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Research article

Experimental investigation on fresh, hardened and durability characteristics of partially replaced E-waste plastic concrete: A sustainable concept with machine learning approaches

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ABSTRACT

The rapid global expansion of e-waste poses significant environmental and health risks, making it crucial to find sustainable uses and mitigate its harmful effects. The significance of this research is to look into the impact of e-waste as a possible substitute for natural coarse aggregates (NCA) on the fresh, hardened and durability characteristics of concrete, alongside machine learning (ML) predictive analysis. Four kinds of concrete mixes were made with produced coarse aggregates as a substitute material for NCA, and substitution levels were calculated as 0 %, 10 %, 15 % and 20 % (by mass of NCA). Compressive and splitting tensile tests evaluated the mechanical properties of e-waste concrete, whereas water permeability and electrical resistivity tests assessed durability to determine the optimal e-waste proportion for construction. The compressive and tensile strengths of e-waste concrete were reduced by 13.41%–25.50 % and 11%–19.26 %, respectively, for replacement levels ranging from 10 % to 20 % at 28 days. The specimens, evaluated at 300 °C, exhibited reductions in compressive strength by 15.26%–30.87 % and tensile strength by 10.52%–19.74 % for e-waste replacement levels of 10%–20 %, respectively. With high coefficient correlation (R^2) values, the linear regression (LR) model predicted mechanical property outcomes more accurately than the random forest (RF) model. The electrical resistivity test showed better results increased range of 239.06 %–478.82 %. The findings of the water permeability test improved when the quantity of e-waste plastic was increased by 15 %. In terms of all the percentage results, the 15 % replacement produced the best results and produced a sustainable construction material.

1. Introduction

In the global construction sectors, concrete is the most frequently employed material. A ubiquitous material, cement concrete is distinguished by its superior compressive strength, longevity, and shape-ability [1]. With meticulous planning, specifications, and manufacturing, this engineered material can generate concrete that exhibits exceptional performance in construction applications. At the turn of the last decade, the production of global cement increased from 1.0 billion tonnes per year to approximately 1.7 billion tonnes per year [2]. 4.6 billion tonnes of cement were produced in 2015, which is more valuable than the population's food

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consumption [3]. The global CO_2 emissions are currently 7 % attributed to cement production. However, this figure is expected to increase to 24 % by 2050 due to the increasing demand for cement in fast-track development initiatives [4]. There are numerous negative consequences associated with cement production, including the loss of biodiversity, excessive energy consumption, environmental degradation, and CO_2 emissions. To mitigate the increasing temperatures that are the result of human-induced greenhouse gas emissions, and the reduction of natural resources, researchers and specialists are perpetually in pursuit of more sustainable and environmentally friendly concrete [5].

In the 1960s, the plastics industry in the world expanded from 15 million metric tonnes to 322 million metric tonnes by the 2000s [6]. The remaining 31 %–90 % of this total is incinerated or disposed of in landfills, with recyclables comprising less than 30 % [7]. This poses health hazards in the long term, considerably degrades the environment, and occupies a significant amount of space. Consequently, there is a significant opportunity to expand secondary sectors that recycle plastic and utilize industrial trash to circumvent these challenges. The most promising applications for these materials are in the field of lightweight or normal-weight concrete, such as aggregate substitution (aggregates comprise 60–75 % of the concrete volume). The annual disposal of vast quantities of plastics in landfills and oceans is a consequence of a severe scarcity of recycling capacity; only 25 % of plastic trash is recycled and repurposed. The global production of plastic waste in 2013 was approximately 0.29 billion tonnes, which resulted in significant pollution concerns [8]. The consequences of electronic waste (e-waste) on human health and ecosystems are catastrophic and are anticipated to aggravate on a global scale. From 2014 to 2019, the quantity of electronic waste that was disposed of increased by 21 %, resulting in a total of 53.6 million tonnes [9]. Bangladesh generates nearly 2.8 million tonnes of electronic waste annually, with an annual expansion rate of 20 % [10]. Television sets account for 0.17 million metric tonnes of e-waste, whereas mobile phones account for 10,540 metric tonnes [11]. It is imperative to recognize and mitigate the adverse environmental consequences of e-waste to address the alarming situation of its proliferation. According to the United States Environmental Protection Agency (EPA) [12], only over 5 % of electronic waste is recycled globally. This equates to an annual increase of approximately 6–10 %.

Coarse aggregate comprises a substantial proportion of the total volume of concrete. Concrete's qualities are significantly influenced by its aggregates, which account for approximately 65–80 % of its volume [13–22]. Due to the scarcity of natural aggregates in their respective countries, numerous nations depend on imports to satisfy their aggregate requirements. The aggregate demand is expected to increase by 59 % by 2025, according to the world aggregate construction market [23]. As a consequence of the accelerated urbanization and development that have resulted in increased natural rock mining, landscapes are being severely degraded and pollution levels are increasing. This has in turn led to substantial infrastructure investment. It is imperative to prioritize the preservation of natural resources and the depletion of basic materials to mitigate the effects of climate change [24].

Consequently, the concrete industry has adopted a variety of natural aggregate alternatives, including refuse products from demolition, plastic, and paper. Numerous studies have investigated the feasibility of incorporating recycled materials into concrete, including plastic, glass, discarded tyres, cardboard, and electrical waste. Therefore, there is an increasing trend to identify alternative materials that can serve as concrete aggregates. Previous research has indicated that the concrete industry has numerous potential applications for recycling materials such as polyester and glassware, which are a global environmental concern due to the high volume of garbage that is sent to landfills [25–36]. The production of plastic is increasing due to its numerous desirable characteristics, such as its resistance to water, impacts, and wear and tear. Zareei, Ameri [37] assert that concrete that incorporates 10–50 percent plastic coarse aggregate produced from e-waste exhibits superior workability and durability, but it exhibits reduced compressive strength and abrasion resistance. Once more, the hardened, microstructural, and durability characteristics of concrete can be enhanced by recycled glass powder and slurry, which in turn contributes to sustainable development and reduces carbon emissions. A study conducted by Gayana and Chandar [38] discovered that the use of iron ore refuse as coarse aggregates can enhance the quality of concrete. In particular, they discovered that the optimum compressive strength was achieved with a 40 % substitution, which implies that this material could be utilized as a sustainable pavement material. A study conducted by Ullah, Qureshi [39] assessed the influence of crushed electronic waste on the functionality of concrete as part of our research on the durability of concrete made from recycled electronic refuse. Plastic garbage was substituted for coarse aggregate in a ratio of 0 %–20 %. The outcomes reflected that the tensile strength increased, while the compressive and flexural strengths decreased as the level of E-waste increased. According to research conducted by Belmokaddem, Mahi [40], the efficacy of concrete can be influenced by plastic trash, such as HDPE and PET. Varying from zero to ten percent by volume, plastic garbage was employed as a substitute for coarse aggregate. The results indicated that a minimum reduction of 35 % in CS and a growth of 21 % in splitting tensile strength (STS) were observed when coarse aggregate was replaced by PET aggregate at a 10 % rate. Additionally, the density of fresh units decreased by 4 %. The hardened capabilities and durability characteristics of EPW concrete have been the subject of previous research. As Harrison [41] has demonstrated, the resistance to sulphate and chloride attacks increases as the fraction of EPW aggregates increases. Tang, Li [42] achieved comparable outcomes by conducting a comparison of the chloride attack and sulphate on traditional and e-waste concrete. Computer-aided tools are indispensable for simulating the intricate behaviour of composite materials and forecasting their overall behaviour based on their constituents. It is possible to reduce the need for costly equipment and save time, effort, and material costs by predicting the characteristics without doing trials. Many published publications have discussed the use of various machine-learning techniques on concrete [43–52]. Dantas, Leite [53] have noted that artificial neural networks (ANN) have enabled the advancement of economic forecasts related to compressive strength and decline. Yuan, Wang [54] used a combination of evolutionary algorithms and ANFIS to develop a hybrid model that accurately predicted the compressive strength of concrete. A genetic algorithm was employed to optimize the thresholds and weights of a back-propagation artificial neural network. A wide range of machine learning algorithms, such as Artificial Neural Networks (ANN), Fuzzy Logic (FL), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), and Genetic Algorithms (GA), were used to forecast the starting and final properties of concrete made with plastic aggregates.

Previous research has explored the implication of various types of plastics (such as PVC, HDPE, and PET bottles) as alternatives for coarse and fine aggregates in concrete, as discussed earlier in the discussion. However, the majority of the study concentrated on mechanical qualities, with very few studies emphasizing the durability features of plastic concrete and none focusing especially on heat test analysis of EPW concrete. This research aims to evaluate the influence of including plastic-based aggregates as a partial replacement for coarse aggregates in concrete. This study aimed to investigate the workability, mechanical properties (compressive strength and tensile strength), and durability properties (thermal exposure, water permeability test, electrical resistivity test) of concrete by adding varying percentages of Portland cement replacement (0–20 %) with natural coarse aggregates. Unlike previous studies, which typically focus on room temperature properties, this research compares the concrete's compressive and splitting tensile strength at elevated temperatures with its performance at room temperature. Additionally, the use of machine learning (ML) techniques—random forest (RF) and linear regression (LR)—to predict the compressive and splitting tensile strength further distinguishes this work. This innovative approach enhances the understanding of the performance and durability of concrete with e-waste aggregates at elevated temperatures while employing predictive ML techniques to reliably forecast mechanical properties. This comprehensive exploration not only broadens the scope of existing literature on e-waste utilization in concrete production but also establishes a new paradigm for future research endeavours aimed at developing eco-friendly construction materials.

2. Materials and experimental setup

2.1. Materials

Ordinary Portland Cement (OPC), the most common type of cement on earth, has several practical uses. The research followed the guidelines laid out in ASTM C150/C150M − 17 [55] and utilized a type I Ordinary Portland Cement (OPC) (CEM I/52.5 N) that was locally collected. Fine aggregates, such as Sylhet sand, and coarse aggregates, such as stone chips, are both used in the concrete mixture. ASTM C144-18 [56] and ASTM C128-12 [57] were utilized to measure the fineness modulus and specific gravity of sand. A transparent technical plastic called acrylonitrile butadiene styrene (ABS) was utilized as electronic trash for this research. Polycarbonate is also a member of this family. Obsolete electronics, such as printers, controllers, keyboards, and computers, from a nearby retailer were obtained. Non-biodegradable plastics from these electronics were utilized to manufacture plastic coarse aggregate (PCA). Ensuring compatibility with conventional concrete formulations, these plastics were processed into a form that resembles the size, shape, and texture of natural coarse aggregate (NCA). Fig. 1 shows a schematic analysis of the whole production procedure. Here plastic aggregates are manufactured from discarded electronics as shown in Fig. 1(a). Gathering the waste, washing it, drying it, and finally shredding or grinding it are all steps in the plastic waste treatment process as depicted in Fig. 1(b). The first step is to use tap water to wash, rinse, and dry the raw plastic E-waste. After that, the raw E-waste was ground or crushed into little pieces using an electric crusher as illustrated in Fig. 1(c). The next step was to screen the ground E-waste for any metal, wire, leather, or other non-plastic materials. In the end, particle shredding was used to create PCA with NCA-sized and -shaped dimensions. The chemical properties of OPC are detailed in Table 1. Table 1 indicates that OPC mostly comprises CaO (62.14 %), SiO_2 (20.70 %), and Al_2O_3 (5.96 %). The alkalinity and dust emission of raw OPC can pose health risks; however, the compounds are not detrimental in their solidified state. CaO is highly alkaline and can irritate the skin and damage the eyes without appropriate protection. Inhalation of SiO_2 in dust form can lead to pulmonary complications (silicosis) over time. While not detrimental, moderate concentrations of Fe_2O_3, MgO, K_2O, Na_2O, and SO_3 might enhance the material's alkalinity and reactivity. It is essential to manage OPC with caution and utilize protective equipment; nevertheless, after it has cured in concrete, it does not present toxicity issues.

The results of several tests were recorded in Table 2 to ascertain the physical properties of plastic coarse aggregate (PCA), fine aggregate (FA), and coarse aggregate (CA). The grading curve of PCA, FA, and CA is shown in Fig. 2, which is based on data gathered from sieve analysis experiments. The gradation curve for aggregates revealed a steep decline in the case of PCA, indicating a larger proportion of bigger particles indicating poor gradation consistency. On the other hand, a gradual curve suggests good gradation consistency with a more even distribution of particle sizes in the case of FA and a sharp drop for larger sizes, levelling off for smaller sizes, reflecting a mix with significantly larger particles showing moderate gradation consistency in the case of CA.

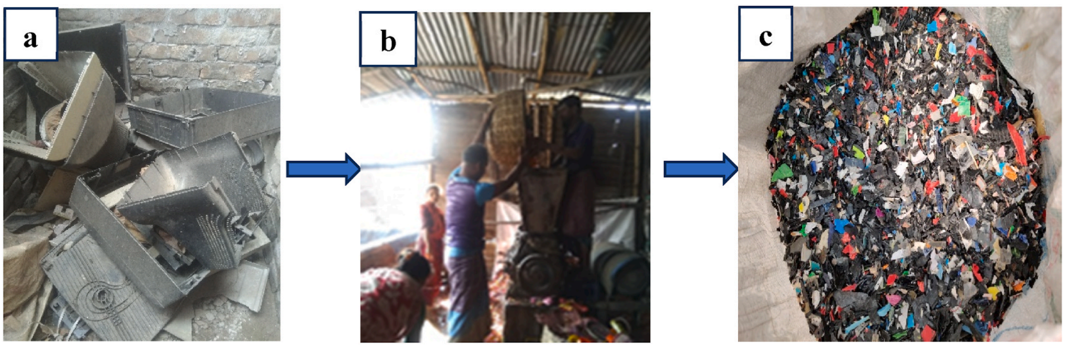

Fig. 1. The manufacturing process of PCA (a) collecting e-waste plastic (b) shredding or grinding (c) ground or crushed into little pieces.

Table 1
Chemical properties of OPC.

Substances	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	K_2O	Na_2O	LOI
OPC (%)	62.14	20.70	5.96	3.34	2.01	3.94	0.46	0.28	1.07

Table 2
Physical properties FA, CA, and PCA.

Materials	Properties	Unit	Value
Fine aggregate	Specific gravity	–	2.60
	Absorption	%	1.37
	Fineness modulus	–	2.65
	Unit weight	kg/m^3	1630.80
Coarse aggregate	Specific gravity	–	2.71
	Absorption	%	1.23
	Fineness modulus	–	7.71
	Unit weight	kg/m^3	1405.13
E-waste plastic as coarse aggregate	Specific gravity	–	1.26
	Fineness modulus	–	5.14

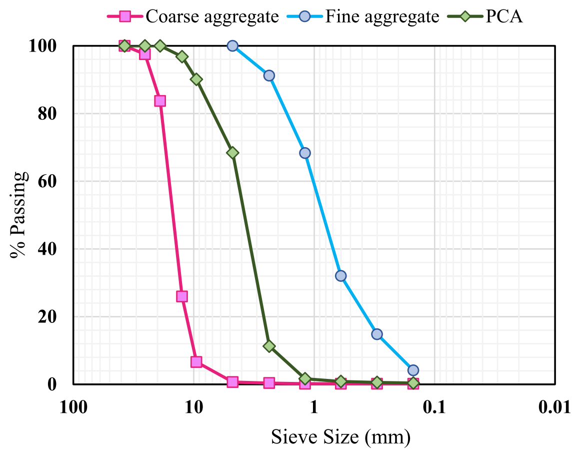

Fig. 2. Gradation curve of PCA, FA and CA.

2.2. Concrete mix proportion

The M20 concrete mixture was used to create five distinct varieties of concrete mixes that included PCA as a partial replacement for coarse aggregate. Cement, sand, and stone chip proportions were 1:1.5:3, with a water-to-cement ratio of 0.45. A range of percentages—0%, 10 %, 15 %, and 20%—of recycled plastic from electronics were incorporated into the coarse aggregate used to mix the concrete. In Table 3 various PCA concrete mix proportions are mentioned. Different combinations were designated as PCA10, PCA15, PCA20, and CM. The names of the mixes were given according to the fractions of plastic coarse aggregate (PCA) used: 10, 15, and 20, with CM standing for the control mix. The incorporation of recycled plastic as a substitute for traditional coarse aggregate not only addresses environmental concerns by reducing plastic waste but also explores the potential of enhancing certain concrete properties. By comparing the performance of these modified mixes to the CM, the study investigates the viability of using PCA in normal-strength concrete, highlighting its implications for durability, mechanical properties, and eco-friendly concrete production. To

Table 3
Concrete mixing ratios in $Kg/m.^3$.

Mix ID	W/C	OPC	Fine aggregate	Coarse aggregate	E-waste plastic	Water
CM	0.45	535	988	1364	0	289
PCA10	0.45	535	988	1228	136	289
PCA15	0.45	535	988	1160	204	289
PCA20	0.45	535	988	1092	272	289

achieve a saturated surface dry condition, coarse aggregates were soaked in water for 24 h, air-dried, and then combined with other materials.

2.3. Experimental procedures

Several experiments were performed to evaluate the samples' fresh, hardened, and durability properties. Following the guidelines laid out by ASTM C143 [56], a slump examination was performed to ascertain the samples' workability as in Fig. 3(a). After positioning the cone adjacent to the slumped concrete, the slump was determined by extending the temping rod over the cone to encompass the depressed concrete area. Compressive and splitting tensile strength tests were used to measure the mechanical properties of concrete that contained plastic aggregate. Standard cylindrical samples were evaluated for compressive and splitting tensile strengths according to ASTM C39/C39M − 12 [58] and ASTM C496/C496M − 17 [59], in Fig. 3(b) and (c) respectively, following a 7-day and a 28-day curing time, with dimensions of 100 mm in diameter and 200 mm in height, respectively. Water permeability and electrical resistivity tests were performed to explore the durability qualities in Fig. 3(d) and (e). The procedure for the electrical resistivity test followed the guidelines laid out by ASTM C1760-12 [60]. As per the standard BS EN-12390-8 [61], cylindrical specimens measuring 100 mm × 200 mm were used for the water permeability test. In addition, the analysis of thermal exposure was evaluated.

2.4. Machine learning methodologies

A comprehensive comparison model was developed to predict the mechanical properties of concrete including e-plastic waste aggregate following the discovery of the machine learning (ML) approach. The inquiry employed linear regression (LR) and random forest (RF) for analysis. The model's accuracy is measured using Equations (1)–(3), which consider numerous metrics. Fig. 4 depicts the framework employed for the predictive evaluation of the model.

$$\text{Mean Square Error, MSE} = \frac{1}{n}\sum_{i=1}^{n}(Y - Y_i)^2 \tag{1}$$

$$\textit{Mean Absolute Error}, MAE = \frac{1}{n}\sum_{i=1}^{n}|Y - Y_i|^2 \tag{2}$$

$$\textit{Root Mean Square Error}, RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y - Y_i)^2} \tag{3}$$

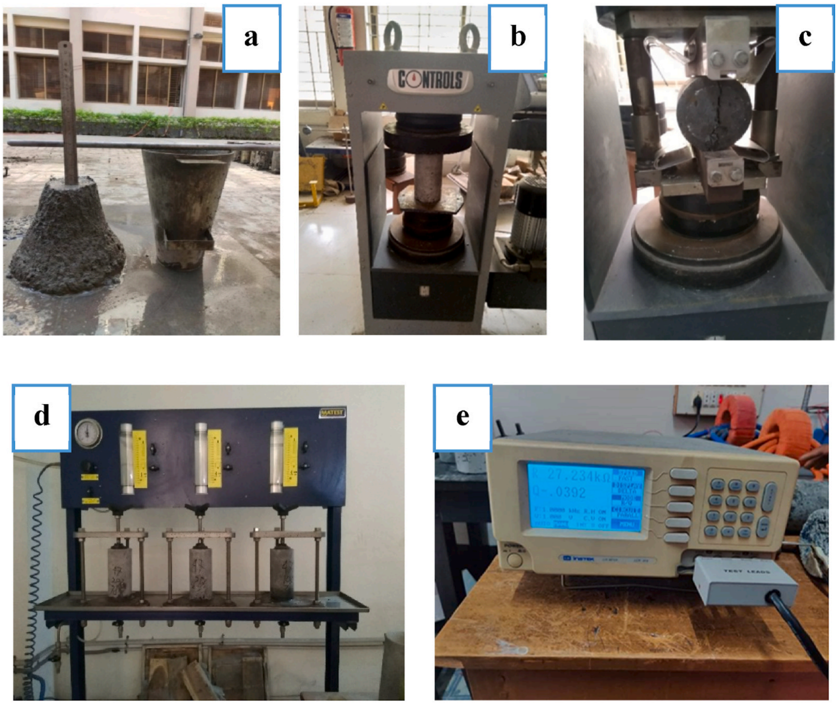

Fig. 3. Instrument setup of (a) slump test (b) compressive strength (c) splitting tensile strength (d) water permeability and (e) electrical resistivity test.

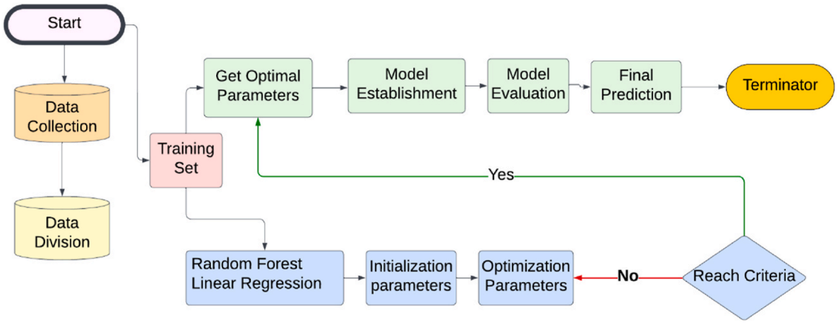

Fig. 4. The proposed models' flowchart.

Random Forest is a kind of decision tree that provides a more refined representation for predicting outcomes. It was developed by Breiman in 2001 by combining regression and classification trees with bagging [62]. The Random Forest algorithm utilises a significant quantity of decision trees that are generated randomly. These trees are then adjusted using information obtained from different subsets of the training data. The Random Forest algorithm functions as an estimator. It mitigates overfitting by employing the median of the decision trees to get more precise forecasts. It is a form of ensemble learning that uses trees that adhere to the boosting technique [63]. This technique seeks to enhance the current situation by integrating new learners into the system, where each new group of learners is paired with the discarded data from the prior group of learners. Linear regression (LR) is a widely used statistical method for examining the influence on parameters that function as inputs as well as outputs. Its widespread integration into several machine learning packages has recently led to its increasing prominence as a machine learning technique. Galton, throughout his investigation, introduced the concept of regression to the mean [64]. Galton introduced the term "regression" to explain the pattern of extreme data points to move closer to the average value over a period. The aim of linear regression (LR) is to identify the most appropriate line in a dataset by limiting the discrepancy between the recorded and predicted outcomes.

The linear model's capacity for interpretability further enhances its appeal, enabling a straightforward understanding of how each input factor contributes to the predicted mechanical properties of concrete mixtures. While RF excels in handling complex, nonlinear interactions, its relative complexity can sometimes obscure insights into variable importance and relationships. In contrast, the LR model's simplicity and clarity make it particularly effective for scenarios where relationships are predominantly linear, as is often the case in concrete properties influenced by well-defined material proportions. In specific contexts, the methodologies employed in this study not only provide enhanced predictive accuracy but also facilitate a more nuanced understanding of the underlying mechanics, especially when integrating innovative materials like e-waste aggregates.

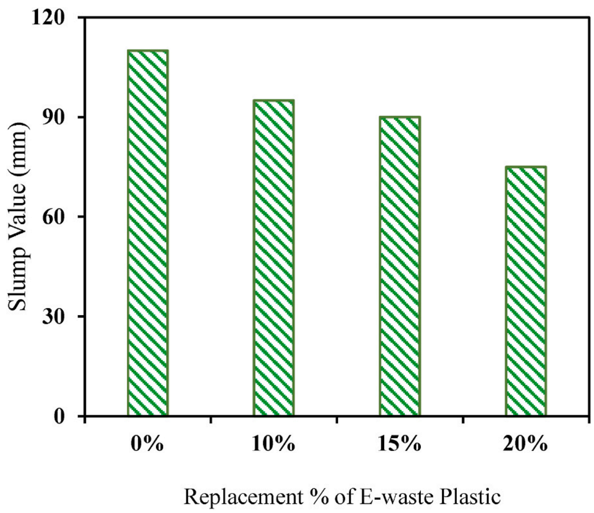

Fig. 5. Cone slump test data.

3. Results and discussion

3.1. Fresh properties

3.1.1. Slump test

The feasibility of PCA was assessed using a slump test, and Fig. 5 illustrates the outcomes for several concrete mixtures. According to Mohammed, Mohammed [65], the slump test is not effective in assessing the workability of concrete when a large amount of PVC aggregate is used as a replacement for sand. During the initial casting phase, the slump test is employed to assess the workability or flowability of laboratory-prepared concrete mixtures. The test findings showed that when the concentration of PCA grew in the concrete mixture, the slump value decreased. The test results indicate that the slump value of the control concrete is 110 mm. The workability of the EPW concrete mix was diminished by 15.79 % when 10 % of the natural coarse aggregate was replaced with PCA. Additionally, it was seen that for every 5 % addition in the replacement percentages of PCA, there was an average loss of 12.77 % in the slump value of the mix. The PCA 15 mix achieved a slump value of 90 mm, indicating a workability range classified as medium according to ASTM C143 [56].

There is evidence to suggest that the slump values decrease as the percentage of e-waste aggregate increases. Plastic coarse aggregates (PCA) feature uneven forms and rough surfaces, unlike natural aggregates. This irregularity increases particle surface area and friction, limiting concrete mix flow. As a result, the slump test, which measures concrete mixing, placement, and compatibility, was reduced. The rough surface and angular forms of plastic aggregates increase inter-particle friction. Natural aggregates reduce particle friction in concrete mixes, making them more fluid. Plastic particles have a 'locking' effect due to increased friction, reducing slump values. Due to their surface properties, plastic particles absorb less water than natural aggregates, leaving less free water in the mix to aid fluidity. This and higher friction stiffen the mix, reducing the slump. Thus, increasing e-waste aggregate reduces slump because the rough surface roughness and irregular form of the plastic particles disturb the concrete mix's flow, limiting workability.

Diverse investigations yield comparable findings. The slump of the concrete matrix showed varying results when CA was directly replaced with plastic [66]. Madandoust, Ranjbar [67] discovered that when EPS was used as a substitute for CA, there was a rise in slump values of up to 40 %. However, when the replacement ratio was increased to 80 %, the slump values fell by 16 % [66]. A study conducted by Mohammed, Mohammed [65] discovered that the slump of concrete remains almost the same when up to 30 % of coarse aggregate is replaced with PVC aggregate, compared to concrete with fine aggregate replacement. Nevertheless, there is a significant decrease in slump when 45 % of the coarse aggregate is substituted with PVC aggregate. By substituting a portion of the coarse aggregate with PVC granules, which primarily consist of a high proportion of tiny particles or powder, the overall surface area to weight ratio is raised. Consequently, it becomes necessary to increase the water content to adequately surround these particles. Due to the uniform water/cement ratio in all mixtures, the effective water/cement ratio will be low, resulting in a decrease in workability. Akçaözoğlu, Akçaözoğlu [68] conducted a similar process on concrete using shredded PET waste aggregate.

In contrast, a different result was observed: the comfort of working with RPAC significantly improved as the substitution amount of PCA increased, when contrasted to the control mixture. The rise in slump test outcomes with greater proportions of substitution can be ascribed to the utilization of impermeable plastic aggregate in the concrete mixture [69].

3.2. Mechanical properties

3.2.1. Compressive strength test

Fig. 6 displays The concrete's compressive strength test outcomes in cylinders after 7 and 28 days. The data indicates that the

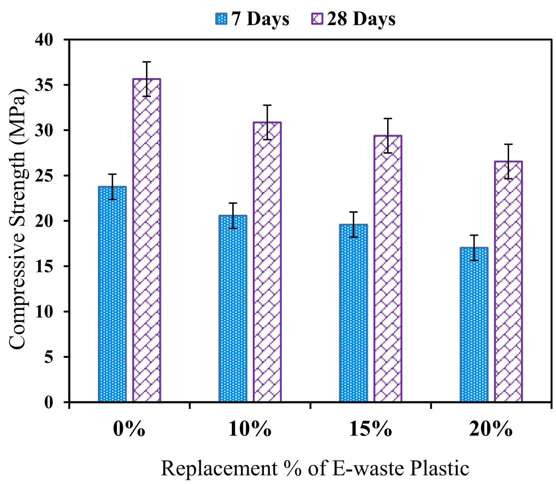

Fig. 6. Compressive strengths of cylindrical specimens at 7 days and 28 days.

compressive strengths after 7 and 28 days are diminishing as the percentage of e-waste increases. The substitution of 10 % of NCA resulted in a reduction of 13.42 % in compressive strength. Each 5 % substitution of NCA resulted in a reduction of compressive strength of 17.55 % and 28.32 % after 7 days. After a curing time of 28 days, it is seen that The compressive strength of the control mix is determined as 36.64 MPa, which is 33.33 % higher than the compressive strength of the 7-day mix with 0 % replacement of NCA. The compressive strength fell by 13.41 %, 17.54 %, and 25.50 % after 28 days when replaced with 10 %, 15 %, and 20 % respectively.

Prior studies have indicated that the compressive strength experienced a decrease ranging from 33 % to 97 % when both coarse aggregate (CA) and fine aggregate (FA) were substituted with plastic at various levels of replacement (ranging from 25 % to 100 %). Most investigations have linked the decrease in strength to the weak interfacial transition zone caused by inadequate interaction among the plastic particulates and cement paste [70]. This hinders the cement hydrated surrounding the plastic particulates, resulting in reduced bonding [71,72].

The poorer chemical bonding between e-waste plastic and cement compared to the bonding between cement and stone chips is the explanation behind this. The planar morphology of electronic waste aggregates leads to a diminished bond between the cement paste and the electronic waste aggregates, leading to a reduction in compressive strength. Moreover, due to its resistance, plastic can impede the necessary amount of water from entering the specimens while they are being cured. A further factor contributing to the decrease in strength may be an abundance of water in the binder as a result of its low water retention capacity. Plastic aggregates generally have a lower specific gravity compared to natural aggregates [73]. Consequently, the reduced weight of these materials can result in a decrease in the overall density of the concrete mixture, thus impacting its structural integrity. The earlier research has also observed and documented a decrease in compressive strength [74,75].

3.2.1.1. Machine learning methodologies for compressive strength. Fig. 7 displays a boxplot that represents the anticipated and actual correlation. Boxplots are commonly used to display statistical distributions. They present a concise summary of the data by showing five key variables: the minimum, first quartile, median, third quartile, and maximum. The studies report individual statistics such as the mean, interquartile range, median, lowest value, and maximum value. Considering the median margins displayed in the respective boxes, it can be inferred that there was likely little difference among the different groups in each dataset. The range of these findings was relatively small, as indicated by both the interquartile range and the length of the box. None of the offered models, including RF and LR, had any unexpected outcomes.

The reliability of predictions made by the RF and LR approaches is demonstrated by their agreement with experimental results, as depicted in Fig. 8. The RF model had a proportional connection coefficient of 0.9862, while the LR model had a coefficient of 0.99715. The linear regression (LR) model produced MSE, MAE, and RMSE values of 0.1, 0.26, and 0.315, respectively. On the other hand, the random forest (RF) model generated MSE, MAE, and RMSE values of 0.74, 0.726, and 0.85, respectively. This demonstrates that the LR model is quite precise in predicting results. Abd and Abd [76] observed that when conducting a compressive strength test on light-weight foamed concrete, the application of support vector machine (SVM) analysis yielded a highly similar coefficient of regression ($R^2 = 0.987$).

3.2.2. Splitting tensile strength

Fig. 9 illustrates the range of splitting tensile strength (STS) results for PAC blends with different concentrations of PCA. The data illustrates that the tensile strengths of all samples, irrespective of the extent of partial substitution with E-W polymers, exhibit an increase after 28 days in comparison to the values observed after 7 days. The split tensile strength of the control mix was determined to be 3.27 MPa after a period of 28 days. When comparing different mixtures of concrete, the ones with 10 %, 15 %, and 20 % pulverized

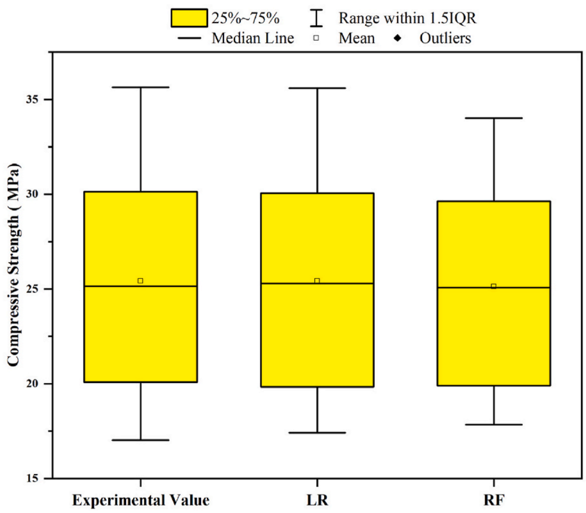

Fig. 7. Variance of compressive strength data shown via box plot.

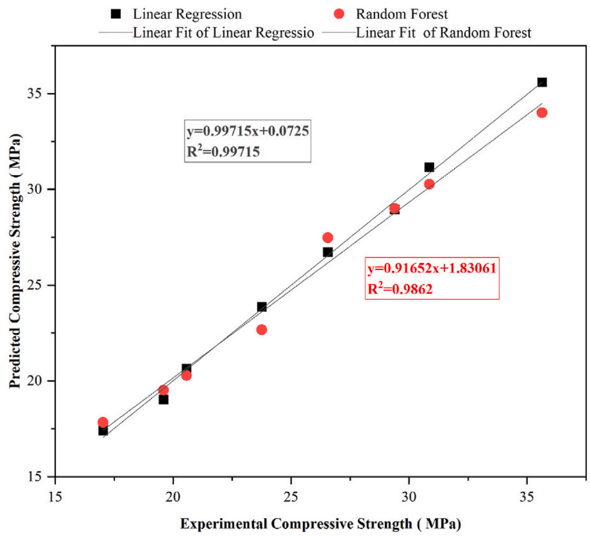

Fig. 8. Association among compressive strength experimental and anticipated findings.

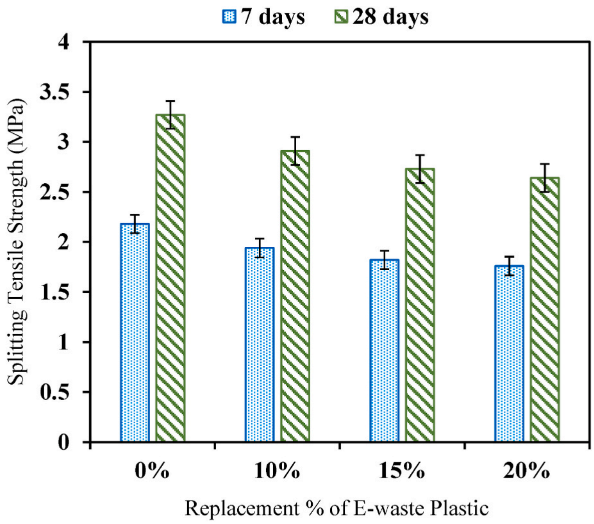

Fig. 9. Splitting Tensile strength of cylindrical specimens at 7 days and 28 days.

coal ash (PCA) replacing natural coarse aggregates (NCA) exhibited STS values of 2.91 MPa, 2.73 MPa, and 2.64 MPa, respectively. The highest decrease of 19.26 % was recorded when the replacement level was 20 %, while the lowest decrease of 11.01 % was reported when the replacement level was 10 %, compared to the control mix. Many previous researchers have observed a deterioration in the STS test results when NCA is replaced by plastic aggregates. According to the research conducted by Mohammed, Mohammed [65], replacing coarse aggregate with PVC aggregate results in a lesser reduction in splitting tensile strength (63 % for 85 % aggregate replacement) compared to the reduction in compressive strength. Fig. 9 illustrates that the drop in splitting tensile strength at 28 days is smaller than the reduction in compressive strength at the same curing days. The possible cause for this phenomenon is that the interfacial transition zone (ITZ) surrounding plastic aggregates may exhibit lower strength and higher porosity in comparison to the ITZ surrounding natural aggregates. The reduced ITZ weakens the material's ability to withstand tensile stresses, which is critical for maintaining its tensile strength.

The decrease in splitting tensile strength seen in this investigation, with 50 % PVC aggregate concentration, is 24.2 %, which is higher than the 22.38 % found in the study conducted by Haghighatnejad, Mousavi [75] with 20 % PVC aggregate content. Prior research has demonstrated that substituting CA with varying quantities of other plastic particles, ranging from 15 % to 80 %, resulted in a significant decrease in the splitting tensile strength of concrete in the range of 47 %–72 % [77–79]. The cause of this can be linked to the characteristics of flakey particles combined with a thick and poorly developed transition zone. Due to their flaky and uneven forms, PVC particles create voids and disrupt mix compactness, making the matrix less cohesive. These flaws degrade the internal structure, reducing tensile strength when external forces are applied. Additionally, PVC particles provide a thicker and less developed interfacial transition zone (ITZ), where aggregate and cement paste bond. The concrete's mechanical qualities depend on the ITZ, and a badly constructed zone might weaken the chain. The rough, flaky particles increase this thickness and weaken the connection, making the concrete more tensile. This reduced transition zone and the disruptive shape of PVC particles cause a greater tensile strength drop than in prior tests with lower PVC concentrations.

The decrease in the splitting tensile strength of EPW concrete can be attributed to the inadequate bonding between PFA and cement paste as a result of the polished surface. A comparable outcome was documented by Zhou, Slater [80]. In addition, PCA has lesser unit weight, density, stiffness, and resilience when contrasted to NCA. Consequently, it forms a region of intense stress that encourages the spread of deterioration, which is likewise recognized as the underlying reason for the decrease in strength [81]. However, some researchers argued that this decrease was caused by a decrease in the link between plastic particulates and cement paste. This was due to the presence of water accumulated on the surface of the particulates of plastic and a decrease in the modulus of elasticity of the plastic particles [82].

3.2.2.1. Machine learning methodologies for splitting tensile strength. Fig. 10 presents a box diagram illustrating the distribution of splitting tensile strength, which is similar to the method used to explain the distribution of compressive strength. The interquartile ranges for the strength values were 1.76 MPa–2.18 MPa after 7 days and 2.64 MPa–3.27 MPa after 28 days, indicating a small degree of variation over time. The medians of all the data sets are tightly confined within their respective boxes, suggesting a negligible occurrence of outliers or aberrant distributions.

Fig. 11 illustrates the accuracy of the RF and LR projections by comparing them with experimental data. The linearity coefficients for the RF and LR models were 0.98 and 0.9979, respectively. The Linear Regression (LR) technique achieved a Mean Squared Error (MSE) of 0.000584, a Mean Absolute Error (MAE) of 0.0225, and a Root Mean Squared Error (RMSE) of 0.023. The Random Forest (RF) approach yielded values of 0.003953, 0.053, and 0.062. Within our current investigation, Li, Yu [83], used shapley additive explanations (SHAP) analysis to examine the fiber-reinforced foam concrete in a splitting tensile strength test. The results showed a regression coefficient that was statistically pretty equivalent.

3.3. *Durability properties*

3.3.1. *Water permeability test*

Fig. 12 illustrates the water penetration depth of all specimens after 7 and 28 days of cure. Based on the experimental findings, the mixture that had 10 % and 20 % replacement with PCA exhibited water penetration values of 17 mm and 13 mm after 28 days. Both PCA 10 and PCA 20 exhibit values that are lower than the 7-day penetration depth. The water infiltration rate of PCA 15 exhibited a decrease of 39.28 % and 45 % in comparison to the reference mixture CM after 7 and 28 days of curing, respectively. Nevertheless, all the concrete examples that included PCA exhibited a reduced level of water permeability in comparison to the control specimens. The mixture, which contained no e-plastic aggregate, displayed a water penetration value of 28 mm and showed a completely distinct behaviour. It proposed that the quality of the concrete might be subpar. The PCA 10 and PCA 20 values exhibited a minor deviation from the permissible range of 25 mm penetration.

Fig. 13 illustrates the coefficient permeability values for various percentages of NCA substitutions. The permeability coefficient progressively increases with time for all replacement percentages, suggesting that the duration of the curing process has a substantial impact on the material's permeability. The 15 % replacement displays the lowest permeability for both 7-day and 28-day curing periods, suggesting it may be the most effective balance for reducing water penetration. The permeability coefficient for PCA10 and PCA20 at 7 days of curing is 24.8 % and 58.4 % higher, respectively, compared to the control mixture. In contrast, the permeability

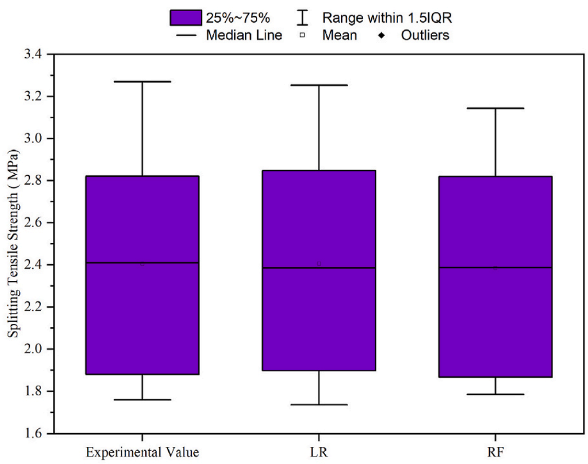

Fig. 10. The variance of splitting tensile strength data is shown via a box plot.

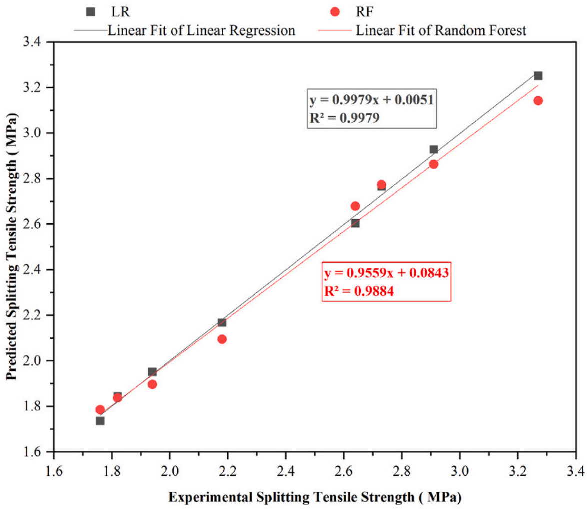

Fig. 11. Association among splitting tensile strength experimental and anticipated findings.

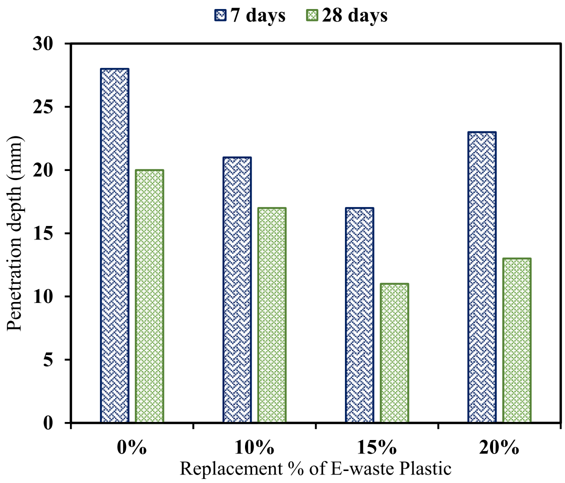

Fig. 12. Penetration depth analysis at 7 and 28 days.

coefficient decreased by 20.7 % for PCA10 compared to the control mix but increased by 18.7 % for PCA20 compared to CM at 28 days. The data indicates that PCA 15 has lower values compared to the other mixes after both 7 and 28 days of curing. Specifically, the reduction is 19.2 % after 7 days and 32.1 % after 28 days. Conversely, when 20 % of the material is replaced with e-waste plastic aggregates, the permeability values are the highest, particularly after 28 days. This suggests that using higher percentages of e-waste plastic aggregates may undermine the impermeability of the material.

In their study, Yücel, Dutkiewicz [84] found that including waste ballast aggregate in concrete mixtures enhanced both the mechanical and durability properties. This resulted in a significant lessen in water penetration, with reductions of 23.8 % and 26.3 % observed after 7 and 28 days, respectively. This circumstance may be explained by observing that the waste ballast possesses a larger density than the crushed stone [84]. Similar results can be seen in other research. During a distinct investigation, the infiltration of water through the concrete during compression was most significant for the control PAC. Subsequently, the PAC was accompanied by PET aggregation exposed to $Ca(ClO)_2$ and H_2O_2. The rate of water penetration was reduced by 1.5 % for PAC with H_2O_2 and by 6.61 % for PAC with $Ca(ClO)_2$, compared to the control mix. The use of chemicals to treat PET aggregates resulted in a decline in the permeability of the concrete. As the spaces between particulates become smaller, the number of porosity reduces, resulting in a more fragmented and inefficient pore system for fluid movement. This leads to a drop in permeability [85].

E-waste plastic aggregates have diminished porosity and decreased water absorption relative to natural aggregates. Consequently, they generate fewer conduits for water flow within the concrete structure, especially at elevated replacement levels. This may affect internal moisture dynamics, potentially diminishing water flow and impacting the concrete’s overall permeability and durability.

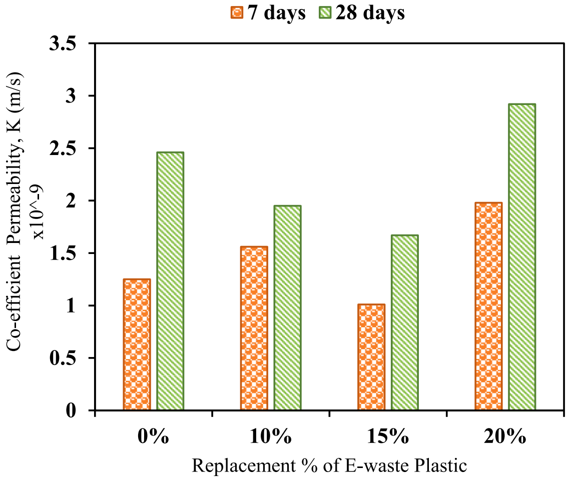

Fig. 13. Water Permeability Test Results Comparison of Concrete after 7 days and 28 days.

3.3.2. Electrical resistivity test

Fig. 14 depicts the electrical resistivity of different substitutions of NCA during the 7- and 28-day curing periods. The figure demonstrates that the control mixture (CM) had the lowest value among all the mixtures, placing it in the high-level resistivity as per ASTM C1760-12. Higher percentages of e-waste plastic replacement result in an increase in electrical resistance. This pattern remains constant across both a 7-day and 28-day period. After 7 days, PCA-10 exhibited a resistance value of 15.98 Ω-m, which increased to 28.09 Ω-m after 28 days. The resistivity of the PCA-15 mix was 21.4 Ω-m at 7 days and 38.03 Ω-m at 28 days, indicating an almost moderate level of resistivity.

The resistivity values increase at 28 days compared to 7 days for all replacement levels due to the ongoing hydration process and probable enhancement in the concrete's microstructure over time. The resistivity increases by 239.06 %, 354.06 %, and 478.87 % when the coarse aggregate is replaced with 10 %, 15 %, and 20 % accordingly, after 7 days. Stone, being composed of clay, has the ability to absorb water and conduct electricity. However, plastic is an insulator when it comes to electricity. Therefore, the ability to resist grows. The resistivity at 28 days of curing shows a rising rate of 276.6 %, 75.8 %, 77.7 %, and 146.0 % sequentially compared to the resistivity at 7 days. After a curing phase of 28 days, the results demonstrate improved performance due to a more effective hydration reaction compared to the 7 days.

Following ASTM C1760 [86], the electrical resistivity test showed that the PCA-20 mix demonstrated outstanding durability among all other mixes, falling within the moderate range. The resistivity of the PCA-20 mix was 27.28 KΩ-m after 7 days, and it increased to 67.09 Ω-m after 28 days. The integration of PCA into the concrete matrix greatly reduced the paths for ion movement, resulting in a highly condensed matrix. The durability of the NCA was improved when plastic aggregates (PCA) were used instead of the control mix.

Previous research indicates that self-consolidating concrete, which is made using recycled aggregates and blended cement, can maintain its electrical resistivity. Specifically, it was observed that using 50 % coarse reused concrete aggregates (CrRCA) and 100 % fine reused concrete aggregates (FnRCA) resulted in higher electrical resistivity compared to the control self-consolidating concrete mixture, regardless of the curing period [87]. According to Sasanipour and Aslani [88], the electrical resistivity of SCC mixes lessened as the amount of recycled coarse aggregate replacement increased relative to the reference mix. The study by Sasanipour and Aslani [88] indicates that replacing more than 25 % of the coarse recycled concrete aggregates (RCAs) has a substantial impact on the durability features of self-compacting concrete, such as electrical resistivity and resistance to chloride ions. Various factors influence the electrical resistivity of concrete. Concrete that has a higher level of porosity often exhibits a lower electrical resistance due to the presence of pores that allow for the passage of electric current [89]. The electrical resistivity of concrete reduces as the moisture content increases due to the conductivity of water [90].

3.4. Thermal exposure analysis

The primary drawback of utilising plastic as an aggregate in concrete is its limited fire resistance and its propensity to ignite quickly. The mechanical performance of EPW concrete and its durability qualities were tested to assess the viability of using PCA in concrete. Measuring the fire resistance of structures requires considering the impact of high temperatures on the compressive strength of building materials [91,92]. Due to plastic's flammability, there is a potential risk of fire accidents when employing plastic with concrete. The specimens were subjected to oven drying at a temperature of 300 °C for 1 h. The reason for this is that subjecting the plastic to temperatures beyond 300 °C can result in substantial breakdown, which in turn leads to notable alterations in both the structure and chemistry of the material. Once again, the testing conditions and findings are guaranteed to be consistent and reliable.

The data from Figs. 15 and 16 demonstrate a decline in both compressive strength and splitting tensile strength. Fig. 15(a)

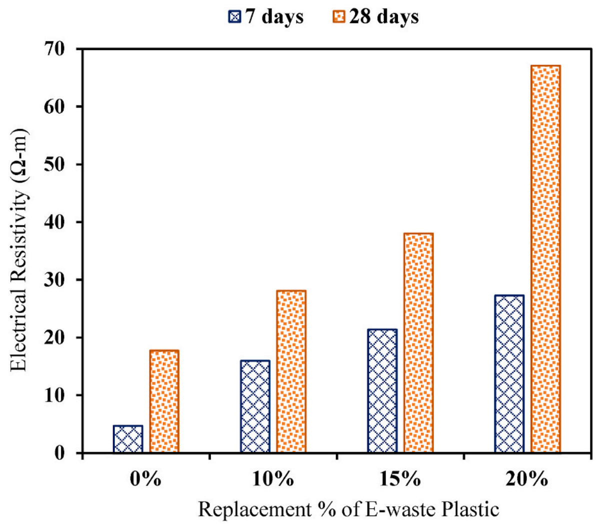

Fig. 14. Electrical resistivity of replacement percentages of coarse aggregate by e-waste plastic before vs after heat treatment at 7 and 28 days.

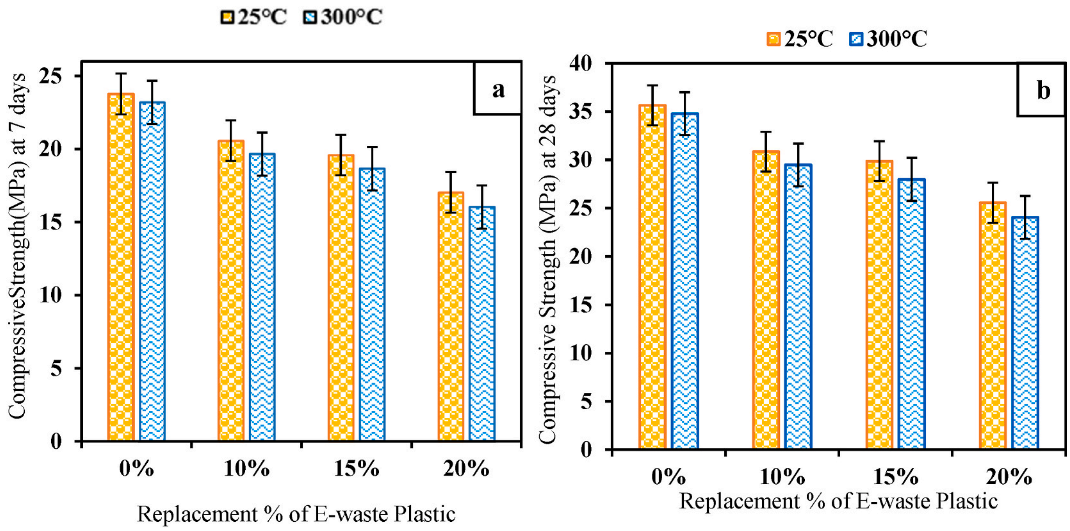

Fig. 15. Compressive strength before and after heat treatment at (a) 7 days and (b) 28 days.

illustrates a reduction in compressive strength of 15.29 %, 19.55 %, and 30.99 % at 300 °C when compared to the control mixture. Fig. 15(b) shows a lesser reduction in compressive strength at 28 days compared to 7 days. Fig. 16(a) and (b) illustrate a reduction in tensile strength. The findings indicate a consistent and uninterrupted increase in tensile strength over a period of time, regardless of the amount of e-waste plastic used as a substitute. More precisely, there is a calculated 50 % improvement observed between the 7th and 28th day. As the plastic inner side of the specimen melts, it constricts the air pores. On one side, it exhibits poor adhesion with concrete due to the melting of plastic, while on the other side, it decreases the porosity. Given that the strength drop remains rather constant, it may be concluded that electronic waste concrete is capable of withstanding fire. The process of pore water crystallization can be expedited by low temperatures, resulting in an accelerated deterioration of concrete due to its heterogeneous nature. Low temperatures can accelerate the crystallization of pore water, which in turn can speed up concrete rupture owing to the homogeneity of the material [93]. Prior research has also discovered that when the proportion of plastic waste aggregate rises, the heat generated during the chemical reaction of concrete formation may increase. This increase in heat might potentially result in a reduction in both the compressive strength and split tensile strength of the concrete [94]. Bellary [95] found that including waste polyethylene terephthalate (PET) in concrete as a partial replacement for aggregates leads to enhanced compressive strength and flexural strength measurements after subjecting the samples to heat treatment for 7 and 28 days. Ullah, Qureshi [39] noted that about 21%–26 % compressive strength reduction has been reported at 150 °C, while approximately 39 % strength reduction has occurred at 300 °C. J. R. Correia, Lima [96] found that compressive strength degradation increases when natural aggregates (NAs) are replaced with pre-wetted aggregates (PWAs). The average compressive strength of CPWA is significantly reduced (0.51 of residual compressive strength) when subjected to

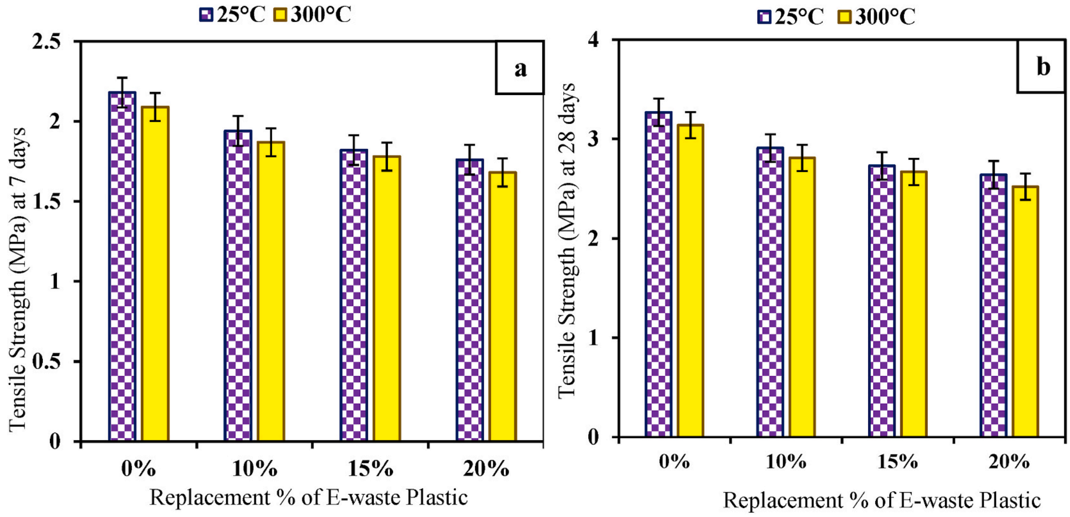

Fig. 16. Tensile strength before and after heat treatment at (a) 7 days and (b) 28 days.

a temperature of 600 °C. The cause or explanation for The increase in porosity resulting from the thermal decomposition of PWAs is anticipated to cause a decrease in compressive strength. However, this negative effect is partially offset by the improved ability of the voids formed to accommodate thermal expansions. Moreover, this increased porosity facilitates the release of trapped gases, hence diminishing the accumulation of internal pressures.

4. Conclusion

Based on the findings of this thesis, the following conclusions are summarized.

- The compressive strengths of e-waste concrete reduced in the range of 13.43%–28.32 % and 13.41%–25.50 % respectively in 7 days and 28 days with the replacement percentage of 10 %–20 % as the texture of e-waste plastic is smooth and creates a poor adhesion to concrete.
- The tensile strength results revealed that the tensile strengths of e-waste concrete reduced in the range of 11.01%–19.06 % and 11%–19.26 % respectively in 7 days and 28 days with the replacement percentage of 10 %–20 %.
- The compressive strength of e-waste concrete, when mixed with various amounts of plastic, decreased by 2.39–6.30 % after 28 days at 300 °C compared to ambient temperature (25 °C).
- Following heat treatment at 300 °C, the splitting tensile strength of e-waste concrete decreased by 2.20%–4.54 % at 7 days and 2.14%–4.44 % at 28 days, compared to ambient temperature, which is lower than the reduction in compressive strength.
- In the electrical resistivity, 20 % E-W plastic concrete showed the best result as the lowest electricity passed through the mix compared with the other proportions. An increasing rate of durability in E-W plastic concrete was measured at 7 and 28 days for the mixes. Hence, 20 % replacement of coarse aggregate by E-W is optimum in this regard.
- In the WPT, the permeability of the 15 % mix was lower than the other mixes at 7 days and 28 days. Hence, a 15 % mix was found as the optimum.
- The linear regression (LR) model consistently outperformed the random forest (RF) model in both compressive and tensile tests, demonstrating superior proportional connection coefficients and lower error metrics.
- After studying several durability perspectives, it has been determined that replacing 15 % of the coarse aggregate with E-waste plastic concrete is the most optimal option.

In addition to assessing the immediate mechanical and durability properties of concrete with e-waste aggregates, it's vital to examine the long-term performance and challenges in construction. Factors such as environmental exposure, stress conditions, and the diverse composition of e-waste can affect durability and overall performance. While initial findings suggest enhanced electrical resistivity and reduced water permeability, further research is necessary to understand how e-waste concrete behaves over time under different weather and load conditions. Key challenges include ensuring consistent quality, addressing variability, managing aging effects, and tackling practical issues in handling, mixing, and placement to achieve optimal performance.

CRediT authorship contribution statement

Md. Hamidul Islam: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Zannatun Noor Prova:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Md. Habibur Rahman Sobuz:** Writing – review & editing, Writing – original draft, Validation, Investigation, Formal analysis, Data curation. **Nusrat Jahan Nijum:** Writing – review & editing, Writing – original draft, Validation, Formal analysis. **Fahim Shahriyar Aditto:** Writing – review & editing, Writing – original draft, Validation, Formal analysis.

Ethical consideration

We have reviewed Ethics in Publishing as well as Heliyon's Ethics and Editorial Policies for this research.

Data and code availability statement

Data will be made available on request. For requesting data, please write to the corresponding author.

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Declaration of competing 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.

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