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S Bozorgmehr Nia
R & D Manager at Aptus Research Company, Alborz, Iran

MR Adlparvar
Associate Professor, Department of Faculty of Civil Engineering of Qom University, Qom, Iran

Corresponding Author:
MR Adlparvar
Associate Professor, Department of Faculty of Civil Engineering of Qom University, Qom, Iran

The effects of waste polyethylene terephthalate (PET) particles on the properties of fresh and hardened self-consolidating concrete

S Bozorgmehr Nia and MR Adlparvar

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Abstract

Self-compacting concrete (SCC) due to several economical and technical advantages is increasingly used in construction industry. It can be improved on strength behavior when the particles are added. Although the workability as a significant factor for this concrete must be maintained. This investigation experimentally evaluated the effects of PET (polyethylene terephthalate) particles on the properties of either fresh or hardened SCC. This particles resulting from cutting and pulverizing water and bavarage bottles and plastic bags. Fresh properties of SCC have been investigated by slump flow, V-funnel and L-box tests. Hardended properties were tested for compressive strength, splitting tensile strength, flexural strength, shrinkage and ultrasonic pulse velocity (UPV) tests on different ages. The results showed that 3 Kg/m^3 PET particles can be considered as suitable contents regarding to fresh and hardened properties of SCC. However, the addition of PET particles have caused a slight decrease in compressive strength.

Keywords: Self-compacting concrete; fresh properties; mechanical properties of concrete; waste polyethylene terephthalate (PET)

1. Introduction

The reuse of plastic wastes plays an important role in sustainable solid waste management. From different points of view, it helps to save natural resources that are not replenished, Landfill space is limited, and the conditions in landfills make it impossible for plastic, that can be converted to biodegrade. Recycling plastic water bottles helps to conserve space that can be used for other waste. it decreases the pollution of the environment and it also helps to save and recycle energy production processes. one of the alternatives for reduction of their negative effects is the application of these materials in other industries. Construction industry can consume a large amount of PET wastes without any environmental problem. The current applications of recycled PET in the construction industry include their use as admixture for fiber concretes. In other hand, SCC is one of the newest types of high-performance concrete which used in many countries for different architectural and structural applications. It pass from the dense network reinforcement which make it different from ordinary concrete. SCC provides a better environmental condition by eliminating the vibration noise, however by adding waste PET particles can be fully introduced an eco-friendly concrete. Another characteristics of SCC is its high viscosity and stability that is due to using more fillers and cementitious materials. Increasing the cementitious materials and fillers in SCC, it will increase the brittleness of concrete matrix and more early-age cracking of SCC (due to plastic shrinkage, as well as thermal stress) and more drying shrinkage, comparing to normal concrete. Considering the successful experience of using particles in concretes during the past years to improve these shortcomings of concretes, the use of particles is a good idea to promote the ductility and to reduce early-age cracking of SCC [1-5]. Beside due to the presence of particles which reduces the workability parameters of fresh concrete, maintaining the fresh properties of SCC within the desire range, limit the content of particles used in SCCs [6-8]. The use of fiber-reinforced concrete (FRC) has been increased in building structures because majority of using particles in concrete show improvement on toughness, compressive strength, flexural strength, tensile strength, impact strength as well as the failure mode of the concrete [6, 9-12].

The use of steel particles has become popular in FRC, specially their structural application is considered.In some cases, using steel particles could be more effective than the classic method of reinforcing the concrete with bars, such as below [13-15]:

- Thin sections: due to a small cover of concrete and geometric complications, the use of bars is not possible and the use of particles with a high volume percentage could be considered as a good replacement.
- Elements which are under severe loading, heavy loads and large displacements (such as the interior cover of tunnels and explosion resistant structures): In such structures, particles act as additional reinforcements PET has been used increasingly in recent years (especially use as PET bottles) [16, 17]. Burying or burning a great amount of these disposable materials does a lot of harm to the environment [18]. Nowadays, researchers have investigated many effects of plastic waste on mortar and concrete [19-21], especially as mortar and concrete fiber reinforcement. Pereira de Oliveira and Castro-Gomes [22] investigated the effect of PET fiber on cement-lime mortar. The results indicated that, the PET fiber incorporation did not significantly change the magnitude of the mortar compressive strength. Whereas, significantly improved the flexural strength of mortar with a major improvement in mortar toughness. A study by Foti [23] exploring the effect of PET particles on the ordinary concrete. The test results showed that, the addition of PET particles decreased the compressive strength of plain concrete. Similar conclusion has been reported by Kim *et al*., [24]. In both studies, good results in terms of increased ductility of the fiber-reinforcement concrete had been obtained.

Based on experiments of other authors, limited works have been done on SCCs containing PET particles. Therefore, the effects of PET fiber on characteristics of fresh and hardened SCC were considered and were compared with SCC without fiber.

2. Experimental program

2.1 Materials

The cement used for the mixtures is ordinary portland cement CEM I- 42.5, from Abyek cement factories, with a density of 3.15 gr/cm^3 and Blaine fineness of 3100 cm^2/gr. In addition, silica fume (SF) which produced at Ferro Alloy Azna factory with specific gravity 2.12 gr/cm^3 wsa used as cementitious materials. Chemical compositions of the cement and Silica fume are presented in In Table 1.

In this study, the used coarse and fine aggregates - combination of natural and crushed- meet the requirements of ASTM C33. The aggregates with a nominal maximum size of 12.5 mm, specific gravity of coarse aggregate (CA) were 2600 kg/m^3 in SSD condition and water absorption of 2.2%. The specific gravity, water absorbtion and fineness modulus of fine aggregate (FA) were 2500 kg/m^3, 3.2 and 2.9, respectively.

Also, quarry waste stone powder (QWSP) with specific gravity 2.7 gr/cm^3 was used as fine filler.

Table 1: Chemical characteristics of cement and silica fume

Chemical composition (%)	Cement	Silica fume
CaO	63.24	0.49
SiO_2	21.54	95.10
Al_2O_3	4.95	1.32
Fe_2O_3	3.82	0.87
MgO	1.55	0.97
SO_3	2.43	0.10
Na_2O	0.61	0.57
K_2O	0.30	0.35

To achieve the desired workability in fresh SCC mixes, a polycarboxylic superplasticizer (SP) complying with ASTM C494 type-F range, by name P-10 with density of 1.06 gr/cm^3 (at 20 °C) and PH of approximately 7.0 was used.

The waste PET (used as aggregate) obtained from waste PET bottles, crushed into granules by a shred machine and passed through sieve size of 6.35 mm (1/4 inch). Polyethylene Terephthalate (PET) is a polymer with tensile modulus of elasticity of 2.9 GPa and flexural modulus of elasticity of 2.4 GPa. Its maximum tensile strength is about 60 MPa and has high chemical resistance. The specific gravity and water absorption of PET are 1200 kg/m^3 and 0.16%, respectively. Fig. 1 shows the view of PET particles used in this study.

Fig 3: PET particles used in this study

2.2 Mixture proportions

In this research, The normal Portland cement in SCC mixes was replaced with 10% of silica fume and water to total cementitiouse materials ratio (w/cm) of 0.40 was constant for all mixes. SCC mixes were prepared with total powder content of 450 kg/m^3 (cement and silica fume) and coarse and fine aggregate contents of 660 kg/m^3 and 860 kg/m^3, respectively.

SCC mixture without PET particles (Control mixture) was made based on the recommendation given by EFNARC committee [25], with high passing ability in crossing the bars, great stability against segregation and bleeding (despite of adding particles in different mixtures, the desired factors of regulation were maintained).

According to results of the performed initial mix designs, PET particles decrease the workability of the control SCC mix. Therefore, in order to maintain rheological properties of SCC, up to 20% of fine aggregates were replaced by quarry stone powder materials as filler.

Considering the use of PET particles, crushed sand and gravel and their negative effects on flow properties, increasing the superplasticizer additive dosage required. The mixtures proportions are shown in Table 2.

Table 2: Mix proportions for self-compacting concrete (kg/m^3).

Mix ID	Water (kg/m^3)	Cement (kg/m^3)	SF (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	QWSP (kg/m^3)	SP(kg/m^3)	PET (kg/m^3)
Control	180	400	50	660	860	250	4.41	-
PET3	180	400	50	660	860	250	4.80	3
PET5	180	400	50	660	860	250	5.12	5
PET7	180	400	50	660	860	250	5.38	7

2.3 Concrete Casting

According to Table 2, the amounts of 3, 5 and 7 kg/m^3 PET particles were added to the control mixture. Then, the effects of these amounts of particles on the workability of fresh concrete were investigated. Finally, hardened concrete tests were carried out on the mixtures which had suitable fresh concrete properties.

The mixing procedure and time are very important, thus the mixing process was kept constant for all concrete mixtures. All the ingredients were first mixed under dry condition in the concrete mixer for one minute. Then about 60% of the mixing water added to the dry mix and mixed thoroughly for two minute. Later, required quantities of PET particles were sprinkled over running mixer gradually and mixed for one minute to get a uniform mix. Finally, the SP with remaining water was poured into mixer, and the concrete was mixed for 3 min. At the end, to complete the production, flowability, passing ability and resistance to segregation of prepared mixtures are measured and molding specimens were performed. The specimens were covered with cling film to prevent water loss for 24 h after casting. After demoulding, all specimens were kept in a water tank at 22±2 until the age of tests.

2.4 Fresh concrete tests

In this investigation, slump flow, T_{50}, V-funnel and L-box tests were performed according to the procedure recommended by EFNARC committee [25]. Slump flow test has been proposed to assess filling ability of concrete in the absence of obstructions. Slump flow is not a suitable factor to exactly indicate the fresh properties of SCC. But, if the slump flow is kept within a desirable range, it is possible to evaluate the requirements of SCC. All SCC mixtures with slump flow values between 650 and 800 mm were proposed in the present study. The visual stability index (VSI) was used in relation to slump flow test as the simplest well known method to detect stability. According to this index, self-compatibility of concrete is scaled into four groups between 0 (highly stable) and 3 (highly unstable). After removing the slump cone, the segregation resistance of SCC can be inspected visually by measuring a coarse aggregate pile or the thickness of cement paste extended beyond the coarse aggregate. Generally, a VSI from 1 (stable matrix) to 0 has been regarded as acceptable. Viscosity can be evaluated by the T_{50} or V-funnel times. The L-box is utilized to determine passing ability of SCC when flowing through confined or reinforced areas. The workablity limits suggested by EFNARC committee are presented in Table 3.

Table 3: Slump flow, viscosity and passing ability limits with respect to EFNARC [25]

Method	Unit	Typical range values	
		Min	Max
Slump flow	cm	65	80
t_{50} Slump flow	s	2	5
V-funnel	s	6	12
L-box	H1/H2	0.8	1

2.5 Hardened concrete tests

The experiments carried out in the hardened phase consist of: compressive strength, splitting tensile strength, flexural strength, and shrinkage.

Compressive strength was studied on three 100 mm cube at curing ages of 3, 7, 14, 28, 42 and 90 days in accordance with ASTM C39 at the rate of loading was 0.25 MPa/s. Splitting tensile strength was studied on three 150 X 300 mm cylindrical at curing ages of 3,7, 14, 28, 42 and 90 days. This test was performed according to procedure recommended by ASTM C 496 and the rate of loading was 1.2 MPa/s. Flexural strength tests were carried out on three prismatic specimens 150 X 150 X 650 mm at curing ages of 28 and 90 days. This test was performed according to procedure recommended by ASTM C 78 and the rate of loading was 1MPa/min.

Shrinkage tests were investigated on three prismatic specimens 70 X 70 X 280 mm at ages of 3, 7, 28 and 90 days in accordance with ASTM C 157. After demolding, the test specimens were kept in curing room until the age of testing.

The ultrasonic pulse velocity test was conducted according to ASTM C 597 on three 100 mm cube at curing ages of 14, 28, 42 and 90 days.

3. Result and Discussion

3.1 Fresh concrete results

The fresh properties of all SCC mixtures were studied and results of these tests were shown in Table 4.

Table 4: Fresh concrete test results

Mix ID	Slump flow (mm)	VSI	T_{50} (sec)	V-funnel (sec)	Blocking ratio
Control	67	0	1.8	5	1
PET3	68	1	2.4	6	0.91
PET5	65	3	4.9	15.3	0.78
PET7	61	3	8.5	19	0.7

As mentioned earlier, the viscosity of SCCs, as dicated by T_{50} measurements of slump flow test and V-funnel test. The results demonstrated that PET4 and PET5 mixtures had not suitable viscosity, seemed to be affecred by fiber inclusion, giving longer slump flow time (T_{50}) and V-funnel test and poienting out to a less flowing concrete. The L-box test showed that the passing ability of these two SCCs mixtures decreased in PET5 mixtures, the considerable blockage were observed. Also, In the all of above mixtures, the significant segragation and bleeding were observed. So, as the contents of particles increased, the workability decreased. This can be due to the shape of PET aggregates. The PET aggregates stick together and negatively affect on rheological.

Although, the waste PET particles replacement addition of 3 kg/m^3 PET had caused a slight decreas in workability parameters, the results of the fresh concrete properties of these mixtures were maintained within the desirable ranges. Also, visual inspection of fersh concrete did not dictate any segregation and bleeding in PET mixtures. The plane shape of PET particles decreases the congestion between concrete components, disturbs concrete matrix by high air content values and makes a perforated concrete structure.

3.2 Hardened concrete results

Based on fresh concrete tests results, the maximum permitted amounts of PET particles were 3 kg/m^3 respectively in order to preserve the workability of SCCs. Hence, for hardened concrete tests, PET3 mixtures along with Control mixture were considered.

3.2.1 Compressive strength

The results of compressive strength test were shown in Figure 4. It can be observed that the compressive strength of all mixtures increased by the age of concrete. Moreover, the addition of steel particles to concrete enhanced the compressive strength, but the inclusion of PET particles reduced the compressive strength in all concrete ages. For example at the age of 28 day, The presence of steel fiber caused an improvement in the compressive strength of SCC up to 9.6%, whereas, the PET fiber had caused a decrease down to 6.9%.

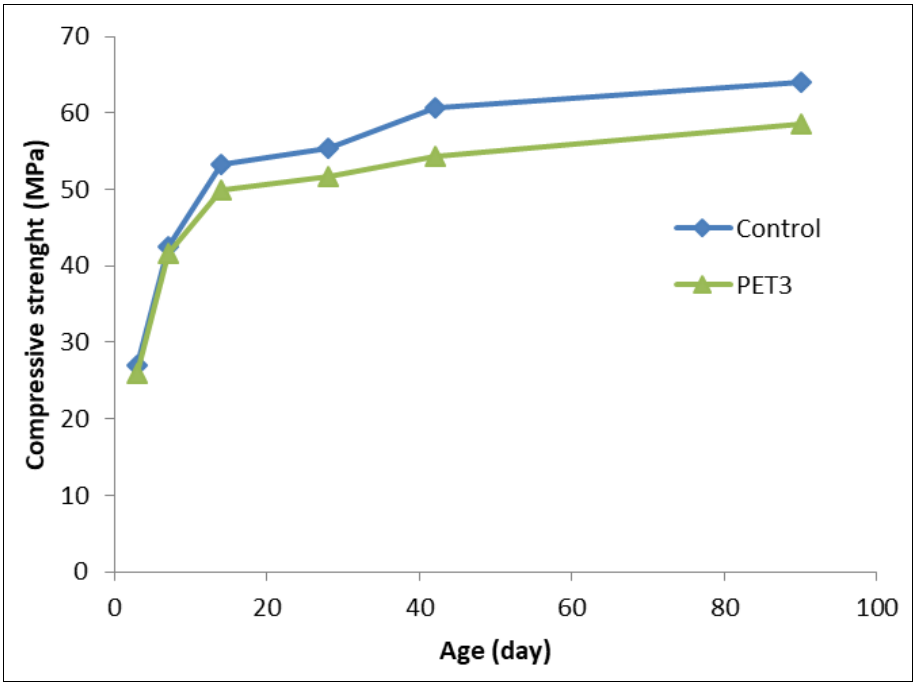

Fig 4: Compressive strength of control, steel and PET mixtures

In all ages, the most important observation during testing was the change of the failure mode of the concrete as the particles were included in SCC. Specially, this event in the mix containing steel fiber was more clear. The failure mode changed from sudden failure into a more ductile failure. This due to the strong bond between particles and the concrete, and the effect of particles in preventing concrete from sudden explosive failure.

3.2.2 Splitting tensile strength

The results of splitting tensile strength were shown in Figure 5.

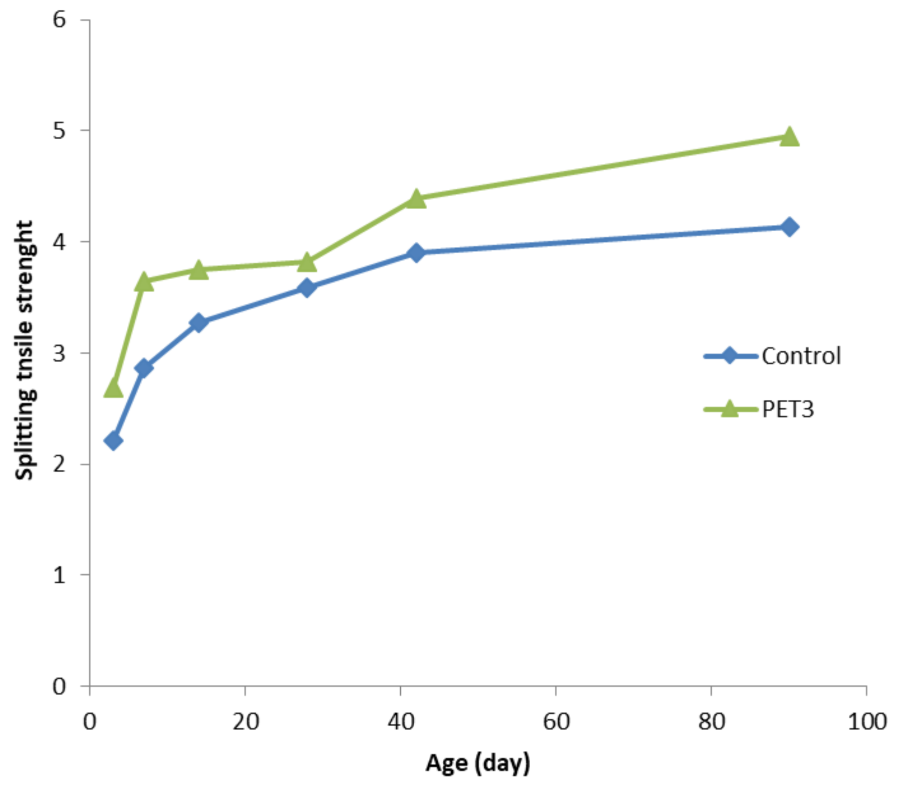

Fig 5: Splitting tensile strength of all mixtures

The results indicate that presence of both steel and PET particles increased the splitting tensile strength in all ages, however the increasing rate in steel concrete mixture was found to be higher. This behavior can be explained that steel particles have higher tensile strength than PET particles and the bond between steel particles and concrete is higher than bond between PET particles and concrete (due to physical properties of steel particles such as: strong surface and two ends hooked).

Moreover, in both concretes containing particles, the failure mode changed from sudden explosive failure into ductile failure and the test cylinders did not completely split in two separate halves at failure due to the inclusion of particles. This event could be due to strong bond between particles and concrete.

The splitting tensile strength of SCC mixtures versus cylindrical compressive strength was presented in Figure 6. It should be noted that the 100 mm cube compressive strength was converted to cylindrical strength by applying suitable conversation factor [28]. Accordingly, it can be seen that splitting tensile strength values of all SCC mixture lie in the range of bound value suggested by CEB-FIP [29] code for normal concrete.

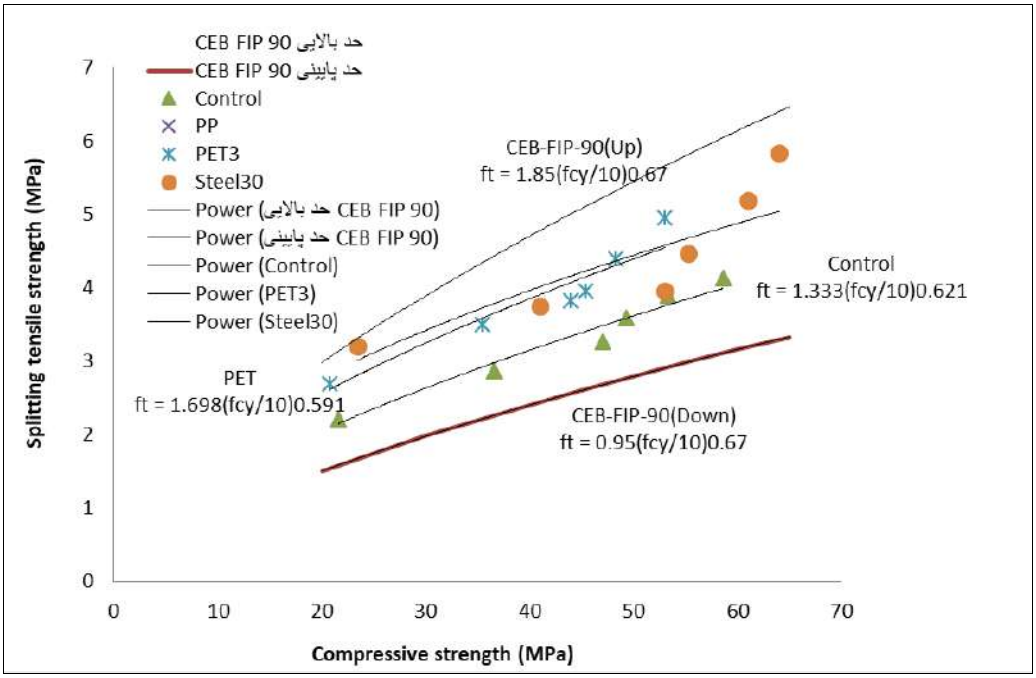

Fig 6: Variation splitting tensile strength vs. compressive strength

3.2.3 Flexural strength

The results of flextural strenght test were shown in Figure 7.

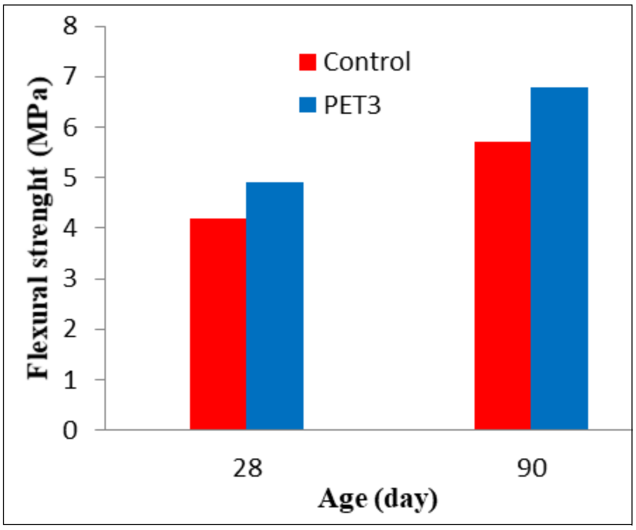

Fig 7: Flexural strength of all mixtures

The obtained results showed the effectiveness of both steel and PET particles in improving the flexural behavior of concrete, where the performance of concrete containing steel particles was slightly better. This test, like splitting tensile strength, in both concrete containing particles, the failure mode changed from sudden explosive failure into ductile failure and the test specimens did not completely split two separate halves at failure due to the inclusion of particles.

3.2.4 Shrinkage

The results of shrinkage test were shown in Figure 8.

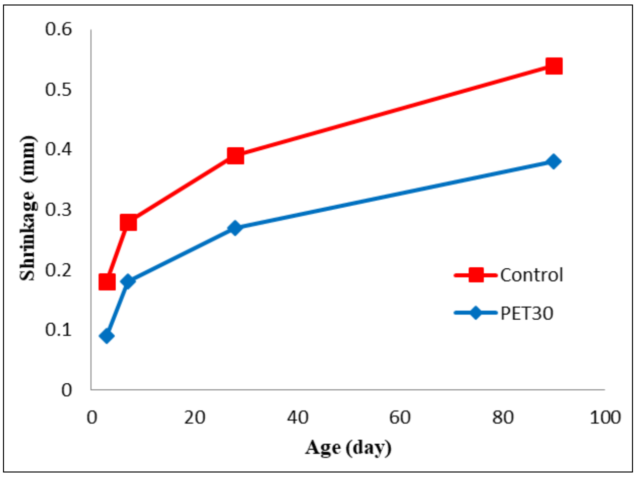

Fig 8: Shrinkage measurements of all mixtures

As can be observed that presence of steel and PET particles decrease the amount of shrinkage. Although, concrete containing steel particles showed a better performance. These improvements on shrinkage behavior could be due to strong bond between particles and concrete which reduces the shrinkage enhancement.

In the other words, after occurrence of microcracks in the concrete matrix (because of shrinkage), the stresses are transferred from matrix to particles in the cracked parts of the concrete matrix and considering to long-term resistance of particles, the particles are able to withstand greater tensile strain and they prevent the crack propagation and the localization of microcracks into macrocracks, so the shrinkage are decreased.

3.2.5 Ultra pulse velocity (UPV)

The ultrasonic pulse velocity (UPV) method was applied to characterize the uniformity of fiber reinforced SCC. Figure 9. presents the UPV values of all SCC mixtures at different curing ages.

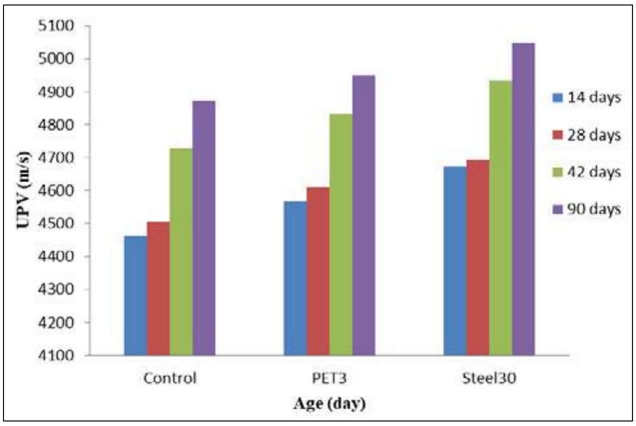

Fig 9: UPV of SCC mixtures at different curing ages

However, a slight increase was observed in the UPV of SCCs containing particles, but it was not significant. So, UPV did not seem to be affected by using of particles. This observation is in agreement with the results found in other studies [26, 30]. The negligible variation in the UPV test results can be as an indication of the uniformity of concrete matrix in all mixes. Also, it was clear from Figure 9, that, as hydration continued, the UPVs increase for all SCC mixtures.

4. Conclusion

Based on the results of this experimental study, the following conclusions can be drawn:

1. Considering to fresh concrete tests, the amounts of 30 kg/m^3 steel particles and 3 kg/m^3 PET particles can be regarded as the most appropriate amounts of particles which added to SCC mixtures.
2. The addition of steel particles decreased the flow ability in slump flow test, increased the flow time in slump flow (T_{50}) and V-funnel tests and decreased the passing ability in L-box test, but these results were not significant about SCC containing PET particles.
3. Steel concrete had the most compressive strength in all ages, whereas PET particles had caused a decrease in compressive strength.
4. Steel and PET concretes had more splitting tensile strength than Control concrete in all ages and SCC containing steel particles had the best performance.
5. The presence of both steel and PET particles caused an improvement in the flexural strength of SCC up to 20% and 18% respectively.
6. In compressive strenght, splitting tensile strenght and flexural strenght tests, the failure mode of the concrete changed from sudden failure into a more ductile failure as particles used in SCCs.
7. In fiber reinforced concrete, better performance was observed in decreasing drying shrinkage and SCC containing steel particles had the best performance.

8. The UPV test of the SCC mixtures showed to be unaffected by the steel and PET particles inclusion.

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