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Upcycling PET Waste as Hybrid Aggregates in Self-Compacting Concrete: Synergistic Effects on Rheology and Strength

Baitollah Badarloo [a*], Mahdi Moradi [b], Hamid Reza Koohestani [c], Ali Attarzadeh [a]

[a] *Department of Civil Engineering, Qom University of Technology (QUT), Qom 37181-46645, Iran*
[b] *Department of Civil Engineering, Qo.C., Islamic Azad University, Qom, Iran*
[c] *Department of Civil Engineering, Shahab-Danesh University, Qom, Iran*

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ABSTRACT

The escalating demand for construction aggregates, combined with the growing environmental concerns associated with plastic waste, highlights the need for innovative and sustainable concrete technologies. This study evaluates the feasibility of upcycling Polyethylene Terephthalate (PET) waste as a partial replacement for natural aggregates in Self-Compacting Concrete (SCC). Unlike previous studies that relied on single replacement strategies, this work introduces a novel approach by examining the synergistic interaction between granulated PET (fine aggregate) and flake PET (coarse aggregate). A comprehensive experimental program was conducted using 20 mix design configurations, comprising 120 cubic and 80 cylindrical specimens. Key variables included PET morphology, replacement ratios, and targeted strength classes. The results showed that hybrid incorporation of PET types produced overall superior performance compared to single-mode substitutions. Mixes containing up to 180 kg/m³ of PET maintained acceptable rheological properties required for SCC. Although replacing 10% of both fine and coarse aggregates resulted in moderate reductions in compressive and tensile strengths (25% and 22%, respectively), the mixtures still demonstrated adequate performance for non-critical structural applications. Overall, the findings provide meaningful insights into high-volume plastic waste utilization in SCC, supporting more sustainable construction practices while reducing reliance on natural aggregates.

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1. Introduction

The escalating global consumption of plastics has led to a severe environmental crisis, as plastic waste production reached approximately 400 million tons in 2020 and is projected to reach 1,100 million tons 1,100 million tons by 2050 [1]. Currently, plastic waste accounts for roughly 12% of global solid waste [2]. Despite various recycling efforts, global statistics indicate that only 32.5% of plastic waste is mechanically recycled and 42.6% is recovered for energy, while a substantial 24.9% accumulates in landfills or pollutes natural ecosystems [3]. Among various plastics, Polyethylene Terephthalate (PET) is widely used in packaging for beverages and pharmaceuticals. The non-biodegradability and long-term persistence of PET pose critical threats, including groundwater contamination, soil degradation, and chemical leaching [4]. Consequently, developing sustainable strategies to upcycle PET waste into value-added materials has become a priority for the circular economy.

The construction industry offers substantial potential capacity for recycling waste materials, especially considering the estimated concrete demand of 18 billion tons by 2050 [5]. Incorporating PET waste into concrete not only mitigates environmental pollution

* Corresponding author.
E-mail addresses: badarloo@qut.ac.ir (B. Badarloo).

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but also addresses the depletion of natural aggregate resources [6]. Previous investigations have explored the utility of PET as both fiber reinforcement and aggregate replacement in conventional concrete. While PET incorporation can enhance specific properties such as energy absorption and impact resistance [7, 8], it often compromises mechanical strength. For instance, replacing aggregates with PET often leads to density reduction and strength loss proportional to the replacement level [7]. Additionally, the inclusion of 1.5% PET fibers has been shown to reduce compressive strength by up to 10% while slightly improving tensile and flexural behaviors [8, 9].

In recent years, Self-Compacting Concrete (SCC) has gained prominence due to its superior flowability, homogeneity, and ability to consolidate under its own weight without mechanical vibration [10, 11]. Given the stringent rheological requirements of SCC, incorporating waste plastics presents unique challenges compared to conventional concrete. Extensive research has focused on using PET fibers in SCC, which are typically capped at 2% by volume to avoid blocking and segregation issues [12-17]. These studies show that although PET fibers can enhance tensile performance, they significantly reduce flowability and often cause rheological instability when used above 1% [12-17]. It is important to note that the primary objective of utilizing PET in this context extends beyond merely enhancing concrete properties to include the effective diversion of waste from the environment. Therefore, using PET as a volumetric aggregate replacement enables higher recycling rates and better supports this environmental objective.

PET has been used as fine aggregates in numerous studies, constituting up to 20% of SCC [7, 14, 18-20]. An increase in PET content generally leads to reduced slump-flow diameter and increased V-funnel time [14, 18-20]. However, some studies have reported contradictory trends [7]. It has also been reported that PET replacement levels above 10% can reduce slump flow to approximately 400 mm [14, 18-20]. Additionally, higher PET contents have been associated with longer V-funnel times and, in some cases, complete blockage [7, 14, 18-20]. However, there are reports with contrary results [18]. For instance, the compressive strength of SCC decreases with the increased PET content in conventional concrete, with the reduction percentage of strength corresponding to the percentage of PET used [7, 14, 18-20]. The study by Sadrmomtazi et al. [20] indicates that adding 15% PET aggregates results in an approximately 48.3% reduction in compressive strength while replacing 2.5% PET aggregates results in an 8% reduction in compressive strength [20]. Some researchers have suggested that PET replacement levels up to 15% may be feasible in SCC. However, replacements beyond this limit lead to unacceptable results in the rheological properties of SCC [7, 14, 18-20]. There are a limited number of studies on the use of PET as coarse aggregates. Odeyemi et al. [21] used PET and rubber crumbs at 10, 20, and 30 percent as replacements for coarse aggregates in SCC. Their results showed that the addition of PET leads to a reduction in compressive strength, with the least reduction observed in samples containing 10% PET, showing an 18.5% decrease in compressive strength. In their study, Odeyemi et al. [21] used PET as a coarse aggregate replacement and designed mixtures for a 20-MPa strength class. Beyond PET, other polymer-based waste materials and supplementary cementitious components have also been investigated in SCC. Abedi Mavaramkolaei et al. [22] studied SCC with recycled nylon granules replacing fine aggregates at 0–15% and, using three-point bending and the Boundary Effect Method (BEM), reported reductions of about 20–24% in fracture energy and toughness but a roughly 23% increase in a ductility-related crack length parameter at 15% replacement, illustrating the trade-off between strength and ductility in polymer-modified SCC. In another related study, Farrokh Ghatte and Nazari [23] employed gene expression programming (GEP) to model the compressive strength of SCC containing rice husk ash, achieving a correlation coefficient of about 0.97 with low prediction errors and providing an explicit predictive equation, which highlights the potential of advanced data-driven tools for designing sustainable SCC mixtures with waste-derived ingredients.

A critical gap remains in the existing literature as most studies have isolated the effects of PET either as fibers or as a single type of aggregate replacement. To the best of the authors' knowledge, no comprehensive study has systematically investigated the synergistic effects of simultaneously replacing both fine and coarse natural aggregates with granulated and flake PET in SCC. Furthermore, the existing contradictory findings regarding rheological performance necessitate a more rigorous examination of mixture variables. This study aims to bridge this gap by conducting a multi-variable experimental program to evaluate the influence of PET morphology, replacement ratios, and their combined interaction on the fresh and hardened properties of SCC across different strength classes. The primary objective is to identify an optimal mix design that maximizes PET waste utilization while meeting the essential mechanical and rheological requirements for structural SCC.

2. Materials and experimental methods

2.1. Constituent materials of PET-SCC

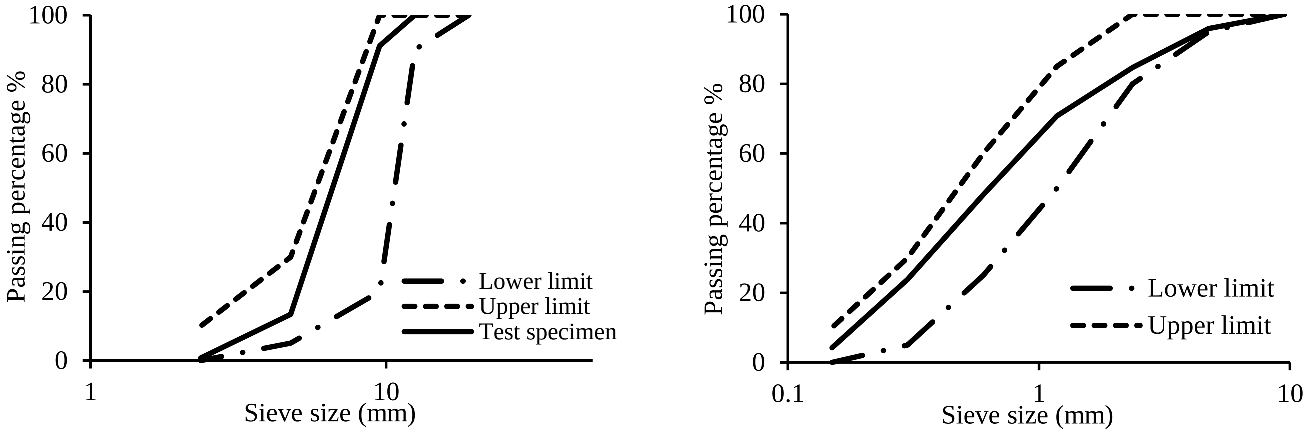
2.1.1. Sand and gravel specifications

Semi-crushed gravel with a nominal maximum aggregate size of 9.5 mm was used to produce concrete, with river sand with standard grading being utilized. Table 1 presents the specifications of the sand and gravel used. Additionally, Fig. 1 provides a comparison of grading curves based on ASTM C33 [24].

Table 1. Properties of aggregates.

Properties	Coarse aggregate	Fine aggregate	Granule PET	Flake PET
Coefficient of Curvature (CC)	1	0.53	0.92	2.4
Coefficient of Uniformity (CU)	1.83	7.5	2	4.3
Los Angeles abrasion (%)	17.5	-	-	-
Fractured particles	47%	0%	-	-

Material finer than 75µm	1%	3.50%	-	-
Fineness Modulus	5.94	2.72	-	-

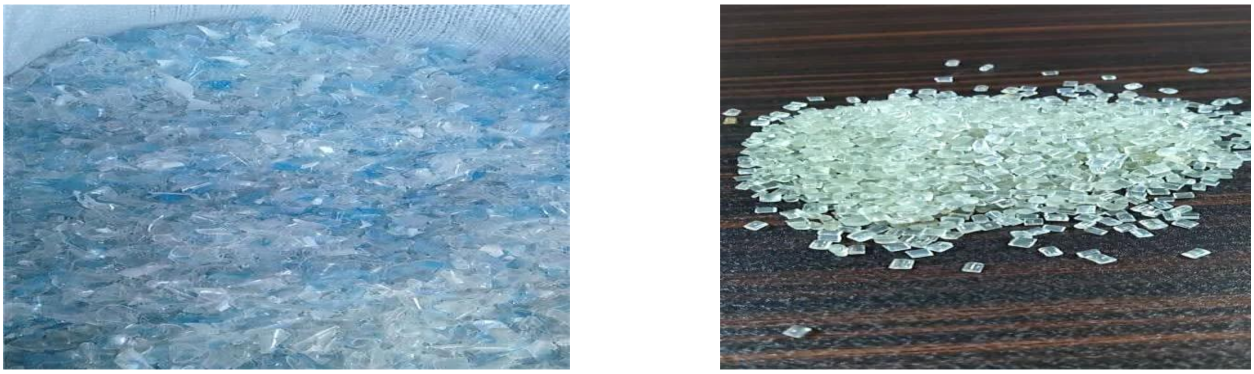


(a) **(b)**

Fig. 1. Grain size distribution chart control of aggregates according to ASTM C33 [24] (a) Results of gravel (b) Results of sand.

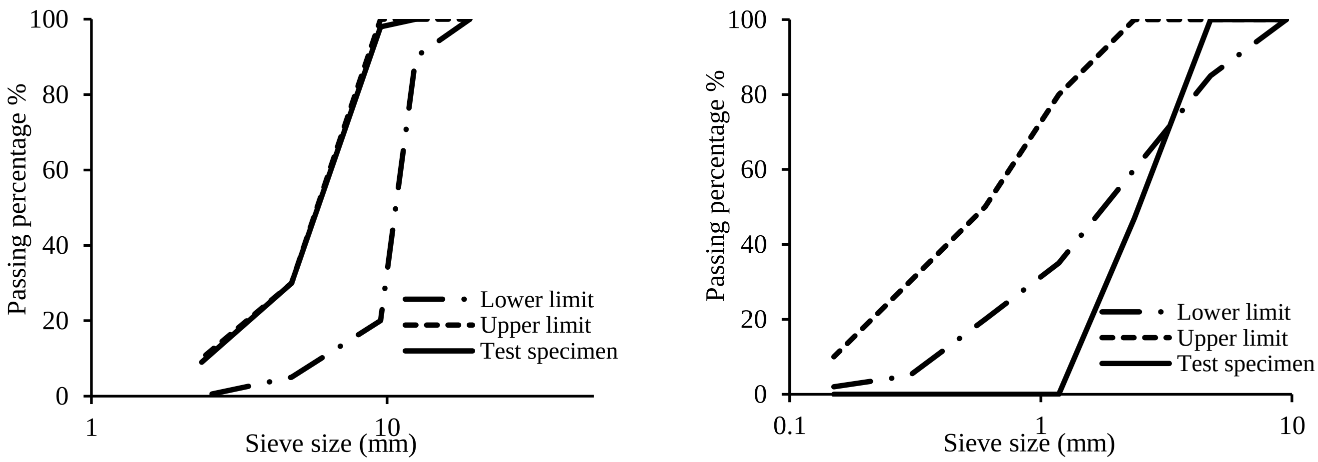
2.1.2. PET specifications

This study employed two different types of recycled PET materials to replace fine and coarse aggregates. Recycled PET granules were sourced from Rata Shomal Recycling Industries, Rata Shomal Recycling Industries in Amol, Iran, and recycled PET flakes were obtained from Qom, Iran. Fig. 2 shows the PET materials used in this study. The specifications of the PET granules and PET flakes used are listed in Table 2. As there is no standard grading system for PET aggregates, the grading curves were prepared similarly to conventional aggregates based on ASTM C33 [24]. Fig. 3 compares these grading curves with conventional aggregate criteria.



(a) **(b)**

Fig. 2. Recycled PET (a) PET flakes (b) PET granules.



(a) **(b)**

Fig. 3. Grain size distribution chart control of PET according to ASTM C33 [24] (a) Flake PET (b) Granule PET.

Table 2. Physical properties of used PET.

Physical property of PET Results	Flake PET	Granule PET
Specific gravity (gr/cm^3)	1.35	1.3
Chemical description (gr/cm^3)	0.68-0.72	0.7
Color tone	Clear, light blue, blue	light green
Approx. melting point	240-250 ^0C	240-250 ^0C

2.1.3. Superplasticizer

Superplasticizers are essential for achieving adequate workability in self-compacting concrete. Polycarboxylate-based superplasticizers exhibit superior performance compared to other superplasticizer types. A polycarboxylate-based superplasticizer, with its properties listed in Table 3, was used in this study.

Table 3. Properties of superplasticizer.

Type	Modified Polycarboxylate
Color	Dark purple
State	Liquid
State Specific gravity (gr/cm^3)	1.1
PH	5±2

2.1.4. Cement

In this study, Type II Portland cement was used. The specifications of this cement are presented in Table 4.

Table 4. Main composition of cement.

Physical characteristics	Value	Chemical composition	Cement (%)
Outlet start (min)	180	SiO2	20.35
End of the outlet (min)	225	Al2O3	4.65
2-day compressive strength (MPa)	28.1	Fe2O3	3.45
28-day compressive strength (MPa)	55.1	SO3	2.69
		CaO	63.63
		MgO	1.52
		K2O	0.73
		Na2O	0.33

2.2. Mix design

Generally, the production method of self-compacting concrete (SCC) is similar to conventional concrete, with the main difference lying in the specific rheological criteria of SCC. The SCC mixtures in this study were proportioned according to the EFNARC [25] guidelines using a conventional empirical mix design approach. The total aggregate content was initially estimated based on the framework proposed by Edamatsu et al. [26]. The water–cement ratios of 0.40 (for the target C25 strength class) and 0.36 (for the target C35 strength class) were determined through preliminary trial batches. In these trials, 7-day compressive strengths were used as a predictor to ensure that the mixtures would reach the required 28-day strengths while still maintaining adequate flowability for SCC. The initial superplasticizer dosage was selected based on values commonly reported in similar SCC studies [26]. This dosage was then refined through iterative trial mixtures using slump flow as the main control parameter until the mixtures satisfied the flowability limits recommended by EFNARC [25].

(a) (b)

Fig. 4. Concrete samples (a) Cylindrical samples (b) Cubic samples.

SCC with two strength classes, C25 and C35, was studied, and three groups of mixtures were examined for each class. Flake PET replaced coarse aggregates in the first group, Granule PET replaced fine aggregates in the second group, while Granule and Flake

PET replaced fine and coarse aggregates simultaneously in the third group. The replacement ratios were 5%, 10%, and 20% by the weight of the respective aggregates. Table 5 presents the mix designs used in this study for easier identification. To facilitate the identification of the mixtures, a specific naming convention was adopted. In this notation, the first part indicates the target concrete strength class (e.g., C25 or C35). The numerical value represents the replacement percentage of natural aggregates by PET waste (by weight). The letters "G" and "F" denote the type of PET used, corresponding to granules and flakes, respectively. For example, C35-10GF denotes a mixture in the C35 strength class containing a hybrid replacement of 10% PET granules and 10% PET flakes (20% total PET). The concretes were produced in accordance with the mix designs. Subsequently, tests, including slump flow, visual stability index (VSI), and V-funnel, were performed on fresh concrete. Sampling was carried out after completing the fresh concrete tests. Four standard cylindrical (150×300 mm) and six cubic (150×150×150 mm) samples were prepared for each mix design, totaling 120 cubic and 80 cylindrical samples, as illustrated in Fig. 4.

Table 5. Concrete mixture composition.

Mixture ID	PET type	PET level	PET	Coarse aggregates	Fine aggregates	Cement	Water	SP	W/C	Concrete mixture type
Unit	-	%			kg/m^3				-	MPa
C25	-	0	0	700	1100	370	148	1.5	0/40	**C25**
C25-05G	Granule PET	5	55	700	1045	370	148	1.5	0/40	
C25-10G		10	110	700	990	370	148	1.5	0/40	
C25-20G		20	220	700	880	370	148	1.5	0/40	
C25-05F	Flake PET	5	35	665	1100	370	148	1.5	0/40	
C25-10F		10	70	630	1100	370	148	1.5	0/40	
C25-20F		20	140	560	1100	370	148	1.5	0/40	
C25-05GF	Flake + Granule PET	5	90	665	1045	370	148	1.5	0/40	
C25-10GF		10	180	630	990	370	148	1.5	0/40	
C25-20GF		20	360	560	880	370	148	1.5	0/40	
C35	-	0	0	670	1040	460	170	3	0/36	**C35**
C35-05G	Granule PET	5	52	670	988	460	170	3	0/36	
C35-10G		10	104	670	936	460	170	3	0/36	
C35-20G		20	208	670	832	460	170	3	0/36	
C35-05F	Flake PET	5	33/5	636/5	1040	460	170	3	0/36	
C35-10F		10	67	603	1040	460	170	3	0/36	
C35-20F		20	134	536	1040	460	170	3	0/36	
C35-05GF	Flake + Granule PET	5	85.5	636/5	988	460	170	3	0/36	
C35-10GF		10	171	603	936	460	170	3	0/36	
C35-20GF		20	342	536	832	460	170	3	0/36	

The samples were demolded after 24 hours and then cured under standard conditions until testing, as depicted in Fig. 5. Furthermore, various tests were performed on hardened concrete, including density, compressive strength, and split tensile strength tests. The results of each test are presented and discussed in the following sections.

Fig. 5. Sample storage pool.

3. Experimental test results

3.1. Fresh concrete properties

The slump flow test and Visual Stability Index (VSI) are among the most vital criteria for controlling the rheological properties of SCC. These tests were used to evaluate the flowability and segregation resistance of the mixtures. According to EFNARC [25], the slump flow should be between 550 and 850 mm. The VSI ranges from 0 to 3 and indicates the degree of segregation of SCC, with values of 0 or 1 considered acceptable. Fig. 6 illustrates images of the slump test for a number of samples. Other SCC characteristics include its viscosity and filling ability, which are controlled by the V-funnel test. According to EFNARC [25], V-funnel times of up to 25 seconds are acceptable. Fig. 7 displays the V-funnel test and the experimental equipment used in this study. The results of the fresh concrete tests are summarized in Table 6.

(a) (b) (c)

Fig. 6. Slump flow test (a) C25-05F (VSI = 0) (b) C25-10G (VSI = 1) (c) C25-20F (VSI = 3).

(a) (b)

Fig. 7. The process of V-funnel test (a) Flattening the surface (b) Opening the valve.

The incorporation of PET generally reduced the flowability of SCC mixtures, as reflected by the measured slump-flow values. For both C25 and C35 mixtures, increasing the PET content led to a progressive decrease in slump flow. This reduction can be attributed to the lower specific gravity of PET compared with natural aggregates and the increased internal friction between mixture components, which restricts the movement of aggregates and reduces the ability of SCC to flow under its own weight. For example, in the C25 mixtures the slump flow decreased from 70 cm in the control mixture to about 65 cm with 10% PET flakes, whereas it dropped more considerably to around 50 cm with 10% PET granules (Table 6). These results indicate that PET granules have a stronger negative influence on the flowability of SCC than PET flakes, likely due to the higher internal friction induced by the granular particles within the fresh mixture. The results also show that mixtures with 20% PET replacement did not satisfy the rheological requirements of SCC. In contrast, mixtures with 10% replacement achieved relatively acceptable performance. Among them, the C25-10GF sample, which included 10% replacement of fine aggregate and 10% replacement of coarse aggregate with PET (corresponding to about 180 kg of PET consumption), showed satisfactory results. This finding suggests that combining two types of PET particles can increase the usable volume of PET in SCC while maintaining acceptable workability. The addition of PET weakens the results of the SCC rheological tests, an issue quite evident in Fig. 8. This situation is similarly observed in the V-funnel time improve due to the more suitable grading of PET Flake, with its grading curve falling within the ASTM C33 [24] specified range (Fig. 3a).

Table 6. Fresh SCC tests result.

Mixture ID	Slump-flow (cm)	Visual Stability Index	V-funnel time (seconds)	Viscosity class
C25	70	0	8	VS1
C25-05F	68	0	9	VS2
C25-10F	65	2	11	VS2
C25-20F	60	3	13	VS2
C25-05G	60	0	10	VS2
C25-10G	50	1	13	VS2
C25-20G	35	3	-	-
C25-05GF	60	0	10	VS2
C25-10GF	50	1	13	VS2
C25-20GF	45	3	17	VS2
C35	75	0	8	VS1
C35-05F	70	0	9	VS2
C35-10F	67	1	10	VS2
C35-20F	60	2	14	VS2
C35-05G	62	0	12	VS2
C35-10G	54	1	17	VS2
C35-20G	35	3	-	-
C35-05GF	65	0	11	VS2
C35-10GF	55	1	15	VS2
C35-20GF	45	2	25	VS2

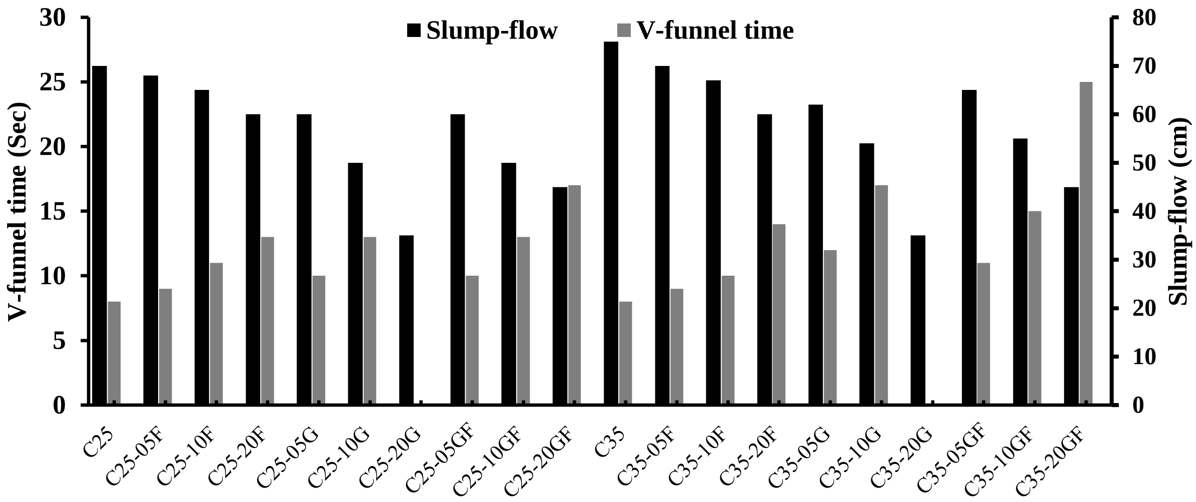


Fig. 8. Results of slump and V-Funnel tests.

A clear synergistic effect was observed when PET flakes were combined with PET granules. As shown in Table 6, mixtures with only PET granules exhibited the poorest flowability; at the 20% replacement level they even experienced complete blockage in the V-funnel. In contrast, adding PET flakes to these mixtures, despite the total PET content being higher—improved flow performance and eliminated blockage. This indicates that the beneficial influence of the flakes compensates for, and partially counteracts, the adverse effect of the granules. This synergy arises from the complementary roles of the two PET types. The flat, plate-like geometry of flakes reduces particle interlocking and helps disperse the granules, while the granules occupy part of the voids created by larger flake particles. The resulting packing condition lowers interparticle friction and prevents localized accumulation of PET granules that would otherwise hinder flow. Consequently, hybrid mixtures show superior flowability compared with mixtures containing only PET granules, particularly in the V-funnel where sensitivity to blockage is high. A comparison of the results for different concrete grades indicates that with the increased concrete grade, the slump flow and visual stability of PET-SCC improve while the V-funnel time increases. These results are due to the increased cement content and the increased viscosity of the cement paste.

3.2. Hardened concrete tests

3.2.1. Density test of hardened concrete

The density of the samples was determined using cubic samples, with 150×150×150 mm dimensions, in accordance with the ASTM C642 [27]. Three cubic specimens were tested, and the average values are reported in Table 7. The results show a clear decrease in concrete density with increasing PET content. A 20% replacement of either fine or coarse aggregates led to an approximate 7% reduction in density, whereas the combined replacement of both fine and coarse aggregates at the same level resulted in an approximate 11% reduction. Notably, the density values of mixtures containing both PET flakes and granules were slightly higher than those predicted based solely on the PET replacement level. This behavior can be attributed to improved compaction in the hybrid mixtures, which is consistent with their superior rheological performance observed in the fresh concrete tests.

3.2.3. Compressive and split tensile strength tests

Compressive strength is one of the most critical mechanical properties of SCC, as it directly influences the structural performance and durability of concrete. For each mix design, six cubic specimens (150 × 150 × 150 mm) were prepared. Three specimens were tested at 28 days, and the remaining three were tested at 90 days. Compressive strength tests were conducted in accordance with ASTM C39 [28], and the average results are presented in Table 7. Table 7 summarizes the average results for the 28-day and 90-day compressive strength samples. Split tensile strength tests were performed in accordance with ASTM C496 [29]. Four standard cylindrical specimens were prepared for each mix design and tested using a 2000 kN hydraulic testing machine (Fig. 9). Standard loading arrangements were applied to ensure failure along the loading axis, as specified by the test method.

Table 7. Results of hardened concrete tests for samples.

Mixture ID	Density kg/m^3	Average compressive strength		Average splitting tensile strength	
		28-day	90-day	28-day	90-day
C25	2350	31.2	35.2	2.8	3.2
C25-05F	2310	29.3	33.6	2.6	3.0
C25-10F	2250	25.4	30.3	2.2	2.6
C25-20F	2200	18.6	20.1	2.1	2.3
C25-05G	2310	24.7	30.9	2.4	2.8
C25-10G	2270	20.8	25.6	1.8	2.2
C25-20G	2170	9.3	10.2	1.5	1.6
C25-05GF	2320	27.3	32.6	2.3	2.6
C25-10GF	2270	23.3	29.0	2.2	2.7
C25-20GF	2100	18.0	21.6	1.7	2.1
C35	2360	41.2	45.7	3.5	3.9
C35-05F	2320	39.0	41.8	3.1	3.7
C35-10F	2260	35.7	39.5	3.1	3.5
C35-20F	2200	26.8	30.9	2.9	3.1
C35-05G	2320	24.3	26.1	3.2	3.4
C35-10G	2250	30.9	34.4	3.0	3.3
C35-20G	2150	20.4	22.5	2.5	2.7
C35-05GF	2310	32.0	36.8	3.1	.5
C35-10GF	2270	30.8	34.2	3.0	3.3
C35-20GF	2050	17.7	20.4	2.4	2.6

Table 7 presents the compressive and splitting tensile strengths at 28 and 90 days. Among all mixtures, the most favorable overall performance was obtained when 5% of the coarse aggregates was replaced with PET flakes. For the C35-05F mixture, the 28-day compressive strength decreased by only 5% relative to the control C35 mixture, while all SCC rheological criteria were fully satisfied. This indicates that low-level incorporation of flake-type PET can be tolerated without significantly compromising the mechanical properties of SCC. In contrast, the poorest mechanical performance was recorded for mixture C25-20G, with a reduction of approximately 70% in 28-day compressive strength. It must be emphasized, however, that this mixture did not satisfy the essential rheological requirements of SCC. The slump flow was only 35 cm, the Visual Stability Index reached 3, and complete blockage occurred in the V-funnel test, leading to severe compaction deficiencies. Therefore, this mixture cannot be considered a valid SCC composition, and its low strength is primarily attributed to inadequate flowability and poor consolidation rather than the intrinsic effect of PET aggregates. Beyond these two extremes, the overall trend among the remaining mixtures reveals a clear correspondence between rheological behavior (Table 6) and compressive strengths (Table 7). As expected, increasing the PET content generally reduced compressive strength; however, mixtures with improved flowability and reduced interparticle friction achieved better compaction, which effectively limited this reduction. This interpretation is further supported by Fig. 10, where the concurrent decrease in density and compressive strength across mixtures illustrates the direct influence of compaction efficiency on mechanical performance. This relationship is clearly reflected in the 10% replacement mixtures. The granule-only mixture C25-10G, which exhibited the weakest rheological performance, experienced the highest strength reduction (33%). The flake-only mixture C25-10F, benefiting from enhanced flowability, showed a smaller reduction of 19%. The hybrid mixture C25-10GF, despite containing a total of 20% PET (10% flakes + 10% granules), showed a 25% reduction—smaller than expected considering the doubled PET content and the poor behavior of granules. This confirms that improved rheology enhanced compaction and mitigated strength loss. A similar, though less pronounced, trend was observed for the C35 mixtures.


(a) (b) (c)

Fig. 9. Splitting tensile test (a) 2000 KN hydraulic jack (b) Set up for splitting tensile test (c) Sample after the test.

Table 7 presents the compressive and splitting tensile strengths at 28 and 90 days. Among all mixtures, the most favorable overall performance was obtained when 5% of the coarse aggregates was replaced with PET flakes. In this case (C35-05F), the 28-day compressive strength was only 5.4% lower than that of the C35 control mixture, while all SCC rheological criteria were fully satisfied. This result demonstrates that a low-level incorporation of flake-type PET can be accommodated without substantially compromising the mechanical properties of SCC. In contrast, the poorest mechanical performance occurred in mixture C25-20G, which experienced an approximately 70% reduction in 28-day compressive strength. It must be emphasized, however, that this mixture did not satisfy the essential rheological requirements of SCC. The slump flow was only 35 cm, the Visual Stability Index reached 3, and complete blockage occurred in the V-funnel test, leading to severe compaction deficiencies. Therefore, this mixture cannot be considered a valid SCC composition, and its low strength is primarily attributed to inadequate flowability and poor consolidation rather than the intrinsic effect of PET aggregates. Beyond these two extremes, the overall trend among the remaining mixtures reveals a clear correspondence between rheological behavior (Table 6) and compressive strengths (Table 7). As expected, increasing PET content generally reduced compressive strength. Nevertheless, mixtures with superior flowability and lower interparticle friction achieved better compaction, which effectively mitigated the strength reduction. This interpretation is supported by Fig. 10, where the concurrent decrease in density and compressive strength across mixtures highlights the governing role of compaction efficiency in the mechanical response of SCC. This relationship is especially evident in the 10% replacement mixtures. The granule-only mixture C25-10G, which exhibited the poorest rheological performance, showed the greatest strength reduction (33%). The flake-only mixture C25-10F, benefiting from improved flowability, experienced a smaller reduction of 19%. The hybrid mixture C25-10GF, despite containing a total of 20% PET (10% flakes + 10% granules), showed a 25% reduction, which is lower than expected given both the doubled PET content and the unfavorable characteristics of the granules. This confirms that enhanced rheology promoted better compaction and helped limit the strength loss. A similar, although less pronounced, trend was observed in the C35 mixtures.

Table 7 shows that the splitting tensile strength followed a trend similar to that observed for compressive strength. The largest reductions were recorded in mixtures containing 20% PET granules, reaching 48% for C25 and 27.5% for C35. In contrast, the hybrid mixtures exhibited comparatively better performance, with reductions of 38% and 31% for C25 and C35, respectively, despite containing a higher total PET content than mixtures incorporating PET granules alone. This behavior highlights the beneficial effect of combining the two PET geometries. These findings are consistent with previous studies on PET-modified concrete, which generally report a reduction in compressive strength with increasing PET content. For example, Sadrmomtazi et al. [20] observed that replacing 2.5% of aggregates with PET resulted in an 8% decrease in compressive strength, whereas a 15% replacement led to a 48.3% reduction. Several other studies have suggested that the acceptable limit of PET replacement in SCC is approximately 15%, beyond which the rheological properties deteriorate and the concrete can no longer be classified as self-compacting [7,17–20]. The present results further extend the existing literature by demonstrating that hybrid PET replacement can outperform single-type PET mixtures, an observation that has not been explicitly reported in previous studies.

Fig. 11 illustrates the percentage increase in the 90-day tensile and compressive strengths of samples compared to their 28-day conditions. As observed, in most cases, samples containing PET exhibited a higher rate of strength growth compared to conventional SCC. Thus, it can be concluded that adding PET not only has no adverse impact on the long-term strength gain of SCC but also enhances its strength following 90 days. This improvement in class C25 SCC-PET strength led to an average of 5% higher tensile and compressive strength compared to conventional SCC. However, examining the average changes in tensile and compressive strengths in class C35 reveals that the improvement in strength is not as significant. This highlights the need for further studies in this area.

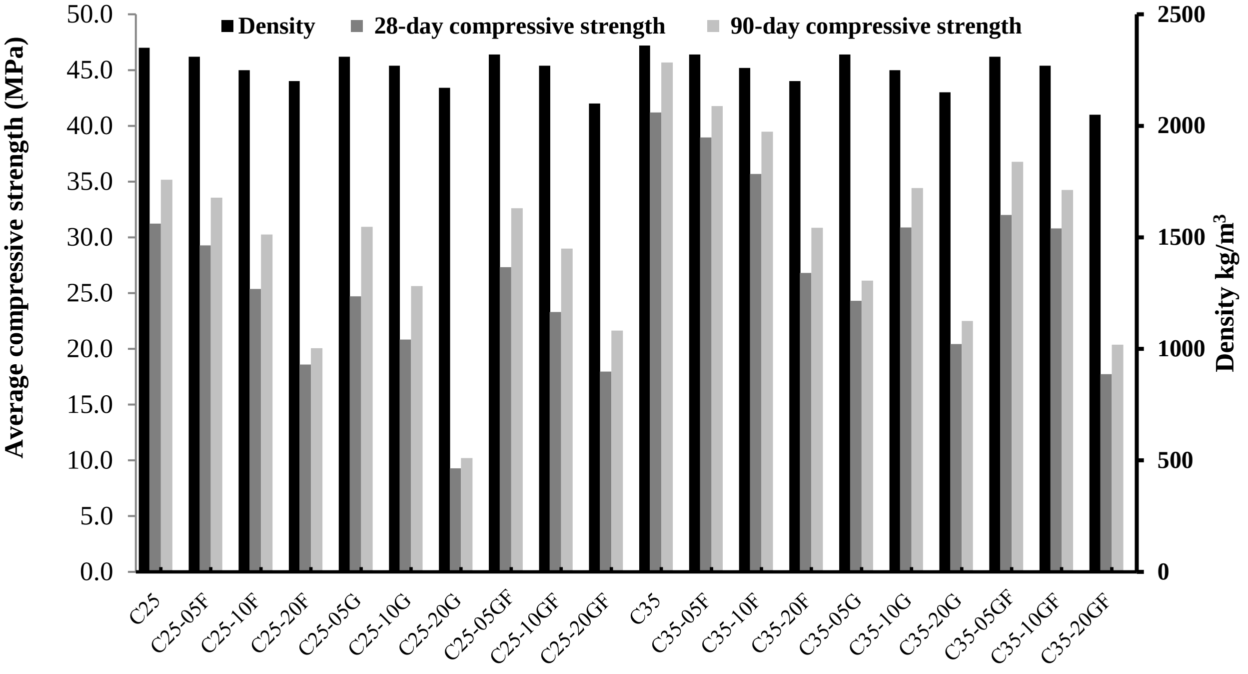


Fig. 10. Results of density and 28-Day and 90-Day compressive strength tests.

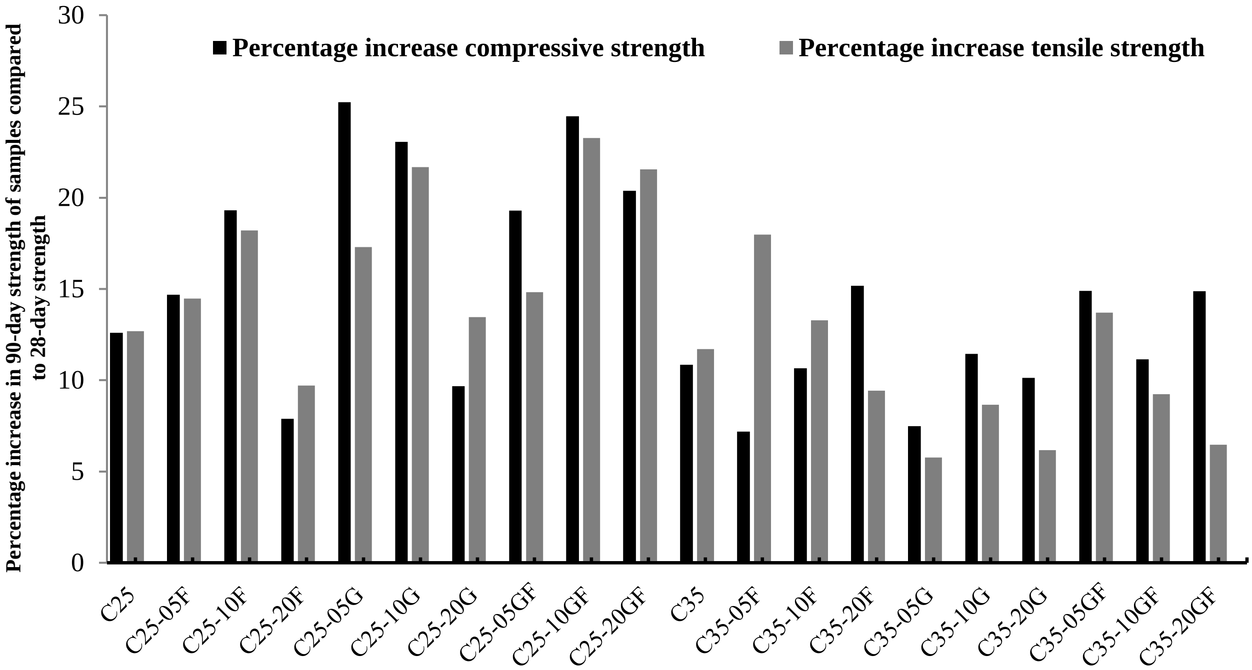


Fig. 11. The percentage increase in the 90-day tensile and compressive strengths of samples compared to their 28-day conditions.

Table 8. Images of samples after compressive strength test.

C35-20GF

C35-20G

C35-20F

C35-05GF

C35-10GF

C35-20F

C35-05GF-90

C35-10GF-90

C35-20F-90

Table 8 displays selected specimens after the compressive strength tests. As seen in the images, mixtures containing PET flakes generally exhibited better compaction compared with those containing PET granules (e.g., C35-20G). The least compacted textures were observed in granule-only mixtures, consistent with their weaker rheological performance. Moreover, the presence of PET reduced the overall cohesion of the concrete; mixtures with higher PET contents tended to lose structural integrity after loading and disintegrated more easily. The 90-day specimens displayed more brittle failure patterns, but the crack propagation remained consistent with standard compressive failure modes.

4. Conclusion

This study investigated the performance of Self-Compacting Concrete (SCC) incorporating hybrid PET waste as a replacement for natural aggregates. Based on the experimental results and the analysis of rheological and mechanical properties, the following conclusions can be drawn.

- Up to 180 kg of PET per cubic meter of SCC was successfully incorporated through hybrid aggregate replacement, exceeding the PET contents reported in most previous studies.
- A clear synergistic effect was observed in the hybrid mixtures. While the mixture containing 20% PET granules (C25-20G) failed to satisfy SCC rheological requirements due to V-funnel blockage, the hybrid mixture with 10% flakes + 10% granules (20% total PET) met all SCC criteria. This indicates that PET flakes improve the flowability and passing ability of mixtures containing PET granules.
- The best mechanical performance was achieved with 5% PET flakes (C35-05F) as a replacement for coarse aggregates, resulting in only a 5.4% reduction in 28-day compressive strength compared with the control mixture. PET incorporation did not negatively affect long-term strength development. In the C25 mixtures, PET-modified SCC showed an average 5% greater strength gain between 28 and 90 days compared with the control mixtures, whereas the improvement was less pronounced in the C35 mixtures.
- From a sustainability perspective, the optimum replacement level for maximizing waste utilization was the hybrid mixture containing 10% flakes and 10% granules (20% total PET). This mixture maintained all SCC rheological limits while limiting the compressive strength reduction to 25% (C25-10GF), which is considerably lower than expected for such a high PET content.
- A simultaneous decrease in density and compressive strength was observed, indicating that the strength reduction is mainly associated with lower compaction efficiency and the lower specific gravity of PET aggregates.
- Although the experimental results clearly showed reductions in mechanical strength with increasing PET content, the underlying microstructural mechanisms require further investigation. Future studies are therefore recommended to conduct Scanning Electron Microscopy (SEM) analysis in order to examine the interfacial transition zone (ITZ) between PET aggregates and the cementitious matrix. Such analysis would provide deeper insight into the bonding characteristics, interfacial behavior, and potential failure mechanisms responsible for the strength reduction observed in SCC containing PET.

Statements & Declarations

Author Contributions

Baitollah Badarloo: Conceptualization, Methodology, Formal analysis, Project administration, Supervision, Writing - Review & Editing.

Mahdi Moradi: Investigation, Methodology, Visualization, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing.

Hamid Reza Koohestani: Conceptualization, Investigation, Methodology, Writing - Review & Editing.

Ali Attarzadeh: Investigation, Methodology, Visualization, Validation, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing.

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Data availability

The data presented in this study will be available on interested request from the corresponding author.

Declarations

The authors declare no conflict of interest.

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