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Fresh, Mechanical and Absorption Characteristics of Self-Consolidating Concretes Including Low Volume Waste PET Granules

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Abstract

This study evaluates the effect of waste polyethylene terephthalate (PET) granules on the fresh, mechanical and absorption characteristics of self-consolidating concretes (SCCs). Fine aggregates were replaced with different percentages (from 0% to 8%) of PET granules obtained by crushing waste PET bottles. The fresh properties of SCC containing PET granules were determined using slump flow and V-funnel flow time tests. Mechanical properties (compressive strength and splitting tensile strength tests) and absorption properties (sorptivity and water absorption tests) were evaluated. The results indicated that utilization of waste PET granules in production of SCC could be an effective way for recycling purpose. The maximum amount of PET replacement should be limited to 5%. Exceeding 5% of PET content may result in an increase of V-funnel flow time to overpass the limiting value, decrease in compressive strength, reduction in sorptivity and increase in the water absorption. The production of high performance SCC containing 5% PET granules satisfies all the requirements for SCC with satisfactory outputs.

Keywords: Self-Consolidating Concrete; Polyethylene Terephthalate; Hardened Properties; Mechanical Properties; Aggregate.

1. Introduction

Self-consolidating concretes (SCCs) are known as a greatly coherent and flowable concretes that are capable to consolidate under their own weight without compaction and vibration. SCCs were developed firstly in Japan in 1980s to increase stability and durability of concrete structures [1-5]. SCC decreases the risk of poor workmanship during casting and compaction of concrete. Moreover, economic efficiency, less human work, more freedom to designers and lowering noise level on the construction site are other advantages of using SCC [6].

PET is a kind of polyesters made of the composition of ethylene glycol and terephtalic acid and it's called as "polyethylene terephthalate". PET is one of the mostly utilized plastics in the package industry because of high stability, high pressure tolerance, non-reactivity with substances and great quality of gas trapping which can preserve the gas in the gaseous drinks. The manufacturing of PET bottles increased especially in USA, Canada, Asia and Western Europe due to the increase in the beverage consumption [7-9]. The overall amount of recyclable PET bottles in the United States was about 23.4×10^8 kg in 1 year, whereas the recycled quantity was just about 6.53×10^8 kg which is 28% of the existing amount [10]. There are different methods for disposing PET bottles such as burial, incinerate and recycling [11]. It can be useful to profit from the generated heat during incineration, but the combustion of PET bottles may produce poisonous

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gasses. Another problem arises from the fact that these materials slowly decompose and need hundreds of years to return to the cycle of nature. So it seems that recycling PET waste is the best way because of environmental compatibility and economic benefits [12].

The present application of recycled PET waste in the construction industry includes its use as resin for polymer concrete [13-17] and as fiber for reinforced concrete [18]. The most economical way is using PET particles as a substitute of aggregates. As a result, using PET waste as an aggregate in concrete has some benefits such as decreasing the usage of natural resources, the wastes consumption, preventing the environmental pollution and economizing energy [19, 20].

Albano et al. [12] evaluated the mechanical behavior of the PET waste particles in which, the volume substitution ratios were 10% and 20% and the average PET particle size were about $0.26\ cm$ and $1.14\ cm$. Result shows a reduction in tensile strength, compressive strength and modulus of elasticity. Adding PET to the concrete mixture leads to decrease in concrete rigidity, which is useful when flexibility of the material is needed. Moreover, adding PET particles to the concrete mixture results in reduction of slump, increase of water absorptions, and also reduction in the pulse velocity. Chio et al. [21] studied the effect of sand replacement with PET aggregates which were made of PET particles and stone powder on the properties of concrete. A decrease in concrete unit weight and an increase in water absorption were noticed. It was concluded that as the substitution percentage increases, the flow value increases as well. In addition, this replacement has reduced the compressive strength.

Akçaozoglu et al. [22] examined the effect of PET waste particles as aggregate on two groups of mortars. One of them was entirely made of PET aggregates and the other one was made of both sand and PET aggregates. The result shows that the unit weight, compressive strength and tensile–flexural strength of the mortars including PET aggregates are less than the mortars containing combination of both sand and PET aggregates. Both mortars had much lower unit weight, compressive strength and tensile–flexural strength compared with reference sample mortars.

Foti [23] studied the behavior of concretes reinforced with PET bottles waste fibers. It was concluded that adding small quantity of PET bottle fibers have a noticeable effect on post-cracking behavior of concretes. Additionally, PET fibers enhance the toughness and improve the concrete plasticity. Oliveira and Gomes [24] utilized recycled PET bottle fibers in the reinforced mortar. Different volumes of fibers were added with the variable quantity of 0%, 0.5%, 1%, and 1.5% to the dry mortars. It was reported that utilizing PET fibers makes an important development on compressive strength of reinforced mortar, besides a notable effect on the flexural strength and increase in the toughness.

Sadrmomtazi et al. [25] studied the fresh and hardened properties of SCC including waste PET particles. It was concluded that using PET particles in SCC reduces the compressive, flexural and tensile strengths. However, the electrical resistance was not affected by using PET particles. Test results showed that using PET particles can lead to a decrease in the brittleness of concrete. Safi et al. [26] investigated the possibility of using PET as fine aggregates in the production of self-compacting mortar. The test results showed that fluidity is greatly developed by adding PET waste.

Torgal et al. [27] studied the properties and durability of concrete containing tyre rubber and PET. They found that that tyre waste concrete is specially recommended for concrete structures located in areas of severe earthquake risk and also for applications submitted to severe dynamic actions. As to PET based concrete the investigations show that this material is very dependent on the treatment of these wastes.

This study researched the effect of PET granules on the fresh, mechanical and absorption characteristics of SCC. Fine aggregate was replaced with different percentages (from 0-8%) of PET granules obtained by crushing waste PET bottles. The effect of PET on the Slump Flow (SF), V-Funnel (VF) flow time, compressive strength, splitting tensile strength, sorptivity and water absorption of SCC was examined.

2. Experimental Study

In this study, experimental program was conducted to evaluate the properties of SCC made with waste granular PET. SF time, SF diameter, VF time tests were carried out to identify the characteristics of fresh SCCs. The splitting tensile strength and compressive strength tests were carried out to classify the mechanical properties of hardened concretes. Absorption properties of SCCs were evaluated by performing the water sorptivity and water absorption tests.

2.1. Materials

Normal Portland cement CEM-I 42.5R which conforms to TS EN 197-1 [28] was used in preparation of mixtures. It was obtained from Limak Gaziantep Cement Factory. The chemical composition and physical properties of the cement are presented in Table 1.

Table 1. Chemical composition and some physical properties of the cement used in the study

Analysis Report (%)	Cement
CaO	62.58
SiO_2	20.25
Al_2O_3	5.31
Fe_2O_3	4.04
MgO	2.82
SO_3	2.73
K_2O	0.92
Na_2O	0.22
Loss on ignition	3.02
Specific gravity	2.99
Fineness (m^2/kg)	327

Coarse aggregates utilized in concrete specimens is river gravel with a nominal particle size of 16 mm to avoid the blocking effect of aggregates. Fine aggregates is a mix of crushed stone and river sand with a nominal particle size of 5 mm.

The grading of aggregates was obtained through the sieve analysis. Table 2. shows the physical properties of coarse and fine aggregates. Aggregate grading curves with Fuller's reference curve [29] are shown in Figure 1. The aggregates fractions were adjusted to have maximum density of concrete. A polycarboxylic-ether type superplasticizer (SP) has been used with a specific gravity of 1.07 and pH of 5.7.

Table 2. Sieve analysis and physical properties of the fine and coarse aggregates

Sieve Size (mm)	Coarse	Natural sand	Crushed Sand
16	100	100	100
8	59	100	100
4	5	83	92
2	2	58	67
1	1	42	45
0.5	1	25	24
0.25	0.6	6	9.3
Fineness Modulus	5.32	2.87	2.63
Specific gravity	2.74	2.65	2.41

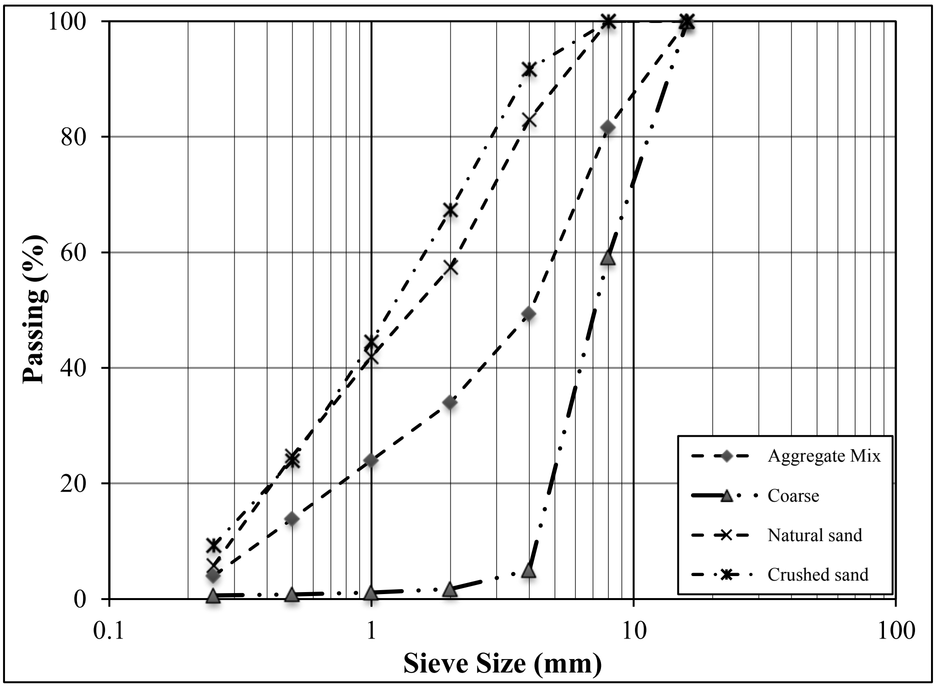

Figure 1. Grading curves of the aggregates used

To observe the effect of PET granules on the fresh and hardened properties of SCC, fine aggregates were replaced with different percentages (0%, 1%, 2%, 3%, 4%, 5%, 6%, 7% and 8%) of PET granules. As it can be observed from Figure 2 the shape of PET granules look like elongated fibers. Therefore sieve analysis was not applied. The PET granules were obtained from a local PET crushing plant.

Figure 2. Photographic view of PET granules

2.2. Concrete Mixtures

SCC mixes were produced with a constant water/binder ratio of 0.32 and total binder content of 570 kg/m^3. Fine aggregates were replaced with different percentages (from 0-8%) of PET granules. During trials it was observed that for the SCCs having more than 8% of PET granules required too much High Range Water Reducing Admixtures (HRWRA). The concretes were separated into two groups according to the amount of HRWRA. Group 1 (up to 5% replacement level) contained 1.5% HRWRA, while Group 2 (PET6, PET7, and PET8) had 1.6%. Coding of the mixtures was based on the replacement level of PET granules. For example, PET3 means SCC mixture containing 3% PET granules. Details of the mix proportions of SCCs are given in Table 3.

Table 3. Details of mix proportions of SCCs, kg/m^3

Materials	Mixtures								
	PET0	**PET1**	**PET2**	**PET3**	**PET4**	**PET5**	**PET6**	**PET7**	**PET8**
Cement	570	570	570	570	570	570	570	570	570
Water	182.4	182.4	182.4	182.4	182.4	182.4	182.4	182.4	182.4
Coarse aggregate	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Medium aggregate	771.9	771.9	771.9	771.9	771.9	771.9	771.9	771.9	771.9
Natural sand	655.3	648.8	642.2	635.7	629.1	622.6	616.0	609.5	602.9
Crushed sand	249.0	246.5	244.0	241.5	239.0	236.5	234.0	231.5	229.0
PET	0.0	4.7	9.5	14.2	18.9	23.7	28.4	33.1	37.9
SP	8.55	8.55	8.55	8.55	8.55	8.55	9.08	9.08	9.08
Unit weight	2436.3	2432.0	2427.7	2423.4	2419.1	2414.8	2410.5	2406.2	2401.9

2.3. Test Methods

Fine and coarse aggregates were mixed together for 30 sec in a mixer. Thereafter, 1/3 of the mixing water was added to the concrete mixer and mixing continued for 1 min more. Next, the aggregates absorbed the water in the mixer for 1 min. After adding cement and mineral additives to the mixer, the mixing continued for another 1 min. Lastly, the SPs were added together with the remaining water to the mixer, and the concretes were mixed for 3 min and then left for 1 min rest. Thereafter, the concretes were mixed for extra 2 min to finish the mixing procedures [30]. The concrete was designed for a SF of $70 \pm 3\ cm$ which was obtained by adjusting the amount of SP by trial-error. Specimens were casted without vibration and compaction. After casting the SCCs in specimen moulds, plastic sheet were used to cover the specimens which they kept in laboratory for 24 h. Thereafter, SCC samples were demoulded and cured in water $(23 \pm 2\ ^oC)$ until testing day.

2.3.1. Fresh Properties

There are limitations defined by EFNARC [31] for classification of concrete as SCC to provide ease of flow through reinforcement and formwork without compaction and vibration. These limitations are segregation resistance, passing ability, filling ability, flowability and viscosity. Table 4 shows the properties of fresh concrete according to EFNARC [31].

Table 4. Slump flow, viscosity, and passing ability classes with respect to EFNARC [30]

Slump flow classes		
Class	Slump flow diameter (mm)	
SF1	550-650	
SF2	660-750	
SF3	760-850	
Viscosity classes		
Class	T_{500} (sec)	V-funnel time (sec)
VS1/VF1	≤2	≤8
VS2/VF2	>2	9 to 25
Passing ability classes		
PA1	≥0.8 with two rebar	
PA2	≥0.8 with three rebar	

2.3.1.1. Slump Flow Test

In this study, SF of all control mixes was adjusted to be $75 \pm 3\ cm$ whilst SF time (T_{50}) was measured. After determination of a constant amount of superplasticizer, fine aggregates were replaced with PET granules with different percentages (from 0-8%).

SF test was performed according to EFNARC [31]. To measure SF, an ordinary cone (EN 12350-2) is filled with SCC without any compaction and leveling. The cone is lifted and the average diameter of the spreading concrete is measured as shown in Figure 3. The time ($T_{500\ mm}$) was recorded for the concrete to reach the $500\ mm$.

Figure 3. Measurement of slump flow diameter

2.3.1.2. V-Funnel Flow Time

VF flow test for SCC was performed according to EFNARC [31]. The flow time is determined in this test. The funnel completely filled with fresh SCC without any compacting or tamping, and the flow time (t) is measured as the time between the opening of bottom outlet and complete emptying of the funnel.

2.3.2. Hardened Properties

2.3.2.1. Compressive Strength

To measure the compressive strength of SCCs, cubical samples of $150\ mm$ were tested after 28 days in accordance with ASTM C 39. Servo controlled $3000\ kN$ capacity compressive strength device was used as shown in Figure 4. Three samples were tested for each experiment and the average value was considered for the study. The standard pace rate was selected equal to $0.2\ MPa$ per second. The pace loading was equal to $4.5\ kN$ per second.

Figure 4. Compressive strength device

2.3.2.2. Splitting Strength

According to ASTM 496, splitting tensile strength of SCC was measured by testing cylindrical samples (200×100 mm dia.) after 28 days. The standard pace rate was selected equal to 1 MPa per minute.

2.3.2.3. Water Absorption

To perform the water absorption test, dried cube samples were immersed in water at $25\ °C$ for 96 hour at the age of 28 days and noticing the percentage of water absorbed per unit initial mass.

2.3.2.4. Sorptivity

Water sorptivity was measured on four samples (50×100 mm dia.) cut from cylindrical samples (200 x 100 mm dia.). Before test, samples were dried in an oven at $100 \pm 5\ °C$ until having a constant mass. The test was performed on the concrete surface which is in contact with a thin water layer while paraffin was applied on the other sides of the specimens, so that the dominant invasion mechanism was the capillary suction. Water sorptivity was evaluated by the water uptake from the concrete per unit cross-sectional area with time. The test was implemented after 28 days. The schematic presentation of the test set up is presented in Figure 5.

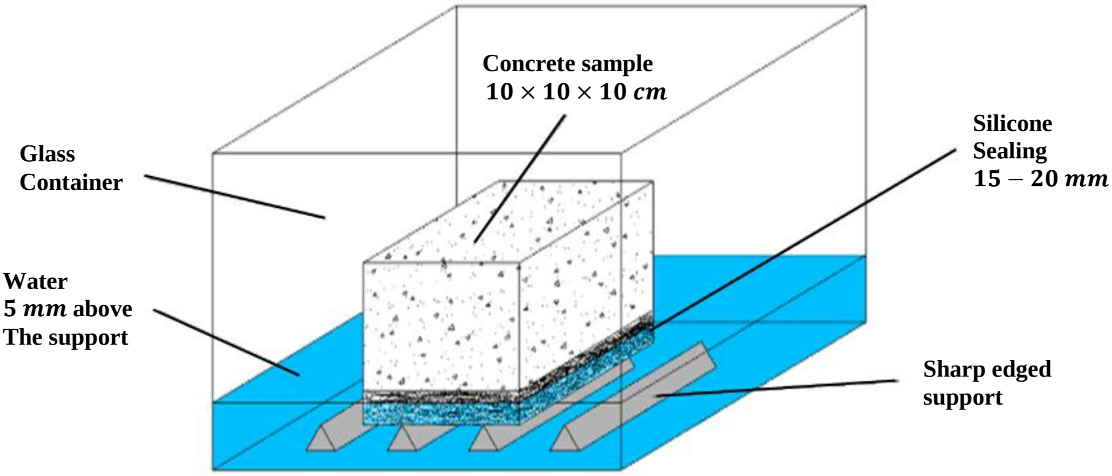

Figure 5. Sorptivity test set up

3. Results and Discussions

3.1. Fresh Properties

In order to provide a high slump flow diameter for control mixture, HRWRA was used as $8.55\ kg/m^3$ (1.5%). For observation of the effect of addition PET granules, the amount of the chemical admixture was kept constant. However when exceeding 5% replacement level of PET, the slump flow diameter decreased dramatically. Therefore, the amount of HRWRA was increased to 1.6% to provide a proper slump flow diameter. The variation of the slump flow diameter and slump flow time is shown in Figures 6 and 7. Figure 6 indicates that increasing the amount of PET granules is resulted in significant reduction in slump flow diameter from 775 mm to 660 mm. Increasing the amount of HRWRA from 1.5% to 1.6% resulted in enhancement in slump flow diameter of the concrete containing 6% PET. The slump flow diameter was measured as $700\ mm$. However for 7% and 8% PET replacement levels the sharp reduction levels were observed especially for PET8 concrete ($535\ mm$).

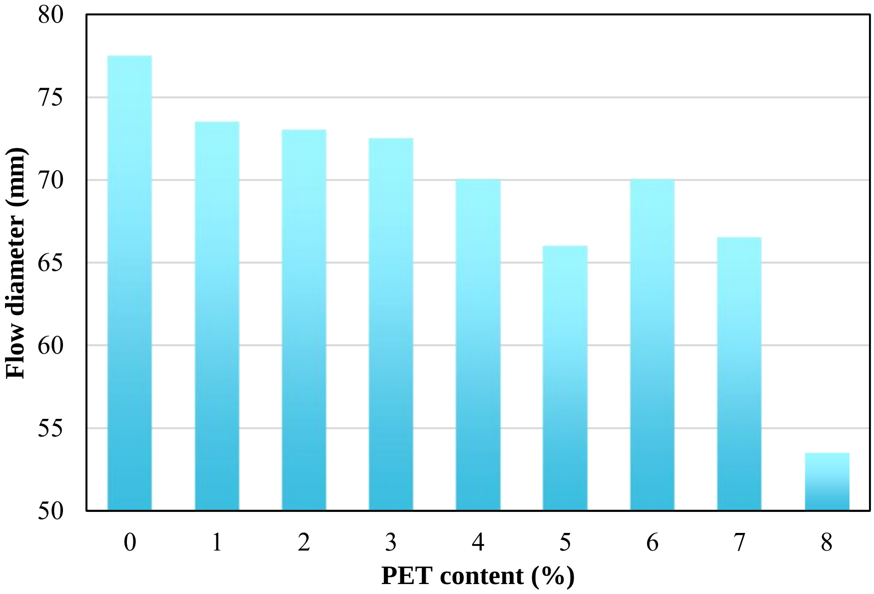

Figure 6 Variation of slump flow diameter with PET content

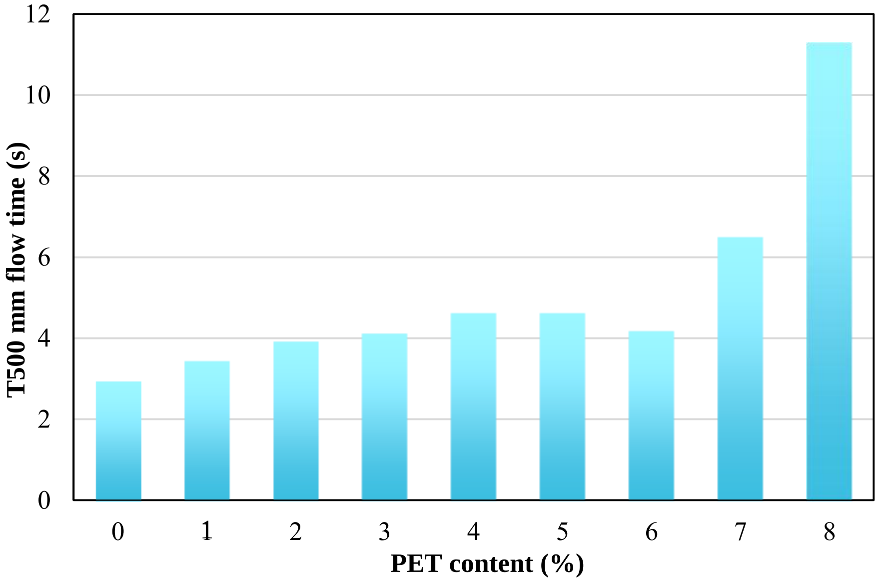

Figure 7. Variation of T_{500mm} slump flow time with PET content

Similarly T_{500mm} slump flow time was increased for the SCCs while increasing the PET content. Nevertheless, the tendency of increment is not similar for SCCs with higher than 5% PET content. Figure 7. illustrates that while there is a gradual increase in the T_{500mm} time in SCCs up to PET5, significant increase was observed for PET6, PET7 and PET8. The range of T_{500mm} slump flow times for SCCs containing up to 5% PET is $2.93 - 4.96\ sec$ while for the others $4.17 - 11.28\ sec$ was observed.

VF flow times of the SCCs are shown in Figure 8. The flow times measured for SCCs up to 5% PET remained below $25\ sec$ while the values for the other SCCs were above this limiting value. Therefore, it can be concluded that the PET replacement level of more than 5% causes the concrete to be more viscous than it can be allowed according to EFNARC [31] limitations. High viscosity may cause higher friction in the forms and difficulty in consolidation of the concrete.

This behavior could be attributed to the friction characteristics and specific surface area of PET particles. PET particle has more specific surface area in the comparison with the natural sand because of its shape. So that, more friction among particles will lead to a decrement in the workability in mixtures. As the PET content increases, the fresh concrete plasticity and consistency are decreased [32].

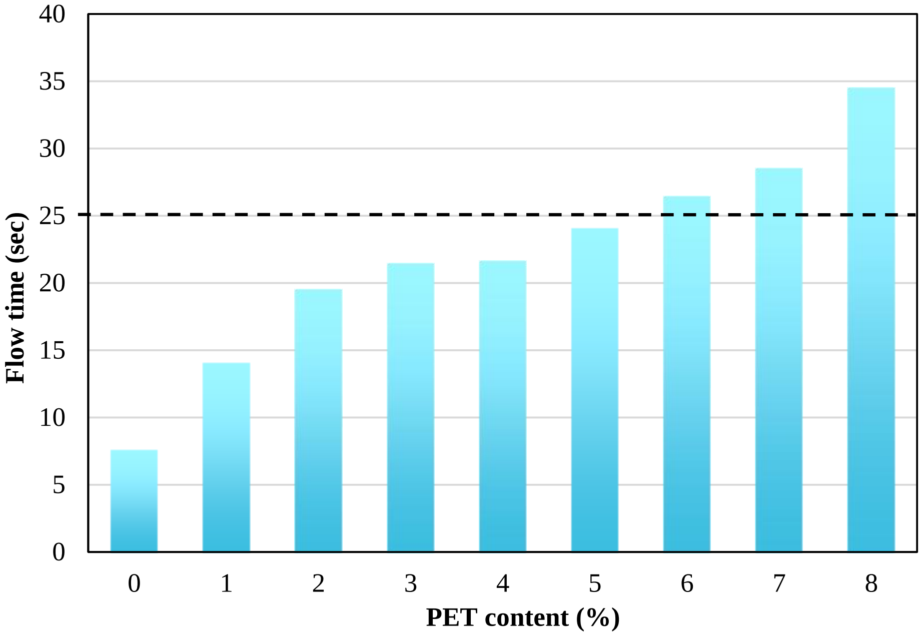

Figure 8. Variation of V-funnel flow time with PET content

3.2. Hardened Properties

The measured hardened properties of the SCCs produced are mechanical properties in terms of compressive and splitting tensile strength and absorption characteristics by total absorption and sorptivity after 28 days of curing. The discussion of the findings is given below.

The variation of the compressive strength of the SCC with increasing the amount of PET granules is given in Figure 9. The results indicated that there is a reduction in the compressive strength of concrete as the amount of PET increases. Increasing the amount of PET particles results in weak cohesion between matrix and PET granules as well as acting as a barrier between paste and the aggregate the compressive strength decreases. The figure also illustrated that there is a strong relation between the content of PET and observed compressive strength value.

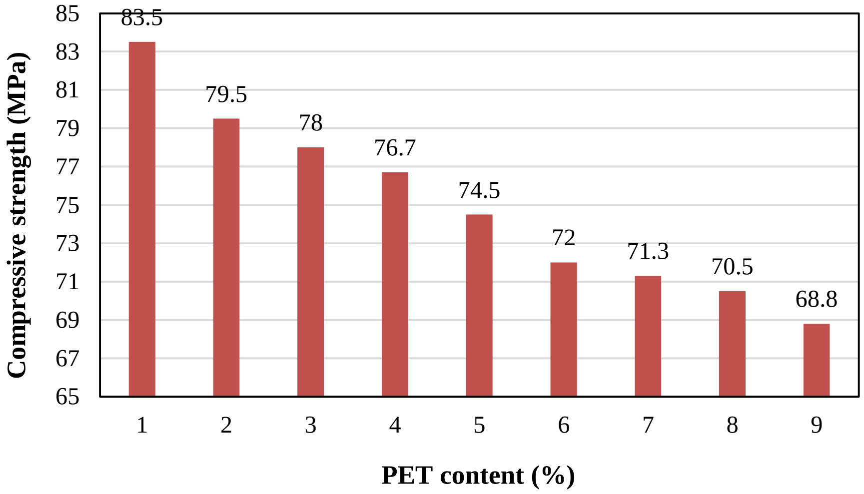

Figure 9. Compressive strength of SCCs

The test results indicating the splitting tensile strength of SCCs are illustrated in Figure 10. In contrast to compressive strength behavior increasing PET particles up to 5% resulted in slight improvement of tensile capacity up to 5%. However, exceeding this critical value caused reduction because of high replacement level. In the study of Rahmani et al. [32], they explained the phenomenon as the increase of the probability of inter locking between the PET particles and fractured surface due to the special shape of PET particles and flexibility. This situation can therefore be attributed to crack arrestment of the PET particles through acting like fiber. However, when exceeding a certain limit as a result of deterioration of the bond between paste and natural aggregate, the tensile strength decreased.

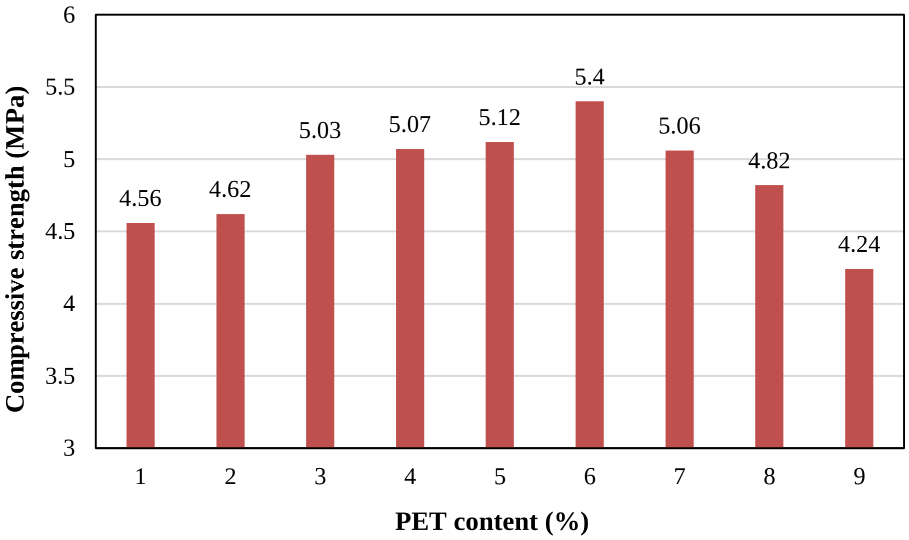

Figure 10. Splitting tensile strength of SCCs

In the study of Hannawi et al. [33] recycled polycarbonate and PET materials were used in concrete production. Scanning electron microscopy analysis indicated a weakened cohesion among plastic aggregates and texture. A lower modulus of elasticity and decrease of compressive strength for mortars with the increase in PET particles amount was also reported. This fact made the samples more flexible, so, the concrete may withstand the loads for some time without collapse after the failure. Besides, the study reported that replacing some percentage of sand with these plastic particles not only develops the flexural strength and the toughness factor, but also causes these composite to absorb extra energy. This characteristic is so much interesting for lots of civil engineering utilizations such as structure subjected usually to dynamic and impact loads.

Figure 11. exhibits the relation between compressive strength and splitting tensile strength of the SCCs produced. The correlations indicated that the relation between compressive and splitting strength is irregular. However, when considering a higher order curve fitting, it was found that a parabolic curve with 2nd degree provides a reasonable correlation between these two critical mechanical properties.

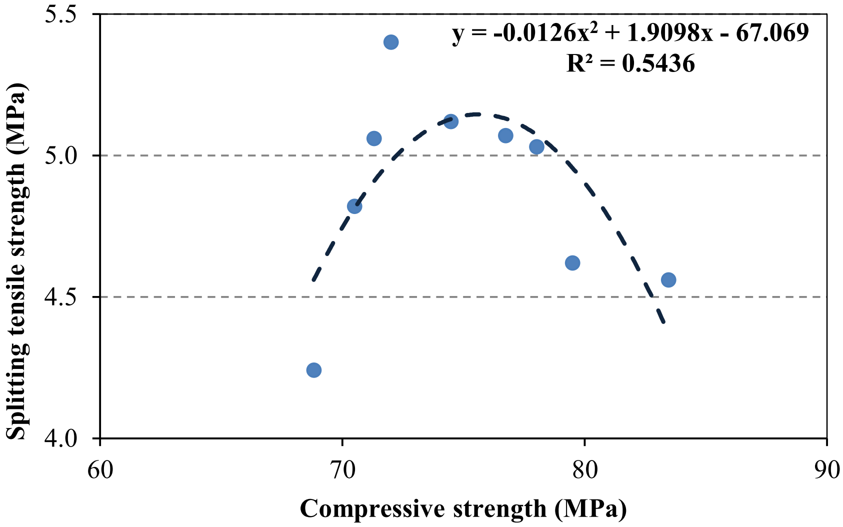

Figure 11. Correlation between compressive strength and splitting tensile strength

Water absorption and sorptivity test results of the SCCs versus PET content of the SCCs are exhibited in Figures 12 and 13. Figure 13 clearly indicates that the porosity of concrete increases as the amount of PET increases the SCCs. The variation of the data proved that there is a good agreement with variation of amount of PET and porosity. Nevertheless, when observing the sorptivity values of the concretes, SCCs with more than 5% PET indicated a decreasing tendency. This can be explained by disturbance of the capillarity of the concrete by the excess amount of PET particles. Therefore it can be inferred that without observing total water absorption of the concrete, tendency of the sorptivity values in this aspect can be misleading to comment on the capillarity of the SCCs.

Figure 14 indicates the relation between water absorption and sorptivity of concretes. Since the results of sorptivity and water absorption obtained for PET6, PET7, and PET8 are contradictory, a parabolic curve having 2nd order provided a prominent correlation between these properties.

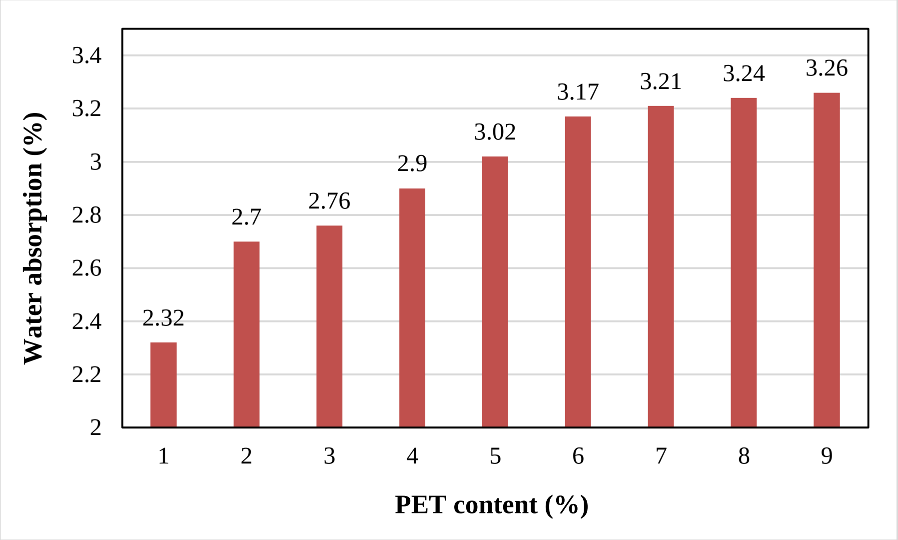

Figure 12. Water absorption values of SCCs

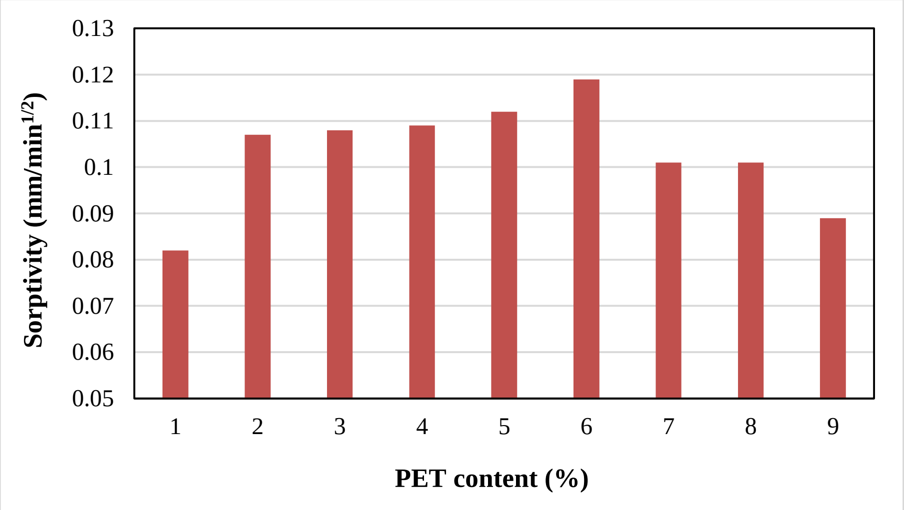

Figure 13. Sorptivity indices of SCCs

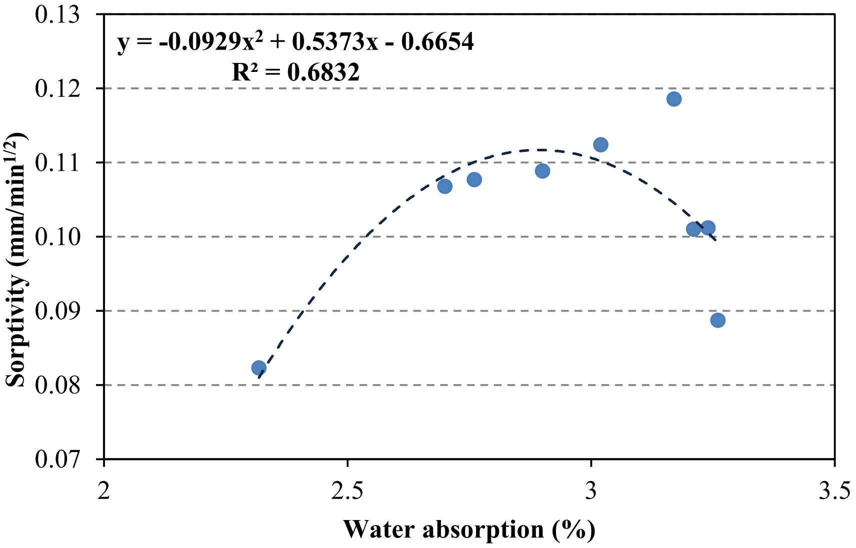

Figure 14. Correlation between water absorption and sorptivity of SCCs

4. Conclusion

In the current study recycled PET granules obtained through crushing of PET bottles or containers were used as a sand replacement material in the production of SCCs. The following conclusions could be drawn from the data developed in the reported study:

- Utilization of waste PET granules in production of SCC could be an effective way for recycling purpose. However, in order not to get loss of workability the maximum amount of PET replacement level should be limited to 5%. When exceeding 5% of PET content, significant increase in the amount of chemical admixture is required. Moreover, the flow and viscosity behavior of SCC is affected significantly. The results indicated that for PET replacement levels of 6% and higher, VF flow time overpassed $25\ sec$.
- Inclusion of PET particles in SCC resulted in decrease in the compressive strength. The compressive strength control concrete was $83.4\ MPa$ while PET8 had $68.8\ MPa$. However, the inclusion of PET particles up to 5% resulted in undistinguishable improvement in the splitting tensile strength capacity. However, beyond this value slight decrease was also observed.
- Being an important indication of pore structure of the concrete, water absorption test result proved that increasing the amount of PET caused occurrence of void in concrete. Since the PET particles are slender and flexible, during casting some particles may be curled to create void inside the concrete. Therefore as the amount of PET increased in SCC water absorption values increased from 2.3% to 3.3% from PET0 to PET8 respectively.
- The tendency of the deterioration in sorptivity values was similar to water absorption up to 5% of the PET. However, as a result of disturbance of the capillary behavior of the concrete due to the excess amount of PET, reduction in the sorptivity values were observed in SCCs with more than 5% PET.
- Although there was an increase in the water absorption values, due to the mix design parameters assigned for the experimental study, strength and absorption values of the SCCs produced were still better than conventional concrete. PET5 concrete satisfied all the requirements for SCC with reasonable performance in the hardened properties. The results obtained for this concrete are $5.4\ MPa$, $72.0\ MPa$, 3.1%, and $0.1186\ mm/\text{min}^{1/2}$ for splitting tensile strength, compressive strength, water absorption, and sorptivity, respectively. Therefore, it can be concluded that by adjusting concrete mix parameters, production of high performance SCC containing 5% PET granules is possible with satisfactory outputs.

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