Hindawi
Advances in Civil Engineering
Volume 2019, Article ID 6960216, 12 pages
https://doi.org/10.1155/2019/6960216

Research Article

The Influence of Nano-SiO_2 and Recycled Polypropylene Plastic Content on Physical, Mechanical, and Shrinkage Properties of Mortar

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Received 6 June 2019; Revised 24 August 2019; Accepted 13 September 2019; Published 20 October 2019

Academic Editor: Behzad Nematollahi

This work is aimed to study the possibility of recycling plastic waste (polypropylene (PP)) as aggregate instead of sand in the manufacturing of mortar or concrete. For this, an experimental study was carried out to evaluate the influence of nano-SiO_2 and recycled PP plastic particles' content on physical, mechanical, and shrinkage properties and microstructure of the mortars with recycled PP plastic particles. The sand is substituted with the recycled PP plastic particles at dosages (0%, 20%, 40%, and 60% by volume of the sand). The nano-SiO_2 content is 5% by weight of cement. The physical (porosity, water absorption, and density), mechanical (compressive and flexural strength) and shrinkage properties of the mortars were evaluated, and a complementary study on microstructure of the interface between cementitious matrix and PP plastic particles was made. The measurements of physical and mechanical properties showed that PP-filled mortar had lower density and better toughness (higher ratio of flexural strength to compressive strength). However, the compressive strength and flexural strength of PP-filled mortar is reduced, and the porosity, water absorption, autogenous shrinkage, and dry shrinkage increased as compared to normal cement mortar. The addition of nano-SiO_2 reduced the porosity, water absorption, and drying shrinkage of PP-filled mortar and effectively improved the mechanical properties, but increased its autogenous shrinkage. A microscopic study of the interfacial zone (plastic-binder) has shown that there is poor adhesion between PP plastic particles and cement paste. From this work, it is found that recycled PP plastic waste has a great potential to be a construction material. It can be used as partial replacement of natural aggregates instead.

1. Introduction

Plastic, a common macromolecule compound, is widely used in all walks of life for its excellent properties of low density, high durability, high impact resistance, and easy processing [1]. According to statistics, the global plastic production in 2017 is nearly 350 million tons [2], and the annual output is growing steadily. China is not only a big producer of plastics, but also a big consumer of plastics. Its total plastic consumption accounts for about a quarter of the world, and has become the largest plastic consumer in the world [3]. Plastics offer many benefits to the society, but unfortunately also drawbacks. For a long time, the main treatment methods of plastic waste in various countries are landfill, incineration, and transportation to other countries. Due to the very low biodegradability of plastic waste [4–6], landfill will make it exist in the soil for a long time, increasing the burden of land resources, while incineration of plastic waste will produce polycyclic aromatic hydrocarbons, carbon monoxide, and other harmful substances, thereby seriously contaminating the environment. Under the background of global resource shortage, recycling plastic waste can reduce resource waste, avoid environmental pollution, and achieve sustainable development. However, the status of recycling plastic waste is not satisfactory. Even in the developed countries, it is difficult to have a high recycling rate of plastic waste in the areas where infrastructure construction is relatively perfect. For instance, the recycling rate of plastic waste is below 40% in almost all European countries [7]. In 2012, the total amount of plastic waste in municipal solid waste was 31.7 million tons in the United States, only 8.8% of which was recycled [8]. Therefore, how to treat plastic waste efficiently and improve the recycling rate is a difficult problem to be solved urgently.

At present, a promising method of recycling plastic waste is to grind it into recycled plastic particles and mix them into concrete or mortar instead of original building materials [5–7, 9, 10]. In this way, not only plastic waste can be effectively utilized, but also the environment can be protected, and thus good economic and social benefits can be achieved.

In the past ten years, many researchers have studied the application of plastic waste particles in concrete or mortar. Albano et al. [11] mixed recycled polyethylene terephthalate (PET) into concrete instead of original fine aggregates to study its mechanical behavior. The results indicated that PET-filled concrete showed a decrease in compressive strength, splitting tensile strength, modulus of elasticity, and ultrasonic pulse velocity; however, the water absorption increased when volume proportion and particle size of PET increased. Ismail and Al-Hashmi [12] used plastic waste of fabriform shapes as a partial replacement for sand and found that the results showed a tendency for compressive strength and flexural strength values of plastic waste concrete mixtures to decrease below the plain mixtures by increasing the plastic waste ratio. When plastic waste ratio in concrete was 20%, the flexural strength at 28 days curing age was 30.5% lower than that of the reference concrete. Liang et al. [13] put recycled PP plastic powder into concrete substituting part of fine aggregates, and the results showed that the higher the substitution rate of PP plastic powder, the lower the compressive strength, and the cube compressive strength of PP-filled concrete was 26.2% lower than reference concrete at 20% of substitution of PP plastic particles. Frigione [14] substituted the 5% by weight of fine aggregate (natural sand) in concrete with an equal weight of PET aggregates manufactured from the waste unwashed PET bottles (WPET). It was found that the WPET concrete displayed similar workability characteristics, compressive strength, and splitting tensile strength slightly lower than the reference concrete. It can be seen that the addition of plastic waste particles has a negative impact on the mechanical properties of concrete or mortar. However, it can improve the ductility of concrete or mortar because plastic has certain elasticity. For example, Rebeiz and Craft [15] incorporated plastic waste particles into asphalt concrete and found that the incorporation of plastic waste particles can increase the toughness of asphalt concrete and reduce the occurrence of cracks. Liu et al. [16] put recycled ABS/PC plastic particles into normal concrete to make a plastic modified concrete, and found that the ductility of the modified concrete was improved. Foti [17] made PET bottles into fibers and mixed them into concrete. The results showed that the average tensile strength of the fiber-reinforced concrete is very high, indicating that the ductility of concrete can be improved by adding PET fibers. Hannawi et al. [18] replaced partial natural aggregates by polycarbonate (PC) and PET waste in mortar, and found that the calculated flexural toughness factors increased significantly with increasing volume fraction of PET and PC aggregates. Kou et al. [19] replaced river sand with polyvinyl chloride (PVC) plastic waste granules in percentages of 0%, 5%, 15%, and 30% by volume in concrete. It was found that the concrete prepared with partial replacement by PVC was lighter, more ductile, and had lower drying shrinkage and higher resistance to chloride ion penetration.

The plastic-filled concrete or mortar shows a decrease in compressive strength compared to normal concrete, which limits the application of plastic waste in concrete or mortar. As one of the three emerging technologies in the 21st century, nanotechnology has developed rapidly and is widely used in various industries, including construction industry. Previous studies have shown that the unique size effect of nanomaterials can improve the microstructure of the interfacial transition zone (ITZ) between hardened cement paste and aggregates, and the strength of concrete is increased [20–24]. Therefore, the mechanical properties of plastic-filled concrete can be improved by adding nanomaterials. Hasan-Nattaj and Nematzadeh [25] found that the introduction of nano-SiO_2 in the fiber-reinforced concrete improved the elastic modulus due to an increase in the compactness of the cement paste bond with aggregates. The experiments of Nazari and Riahi [26] showed that the strength and water permeability of the specimens have been improved by adding SiO_2 nanoparticles in the cement paste up to 4.0 wt.%. Zhao and Liu [27] found that the introduction of nano-SiO_2 in rubber-recycled concrete amazingly improved the microstructure of rubber-recycled concrete, and the mechanical properties of rubber-recycled concrete are significantly improved. Jo et al. [28] experimentally studied the properties of cement mortars with nano-SiO_2. The results showed that nanoscale SiO_2 behaved not only as filler to improve mortar cement microstructure, but also as a promoter of pozzolanic reaction.

Polypropylene (PP) plastic is one of the most commonly used consumer plastics, which is widely used in food packaging industry. The PP plastic waste can be ground into particles and applied in concrete or mortar, which can prevent the environmental contamination caused by plastic waste and realize recycling plastic waste. Based on the above research results, the purpose of this paper is to study the possibility of recycling plastic waste as aggregate partially instead of sand in the mortar or concrete, the effects of recycled PP plastic particles content and nano-SiO_2 on physical, mechanical, and shrinkage properties of mortar, and to analyze the microcharacteristics of PP-filled mortar with nano-SiO_2 by scanning electron microscopy (SEM). The research results can provide references for the application of plastic waste and nanotechnology in concrete or mortar.

2. Materials and Methods

2.1. Materials Used. The materials used in this work were Portland cement, sand, a polycarboxylate-based superplasticizer, nano-SiO_2 and recycled PP plastic particles. The

Portland cement was purchased from Huainan Shunyue Cement Co., Ltd (China), whose strength grade was 42.5 MPa, density was 3120 kg/m^3, and specific surface area was 1.447 m^2/g. The chemical composition of the cement is shown in Table 1. The sand was obtained from local sources with fineness modulus of 2.6 and apparent density of 2650 kg/m^3. The superplasticizer was produced by Shanxi Qinfen Building Materials Co., Ltd (China), whose water reduction rate was 30%. The nano-SiO_2 (content ≥99.5%, powder, particle size ≈ 30 ± 5 nm and specific surface area is 200 m^2/g) was produced by Shanghai Keyan Industrial Co., Ltd. The recycled PP plastic particles were purchased from Zhejiang Yuyao Fengli Plastic Co., Ltd (China), which were short columns with lengths from 2 mm to 3.5 mm, elastic modulus of 0.97 GPa, water capacity of less than 0.4%, and relative density of 0.89~0.92 g/cm^3 as shown in Figure 1.

Table 1: The main chemical composition of the cement.

Compounds	CaO	SiO_2	Al_2O_3	SO_3	MgO	Fe_2O_3
Percentage (%)	63.8	20.65	4.52	2.70	2.16	2.28

Figure 1: Recycled PP plastic particles with lengths from 2 mm to 3.5 mm.

2.2. Mix Design and Processing of Mortars. The mix proportions of mortars are shown in Table 2. The content of the superplasticizer was the percentage of the weight of the cementitious materials. The dosage of superplasticizer was controlled in order to avoid the floating phenomenon of recycled PP plastic particles due to its light density. The plastic particles were added into mortars replacing 0%, 20%, 40%, and 60% sand by volume. The nano-SiO_2 content was the 5% by weight of cement. Brief procedure for mortar processing was as follows: (1) put the nanoparticles, cement, and sand in the mixing pot and mix for 2 min, (2) add water and superplasticizer into the mixing pot slowly, and mix for additional 3 min, and (3) add the recycled PP plastic particles into the mixing pot and mix for additional 3 min. During the mixing process, the flowability and workability of the mortar mixtures were kept consistent by adjusting the dosage of the superplasticizer. When this mixing process was finished, the recycled PP plastic particles and nano-SiO_2 were homogeneously distributed throughout the mortar.

2.3. Physical Properties Test of Mortar Specimens. The dry weight D, suspended weight S, and saturated weight W of test mortar specimens at day 28 were measured according to ASTM C20-00 [29]. Brief procedure for physical properties test of mortar specimens was as follows: (1) dry the test mortar specimens in an oven at 105°C to constant weight and weigh the dry weight D, (2) place the test mortar specimens in distilled water, boil for 2 hours, and weigh the suspended weight S of each test specimen after boiling and cooling for a minimum of 12 hours and while suspended in water, and (3) blot each specimen lightly with a moistened smooth linen or cotton cloth to remove all drops of water from the surface and determine the saturated weight W. The apparent porosity P, the water absorption A, apparent specific gravity T, and bulk density B are, respectively, calculated according to formulas (1)~(4):

(1) Apparent porosity:

$$P = \frac{W - D}{W - S} \times 100\%. \tag{1}$$

(2) Water absorption:

$$A = \frac{W - D}{D} \times 100\%. \tag{2}$$

(3) Apparent specific gravity:

$$T = \frac{D}{D - S}. \tag{3}$$

(4) Bulk density:

$$B = \frac{D}{W - S}. \tag{4}$$

2.4. Flexural and Compressive Strength Test. The flexural and compressive strength of mortar specimens were determined according to ASTM C348-18 [30] and ASTM C349-18 [31] by molding 24 prism specimens with 40 by 40 by 160 mm, as shown in Figure 2. The mortar specimens were removed from the molds after curing for 24 h in a standard curing box at a temperature of (23 ± 1)°C and a relative humidity of more than 95%. Then, immerse the specimens in saturated lime water for 3 d, 7 d, or 28 d.

2.5. Autogenous Shrinkage. According to ASTM C1698-09 [32], the autogenous shrinkage strain of mortar specimens were measured. The fresh mixture was slowly poured into the corrugated mold during vibration, and then placed on the corrugated plastic support rack. During the tests, maintain the surrounding air temperature at 23.0 ± 1.0°C. At the time of final setting t_{fs}, the first length $L(t_{fs})$ was measured. The autogenous strain of the specimen at time t, expressed as μm/m, is calculated with the following formula:

$$\varepsilon_{autogenous} = \frac{L(t) - L(t_{fs})}{L(t_{fs})} \times 10^6\ \mu\text{m/m}, \tag{5}$$

where $L(t)$ is the length of the specimen at time t.

Table 2: Mix proportions of the mortar.

Experimental conditions	Water-to-cement (W/C) ratio	SP (%)	Mix proportion (g/kg)				
			Cement	Sand	Water	PP plastic	Nano-SiO_2
PP0	0.3	0.65	384.6	500	115.4	0	0
PP2	0.3	0.4	384.6	400	115.4	34.7	0
PP4	0.3	0.35	384.6	300	115.4	69.4	0
PP6	0.3	0.3	384.6	200	115.4	104.2	0
PN0	0.3	0.8	384.6	500	115.4	0	19.2
PN2	0.3	0.5	384.6	400	115.4	34.7	19.2
PN4	0.3	0.45	384.6	300	115.4	69.4	19.2
PN6	0.3	0.4	384.6	200	115.4	104.2	19.2

(a)

(b)

Figure 2: Flexural and compressive strength test of PP-filled mortar specimens.

2.6. Dry Shrinkage. According to ASTM C596-18 [33], the dry shrinkage of mortar specimens with 20 by 20 by 280 mm was determined. Moist cure the specimens in the molds in the standard curing box for 24 h. Then, remove the specimens from the molds and cure in lime-saturated water for 48 h. At the age of 72 h, remove the specimens from water, wipe with damp cloth, and immediately obtain a length comparator reading for each specimen. Then, place the specimens in air storage with temperature of $(23 \pm 1)^{\circ}$C and relative humidity of (50 ± 3)%. Obtain a length comparator reading for each specimen after 1, 2, 3, 4, 5, 6, 7, 14, 21, and 28 days of air storage. Drying shrinkage is calculated by equation,

$$\varepsilon_{\text{dry}} = \frac{l(t) - l(t_0)}{l(t_0)} \times 10^6 \,\mu\text{m/m}, \tag{6}$$

where $l(t)$ is the length of the sample at the measuring time, and $l(t_0)$ is the initial length of the sample at the age of 72 h.

2.7. Microscopic Test. When curing time up to 28 days, crush the PP-filled mortar specimens into small pieces with a size of about 8 by 8 by 5 mm, and polish them by a polishing machine, and then dry them in a vacuum drying oven for 48 hours. Fix the dried mortar pieces on a circular platform with a diameter of about 5 cm with double-sided adhesive tape and apply a proper amount of conductive tape to both sides of the mortar pieces, and then remove their surface debris with the ear wash balls. Then, spray the mortar pieces containing paste and plastic with metal coating by magnetron sputtering in magnetron ion diffractometer (MSP-2S), 120 seconds on the front and 30 seconds on the sides. Finally, the microstructures were studied by scanning electron microscopy (HITACHI S3400). In this experiment, the specimens were placed in the center of the scanning electron microscope, and the bonding interface between the recycled PP plastic particles and the cement paste was observed.

All parameters above are explained with mean and standard deviation (SD) values.

3. Results and Discussion

3.1. Physical Properties. The effect of the recycled PP plastic particles' content on physical properties (apparent porosity, water absorption, apparent specific gravity, and bulk density) of the PP-filled mortar after 28 d curing age is shown in Figure 3. The apparent porosity and water absorption have increased considerably for all mortar specimens with the increase of the content of replacement of sand by recycled PP plastic particles. The apparent specific gravity and bulk density have decreased with the increase of recycled PP plastic ratio. For example, compared to PP0, the apparent porosity and water absorption of PP6 increased by 72.02% and 117.02%, respectively, while the apparent specific gravity and bulk density decreased by 15.71% and 20.52%, respectively. The decrease in density of mortars can be attributed to the fact

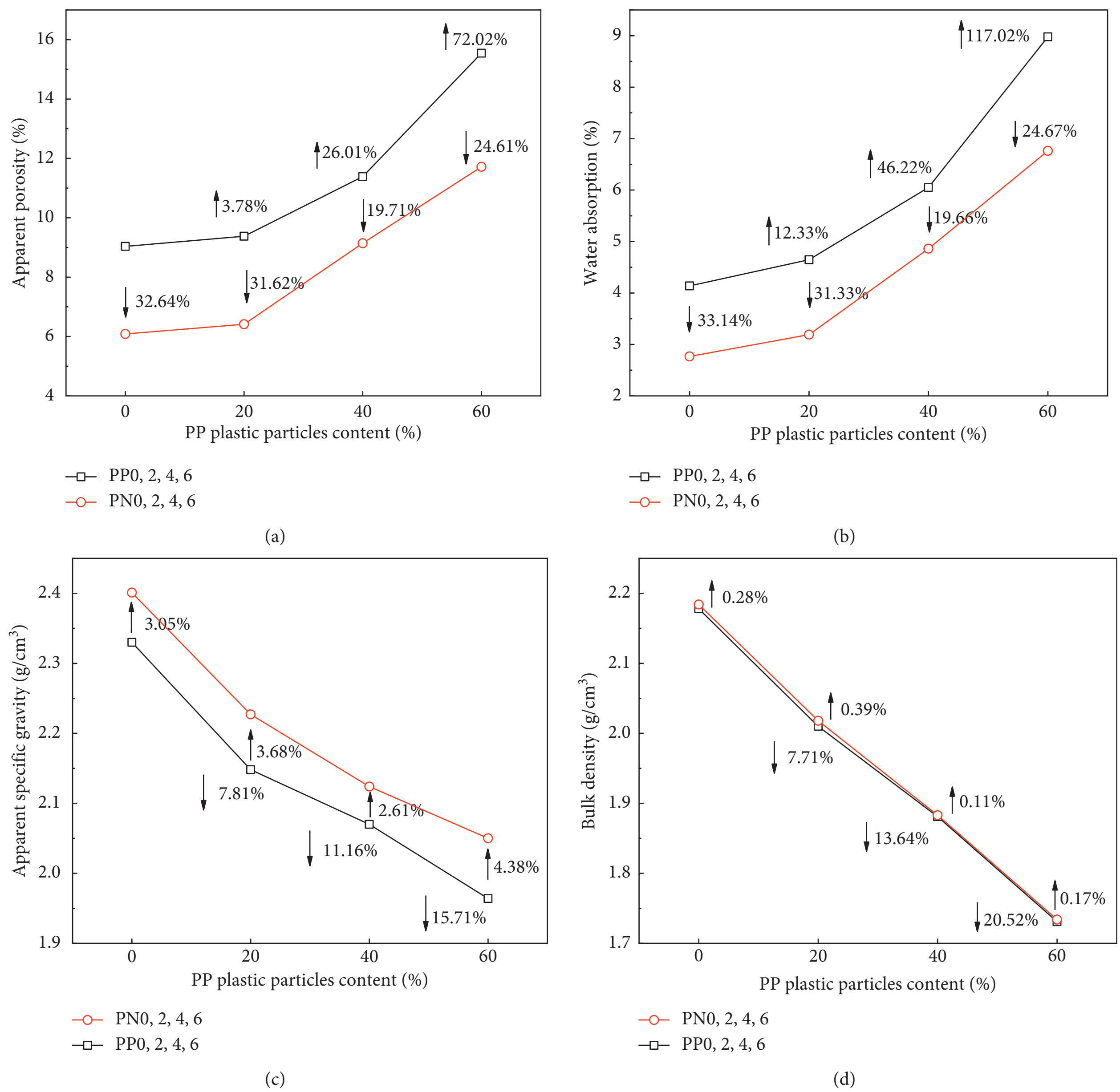

Figure 3: Effect of the recycled PP plastic particles content on physical properties of the PP-filled mortar: (a) apparent porosity, (b) water absorption, (c) apparent specific gravity, and (d) bulk density.

that the density of recycled plastic is lower than that of sand [34]. The images shown in Figure 4 clearly show the good distribution of recycled PP plastic particles in the mortar mixes and there is no phenomenon that PP plastic particles are floating due to their light weight. It should also be noted this distribution has favored to obtain a lightweight mortar [5]. Comparing the curves of PP and PN in Figure 3, it is found that the physical properties of mortar specimens were improved after adding nano-SiO_2. For example, compared to PP6, the apparent porosity and water absorption of PN6 were reduced by 24.61% and 24.67%, respectively, and the apparent specific gravity increased by 4.38%, while the bulk density only increased by 0.17%. This shows that the addition of nano-SiO_2 can improve the pore structure of plastic mortars, reduce the porosity and water absorption [35, 36], make them more compact, and thus improve the bulk density of plastic mortar.

3.2. Mechanical Properties

3.2.1. Compressive Strength. Test compressive strength results are shown in Figure 5. The compressive strength of PP-filled mortars decreased with increase in plastic waste content at all curing times. Compared to control mixes PP0, the compressive strength of PP2, PP4, and PP6 decreased by 15.19%, 38.98%, and 53.53%, respectively, at day 28, which shows that the compressive strength of PP-filled mortars has an approximate linear reduction relationship with the

Figure 4: The photographs of mortar specimens' section with different recycled PP plastic particles' content: (a) PP0, (b) PN2, (c) PP4, and (d) PN6.

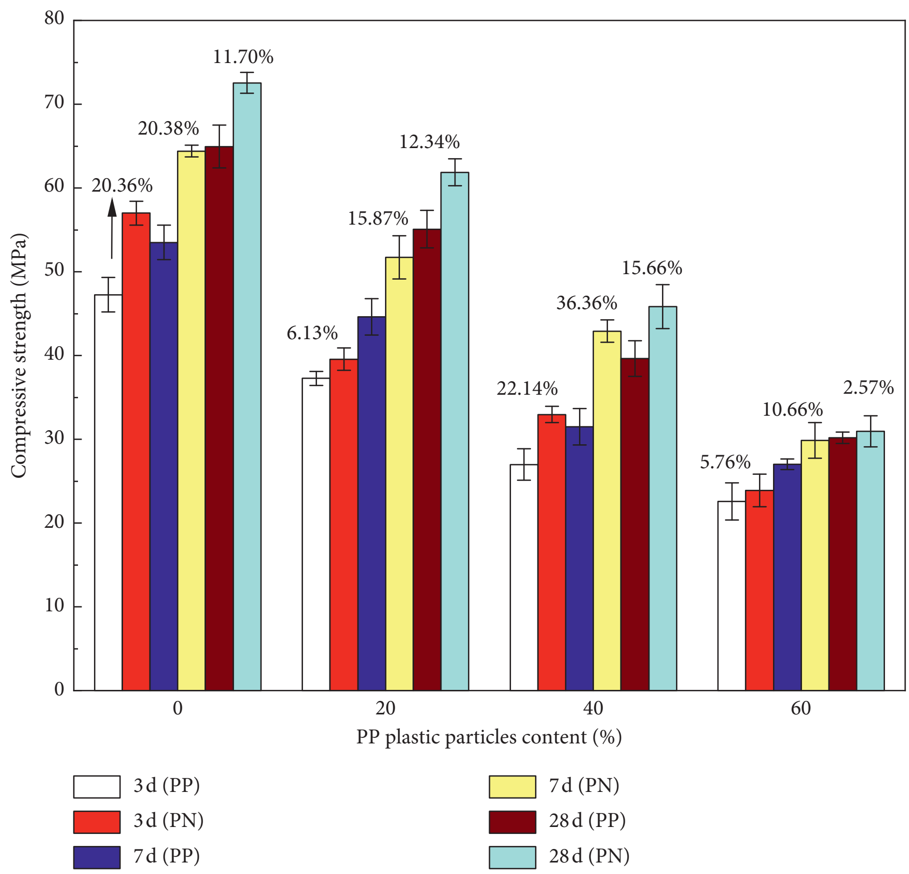

Figure 5: Evolution of the compressive strength of mortars as function of curing time (3, 7, and 28 d). The error bars represent the standard deviation of six test specimens.

dosage. The reduction in the compressive strength of PP-filled mortars might be due to either a very poor bond strength between the cement paste and the surface of the recycled PP plastic particles or the low strength of this recycled PP plastic particles and or the hydrophobic nature of plastic waste, which can inhibit cement hydration reaction by restricting water movement. The plastic has smaller elastic modulus [37], and its ability to transfer stresses is poor, playing the role of 'porosity'. The fracture section after the compression test is shown in Figure 6. The grooves left by the recycled PP plastic particles peeling off from cement paste can be clearly seen in Figure 6, which shows the low bond strength between the surface of the recycled PP plastic particles and the cement paste.

Therefore, improving the compressive strength of plastic mortar or concrete is the key to the application of plastic waste in mortar or concrete. When 5% nano-SiO_2 was added to the mortars, the compressive strength of the mortars was obviously improved. The compressive strength of PN0, PN2, PN4, and PN6 increased by 20.38%, 15.87%, 36.36%, and 10.66%, respectively, compared to PP0, PP2, PP4, and PP6 at day 7. This is due to the physical properties

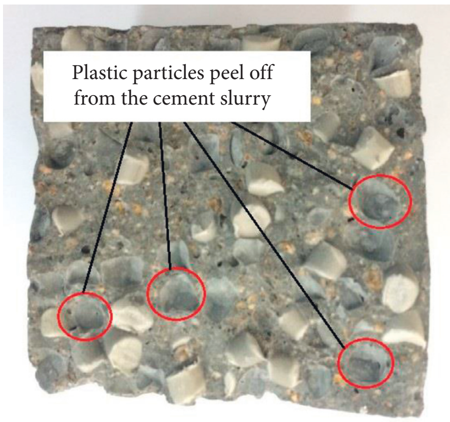

Figure 6: The photograph of the mortar's fracture section.

of nano-SiO_2. The nano-SiO_2 particle size is very small, which can be used as a physical filler to make the interface between the aggregates and cement paste more compact. At the same time, the nano-SiO_2 has high activity. Nano-SiO_2 can react with $Ca(OH)_2$ in the interfacial transition zone between the aggregates and cement paste to form C-S-H gel [26], which can enhance the structure of the interfacial transition zone and thus increase the compressive strength of plastic mortar.

3.2.2. Flexural Strength. The results of the flexural strength of mortar specimens have been given in Figure 7. According to these results, the flexural strength of mortar specimens decreased with the increase in PP plastic particles content. Compared to control mixes PP0, the flexural strength of PP2, PP4, and PP6 decreased by 9.70%, 31.08%, and 43.04%, respectively, at the age of day 28. This is due to the low resistance of the plastic waste [5]. When nano-SiO_2 was added, the flexural strength of mortar specimens was bigger than that of mortar specimens without nano-SiO_2. For example, compared to PP0, PP2, PP4, and PP6, the flexural strength of PN0, PN2, PN4, and PN6 increased by 12.38%, 12.77%, 16.93%, and 3.96%, respectively, at day 28. Therefore, the addition of nano-SiO_2 can compensate for the negative impact on the flexural strength of mortar specimens to a certain extent because of the use of plastic waste as sand-substitution aggregate, which will promote the application of plastic waste in mortar or concrete.

3.2.3. Flexural-Compressive Ratio. The flexural-compressive ratio of mortar specimens as function of the recycled PP plastic particles content is shown in Figure 8. According these results, the flexural-compressive ratio of plastic mortar increased with the increase in recycled PP plastic particles content. Compared to the control mixes PP0, the flexural-compressive ratio of PP2, PP4, and PP6 increased by 6.47%, 12.95%, and 22.57%, respectively, at day 28. This shows that recycled PP plastic particles can effectively improve the toughness of mortar because the flexural-compressive ratio can reflect the toughness of concrete or mortar, and the greater the flexural-compressive ratio, the better the toughness of concrete [38]. The results of PN, adding nano-SiO_2, are consistent with and are slightly higher than those of PP without nano-SiO_2. This is due to that adding nano-SiO_2 can improve mortar structure and increase its strength. The strength of PP-filled mortar is less than that of the control normal mortar; however, PP-filled mortar has better toughness, which has potential application in construction and buildings with toughness requirements.

For the mortar specimens with 20–60% of substitution of recycled PP plastic particles by volume of the sand, the compressive strength at day 28 decreased by between 15.19% and 53.53%, and the flexural strength decreased by between 9.70% and 43.04%. Therefore, if there is a requirement for the strength of the concrete or mortar, it is suggested that the substitution ratio of plastic waste should be controlled within 20% by volume of the sand. When conditions permit, a certain amount of nano-SiO_2 can be added into the concrete or mortar to increase its strength and toughness. For non-load-bearing structures without too high strength requirements or buildings with toughness requirements, the amount of recycled PP plastic particles can be increased appropriately.

3.3. Autogenous Shrinkage. The results of the autogenous shrinkage of mortar specimens as function of curing time are shown in Figure 9.

According to the results, the autogenous shrinkage of mortar specimens increased slightly with increase in the recycled PP plastic particles content. Compared to PP0, the autogenous shrinkage of PP2, PP4, and PP6 increased by 7.39%, 18.75%, and 27.08%, respectively, at day 28. This can be attributed to the facts that the addition of PP plastic particles results in the mortar specimens less compact, and the elastic modulus of plastic particles is smaller than that of natural aggregates [37], while the autogenous shrinkage of mortar increases with the decrease of elastic modulus of aggregates [39]. Moreover, with the increase of recycled PP plastic particles content, the porosity of PP-filled mortar increases gradually, and its stiffness decreases gradually, which will result in the increase of deformation and autogenous shrinkage.

It can also be seen from Figure 9 that the incorporation of nano-SiO_2 had a great influence on the autogenous shrinkage deformation of plastic mortar. At day 28, compared to PP0, PP2, PP4, and PP6, the autogenous shrinkage of PN0, PN2, PN4, and PN6 groups increased by 46.59%, 74.43%, 73.21%, and 115.35%, respectively. This observation was already verified by Guo et al. [40]. Nano-SiO_2 can refine the pore size distribution in the plastic mortar [41], which leads to an increase of capillary tension and a corresponding increase of autogenous shrinkage. At the same time, the larger specific surface area of nano-SiO_2 [25, 42] leads to the rapid combination of nano-SiO_2 and the mixed water in the mortar, which further aggravates the water shortage between the pores of the cement paste, reduces the relative humidity inside the cement paste, and increases the autogenous shrinkage.

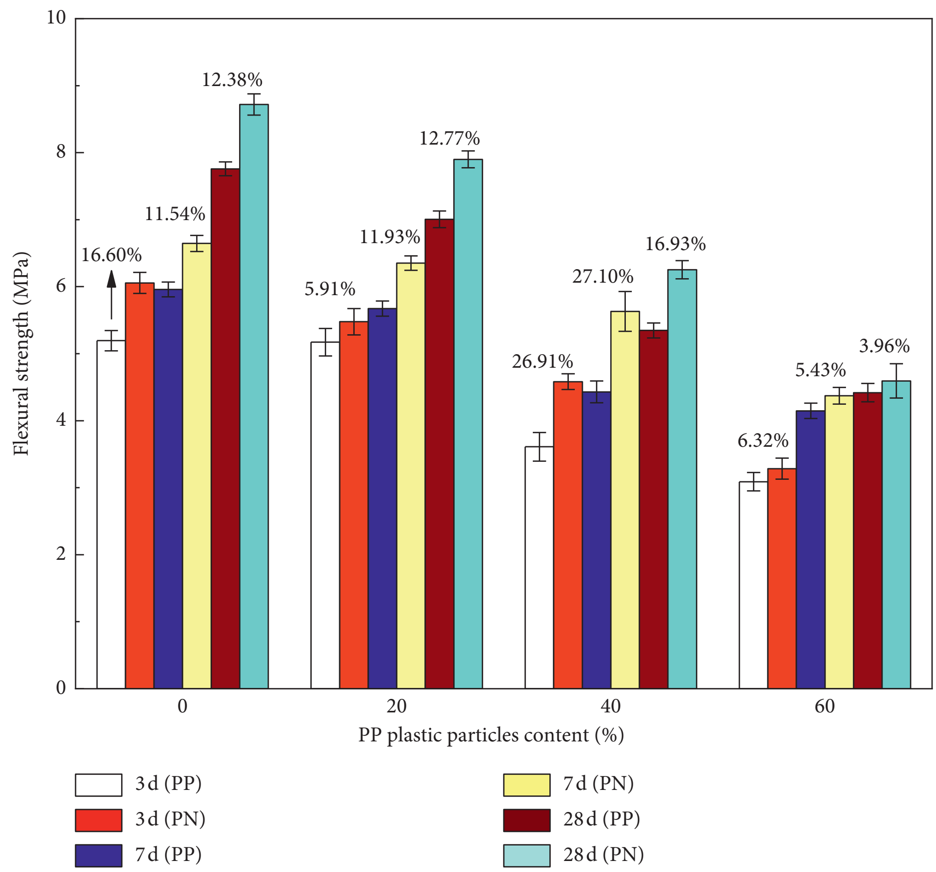

Figure 7: Evolution of the flexural strength of mortars as function of curing time (3, 7, and 28 d). The error bars represent the standard deviation of three test specimens.

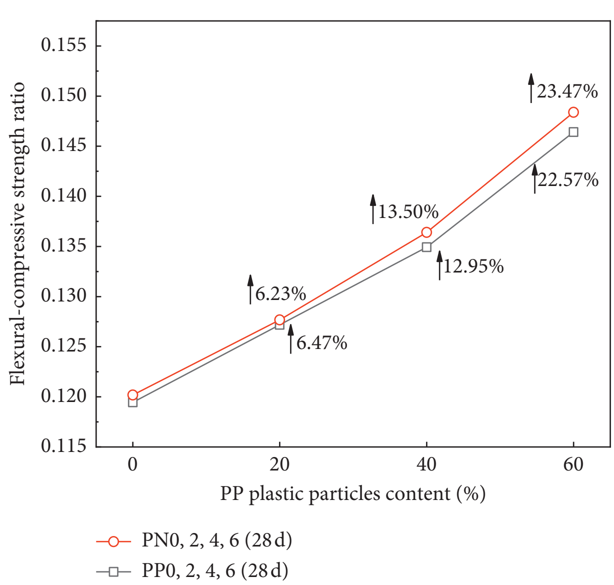

Figure 8: Evolution of the flexural-compression ratio of mortars as function of plastic waste content.

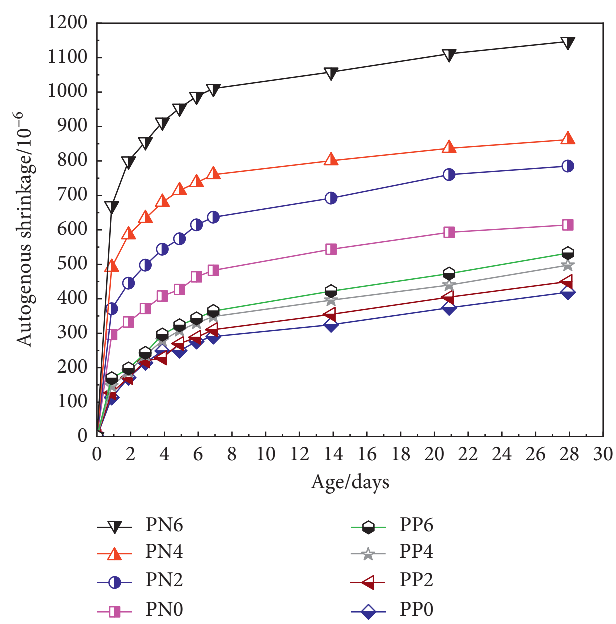

Figure 9: The autogenous shrinkage strain of plastic mortar vs curing time.

3.4. Drying Shrinkage. The drying shrinkage curves of plastic mortar are shown in Figure 10.

Similar to autogenous shrinkage, the drying shrinkage of mortars increased with the increase in recycled PP plastic particles' content. Compared to PP0, the drying shrinkage of PP2, PP4, and PP6 increased by 12.06%, 22.06%, and 34.49%, respectively, at day 28. The reason is that with the

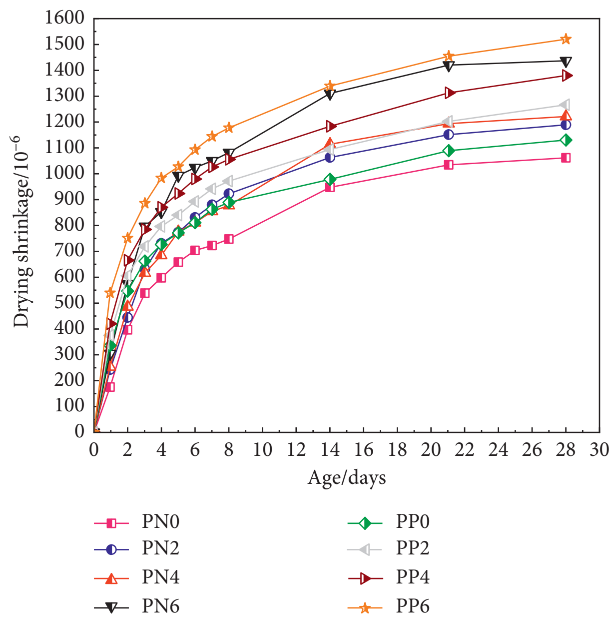

Figure 10: The drying shrinkage of the plastic mortar vs curing time.

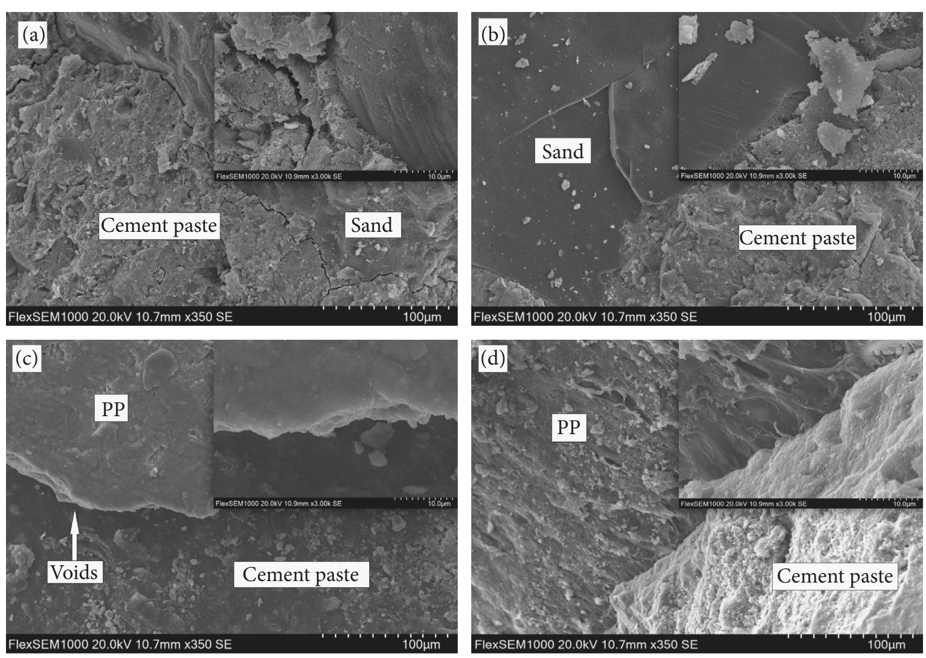

Figure 11: SEM pictures of the mortar specimens at day 28. (a) PP0, (b) PN0, (c) PP6, and (d) PN6.

increase of recycled PP plastic particles' content, the internal porosity of mortars increases gradually, and free water and capillary water in mortar are easier to evaporate [43], and the drying shrinkage deformation is greater. It can also be seen from Figure 10 that the drying shrinkage deformation of plastic mortar can be decreased by adding nano-SiO_2. Compared to PP0, PP2, PP4, and PP6, the drying shrinkage of PN0, PN2, PN4, and PN6 decreased by 6.06%, 6.11%, 11.48%, and 5.48%, respectively, at day 28. This may be because the microfilling effect of nano-SiO_2 can reduce the content of capillary pores in plastic mortar, and the shrinkage of plastic mortar is usually caused by water loss of capillary pores. The refinement pore size of nano-SiO_2 can increase the difficulty of moisture migration and reduce the shrinkage of plastic mortar [44]. In addition, in cement hydration process, nano-SiO_2 consumes a large amount of CH to form dense C-S-H, resulting the plastic mortar's microstructure more compact and firm, and more resistant to shrinkage deformation due to water dispersion loss [45]. The results of this study are consistent with the results of studies by Li and Yao [45], Güneyisi et al. [46], and Du and Pang [47]. Furthermore, the drying shrinkage of plastic mortar was larger than its autogenous shrinkage whether nano-SiO_2 was added or not, which is related to the drying shrinkage mechanism. Drying shrinkage is the result of the combined action of volume shrinkage and internal autogenous shrinkage caused by the loss or migration of pore water in concrete in the air.

3.5. Microstructural Study. The SEM of PP0, PN0, PP6, and PN6 at curing age of 28 days is shown in Figure 11, which magnifies the microstructure 350 times and 3000 times. It is observed in Figure 11(a) that there are some obvious cracks and voids at the interface between sand and cement paste. Compared to PN0, the structure of PP0 is less dense, and PP0 has more porosity and wider cracks. By contrast, it is observed in Figure 11(b) that the structure of PN0 is more compact with fewer cracks. This is due to the size effect of the nano-SiO_2, which can fill into the pores between sand and cement paste, make the structure denser, and improve the strength of mortar. The poor adhesion between the plastic and the cement paste is clearly observed in Figure 11(c). Compared to PP0, PP6 has more porosity and wider cracks, and the structure of PP0 is less dense. And, it is noticeable that the recycled PP plastic particles can be manually and easily pulled out from the matrix at the fracture section of the mortar specimens, which is consistent with the results of SEM. Figure 11(d) shows that the structure of PP-filled mortar with nano-SiO_2 is denser with relatively good adhesion between the plastic and cement paste. Compared to PP0 and PP6, the PN0 and PN6 become more compact and uniform due to the filling effect of the nano-SiO_2, and then improved strength can be achieved.

4. Conclusions

This paper has presented the results of a systematic study on the influence of nano-SiO_2 and recycled PP plastic particles' content on physical, mechanical, and shrinkage properties of mortar. From the results obtained from this study, the following conclusions can be drawn:

(i) This plastic waste type can be used successfully as aggregate instead of sand in mortar.

(ii) With the increase in the replacement ratio of sand by recycled PP plastic particles:

  (1) The apparent porosity and water absorption of plastic mortar increase,
  (2) The apparent specific gravity, bulk density, compressive strength, and flexural strength decrease,
  (3) The toughness is improved because the flexural-compressive ratio increases, and
  (4) The autogenous shrinkage and dry shrinkage increase.

(iii) The addition of nano-SiO_2 reduces the porosity, water absorption, and drying shrinkage of plastic mortar, increases its density and flexural-compressive ratio, and effectively improves the compressive and flexural strength of plastic mortar. However, the addition of nano-SiO_2 also increases the autogenous shrinkage of plastic mortar. Therefore, when using nano-SiO_2 to enhance the mechanical properties of plastic mortar, the adverse effect on autogenous shrinkage strain of plastic mortar should be considered.

(iv) The results of SEM show that there is a poor adhesion between recycled PP plastic particles and cement paste. Nano-SiO_2 can make the interface structure between cement paste and aggregates (natural aggregate and PP plastic aggregate) more compact, thus improving the mechanical properties of plastic mortar.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

This work was funded by the National Natural Science Foundation of China (Project No. 41440018, 41977236, and 41672278) and the National Natural Science Foundation of China Overseas and Hong Kong-Macao Scholar Cooperative Research Foundation (Project No. 51728201).

References

[1] D. Lithner, Å. Larsson, and G. Dave, "Environmental and health hazard ranking and assessment of plastic polymers based on chemical composition," *Science of the Total Environment*, vol. 409, no. 18, pp. 3309–3324, 2011.
[2] PlasticsEurope, *Plastics—the Facts 2018 an Analysis of European Plastics Production, Demand and Waste Data*, Association of Plastic Manufacturers Brussels, Bruxelles, Belgium, 2018.
[3] D. Chen, X. Huang, P. Wang, X. Liang, and X. Zhou, "Recycling effective ways of waste plastics," *Engineering Plastics Application*, vol. 40, pp. 92–94, 2012.
[4] A. Poonyakan, M. Rachakornkij, M. Wecharatana, and W. Smittakorn, "Potential use of plastic wastes for low thermal conductivity concrete," *Materials*, vol. 11, no. 10, p. 1938, 2018.
[5] B. Safi, M. Saidi, D. Aboutaleb, and M. Maallem, "The use of plastic waste as fine aggregate in the self-compacting mortars: effect on physical and mechanical properties," *Construction and Building Materials*, vol. 43, pp. 436–442, 2013.
[6] S. Yang, X. Yue, X. Liu, and Y. Tong, "Properties of self-compacting lightweight concrete containing recycled plastic particles," *Construction and Building Materials*, vol. 84, pp. 444–453, 2015.
[7] C. Jacob-Vaillancourt and L. Sorelli, "Characterization of concrete composites with recycled plastic aggregates from postconsumer material streams," *Construction and Building Materials*, vol. 182, pp. 561–572, 2018.

[8] L. Gu and T. Ozbakkaloglu, “Use of recycled plastics in concrete: a critical review,” *Waste Management*, vol. 51, pp. 19–42, 2016.
[9] N. Saikia and J. de Brito, “Use of plastic waste as aggregate in cement mortar and concrete preparation: a review,” *Construction and Building Materials*, vol. 34, pp. 385–401, 2012.
[10] R. Siddique, J. Khatib, and I. Kaur, “Use of recycled plastic in concrete: a review,” *Waste Management*, vol. 28, no. 10, pp. 1835–1852, 2008.
[11] C. Albano, N. Camacho, M. Hernández, A. Matheus, and A. Gutiérrez, “Influence of content and particle size of waste pet bottles on concrete behavior at different w/c ratios,” *Waste Manag*, vol. 29, pp. 2707–2716, 2009.
[12] Z. Z. Ismail and E. A. Al-Hashmi, “Use of waste plastic in concrete mixture as aggregate replacement,” *Waste Management*, vol. 28, no. 11, pp. 2041–2047, 2008.
[13] J. Liang, H. Chen, Y. Xiao, L. Guo, and T. Jiang, “Research on of compressive performance modified concrete with recycled PP powder,” *Concrete*, vol. 331, pp. 79–81, 2017.
[14] M. Frigione, “Recycling of PET bottles as fine aggregate in concrete,” *Waste Management*, vol. 30, no. 6, pp. 1101–1106, 2010.
[15] K. S. Rebeiz and A. P. Craft, “Plastic waste management in construction: technological and institutional issues,” *Resources, Conservation and Recycling*, vol. 15, no. 3-4, pp. 245–257, 1995.
[16] F. Liu, H. Huang, X. Xia, L. Li, G. Zhong, and Y. Guo, “Mechanical test on modified concrete with recycled plastic particles and its numerical simulation,” *Journal of Building Materials*, vol. 14, no. 2, pp. 173–179, 2011.
[17] D. Foti, “Preliminary analysis of concrete reinforced with waste bottles PET fibers,” *Construction and Building Materials*, vol. 25, no. 4, pp. 1906–1915, 2011.
[18] K. Hannawi, S. Kamali-Bernard, and W. Prince, “Physical and mechanical properties of mortars containing PET and PC waste aggregates,” *Waste Management*, vol. 30, no. 11, pp. 2312–2320, 2010.
[19] S. C. Kou, G. Lee, C. S. Poon, and W. L. Lai, “Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes,” *Waste Management*, vol. 29, no. 2, pp. 621–628, 2009.
[20] J. Gaitero, “Multi-scale study of the fibre matrix interface and calcium leaching in high performance concrete,” Ph. D. thesis, University of the Bask Country (UPV-EHU), Bilbao, Spain, 2008.
[21] A. Porro, J. S. Dolado, I. Campillo, E. Erkizia, Y. D. Miguel, and Y. S. D. Ibarra, “Effects of nanosilica additions on cement pastes,” in *Proceedings of the International Conference Held at the University of Dundee: Applications of Nanotechnology in Concrete Design*, pp. 87–96, Thomas Telford Publishing, Scotland, UK, July 2005.
[22] K. Sobolev, I. Flores, R. Hermosillo, and L. M. Torres-Martínez, “Nanomaterials and nanotechnology for high-performance cement composites,” in *Proceedings of the ACI Session on Nanotechnology of Concrete: Recent Developments and Future Perspectives*, pp. 91–118, Denver, CO, USA, November 2006.
[23] T. Ji, “Preliminary study on the water permeability and microstructure of concrete incorporating nano-SiO_2,” *Cement and Concrete Research*, vol. 35, no. 10, pp. 1943–1947, 2005.
[24] H. Li, H.-g. Xiao, J. Yuan, and J. Ou, “Microstructure of cement mortar with nano-particles,” *Composites Part B: Engineering*, vol. 35, no. 2, pp. 185–189, 2004.
[25] F. Hasan-Nattaj and M. Nematzadeh, “The effect of forta-ferro and steel fibers on mechanical properties of high-strength concrete with and without silica fume and nano-silica,” *Construction and Building Materials*, vol. 137, pp. 557–572, 2017.
[26] A. Nazari and S. Riahi, “The effects of SiO_2 nanoparticles on physical and mechanical properties of high strength compacting concrete,” *Composites Part B: Engineering*, vol. 42, no. 3, pp. 570–578, 2011.
[27] Q. Zhao and Y. Liu, “Research on mechanical properties of concrete with nano-silica, rubber and recycled concrete,” *Journal of Henan University (Natural Science)*, vol. 46, pp. 111–115, 2016.
[28] B.-W. Jo, C.-H. Kim, G.-H. Tae, and J.-B. Park, “Characteristics of cement mortar with nano-SiO_2 particles,” *Construction and Building Materials*, vol. 21, no. 6, pp. 1351–1355, 2007.
[29] ASTM, *Standard Test Method for Apparent Porosity, Water Absorption, Apparent Specific Gravity, and Bulk Density of Burned Refractory Brick and Shapes by Boiling Water ASTM C20-00*, ASTM International, West Conshohocken, PA, USA, 2015.
[30] ASTM, *Standard Test Method for Flexural Strength of Hydraulic-Cement Mortars ASTM C348-18*, ASTM International, West Conshohocken, PA, USA, 2018.
[31] ASTM, *Standard Test Method for Compressive Strength of Hydraulic-Cement Mortars Using Portions of Prisms Broken in Flexure ASTM C349-18*, ASTM International, West Conshohocken, PA, USA, 2018.
[32] ASTM, *Standard Test Method for Autogenous Strain of Cement Paste and Mortar ASTM C1698-09*, ASTM International, West Conshohocken, PA, USA, 2014.
[33] ASTM, *Standard Test Method for Drying Shrinkage of Mortar Containing Hydraulic Cement ASTM C596-18*, ASTM International, West Conshohocken, PA, USA, 2018.
[34] N. Saikia and J. de Brito, “Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate,” *Construction and Building Materials*, vol. 52, pp. 236–244, 2014.
[35] L. Chen and D. F. Lin, “Applications of sewage sludge ash and nano-SiO_2 to manufacture tile as construction material,” *Construction and Building Materials*, vol. 23, no. 11, pp. 3312–3320, 2009.
[36] A. Heidari and D. Tavakoli, “A study of the mechanical properties of ground ceramic powder concrete incorporating nano-SiO_2 particles,” *Construction and Building Materials*, vol. 38, pp. 255–264, 2013.
[37] Z. Dong, K. Zhao, and Y. Wang, “Research status of recycled PET concrete,” *Concrete*, vol. 329, pp. 100–104, 2017.
[38] J. Yang, Z. Feng, and X. Jiang, “Toughness and rigidity of composite additives modified concrete,” *Science Technology and Engineering*, vol. 15, pp. 279–283, 2015.
[39] L. Wu, N. Farzadnia, C. Shi, Z. Zhang, and H. Wang, “Autogenous shrinkage of high performance concrete: a review,” *Construction and Building Materials*, vol. 149, pp. 62–75, 2017.
[40] B. Guo, R. Sun, and F. Zheng, “Experimental study of concrete autogenous shrinkage with superfine active silica,” *Ready-Mixed Concrete*, vol. 1, pp. 24–28, 2007.
[41] Z. Wu, C. Shi, K. H. Khayat, and S. Wan, “Effects of different nanomaterials on hardening and performance of ultra-high strength concrete (UHSC),” *Cement and Concrete Composites*, vol. 70, pp. 24–34, 2016.
[42] A. Pourjavadi, S. M. Fakoorpoor, A. Khaloo, and P. Hosseini, “Improving the performance of cement-based composites

containing superabsorbent polymers by utilization of nano-SiO_2 particles," *Materials & Design*, vol. 42, pp. 94–101, 2012.

[43] X. Wang, W. Xu, J. Feng, and P. Zhu, "Experimental research on the influence of recycled coarse aggregate on the shrinkage of concrete," *Concrete*, vol. 310, pp. 59–62, 2015.

[44] J. Zeng, Z. Fan, and S. Wang, "Comparative research on effect of metakaolin and silica fume on mortar drying shrinkage," *Journal of Wuhan University of Technology*, vol. 36, pp. 115–120, 2014.

[45] J. Li and Y. Yao, "A study on creep and drying shrinkage of high performance concrete," *Cement and Concrete Research*, vol. 31, no. 8, pp. 1203–1206, 2001.

[46] E. Güneyisi, M. Gesoğlu, S. Karaoğlu, and K. Mermerdaş, "Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes," *Construction and Building Materials*, vol. 34, pp. 120–130, 2012.

[47] H. Du and S. D. Pang, "High performance cement composites with colloidal nano-silica," *Construction and Building Materials*, vol. 224, pp. 317–325, 2019.


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