3rd Conference on Sustainability in Civil Engineering (CSCE’21)
Department of Civil Engineering
Capital University of Science and Technology, Islamabad Pakistan

EVALUATING THE MECHANICAL AND DURABILITY PERFORMANCE OF CONCRETE UTILIZING PLASTIC FINE AGGREGATE

[a] Kiffayat Ullah*, [a] Dr. Irshad Qureshi, [b] Tahir Ahmad, [c] Afnan Ahmad

a: Civil Engineering, UET Taxila, Pakistan, kiffayat8@gmail.com & irshad.qureshi@uettaxila.edu.pk
b: College of Civil and Transportation Engineering, Hohai University, China, tahirahmad667@gmail.com
c: civil and Environmental Engineering, Universti Technologi Petronas (UTP) Perak, 32610, Malaysia, afnan_19001642@utp.edu.my
* Irshad Qureshi: Email ID: irshad.qureshi@uettaxila.edu.pk

Abstract- This study evaluates the mechanical and durability characteristics of eco-friendly concrete comprising of electronic plastic waste (EPW) as partial replacement of fine aggregate. Such an approach not just only reduces the negative effects of EPW on the surrounding world, but also helps in avoiding excessive quarrying for the production of natural aggregate. For this purpose, four M20 grade concrete mixes were prepared, substituting natural fine aggregates with plastic fine aggregates (PFA) using 0%, 10%, 15%, and 20% substitution levels. The mechanical efficiency of EPW concrete was evaluated based on the compressive strength while some of the durability properties were assessed through, sorptivity coefficient and alternate wetting and drying. The findings showed that by 10%, 15%, and 20% PFA replacement, compressive strength decreased by 2.6%, 9%, and 13.6%, respectively. Conversely, EPW concrete provided acceptable to excellent performance in the workability, and also shows positive results for required durability properties such as sorptivity coefficient, and alternate wetting and drying.

Keywords- Eco-friendly concrete; Electronic plastic waste; Natural aggregates; Plastic fine aggregate (PFA).

1 Introduction

Concrete is one of the most prominent and frequently used construction materials on the earth. Its global production is approximately 5.3 billion cubic meters per year, The world's second most utilized material in the universe after water[1]. Besides that, increased urbanization is driving the market growth for infrastructure, which in turn is going to increase the utilization of concrete. The extreme utilization of concrete is draining natural aggregate resources, which is thought to be a disastrous exercise as it harms watersheds and other ecosystem functions[2]. But on the other hand, Plastic materials, have become a significant environmental threat and are discarded in substantial volumes day after day. Every year, approximately 30 million tonnes of solid waste are generated in Pakistan[3], and 299 million tons of plastic waste were produced worldwide in 2013 [4]. A fraction of this plastic waste is recycled, whereas the remainder is frequently tossed aside in landfills, rivers, and seas, or burnt. All such mitigation strategies pollute the land and harm aquatic organisms, while burning emits toxic fumes.

Electronic plastic waste (EPW) comprises the plastic from dismantled household items, machines, televisions, freezers, radio equipment, etc. In Pakistan, the total amount of electronic waste produced is roughly 433 kilograms per capita, and 44.7 million tonnes of Electronic waste (E-waste) were noted globally in 2016[5]. Only around 12.5 percent of E-waste is effectively recycled globally, while the remaining portion is thrown away or burned. [6]. EPW's negative environmental impacts necessarily require its recycling and potential use in the construction industry.

Several attempts were made to study the effectiveness of EPW aggregates as a partial alternative to natural aggregates. Plastic waste (electronic and PET products) has been shredded into fine aggregates to evaluate its potential in concrete. K.

Alagusankareswari et al. [7] substituted fine aggregates by 0%, 10%, 20%, and 30% of EPW aggregates in concrete. About 3.8%, 7.25%, and 10.96% reduction in the self-weight were observed replacing 10%, 20%, and 30% fine aggregates. Likewise, the compressive strength was decreased by 7.6%, 21.47%, and 26.11%, and tensile strength was reduced by 1.67%, 20.98%, 38.98%, respectively with the increment of EPW replacement ratio. Similarly, the effect of EPW fine aggregate in partial replacement of natural sand was assessed by Basha et al. on concrete properties [8]. They recommended a 20% replacement ratio by obtaining the compressive strength of 32.2 MPa and split tensile strength of 4.8 MPa at 28 days of curing. Some author also studied the thermal performance of PFA concrete,as shown in Figure 1 Such as It is important to mention that the ABS plastic is heated to the melting point only to reshape it and is not burned. The corresponding author have performed the TGA analysis of concrete with this particular plastic type and it was observed that up to 2000 C, the change in weight of the sample is negligible compared to control sample meaning the release of substances and gases is at minimum. Furthermore, if this plastic is not reused using only the melting process, it may be burned, land filled or thrown into sea which would create more serious environmental problems[9]. Lili et al. replaced fine aggregate with coal bottom ash (CBA) in roller compacted concrete (RCC), and the results of compressive strength, deformation, stress strain curve, and splitting tensile strength indicate a decreasing trend with CBA material. However, in the case of uniaxial compressive strength, the disruption growth process is delayed[10]. Similarly, li et al. has also used Aragonite and calcite calcium carbonate whisker (CW) for improving the mechanical properties of cementitious composites. It has been added as a high-performance, low-cost, micro fiber material. Which showed a significant decrease in the heat of hydration of cement and the total amount of non-evaporable water. Also an increase in the yield stress and plastic viscosity of cement past was observed[11] Also, Lili et al. investigates the effect of high temperature on the microstructure of CW reinforced cement paste using nanoindentation and a mercury intrusion porosimetry test. The result shows that the fractal component of calcium carbonate whisker reinforced cement paste increased with increasing temperature and porosity[12]Other plastic types like high-density polyethylene (HDPE) plastic have also been utilized in concrete as a fine aggregate substitute by Amalu et al. [13]. The results indicate that for all concrete mixes and at all curing ages, the compressive strength decreased from 24.44 MPa (controlled) to 17.55 MPa (25% HDPE substitution). Choi et al. [14] used PET waste from plastic jugs as a fine aggregate substitute in concrete for the fresh and mechanical properties assessment. About 21% reduction in the compressive strength was found utilizing 75% PET waste plastic as natural fine aggregate replacement. But in our case with the replacement of PFA in concrete the compressive strength decreased by 13.6% which represents the positivity of using PFA in concrete.

Past studies investigated the use of various plastics (PVC, HDPE) as a fine aggregate substitute in concrete. However, only a few studies have been published on EPW as a fine aggregate substitute in concrete, reviewing its mechanical and durability properties. As a result, this research looks into the mechanical and durability properties of EPW concrete that uses manufactured PFA as a natural fine aggregate substitute. It is intended to develop durable lightweight concrete, ensuring a feasible replacement ratio, and reducing the reliance of the construction industry on natural fine aggregate. For this purpose, PFA was used as a replacement of natural sand with substitution levels of 0%, 10%, 15%, and 20% of natural fine aggregate. The compressive strength test was performed to assess the mechanical properties of EPW concrete while sorptivity coefficient and alternate wetting and drying tests were adopted to evaluate the durability properties.

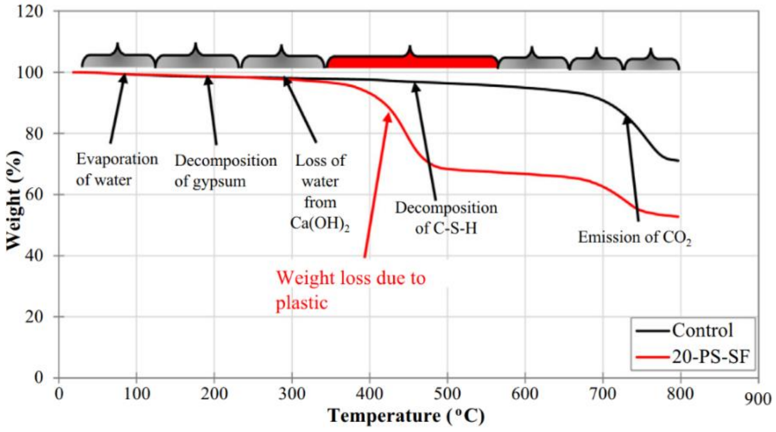

Figure 1 TGA analysis of EW[9]

2 Experimental Detail

The Fauji Cement Company Limited's Ordinary Portland Cement (OPC) of grade 53 is used as a binding agent. The OPC used is a general-purpose Type-I cement according to ASTM C150/C150M. In Table 1 Both the physical and chemical properties of OPC provided by the vendor are listed. The concrete mixture was made with potable water appropriate for drinking.

Table 1. General properties of Portland cement

Chemical properties	Results (%)	Physical properties	Results
SiO_2	22.5	Fineness modulus	93.4%
SO_3	5	Specific gravity	322
Loss on ignition	1.70	Initial setting time	110min
Al_2O_3	2.80	Final setting time	180min
MgO	1.76	28-day compressive strength	47MPa

2.1 Aggregates

To develop a concrete mix, natural sand of the Lawrencepur quarry was utilized as a fine aggregate. It has a fineness modulus of 2.73, is dark in color, and is classified as medium sand. In this study, coarse aggregates from the local market were used, which were processed by grinding rocks with a maximum size of 20mm. The EPW is depicted shown in Figure 2, had been bought from the Rawalpindi local store and was composed of scrap computer equipment such as computer mouses, keyboards, printers, and so on, which have been processed in three stages before being altered into a manufactured plastic fine aggregate (PFA). The process initiates with the washing of EPW using ordinary tap water followed by shredding the plastic into smaller pieces in a mechanical shredder. To remove other similar objects such as wires, steel, etc., all the broken EPW was then screened out in the second stage. After screening, the shredded EPW was melted in a kiln at a high temperature (200° C), followed by cooling in water to turn it into plastic rocks. The plastic rocks were eventually crushed and ground to turn into plastic fine aggregates (PFA) in the last stage. The detail process of preparation of EW is shown in Figure 3. The general properties of all aggregates (fine, coarse, and PFA) are enlisted in Table 2.

Figure 2. Dumped electronic wastes (E-waste)

Figure 3 Detail process of preparation of PFA

Table 2.General properties of aggregates (coarse, fine, and PFA)

Properties	Coarse aggregate	Natural fine aggregate	Plastic fine aggregate
Maximum nominal size(mm)	20	4.73	4.72

Minimum nominal size(mm)	4.75	0.074	0.149
Fineness modulus	7.21	2.73	3.18
Specific gravity	2.71	2.61	1.21
Saturated surface dry water	1.08	0.49	0

2.2 Mix composition:

Four different types of concrete mixes were produced incorporating plastic fine aggregate (PFA) in partial replacement of natural sand by adopting the M20 concrete mix. The number of samples tested is listed in table. while the mix composition is demonstrated in table

Table 3 Detailed summary of all tests

Properties	**Dimensions of specimens**	**No of Specimens**			
		P0	P10	P15	P20
Slump	Standard cone size	3	3	3	3
Compressive strength (28 days)	100 ×100 ×100 mm^3 (cubic)	3	3	3	3
Sorptivity coefficient (28 days)	100× 50 mm (Disk)	3	3	3	3
Alternate wetting & drying	100 ×100 ×100 mm^3 (cubic)	3	3	3	3

Table 4 Mix composition of PFA concrete

Mix ID	**PFA (%)**	**Cement (kg/m^3)**	**Water (kg/m3)**	**Coarse aggregate (kg/m^3)**	**Sand (kg/m^3)**	**PFA (kg/m^3)**
P0	0	424	212	44.13	676	-
P10	10	424	212	44.13	608	52
P15	15	424	212	44.13	575	79
P20	20	424	212	44.13	541	105

3 Results

3.1 Fresh property

3.1.1 Slump

The slump test, which is a measure of concrete consistency and fluidity, was used to assess EPW concrete's workability. Figure *4* depicts the results of the slump test performed on EPW concrete. An increasing trend was observed in the workability of EPW concrete mix with the increasing amount of PFA. The enhancement in the workability by 30.16% with 10% replacement of natural fine aggregate with the PFA and an almost 10% increment in the slump value was reported for every 5% further increment in substitution of PFA in EPW concrete mix as shown in Figure *5*.
The increase in workability of EPW concrete mix with the addition of PFA may be due to PFA's extremely low water absorption. As observed and reported in previous experiments, the excess water in the mix aids in increasing workability [13]–[15]. However, the workability of concrete depends upon numerous factors including aggregate size, water absorption capacity, and shape. The size of PFA was regulated during processing, but a higher slump value is due to the excess of free water in EPW concrete.

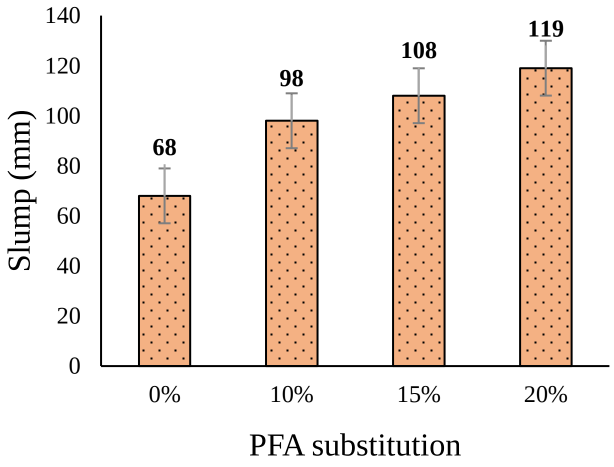

Figure 4. The slump of EPW concrete mixes

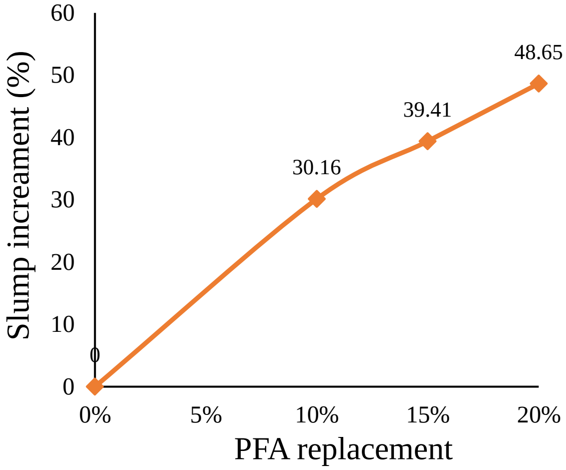

Figure 5.Slump % increased with PFA substitution

3.2 Mechanical property

3.2.1 Compressive strength

The compressive load carrying capacity of EPW concrete is assessed by performing Compressive strength tests for cubes of 100mm. The 28-day compressive strength test results of P0, P10, P15, and P20 are shown in Figure 6. It has shown that the compressive strength of EPW concrete decreases with an increasing percentage of PFA. About 2.6%, 9%, and 13.6% decrease in the compressive strength was noticed for P10, P15, and P20 samples, in Figure 7 respectively.

The decrease in compressive strength is because of the PFA's smooth surface texture, which produces a weak interfacial bond between PFA and cement paste [16]. Furthermore, the plastic aggregates have hydrophobic nature, which produces excess water in the mixture and reduces the strength of EPW concrete. However, some studies relate the decrease in compressive strength to the imbalanced moduli, which occurs when PFA particles have a lower elastic modulus than the adjacent cement paste, resulting in small cracks. The outcomes of EPW concrete compressive strength support the previous work [7], [10], [11], performed on the plastic waste utilization as partial replacement of natural aggregates.

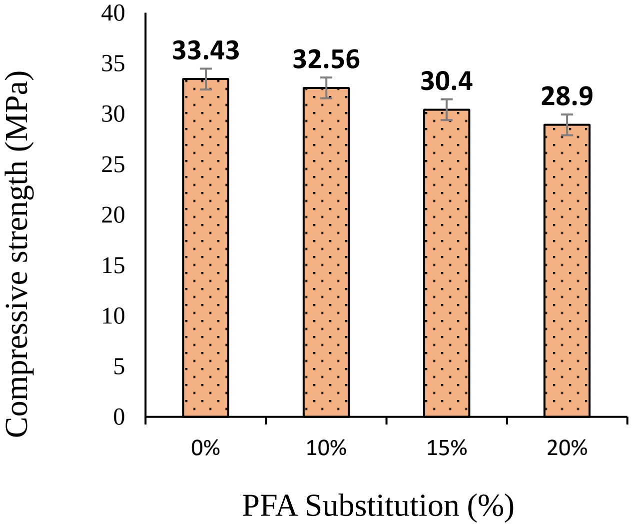

Figure 6. Compressive strength of EPW concrete at 28 days

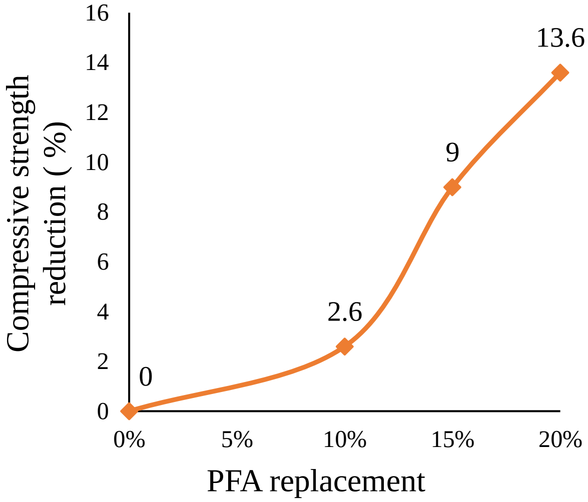

Figure 7 Compressive strength decrease with PFA replacement.

3.3 Durability property

3.3.1 Sorptivity coefficient

The amount of water absorbed by a substance through capillary action per unit area is known as the sorptivity coefficient (SC). Materials with a high sorptivity coefficient are more vulnerable to degradation, which affect durability adversely. The sorptivity coefficient of the specimen was measured by taking the weight gain of a specimen after immersing it in water for 6 hours. Figure 8 shows the experimental results of the sorptivity coefficient for all mixes of EPW concrete (P0, P10, P15, and P20). For SC 100mm*50mm disk was prepared and tested. It can be seen in Figure 9 that the sorptivity coefficient decreases with the increasing percentage of PFA substitution. Water absorption cumulative reduction reaches up to 57.25% for P20, highlighting the role of PFA in sorptivity coefficient reduction. The cumulative reduction in sorptivity coefficient shown in Figure **9** eventually adds to the EPW concrete durability enhancement. This significant decrease in water absorption can be attributed to the impervious nature and non-absorbent behavior of plastic aggregates [18].

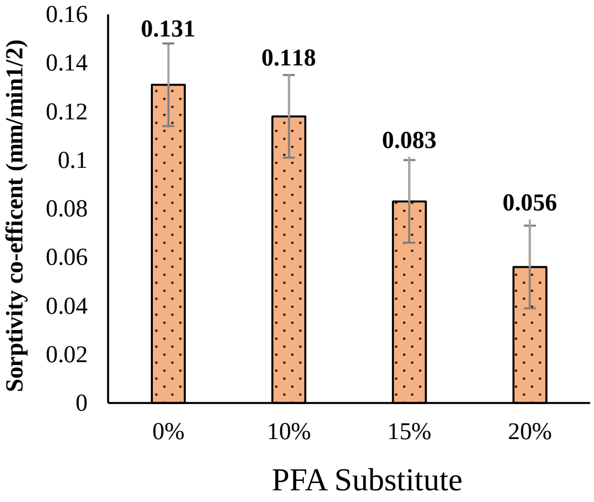

Figure 8 *The sorptivity coefficient of EPW concrete*

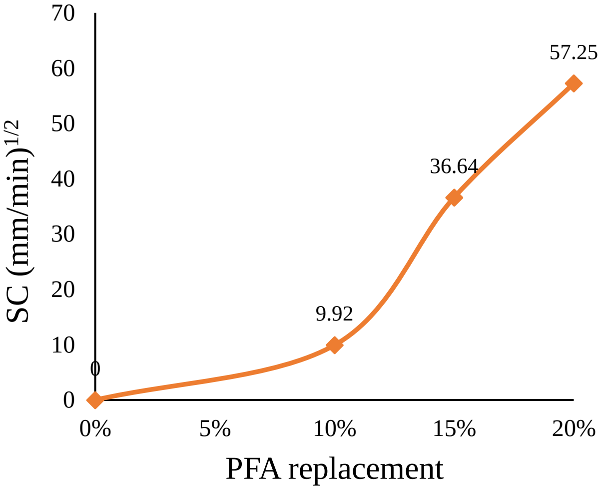

Figure 9 SC reduction with PFA replacement

3.3.2 Alternate wetting and drying

This experiment reflects the ability of concrete to degrade when subjected to alternate wetting and drying cycles, such as sea tidal waves. In this test EPW concrete samples were exposed to alternate wetting and drying procedure for 25 cycles. The compressive strength reduction of EPW concrete upon exposure to 25 alternate wetting and drying conditions in addition to the average loss in compressive strength is shown in Table 5. While Figure 10 illustrate the comparative compressive strength of all percentages with PFA incorporation after 0 and 25 cycles of alternate wetting and drying. The results show that the compressive strength is affected negatively while resistance to strength degradation in 25 cycles is significantly increased with the incorporation of PFA. When compared to P0, the higher percentage of PFA (P20) generates additional resistance to alternative wetting and drying cycles. This progress is attributed to PFA's non-absorbent nature as compared to natural fine aggregates. In the control mix, compressive strength degradation is 24.3% for PO. Likewise, the compressive strength reduction for P10, P15, and P20 is approximately 21.3%, 8.88%, and 14.1%, respectively.

Table 5. Compressive strength of EPW concrete after 25 cycles of alternate wetting and drying.

Mix Id	**Compressive strength (MPa)**	**Compressive strength reduction (%)**
	25 cycle	25 cycle

PO	25.3	24.3
P10	25.6	21.4
P15	27.7	8.88
P20	28.0	3.11

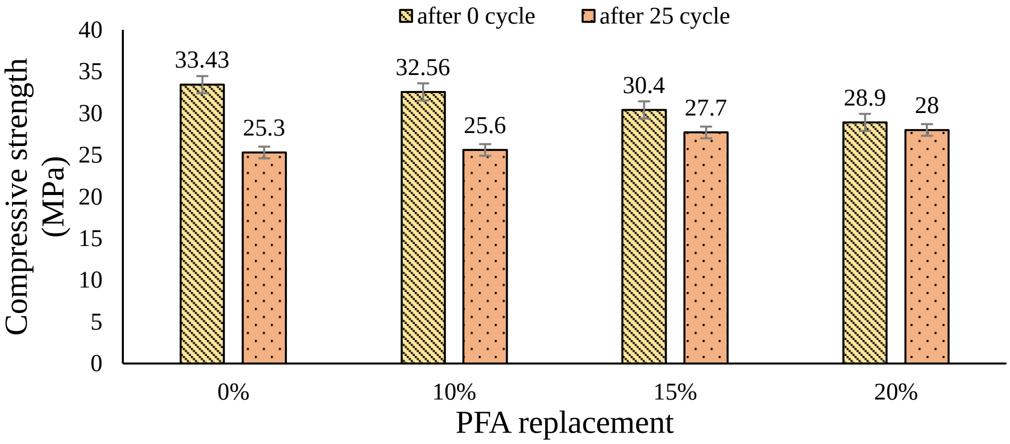

Figure 10 Alternate wetting and drying before and after 25 cycles.

4 Conclusion

The research provides a review of the effect of PFA inclusion on EPW concrete results. The influence of increasing replacement levels (10%, 15%, and 20%) of natural fine aggregates by PFA on the fresh, mechanical, and durability properties of EPW concrete is demonstrated. Increasing the substitution level of sand by PFA leads to the following conclusions:

•The workability of EPW concrete significantly improved due to the non-absorbent smooth surface texture of PFA.

• The mechanical properties (compressive strength) of EPW concrete were substantially decreased as a result of poor and ineffective bonding of PFA with the cement paste to remain firm. However, EPW concrete is still preferred to utilize for construction purposes because the minimum compressive strength accomplished by EPW concrete is greater than the minimum pressure required (17.5 MPa).

•The sorptivity coefficient values significantly reduced due to the non-absorbent nature of PFA in EPW concrete. Minimizing the water absorption capability of EPW concrete mitigates several issues e.g., concrete spalling, reinforcement corrosion, etc., improving the durability properties of EPW concrete.

•The percentage reduction in compressive strength after 25 cycles of alternate wetting and drying tends to decrease with increasing PFA percentage as the PFA has lower water absorption and does not permit the smooth swelling and shrinkage of concrete, making the EPW concrete suitable for offshore construction activities.

This study demonstrates the production of PFA from raw electronic waste and its suitability for use as a natural fine aggregates substitute in concrete mixes. The negative impact of PFA on mechanical properties limits the use of EPW concrete in projects where concrete strength is critical. However, the increased durability of EPW concrete in respective properties extends its usage in other applications such as coastal or offshore structures, etc.

Further research works are suggested to elevate the mechanical characteristics of EPW concrete using pozzolanic materials i.e., silica fume, nanoparticles, etc. Moreover, it is important to examine some other durability characteristics such as freezing and thawing, chloride migration, wear resistance, ultrasonic pulse velocity, temperature resistance, etc. along with the chemical and microstructural properties of EPW concrete for the proper application of PFA concrete

Acknowledgment

First of all, the authors would like to thank the editor and all the reviewers for suggesting improvements for the manuscript. The following line is also added in acknowledgements as an appreciation for the anonymous reviewers.The authors would like to express their gratitude to the entire staff of the Civil Department's concrete research laboratory at the University of Engineering and Technology (UET) for their continuous experimental support.

References

[1] C. Roskos, D. Cross, M. Berry, and J. Stephens, "Identification and Verification of Self-Cementing Fly Ash Binders for ' Green ' Concrete," *2011 World Coal Ash Conf.*, 2011, [Online]. Available: http://www.flyash.info/.

[2] D. Padmalal and K. Maya, "Introduction," *Environmental Science and Engineering (Subseries: Environmental Science)*, no. 9789401791434. Springer Berlin Heidelberg, pp. 1–7, 2014, doi: 10.1007/978-94-017-9144-1_1.

[3] "The Looming Plastic Pollution Crisis | Pakistan Today." https://www.pakistantoday.com.pk/2019/03/14/the-looming-plastic-pollution-crisis/ (accessed Sep. 23, 2020).

[4] D. K. A. Barnes *et al.*, "Accumulation and fragmentation of plastic debris in global environments Accumulation and fragmentation of plastic debris in global environments," no. June, 2009, doi: 10.1098/rstb.2008.0205.

[5] H. Bin Hameed, Y. Ali, and A. Petrillo, "Environmental risk assessment of E-waste in developing countries by using the modified-SIRA method," *Sci. Total Environ.*, vol. 733, p. 138525, 2020, doi: 10.1016/j.scitotenv.2020.138525.

[6] T. Haque, "Introduction to Electronics (E-Waste) Recycling," *The balance small bussiness*, 2019. .

[7] K. Alagusankareswari, S. Sandeep Kumar, K. B. Vignesh, and K. Abdul Hameed Niyas, "An experimental study on E-waste concrete," *Indian J. Sci. Technol.*, vol. 9, no. 2, pp. 3–7, 2016, doi: 10.17485/ijst/2016/v9i2/86345.

[8] M. Basha S, B. Reddy Ch, and V. K, "Strength behaviour of geopolymer concrete replacing fine aggregates by M-sand and E-waste," *Int. J. Eng. Trends Technol.*, vol. 40, no. 7, pp. 401–407, 2016, doi: 10.14445/22315381/ijett-v40p265.

[9] K. Ali, M. I. Qureshi, S. Saleem, and S. U. Khan, "Effect of waste electronic plastic and silica fume on mechanical properties and thermal performance of concrete," *Constr. Build. Mater.*, vol. 285, p. 122952, May 2021, doi: 10.1016/j.conbuildmat.2021.122952.

[10] R. C. Using, C. Bottom, and A. Entirely, "Constitutive Model of Uniaxial Compressive Behavior for," 2021.

[11] L. Li, M. Cao, and H. Yin, "Comparative roles between aragonite and calcite calcium carbonate whiskers in the hydration and strength of cement paste," *Cem. Concr. Compos.*, vol. 104, no. June, 2019, doi: 10.1016/j.cemconcomp.2019.103350.

[12] L. Li, Z. Li, M. Cao, Y. Tang, and Z. Zhang, "Nanoindentation and porosity fractal dimension of calcium carbonate whisker reinforced cement paste after elevated temperatures (up to 900◦C)," *Fractals*, vol. 29, no. 2, pp. 1–16, 2021, doi: 10.1142/S0218348X21400016.

[13] R. . Amalu, Azeef Ashraf, Muhammad Hashim, Rejith.K.U, Vijitha.V, "Use of Waste Plastic As Fine Aggregate Substitute in," *Int. J. Sci. Eng. Res.*, vol. 7, no. 4, pp. 172–177, 2016.

[14] Y. W. Choi, D. J. Moon, J. S. Chung, and S. K. Cho, "Effects of waste PET bottles aggregate on the properties of concrete," *Cem. Concr. Res.*, vol. 35, no. 4, pp. 776–781, 2005, doi: 10.1016/j.cemconres.2004.05.014.

[15] E. del R. Castillo, N. Almesfer, O. Saggi, and J. M. Ingham, "Light-weight concrete with artificial aggregate manufactured from plastic waste," *Constr. Build. Mater.*, vol. 265, p. 120199, 2020, doi: 10.1016/j.conbuildmat.2020.120199.

[16] Z. Z. Ismail and E. A. AL-Hashmi, "Use of waste plastic in concrete mixture as aggregate replacement," *Waste Manag.*, vol. 28, no. 11, pp. 2041–2047, 2008, doi: 10.1016/j.wasman.2007.08.023.

[17] S. Akçaözoğlu, C. D. Atiş, and K. Akçaözoğlu, "An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete," *Waste Manag.*, vol. 30, no. 2, pp. 285–290, 2010, doi: 10.1016/j.wasman.2009.09.033.

[18] B. T. A. Manjunath, "Partial Replacement of E-plastic Waste as Coarse-Aggregate in Concrete," *Procedia Environ. Sci.*, vol. 35, pp. 731–739, 2016, doi: 10.1016/j.proenv.2016.07.079.