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MECHANICAL PROPERTIES OF LAUNDRY WASTEWATER CONCRETE INCORPORATING POLYETHYLENE 2 TEREPHTHALATE (PET) AS PARTIAL REPLACEMENT FOR SAND

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Abstract

Today's scarcity of fresh water and a rise in polyethylene terephthalate (PET) waste in the environment results from the increase in population. This study examines the impact of utilizing laundry wastewater and PET in concrete production. Laundry wastewater (LWW) and varying percentages of PET (0% to 30%) used as partial replacement for fine aggregate were used to produce 84 concrete cylinders and 84 concrete cubes. The results showed that a 30% PET replacement significantly reduced the workability of concrete by 50% compared to the control mix, and the compaction factor was reduced by 5%. The PET-modified concrete with 5%, 10% and 15 % achieved a target compressive strength of 13.5 N/mm² at 7 days but did not meet the target at 14 and 28 days, unlike the control mix. Prolonged curing time resulted in increased split tensile strength, except for the 5% PET replacement, which showed a decrease at 28 days. Scanning electron microscope (SEM) analysis revealed that the cement and 10% PET aggregates possessed the strongest bond, while the 15% to 30% PET replacement exhibited weak interfacial transition zone (ITZ). Certain properties of the LWW such as increased suspended solids and organic compounds present in detergents and bleach could have reduced the bond strength between cement and aggregates. Regression analysis indicated that the percentage of pulverized PET is a reliable predictor of slump and compressive strength, but less so for tensile strength.

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1.0 INTRODUCTION

Concrete is widely recognized as the most extensively utilized building material, second only to water in terms of overall use [1]. Its primary components include cement, fine aggregate, coarse aggregate, and water [2]. Recent estimates suggest that approximately 25 billion tons of concrete have been produced annually in the past few years [3]. Annually, the usage of concrete is projected to be around 11 billion metric tons [4], with the construction industry consuming nearly 2 billion tons of Portland Cement each year [3]. The construction sector is also a major consumer of water [5], using about four trillion liters of fresh water annually for concrete manufacturing [6]. To address the challenges of waste disposal and recycling, a more sustainable approach involves incorporating waste materials into concrete production, which can also help conserve natural resources [7]. Thus, replacing fresh water with domestic and industrial wastewater in concrete production represents a crucial step toward environmental sustainability [8]. Sewage from bathing, laundry, and kitchens is also considered to be a type of wastewater [9]. Wastewater can be used in construction projects since it has chemical and physical characteristics such as high limits of salt, chloride, sulfate, alkali, and potassium which are specified for concrete production process [10].

The significant increase in urbanization and environmental development has led to the depletion and excessive use of natural resources in concrete production [11], creating an urgent need for alternative materials. Our current environment is heavily burdened with plastic waste due to its slow degradation rate, which causes long-lasting environmental impacts [12]. Polyethylene terephthalate (PET), a prevalent consumer plastic, is widely used in products such as beverage bottles, food packaging, and other good [13]. Addressing plastic pollution is a critical challenge faced by countries worldwide [14].

Incorporating plastic wastes as partial replacements for fine or coarse aggregates in concrete production offers a sustainable method to address plastic pollution [15, 16]. PET plastic waste has been utilized in the creation of mortar [17], bricks and masonry [18], and concrete [12, 19, 20, 21, 22]. Aggregates typically constitute 65 to 80% of a concrete mix due to their crucial role in properties such as dimensional stability, porosity, density, durability, strength, and workability [23]. Using plastic waste in place of traditional aggregates in cement production not only reduces the consumption of non-renewable materials like rocks and sands but also offers a secure method for reusing or disposing of plastic waste [14]. This practice results in the production of lightweight concrete, which can mitigate the risk of earthquake damage [24]. The addition of PET fibers to concrete significantly enhances its ductility [25]. Additional advantages encompass better thermal insulation, decreased construction costs, and shorter processing duration [26].

This study is focused on examining the mechanical properties of concrete made from laundry wastewater and pulverized polyethylene terephthalate, with specimens tested at an interval 7, 14, 21, and 28 days of curing.

2.0 METHODOLOGY

This research employed locally obtained materials.

2.1 Cement

The study utilized Dangote 3X brand Ordinary Portland Cement (OPC) with Grade 42.5 N and a density of 1440 kg/m^3, meeting the standards outlined in ASTM C150 [27]. Wastewater was employed as a binder for hydration. The physical properties as well as the chemical composition of the Dangote 3X brand with Grade 42.5 N are presented in Table 1.

Table 1: Composition of 42.5 N grade cement [28, 29,30]

Chemical Composition (%)	
Alumina (Al_2O_3)	4.44
Magnesia (MgO)	2.32
Silicate (SiO_2)	20.71
Lime (CaO)	62.80
Sulfur trioxide (SO_3)	2.37
Iron Oxide (Fe_2O_3)	2.78
Chloride (Cl^-)	0.007
Potash (Na_2O+K_2O)	0.88
Free Calcium Oxide (*f*-CaO)	0.78
Loss of ignition	3.38

2.2 Aggregates

Gc85/20 10/20 coarse aggregate (CA) was incorporated into the concrete mixes to improve workability. The CA, with a maximum size of 20mm, exhibited a typical relative density (specific density) of 2200 kg/m^3 when measured oven dry (OD), and an aggregate crush value of 20.1%. Fine aggregate (FA) was sourced locally from the Federal University of Technology Akure (FUTA), in the form of river sand. The FA had a moisture content of 3.8%, a specific gravity of 2.65, and a loose bulk density of 1600 kg/m^3.

Figure 1: Plastic shredder

Figure 2: Shredded PET plastic waste

2.3 Pet Flakes

Waste plastic bottles, sourced from FUTA, were used as the PET plastic aggregate. These bottles underwent a cleaning process to remove labels, adhesives, and any visible impurities before being reduced to smaller sizes with a plastic shredder (see Figure 1). The resulting PET waste aggregate attained a minimum size comparable to river sand (as depicted in Figure 2).

2.4 Laundry Wastewater

The experimental setup utilized laundry wastewater sourced from hostels situated within the FUTA campus. Physicochemical tests were conducted at the Chemistry laboratory, FUTA, following the protocols outlined in Rainwater and Thatcher [30] for the collection and analysis of water samples. Figure 3 illustrates the sample of laundry wastewater utilized in this study.

Figure 3: Laundry wastewater

2.5 Preparation of Concrete Samples

The research involved seven different sample mixtures: one control mixture (100% fine and coarse aggregates), and six mixtures that included aggregates modified with PET. These mixtures utilized fine aggregates (sand) and pulverized PET plastic particles in different ratios (100:0, 95:5, 90:10, 85:15, 80:20, 75:25, and 70:30). The mix ratio 1:2:4 was selected for the investigation, aiming for 20 N/mm^2 target strength for concrete grade M20, with 0.55 laundry wastewater/cement ratio, as specified in Table 2. Concrete samples were prepared using hand mixing techniques and poured into designated frames. Cube specimens with dimensions 150 x 150 x 150 mm^3 and cylindrical specimens with dimensions 100 mm x 200 mm were then extracted from the fresh concrete mixtures [12]. The concrete samples, after curing, were submerged in a pool of potable water for a period of 28 days.

Table 2: Concrete mix design

	Content of components in kg/m^3				
Concrete Batch	**Cement**	**Natural-FA**	**PET-FA**	**Granite**	**Laundry wastewater**
PET 0%	307	687	0	1245	153
PET 5%	307	653	34	1245	153
PET 10%	307	618	69	1245	153
PET 15%	307	584	103	1245	153
PET 20%	307	550	137	1245	153
PET 25%	307	515	172	1245	153

2.6 Tests Conducted on Concrete

The research encompassed three categories of tests: fresh PET-modified concrete workability tests, aimed at assessing mix consistency and fluidity; hardened PET-modified concrete tests, aimed at assessing the concrete's mechanical properties; and microstructural analysis. The processes stated in pertinent standards were used to carry out all experimental tests [20].

2.6.1 Tests on the fresh concrete

The effect of the PET plastic aggregates on the fresh concrete's workability and consistency were determined using the slump cone and compaction factor. These assessments were carried out using the guidelines outlined in ASTM C143 [32]. While mixing each concrete batch, a flat, smooth, non-absorbent surface was set up, and the slump cone was placed on this surface. The cone was filled with concrete in three equal layers, with each layer tamped 25 times. After the top layer was tamped, the concrete surface was leveled with a trowel, and the slump cone was carefully raised vertically. The difference in height of the highest point of the subsided concrete and the slump cone was measured in millimeters using a measuring tape, to derive the slump value of the concrete.

For the compaction factor test, the empty weight of the cylinder (W) was measured and recorded. Using a hand scoop, concrete was poured into the higher pan until it reached the desired level. The upper pan's bottom lid was opened, letting the concrete drop into the lower pan. Afterward, the lower pan's bottom lid was opened, making way for the concrete enter into the base cylinder. The outer surface of the cylinder was cleaned, and the partially compacted concrete's weight was measured and recorded as (W1). Subsequently, the concrete in the cylinder was removed and the same concrete mix in layers of five centimeters depth was put into it. Each layer was firmly compacted to achieve complete compaction, and the upper surface was leveled. The fully compacted cylinder was weighed, and the value was recorded as (W2). The compaction factor for each design mix was established by computing the weight ratio of the partially compacted concrete to the fully compacted concrete.

2.6.2 Test on the dry concrete

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The tests on the hardened concrete samples were carried out in the Structural laboratory FUTA, and conducted after 7, 14, 21 and 28 curing days.

2.6.2.1 Test on compressive strength

The Universal Compressive Strength Machine (UCSM) (see Figure 4), boasting a capacity of 1000 KN, was utilized to crush the samples of the concrete cubes following ASTM C39 [33] guidelines. Concrete samples were positioned in the UCSM, and a load of 3 kN/s was gradually applied to the 150 x 150 x 150 mm^3 cube samples until failure occurred. The compressive strength of the concrete was determined by taking the ratio of the failure load and the cross-sectional area resisting the load.

Figure 4: Universal compressive strength machine

2.6.2.2 Test on split tensile strength

The Universal Tensile Strength Machine (UTSM) was employed to crush the cylindrical concretes in accordance to ASTM C496 [34] specifications. Concrete cylinders were horizontally positioned in the UTSM and steel strips were used to support it above and below along the splitting axis. A load was then applied to the 100 mm x 200 mm concrete cylinder samples till it split. Afterwards, the failure loads that were recorded was used to determine the concrete mix batch result.

2.7 Microstructural Analysis

A standard PHENOM ProX scanning electron microscope (SEM) was employed to assess the PET plastic impact on the microstructure of the concrete at 5%, 10%, 15%, 20%, and 25% PET plastic replacement levels, excluding the 30% PET plastic replacement level because it gave the least compressive strength. Between the cement/concrete matrix and the plastic aggregate was the interfacial zone, which was captured using SEM [12]. This study followed the standard procedure outlined by Akinbile et al. Additionally, the composite's elemental composition in terms of quantity and quality was conducted using Rigaku Mini Flex 600 (XRD).

3.0 RESULTS AND DISCUSSION

3.1 Physicochemical Analysis of Laundry Wastewater

The tests for the physicochemical properties conducted on the laundry wastewater (see Table 3) revealed that parameters such as color, turbidity, TSS, COD, and BOD exceeded the World Health Organization (WHO) permissible limit for potable water, which is the most suitable water for concrete production. Although high pH levels can lead to reduced cement hydration and increased risk of alkali-silica reaction, however, the pH, electrical conductivity, and hardness were found to be within the limits provided by WHO.

Table 3: Physicochemical parameters of laundry wastewater sample

Parameter	Result	WHO permissible limit for potable water
pH	6.96	6.5-8.5
Temperature	24ºC	
Colour	225Hazen	50
Turbidity	40 NTU	5
Electrical Conductivity	189uS	200
Total Dissolved Solid (TDS)	127 mg/L	500
Total Suspended Solid (TSS)	70 mg/L	20
Hardness	100 mg	300
Chemical Oxygen Demand (COD)	255 mg/L	80
Biochemical Oxygen Demand (BOD)	80 mg/L	2.0

3.2 Results of Tests Carried out on Fresh Concrete

3.2.1 Slump test

From the findings, increasing % of the PET waste results in a decline in the concrete's workability as outlined in Table 4. Notably, a 30% replacement rate demonstrates a substantial decrease in concrete workability, reaching 50% reduction compared to the reference concrete mix. The decline can be attributed to the increased surface area of PET plastic relative to fine aggregates (sand) [21], which reduces the ability of plastic in the mixture to absorb excess water, consequently resultng in the dryness of the slump [34]. Furthermore, it is worth noting that the properties of the laundry wastewater used may have also influenced the obtained test results. This result was collaborated by [21, 36, 37, 38, 39].

3.2.2 Compaction factor test

The findings indicate that the compaction factor remained constant at 0.96 for PET-modified concrete mixes containing 5% to 10% PET and at 0.93 for mixes containing 20% to 30% PET (refer to Table 5). While previous research by Amalu et al. reported a consistent increase in the compaction factor, this result agrees with the result by Bamigboye et al., who investigated the use of heated PET plastic fine aggregate.

Table 4: Slump test

% of Pulverized PET	Slump (mm)
0	60
5	57
10	55
15	50
20	45
25	35
30	35

Table 5: Compaction factor test

% PET replacement of fine aggregate	Weight of partially compacted concrete with cylindrical mold (kg), W_1	Weight of fully compacted concrete with cylindrical mold (kg), W_2	Compaction factor
0	17.0	17.2	0.98
5	17.0	17.8	0.93
10	16.4	16.8	0.96
15	16.4	17.0	0.95
20	16.8	17.6	0.93
25	17.0	17.8	0.93
30	15.8	16.6	0.93

3.3 Results of Tests Carried out on Dry Concrete

3.3.1 Test on dry density

The dry density results reveal that as the percentage of PET plastics in the cube and cylindrical concrete samples increased, the concrete samples had dry density reductions as presented in Table 6. These findings are consistent with previous studies [12, 21, 24, 39, 41, 42, 43]. A decrease in the density of cube and cylindrical concretes by 10% and 7% respectively was caused by the 30% increase of the PET, as a result of the PET plastic's low density. This modest reduction in dry density can be of benefit where a considerably great concrete structure is to be built on a weak soil [21]. The bulk density reduction of 13.75% between the PET plastics and the fine aggregates [37], the bulk density reduction of 37% between the PET plastic and the granites, and the increased pore formation due to the PET plastic [12], resulted in an overall reduction in density. Also, the laundry wastewater may have introduced air bubbles or other gases into the concrete, increasing porosity and reducing dry density.

Table 6 illustrates that cylindrical concrete samples with 5% and 10% replacement at 28 days exhibited the same density of 2612 kg/m^3, while samples with 15% and 20% replacement had the same density of 2569 kg/m^3. The cube samples had densities reducing from 2497 kg/m^3 for the sample with 5% replacement to 2390 kg/m^3 for the sample with 30% replacement. Generally, Table 6 shows a decrease in dry density values and an increasing PET waste content for both cube and cylindrical concrete samples.

Table 6: Dry density

% of pulverized PET	Cube Density (kg/m^3)	Cylinder Density (kg/m^3)
0	2667	2654
5	2497	2612
10	2469	2612
15	2454	2569
20	2439	2569
25	2420	2548
30	2390	2463

3.3.2 Test on compressive strength

Figure 5 illustrates the graph of compressive strength plotted against the different percentages of PET waste when left to cure for 7, 14 and 28 days. The results show a steady compressive strength increase with curing age, alongside a compressive strength decrease as the PET percentages increase. At 28 days, the control sample experienced a 10% increase in compressive strength, while the PET-modified mixes exhibited decreases of 5.75%, 7.5%, 10.55%, 13.5%, 15.25%, and 17.75% with 5%, 10%, 15%, 20%, 25%, and 30% pulverized PET mix, respectively. At day 7 of curing, the result of the test on compressive strength showed that the PET-modified mixes achieved the target strength, and failed to achieve it when the test was carried out on the other curing days. This decreasing trend aligns with findings from previous studies [6, 18, 37, 42, 43, 44, 45], while others [21, 41, 42] have reported that the compressive strength increased.

Dawood et al. suggested that reasons for improved compressive strength include a low water-to-cement ratio and the PET plastic's size. According to Almeshal et al., low modulus of elasticity ratio between the PET plastic and natural aggregates, reduced water absorption, increased pores and voids have resulted in a decreased compressive strength. Additionally, the decrease in results obtained can be attributed to the high level of organic compounds in the laundry wastewater, which can interfere with cement hydration and reduce strength.

3.3.3 Test on split tensile strength

The test on split tensile strength was conducted on the concrete cylinders. The results depicted in Figure 6 indicate that the split tensile strength at 28 days decreased as the replacement percentage increased up to 10%, increased at 15%, then decreased up to 25%, and subsequently increased at 30% to reach the same value of 1.4 MPa as the control sample. This result agrees with the result stated Dawood et al. Generally, split tensile strength increased with increased curing days, except for the 5% PET replacement, where a decrease in split tensile strength at 28 days was observed.

The trend observed in this study contradicts findings from other studies [12, 20, 39, 42, 44]. Black

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suggested that the weak interfacial zone which exists between the particles of the PET plastic and the cement was the cause of the decrease split tensile strength. On the other hand, Dawood et al. stated that because PET plastic possessed sharp edges which causes reduced slipping, the split tensile stress is increased. The laundry wastewater may alter the cement paste composition, leading to changes in the cement paste density and reduced tensile strength.

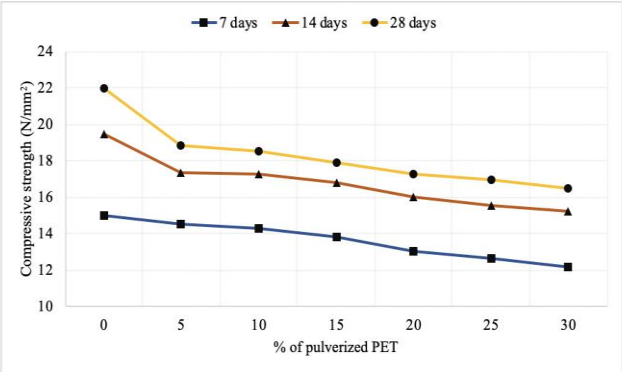

Figure 5: Result for compressive strength tests

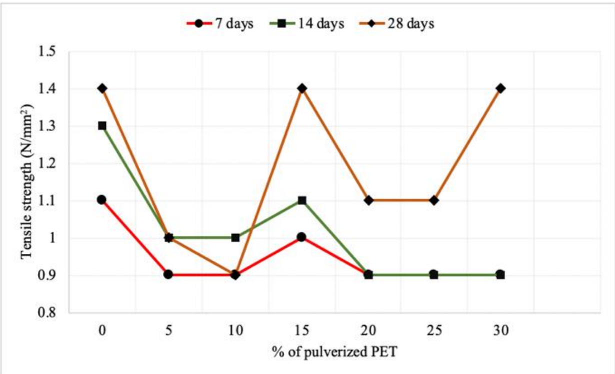

Figure 6: Result for tensile strength tests

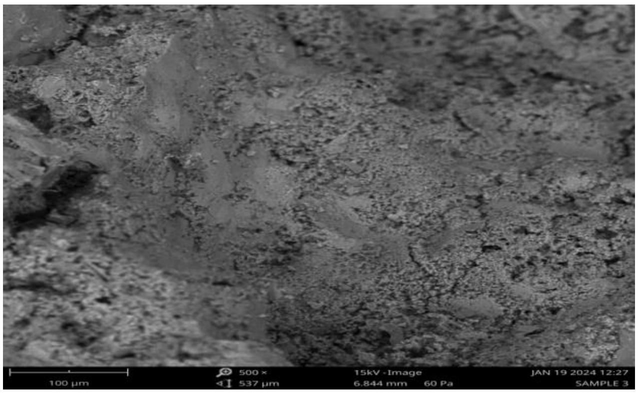

Figure 7: SEM of concrete with 10% PET

3.4 Scanning Electron Microscopy (SEM)

The SEM experiment depicted in Figures 7 and 8 shows the impact of 10% and 15% pulverized PET on the surface structure of the resulting concrete, the 5% and 25% pulverized PET sample gave a similar result as the 10% and 15% pulverized PET respectively. Similar to observations by Black [12], the surface of the pulverized PET exhibits characteristics akin to a porous material. Figure 7 shows that the Ordinary Portland Cement (OPC) bonds satisfactorily with the 10% PET plastic aggregates. Conversely, Figure 8 reveals that by increasing the PET plastic, the OPC and the PET aggregates had honeycombs and large pore spaces because of the weak interfacial transition zone (ITZ) formed [20].

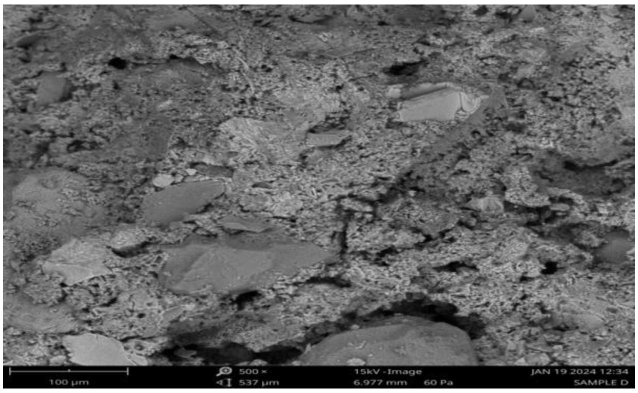

Figure 8: SEM of concrete with 15% PET

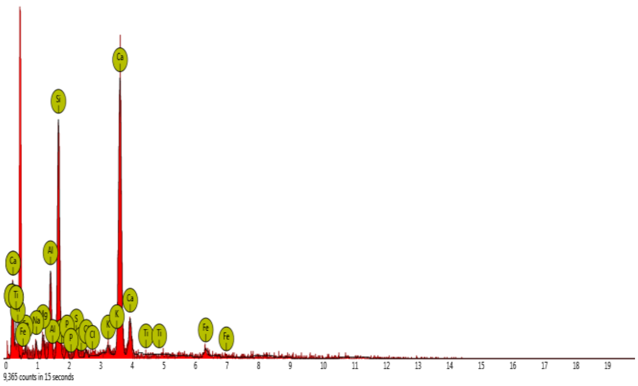

Figure 9: EDX Spectrum of concrete with 10% PET

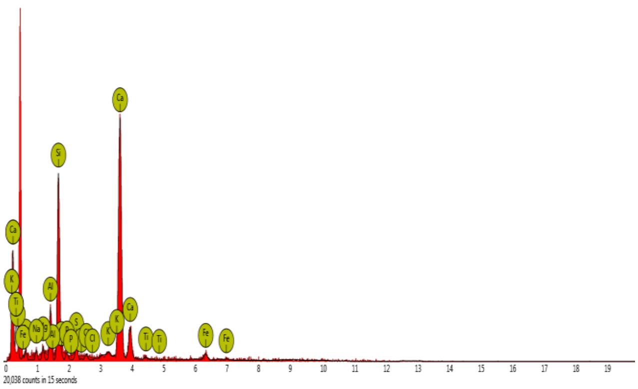

Figure 10: EDX Spectrum of concrete with 15% PET

3.5 Energy - Dispersive X-Ray Spectroscopy (EDX)

The EDX analysis revealed that the X-ray emitted produced a variation in the chemical compositions of individual samples at different spots [20]. Both 10% and 15% PET-modified composites exhibited higher quantities of Ca and Si, along with negligible percentages of Fe, Ti, Cl, Al, K, Na, and P, as depicted in Figures 9 and 10. Tables 7 and 8 present the EDX elemental intensity results for the 10% and 15% PET compositions, respectively.

Table 7: EDX elemental result for 10% PET

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
20	Ca	Calcium	50.22	57.58
14	Si	Silicon	24.84	19.96
13	Al	Aluminum	8.60	6.64
26	Fe	Iron	3.03	4.83
11	Na	Sodium	3.90	2.57
16	S	Sulfur	2.68	2.46
12	Mg	Magnesium	2.98	2.07
15	P	Phosphorus	1.45	1.28
17	Cl	Chlorine	1.95	1.07
19	K	Potassium	0.70	0.79
22	Ti	Titanium	0.54	0.75

Table 8: EDX elemental result for 15% PET

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
20	Ca	Calcium	45.44	53.44
14	Si	Silicon	25.43	20.96
13	Al	Aluminum	11.17	8.84
26	Fe	Iron	2.67	4.37
11	Na	Sodium	4.88	3.39
16	S	Sulfur	4.34	3.10
12	Mg	Magnesium	2.17	2.04
15	P	Phosphorus	1.75	1.59
17	Cl	Chlorine	1.19	1.37
19	K	Potassium	0.96	1.00
22	Ti	Titanium	0.00	0.00

3.6 Statistical Analyses

3.6.1 Correlation

Correlation was conducted to explore the variable's potential relationships. Pearson correlation coefficients (r) were calculated and are presented in Table 9. The % of pulverized PET exhibited a small positive correlation with Tensile Strength (r = 0.146), a high negative correlation with compaction factor (r = -0.699), and very high negative correlations with slump (r = -0.975) and compressive strength (r = -0.905). The compressive strength demonstrated very high positive correlations with slump (r = 0.837) and compaction factor (r = 0.841). Tensile Strength showed a small negative correlation with slump (r = -0.161), and small positive correlations with compaction factor (r = 0.255) and compressive strength (r = 0.150).

A simultaneous increase between two variables indicates a positive correlation, while a negative correlation means that an increase in one variable gives a resultant decrease in the other variable. It's important to note that causality (cause and effect relationship) cannot be implied from correlation, rather it explains to what the degree the variables are connected.

Table 9: Correlation Coefficient Matrix

Parameters	% of pulverized PET	Slump (mm)	Compaction Factor	Compressive Strength	Tensile Strength
% of pulverized PET	1				
Slump (mm)	-0.975	1			
Compaction Factor	-0.699	0.687	1		
Compressive Strength	-0.905	0.837	0.841	1	
Tensile Strength	0.146	-0.161	0.255	0.150	1

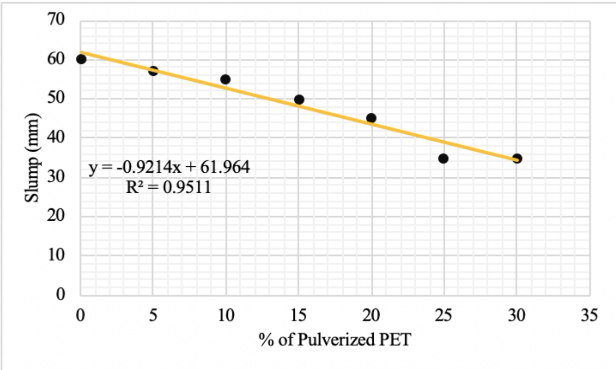

Figure 11: Slump and % of pulverized PET

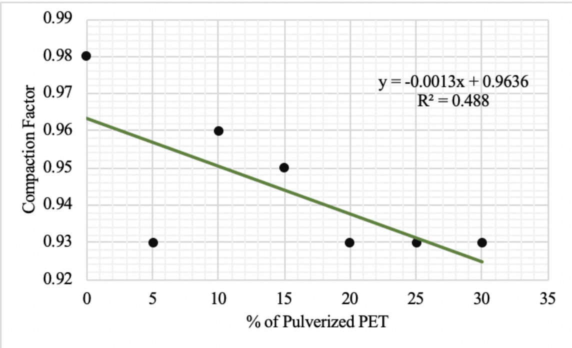

Figure 12: Compacting factor and % of pulverized PET

3.6.2 Regression

Single linear regression (SLR) analyses were conducted to predict the dependent variables using only the independent variable (% pulverized PET). Figures 11 to 14 shows the trend functions and mathematical models from the regression analyses. The linear model for slump as a function of the % of pulverized PET exhibited an R^2 value of 0.9511, indicating that 95% of the variations in slump are explained by the independent variable % of pulverized PET (Figure 11). Similarly, the linear model for compaction factor as a function of the % of pulverized PET showed an R^2 value of 0.488, explaining 48.8% of the variations in the compaction factor (Figure 12). For compressive strength, the linear model as a function of the % of pulverized PET yielded an R^2 value of 0.8189, indicating that 81.89% of the compressive strengths' variation are explained by the independent variable % of pulverized PET (Figure 13). However, the quadratic model for tensile strength as a function of the % of pulverized PET resulted in an R^2 value of 0.2766, indicating that only 27.66% of the variations in tensile strength are explained by the independent variable % of pulverized PET (Figure 140). This suggests that the model for tensile strength is not a good fit, indicating that % of pulverized PET may not be a strong predictor for tensile strength. In summary, the models for slump and compressive strength are deemed to be very good fits, while the model for the compaction factor is considered a considerably good fit. However, the model for tensile strength is not a strong fit. Further details of the regression analyses are provided in Table 10.

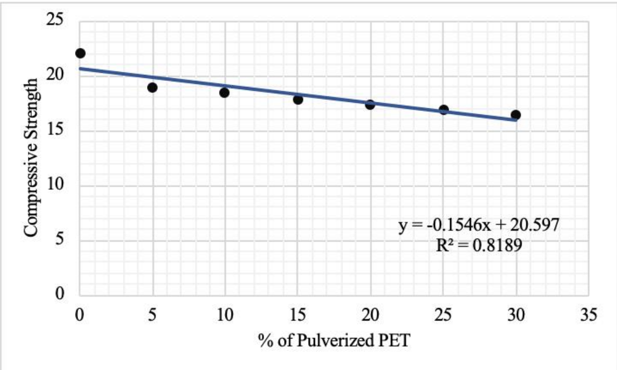

Figure 13: Compressive strength and % of pulverized PET

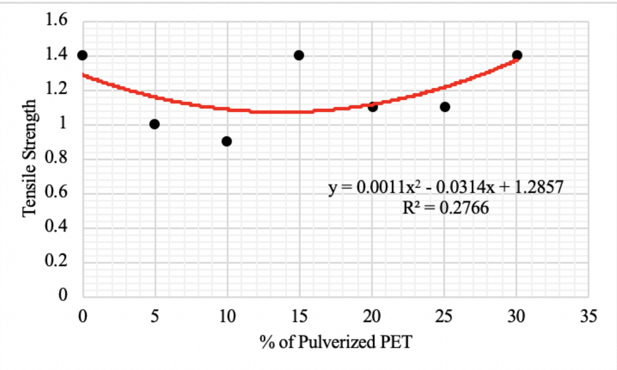

Figure 14: Tensile strength and % of pulverized PET

Table 10: Summary of regression

Criterion	Predictor	Regression Model	R^2
Slump (Sl)	PET	Sl = -0.9214 PET + 61.964	0.95
Compaction Factor (CF)	PET	CF = -0.0013 PET + 0.9636	0.49
Compressive Strength (CS)	PET	CS = -0.1546 PET + 20.597	0.82
Tensile Strength (TS)	PET	TS = 0.0011 PET^2 - 0.0314 PET + 1.2857	0.28

4.0 CONCLUSION

In this study, a 50% reduction in concrete workability was recorded from the 30% PET modified concrete with reference to the control mix. Additionally, while the reference concrete mix experienced 10% compressive strength increase, the presence of PET led to reductions of 5.75% and 17.75% for the 5% and 30% pulverized PET mixtures, respectively by the 28th day of curing. Moreover, the split tensile strength gave an irregular pattern of decrease and increase as the percentage of PET increased. SEM analysis of the 15% PET sample revealed the OPC and PET aggregates formed a weak interfacial transition zone (ITZ).

Laundry wastewater contains contaminants that may affect the fresh and hardened properties of concrete, including compressive strength, tensile strength, and dry density. However, with preliminary treatment and monitoring of the concrete's properties, these effects can be minimized. The regression analysis indicated that the percentage of pulverized PET was a good predictor for slump and compressive strength.

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