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Waste Polyethylene Terephthalate (PET) as a Partial Replacement of Aggregates in Sustainable Concrete

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Abstract: Concrete use is enhanced daily due to infrastructure development, but it has adverse impacts on the environment. Modern lifestyles have led to the increased use of plastic, and, for households, polyethylene terephthalate (PET) plastics are used. However, PET is non-biodegradable and causes adverse impacts on the environment and marine health. So, there is a need to minimize the amount of plastic waste by finding an alternative use for the waste. Our study focuses on creating sustainable concrete by utilizing PET-based plastic waste as a partial substitution for aggregates, aiming to use this concrete for various low-load-bearing construction applications. From our phase analysis study, no adverse effects were found on cement phase formation. We also found that up to 10 wt.% PET incorporation leads to acceptable compressive strength reduction as per ASTM guidelines. To enhance adhesion, the PET was roughened, and, from FESEM, we found effective adhesion of PET waste into the cement matrix. We believe that this sustainable concrete will not only contribute to waste reduction but also promote eco-friendly construction material development.

Keywords: sustainable concrete; waste plastic; compressive strength; aggregate replacement

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1. Introduction

Concrete is considered the second most widely utilized material worldwide after water and its demand is increasing for various construction purposes [1,2]. However, concrete production has a negative environmental impact [3,4]. Concrete is made of cement, water, and aggregates, which provides it strength [5,6]. However, the production of concrete using cement and aggregates produces carbon dioxide and hampers our ecosystem [7–10]. Hence, there is a need to develop an alternate strategy to produce eco-friendly concrete [9,10]. The United Nations environmental program declares the construction sector as *"the toughest to decarbonize"* [11]. It encourages the use of industrial and household waste materials to fabricate sustainable construction materials. The major research question posed in this work is, "Can we design sustainable concrete with acceptable mechanical properties using household plastic waste?"

Plastics are an easily accessible and cheap material [7,12]. The use of plastic in shopping bags or packing materials is increasing daily [7]. Every year throughout the world, the amount of plastic waste produced is more than 359 million tons [7,13,14]. Modern lifestyles produce more plastics, leading to environmental problems as plastics are non-biodegradable and remain in the environmental ecosystem for hundreds of years [5,7,15]. It also has a negative influence on human health and the food chain [7,16,17]. As such, it is necessary to repurpose plastic waste to minimize environmental impact. There are various ways to reduce plastic waste [7], including dumping, recycling, and incineration [7,18]. In the incineration method, energy is produced from waste and that waste then produces clinker by heating limestone [7,19,20]. However, plastic is mainly hydrocarbon, and it releases carbon dioxide upon burning [7,21]. Many of those waste materials are dumped in open places instead of landfilling [15,21]. The utilization of plastic waste in the construction industry is a novel approach [22]. Our goal is to repurpose plastic waste as a sustainable material during concrete manufacturing as a replacement for aggregates. The hypothesis is that the long shelf-life of plastic waste will make it a novel alternative for partially replacing the aggregates in concrete [7,23,24]. The advantages of using plastic waste are that it is low in cost and that this approach helps to resolve the issues with plastic waste disposal [7,25]. Plastic could be used to produce eco-friendly concrete and be used in building construction as non-structural/low load-bearing components [7,26,27].

Household plastic bottles are usually composed of polyethylene terephthalate (PET), which is a polyester composed of terephthalic acid and ethylene glycol [15,28,29]. PET has a varieties of applications such as food packaging, water bottles, etc. due to its non-reactivity and high stability [30]. However, these are non-biodegradable and remain in the ecosystem t for centuries [31,32]. Excessive use of PET can pose an environmental challenge [30]. To dispose of PET, different methods can be used, including recycling, burial, and incineration [15,30,31]. As PET takes hundreds or thousands of years to degrade, recycling is the most environmentally friendly method [15]. However, according to United States Environmental Protection Agency data from 2018, only 29.1% of used plastic bottles and jars are recycled in the US [33,34]. A few prior works have reported that when PET is added to concrete, its workability reduces [15]. Concrete could be made lightweight by using a 0 to 20% volume of plastic [7]. There are two ways to use plastic waste in concrete. The first is by using plastic waste as fibers, while the second is using plastic waste as partial substitutive aggregates [7,35]. However, the optimization of the amount of PET in concrete is a crucial factor that significantly influences its properties. In this regard, the hydrophobic nature of PET poses challenges in terms of bonding with the cement matrix and may produce an inferior concrete.

Concrete's properties depend on the aggregates used as it contains 60–80% aggregates [23]. Compressive strength defines the quality of the concrete structure [36]. Some previous studies have used waste PET as a partial substitution of coarse aggregates in concrete [37–39]. All those studies reported that the substitution of coarse aggregates with a high amount of plastic can reduce concrete's compressive strength due to the hydrophobic properties of plastic aggregates and the weak bond between plastic and concrete [23,36–39]. If the amount of PET is more than 50% then the mechanical properties will decrease sharply [15]. To mitigate these challenges, in our study, we used an optimized amount of PET as a partial substitution of coarse aggregates in the concrete to study mechanical properties, phase analysis, and surface adhesion. As a novel strategy, we performed mechanical roughening of the PET surface to ensure good binding with the cement matrix and validated the adhesion with FESEM. Hence, the novelty of this study is increasing surface adhesion between PET and concrete while also reducing negative environmental effects due to improper PET waste disposal.

2. Materials and Methods

2.1. PET Waste Aggregate Preparation

Waste PET bottles were collected and their labels were removed before undergoing a thorough washing to eliminate any contaminants. Subsequently, the PET bottles were shredded into uniform sizes between 4.75 mm and 10 mm. To improve the adhesion between the PET and the cement matrix, the surfaces of the shredded PET plastics were roughened using 120-grit sandpaper. The prepared PET waste was then utilized as a partial replacement for coarse aggregates in the concrete, providing a sustainable option for incorporating recycled materials into construction practices. Figure 1a shows the PET waste after shredding. Concrete sample preparation with PET waste as a partial substitution is shown in Figure 1b.

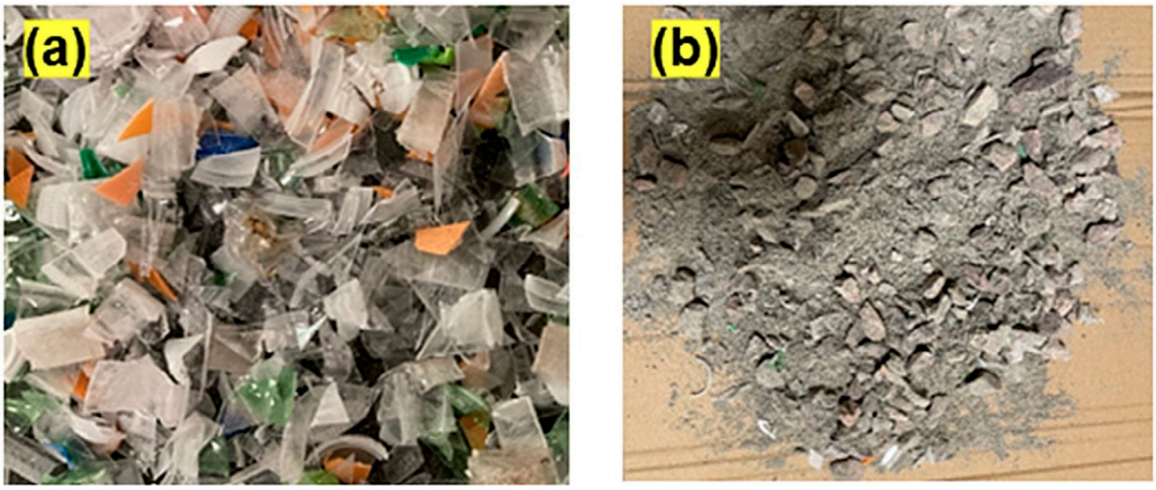

Figure 1. (**a**) PET waste after shredding. (**b**) concrete sample preparation with PET as a partial.

2.2. Concrete Sample Preparation with Waste PET

The materials used in this study included cement, fine aggregate, coarse aggregate, recycled PET waste as a substitution for coarse aggregate, and water. The PET aggregate was incorporated at substitution levels of 5%, 10%, and 15%.Wt. The PET aggregate was surface treated to enhance its bonding properties within the cement matrix. The concrete mix design followed the M20 grade specification by ASTM, with a mix ratio of 1:1.5:3 (cement: fine aggregate: coarse aggregate) and a water-cement ratio of 0.48, as shown in Table 1. The mixing was conducted manually, with water gradually added to the dry materials to ensure thorough blending of all components. The mixed concrete was then cast into cylindrical molds measuring 3 × 6 inches. The concrete was allowed to initially cure in the molds for 24 h. After the initial curing period, the samples were de-molded and subjected to water curing at room temperature for 28 days to ensure full hydration and optimize the mechanical properties of the concrete as per the American Society for Testing of Materials (ASTM) C31/C31M. The masses of the concrete samples were measured after 28 d of curing and the density was computed by dividing the mass of the prepared concrete samples by their volume. Figure 2 shows the process schematic of partially PET substituted concrete sample preparation followed by compressive strength assessment.

Table 1. Concrete mix design.

PET Replacement	W/C Ratio	Water (g)	Cement (g)	Fine Aggregate(g)	Coarse Aggregate (g)	PET Aggregate (g)
0%	0.49	441	900	1350	2700	0
5%	0.49	441	900	1350	2565	135
10%	0.49	441	900	1350	2430	270

2.3. Compressive Strength Test

The compressive strength measurement was performed after curing the concrete for 28 d. The test was conducted using an ELE International ADR compression machine. This test is a critical step in assessing the mechanical properties of concrete, providing essential data on its ability to withstand compressive loads. The test procedure involved subjecting the concrete cylinders to progressively increasing compressive loads until the point of failure. Proper alignment is crucial to obtaining accurate and consistent results. The load at failure is measured in pounds-force (lbf), which denotes the maximum load that the concrete can tolerate before fracturing. To calculate the compressive strength, the maximum load at failure is divided by the cross-sectional area of the concrete. The compressive strength values obtained provide information about the performance of various concrete mixes.

$$\text{Compressive Strength} = \text{Maximum Load (N)}/\text{Cross-sectional area (m}^2) \quad (1)$$

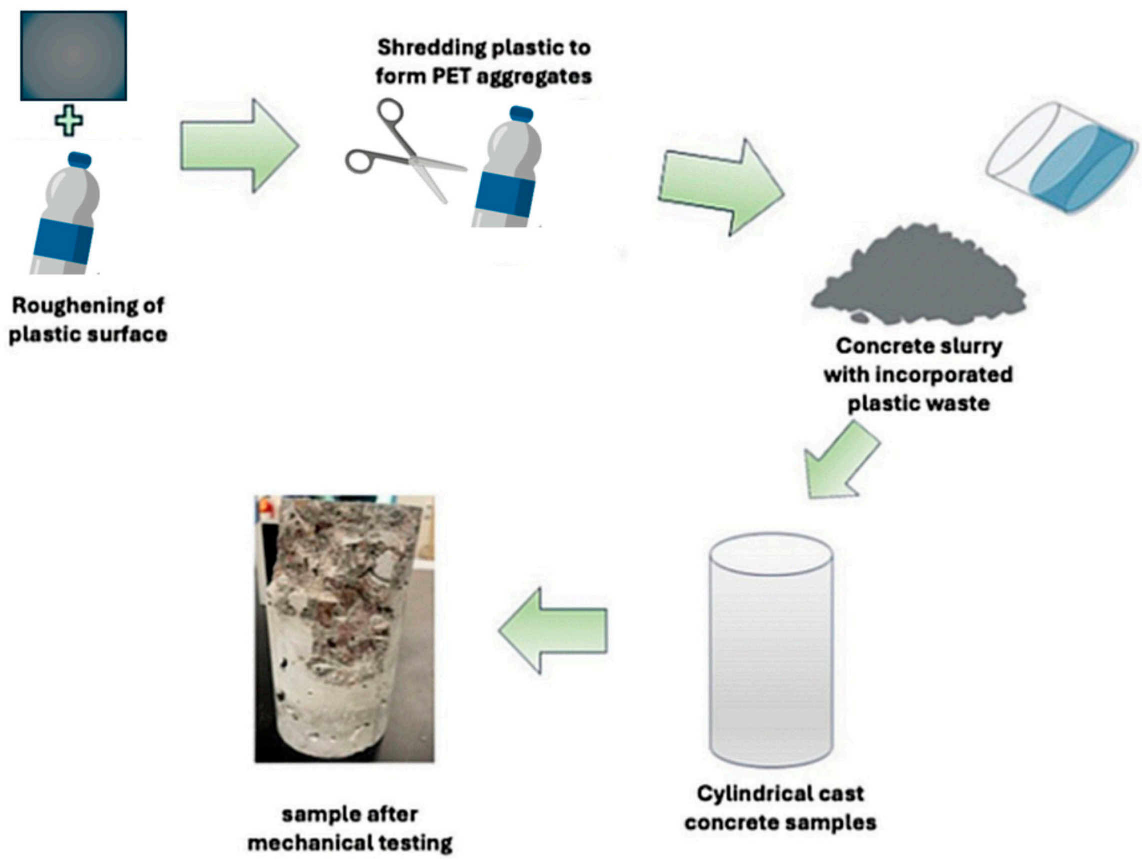

Figure 2. Process schematic of partially PET substituted concrete sample preparation followed by compressive strength assessment.

2.4. Phase Analysis

X-ray diffraction (XRD) analysis was performed on both control and PET concrete samples after a curing period of 28 days. The X-ray analyses were performed using a PANalytical Empyrean diffractometer equipped with CuKα radiation (wavelength = 1.54 Å). The measurements were taken with a step size of 0.015° and a dwell time of 400 s per step, focusing on the 2θ interval from 20° to 60°. Fourier Transform Infrared Spectroscopy (FTIR) was performed on the samples using a Thermo Scientific Nicolet Is50 FTIR instrument. The samples were scanned over a range of 500 to 4000 cm^{-1}. Each sample underwent 32 scans, with multiple samples tested for consistency.

2.5. Microstructural Analysis with Field Emission Scanning Electron Microscopy (FESEM)

FESEM was performed using a JEOL JSM-7600F field emission scanning electron microscope to examine the surface topology of the samples. Before conducting FESEM, coating of the samples was carried out with a thin layer of platinum to enhance conductivity. Images were captured at various magnifications and working distances to obtain detailed morphological information across different scales. The image acquisition was carried out at 15 kV of accelerating voltage and a probe current of 50 nA.

3. Results

The process schematic starting from roughening plastic surface, incorporation into sustainable concrete, and testing of mechanical properties are shown in Figure 1.

The density of the concrete specimens was determined under dry conditions at 28 d prior to the compressive strength testing. The average density values measured were 2429.25 ± 21.25 kg/m^3 for the control specimens, 2397.0 ± 9.13 kg/m^3 for the specimens with 5% PET aggregate replacement, and 2345.25 ± 41.71 kg/m^3 for the specimens with 10% PET aggregate replacement, as shown in Figure 3a and Table 2. A slight decrease in density was observed with increasing PET aggregate content, indicating the lower specific gravity of PET in comparison with natural aggregates. Compressive strength assessment was performed on the concrete specimens after a 28-day curing period. The compressive strength data is shown in Figure 3b. A slight reduction in compressive strength was observed with the incorporation of PET aggregates as compared to the samples without any PET incorporation. The average compressive strength values were 22.99 ± 0.59 MPa for the control specimens, 21.68 ± 0.81 MPa for the specimens containing 5% PET aggregate replacement, and 20.62 ± 0.87 MPa for those with a 10% PET aggregate replacement.

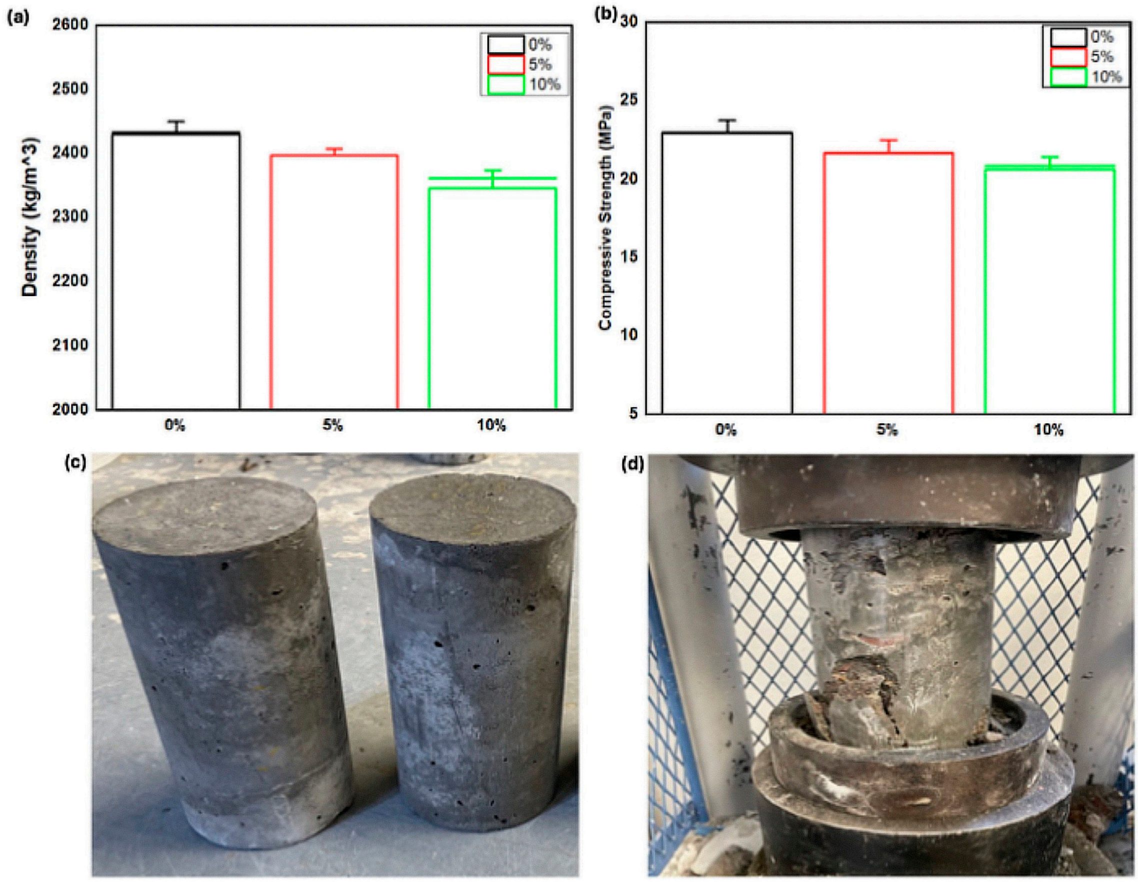

Figure 3. (**a**) Density plot of concrete samples, (**b**) Compressive strength plot of concrete samples, (**c**,**d**) image of concrete sample before and after failure during compression test.

Table 2. Density and compressive strength results.

Percent of Pet Aggregate	Water Cement Ratio	Density (Kg/m^3)	28 Days Compressive Strength (MPa)
0	0.48	2429.25 ± 21.25	22.99 ± 0.59
5	0.48	2397.0 ± 9.13	21.68 ± 0.81
10	0.48	2345.25 ± 41.71	20.62 ± 0.87

X-ray diffraction (XRD) analysis of the concrete samples (Figure 4a) both with and without PET revealed key phases. Peaks at 18° and 34° 2θ confirmed the presence of Portlandite (Ca $(OH)_2$), while a broad signal around 20° 2θ was attributed to Calcium Silicate Hydrate (C-S-H). A sharp reflection at 26.6° 2θ indicated Quartz (SiO_2) from the aggregates and a peak at 29.5° 2θ signified Calcite ($CaCO_3$), suggesting carbonation. Peaks at 40° and 50° 2θ were assigned to Alite (C_3S). These phases indicate typical hydration and carbonation processes, with potential variations due to PET inclusion. The FTIR plot in Figure 4b shows key peaks at 1050 cm^{-1} for C-S-H stretching, at 1420 cm^{-1} wavenumber the peak showed CH_2 bending, C=O stretching was observed at 1710 cm^{-1}, and C-H bending and O-H stretching were observed at 2820 cm^{-1} and 3540 cm^{-1}, respectively. The various peaks confirm that the cement matrix was not disrupted by the PET aggregate.

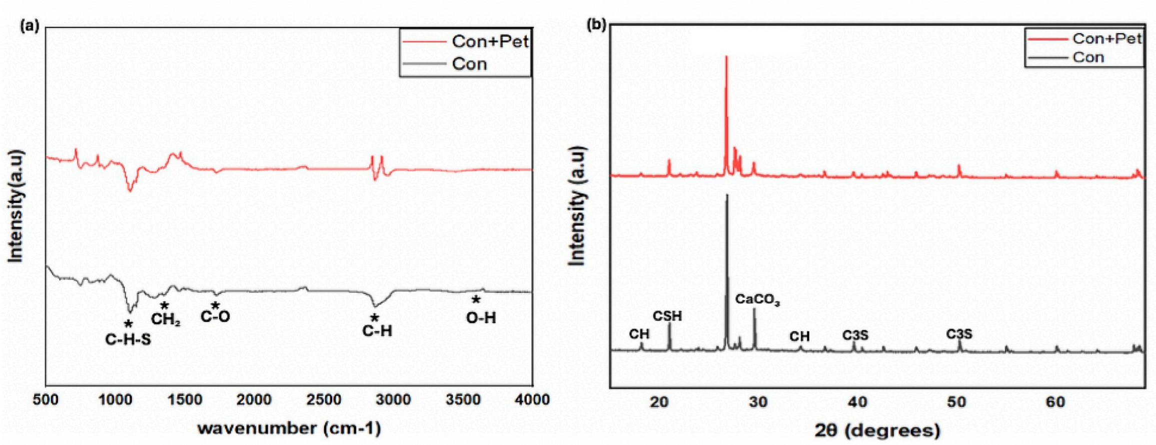

Figure 4. (**a**) FTIR Plot of Concrete and Concrete + PET, (**b**) XRD plot of concrete and concrete + PET.

The SEM analyses of concrete samples with PET aggregate in Figure 5a,b show distinct differences in the bonding behavior between PET and the cement matrix compared to natural aggregate. The PET showed a less bright and more blurred region, as well as a relatively smooth surface with less bonding at the interface with the cement paste. In contrast, natural aggregate exhibited stronger, more cohesive bonding with the cement. Overall, the PET-cement interface displayed an improved interaction due to the surface treatment.

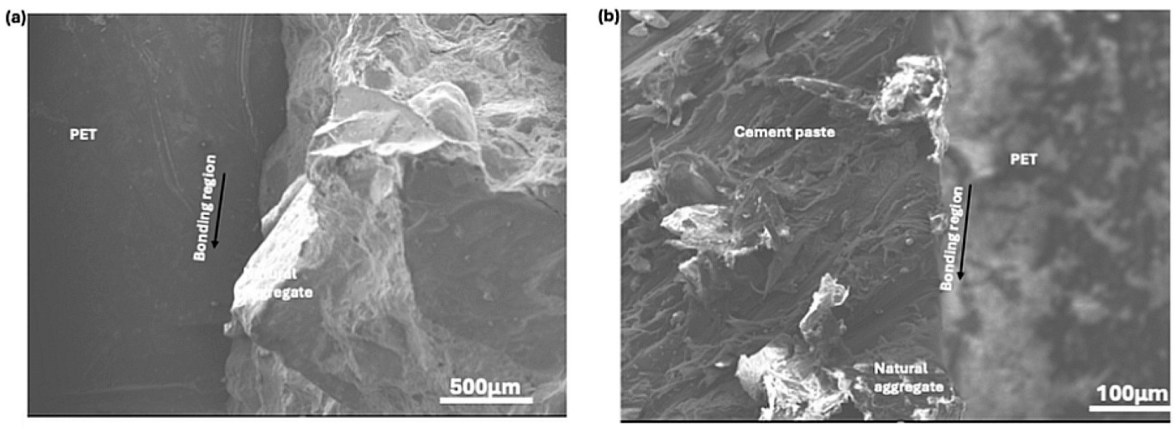

Figure 5. (**a**,**b**) SEM images showing PET aggregate in concrete matrix.

4. Discussion

4.1. Compressive Strength Because of PET Incorporation in Concrete

Compressive strength defines the quality of concrete structure [36]. High amounts of plastic waste can reduce concrete's strength because of the hydrophobic nature of PET aggregates and the weak bond between plastic and concrete [40]. One recent work evaluated that compressive strength reduces with increasing volume of plastic fiber [36]. Another work studied various factors affecting compressive strength and found that compressive strength decreases when PET volume increases and that this is attributed to the reduction in binding and adhesion between cement paste and the aggregate in the presence of PET [36]. Replacing natural aggregate with PET results in a reduction in compressive strength [36]. If the number of fine aggregates replaced is 15% then workability reduces by 40% [36]. Our compressive strength results (Figure 3b) show a slight reduction in compressive strength as a function of PET incorporation than that of the control. The control sample exhibited the highest compressive strength of 22.99 ± 0.59 MPa, while the specimens with 5% and 10% PET substitution showed slight reductions, at 21.68 ± 0.81 MPa and 20.62 ± 0.87 MPa, respectively. The observed strength reduction can be attributed to the less strong bonding at the PET-cement interface and the elastic modulus mismatch between PET and the cementitious matrix in comparison to the natural aggregates and the cement matrix [41]. While the compressive strength of PET-modified concrete is slightly lower than that of the control, the results remain within an acceptable range for certain structural applications, particularly where weight savings and sustainability are prioritized. Additionally, our PET incorporation is in terms of wt. % as compared to vol. % used in some prior studies. Hence, our results show that even with a higher amount of PET addition, the decrease in compressive strength is not very significant. The slight decrease in density with increasing PET content (Figure 3a) is due to the lower specific gravity values of PET in comparison to natural aggregates. The decrease in density can be advantageous for applications that require lightweight construction materials [42].

4.2. Enhancing the Bonding Between PET and Concrete and Phase Analysis

The topographical imaging analyses with the SEM revealed the distinct differences between the PET-cement interface and that of the natural aggregate (Figure 5). PET aggregates usually have a smoother surface and are hydrophobic, which makes them exhibit less bonding compared to natural aggregate [43]. The surface treatment of PET aggregates resulted in improved interaction with the cement matrix as observed by the SEM. The roughened PET surfaces showed improved adhesion, which is critical for the material's structural integrity. The improvement in bonding with surface treatment is promising and is a novel contribution of this work, though further optimization is needed to enhance the overall performance of PET concrete. Our results also indicate no adverse effects on the hydration reaction of cement as a result of PET addition. The XRD analysis (Figure 4a) confirmed the presence of key hydration products such as Portlandite ($Ca(OH)_2$), C-S-H, and Alite (C_3S) across all samples. This indicates that the utilization of PET aggregates did not significantly alter the hydration processes of the cement. The observation of Quartz (SiO_2) and Calcite ($CaCO_3$) show the contributions of aggregate and carbonation effects. These findings suggest that the integration of PET into the concrete matrix does not interfere with the normal hydration and carbonation processes critical for strength development. The FTIR analysis further confirmed the chemical stability of the matrix, with characteristic peaks for C-S-H stretching and O-H stretching. The absence of new peaks or shifts in the spectra indicates that the presence of PET aggregates does not disrupt the chemical composition of the cement matrix.

4.3. PET Reinforced Concrete as a Novel and Sustainable Construction Material

Improper disposal of PET, microplastic generation, and a very slow rate of degradation lead to significant environmental challenges in terms of public health, land fertility, and marine health [44]. On the other hand, the building and construction materials sector is not only a significant contributor to the carbon emission footprint of the world but also "*the toughest to decarbonize*", as mentioned by the UNEP [10,45]. Hence, interest is growing in using various waste materials in the construction industry [10]. In this regard, our sustainable approach is to use PET waste as a partial substitution of aggregates in concrete. This will help to resolve two issues: (i) mitigation of environmental challenges related to improper PET disposal, and (ii) reducing the carbon emission footprint of concrete manufacturing [10]. Most importantly, the use of PET in concrete has a positive role in the circular economy by repurposing plastic waste, which addresses two critical issues: the exhaustion of natural resources and the environmental influence of plastic waste [10,46]. By partially replacing natural aggregates with PET, the building and construction industry can minimize its reliance on virgin natural materials and mitigate the negative environmental effects of plastic waste [47]. However, the balance between the environmental benefits and mechanical performance must be carefully tailored. Our study shows that the novel processing of PET waste through surface roughening contributes to acceptable compressive strength reduction of the final concrete structure and enhances the bonding at the cement and PET interface. This sustainable and alternative concrete can find application as a low-load-bearing structural material in construction. Our future work will be directed toward fabricating PET fiber-reinforced concrete and the assessment of its mechanical properties as a function of fiber replacement and orientation.

5. Conclusions

This study aimed to create sustainable concrete to minimize the negative impacts of plastics and aggregates on the environment. We hope that this study will contribute to promoting eco-friendly construction material fabrication. This investigation demonstrated that up to 10 wt.% PET incorporation leads to compressive strength reduction within an acceptable range as compared to the control sample. To improve the adhesion between the cement matrix and the waste plastic surface, roughening was performed. Due to the novel surface roughening of PET, an effective integration between plastic and concrete is noticed in topographical images. Microstructural analysis shows the successful incorporation of PET waste into the cement matrix. Through various physical characterizations, such as FTIR, XRD, density measurement, and mechanical characterization, our findings highlighted that compressive strength was within an acceptable range, that effective bonding between plastic and aggregates occurred, and that there were no adverse effects on cement phase formation after partial replacement of aggregates with PET. Phase analysis shows no adverse effects on cement phase formation and hydration due to the optimized amount of PET waste incorporation. In summary, our work indicates that sustainable concrete with PET partially replacing natural aggregate can be used for low-load-bearing structural applications.

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Data Availability Statement: Data reported in this paper will be made available upon reasonable request to the corresponding author.

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Conflicts of Interest: The authors declare that there are no conflicts of interest or known financial interests/personal relationships that could have appeared to influence the current work of this paper.

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