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Research Article

Influence of Partial Fine Aggregate Replacement with HDPE Plastic Waste on Concrete Compressive Strength: Melt Processing Vs. Water Quenching

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Abstract: High Density Polyethylene (HDPE) plastic waste, particularly from plastic bags, poses serious environmental challenges due to its non-biodegradable nature. This study evaluates HDPE as a partial fine aggregate replacement in concrete, focusing on the effect of two processing methods, melt processing and water quenching, on compressive strength. Cylindrical specimens (10 × 20 cm) were prepared with substitution levels of 0.00%, 0.50%, 0.70%, and 0.90% by weight of fine aggregate. In melt processing, HDPE was melted and molded into particles, while in water quenching, molten HDPE was rapidly cooled in water and then crushed into aggregate. All mixes were wet cured and tested at 7 and 28 days. Results show that melt processing had a mild positive effect, providing moderate strength improvement, with the highest value of 19.1 MPa at 0.90%. In contrast, water quenching had a stronger effect on strength enhancement, reaching 23.2 MPa at 0.50% and surpassing the melt-processed mixes and the control (18.3 MPa). The trend continued at 28 days, when melt processing achieved 28.6 MPa, while water quenching at 0.50% reached 30.8 MPa, higher than both the control (24.6 MPa) and melt processing. Both treatments exceeded the control strength; however, water quenching produced a greater improvement than melt processing. These findings indicate that HDPE waste can be effectively used as a fine aggregate in concrete, with water quenching offering superior performance for structural concrete elements in architectural applications.

Keywords: Compressive strength; Fine aggregate substitution; HDPE plastic; Melt processing; Water quenching

1. Introduction

The rapid growth of plastic consumption has led to alarming waste accumulation, with high-density polyethylene (HDPE) being among the most common types due to its widespread use in bags and packaging. Being non-biodegradable, HDPE persists for centuries, creating serious environmental risks (Geyer et al., 2017). In recent years, global plastic production has exceeded 350 million tons, with HDPE contributing a significant share to municipal solid waste streams, while recycling rates remain below 20% in many countries (Hopewell et al., 2009). As landfills overflow and recycling struggles to keep up, alternative reuse strategies are increasingly being prioritized. One promising solution is to incorporate plastic waste into concrete, where natural aggregates are partly replaced to reduce environmental impact and conserve resources (Saikia and de Brito, 2014). Although feasibility has been demonstrated, compressive strength remains the main concern (Frigione, 2010). Due to its chemical stability, HDPE offers potential compatibility with cementitious matrices, yet its hydrophobic nature and irregular morphology may hinder strength if not properly processed (Islam et al., 2016). Recent studies have also shown that the morphology, cooling history, and thermal processing route of waste plastics significantly influence interfacial bonding, particle rigidity, and surface roughness parameters that are critical for the mechanical performance of modified concrete.

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Building on these insights, the incorporation of plastic waste in concrete has gained research interest for both environmental and material benefits. Early studies with polyethylene terephthalate (PET) showed that limited substitution levels did not drastically reduce compressive strength (Almeshal et al., 2020; Ismail and Al-Hashmi, 2008; Choi et al., 2005), prompting research into other plastics such as HDPE, LDPE, PP, and PVC (Gesoğlu et al., 2014; Ochi et al., 2007). Performance depends on the type, size, and shape of the plastics. HDPE has been highlighted for its strength-to-weight ratio and chemical resistance (Al-Tulaian, 2017; Marzouk et al., 2007), although its hydrophobic surface weakens the bonding (Siddique et al., 2008). Treatments, such as gamma radiation, alkali soaking, and microwave irradiation, have been applied to enhance adhesion (Rahmani et al., 2013; Albano et al., 2009), particularly for concrete used in architectural applications.

Mechanical studies indicate that plastic waste lowers density and modulus of elasticity, with varied effects on compressive and tensile strength depending on dosage (Kumi-Larbi et al., 2018; Ghernouti et al., 2011; Mahdi et al., 2010). HDPE shows stronger potential than some plastics (Marzouk et al., 2007), and water-quenched HDPE provides rougher surfaces, improving interfacial adhesion compared to melt-processed particles (Safi et al., 2013; Hannawi et al., 2010; Choi et al., 2009). Environmental benefits and lightweight properties have been emphasized in previous studies (Alqahtani et al., 2021; Ferreira et al., 2020; Kou et al., 2009), although challenges such as poor bonding and higher porosity at greater replacement levels persist (Coates and Getzler, 2020; Rahimi and García, 2017). Novel approaches include binder systems, chemical recycling, closed-loop recycling, and alternative uses such as fiber reinforcement, fillers, or geopolymer additives (Alani and Faramarzi, 2021; Ramesh and Yoganandam, 2020; Fraternali et al., 2013; Awwad et al., 2012; Marzouk et al., 2007; Batayneh et al., 2008). Standard testing methods—compressive strength, water absorption, ultrasonic pulse velocity, and scanning electron microscopy (SEM) are widely used to evaluate structural feasibility (Gesoğlu et al., 2014; Li, 2007; Siddique and Naik, 2004). Overall, HDPE is a viable aggregate substitute (Reddy and Gupta, 2018; Jain et al., 2017), but systematic comparisons of melt processing and water quenching are still lacking, forming the basis of this study.

The processing method strongly affects the interaction of HDPE with the cement matrix, yet comparative studies of melt processing and water quenching remain limited (Kou and Poon, 2009). Melt processing typically produces smoother and denser particles, whereas water quenching generates more irregular and textured surfaces due to rapid cooling. These contrasting characteristics may alter the mechanical interlocking, water absorption behavior, and bonding quality of the cement paste. Therefore, comparing melt processing vs. water quenching is essential to identify which route produces HDPE particles that optimize the strength and workability of concrete mixtures. This study experimentally evaluates and compares the compressive strength of concrete containing HDPE processed using both methods. The novelty lies in assessing HDPE at low substitution levels (0.50%–0.90%) using melt processing and water quenching, a range rarely investigated despite its practical relevance for maintaining concrete quality while reducing waste. This study analyzes the influence of these materials on workability and compressive strength through changes in particle surface roughness and paste–aggregate interaction, providing insights for the sustainable reuse of plastic bag waste. The main objective of this study is to determine the effect of HDPE processing on compressive strength at different substitution levels and curing times, thereby enhancing the understanding of HDPE-modified concrete for sustainable construction.

2. Materials and Methods

2.1 Materials

Ordinary Portland Cement (OPC) Type I, natural river sand, crushed river gravel, potable tap water, and post-consumer HDPE plastic bag waste were used in this study. The HDPE waste was sorted, cleaned, and air-dried prior to processing. All raw materials were subjected to standard laboratory characterization procedures to determine their physical and mechanical properties for mix design and subsequent experimental work.

2.1.1 Ordinary Portland Cement (OPC)

Ordinary Portland Cement (OPC) Type I was used as the main binder. A visual inspection was conducted to ensure that the cement was dry, free from lumps, and suitable for concrete production. The cement was also checked to confirm that it met the standard requirements for consistency and fineness. This ensured that the binder would perform reliably during mixing and contribute to the concrete's intended mechanical properties.

2.1.2 Aggregate

Sieve analysis was conducted for both fine and coarse aggregates to determine the particle size distribution in accordance with standard procedures. The parameters measured included retained weight, percentage passing, and fineness modulus. Gradation charts were prepared for both fine and coarse aggregates to confirm compliance with standard limits. These steps ensured that the aggregates used in the concrete mix possessed appropriate grading characteristics for achieving consistent workability and strength.

2.1.3 Water

Potable tap water was used for mixing and curing, in accordance with standard practice requiring water free from impurities that may affect cement hydration. This type of water ensures consistent chemical reactions during concrete setting and hardening. The use of clean, potable water also minimizes the risk of introducing substances that could interfere with the development of strength. Therefore, maintaining water quality is essential for achieving reliable and reproducible experimental results.

2.1.4 High-density polyethylene plastic waste

Post-consumer HDPE was washed, dried, and processed using two treatments: melt processing, in which the material was melted, cooled at room temperature, and crushed into small particles, and water quenching, in which molten HDPE was rapidly cooled in water before being crushed and sieved to obtain fine aggregate-sized particles. Both types of processed HDPE were then sieved to achieve the required particle size distribution for fine aggregate substitution, with sieve analysis conducted at sand weight substitution levels of 0.50%, 0.70%, and 0.90%. Photographs were also taken to document the physical characteristics of HDPE produced by each processing method.

2.1.5 Concrete Mixing Design

Table 1 summarizes the mix design for 20 MPa normal-strength concrete, considering parameters such as specific gravity, moisture content, absorption, slump, and maximum aggregate size. The 20 MPa target was chosen as a common building standard, providing a practical baseline for evaluating HDPE substitution without admixtures. Using the Department of the Environment (DOE) method, the material requirements per 1 m^3 were calculated, including cement, sand, crushed stone, and water. Fine aggregate was partially replaced with HDPE plastic waste at sand weights of 0.50%, 0.70%, and 0.90% in cylindrical specimens.

2.2 Methods

This study examines the effect of HDPE waste processed by melt processing and water quenching on concrete's compressive strength. Using a quantitative experimental method, fine aggregate was partially replaced with thermally treated HDPE at different proportions, and the specimens were water-cured to assess strength development. The research workflow consists of HDPE collection and cleaning, thermal processing and sieving, concrete mix design targeting 20 MPa, specimen and curing, followed by compressive strength testing and analysis of variance. (ANOVA) to evaluate the effects of processing method and substitution level. The complete procedure is illustrated in Figure 1 in the research stages scheme.

Table 1 Mix design proportions for normal concrete determined using the Department of the Environment (DOE) mix design method (Department of the Environment, 1988)

No.	Parameter	Value	Unit
1	Concrete Strength *(fc)*	20	MPa
2	Slump	10	cm
3	Fineness Modulus of the Sand	2.48	-
4	Dry Coarseness Modulus of Gravel	6.54	-
5	Maximum Aggregate Size	20	mm
6	Specific Gravity of the SSD Sand	2.50	-
7	Specific Gravity of the Crushed SSD Stone	2.51	-
8	Moisture Content of Sand *(Wp)*	3.10	%
9	Absorption of Sand *(Rp)*	5.26	%
10	Moisture Content of Crushed Stone *(Wk)*	1.35	%
11	Absorption of Crushed Stone *(Rk)*	2.58	%
12	Loose Dry Unit Weight of Sand	1663	kg/m^3
13	Loose Dry Unit Weight of Crushed Stone	1633	kg/m^3
14	Cylinder Volume (ϕ10 cm $\times$ 20 cm)	0.0016	m^3

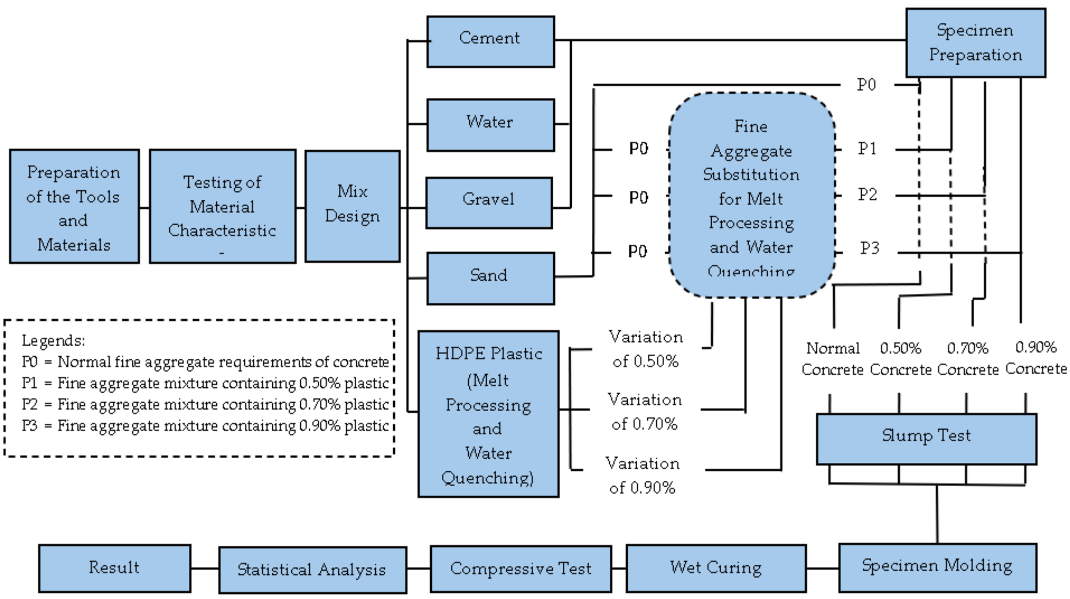

Figure 1 Research stages scheme illustrating the experimental workflow, including HDPE processing, fine aggregate substitution levels (P0–P3), specimen preparation, curing, and compressive strength testing

2.2.1 Specimen Preparation

Specimen preparation involved all equipment cleaning and materials weighing according to the mix design. HDPE replaced fine aggregate at 0.00%, 0.50%, 0.70%, and 0.90% for both melt processing and water quenching, consistent with substitution practices reported in earlier studies

(Choi et al., 2009; Li, 2007). Sand and processed HDPE were mixed first, followed by cement and crushed stone, and water was gradually added to ensure uniformity, an approach aligned with the recommended procedures for plastic-modified concrete (Safi et al., 2013; Marzouk et al., 2007). A total of 42 cylindrical specimens were prepared for compressive strength testing, as shown in Table 2, and the overall preparation workflow is illustrated in Figure 2.

Table 2 Number of specimens tested

Variation in HDPE substitution	Test specimen						Number of test specimens
	Normal concrete		Concrete with melt processing		Concrete with water quenching		
	7 days	28 days	7 days	28 days	7 days	28 days	
0.00%	3	3	–	–	–	–	6
0.50%	–	–	3	3	3	3	12
0.70%	–	–	3	3	3	3	12
0.90%	–	–	3	3	3	3	12
Total							42

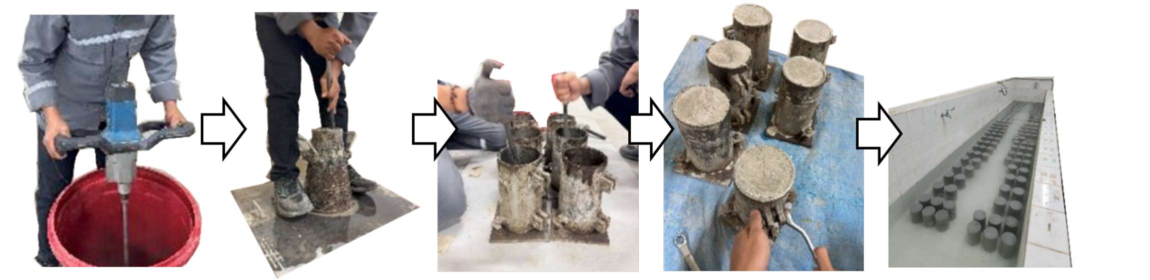

Figure 2 Preparation of concrete test specimens: (a) concrete mixing, (b) slump test, (c) filling the molds, (d) demolded test specimens, and (e) immersion in curing tank. Arrows indicate the sequence of specimen preparation

2.2.2 Slump Testing

Slump testing was performed to assess the workability of fresh concrete before casting. The procedure followed ASTM C143, the standard method for determining the workability and consistency of fresh concrete using a slump cone. The cone was filled in three layers with uniform rodding, and the resulting slump value was measured after the cone was lifted vertically to evaluate the consistency of the mixtures containing HDPE-modified fine aggregate.

2.2.3 Curing Methods

After one day in the molds, the specimens were demolded and placed in a curing tank at approximately 20 °C and 80% relative humidity (RH). This controlled environment was maintained to prevent moisture loss and ensure efficient hydration. Wet curing was performed for 7 and 28 days to ensure proper hydration and strength development under favorable microstructural conditions. Maintaining consistent curing conditions also helped minimize external variability that could influence the concrete's mechanical performance. This approach ensured that the effects observed in the specimens were primarily due to the HDPE substitution and processing methods.

2.2.4 Compressive strength testing

The compressive strength was tested at 7 and 28 days using a 1000 kN UTM. After curing, the specimens were dried, measured, and placed centrally on the machine. A constant load of 2–4 $kg/cm^2/s$ was applied until failure, and the results were recorded. Each reported compressive strength value represents the average of three specimens, and error bars represent the range (minimum–maximum). This procedure ensured consistency across all specimens and allowed reliable comparison of strength variations resulting from different HDPE processing methods and substitution levels.

2.2.5 Statistical Analysis

Statistical analysis was performed to determine the influence of HDPE processing method and substitution level on compressive strength. One-way and two-way analysis of variance were used to compare treatment groups, with additional post hoc tests applied when required. All statistical evaluations were conducted at a confidence level of 95% to ensure reliable and meaningful comparisons. These analyses provided a structured basis for identifying statistically significant differences among the tested mixtures and validating the observed strength trends.

3. Results and Discussion

3.1 Material Characterization

As an initial step in ensuring the quality of the concrete constituent materials, a visual inspection was carried out on the OPC and the water used for mixing. The OPC exhibited a uniform light gray color and fine texture and was free from lumps or contaminants, indicating that the material was in good condition and had not been exposed to moisture. Similarly, the tap water used for both mixing and curing appeared clear, colorless, odorless, and contained no suspended particles. Based on this examination, these primary materials were deemed suitable and compliant with the standards for concrete production, allowing for unbiased interpretation of subsequent test results.

3.1.1 Aggregate

The fine aggregate's particle size distribution was assessed to confirm compliance with standard grading requirements. For fine aggregate (Table 3), the FM was 2.48, indicating that moderately fine sand is suitable for concrete. The highest retained weight was 530 g (69.62%) on the No. 50 (0.30 mm) sieve, with the majority of particles passing the 1.18 mm sieve. The gradation curve (Figure 3(a)) falls within the recommended limits, confirming that the well-graded sand meets the standard specifications, provided that cleanliness and other criteria are satisfied.

Sieve analysis results (Table 4) show that 56.40% of coarse aggregate was retained on the 9.53 mm (3/8") sieve, with a cumulative 97.78% on the No.4 (4.75 mm) sieve. No particles passed through the No. 8 (2.36 mm) sieve, indicating a uniformly coarse distribution. The fineness modulus of 6.54 confirms the coarse gradation of the aggregate, making it suitable for concrete production.

Table 3 Sieve analysis test results of fine aggregates

Sieve Number	Size Classification (+/−)	Retained Weight (g)	Percentage Retained (%)	Percent Passing (%)	Fineness Modulus (%)
No.4 (4.75)	+4.75 mm (retained)	0	0.00	100.00	
No.8 (2.36)	−4.75 mm / +2.36 mm	235	11.90	88.10	
No.16 (1.18)	−2.36 mm / +1.18 mm	245	24.30	75.70	
No.30 (0.60)	−1.18 mm / +0.60 mm	365	42.78	57.22	2.48
No.50 (0.30)	−0.60 mm / +0.30 mm	530	69.62	30.38	
Pan	−0.30 mm (passing)	600	100.00	0.00	

Figure 3(b) shows that the gradation curve exhibits a sharp decline after the 9.53-mm sieve, indicating a predominance of medium to large particles. This distribution aligns with standard coarse aggregate specifications, ensuring favorable interparticle contact and packing, which are essential for concrete strength and stability.

Table 4 Sieve analysis test results of coarse aggregates

Sieve Number	Size Classification (+/−)	Retained Weight (g)	Percentage Retained (%)	Percent Passing (%)	Fineness Modulus (%)
26.5 (1")	+26.5 mm (retained)	0	0.00	100.00	
19.1 (3/4")	−26.5 mm / +19.1 mm	0	0.00	100.00	
9.53 (3/8")	−19.1 mm / +9.53 mm	1145	56.40	43.60	
No.4 (4.75)	−9.53 mm / +4.75 mm	840	97.78	2.22	6.54
No.8 (2.36)	−4.75 mm / +2.36 mm	45	100.00	0.00	
No.16 (1.18)	−2.36 mm / +1.18 mm	0	100.00	0.00	
No.30 (0.60)	−1.18 mm / +0.60 mm	0	100.00	0.00	
No.50 (0.30)	−0.60 mm / +0.30 mm	0	100.00	0.00	
Pan	−0.30 mm (passing)	0	100.00	0.00	

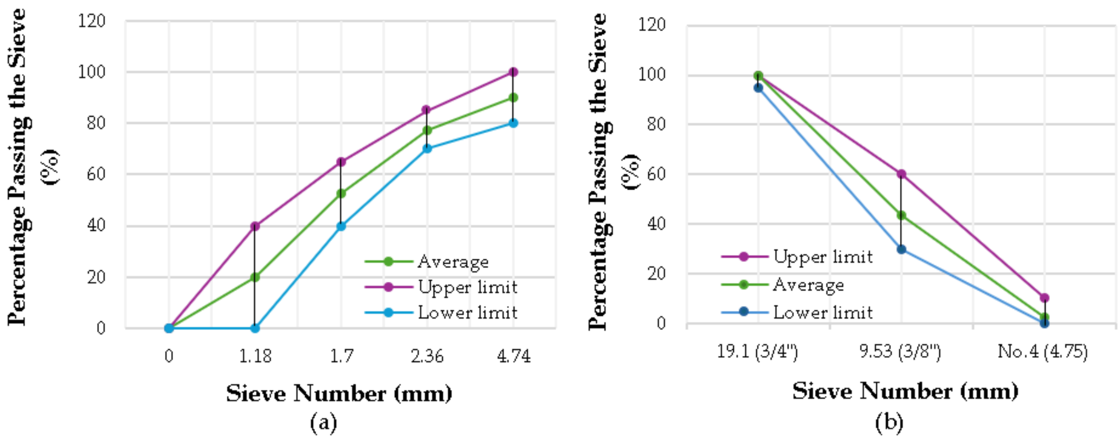

Figure 3 Gradation charts of (a) fine aggregate and (b) coarse aggregate analysis

3.1.2 High-density polyethylene plastic waste

The particle size distribution of HDPE processed through melt processing and water quenching was analyzed to evaluate the gradation behavior of each thermal treatment method. Sieve analysis of melt-processed HDPE (Table 5) at substitution levels of 100%, 0.5%, 0.7%, and 0.9% shows that the No.50 (0.30 mm) sieve, with retained weights of 825 g (0.5%) and 882.6 g (0.9%). This indicates that the particles are finer than conventional fine aggregates. Such fineness is consistent with previous findings that melt processing produces denser and more brittle plastic particles that fracture into smaller, uniform sizes during crushing, resulting in gradation similar to natural fines (Safi et al., 2013; Choi et al., 2009; Marzouk et al., 2007). The observed concentration is consistent with previous studies showing that thermal history governs particle morphology and size distribution, influencing workability and interfacial bonding in cementitious systems (Hannawi et al., 2010; Li, 2007).

Table 6 details the gradation outcomes for fine aggregates processed using the WQM. Notably, higher quantities are retained on finer sieves, such as No. 50, across all substitution levels. For instance, the 0.7% sample shows the greatest retained weight of 937.3 g on No. 50 Sieve, a finer and more uniform particle distribution than those obtained by melting.

A comparison of both methods shows that water quenching produces finer and more consistent particle distributions than melt processing, as indicated by higher retained weights on smaller sieves (No. 30 and No. 50). Thus, the processing method affects texture and gradation, which are key factors for fine aggregate compatibility in concrete.

Figure 4 shows that both treatments yielded particles in the range of 1.75–4.75 mm, but with clear differences. Melt-processed HDPE appears irregular and brittle, whereas water-quenched HDPE forms denser, more uniform particles with better structural integrity. Overall, water quenching provides higher-quality aggregates suitable for concrete substitution.

Passing 4.75 mm sieve (a) Passing 1.75 mm sieve (b) Passing 4.75 mm sieve (c) Passing 1.75 mm sieve (d)

Figure 4 Physical characteristics of high-density polyethylene plastic waste processed using two different techniques: (a-b) melt processing method and (c-d) water quenching method

3.2 Slump Test

The workability of concrete with varying HDPE aggregate contents processed by melt and water quenching methods was assessed by the slump test. Melt-processed HDPE mixes showed reduced slump heights as substitution levels increased, indicating lower workability. The highest slump occurred in the 0.00% control mix, while 0.50%, 0.70%, and 0.90% substitutions produced progressively stiffer cones, as shown in Figure 5 (a-d). Concrete with water-quenched HDPE had a higher slump than melt-processed mixes, although it was still below normal concrete (Figure 5 (e-h)), likely due to its rougher surface improving paste bonding and flow.

Table 7 shows the slump values, with the control at 20 cm and HDPE mixes at 15.35–18.3 cm. Water-quenched HDPE consistently gave higher slump than melt-processed aggregates at equal substitutions, indicating that the treatment method strongly affects workability.

Table 5 Sieve analysis test results of fine aggregates from the melt processing method

Sieve Number	Size Classification (+/−)	Retained Weight (g) – 100%	Retained Weight (g) – 0.5%	Retained Weight (g) – 0.7%	Retained Weight (g) – 0.9%
No.4 (4.75)	+4.75 mm (retained)	0	0	0	0
No.8 (2.36)	−4.75 mm / +2.36 mm	83.2	335.5	311.2	260.7
No.16 (1.18)	−2.36 mm / +1.18 mm	100.9	445.7	515.0	384.4
No.30 (0.60)	−1.18 mm / +0.60 mm	30.8	688.5	727.4	621.4
No.50 (0.30)	−0.60 mm / +0.30 mm	10.5	825.0	799.2	882.6
Pan	−0.30 mm (passing)	8.0	665.5	641.7	333.1

3.3 Compressive Strength

Compressive strength at 7 days declined with HDPE substitution, especially in melt-processed mixes. Water-quenched aggregates performed better at all levels, with the highest strength of 23.2 MPa at 0.50% substitution, while melt-processed mixes ranged from 18.3 to 19.1 MPa, as shown in Figure 6 (a).

At 28 days, all mixes improved in strength, with water-quenched HDPE consistently higher than melt-processed concrete. As shown in Figure 6 (b), the highest value was 30.8 MPa at 0.50% substitution, whereas the melt-processed value peaked at 27.0 MPa (0.70%). Table 8 shows the strength gain from 7 to 28 days, where the control reached 18.3 and 24.6 MPa, whereas water-quenched mixes achieved greater increases, confirming the effect of HDPE content and treatment method.

Table 6 Sieve analysis test results of fine aggregates from the water quenching method

Sieve Number	Size Classification (+/−)	Retained Weight (g) – 100%	Retained Weight (g) – 0.5%	Retained Weight (g) – 0.7%	Retained Weight (g) – 0.9%
No.4 (4.75)	+4.75 mm (retained)	0	0	0	0
No.8 (2.36)	−4.75 mm / +2.36 mm	147.5	308.3	213.4	279.6
No.16 (1.18)	−2.36 mm / +1.18 mm	6.0	392.7	317.2	346.5
No.30 (0.60)	−1.18 mm / +0.60 mm	1.0	635.7	599.7	626.0
No.50 (0.30)	−0.60 mm / +0.30 mm	0	861.7	944.5	911.0
Pan	−0.30 mm (passing)	0	802.5	937.3	853.2

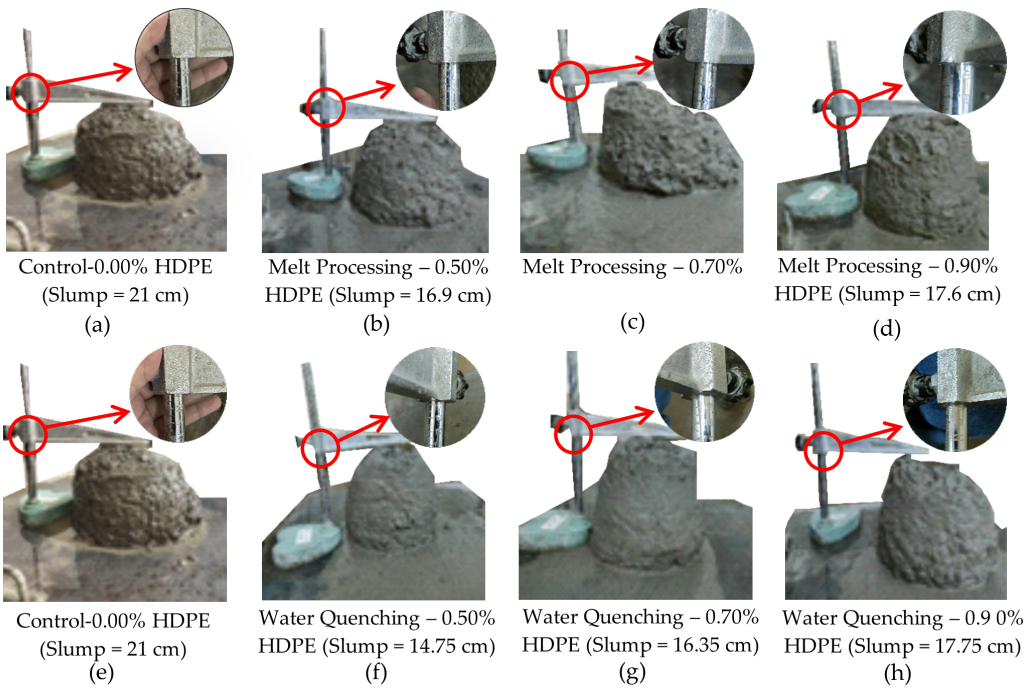

Figure 5 Slump test results for the concrete incorporating HDPE waste processed using the two methods. Subfigures (a–d) represent mixtures with melted processing at 0.00%, 0.50%, 0.70%, and 0.90% HDPE substitution, respectively, while subfigures (e–h) represent mixtures with water quenching at the same substitution levels

Table 7 Slump test results for various concrete mixtures

Variation in the HDPE substitution	Normal concrete	Concrete with melt processing	Concrete with water quenching
0.00%	21 cm	–	–
0.50%	–	16.9 cm	14.75 cm
0.70%	–	18.3 cm	16.35 cm
0.90%	–	17.6 cm	17.75 cm

3.4 ANOVA Results

ANOVA was used to evaluate whether the differences in compressive strength across HDPE substitution levels (0.50%, 0.70%, and 0.90%) and between melt processing and water quenching were statistically significant. The results show clear variation in both 7- and 28-day strengths, with water quenching consistently yielding higher values. ANOVA confirms that these differences are significant, indicating that both HDPE content and processing method notably affect compressive strength.

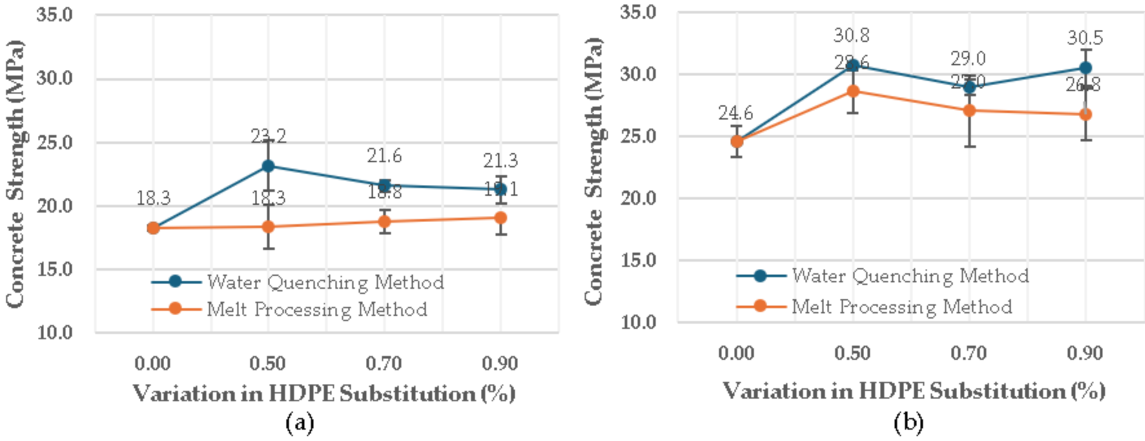

Figure 6 Compressive strength of concrete at (a) 7 and (b) 28 days

Table 8 Compressive strength (MPa) of concrete with various HDPE substitution levels under different processing methods after 7 and 28 days of incubation

Variation in the HDPE substitution	Concrete strength (MPa)					
	Normal concrete		Concrete with melt processing		Concrete with water quenching	
	7 days	28 days	7 days	28 days	7 days	28 days
0.00%	18.3	24.6	–	–	–	–
0.50%	–	–	18.3	28.6	23.2	30.8
0.70%	–	–	18.8	27.0	21.6	29.0
0.90%	–	–	19.1	26.8	21.3	30.5

The results confirm that HDPE substitution level and processing method significantly affect workability and compressive strength. Workability, measured by slump, decreased with higher HDPE content. Melt-processed mixes showed the lowest values (Figure 5), ranging from 15.35 to 16.9 cm different processing methods after 7 and 28 days of incubation (Table 7), due to smoother, nonabsorbent surfaces reducing paste–aggregate bonding. In contrast, water-quenched HDPE produced higher slumps (up to 16.85 cm, Figure 5) because its rougher surface improved the interaction with the paste. These findings align with Gesoğlu et al., 2017 and Ismail and Al-Hashmi, 2008 confirming that water quenching enhances roughness and improves workability.

The compressive strength decreased at higher substitutions but remained superior in water-quenched mixes, reaching 30.8 MPa at 0.50% compared to 27.0 MPa for melt processing. This trend is consistent with Al-Hadithi et al., 2019 and Li, 2007, who noted that surface modification enhances stress transfer and bonding. Tests were conducted in triplicate, with ANOVA and Tukey's post-hoc test showing significant differences ($p < 0.05$), confirming that the processing method critically influences concrete performance.

Compared with other types of recycled plastics commonly studied in concrete, such as PET, PP, PVC, and mixed polymer wastes, HDPE in this study demonstrated a more favorable performance, particularly when processed through controlled thermal treatment. Previous studies have shown that PET and PP aggregates generally produce larger reductions in both slump and compressive strength due to their rigid and hydrophobic surfaces, which hinder bonding and stress transfer within the cementitious matrix. In contrast, the water-quenching method applied to HDPE in this study generated a rougher and more angular particle morphology, allowing improved mechanical interlock and paste adhesion, resulting in higher strength retention (up to 30.8 MPa at 0.50% substitution) compared with typical reductions reported for other polymers. This comparison highlights the novelty of the current findings—namely, that modifying HDPE through thermal processing provides measurable performance enhancements over conventional untreated polymer aggregates, offering a more effective and technically viable pathway for incorporating recycled plastics into structural concrete.

4. Conclusions

This study shows that both the HDPE substitution level and the thermal treatment method significantly affect the concrete performance. Water quenching yielded the best results, especially at 0.50% substitution, surpassing both melt-processed and control mixes in compressive strength at days 7 and 28. This is due to the rougher surface of the water-quenched HDPE, which improves the bonding within the matrix. The results highlight the potential of reusing HDPE plastic bag waste as a partial fine aggregate, with water quenching offering a sustainable solution aligned with CEG goals. Future research is recommended to explore a wider range of HDPE substitution levels, including thresholds beyond 1% to determine the upper limit before performance declines; investigate microstructural mechanisms such as interfacial transition zone (ITZ) characteristics using SEM or X-ray CT to validate the improved bonding of quenched HDPE; evaluate long-term durability aspects including chloride penetration, sulfate resistance, water absorption, shrinkage, and freeze–thaw performance; assess the influence of different cooling media (such as oil quenching, air quenching, or controlled cooling) on surface morphology and mechanical behavior; and expand the application through structural element testing and life-cycle assessment (LCA) to quantify the environmental benefits.

Author Contributions

Nasruddin conceived the main idea and supervised the overall research. Imriyanti designed experimental program and coordinated the laboratory work. Pratiwi Mushar performed the material preparation, specimen casting, and mechanical testing. Muliyadi conducted the data analysis, prepared the graphs and figures, and assisted in manuscript editing. All authors discussed the results and contributed to the final version of the manuscript.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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