Article

A Sustainable Integrated Solution from waste to Civil Construction

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Abstract

Solid waste generation typically consists of human activities, which is generalized by the term Municipal Solid Waste (MSW) that covers household and commercial refuse, consisting of degradable (paper, food waste), partially degradable (wood, and sludge), and non-degradable materials (leather, plastics, glass) MSW. If not disposed of properly, this can cause various environmental, social, and economic problems. First-world countries adopt the Municipal Solid Waste System (MSWM), while developing countries like Pakistan still follow a Linear Waste Management approach by dumping waste at landfill sites without classification or recovery for reuse. This approach differs from MSWM adopted by developed countries, which classifies, separate and processes most of the waste for reuse while dumping only a fraction of it at landfills. With a growing population in Pakistan and less land to go around, the need to study the possibilities arises. This study is designed to investigate local processing options such as using plastic, and reclaimed as-phalt and building material for tuff tiles which result in 29.25 percent gain in compressive strength from reference cement-aggregate tuff tile, while using 15% replacement of coarse aggregate, e-waste in concrete showed 6.4% decrease in strength but 10% decrease in weight from reference cylinder which open window for light weight and earthquake resistant construction, using paper & cardboard slurry with recovered structural elements for concrete production the strength decreases but it can be used in non-load bearing elements; Machine Learning approach was develop between all 25 experimented tested mixes means 75 samples. These were adopted at the campus level by a smart automatic bin system complemented by a mobile application for achieving a Zero Waste Campus, allowing for efficient collection of waste, leaving the system with a possibility to be scaled up for local or national level.

Keywords: Municipal Solid Waste, Zero Waste, Recycling, Closed Loop System.

1. Introduction

Waste generation is a serious sustainability concern, especially in developing countries with a rising population, such as in Pakistan, where the population is projected to reach 9.8 billion by 2050 [1]. Increase in urbanization, industrialization, and poor waste systems also makes this issue more complex [2]. This results in weak living conditions, polluting air and water with solid waste, a byproduct of human activity consisting of both biodegradable and non-biodegradable waste [3]. Requiring an effective implementation of the 5R approach, which is reduce, reuse, recycle, recover, and refuse.

The lack of recycling facilities to address Municipal Solid Waste (MSW) has aggravated the situation [4]. Peshawar, with a population of 4.3 million produce approximately 2208 tons of waste materials each day, with no proper segregation and storage facilities by Water & Sanitation Services Peshawar (WSSP) and small individual firms with only 1/5th of the waste collected [5],[6],[7]. Between 2014 and 2018, the waste was 580 tons to 1016 tons. Moreover, the Peshawar Cantonment Board earns an additional 60 tons of rubbish every day [8]. The major method of disposal is landfill, which has been neglected in such locations as Shamshatto and Chowa Gujjar Gari, Peshawar, which causes environmental hazards [4]. Much of this waste can be used for building materials.

H. Yun et al. (2007) revealed that a 5 percent paper-cement mixture attained 34 MPa compressive strength, in which the water-binder ratio did not have much influence [9]. Fuller (2006) observed that it had high ductility with a higher content of Young's modulus [10]. Ghani et al. (2008) have found that the incorporation of wastepaper (5-15 percent) decreased the strength, though 5 percent has shown better results as compared to the control [11]. The relevant addition of paper cellulose also enhanced thermal insulation and decreased density [12]. The researchers concluded that 5-10 percent pulp replacement with paper strengthened and worked better, but more significantly increased both [13].

Electronic waste (EW) contains toxic substances such as lead, cadmium, mercury, and Polychlorinated biphenyls (PCBs), which are utilized in electronic parts [14]. With development, the electronic waste has increased to 21 to 51 million tons per year [15]. The sustainable solution is the use of EW to partially replace coarse aggregates in concrete, which will decrease landfill pressure and create lightweight concrete. The gain of strength was observed to be maximum at a replacement of up to 20 percent, and it went down at the replacement level afterwards [16]. [17] concluded that compressive, tensile, and flexural strength were enhanced at a maximum of 30% EW use. [18] found strengths, losses of 6.3, 7.5, and 17.1, at 10%, 15%, and 20% replacement, respectively.

Biological decomposition, referred to as composting [19], is an old practice mentioned in ancient Greek, Hebrew, and Arabic books about its significance in agriculture [20]. The practice achieves 3Rs. Reduce, Reuse, and Recycle by restoring organic matter back to the soil on a sustainable basis [21]. It minimizes greenhouse gas effects, increases soil fertility, and lowers water run-off, but cannot overcome such limitations as odor, low nutrient levels, and extends the processing time [22]. Composting is a feasible waste management system in developing countries, as the proportion of organic waste is great [23],[21]. Nevertheless, it is only successful when waste is segregated at the household level [24]. Existing literature primarily focuses on individually studying the impact of plastic recycling, papercrete mixes, or e-waste concrete individually, but the combined study still remains the combined integration of this element, this study investigates the impact of all 3 in one factor, understanding how well each element works with the others.

2. Methodology

2.1. Smart automatic bin system (SABS)

The current literature techniques for smart binning does not include segregation of material directed for building materials, The Smart Automatic Bin System program, based on Arduino, includes three bins for paper/cardboard, plastic, and E-waste, enhancing waste management efficiency at UET Peshawar's Mechanical, Civil, and Computer Science/Electrical Departments, these three departments are in different buildings making the system designed specifically for classification of waste for reuse in building materials as shown in **Figure *1***. The system operates automatically to segregate waste, reducing cross-contamination risks and ensuring accurate data collection. As bins approach capacity, as shown in **Figure 2**, designated personnel empty them for further processing. The separated waste is studied for applications in construction, with paper waste turned into slurry for masonry, plastics recycled into tuff tiles, and E-waste used as a concrete replacement. This system improves waste sorting and recycling significantly.

Figure 1. Smart automatic bin F.V (left) & T.V (right).

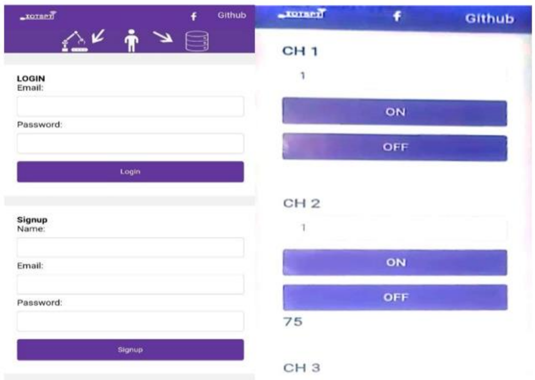

Figure 2. Application signup/login interface (left) & status interface (right).

2.2. Plastic in tuff tiles

Plastic waste globally has increased in the past 50 years, reaching 299 million tons in 2015 [25]. In Pakistan, thousands of tons of dumpsite waste are produced each year with little or no recycling [26], whereas in 14 percent of cases, plastic constitutes 14 percent of the total dumpsite waste. Plastic and rubber waste weighs 6.5 billion tons annually all over the world, and this increases the significantly harmful effects on the environment since these substances decompose slowly [27].

Figure 3. a) Mixture of molten plastic. b) Tuff tile under UTM. c) Failed tuff tile.

The tuff tiles were created from plastic waste using a straightforward molding technique. Coarse aggregates were made from crushed construction and road waste, while market sand served as the fine aggregates. Low-density polyethylene (LDPE) plastic bags from disposal sites were washed, dried, and melted in a controlled heat chamber, as shown in **Figure** *3*. The resulting black paste acted as a binder, combining sand and crushed refuse. This hot mixture was pressed into oiled molds and allowed to dry, resulting in strong and environmentally friendly tuff tiles within two hours. These were tested under a compressive testing machine, as shown in **Figure** *3*.

2.3. Paper and cardboard slurry in mortar

Papercrete, a composite building material based on shredded paper, Portland cement, and sand, can be produced with waste paper, particularly educational institutions' waste, which reduces the consumption of cement and structural dead load [28],[29],[30]. The paper pulp was prepared by shredding collected paper impurities and soaking them in water for 2-3 days before mixing, as shown in Figure 4. Experimental mix ratios of cement, cardboard, and sand were tested. According to ASTM C109, cubic specimens measuring 5cm on each side should cure for 28 days. Compressive tests were performed using a Universal Testing Machine with steel pads to ensure uniform loading [31]. Papercrete also encourages recycling, minimizes landfill waste, and offers a low-cost, environmentally friendly building material that can be used in walls, interiors, and low-cost housing [32].

Figure 4. Paper/Cardboard left for soaking.

Figure 5. Papercrete mix.

Figure 6. Papercrete in molds.

Figure 7. Failed papercrete cube.

2.4. E-waste in concrete

Waste Electrical and Electronic Equipment (WEEE) generates 50 million tons of hazardous waste annually, containing elements like lead and cadmium. This study investigates the use of Electronic Waste (EW) as a partial replacement for coarse aggregates, as shown in **Figure** *8*, in concrete to mitigate environmental impact and reduce landfill costs. We started from 5% minimum to 30% maximum replacement. Ordinary Portland Cement and aggregates were used, with different mix ratios and a water-cement ratio of 0.55. The produced concrete cylinders were cured for 28 days, and tests demonstrated that incorporating EW offers an economical and eco-friendly solution while preserving concrete performance within acceptable standards.

Figure 8. Electronic waste aggregates.

Figure 9. 28-day cured cylinders.

Figure 10. Failed Cylinders.

2.5. Machine learning supplement for material performance prediction

A machine learning analysis was done as a supplement to the study to see if the strength behavior of the tested sustainable materials could be predicted by simple waste percentage inputs. A dataset of 25 experimentally tested mixes of plastic tuff tiles, papercrete, and E-waste concrete has been compiled, including input parameters like plastic content, papercrete content, Electronic waste content, water absorption, density, and weight. The target variable was the 28-day compressive strength (MPa).

A regression pipeline was designed using Python and scikit-learn libraries, employing the concepts of feature scaling, cross-validation, and hyperparameter optimization. Cross-validation with 5 folds was employed in the model because of the limited sample size. Only independent variables were employed in the model. A set of diagnostic plots, including actual vs. predicted values, residual distribution, prediction intervals, and feature importance, was created to validate the reliability of the model. The model file and scripts have been provided as supplementary material.

3. Results and Discussion

3.1. Smart automatic bin system (SABS)

The Smart Automatic Bin System effectively segregated paper, plastic, and E-waste across departments using sensors to detect fill levels and monitor bins in real time. This automation minimized cross-contamination, but manual verification of waste purity remained essential. Live data improved collection efficiency, and the segregated waste contributed to construction experiments, enhancing mortar sustainability with paper slurry, recycling plastic into durable tuff tiles, and incorporating E-waste into concrete as a partial replacement. Overall, the system increased waste sorting accuracy and demonstrated strong potential for sustainable material development.

3.2. Plastic in tuff tiles

The results in **Figure 11** give the average values of three samples for each mix proportion in compression tests. The mix design proportion was taken as 1:1.5:2 mean 1 part binder, 1.5 fines (i.e., sand), and 2 parts of course aggregate (i.e building and road waste). The compressive strength was highest in sample P60, followed by sample P50, and drops as plastic content decreases, and the Reference mix has the lowest. The results clearly indicate that compressive strength increases with the addition of plastic content.

Table 1. Density, Mix proportion, 28 days compressive strength & water absorption results of plastic-added tuff tiles.

Sample	Composition / Mix Design	Strength (psi)	Strength (MPa)	Water Absorption (%)	Density (g/cm^3)
Ref	22.22% Cement + 33.33% Sand + 44.44% Aggregate.	1492	10.29	6.0	2.30
P10	10% plastic + 42.86% sand + 23.81% building waste + 23.81% road waste	1681	11.59	5.3	2.25
P20	20% plastic + 34.29% sand + 22.86% building waste + 22.86% road waste	2130	14.69	4.6	2.20
P30	30% plastic + 30% sand + 20% building waste + 20% road waste	1929	13.30	4.0	2.15
P40	40% plastic + 25.71% sand + 17.14% building waste + 17.14% road waste	3029	20.88	3.2	2.10
P50	50% plastic + 21.43% sand + 14.28% building waste + 14.28% road waste	3868	26.67	2.5	2.05
P60	60% plastic + 17.14% sand + 11.43% building waste + 11.43% road waste	3927	27.08	1.8	2.00

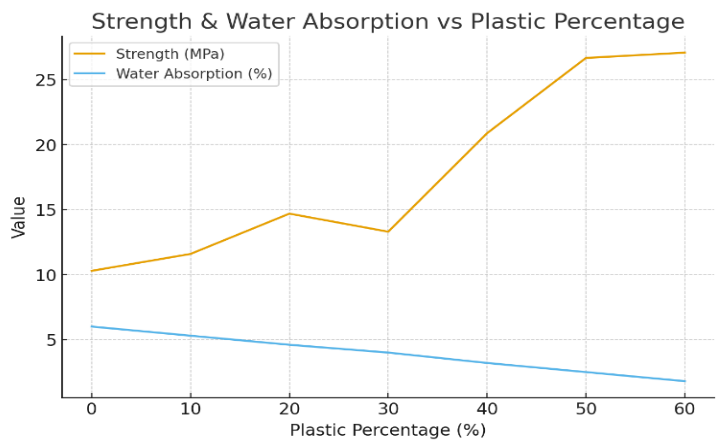

Figure 11. Strength and water absorption vs plastic percentage.

Figure 11 highlights that strength increases with plastic content: 22.6% with 30% plastic and 61% with 50% plastic in sample P50. This demonstrates that recycled plastic bags can be effectively used in tuff tile production, offering an environmentally friendly and cost-effective solution to waste management in Pakistan, while also having potential economic benefits.

3.3. Paper and cardboard slurry in mortar

The test results on compression are shown in **Table 2**; the final values represent the average of three samples for each mix proportion. The mix design was taken as 1:1 for binder (i.e cement) and fine particle (i.e., sand) for reference, while we kept cement constant and replaced sand with papercrete (paper + cardboard slurry) PC by increasing 5% in each mix proportion. The results clearly indicate that the Reference sample has the highest compressive strength among all samples, including PC1 and PC2, and that the higher the percentage of waste papercrete in the mix, the lower the compressive strength in PC40 and PC50.

Figure 12, Figure 13, Figure 14, shows a comparative visual description for initial strength, 28-day rest strength, and water absorption and density performance against different paper content.

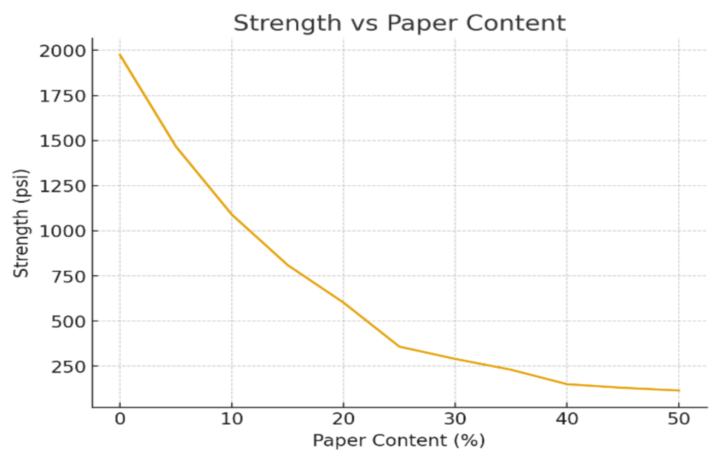

Figure 12. Strength vs Papercrete content.

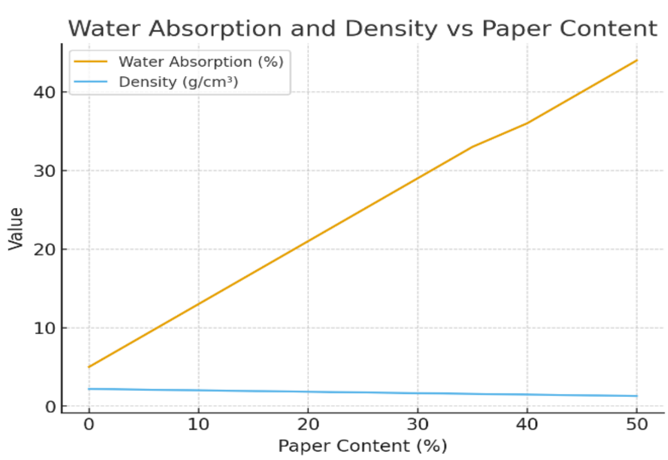

Figure 13. Water absorption vs papercrete content.

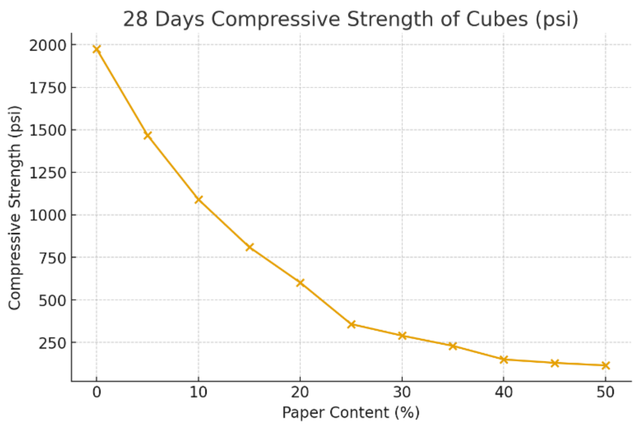

Figure 14. Compressive strength of papercrete.

The graphs show that increasing paper content leads to a clear loss in strength and a rise in porosity. The reference mix (0% paper) reaches about 1974 psi, but strength drops to roughly 1467 psi at 5% paper, 1090 psi at 10%, and continues decreasing steeply to only about 115 psi at 50% paper. Water absorption increases from around 5% in the reference mix to more than 40% at 50% papercrete, while density decreases from about 2.20 g/cm³ to nearly 1.30 g/cm³ over the same range. These numerical trends confirm that adding paper makes the material lighter but significantly weaker and more absorbent, limiting its use to non-load-bearing components. Moreover, by adding different materials (admixtures) in the mix design to gain strenght open research gap for future work.

Table 2. Density, Mix proportions, 28-day compressive strength & water absorption results of the mortar block of dimension 5cm each with added papercrete.

Sample	Composition / Mix Design	Strength (psi)	Strength (MPa)	Water Absorption (%)	Density (g/cm³)
Ref	50% Cement + 50% Sand	1974	13.62	5.0	2.20
PC-5	50% Cement + 45% Sand + 5% papercrete	1467	10.11	9.0	2.11
PC-10	50% Cement + 40% Sand + 10% papercrete	1090	7.52	13.0	2.02
PC-15	50% Cement + 35% Sand + 15% papercrete	810	5.58	17.0	1.93
PC-20	50% Cement + 30% Sand + 20% papercrete	602	4.15	21.0	1.84
PC-25	50% Cement + 25% Sand + 25% papercrete	358	2.47	25.0	1.75
PC-30	50% Cement + 20% Sand + 30% papercrete	290	2.00	29.0	1.66
PC-35	50% Cement + 15% Sand + 35% papercrete	230	1.59	33.0	1.57
PC-40	50% Cement + 10% Sand + 40% papercrete	150	1.03	36.0	1.48
PC-45	50% Cement + 5% Sand + 45% papercrete	130	0.90	40.0	1.39
PC-50	50% Cement + 50% papercrete	115	0.79	44.0	1.30

3.4. Electronic waste in concrete

The results in **Figure 15** and

Table 3 are the mean values of three specimens of each mix proportion tested at 28 days. A suitable mix proportion for concrete was determined, i.e., 1:1.5:3 of cement, fine aggregate (i.e sand), and coarse aggregate with a water to cement ratio of 0.55. We replaced course aggregates with E-waste by increasing 5% in samples. It is observed from the results that the reference cylinders developed a higher compressive strength than the Electronic waste (E-Waste) cylinders. Similarly, the weight at 28 days for the E-Waste cylinders is less than the weights of the reference specimens, which reflects the lightweight nature of the added material, as shown in **Figure 16**.

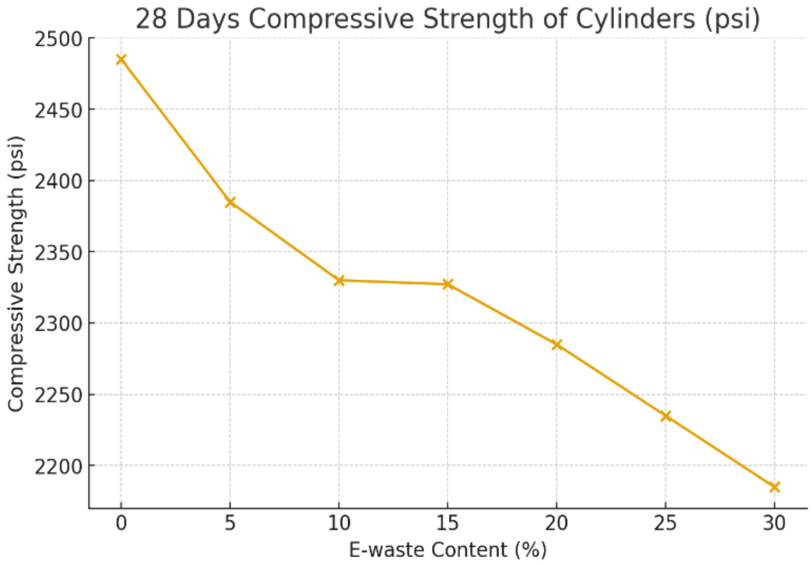

Figure 15. 28 days compressive strength vs E-waste content.

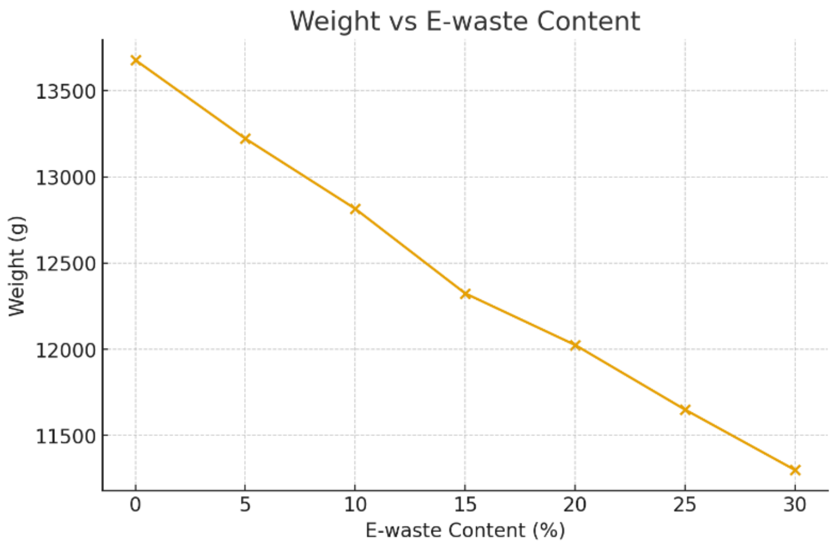

Figure 16. Weights of 28-day cylinders.

The reference cylinders show the highest compressive strength, while strength decreases progressively with higher E-waste content. The 15% replacement mix remains close to the control, with only a small reduction in strength. The weight of the cylinders also decreases with increasing E-Waste, confirming the lightweight nature of the material, as the 15% mix weighs about 12324 g compared to 13677 g for the reference, as shown in **Figure 16**. Due to the lower density of ABS, HIPS, and PCB plastic, weight loss is always more than strength loss. E-waste plastics and PCB pieces behave similarly to plastic. They reduce water absorption, but not as much because concrete still has cement paste pores. EW30 still keeps more than 15 MPa compressive strength. This makes your mix useful for Non-structural blocks, Partition panels, and paver applications

Table 3. E-waste content, 28 days compressive strengths, actual and reduced weights & water absorption results of aggregate replaced E-waste cylinders.

Sample	Composition / Mix design	Strength (psi)	Strength (MPa)	Weight (g)	Weight Reduction (%)	Water Absorption (%)	Water Reduction (%)
Reference	18.18% cement + 27.27% Sand + 54.55% aggregate	2485.1	17.13	13677.3	0	5.3	0
EW5	18.18% cement + 27.27% Sand + 51.82% aggregate + 5% E-waste	2385	16.44	13222	3.3	4.9	1.5
EW10	18.18% cement + 27.27% Sand + 49.09% aggregate + 10% E-waste	2330	16.05	12815	6.3	4.6	3.0
EW15	18.18% cement + 27.27% Sand + 46.36% aggregate + 15% E-waste	2327.2	16.04	12324.2	10	4.4	5.0
EW20	18.18% cement + 27.27% Sand + 43.64% aggregate + 20% E-waste	2285	15.75	12025	12.0	4.2	6.5
EW25	18.18% cement + 27.27% Sand + 40.91% aggregate + 25% E-waste	2235	15.41	11650	14.7	4.1	8.5
EW30	18.18% cement + 27.27% Sand + 38.18% aggregate + 30% E-waste	2185	15.06	11300	17.5	4.0	11.0

3.5. Machine Learning results

Results from the machine-learning model showed a strong linear relationship between the waste content and the resulting compressive strength. Cross-validated performance yielded an average R^2 of 0.82, which indicates that about 82% of the strength variation could be described by the input variables. The prediction error is still acceptable (MAE ≈ 1.9 MPa) given the modest size of the dataset, as shown in **Figure 18** & **Figure 19**. The feature-importance results placed plastic percentage and E-waste percentage as the most influential factors on strength prediction, while density and water absorption contributed secondary effects. The model has predicted the trends of strength reduction arising from laboratory tests, confirming that higher paper content and higher E-waste content lead to gradual strength loss, while higher plastic content in tiles increases strength, as demonstrated by **Figure 19** & **Figure 20**. Although the dataset was limited, the model demonstrates that simple waste-percentage variables can provide an early estimation of material performance.

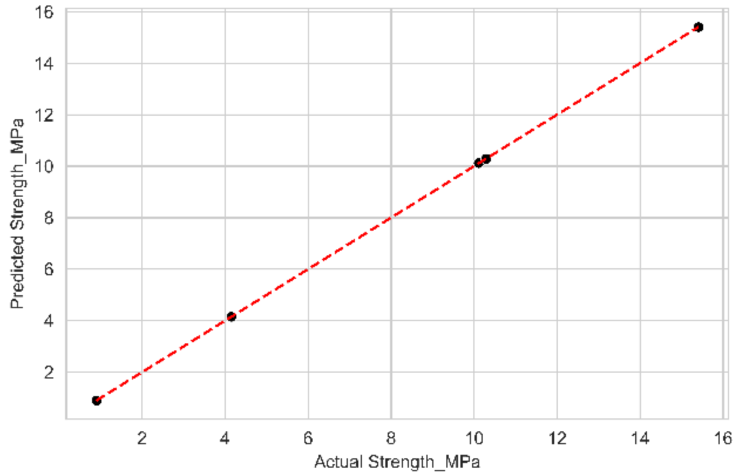

Figure 17. Machine Learning results of 28 days predicted compressive strength in MPa vs 28 days actual compressive strength.

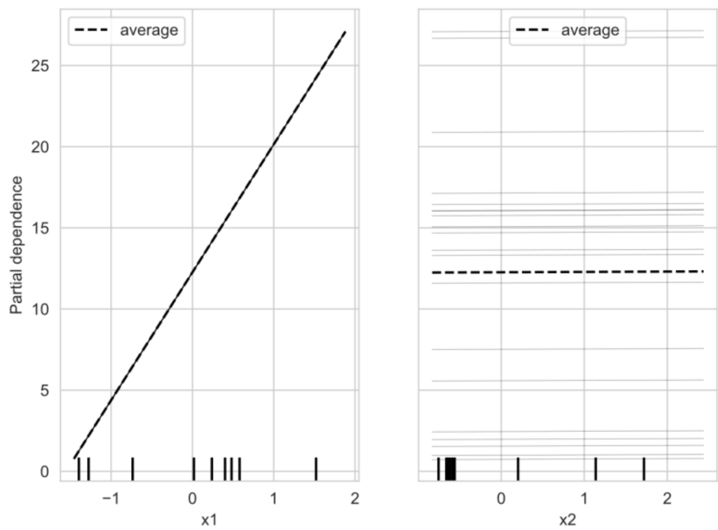

Figure 18. Machine Learning results of the partial dependence of waste.

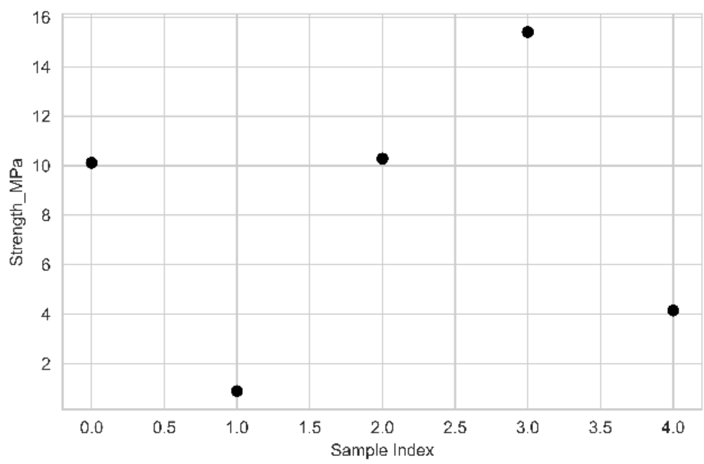

Figure 19. Machine Learning results of 28 days compressive strength in MPa vs Sample Index.

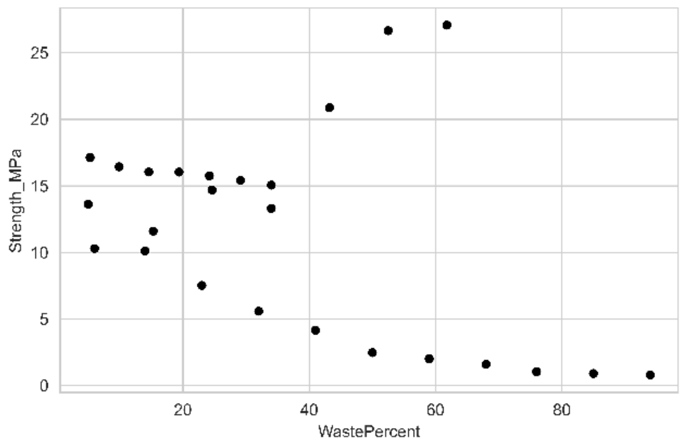

Figure 20. Machine Learning results of 28 compressive strength in MPa vs waste percentage.

4. Conclusion

The Smart Automatic Bin System explained that waste management significantly streamlined with automation, and the reuse of materials is effectively done. The system generated three reliable waste streams-paper, plastic, and E-waste- through ensuring clean separation that supported various sustainable construction experiments. This study underlines the potential of smart technologies in reducing workload, enhancing good environmental practices, and facilitating resource recovery. Overall, the system serves as a practical model for modern, campus-wide waste management solutions that can be spread to the city and country-wide. Moreover, the study shows that the addition of plastic not only improves the compressive strength of tuff tiles but also results in a safer, more ductile pattern of failure. Replacing cement with plastic will make the tiles eco-friendly, as cement has a high carbon footprint, and their durability will be improved because of the flexibility of the material. Secondly study shows that increasing the amount of papercrete reduces the overall compressive strength of the mixes, with the reference ratio (1:1) performing the best. Even though papercrete results in lower strength, its use of waste cardboard & paper makes it an eco-friendly. These mixes can still be effectively used to produce lightweight, low-strength bricks suitable for non-load-bearing walls, offering a practical and sustainable construction alternative. Thirdly, increasing the E-waste content reduces both the compressive strength and weight of the cylinders, with the reference mix showing 6.4% higher strength and 10% greater weight than the 15% replacement. Despite this reduction, using E-waste offers a sustainable and eco-friendly alternative for producing lighter construction materials. The supplementary machine-learning analysis further validated the experimental trends and demonstrated that waste-percentage inputs can reliably estimate strength behavior, offering a rapid screening tool for future material development.

5. Funding

No Financial support was received. Funds were managed by the authors. Moreover, testing was supported at the University of Engineering & Technology, Peshawar laboratory.

6. Data availability

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

7. Author contributions

Conceptualization, Shan Ul Haq; methodology, Shan Ul Haq; software, Muhammad Safi ullah; validation, Subhan hameed and Dasnish Pervez; formal analysis, Shan Ul Haq; investigation, Shan Ul Haq; resources, Muhammad Safi ullah and Shan Ul Haq; data curation, Shan Ul Haq.; writing—original draft preparation, Subhan hameed; writing—review and editing, Shan Ul Haq; supervision, Shan Ul Haq; project administration, Muhammad Safi Ullah; All authors have read and agreed to the published version of the manuscript.

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