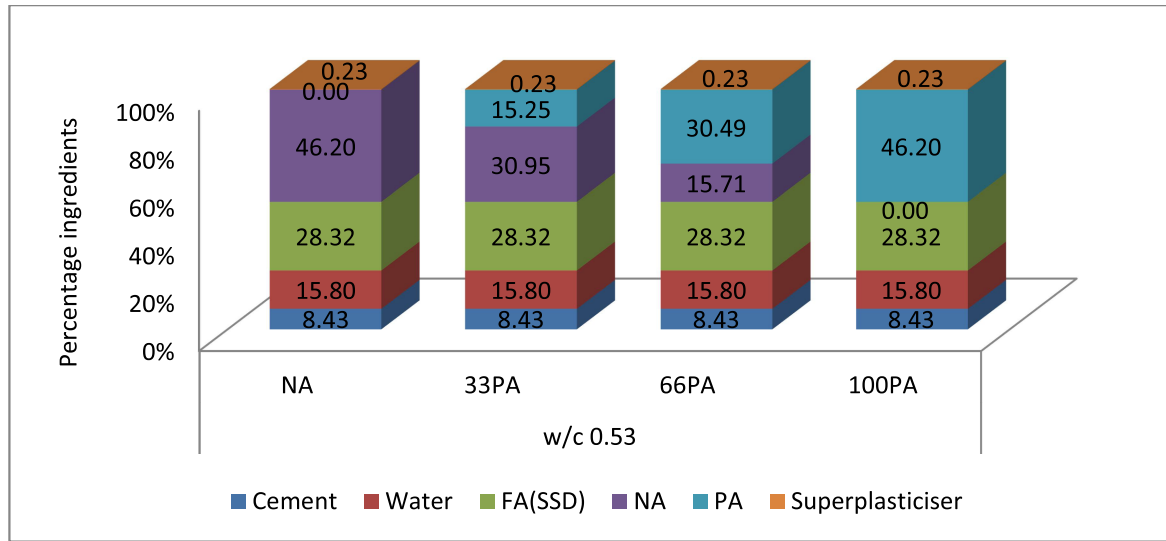


Fig. 2. Volume-wise percentage of ingredients in the concrete mix proportion with w/c-0.53.

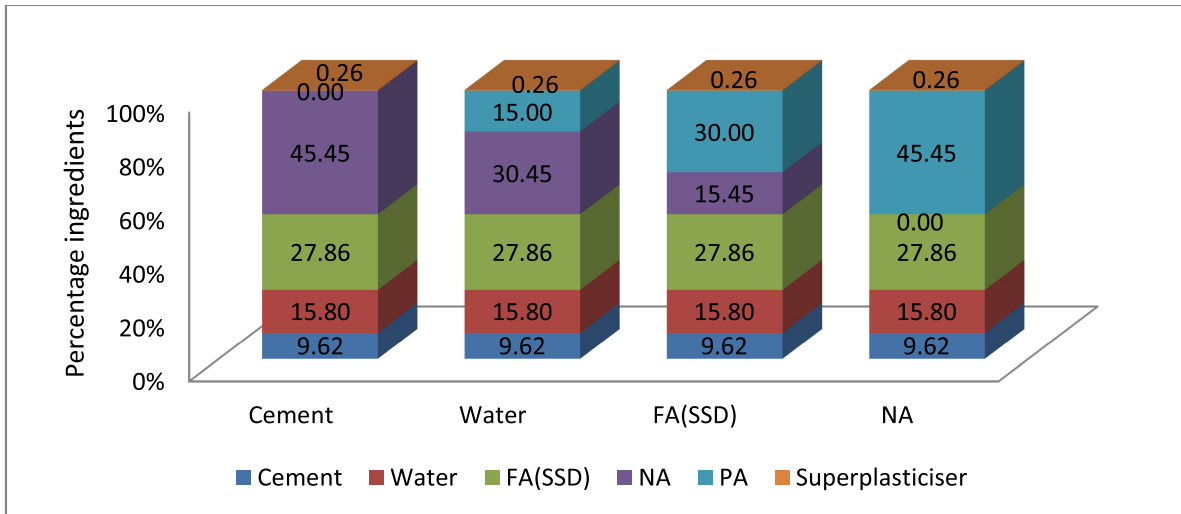


Fig. 3. Volume-wise percentage of ingredients in the concrete mix proportion with w/c-0.47.

details are listed in Table 4. The smaller dimensions of these samples were deliberately selected to enable the testing of thermal conductivity and sorptivity. After casting, the specimens were cured in water for 28 days.

A specific experimental setup, which is illustrated schematically in Fig. 5, was used. It had two chambers of hot water and cold water containing a thermocouple in each box. Concrete samples are placed between hot and cold boxes and sealed with silicon. After that, fill the hot chamber with hot water at about 65° C, and maintain the temperature throughout the process of the experiment. Fill the cold chamber with normal water at about 25° C. Now the heat flows from the hot chamber to the cold chamber through a concrete sample. The temperature difference between the two

chambers as T_1 and T_2 , for the hot and cold chambers, respectively, was noted. Temperatures (T_1 and T_2) were recorded at 10 minute intervals using calibrated thermocouples. This method allowed for the precise determination of heat transfer rates through the concrete samples, providing insights into the insulating properties imparted by the inclusion of e-waste plastic.

Thermal conductivity of concrete was calculated by Eq. (1).

$$k = \frac{QL}{A\Delta T} \quad (1)$$

The data of the constant parameters are shown in Table 4. The rate of heat flow was computed from

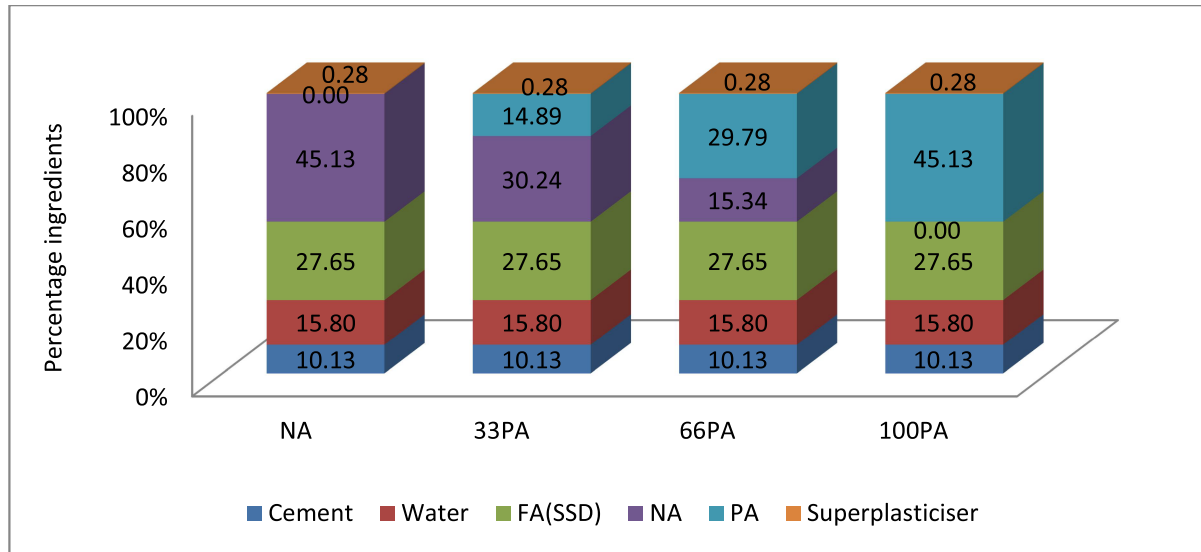


Fig. 4. Volume-wise percentage of ingredients in the concrete mix proportion with w/c-0.43.

Table 4. Sample specifications and constant parameters.

Parameter	Magnitude	Dimensions
Sample Details		
Length	50	mm
Diameter	100	mm
Area	0.013	Square Meter
Time of Heat supplied (Δt)	2	hours
Specific Heat of concrete (C) from literature (Karaki et. al 2021)	0.84	KJ/Kg

Eq. (2).

$$Q = mc\Delta T \quad (2)$$

k: Thermal conductivity (W/m·K)

Q: Heat transfer (W)

L: Thickness of the material (m)

A: Cross-sectional area (m²)

ΔT : Temperature difference (K)

m: Mass (kg)

c: Specific heat capacity (J/kg·K)

Typical computation of k for concrete with NA is as below:

$$Q = 885gm \times 0.84 \times (23.84)^{\circ}C = 2.46$$

$$k = \frac{2.46 \times 0.050}{0.013 \times 23.84} = 0.66 \text{ W/m} \cdot \text{K}$$

Sorptivity of concrete was determined by measuring the rate of water absorption through capillary action. Sorptivity was determined in accordance with ASTM C1585 [46]. Oven-dried specimens were partially immersed in water as shown in Fig. 6 (3–5

mm depth), and mass gain was recorded at 1, 3, 24, and 72 hours. This test served as an indicator of the concrete's porosity and capillary action, both of which are crucial for durability. The experimental data collected from these tests were analyzed to find influence of e-waste content on each property.

6. Results and discussion

6.1. Thermal conductivity

Thermal conductivity of concrete gets significantly affected by aggregate type and the water-to-cement ratio. The Fig. 7 shows that concrete incorporating natural aggregate (NA) exhibits the highest thermal conductivity across all w/c ratios. This outcome is expected since natural aggregates, typically denser and less porous, possess superior heat conduction properties. Concrete with E-waste aggregate (PA) in varying proportions—33% (33PA), 66% (66PA), and 100% (PA)—leads to a progressive decrease in thermal conductivity. This trend highlights the insulating nature of E-waste plastic aggregates, which minimize heat transfer more effectively than natural aggregates due to their lower density and higher porosity.

For concrete with natural aggregates, thermal conductivity decreases slightly on increasing w/c from 0.43 to 0.53, with values dropping to 0.59 from 0.66 W/m·K. A similar trend is observed in concretes PA. For instance, thermal conductivity with 33PA only varies slightly between 0.59 and 0.57 across all w/c ratios, and for concrete 66PA, the values fluctuate minimally (0.52 and 0.53). This trend suggests that with increase in w/c, which generally enhances the

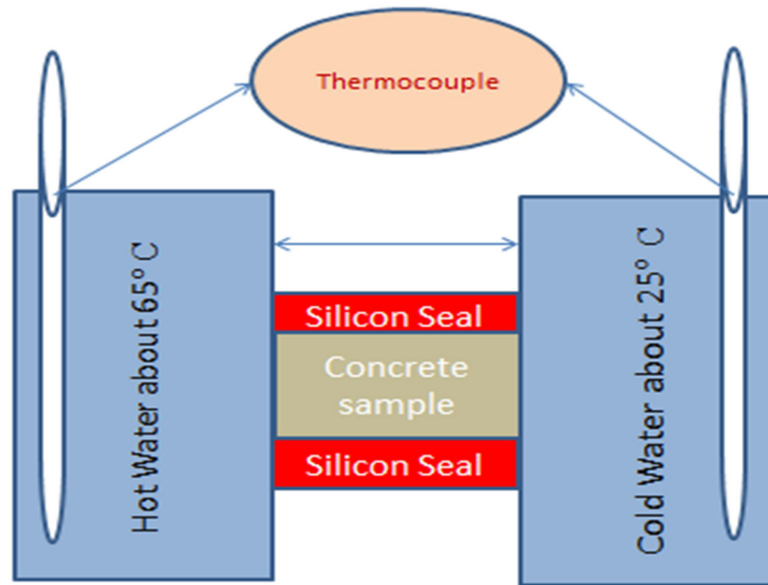


Fig. 5. Setup for the determination of thermal conductivity.



Fig. 6. Sorptivity test.

porosity of the concrete, slightly reduces its thermal conductivity.

First, the thermal conductivity value of approximately 0.66 W/m·K for concrete containing natural aggregates at $w/c = 0.43$ falls within the lower

range reported for conventional concretes. While typical normal-weight concrete exhibits conductivity between 1.1–2.9 W/m·K [5, 20]. Its value depends upon several factors as reviewed by Asadi et al [48]. Several studies have reported reduced values when

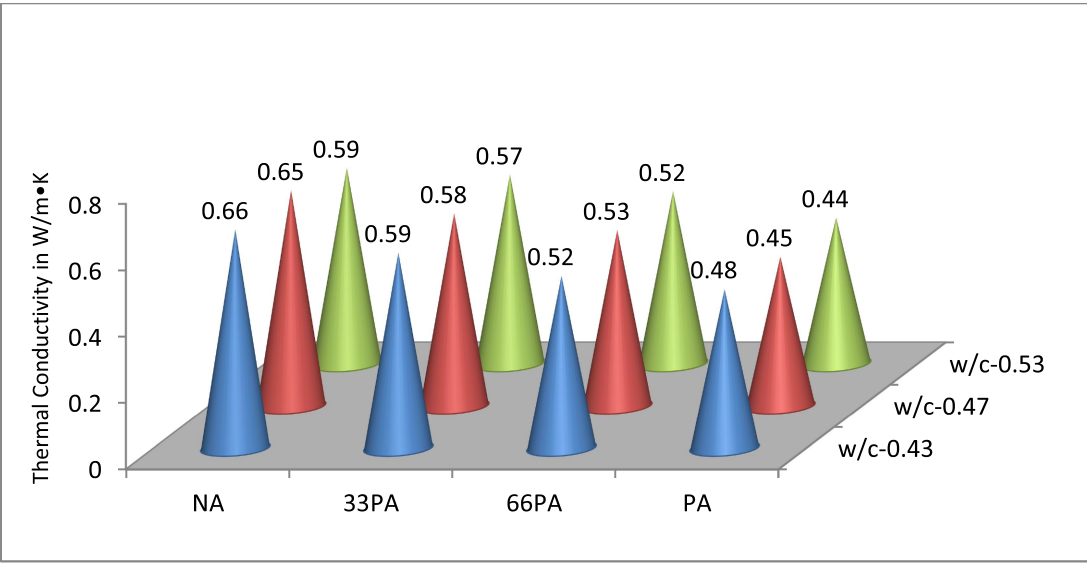


Fig. 7. Thermal conductivity of concrete variation with PA at different water-cement ratios.

lightweight characteristics or increased porosity are present. Poonyakan et al. (2018) reported thermal conductivity values between 0.74–0.96 W/m·K for plastic-modified concretes, while Basha et al. (2020) observed significant reductions in conductivity with the incorporation of recycled plastic aggregates. Furthermore, Pasha et al. (2025) demonstrated improved thermal insulation performance in plastic aggregate concrete. These findings confirm that conductivity values in the range of 0.6–0.7 W/m·K are achievable in concretes containing lightweight or plastic-based aggregates [5, 16, 22]. The difference in the values of thermal conductivity (k) reported by different investigators with different lightweight aggregates indicates that the ‘k’ is also dependent on the type of lightweight aggregates.

Overall, the study indicates that both type of aggregate, temperature and w/c etc. are critical factors to obtain thermal conductivity of concrete. Natural aggregates confirm higher thermal conductivity, while E-waste plastic aggregates, owing to their insulating and lightweight properties, significantly lowers the thermal conductivity. Additionally, higher w/c ratios tend to reduce thermal conductivity marginally by increasing the porosity of the concrete. These findings are particularly relevant for applications where thermal insulation is crucial. For instance, in environments, where thermal insulation is desired, employing higher proportions of E-waste aggregates and higher w/c can be advantageous.

6.1.1. Linear regression analysis of thermal conductivity

The regression analysis was conducted to examine the influence of w/c and replacement level of aggregate.

The resulting linear Eq. (3), indicates a negative relationship between thermal conductivity (k) and both independent variables: water-cement ratio (x_1) and percentage replacement level of PA (x_2). This suggests that higher the w/c or the replacement level, lower the thermal conductivity, thereby enhancing thermal insulation performance of concrete.

$$k = -0.3289x_1 - 0.0018x_2 + 0.7928 \tag{3}$$

Where

- k = Thermal Conductivity
- x_1 = w/c
- x_2 = % Replacement Level of PA

Regression statistics in Table 5 highlight the model’s strength in predicting thermal conductivity. The low standard error (0.015) indicates high prediction accuracy. The model’s F-statistic (126.82) exceeds the critical F-value of 4.26 (df = 2, 9), confirming overall model significance [17]. Likewise, the t-statistic (16.08) is far greater than the critical t-value of ±2.262, validating the individual predictors’ significance; the values of R² (0.966) are close to the model explaining 96.60% of the variation in thermal

Table 5. Regression statistics of thermal conductivity.

Regression Statistics	
R Square	0.966
Standard Error	0.015
Observations	12
F-Values	126.816
t-stats	16.083

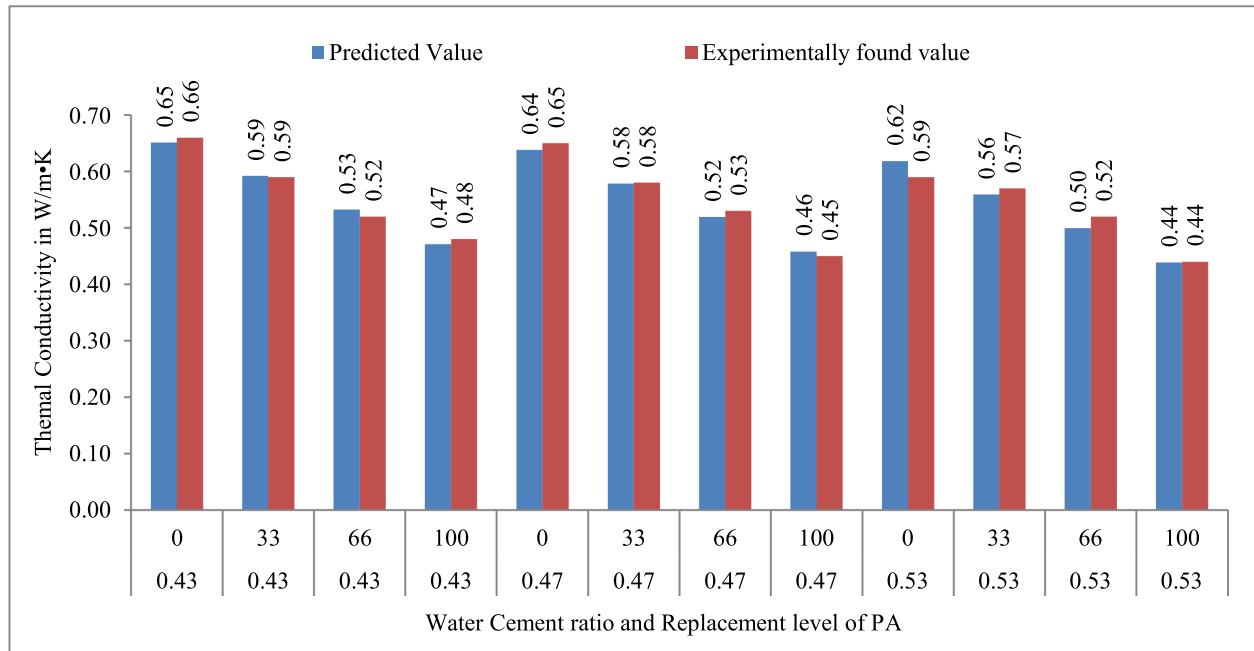


Fig. 8. Predicted and experimental values of thermal conductivity.

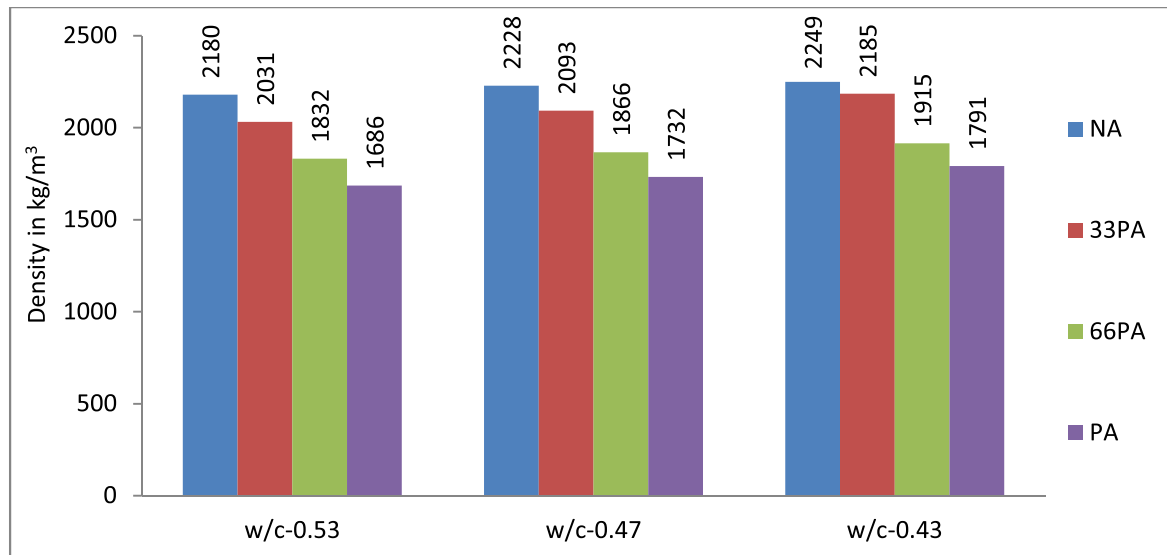


Fig. 9. Density at various w/c.

conductivity based on the w/c ratio and replacement level [18]. Thus, the model is statistically valid and reliable.

Fig. 8 illustrate that across all w/c ratios, a consistent decreasing trend in thermal conductivity is observed with increasing replacement levels, indicating that higher plastic content leads to improved thermal insulation. The predicted values closely align with the actual values, demonstrating the accuracy and reliability of the regression model.

6.2. Density

The Fig. 9, illustrates the density of specimens. The samples are categorized as Normal Aggregate (NA) and 33%–100 % E-waste Plastic Aggregate (33PA–100 PA). The results corroborate known fact of increase in the density with reduction in the w/c (0.53 to 0.43). Fig. 8 shows that concrete with NA, has the highest density across all w/c ratios, and given that the density of the crushed rock aggregates (NA) is

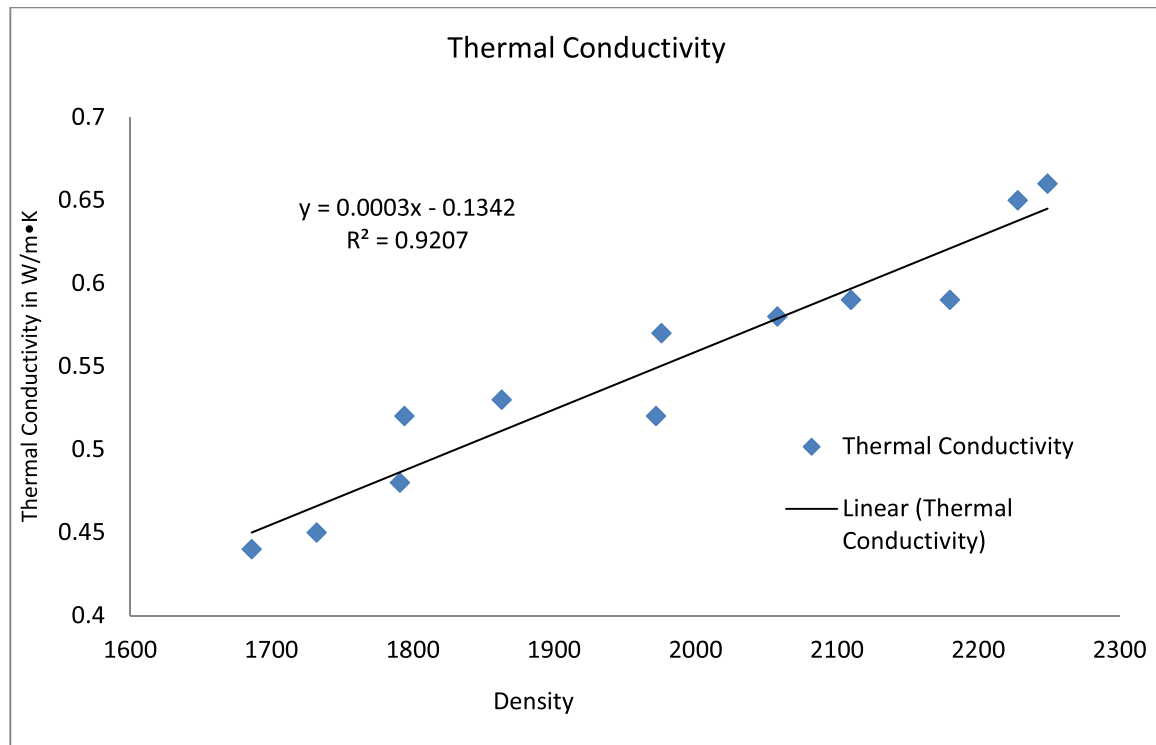


Fig. 10. Thermal conductivity and density.

more than that of the E-waste aggregates. As fraction of PA increased from 33% to 100%, density decreased. At 0.53 w/c, densities were 2180 kg/m³ for NA and 1686 kg/m³ for 100PA, while with 0.43 w/c, densities ranged from 2249 kg/m³ between NA to 1791 kg/m³ for 100PA. Thus, a potential trade-off is observed by incorporating E-waste aggregates for sustainability and the impact on concrete's density. Notably, at a w/c of 0.43, the concrete with 33% PA (33PA) maintains a relatively high density of 2185 kg/m³, suggesting a balance between using partially E-waste aggregates and preserving acceptable material density, probably for structural applications.

6.3. Relation between thermal conductivity and density

Fig. 10 presents the regression among the two properties of concrete. The equation of trend line is as Eq. (4) with R^2 value of 0.920, suggest a strong linear relationship between these two variables.

$$k = 0.0003\rho - 0.1342 \quad (4)$$

Trend of Fig. 10 is expected, as denser materials generally have more solid particles in close contact, which facilitates the transfer of heat through conduction. For example, concrete samples with a density

around 1700 kg/m³ exhibit conductivity of 0.45, while samples of densities around 2250 kg/m³ have conductivity of 0.65.

Overall, the plot illustrates that optimizing concrete's density can help control its thermal conductivity, tailoring it to specific requirements depending on whether heat retention or dissipation is the priority in a given application.

6.4. Sorptivity

Water sorption in concrete describes the process by which concrete absorbs water over time. This absorption occurs because of the porous nature of concrete, where water can penetrate the material through capillary action or by diffusion through the pore structure. The specimen size details were in conformity with ASTM C1585-20. However test duration was limited to 72 hours as no variation in rate of absorption was notice in any sample beyond this as is also evident from Figs. 11 to 13.

Fig. 11 presents the percentage water sorption of concrete at w/c 0.43. Water sorption decreases with time for all aggregate types, indicating gradual saturation. Concrete containing PA exhibits the lowest sorption at all-time intervals, demonstrating superior resistance to water ingress.

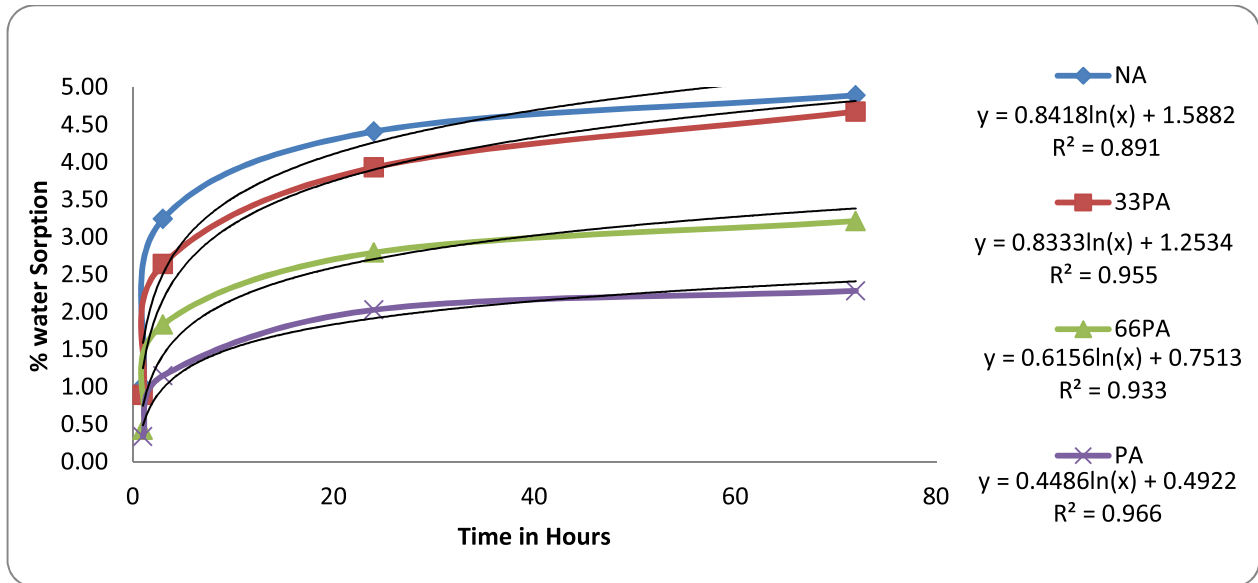


Fig. 11. Water sorption of various concrete mixes at w/c 0.43.

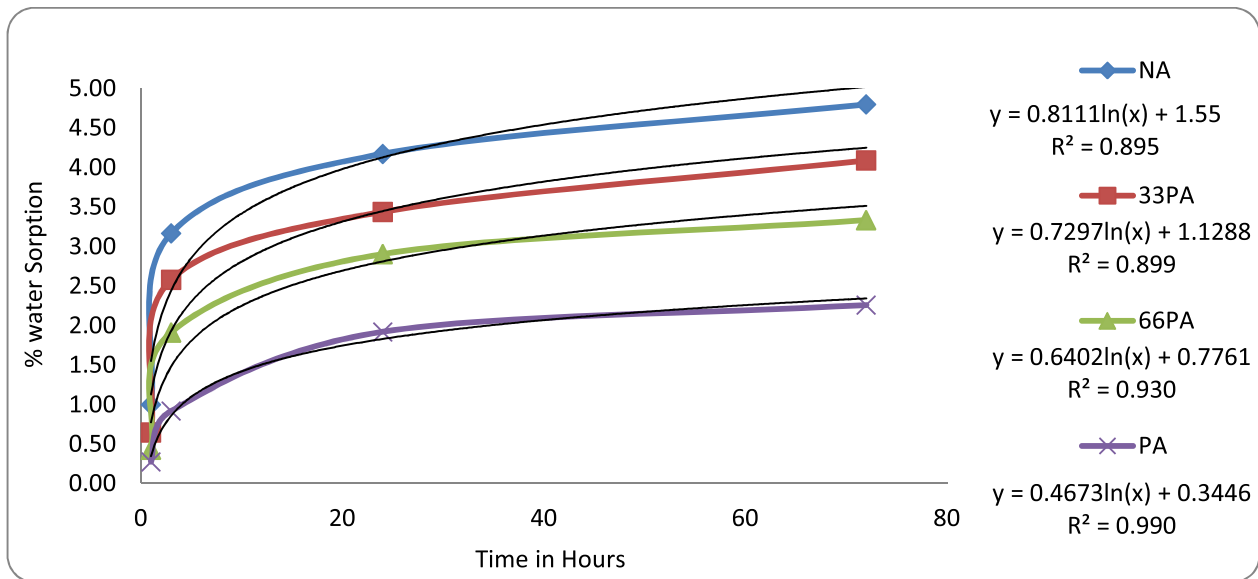


Fig. 12. Water sorption at w/c 0.47.

At w/c 0.43, a clear reduction in sorption is observed with increasing PA content due to the hydrophobic nature of PA [25]. The mix with 100% natural aggregate (NA) shows the highest sorption ($y = 0.8418\ln(x) + 1.588$, $R^2 = 0.891$), reflecting the porous and absorbent characteristics of natural aggregates. Replacement of NA with 33% PA slightly reduces sorption ($y = 0.8333\ln(x) + 1.253$, $R^2 = 0.955$). A more pronounced reduction is seen at 66% PA ($y = 0.6156\ln(x) + 0.7513$, $R^2 = 0.933$), while 100% PA exhibits the lowest sorption ($y = 0.4486\ln(x) + 0.4922$, $R^2 = 0.97$), confirming the

reduced capillary absorption and improved impermeability of E-waste aggregates.

Figs. 12 and 13 show water sorption at w/c 0.47 and 0.53, respectively. In both cases, mixes with PA consistently demonstrate lower sorption than NA mixes, while 33PA and 66PA exhibit intermediate values, with 66PA generally lower than 33PA.

At w/c 0.47 (Fig. 12), sorption follows logarithmic trends and decreases with increasing PA content. The 100% NA mix shows the highest absorption ($y = 0.8111\ln(x) + 1.55$, $R^2 = 0.895$). With 33% PA, sorption decreases moderately ($y = 0.7297\ln(x) +$

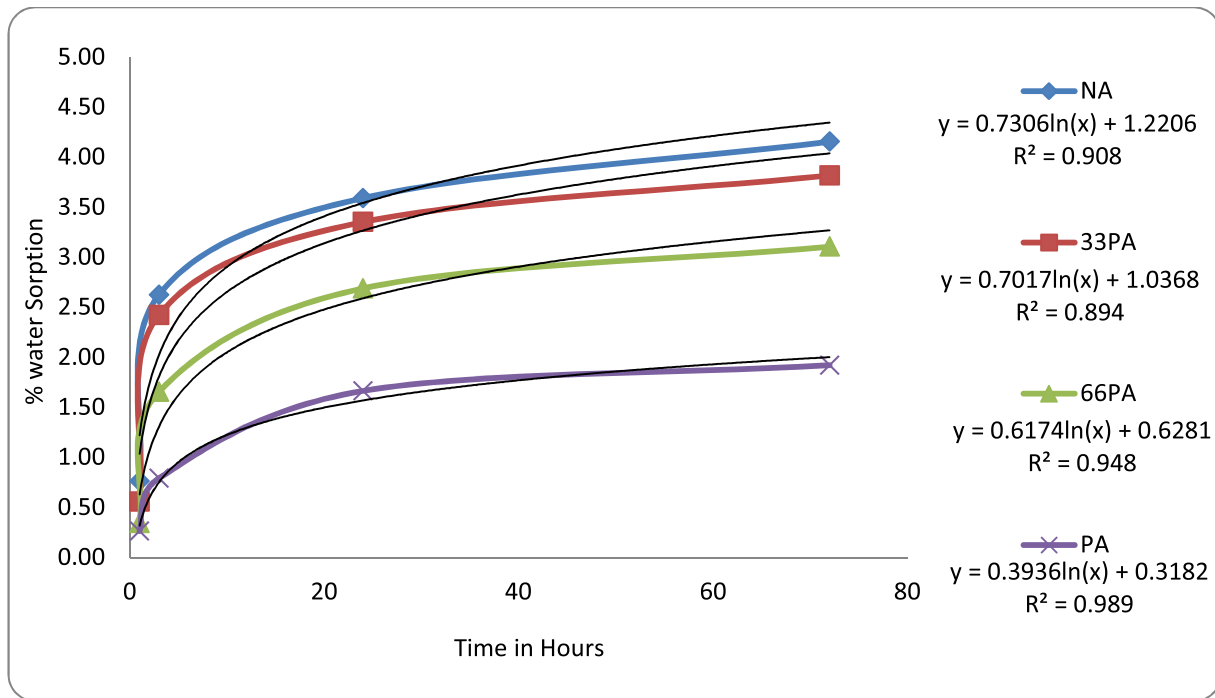


Fig. 13. Water sorption of various concrete mixes at w/c 0.53.

1.1288, $R^2 = 0.899$). At 66% PA, a significant reduction is observed ($y = 0.6402\ln(x) + 0.7761$, $R^2 = 0.930$), while 100% PA shows the lowest sorption ($y = 0.4673\ln(x) + 0.3446$, $R^2 = 0.991$).

Similarly, at w/c 0.53 (Fig. 13), sorption increases over time at a decreasing rate. The 100% NA mix records the highest uptake ($y = 0.7306\ln(x) + 1.2206$, $R^2 = 0.908$). Replacement with 33% PA slightly lowers sorption ($y = 0.7017\ln(x) + 1.0368$, $R^2 = 0.894$), and 66% PA further reduces it ($y = 0.6174\ln(x) + 0.6281$, $R^2 = 0.948$). The 100% PA mix demonstrates the lowest water absorption ($y = 0.3936\ln(x) + 0.3182$, $R^2 = 0.987$).

Figs. 12 and 13, indicates that at the w/c 0.47 and 0.53, concrete with conventional rock aggregate has a tendency of sorption even beyond the 72 hours (as the line connecting the values of the sorption with time, does have an upward slope even beyond 72 hours age), whereas the concrete with PA with similar water-cement ratio does not sorpt water beyond about 24 hours, as evident from a flat straight line connecting values of the sorption with time (without any upward slope). Concrete mixes containing PA aggregate consistently exhibit superior resistance to water ingress compared to the conventional aggregate across all the water-cement ratios and replacement levels, making PA aggregate a preferred choice for mitigating water absorption-related deterioration in structures and, in turn, expect better durability of the resulting concrete.

6.5. Effect of PA replacement on 28-day compressive strength

The 28-day compressive strength of the concrete samples has been as shown in Fig. 14. Results indicate a consistent reduction in strength with increasing E waste aggregate (PA) replacement at all water-cement (w/c) ratios. For w/c = 0.43, the compressive strength decreased from 23.32 MPa (NA) to 21.48 MPa (33PA), 15.26 MPa (66PA), and 14.56 MPa (PA). A similar trend was observed at w/c = 0.47 and 0.53. However, at higher w/c ratio (0.53), the difference between NA and 33PA becomes marginal; indicating that at moderate replacement levels, it may be feasible in structural applications.

Table 6. Density and strength specifications of lightweight concrete.

Properties	ACI 318	33PA (w/c 0.47)
Density	1440–2160	2093
Compressive Strength	> 17.2 MPa	21.03

The recorded density of 2093 kg/m³ falls within the acceptable range for structural lightweight concrete, which is specified as 1440–2160 kg/m³ by ACI 318. The compressive strength achieved was 21.03 MPa, which meets the minimum threshold of 17.2 MPa set by ACI 318. It indicates that with a 33% replacement of PA, the concrete maintains structural adequacy for lightweight applications.

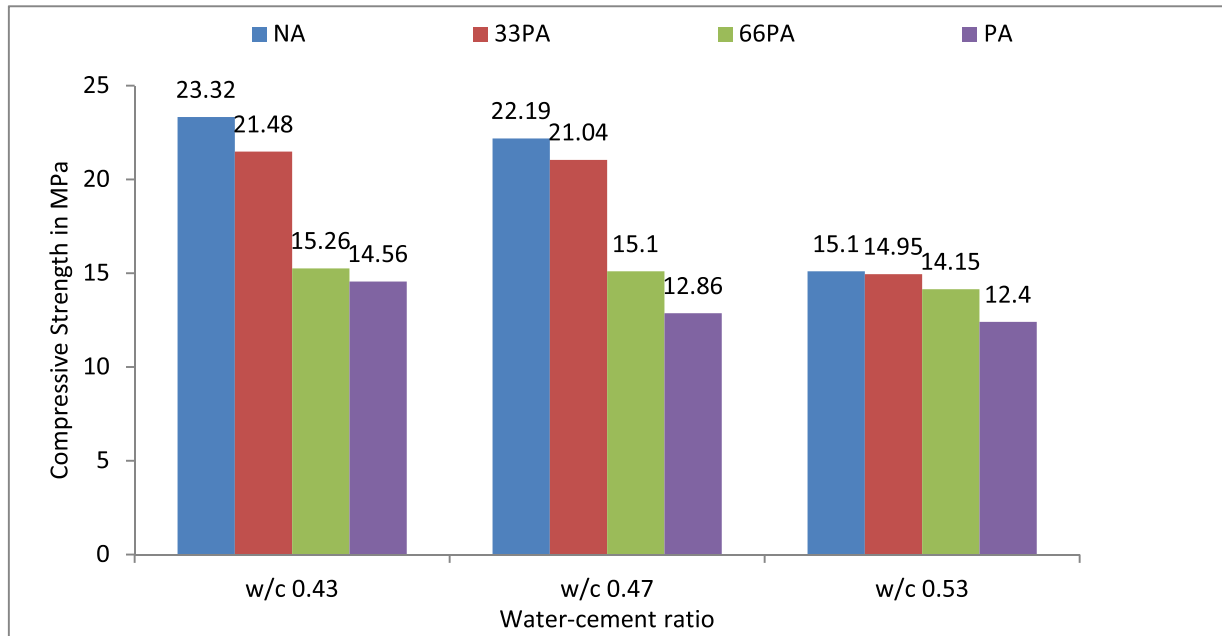


Fig. 14. Compressive strength at 28 days with different water-cement ratios at various replacement level of PA.

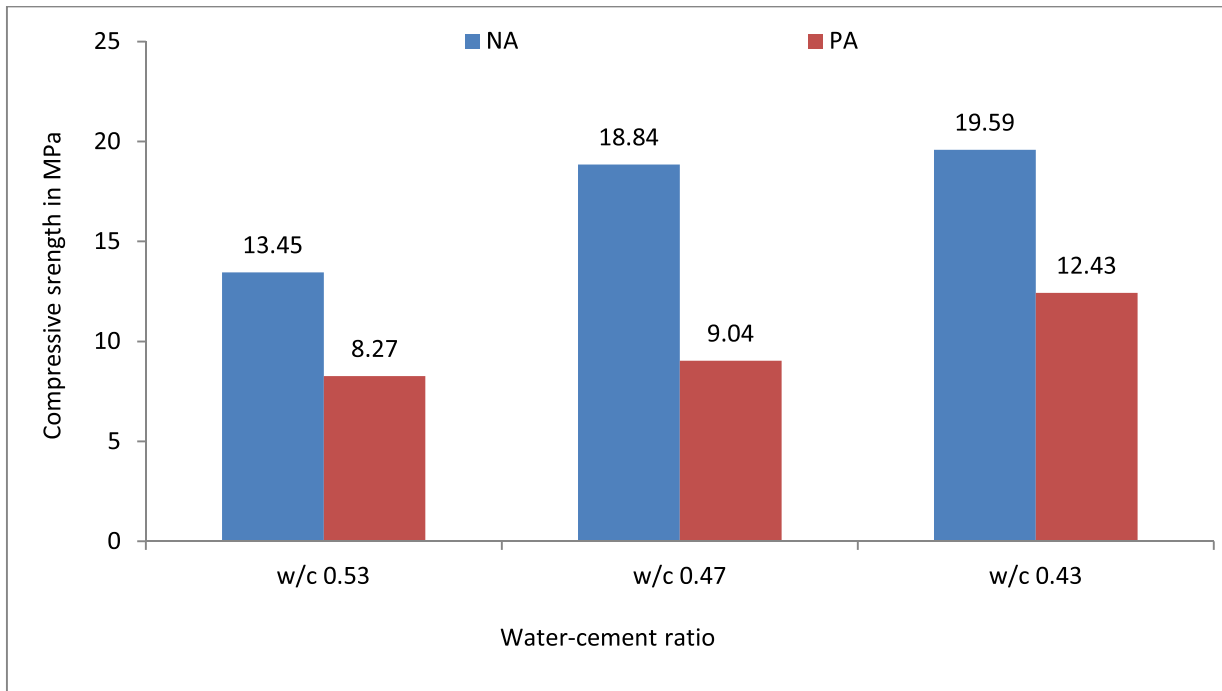


Fig. 15. Compressive strength of concrete with NA and PA at 7 days with different water-cement ratios.

6.6. Flexural strength

Flexural strength values of concrete incorporating plastic aggregates (PA) at different water-cement (w/c) ratios are illustrated in Fig. 16. For conventional concrete with natural aggregates (NA), the flexural strength increased from 5.07 MPa to 6.93

MPa as the w/c ratio decreased from 0.53 to 0.43. In comparison, PA-based concrete exhibited significantly lower flexural strength at higher w/c ratios, with a minimum value of 2.67 MPa recorded at a w/c ratio of 0.53, as shown in Fig. 16. However, a clear improvement in strength is observed with the reduction in w/c ratio. At a w/c ratio of

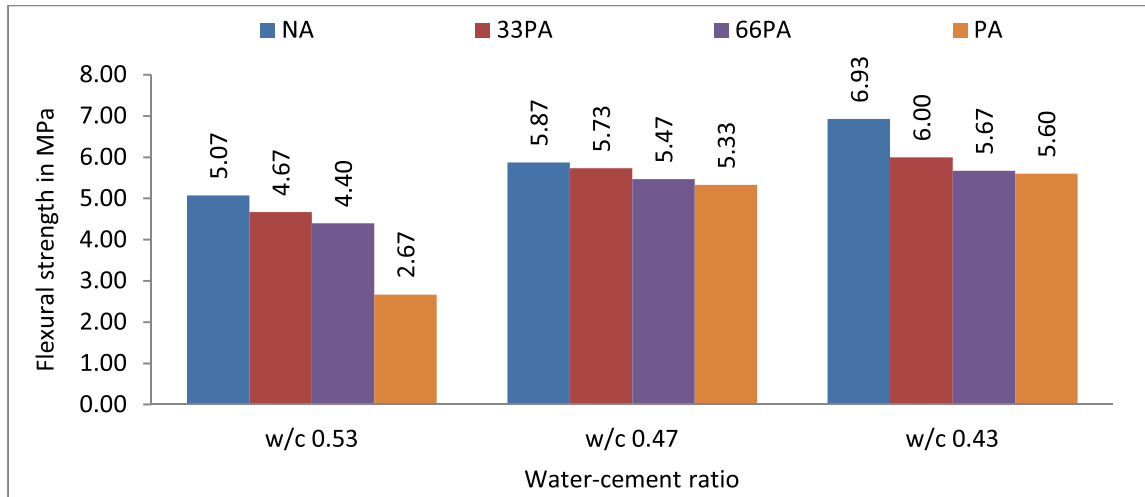


Fig. 16. Strength in MPa under flexure at 28 days age.

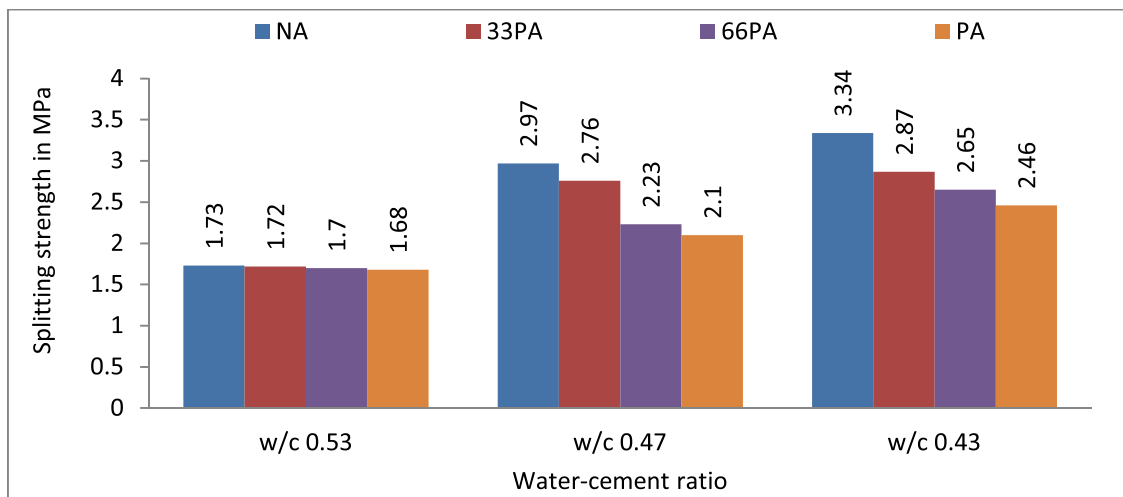


Fig. 17. Split tensile strength in MPa at 28 days age.

0.47, the flexural strength increased to 5.33 MPa, and further improved to 5.60 MPa at a w/c ratio of 0.43. This trend, as evident from the figure, indicates that decreasing the w/c ratio enhances the flexural performance of PA mixes, likely due to improved matrix densification and better interfacial bonding between the cement paste and plastic aggregates.

6.7. Splitting tensile strength

Splitting tensile strength values of concrete mixes incorporating plastic aggregates (PA) at different water-cement (w/c) ratios are presented in Fig. 17. For conventional concrete with natural aggregates (NA), the splitting tensile strength increased from 1.73 MPa at a w/c ratio of 0.53 to 3.34 MPa at 0.43,

indicating a significant improvement with reduction in water content. Concrete containing PA exhibited comparatively lower tensile strength across all w/c ratios. At a w/c ratio of 0.53, the PA mix showed a value of 1.68 MPa, which is slightly lower than the NA mix. However, as the w/c ratio decreased, the tensile strength of PA mixes improved notably, reaching 2.10 MPa at 0.47 and further increasing to 2.46 MPa at 0.43. The observed trend clearly indicates that reduction in w/c ratio enhances the tensile performance of PA-based concrete, primarily due to improved matrix densification and reduced porosity. Despite this improvement, PA mixes consistently show lower tensile strength than NA mixes, which can be attributed to weaker interfacial bonding and lower stiffness of plastic aggregates compared to natural aggregates.

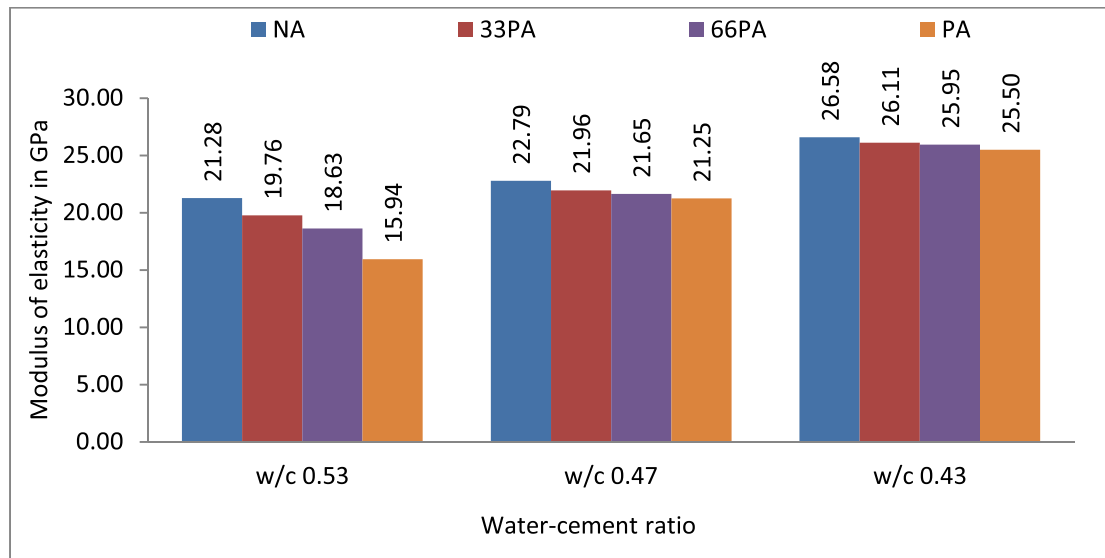


Fig. 18. Values of elastic modulus in Gpa.

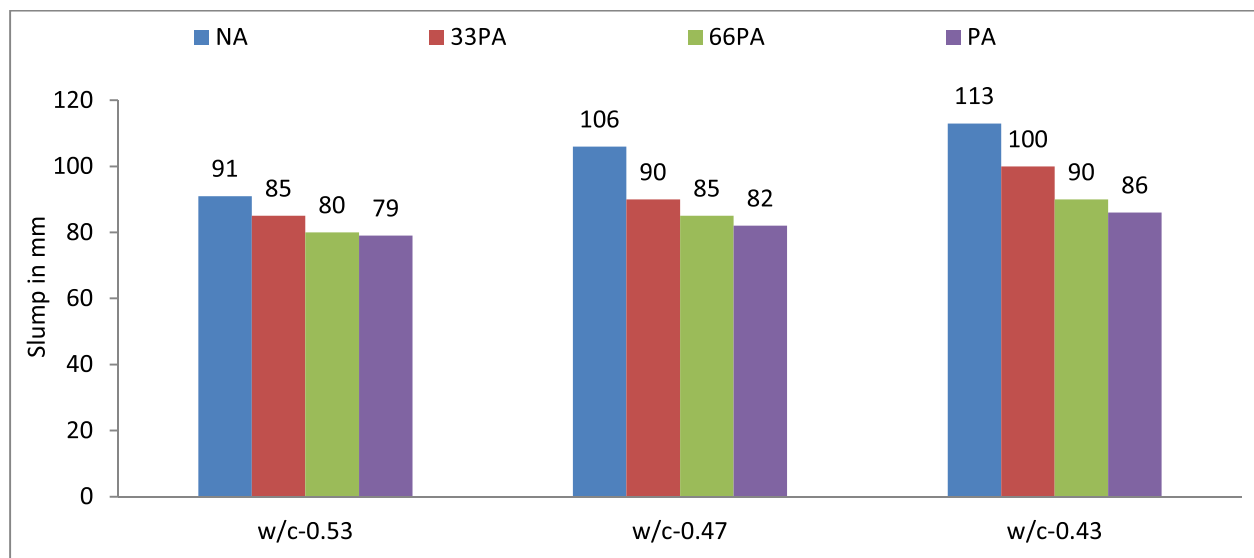


Fig. 19. Slump for a different type of aggregate with a variation of w/c Ratio.

6.8. Modulus of elasticity

The modulus of elasticity values of concrete mixes incorporating plastic aggregates (PA) at different water-cement (w/c) ratios are presented in Fig. 18. For conventional concrete with natural aggregates (NA), the modulus of elasticity increased from 21.28 GPa at a w/c ratio of 0.53 to 26.58 GPa at 0.43, indicating enhanced stiffness with reduced water content. In comparison, PA-based concrete exhibited lower modulus of elasticity values across all w/c ratios. At a w/c ratio of 0.53, the PA mix showed a significantly reduced value of 15.94 GPa. However, as the w/c ratio decreased, a noticeable improvement in stiff-

ness was observed, with modulus values increasing to 21.25 GPa at 0.47 and further to 25.50 GPa at 0.43.

6.9. Workability of concrete

Based on the test results shown in Fig. 19, which compare the slump values for concrete mixtures with different water-to-cement (w/c) ratios (0.53, 0.47, and 0.43), the Slump values for Concrete with NA are 91 mm, 106 mm, and 113 mm respectively. At the replacement level 33% of NA by PA the slump values decrease to 85 mm, 90 mm and 100 mm respectively. Furthermore replacement at 66% of NA by PA, the values decrease to 80 mm, 85 mm and 90 mm

respectively. Slump values for Concrete with PA are 79 mm, 82 mm, and 86 mm. comparing the slump values for concrete with PA; we observe a similar pattern as with NA. As the w/c ratio decreases, the slump values increase. Furthermore, the gradual decrease in slump with increasing the content of PA aligns with established literature as the percentage of RCA increased, it absorbed some water due to adhered mortar and the workability of the mixes get reduced [51].

7. Discussion

From Table 3 (Details of chemical composition of E-waste aggregate used), E-waste plastic contains mainly harmful chemicals (S, Cl, C, Mg), including heavy metals (Te, V, Zn, Cr, Mn, Pb, Ti). E-waste recycling, particularly the informal and unregulated process is a significant source of PBDD/Fs contamination. Open burial and the use of acid baths for recovery of valuable materials releases PBDD/Fs, which are group of brominated compounds that are structurally similar to dioxins. They are formed during the thermal decomposition of BFRs) commonly found in electronic equipment. PBDD/Fs are emerging containment found in E-waste with potential health and environmental implications. They are structurally similar to dioxins and can be even more toxic [26]. Dumping/burying the harmful chemicals and heavy metals in concrete can save society from possible harmful effects or unorganized throwing of the waste for landfill (which may intern cause release of heavy metals and other chemicals in soil or ground water/possible contamination). On the other hand, partial/fully replacement of the conventional rock-based aggregate by the plastic scrap aggregate can help in decreasing the rate of depletion of natural resources/rock. Inclusion of the hazardous waste in concrete can contribute to sustainable development. The environmental safety of E-waste aggregate concrete largely depends on its leachability characteristics. Senthil Kumar et al. (2016) applied the Toxicity Characteristic Leaching Procedure (TCLP) on concrete with 0–50% high-impact polystyrene (HIPS) and reported Cd, Pb, Cu, and Zn in leachates well below USEPA regulatory limits ($Pb < 5.0 \text{ mg/L}$, $Cd < 1.0 \text{ mg/L}$) at 28–90 days; metal release decreased with curing age, indicating progressive immobilisation by cement hydration products [49]. Pauzi et al. found that CRT glass-concretes generally meet TCLP limits except when crushed glass $< 4.75 \text{ mm}$, which produced elevated Pb leachate; they also reported up to 27% loss in compressive strength for 100% crushed CRT — underlining the need to control particle size and morphology when using e-waste aggregates [50].

Klein reported the conductivities of polyethylene and polypropylene 0.43–0.23 at 25°C [19]. In comparison, ordinary concretes incorporating various aggregates typically exhibit thermal conductivities in the range of 1.34–2.92, which is much higher [20]. Tae Sup Yun et al. found conductivity of mortar and concrete as about 2.0 [21]. Poonyakan et al. demonstrated that thermal conductivity values ranged between 0.74–0.96 for LDPE-based concrete, 0.72–0.86 for PP-based concrete, 0.84–0.94 for PET-based concrete, and 0.95–1.02 for mixes with combined plastic aggregates. Similarly, Abu Saleem reported that concrete incorporating recycled plastic exhibited lower sorptivity compared to conventional concrete, suggesting enhanced resistance to water ingress [16].

In another investigation, Pasha et al. evaluated various modified concrete mixes and observed that the mix with 20% plastic aggregate demonstrated most favorable thermal conductivity performance, with a value of $1.84 \text{ W/(m}\cdot\text{K)}$ [22]. This reflects a significant improvement in thermal insulation properties, thereby proving use of plastic aggregate.

The findings of the present study align well with existing research, reinforcing the relationship between w/c ratio, type of aggregate, and thermal conductivity in concrete. In conventional concrete with natural aggregates, it is well established that an increase in the w/c ratio tends to enhance overall porosity, thereby leading to a slight reduction in thermal conductivity. This trend is validated by the observed decrease from 0.66 to $0.59 \text{ W/m}\cdot\text{K}$ as w/c increased from 0.43 to 0.53. A similar behavior is observed in the current investigation involving concrete with PA. The thermal conductivity values show marginal variation with increasing w/c ratio—such as a slight decrease from 0.59 to $0.57 \text{ W/m}\cdot\text{K}$ for 33% plastic aggregate replacement (33PA), and a near-constant (0.52–0.53) for 66% replacement (66PA). These consistent yet small variations suggest that the hydrophobic and low-conductivity nature of plastic aggregates plays a dominant role in thermal behavior, while the influence of increased porosity due to higher w/c a ratio remains secondary but evident.

Basha et al. (2020) reported conductivity (k) of $1.1 \text{ W/m}\cdot\text{K}$. Asadi et al reviewed comprehensively the factors affecting thermal conductivity of concrete. In the present experimental study, a relatively smaller value of thermal conductivity of concrete than Basha et al and other researchers may be due different mineralogical characteristics of the aggregates. Nevertheless, the K of concrete with PA in different proportions are lesser than that with NA, the trend is consistent and in conformity with the published literature with lightweight aggregates. Literature also indicates that the magnitude of decrease of k with

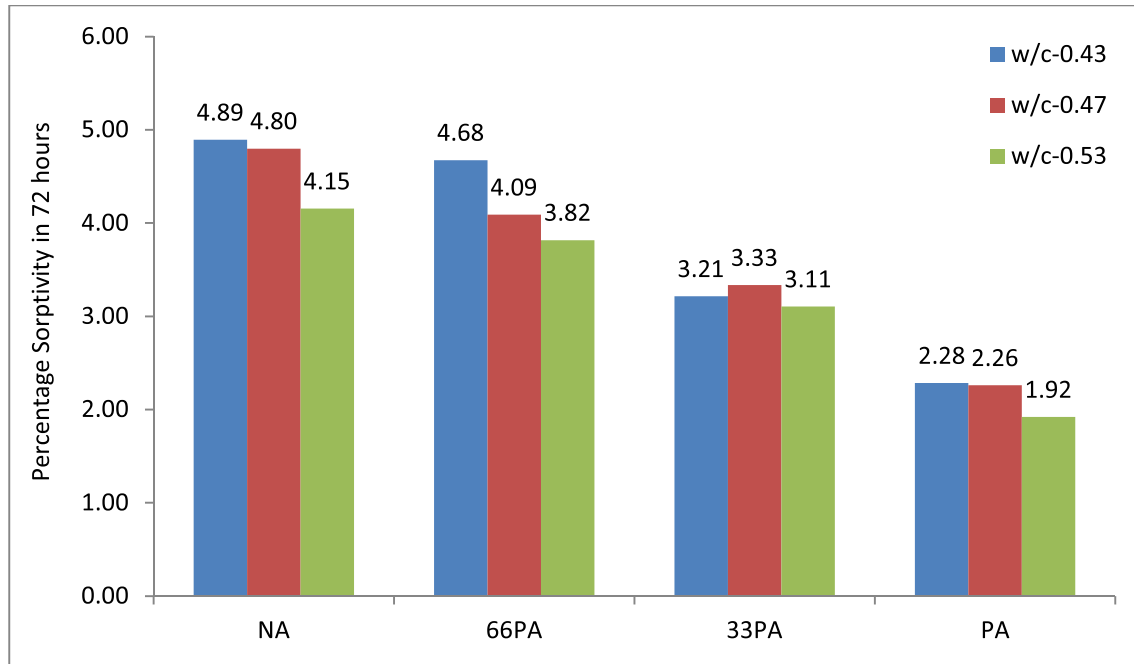


Fig. 20. Sorptivity at 72 hours.

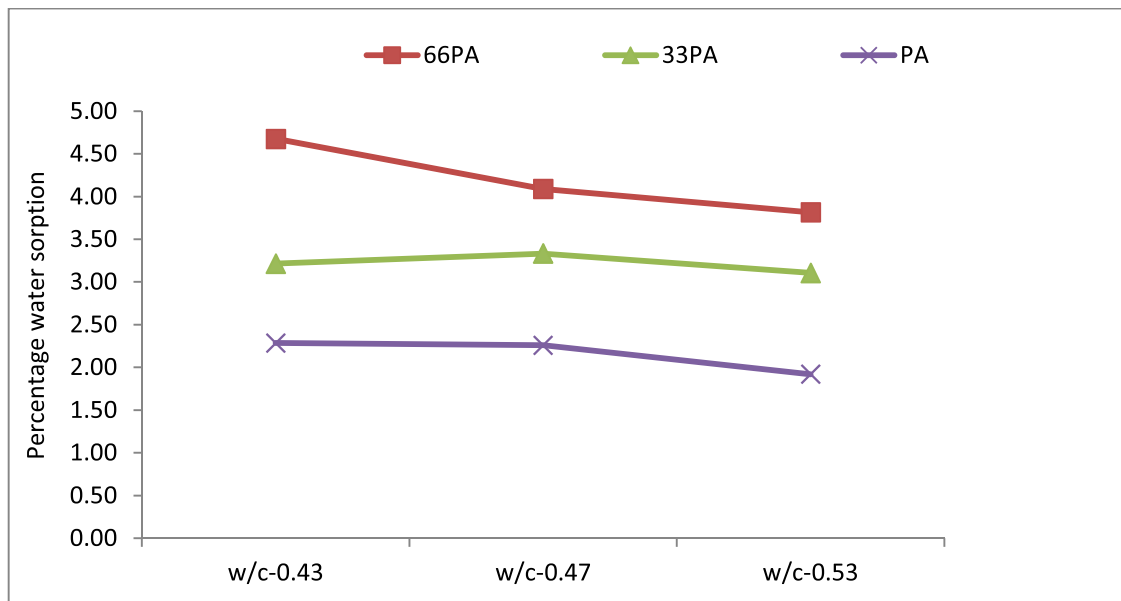


Fig. 21. Variation in sorptivity with w/c.

lightweight aggregates (LWA) also depends on the type of LWA [5, 48]. Hence, is the 'k' falling within a limited range.

Several studies have investigated the effect of partial use of plastic coarse aggregates (PCA) on sorptivity of concrete. In the investigation by Zee-shan et al., sorptivity values showed a consistent decrease with increasing PCA content 12-29% with 10-20% PCA. This reduction was mainly due to the

non-porous and non-absorptive characteristics of PCA [23]. Similarly, another study examining the influence of PCA replacement from 10% to 50% reported a decline in sorptivity ranging from 11.8% to 41.7% compared to plain concrete [24]. In the present study the sorptivity, reduces up to 70% in the concrete with 100% replacement of PA as compare to concrete with NA. PA possess a hydrophobic (water-repellent) and non-porous nature, which significantly influences the

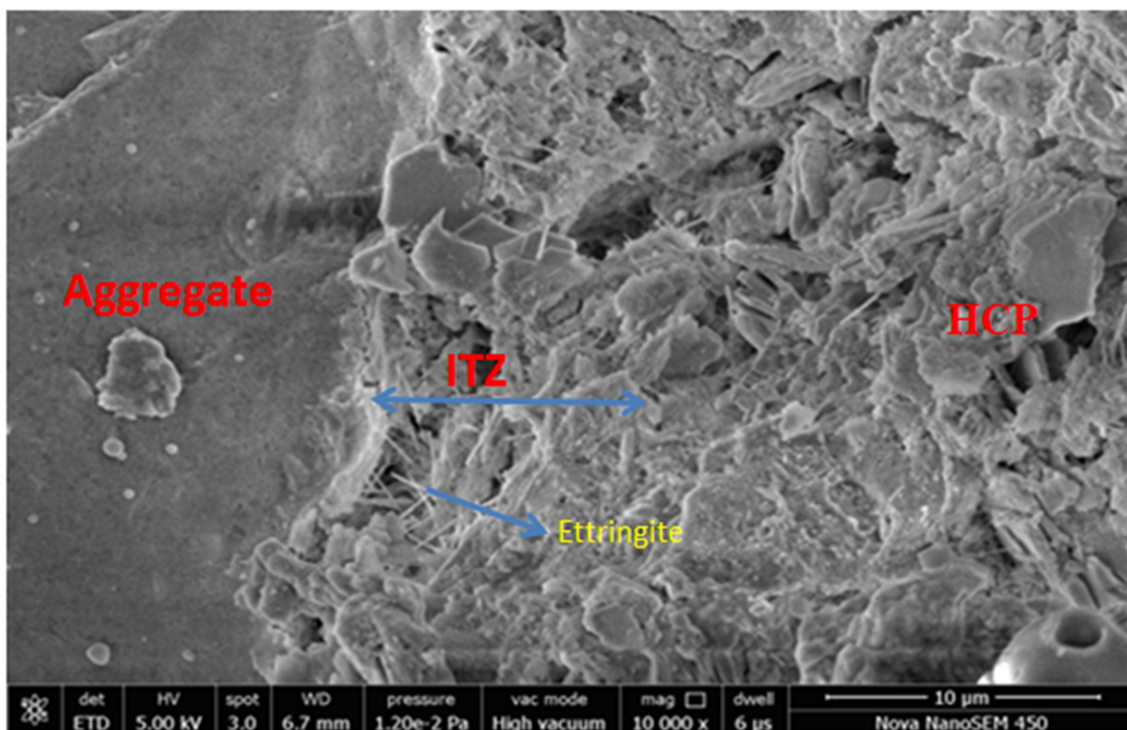


Fig. 22. Interfacial zone microstructure with PA at w/c 0.43.

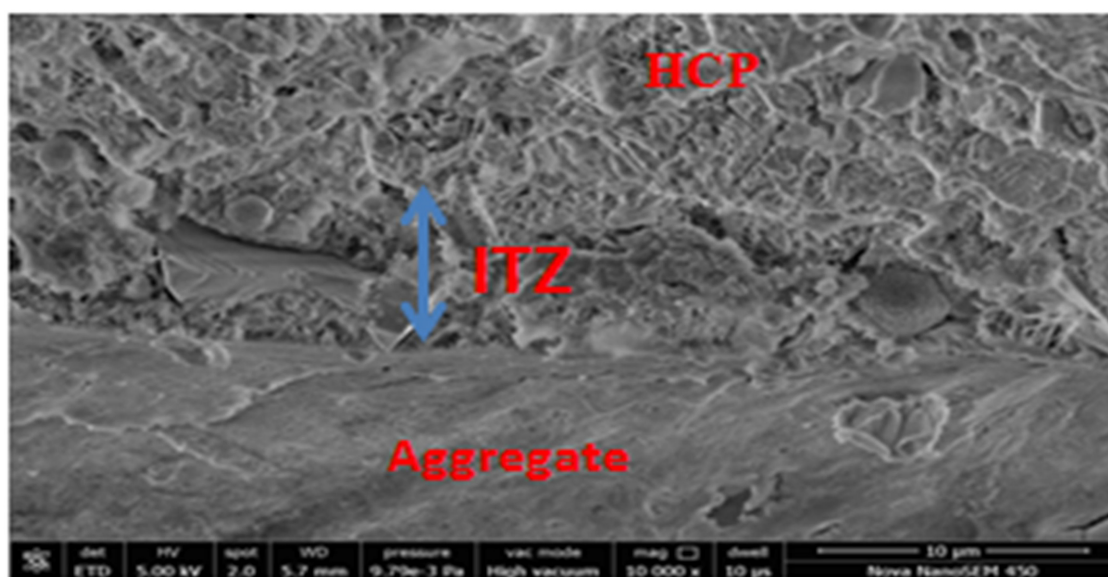


Fig. 23. Interfacial zone microstructure with PA at w/c 0.47.

sorptivity of concrete. Their low water absorption capacity hinders capillary suction and moisture ingress into the concrete. As a result, concrete incorporating e-waste aggregates exhibits reduced sorptivity compared to conventional concrete [25].

Sorptivity values of concretes at the 72 hour age are presented in Figs. 20 and 21. Presents the values

of sorptivity of concrete containing PA with various water-cement ratios.

A decrease in sorptivity (water absorption rate), in e-waste concrete despite a higher water-cement (w/c) ratio may be due to the hydrophobic nature of plastic-based e-waste aggregates. E-waste particles might act as fillers that do not allow water to penetrate through

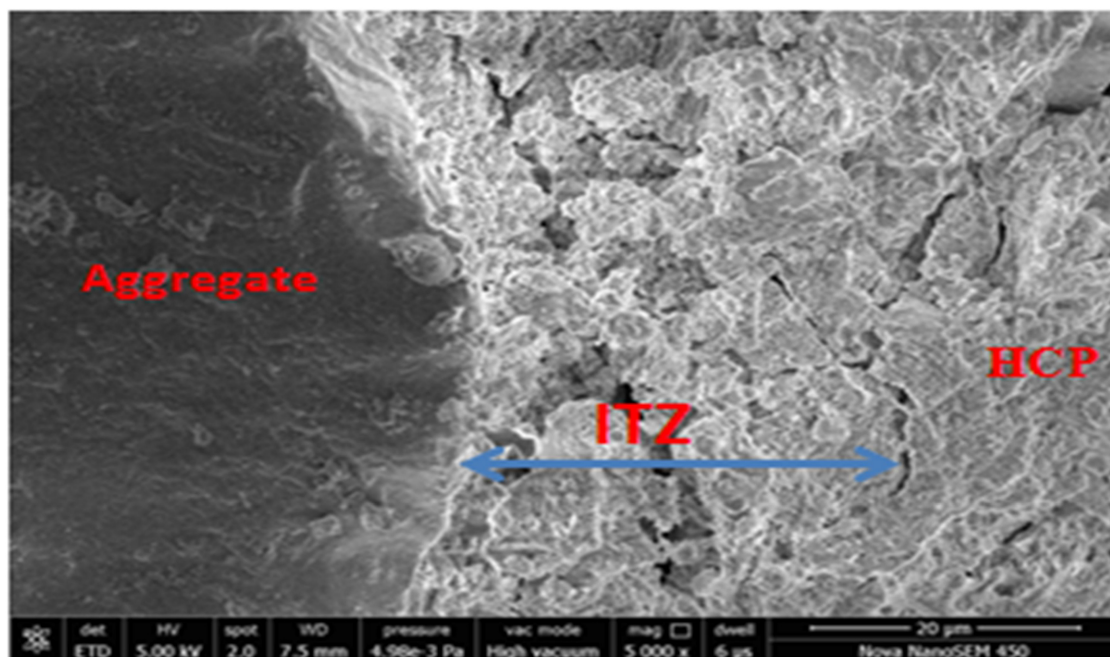


Fig. 24. Interfacial zone microstructure with PA at w/c 0.53.

Table 7. Percentage increment in compressive strength during the period 7–28 day.

Aggregates Type	% Increment in compressive strength at 28 days with 7 Days		
	w/c 0.43	w/c 0.47	w/c 0.53
NA	19.04	17.78	12.27
PA	17.14	42.26	49.94

them. Even if the surrounding cement matrix is more porous due to a higher w/c ratio, the overall absorption through the aggregate component is nil. This, when combined with higher w/c ratios, may lead to improved hydration and denser compaction of the interfacial transition zone (ITZ), reducing the net water absorption of the composite material (concrete), despite higher total porosity. Figs. 22 to 24, shows interfacial zone (ITZ) micrographs of concrete with the three water cement ratios at 28 days age. These images were taken on a Bruker FESEM. A denser ITZ with w/c 0.47 (Fig. 22) as compared to that with w/c 0.43 (Fig. 23). is visible. A higher rate of gain of strength beyond early age (seven days) in the concrete with PA at higher water- cement ratio of 0.53 than at w/c 0.43, as illustrated in Table 7, corroborates better hydration in the concrete mixes at higher water- cement ratio with PA. For definite establishment of the trend noticed in the present study, however requires thorough and more tests with concretes containing PA at various water-cement ratios. In the previous researches and the present study, the similar trend was found for thermal conductivity and sorptivity with PA.

8. Conclusions

- Concrete with PA exhibit lower sorptivity than concrete made with conventional crushed rock aggregate with all the water-cement ratios investigated in this study (0.43, 0.47, and 0.53).
- Thermal conductivity of concrete may be reduced up to 33% when E-waste plastic aggregates are incorporated.
- When coarse aggregates are made of E-waste, conductivity varies linearly to the density of concrete.
- Percentage reduction in Modulus of elasticity of concrete for w/c ratio 0.43 and 0.47 are less than the concrete with w/c ratio 0.53 for all the replacement level of NA by PA.
- Compressive strength of concrete in the range 12–15 N/mm², and 13.0 to 16 N/mm² can be obtained at 28 days and 56 days respectively by replacing NA with PA at a w/c 0.53.
- With the replacement of 33% of NA by PA, the percentage reduction in flexural strength of concrete is only about 2.5% as compared to that of the concrete with NA with w/c 0.47.

9. Recommendations

- As PA content increases from 0% to 100%, conductivity decreases correspondingly.
- Thus, incorporating E-waste in concrete can produce a lightweight concrete with low thermal

conductivity and low sorptivity while also promoting recycling of waste materials.

Acknowledgement

We are thankful to Central Institute of Petrochemicals Engineering & Technology (CIPET) for conducting chemical analysis of E-waste plastic aggregate.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contributions

Rakesh Kumar Saini: Conceptualization, methodology, experimental investigation, data curation, formal analysis, visualization, writing original draft preparation.

Praveen Kumar: Supervision, validation, critical review, and editing of the manuscript.

Both authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Dataset

The dataset generated and analyzed during the current study is not publicly available due to institutional policy but is available from the corresponding author on reasonable request.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

1. UN, United Nations Environment Programme. 2024/2025. 2025 Global Status Report for Buildings and Construction, Global Alliance for Buildings and Construction. Nairobi. www.unep.org/resources/annual-report-2024.
2. Sen B, Kumar G, Thakur B, Dutta A. Comparative assessment of energy performance, GHG emission, and environmental performance of exterior wall alternatives for the buildings in an educational campus in Kolkata, India. *Discover Civil Engineering*. 2025;2(1):59.
3. Chandra S, Berntsson L. Lightweight aggregate concrete. *Elsevier*. 2002.
4. Elgarahy AM, Eloffy MG, Priya AK, Hammad A, Zahran M, Maged A, Elwakeel KZ. Revitalizing the Circular Economy: An Exploration of E-Waste Recycling Approaches in a Technological Epoch. *Sustainable Chemistry for the Environment*. 2024;100124.
5. Basha SI, Ali MR, Al-Dulaijan SU, Maslehuddin M. Mechanical and thermal properties of lightweight recycled plastic aggregate concrete. *Journal of Building Engineering*. 2020;32:101710.
6. Sau D, Shiuly A, Hazra T. Utilization of plastic waste as replacement of natural aggregates in sustainable concrete: Effects on mechanical and durability properties. *International Journal of Environmental Science and Technology*. 2024;21(2):2085–2120.
7. Abu-Saleem M, Zhuge Y, Hassanli R, Ellis M, Rahman M, Levett P. Evaluation of concrete performance with different types of recycled plastic waste for kerb application. *Construction and Building Materials*. 2021;29.
8. Khalil WI, Khalaf KJ. Eco-friendly concrete containing pet plastic waste aggregate. 2017.
9. Choi YW, Kim YJ, Shin HC, Moon HY. Quantitative measurement of water absorption of coarse lightweight aggregates in freshly mixed concrete. *International Journal of Concrete Structures and Materials*. 2020;14*(1): 1–12. <https://doi.org/10.1186/s40069-020-00408-x3>, 123477.
10. Zhang MH, Gjörv OE. Penetrability of lightweight aggregate concrete. *ACI Materials Journal*. 1991;88*(5):462–469. <https://doi.org/10.14359/2014>.
11. Silva RV, de Brito J, Saikia N. Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates. *Cement and Concrete Composites*. 2013;35(1):23–31.
12. Vanitha S, Natarajan V, Praba M. Utilisation of waste plastics as a partial replacement of coarse aggregate in concrete blocks. *Indian journal of science and technology*. 2015; 8(12).
13. Patil PS, Mali JR, Tapkire GV, Kumavat HR. Innovative techniques of waste plastic used in concrete mixture. *International Journal of Research in Engineering and Technology*. 2014;3(9):29–32.
14. Pirzada RA, Kalra T, Laherwal FA. Experimental study on use of waste plastic as coarse aggregate in concrete with admixture superplasticizer polycarboxylate ether. *International Research Journal of Engineering and Technology (IRJET)*. 2018;5(03):558–563.
15. Aldahdooh MAA, Jamrah A, Alnuaimi A, Martini MI, Ahmed MSR, Ahmed ASR. Influence of various plastics-waste aggregates on properties of normal concrete. *Journal of Building Engineering*. 2018;17:13–22.
16. Poonyakan A, Rachakornkij M, Wecharatana M, Smittakorn W. Potential use of plastic wastes for low thermal conductivity concrete. *Materials*. 2018;11(10):1938.
17. Montgomery DC, Runger GC. *Applied statistics and probability for engineers*. John Wiley & sons. 2010.
18. Gujarati DN. *Essentials of econometrics*. Sage Publications. 2021.
19. Klein R. *Laser Welding of Plastics*, 1st ed.; Wiley-VCH: Hoboken, NJ, USA, 2011.

20. Chan J. Thermal Properties of Concrete with Different Swedish Aggregate Materials; Rapport TVBM (5000-Serie); Lund University: Lund, Sweden, 2014.
21. Yun TS, Jeong YJ, Youm KS. Effect of surrogate aggregates on the thermal conductivity of concrete at ambient and elevated temperatures. *Sci. World J.* 2014; 2014:9.
22. Pasha MS, Aslam MF, Hamza M, Ali NM, Jabbar I, Ahmed S, Abbasi HKJ. Sustainable construction: Performance analysis of concrete incorporating E-waste plastic aggregates and silica fume. *Construction and Building Materials.* 2025;474:141103.
23. Ullah Z, Qureshi MI, Ahmad A, Khan SU, Javaid MF. An experimental study on the mechanical and durability properties assessment of E-waste concrete. *J. Build. Eng.* 2021;38:102177.
24. Ahmad F, Jamal A, Mazher KM, Umer W, Iqbal M. Performance evaluation of plastic concrete modified with e-waste plastic as a partial replacement of coarse aggregate. *Materials.* 2021;15(1):175.
25. Danish A, Mosaberpanah MA, Ozbakkaloglu T, Salim MU, Khurshid K, Bayram M, ... Qader DN. A compendious review on the influence of e-waste aggregates on the properties of concrete. *Case Studies in Construction Materials.* 2023;18:e01740.
26. Tue NM, Takahashi S, Subramanian A, Sakai S, Tanabe S. Environmental contamination and human exposure to dioxin-related compounds in e-waste recycling sites of developing countries. *Environmental Science: Processes & Impacts.* 2013;15(7):1326–1331.
27. Camilo JR, Rohden AB, Garcez MR. Concrete with rejected recyclable plastic waste at high temperatures. *Magazine of Concrete Research.* 2021;73(19):973–987.
28. Nwaubani SO, Parsons LA. Properties, durability and microstructure of concrete incorporating waste electrical and electronic plastics as partial replacement for aggregates in concrete. *Case Studies in Construction Materials.* 2021;15:e00731.
29. Rathore V, Rawat A. Effective utilization of electronic waste in concrete mixture as a partial replacement to coarse aggregates. In *AIP Conference Proceedings*. 2019, September:2158(1):020037. AIP Publishing LLC.
30. Bendixen M, Iversen LL, Best J, Franks DM, Hackney CR, Latrubesse EM, Tusting LS. Sand, gravel, and UN Sustainable Development Goals: Conflicts, synergies, and pathways forward. *One Earth.* 2021;4(8):1095–1111.
31. Nandan A, Suresh AC, Saole P, Jeevanasai SA, Chandrasekaran R, Meili L, Selvasembian R. An Integrated Approach for Electronic Waste Management—Overview of Sources of Generation, Toxicological Effects, Assessment, Governance, and Mitigation Approaches. *Sustainability.* 2023;15(24):16946.
32. Shinu NMT, Needhidasan S. An experimental study of replacing conventional coarse aggregate with E-waste plastic for M40 grade concrete using river sand. *Materials Today: Proceedings.* 2020;22:633–638.
33. Manjunath BA. Partial replacement of E-plastic waste as coarse-aggregate in concrete. *Procedia Environmental Sciences.* 2016;35:731–739.
34. Prasanna PK, Rao MK. Strength variations in concrete by using E-waste as coarse aggregate. *Int. J. Educ. Appl. Res.* 2014;4(2):82–84.
35. Ferreira L, De Brito J, Saikia N. Influence of curing conditions on the mechanical performance of concrete containing recycled plastic aggregate. *Construction and Building Materials.* 2012;36:196–204.
36. Jacintho AEPGDA, Cavaliere ISG, Pimentel LL, Forti NCS. Modulus and strength of concretes with alternative materials. *Materials.* 2020;13(19):4378.
37. Raghavendra DS, Sivakumar A. Compressive strength index of different types of lightweight plastic aggregate concrete. *Indian Journal of Science and Technology.* 2015;8(S2):106–111.
38. Manikandan M, Arul Prakash D, Manikandan P. Experimental study on E-waste concrete and comparing with conventional concrete. *Jr. Ind. Pollut. Control.* 2017;33:1490–1495.
39. Kalpana M, Vijayan DS, Benin SR. Performance study about ductility behaviour in electronic waste concrete. *Materials Today: Proceedings.* 2020;33:1015–1020.
40. Saini RK, Kumar P. Thermal conductivity of concrete containing aggregates of e-waste. *Journal of Green Building.* 2025;20(2):227–244.
41. Kothari CR. Research methodology: Methods and techniques. *New Age International.* 2004.
42. Neville AM. *Properties of Concrete* (5th ed.). Pearson Education Limited. 2011.
43. IS 2386: Part 1: 1963 — Methods of Test for Aggregates for Concrete — Part I: Particle Size and Shape (reaffirmed, latest status active as per BIS records).
44. IS 1199: Part 2: 2018 — Fresh Concrete — Methods of Sampling, Testing and Analysis — Part 2: Determination of Consistency of Fresh Concrete (First Revision).
45. Bureau of Indian Standards. IS 3346:1980 – Method of Determination of Thermal Conductivity of Thermal Insulation Materials. New Delhi: BIS. 1980.
46. ASTM International. *ASTM C1585-20: Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes.* ASTM International. 2020.
47. Karaki A, Mohammad M, Masad E, Khraisheh M. Theoretical and computational modeling of thermal properties of lightweight concrete. *Case Studies in Thermal Engineering.* 2021;28:101683.
48. Asadi I, Shafigh P, Hassan ZFBA, Mahyuddin NB. Thermal conductivity of concrete—A review. *Journal of Building Engineering.* 2018;20:81–93.
49. Senthil Kumar K, Gandhimathi R, Baskar K. Assessment of heavy metals in leachate of concrete made with E-waste plastic. *Advances in Civil Engineering Materials.* 2016;5(1):256–262.
50. Pauzi NNM, Jamil M, Hamid R, Abdin AZ, Zain MFM. Influence of spherical and crushed waste cathode-ray tube (CRT) glass on lead (Pb) leaching and mechanical properties of concrete. *Journal of Building Engineering.* 2019;21:365–377.
51. Trivedi SS, Sarangi D, Das BB, Barbhuiya S. Influence of multi-stage processing and mechano-chemical treatments on the hydration and microstructure properties of recycled aggregate concrete. *Construction and Building Materials.* 2023;409:133993, ISSN 0950-0618, <https://doi.org/10.1016/j.conbuildmat.2023.133993>.