

A Novel Approach in the Utilization of Waste Plastic with Enhanced Surfaces as Fine Aggregates in Concrete Production

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ABSTRACT

This paper proposes a novel approach incorporating Polyethylene Terephthalate (PET) with enhanced surfaces as a fine aggregate replacement in concrete production. The PET surfaces were enhanced by being covered with cement or Silica Fume (SF) and kept inside a microwave for a specific time period. Concrete mechanical properties were examined, with its fine aggregate being replaced by PET in volume ratios of 10%, 15%, and 20%. The results demonstrated that the proposed approach significantly improved concrete properties, with an enhancement in compressive strength and a decline in water absorption having been observed. This research provides a promising roadmap for effective, sustainable construction practices.

Keywords-Polyethylene Terephthalate (PET); plastic waste; concrete; mechanical properties

I. INTRODUCTION

Millions of tons of plastic waste are dumped into oceans and landfills, destroying ecosystems and threatening animal lives [1–9]. Approximately 369 million tons of plastic waste are generated annually, while this figure may have tripled by 2040 if no action is taken [10]. More than six billion tons of plastic waste have been produced, with only 9% being recycled [11, 12]. Nearly a million tons of plastic waste enter the oceans annually, significantly impacting marine ecosystems [10]. Additionally, the United States alone generated 42 million tons of plastic waste in 2016 [13]. Religious and industrial activities in regions like Iraq, particularly in the Karbala governorate, generate substantial amounts of plastic waste, including PET, which is resistant to environmental degradation. This accumulation not only leads to habitat destruction, but also contributes to soil and water pollution [14–19]. However, like many other industries that rely on natural resources, the construction sector, a main contributor to global waste, is seeking more sustainable methods, as it causes additional harm through carbon emissions and resource depletion [18, 20, 21]. Non-renewable sources of fine aggregates must be replaced as

they are a key building material, affecting concrete's strength and durability. Thus, incorporating plastic waste as fine aggregate is an effective strategy to reduce the former and pollution, along with the negative effects of using conventional concrete [8, 18, 22, 23]. The methods through which plastic waste is transformed, integrated, and utilized in concrete mixes not only provide a solution to the issues of depleting natural resources and plastic waste, but also enhance the properties of the concrete itself, representing a crucial step towards the expansion of the frontiers of eco-friendly construction. Plastic waste, typically a low-value raw material, can be used as fine aggregates in concrete production. However, directly incorporating untreated plastic often negatively impacts concrete mechanical properties and increases water absorption. Therefore, analyzing the technical aspects, experimental results, and potential applications of plastic waste with enhanced surfaces in concrete is necessary. Given the great amount of prior research on this subject, a further investigation into innovative approaches could significantly advance sustainability efforts [6, 16, 24, 25].

Regarding plastic waste practical use, it is essential to utilize its mechanical properties to enhance its suitability for treatment processes that improve surface characteristics and facilitate bonding with the cement matrix. Mechanical methods, such as milling and grinding, can change the particle shape and size of plastic waste, thereby improving its incorporation as a fine aggregate in concrete mixes [1, 2]. Furthermore, compatibilizers have been utilized for surface modification, enhancing the acceptability of cement pastes. These changes not only boost the performance and durability of concrete, but also reduce water absorption and permeability, which are critical for future engineering structures [2]. Exploring enhanced surface treatments for plastic waste is vital for maximizing its use as a fine aggregate in concrete production. Surface treatments can improve the bonding properties of plastics, promoting better integration with cement-based materials [26]. Methods to enhance the surface characteristics of plastic waste have been investigated, including roughness, hydrophobicity, and adhesion, allowing the material to be tailored for various uses. In studies focusing on Low-Density Polyethylene (LDPE) food containers, fine aggregates were replaced with up to 25% LDPE. Both cement mortar and concrete were then inspected, demonstrating their ability to mitigate the environmental impact of plastic waste [27]. Although it was observed that larger plastic sizes correlated with reduced compressive and tensile strengths, overall concrete quality remained at acceptable levels, indicating that LDPE waste can be incorporated without significantly compromising structural integrity [27]. Authors in [28] highlighted that replacing traditional fine aggregates with LDPE can lower concrete density by as much as 30%, reducing structure weight while maintaining adequate strength. Furthermore, PET waste has shown promising results in enhancing compressive and flexural strengths when replaced appropriately, particularly at ratios of 5-10% [29]. The mechanical properties of concrete can be improved using LDPE waste; for instance, substituting up to 25% of fine aggregates with treated LDPE can maintain a compressive strength comparable to that of a conventional concrete mix, despite initial decreases in density and tensile strength [27]. Similarly, employing recycled Unplasticized Polyvinyl Chloride (UPVC) aggregate as a processed fine aggregate in Alkali Activated Materials (AAMs) exhibited enhanced thermal resistivity and mechanical properties, promoting a circular economy while achieving net-zero targets [30]. These improved surface treatments contribute to the sustainability and effectiveness of concrete mixtures, including plastic waste. Additionally, substituting conventional aggregates with Recycled Mixed Aggregates (RMA) offers environmental advantages [27, 28]. PET investigation showed its ability to effectively replace natural sand with a replacement of up to 10%, improving concrete's compressive strength [29]. This combined approach of reducing waste and improving property fosters sustainable building practices, corresponding with initiatives to lessen the environmental effects of plastic pollution. Employing plastic waste as a fine aggregate in concrete manufacturing provides a convincing solution to the environmental challenges and the ever-rising demands of the construction industry. Moreover, the recyclability of these materials represents a broader commitment to sustainability,

particularly in response to growing construction and demolition waste [31-33]. Thus, this approach helps reduce the environmental impact and provides collection points for further research and development aimed at naturally sustainable construction practices.

II. MATERIALS

1) Cement

Cement is a binder-building material that offers stability, strength, and holds other ingredients together. It was tested in the laboratory, and the obtained results complied with the sulfate resistance cement (Type V) of the Iraqi specification standard [34], locally known as Al-Jeser.

2) Fine Aggregate

Natural sand from the Al-Ukaidher region in Karbala City/Iraq with a maximum particle size of 4.75 mm was utilized, complying with [35].

3) Coarse Aggregate

Natural crushed black gravel from Al-Nebbaee region in Baghdad/Iraq of a maximum size of 19.5mm was used as a coarse aggregate, complying with [35].

4) Silica Fume

SF, or microsilica, is a pozzolanic material composed of ultrafine particles of amorphous silicon dioxide (SiO_2) that conform to [36]. It is a by-product of the ferrosilicon alloy and silicon production process, with spherical particles and an average radius of 75 nm. SF is characterized by its high specific surface area (15000 m^2/kg –25000 m^2/kg) and reactivity, making it a valuable addition to concrete.

5) Water

Tap water was used in preparing and curing concrete specimens.

6) PET

PET is a versatile thermoplastic polyester widely used in the packaging and textile industries. It is characterized by its excellent chemical resistance and mechanical properties. This study used recycled PET with a cylindrical shape of 2.5 mm in diameter and 4mm in height, and a smooth surface texture with no porosity, which made it completely waterproof in addition to its hydrophobic nature, as shown in Figure 1.



Fig. 1. Recycled PET (before treatment).

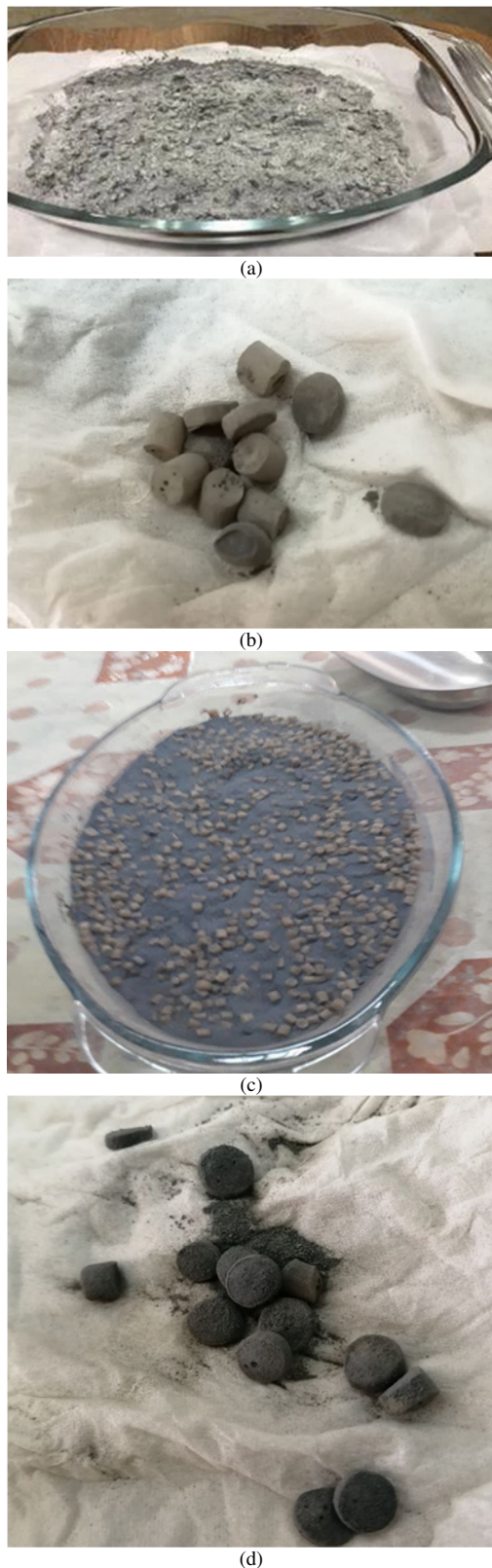


Fig. 2. Roughness preparation of PET surfaces by cement or SF. (a) PET particles immersed in dry cement, (b) PET covered with cement after microwave heating, (c) PET particles immersed in dry SF, (d) PET covered with SF after microwave.

III. ROUGHNESS PROCESS OF PET SURFACES

The adhesion between PET particles and concrete ingredients can be significantly improved by increasing PET surface roughness. This enhancement boosts both the mechanical properties and durability of the concrete. Various methods have been used to improve this adhesion. These include mechanical techniques, like sandblasting or grinding, as well as chemical treatments with acids or alkalis to increase surface reactivity. In this study, a novel and simple approach is introduced. PET particles with smooth surfaces were roughened by direct contact with the dry components of the concrete matrix. Specifically, the PET particles were immersed in dry SF or dry cement powder until fully coated. After coating, the PET particles were placed in a domestic microwave. The microwave had a power of 900 W and a frequency of 2.45 MHz, with a rotating turntable. The particles were heated for 14 min. This controlled microwave treatment caused rapid and localized heating of the binder material on the PET surface. As a result, the binder particles slightly melted and adhered to the PET. This formed a micro-textured surface without deforming or melting the PET particles themselves. Figure 2 illustrates the different stages of this process. Figure 2(a) shows PET particles immersed in dry cement. Figure 2(b) displays the same particles after microwave heating, with cement adhered to their surface. Figure 2(c) depicts PET particles immersed in dry SF. Figure 2(d) shows those particles after microwave treatment, with SF adhered.

IV. MIX PROPORTION

Table I shows the percentages of the used materials (cement, fine aggregate, coarse aggregate, PET, and water) for the ten mixes utilized in the present study. Three weight-replacing percentages of PET waste by fine aggregate were used (10%, 15%, 20%).

TABLE I. MIX PROPORTIONS

No.	Mix designation	Cement kg/m ³	Fine aggregate kg/m ³	Coarse aggregate kg/m ³	PET% by vol.	w/c%
1	Ref.		700		0	
2	Mix-PET10%		630		10	
3	Mix-PET15%		595		15	
4	Mix-PET20%		560		20	
5	Mix-C+PET10%		630		10	
6	Mix-C+PET15%		595		15	
7	Mix-C+PET20%		560		20	
8	Mix-SF+PET10%		630		10	
9	Mix-SF+PET15%		595		15	
10	Mix-SF+PET20%		560		20	
		400		1100		0.45

V. EXPERIMENTAL WORK

A microwave-assisted immersion technique improved the adhesion between the PET particles and the cement or SF particles. First, the PET particles were immersed in dry cement or SF and then subjected to microwave irradiation to produce

roughened PET particles. The microwave energy caused rapid heating and evaporation of the water within the particles, creating a porous layer of cement or SF on their surfaces. These porous layers facilitated mechanical interlocking and chemical bonding with the bulk cement matrix, enhancing the composite material's interfacial strength and overall performance. The experimental program was conducted on a cube with a side length of 10 cm. A total of 270 cubes were cast according to [37], cured, and verified using a universal testing machine. The concrete ingredients were mixed in a pan mixer, with dry components, such as cement, coarse aggregate, and fine aggregate, thoroughly blended before adding the PET with enhanced surfaces. A workable consistency was achieved by stirring the mixtures. The concrete molds were filled in three layers, with each layer compacted 36 times to ensure proper compaction. Specimens were demolded 24 hours after casting and placed in a curing tank for periods of 7, 14, and 28 days.

VI. RESULTS AND DISCUSSION

A. Fresh and Dry Density

Fresh density refers to the density of concrete right after mixing, while it is still in a plastic, workable state. It plays a vital role in mix design because it helps determine the correct proportions of materials needed to achieve the desired properties once the concrete hardens. Fresh density also affects how easily concrete flows and fills molds, which influences construction ease. Variations in fresh density can signal inconsistencies in the mix, potentially impacting the final quality. Dry density, on the other hand, is the density of concrete after it has fully hardened and dried—typically measured after 28 days. It serves as an important indicator of the concrete's strength and durability. Denser concrete is usually stronger and more resistant to water penetration, freeze-thaw cycles, and other environmental factors. Dry density is also essential for structural design and long-term performance evaluation. Concrete density depends mainly on the degree of compaction and the specific gravity of its components. Natural fine aggregate has a higher density than PET waste. As a result, replacing natural sand with PET tends to reduce both fresh and dry densities. The test results showed that fresh density decreased as the percentage of PET replacement increased. When PET replaced natural fine aggregate by 10%, 15%, and 20%, the fresh density dropped by approximately 6.9%, 9.8%, and 12.3%, respectively, compared to the reference mix. Similarly, the 28-day dry density of concrete decreased by 7.3%, 11.2%, and 14.5% for the same replacement levels. This trend is consistent with the findings in [38, 39], where higher PET content led to lower concrete density. A comparable pattern was also observed in lightweight self-compacting concrete containing PET waste. The reduced density is mainly due to the lower specific gravity of PET, which ranges from 0.52 to 1.01 [40–42].

B. Compressive Strength

The compressive strength of the mixes is illustrated in Table II and Figure 3. The highest compressive strength for the mix with 20% PET waste was lower by 9 MPa than that of the reference sample at 7 days. The compressive strength was 19 MPa, lower than that of the control sample at 14 days, and 21

MPa, lower than that of the reference sample at 28 days. This reduction in strength for the 20% PET waste mix is caused by the poor adhesion between PET waste and concrete ingredients. The strength of the concrete mixes increased when the replacement percentage of PET waste decreased. Water accumulates near the PET surfaces, due to the PET waste's insolubility. This revealed that an increase in PET waste improves the strength of concrete up to a specific percentage, however, further addition may decrease strength. PET particles have lower interfacial bonding with the cement matrix than natural aggregates, leading to weaker load transfer. Moreover, PET has a lower modulus of elasticity than natural aggregates, resulting in reduced concrete stiffness. PET particles can introduce voids and increase porosity within the concrete, further weakening the structure. On the other hand, utilizing the proposed roughening technique led to better strength results. For instance, the results were very close to those of the control mix for PET replacements up to 20%. This could be a trend at all ages, possibly due to the better adhesion between roughened PET particles and other concrete ingredients.

TABLE II. COMPRESSIVE STRENGTH RESULTS FOR ALL MIXES

Mix designation	Compressive strength MPa*		
	7 days	14 days	28 days
Ref.	25	29	35
Mix-PET 10%	20	22	25
Mix-PET 15%	18	21	24
Mix-PET 20%	16	19	21
Mix-C+PET 10%	26	28	35
Mix-C+PET 15%	24	28	33
Mix-C+PET 20%	23	26	31
Mix-SF+PET 10%	25	27	34
Mix-SF+PET 15%	22	25	31
Mix-SF+PET 20%	20	23	29

* Every single result represents the meaning of three specimens.

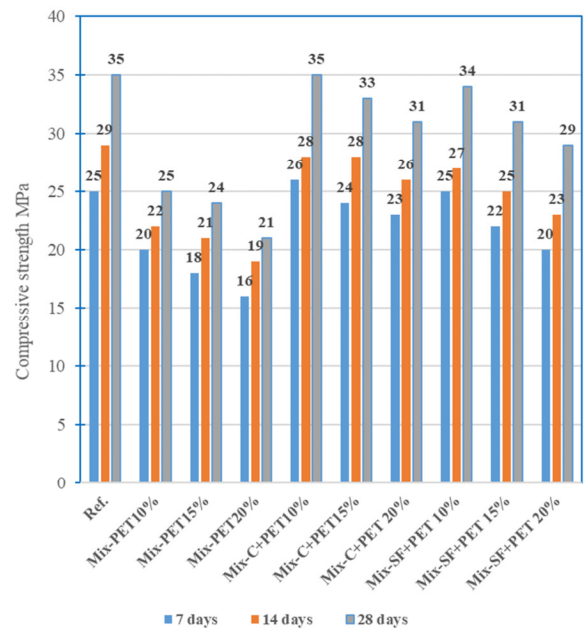


Fig. 3. Compressive strength for all mixes.

C. Water Absorption

Water absorption measures the porosity of a material. It is determined by how much water a material absorbs under specific conditions and is typically proportional to the square root of time. In hardened concrete, porosity can be assessed through water saturation, where water moves through tiny pores in the microstructure [38]. Concrete containing PET aggregates has been tested to evaluate its porosity and its ability to resist steel reinforcement corrosion [39, 43-45]. As demonstrated in Table III, water absorption increases when PET aggregates are added without surface treatment using cement or SF. This agrees with the findings of [39], indicating that water absorption grows significantly as PET content increases. For example, concrete with 20% untreated PET had higher water absorption than the control mix. Water absorption values ranged from 5.12% at 10% PET content to 5.72% at 20%. In contrast, the reference concrete absorbed just over 4% water. This decline in performance is primarily due to the hydrophobic nature of PET, which repels water and creates voids that allow moisture to penetrate the concrete. Similar observations were made in [45], where replacing 10%, 25%, and 50% of natural sand with plastic particles in foam concrete led to great increases in water absorption at higher replacement levels. At 50% replacement, water absorption rose by 117%, mainly due to the increased porosity of plastic aggregates. Furthermore, in [44], concrete with 20% polyethylene (PE) and PVC aggregates had 200% and 140% higher porosity, respectively. These findings highlight the risks of using untreated plastic waste in concrete. However, when PET particles are treated with cement or SF to enhance their roughness, water absorption decreases—even as the PET content increases. Cement acts as the primary binder in concrete, while SF is a fine, highly reactive material that reacts with calcium hydroxide to form additional cementitious compounds. Both materials help refine the concrete's pore structure, making it denser and less permeable. PET disrupts the compact packing of aggregates, creating potential pathways for water intrusion. Nevertheless, cement and SF can fill these voids and strengthen the matrix. SF is especially effective due to its pozzolanic reaction, which creates a denser microstructure. It also improves surface roughness, further reducing water absorption. In summary, although untreated PET increases water absorption due to its hydrophobic properties, surface treatments with cement or SF can counteract this effect and improve concrete durability [46].

TABLE III. WATER ABSORPTION RESULTS FOR ALL MIXES

Mix designation	Water absorption (%)
	28 days
Ref.	4.31
Mix-PET10%	5.12
Mix-PET15%	5.37
Mix-PET20%	5.72
Mix-C+PET10%	4.47
Mix-C+PET15%	4.29
Mix-C+PET 20%	4.09
Mix-SF+PET 10%	4.52
Mix-SF+PET 15%	4.31
Mix-SF+PET 20%	4.27

VII. CONCLUSIONS

Growing concerns about environmental damage and the depletion of natural resources have encouraged researchers to seek sustainable solutions in construction. One promising approach is the use of PET waste as a partial replacement for fine aggregates in concrete. While this method offers clear environmental benefits, there is limited knowledge about how untreated and surface-enhanced PET particles affect the mechanical and durability properties of concrete. This study aimed to fill that gap. It systematically examined how both untreated and modified PET particles influence concrete performance. Based on the experimental results, several key conclusions were drawn:

- Untreated PET particles used directly as a fine aggregate replacement resulted in a decrease in compressive strength at all levels of substitution and curing ages. This reduction can be attributed to the poor bonding site between the smooth surface of PET and the cement matrix.
- Surface-enhanced PET particles improved mechanical performance. Modifying the surface enhanced the interfacial bonding with cement paste, causing increased compressive strength and durability within the concrete matrix. This is a sustainable and achievable way of utilizing PET waste, benefiting concrete mechanical properties and waste management.
- Using PET in concrete creates clear environmental fringe benefits, including reducing natural aggregate use and diverting non-biodegradable waste from dumpsites. This aligns with national strategies for promoting circular economy practices within the construction sector.
- At low replacement levels, roughened PET particles gave nearly equivalent compressive strength with some changes in water absorption value. Increasing the percentage replacement, however, led to a significant decline in strength because of the lower stiffness and strength than natural aggregates, weakening load transfer, and interfacial bonding.
- Increased PET levels resulted in higher water absorption due to the intrinsically increased hydrophobicity of PET, creating additional voids and channels for moisture ingress, which may threaten durability.

Previous research mainly focused on untreated plastics or their scope of mechanical properties. In contrast, this work covers microstructural interactions, mechanical strength, and water absorption. The findings show that surface-treated PET waste can successfully replace part of the fine aggregate, offering both environmental and mechanical benefits. While challenges remain, especially at higher replacement levels, this approach offers a promising path toward eco-efficient concrete. It also opens the door for future studies focused on optimizing surface treatment methods and evaluating their long-term durability.

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