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Review

Use of recycled plastics in concrete: A critical review

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ABSTRACT

Plastics have become an essential part of our modern lifestyle, and the global plastic production has increased immensely during the past 50 years. This has contributed greatly to the production of plastic-related waste. Reuse of waste and recycled plastic materials in concrete mix as an environmental friendly construction material has drawn attention of researchers in recent times, and a large number of studies reporting the behavior of concrete containing waste and recycled plastic materials have been published. This paper summarizes the current published literature until 2015, discussing the material properties and recycling methods of plastic and the influence of plastic materials on the properties of concrete. To provide a comprehensive review, a total of 84 studies were considered, and they were classified into sub categories based on whether they dealt with concrete containing plastic aggregates or plastic fibers. Furthermore, the morphology of concrete containing plastic materials is described in this paper to explain the influence of plastic aggregates and plastic fibers on the properties of concrete. The properties of concretes containing virgin plastic materials were also reviewed to establish their similarities and differences with concrete containing recycled plastics.

Contents

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1. Introduction

Since the 20th century, plastics have been used increasingly in a large range of products because of their favorable properties, including low density, high strength-to-weight ratio, high durability, ease of design and manufacture, and low cost. Currently, polymer products are widely used in almost every field, particularly in packaging, building and construction, automotive, electrical and electronics, agriculture, and other industries. The global plastic production in 2012 is reported to have increased to 288 million tons (Europe, 2013). More than half of this amount was used for one-off disposable consumer products, which contributed greatly to the production of plastic-related waste. Most types of plastics are not biodegradable and are chemically unreactive in the natural environment; hence, such polymer products persist for decades, even for centuries. Some common types of plastics such as polyvinyl chloride (PVC) and polycarbonate (PC) can release toxic compounds into the air, water, and soil slowly under certain circumstances. Hence, plastic wastes are considered to be a serious environmental problem universally.

In 2012, 45.9 million tons of plastics were consumed in Europe; of this, 25.2 million tons of plastic ended up in the waste stream (Europe, 2013). Fig. 1 shows the treatment of post-consumer plastics in 2012 by EU-27+2. In 2012, approximately 26% of the total plastic waste was mechanically recycled; 0.3% was collected for feedstock recycling; 35.6% was recovered for energy; and the rest 38.1% was disposed. Energy recovery data included plastic waste consumed in municipal solid waste (MSW) incineration and waste used as refuse derived fuel material. However, as can be seen in Fig. 1, in 19 out of 29 countries, the energy recovery rate was lower than the average value of 36%.

Table 1 lists the types and quantities of plastics in MSW in USA in 2012 (EPA, 2014). The plastics in MSW were classified as polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene/linear low-density polyethylene (LDPE/LLDPE), poly lactic acid (PLA), polypropylene (PP), polystyrene (PS), and other resins. A total of 31.7 million tons of plastics were generated, and this amount accounted for 12.7% of the total MSW generated in 2012; only 8.8% of the waste plastics were recycled. Among the different types of plastics, PET and other resins accounted for the highest recycling rate (approximately 20%), and they were followed by polyethylene, including HDPE and LDPE/LLDPE (approximately 15%). However, PVC, PLA, PP, and PS, which accounted for 32% of the total weight

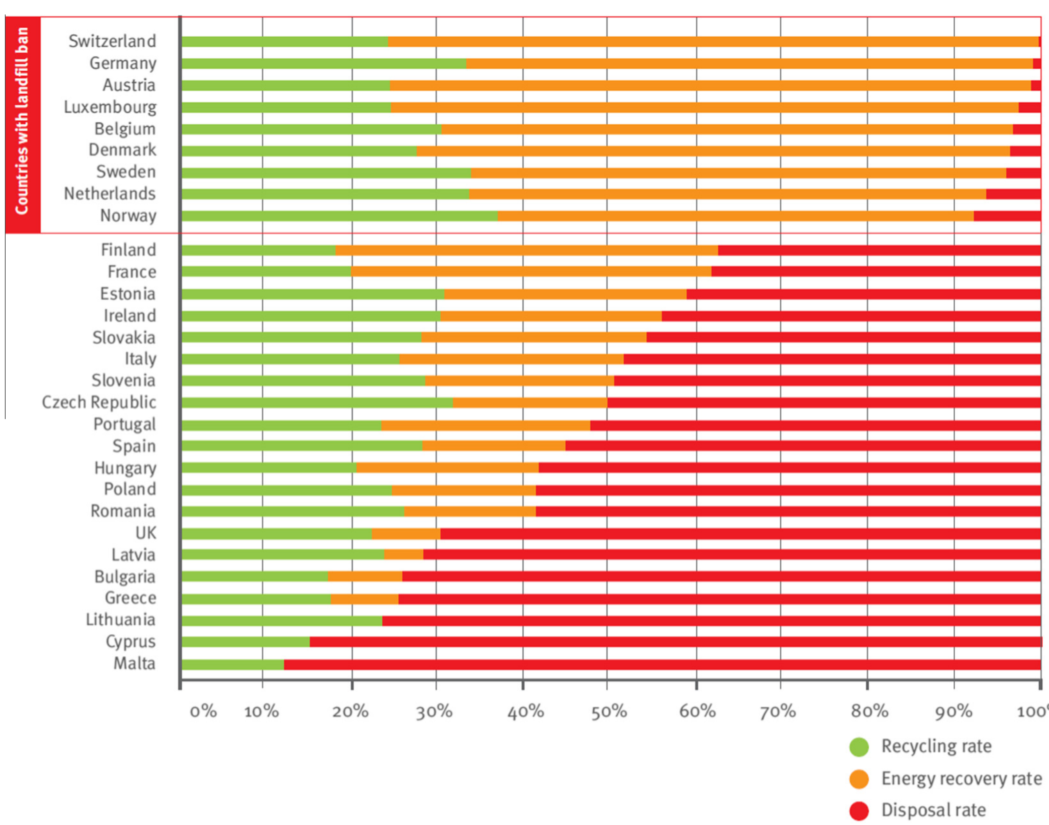

Fig. 1. Treatment of post-consumer plastics in 2012 by EU-27+2 (Europe, 2013).

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Table 1
Types and quantities of plastics in municipal solid waste (MSW) in the USA in 2012 (EPA, 2014).

Type of plastic polymer	Generation	Recovery		Discards
	(1000t)	(1000t)	Rate (%)	(1000t)
PET	4520	880	19.5	3640
HDPE	5530	570	10.3	4960
PVC	870	Neg.	Neg.	870
LDPE/LLDPE	7350	390	5.3	6960
PLA	50	Neg.	Neg.	50
PP	7190	40	0.6	7150
PS	2240	20	0.9	2220
Other resins	4000	900	22.5	3100
Total Plastic in MSW	31,750	2800	8.8	28,950

of MSW, were almost not recycled at all. Table 2 presents the quantity of plastics generated and recycled in MSW from 1960 to 2012 in USA (EPA, 2014). The quantity of plastics generated in MSW increased from 0.39 million tons to 31.75 million tons in the last 50 years. The amount of plastic-related waste produced in 2012 was almost 80 times that in 1960. However, the recycling of plastic waste did not start until 1980, and the recycling rate in that year was 0.3%. In spite of improvements in technology and awareness in the period of 30 years, the recycle rate increased to only 8.8% in 2012.

Post-consumed plastic waste can be treated by three main methods: land-filling, incineration, and recycling according to the principle of waste hierarchy (Gertsakis and Lewis, 2003). Land-filling is now considered the last resort in dealing with plastic waste because it requires a huge amount of space and causes long-term pollution problems. Incineration is adopted in some countries because of the high calorific value of the polymer and because the waste is completely eliminated. However, a great amount of carbon dioxide and poisonous chemicals are released, and toxic fly ash and bottom ash are produced. Recycling of waste plastics is, therefore, the best solution to reduce the environmental impact in terms of natural resource and energy consumption, pollution, waste disposal, and global warming. Among the various types of recycling management approaches, the reuse of waste and recycled plastic material in the construction industry is considered an ideal method for disposing plastic waste. By this method, recycled plastics can be reused without degradation in quality during the service cycle, and more importantly, the recycled plastics substitute the use of virgin construction materials.

The use of recycled plastic materials in conventional cement mortar and concrete has been researched extensively. In the past, plastics were used in concrete mainly in two forms: (i) plastic aggregates (PA), which replaced natural aggregates and (ii) plastic fibers (PF), which were used in fiber-reinforced concrete (FRC). The properties of fresh and hardened concrete incorporating plastic materials were investigated in several previous studies (Pacheco-Torgal et al., 2012; Saikia and de Brito, 2012; Siddique et al., 2008), which are summarized in Tables 3–5. However, the detailed material properties of plastics were not provided in these reviews, and some of the important properties of concrete, including its stress-strain curve, abrasion resistance, creep, and carbonation, were not considered in the reviews reported in (Pacheco-Torgal et al. (2012) and Siddique et al. (2008). Furthermore, the review reported in Saikia and de Brito (2012) was limited to plastic aggregates, and it did not cover reports on concrete containing plastic fibers. Additionally, none of the previous reviews provided any information about the morphology of concrete containing plastic materials; in more recent studies, significant efforts have been made to explain the behavior of concrete containing plastic materials through scanning electron microscopy (SEM) observations. However, the existing reviews only cover the research before 2010, while more than 50 of the 84 reports published on concrete incorporating plastic materials were published between 2010 and

Table 2
Quantities of plastic generated and recycled in MSW from 1960 to 2012 in the USA (EPA, 2014).

Year	1960	1970	1980	1990	2000	2005	2008	2010	2011	2012
Generated (1000t)	390	2900	6830	17,130	25,550	29,380	30,260	31,290	31,840	31,750
Recovery (1000t)	Neg.	Neg.	20	370	1480	1780	2140	2500	2660	2800
Recovery Rate	Neg.	Neg.	0.30%	2.20%	5.80%	6.10%	7.10%	8.00%	8.40%	8.80%

Table 3
Material properties summarized in previous review studies on use of plastic aggregates and fibers in concrete.

References	Types of composite	Type of plastic	Recycle procedure	Mix design	Alkali resistance of plastic
Siddique et al. (2008)	PA, PF	PA: PET; PF: PP;	✓	✓	X
Saikia and de Brito (2012)	PA	PA: PET, PS, PC, PVC, Melamine, PUR	✓	✓	PA
Pacheco-Torgal et al. (2012)	PA, PF	PA: PET, PS, PVC, Melamine, PUR; PF: PET	X	✓	PA, PF

PA: Plastic aggregate.
PF: Plastic fiber.

Table 4
Physical and hardened mechanical properties summarized in previous review studies.

References	Physical properties			Hardened mechanical properties							
	Slump	Density	Air content	Compressive strength	Splitting tensile strength	Flexural strength	Flexural toughness	Impact resistance	Modulus of elasticity	Stress strain curve	Abrasion resistance
Siddique et al. (2008)	PA, PF	PA	PF	PA, PF	PA	–	–	PF	PA	–	PF
Saikia and de Brito (2012)	PA	PA	PA	PA	PA	PA	PA	–	PA	PA	PA
Pacheco-Torgal et al. (2012)	PA	–	–	PA, PF	PA, PF	–	PA, PF	–	PA, PF	–	–

PA: Plastic aggregate.
PF: Plastic fiber.

Table 5
Durability related and other properties summarized in previous review studies.

References	Durability related properties							Other properties	
	Carbonation	Chloride penetration	Shrinkage	Absorption	Freeze thaw resistance	Air/water permeability resistance	Temperature influence	Thermo-physical properties	Fire resistance
Siddique et al. (2008)	–	PF	–	–	–	PF	PC	–	–
Saikia and de Brito (2012)	PA	PA	PA	PA	PA	PA	–	PA	PA
Pacheco-Torgal et al. (2012)	–	–	PF	–	–	–	–	PA	–

PA: Plastic aggregate.
PF: Plastic fiber.

2015. Therefore, an up-to-date comprehensive review covering concretes incorporating PAs and PFs and providing the detailed properties of plastic and concrete containing plastic materials is necessary for a better understanding of the behavior of this important construction material.

This paper aims to provide an all-encompassing review of the existing reports on the use of recycled plastics in concrete between 1994 and 2015. In all, 84 works were reviewed and classified into sub-categories: the studies dealing with concrete containing plastic aggregates (49 studies) and those dealing with concrete containing plastic fibers (35 studies). The material properties of plastic, the recycling methods, and the influence of plastic materials on the properties of concrete are summarized in this paper. Furthermore, this paper presents the first review that delves into the morphology of concrete containing plastic materials as studied by SEM to explain the influence of PA and PF on concrete properties. Moreover, this is the first study to review concretes containing virgin plastic materials to clearly establish similarities and differences between concretes containing recycled and virgin plastic materials.

2. Material properties of plastics used in concrete

Generally, two forms of plastics, namely, PA and PF, are used in concrete. Recycled PAs are extracted from different types of plastic waste. Tables 6 and 7 list the types and properties of PA and PF used in concrete as reported in literature. The tables also summarize the recycling methods for PA and PF; these methods typically involve direct mechanical recycling or melting. The former is an efficient and economical way to obtain recycled PA and PF, while the latter yields materials with more uniform size and properties.

2.1. Plastic aggregates and fibers

The PAs used in previous studies were coarse aggregates (CA) and fine aggregates (FA). It is no surprise that the bulk density of PA is much lower than that of typical natural aggregates; hence, PA is suitable for manufacturing lightweight concrete. The data in Table 6 show that the specific gravity of all types of PA is 0.9–1.4, which is much lower than that of natural aggregates commonly used in concrete. Moreover, it can be seen from Table 6 that the bulk density of PA is much lower than its specific gravity due to the hollow sections between PA particles. The bulk density of PA differs based on the recycling method. Typically, the direct mechanical recycling method leads to a relatively low bulk density, whereas the melting process leads to a higher bulk density of PA, such as the case in waste expanded polystyrene (EPS). In general, angular recycled EPS aggregates were prepared by crushing waste PS, and EPS aggregates in the form of beads were prepared using recycled granulates (Sabaa and Ravindrarajah, 1997; Tang et al., 2008). In order to avoid segregation in the concrete matrix, the EPS aggregates were coated with a hydrophilic chemical. The bulk density of recycled EPS aggregates prepared by this method ranges from 24 to 27 kg/m^3. However, Kan and Demirboğa (2009a, 2009b) prepared modified EPS (MEPS) aggregates by heating crushed waste EPS in an oven; the obtained CA and FA had bulk densities of 220–240 kg/m^3 and 310–340 kg/m^3, respectively. In comparison with natural aggregates, PAs generally have lower bulk density, lower water absorption, and higher ultimate tensile strength, but much lower melting points. Some of the studies suggested a new type of aggregates that could be obtained by mixing melted plastic with natural aggregates in order to realize better aggregate properties than that achieved by the normal recycling method. Choi et al. (2005, 2009) prepared waste PET lightweight aggregates (WPLA) by mixing molten granulated waste PET bottle with granulated blast furnace slag (Choi et al., 2005) and river sand (Choi et al., 2009). These two types of WPLA had smooth surfaces and rounded shape, with a bulk density of 844 kg/m^3 and 0% water absorption, and were used as fine aggregates in concrete. In contrast, PET aggregates manufactured by direct mechanical recycling had a bulk density of 200–500 kg/m^3, and 0.11–0.75% water absorption. The physical and mechanical properties of concrete containing WPLA were better than those of concrete containing directly recycled PET FA, as discussed in further detail in Section 3.

The purpose of using plastic fibers in concrete is to enhance the mechanical and durability properties of conventional concrete in addition to securing environmental benefits. Plastic fibers can act as reinforcement to replace steel fibers in FRC as steel is a high energy consuming material with a relatively high price, and it is susceptible to corrosion. Plastic fibers on the other hand are cost-effective, have lower carbon footprint and are corrosion resistant. Furthermore, compared to the steel fibers, plastic fibers often exhibit better strength to weight ratio and elongation (i.e. steel fibers: strength to weight ratio of 192 kN m/kg and elongation of 3.2% vs PP fibers: strength to weight ratio of 889 kN m/kg and elongation of 9.1%) (Yao et al., 2003). As seen from the data in Table 7, the tensile strength and elongation of recycled PET fibers typically exceed 350 MPa and 20% (Fraternali et al., 2014), respectively. Among these fibers, those fabricated by the melting process have a higher tensile strength (Kim et al., 2010). Ochi et al. (2007) used pellets recycled from PET bottles as the raw material for producing PET fibers. The pellets were melted, extruded from a nozzle, and drawn into fibers while warm. Thus, the polymer chains aligned in the longitudinal direction of the fiber so that the tensile strength of fiber increased and exceeded 450 MPa, while the strength of normal recycled PET fiber was less than 400 MPa. In addition to recycled PET fibers, recycled PP fibers are also used in plastic FRC. Meddah and Bencheikh (2009) used various lengths of waste polypropylene fibers (WPF) obtained from PP storage bags.

Table 6
Recycling method and properties of plastic concrete aggregates as reported in literature.

No.	References	Type of plastic	Origin of plastic waste	Recycle/treating procedure	Particle size (mm)/shape	Density[a]	Other properties[b]
1	Ravindrarajah and Tuck (1994)	EPS	Virgin	NA	⩽4.75/beads	PD: 67; BD: 35	Chemical coating
2	Lai et al. (1996)	EPS	Virgin	NA	2.6 average/beads	BD: 55	Chemical coating
3	Naik et al. (1996)	HDPE	HDPE waste	Shredding	Small particles		–
4	Sabaa and Ravindrarajah (1997)	EPS	Waste EPS	Crushing	⩽3.7/angular	PD: 58.5; BD: 26.8	FM: 3.68
5	Ravindrarajah (1999)	EPS	Virgin	NA	3 average/beads	SG: 0.67	–
6	Malloy et al. (2001)	Mixed plastic	Waste plastic	–	–	–	–
7	Babu and Babu (2003)	EPS	Virgin	NA	Type A: 6.3 mostly/beads Type B: 4.75 mostly/beads	Type A: BD: 9.5; SG: 0.014 Type B: BD: 20; SG: 0.029	–
8	Chen and Liu (2004)	EPS	Virgin	NA	Type A: 3 mostly/beads Type B: 8 mostly/beads	Type A: BD: 20 Type B: BD: 8.5	–
9	Elzafraney et al. (2005)	Mix plastic of HDPE, PVC and PP	Waste HDPE, PVE and PP	Grinding	⩽10/irregular shape	PVC: BD: 684; SG: 1 HDPE: BD: 534; SG: 1 PP: BD: 460; SG: 1	–
10	Choi et al. (2005)	PET	PET bottles	Melted PET mix with GBFS	Round and smooth	PD: 1390; BD: 844	Absorption: 0; FM: 4.11
11	Babu et al. (2005)	EPS	Virgin	NA	Type A: 6.3 mostly/beads Type B: 4.75 mostly/beads	Type A: BD: 9.5; SG: 0.014 Type B: BD: 20; SG: 0.029	–
12	Laukaitis et al. (2005)	PS	PS foam plastic	Crumbling	⩽10.2/irregular shape	–	–
13	Haghi et al. (2006)	EPS	Virgin	NA	Type A: 8/beads Type B: 6/beads Type C: 3/beads	Type A: BD: 12; SG: 0.01 Type B: BD: 16; SG: 0.014 Type C: BD: 20; SG: 0.029	–
14	Babu et al. (2006)	EPS and UEPS	Virgin	NA	⩽8/spherical	Type P: BD: 23.6; SG: 0.029 Type Q: BD: 9; SG: 0.014 Type U: BD: 66.5; SG: 1.02	–
15	Kumar and Prakash (2006)	HDPE	Waste HDPE	Heated coarse aggregate mix with plastic powder	⩽2.36	BD: 945–962; SG: 1.04	MP: 75–100 °C Elongation: over 500%
16	Batayneh et al. (2007)	Not mentioned	Waste plastic	Grinding to small sized particles	⩽9.5/small particles	–	–
17	Marzouk et al. (2007)	PET	PET bottles	Shredding after washing	Type A: ⩽0.5 Type C: ⩽0.2 Type D:⩽0.1	Type A: BD: 326 Type C: BD: 345 Type D: BD: 408	–
18	Tang et al. (2008)	EPS	Waste EPS	–	4 average/beads	BD: 24	Chemical coating
19	Panyakapo and Panyakapo (2008)	Melamine	Melamine waste	Grinding	⩽10/irregular shape	SG: 1.48	TS: 60; MP: 300 °C; Elongation: 0.79%; Absorption: 5.6%
20	Ismail and AL-Hashmi (2008)	Mix plastic of 80% PET and 20% PS	Plastic containers	Crushing	Irregular shape with length of 0.15–12 and width of 0.15–4	BD: 386.7	TS: 34.4; Absorption: 0.02%
21	Kan and Demirboğa (2009b)	Modified EPS	Waste EPS	Thermal treatment	Coarse: 4–16 Fine: 0–4	Coarse: SG: 0.22–0.24 Fine: SG: 0.31–0.34	Absorption: 4.1%

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Table 6 (*continued*)

No.	References	Type of plastic	Origin of plastic waste	Recycle/treating procedure	Particle size (mm)/shape	Density[a]	Other properties[b]
22	Asokan et al. (2009)	Glass fiber reinforced plastic (GRP)	GRP industry waste	Grinding	Powder and fiber form	–	–
23	Choi et al. (2009)	PET	PET bottles	Melted PET mix with river sand	⩽4.74/smooth and rounded	BD: 844; SG: 1.39	–
24	Albano et al. (2009)	PET	PET bottles	–	Small: 0.26/irregular shape big: 1.14/irregular shape	–	MP: 248 °C
25	Kou et al. (2009)	PVC	PVC pipes	Grinding	⩽5/irregular shape	BD: 546; SG: 1.4	Absorption: 0
26	Yesilata et al. (2009)	PET	PET bottles	Shredding	Thickness: 1	BD: 200	
27	Remadnia et al. (2009)	PET	PET bottles	Shredding after washing	⩽4/granules	BD: 327	TS: 75; MP: 249–271 °C Elongation: 70% Absorption: 0
28	Akçaözoğlu et al. (2010)	PET	PET bottles	Shredding after washing	⩽4/granular	SG: 1.27	–
29	Asokan et al. (2010)	Glass fiber reinforced plastic (GRP)	GRP industry waste	Grinding	⩽2/powder and fiber form	–	–
30	Lima et al. (2010)	Ethylene vinyl acetate (EVA)	Waste EVA from footwear industry	Cutting	⩽9.5/small particles	BD: 100; SG: 0.24	FM: 4.78; Absorption: 44.3%
31	Frigione (2010)	PET	PET bottles	Grinding	⩽2.36/small particles	BD: 660; SG: 1.32	
32	Fraj et al. (2010)	Polyurethane (PUR)	Rigid PUR foam waste	Immersed in water for 24 h before mixing for some group	⩽20	BD: 21; SG: 0.045	Porosity: 98%; Absorption: 13.9% in vol; MoE: 5.6 MPa
33	Madandoust et al. (2011)	EPS	Virgin	NA	Type A: 4.75 mostly/beads Type B: 9.5/beads	Type A: BD: 13.6; SG: 0.025 Type B: BD: 10.4; SG: 0.018	Absorption: 0
34	Galvão et al. (2011)	PET and LDPE	PET bottles and LDPE bags	Crushing after washing	PET: ⩽12.5; LDPE: ⩽4.8	PET: SG: 1.32 LDPE: SG: 0.86	PET: Absorption: 7.4% LDPE: Absorption: 3.9%
35	Ramadevi and Manju (2012)	PET	PET bottles	Shredding	–	–	–
36	Ferreira et al. (2012)	PET	PET bottles	Pc and Pf: shredding; Pp: thermal treatment	Pc, Pf: lamellar and irregular Pp: regular cylindrical granules	Pc: BD: 261; SG: 1.31 Pf: BD: 438; SG: 1.28 Pp: BD: 739; SG: 1.31	Pc: Absorption: 0.73% Pf: Absorption: 0.09% Pp: Absorption: 0.36%
37	Xu et al. (2012)	EPS	Virgin	NA	3 mostly/beads	BD: 30	
38	Wang and Meyer (2012)	High impact polystyrene (HIPS)	HIPS electronics waste	Shredding	⩽4/irregular shape	SG: 1.04	–
39	Rai et al. (2012)	Not mentioned	Waste plastic	–		SG: 0.91	FM: 3.2
40	Silva et al. (2013)	PET	PET bottles	Pc and Pf: shredding; Pp: thermal treatment	Pc: ⩽11.2; Pf, Pp: ⩽4 Pc, Pf: flaky Pp: regular cylindrical granules	Pc: BD: 261; SG: 1.3 Pf: BD: 438; SG: 1.28 Pp: BD: 739; SG: 1.3	Pc: Absorption: 0.75% Pf: Absorption: 0.11% Pp: Absorption: 0.39%
41	Herki et al. (2013)	EPS	Waste EPS	Mixed cement with waste EPS	⩽8 mm	BD: 457; SG: 0.8	FM: 5.58; Absorption: 13%
42	Ge et al. (2013)	PET	PET bottles	Shredding	⩽9.5/flaky	–	–
43	Juki et al. (2013)	PET	PET bottles	Grinding	⩽5/granulate		
44	Saikia and de Brito (2013)	PET	PET bottles	Pc and Pf: shredding; Pp: thermal treatment	Pc: ⩽11.2; Pf, Pp: ⩽4 Pc, Pf: flaky Pp: regular cylindrical granules	Pc: BD: 351; SG: 1.34 Pf: BD: 555; SG: 1.34 Pp: BD: 827; SG: 1.34	Pc: Absorption: 0.18% Pf: Absorption: 0.25% Pp: Absorption: 0.10%

Table 6 (*continued*)

No.	References	Type of plastic	Origin of plastic waste	Recycle/treating procedure	Particle size (mm)/shape	Density[a]	Other properties[b]
45	Chaudhary et al. (2014)	LDPE	LDPE bags	Shredding	⩽2.36	SG: 0.93	FM: 5.92
46	Ferrándiz-Mas et al. (2014)	EPS	Waste EPS	–	⩽1/Ground ⩽0.5/powdered	Ground: BD: 13 Powdered: BD: 22	Ground: Absorption: 1%; Powdered: Absorption: 3%
47	Saikia and de Brito (2014)	PET	PET bottles	Pc and Pf: shredding; Pp: thermal treatment	Pc: ⩽11.2; Pf, Pp: ⩽4 Pc, Pf: flaky Pp: regular cylindrical granules	Pc: BD: 351; SG: 1.34 Pf: BD: 555; SG: 1.34 Pp: BD: 827; SG: 1.34	Pc: Absorption: 0.18% Pf: Absorption: 0.25% Pp: Absorption: 0.10%
48	Akçaözoğlu and Ulu (2014)	PET	PET bottles	Crushing after washing	⩽4/granules	SG: 1.27	–

NA: not applicable.
[a] PD: particle density (kg/m^3); BG: bulk density (kg/m^3); SG: specific gravity.
[b] FM: fineness modulus; MP: melting point; TS: tensile strength (MPa); MoE: modulus of elasticity.

Table 7
Recycling method and properties of plastic fibers used in concrete as reported in literature.

No.	References	Type of plastic	Origin of plastic fiber	Recycle procedure	Length (mm)	Aspect ratio	Shape	Other properties[a]
49	Wang et al. (1994)	PP and nylon fiber	Carpet industrial waste	Disassembled mechanically	Type I: 12–25 Type II: 3–25	–	–	–
50	Sanjuan and Moragues (1997)	PP fiber	Virgin	NA	14	–	Rectangular cross-section	SG: 0.90; MoE: 3.5; TS: 560–770
51	Toutanji et al. (1998)	PP fiber	Virgin	NA	12.5 and 19	–	Fibrillated PP fiber	SG: 0.91; TS: 550–760; MoE: 3.5; MP: 160 °C
52	Kayali et al. (1999)	PP fiber	Virgin	NA	–	–	–	–
53	Mesbah and Buyle-Bodin (1999)	PP fiber	Virgin	NA	10	285	–	–
54	Toutanji (1999)	PP fiber	Virgin	NA	6–51	–	–	–
55	Wang et al. (2000)	PP and nylon fiber	Carpet industrial waste	Disassembled mechanically	12–25	–	–	–
56	Yao et al. (2003)	PP fiber	Virgin	NA	15	150	Smooth and straight	SG: 0.9; MoE: 8; Elongation: 8.1%; TS: 800
57	Kayali et al. (2003)	PP fiber	Virgin	NA	19	152	Fibrillated PP fiber	
58	Silva et al. (2005)	PET fiber	PET bottles	Sub product	20	769	–	TS: 320; MoE: 41.8; MP: 252.8 °C Elongation: 70.7%
59	Martínez-Barrera et al. (2005)	PP fiber	Virgin	NA	6 average	10–30	–	PP fibers were treated by gamma irradiation
60	Han et al. (2005)	PP fiber	Virgin	NA	19	271	–	SG: 0.9; TS: 560; MP: 162 °C

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Table 7 (*continued*)

No.	References	Type of plastic	Origin of plastic fiber	Recycle procedure	Length (mm)	Aspect ratio	Shape	Other properties[a]
61	Song et al. (2005)	PP and nylon fiber	Virgin	NA	PP: 19 Nylon: 19	–	–	PP: SG: 0.91; MoE: 4.11; TS: 430; MP: 160 °C Nylon: SG: 1.14; MoE: 5.17; TS: 890; MP: 225 °C
62	Richardson (2006)	PP fiber	Virgin	NA	12–50	–	Monofilament and crimped	–
63	Martínez-Barrera et al. (2006)	Nylon fiber	Virgin	NA	5	125–166	–	Nylon fibers were treated by gamma irradiation
64	Sivakumar and Santhanam (2007)	PP fiber	Virgin	NA	20	200	–	SG: 0.9; TS: 450; MoE: 5; Elongation: 18%
65	Ochi et al. (2007)	PET fiber	PET bottles	Drawn into fiber after melting process	30 and 40	43–57	Indented surface	SG: 1.34; TS: over 450
66	Suji et al. (2007)	PP fiber	Virgin	NA	12–24	–	–	SG: 0.9; TS: 550–760; MoE: 3.5
67	Wongtanakitcharoen and Naaman (2007)	PP and PVA fiber	Virgin	NA	PP: 19 PVA: 12	PP: 280 PVA: 300	–	PP: SG: 0.9; TS: 810; MoE: 3.34 PVA: SG: 1.3; TS: 1560; MoE: 40
68	Hsie et al. (2008)	PP fiber	Virgin	NA	–	–	Staple/monofilament	–
69	Meddah and Bencheikh (2009)	PP fiber	Waste fiber	–	30, 50 and 60	–	Flat fiber with rectangular cross section	TS: 450
70	Khadakbhavi et al. (2010)	HDPE fiber	Waste HDPE pots, buckets, cans, drums and utensils	Cutting	20–100	20–100	Straight	SG: 0.9
71	Kim et al. (2010)	PET and PP fiber	PET bottles Virgin PP fiber	Slit into fiber after melting process	50	PET: 100 PP: 131	PET: embossed PP: crimped	PET: SG: 1.38; MoE: 10.2; TS: 420; Elongation: 11.2% PP: SG: 0.91; MoE: 6; TS: 550; Elongation: 15%
72	Nili and Afroughsabet (2010)	PP fiber	Virgin	NA	12	54	Straight	SG: 0.91
73	Fraternali et al. (2011)	PET and PP fiber	PET bottles Virgin PP fiber	–	PET/a: 40 PET/b: 52 PET/c: 52 PP: 47	PET/a: 36 PET/b: 74 PET/c: 74 PP: 58	PET/a, PET/b: circular and straight PET/c: circular and crimped PP: oval and embossed	PET/a: SG: 1.34; TS: 550; Elongation: 27% PET/b: SG: 1.34; TS: 264; Elongation: 26% PET/c: SG: 1.34; TS: 274; Elongation: 19% PP: SG: 0.9; TS: 250; Elongation: 29%
74	Martínez-Barrera et al. (2011)	PP fiber	Virgin	NA	10	33	–	PP fibers were treated by gamma irradiation
75	de Oliveira and Castro-Gomes (2011)	PET fiber	PET bottles	Cutting	35	31	–	–
76	Karahan and Atiş (2011)	PP fiber	Virgin	NA	–	–	Fibrillated PP fiber	SG: 0.91; TS: 400–600
77	Mazaheripour et al. (2011)	PP fiber	Virgin	NA	12	–	–	SG: 0.9; TS: 350; MP: 160 °C
78	Bagherzadeh et al. (2011)	PP fiber	Virgin	NA	F1, F3, F4: 12 F2: 19	F1: 54; F2: 86; F3: 26; F4: 0.16	F1, F2, F3: monofilament F4: fibrillate	F1: SG: 0.91; TS: 445; Elongation: 18% F2: SG: 0.91; TS: 450; Elongation: 18% F3: SG: 0.91; TS: 480; Elongation: 19% F4: SG: 0.91; TS: 450; Elongation: 16%
79	Pelisser et al. (2012)	PET fiber	PET bottles	–	20	80	–	SG: 1.33; MP: 252.8 °C; Absorption: 3.3%
80	Kakooei et al. (2012)	PP fiber	Virgin	NA	–	–	Circular	MP: 160–170 °C; Absorption: 0
81	Nibudey et al. (2013)	PET fiber	PET bottles	–	25	35 and 50	–	SG: 1.34; Absorption: 0
82	López-Buendía et al. (2013)	PP fiber	Virgin	NA	40	54	–	PP fibers were surface treated
83	Fraternali et al. (2014)	PET fiber	PET bottles	–	PET/a: 40 PET/c: 52	PET/a: 36 PET/c: 74	PET/a: smooth PET/c: crimped	PET/a: SG: 1.34; TS: 550; Elongation: 27% PET/c: SG: 1.34;TS: 274; Elongation: 19%

NA: not applicable.
Aspect ratios are defined as the ratio of the fiber length to diameter.
[a] SG: specific gravity; MP: melting point; TS: tensile strength (MPa); MoE: modulus of elasticity (GPa).

The properties of WPF are very similar to those of the standard industrial polypropylene fibers commonly used as reinforcement for cement matrix.

Virgin EPS aggregates (Babu and Babu, 2003; Lai et al., 1996; Xu et al., 2012) and virgin PP and nylon fibers (Bagherzadeh et al., 2011; Richardson, 2006; Song et al., 2005) are also widely used in concrete mix. Hence, the properties of concrete containing virgin plastic materials are also reviewed to establish similarities and differences of such concrete from those containing recycled plastics. The properties of virgin plastic material are also summarized in Tables 6 (PA) and 7 (PF). Normally, the bulk density of virgin EPS aggregates is 35 kg/m^3, and that of recycled EPS aggregates is 24–27 kg/m^3. Virgin PP fibers have a specific gravity of 0.9 and an ultimate tensile strength of 550–760 MPa, while recycled PP fibers have a tensile strength of approximately 450 MPa. Further, virgin nylon fibers have a specific gravity of 1.14 and an ultimate tensile strength of 890 MPa.

2.2. Preparation of concrete containing plastic aggregates and plastic fibers

PA concrete is typically manufactured by replacing natural CA or FA with plastic CA or FA of the same volume, which is called direct volume replacement. The types and substitution levels of PAs used in previous studies are listed in Table 8. In most previous studies, the dosage of plastic fiber was less than 3% by total volume of concrete as admixtures. The types and contents of plastic fibers used in previous studies are listed in Table 9. In general, PA and PF concrete are quite similar to the conventional concrete in terms of preparing, casting and curing of the concrete.

3. Review of properties of concrete containing plastic aggregates and plastic fibers

In this section, research findings related to the effects of PA and PF on the properties of concrete are presented, and the subcategories of concrete containing PA and PF are summarized in Figs. 2 (PA) and 3 (PF). Figs. 2 and 3 provide the following information with the reference number listed in Tables 6–9: the physical properties of concrete, including slump, density, and air content; mechanical properties, including compressive strength, splitting tensile strength, flexural strength, elastic modulus, stress-strain curve, impact resistance, abrasion resistance, and pulse velocity; durability-related properties, including change in strength, absorption, chloride penetration, carbonation, shrinkage, creep, and freeze thaw resistance; and other properties such as thermophysical properties and fire resistance. Furthermore, the morphology of concrete containing different types of PA and PF as reported in the literature are summarized in Figs. 2 and 3.

3.1. Physical properties of concrete containing plastic aggregates and fibers

3.1.1. Slump

3.1.1.1. Effect of PA. The slump of PA concrete is affected by a number of factors such as water-cement ratio (w/c), substitution level of plastic aggregates (R_{PA}), and the shape of the waste plastic. Fig. 4 shows the representative results obtained from the existing studies (Albano et al., 2009; Batayneh et al., 2007; Choi et al., 2005, 2009; Ismail and Al-Hashmi, 2008; Kan and Demirboğa, 2009b; Kou et al., 2009; Madandoust et al., 2011; Rai et al., 2012; Tang et al., 2008) on the effect of R_{PA} on the slump. In some studies, the slump of fresh concrete was greatly influenced by the increase in R_{PA}, and the slump showed a tendency to decrease (Albano et al., 2009; Batayneh et al., 2007; Ismail and Al-Hashmi, 2008; Kan and Demirboğa, 2009b; Madandoust et al., 2011; Rai et al., 2012). This is attributed to the non-uniform shapes of PAs, which results in low fluidity. Ismail and Al-Hashmi (2008) observed that the slump reduced up to 95% the value for natural aggregate concrete at 20% substitution of FA. However, in some circumstances, R_{PA} has no significant influence on the slump value (Kou et al., 2009; Tang et al., 2008). Tang et al. (2008) reported that the slump value of fresh lightweight concrete containing 20–80% PS CA was generally similar to that of the corresponding normal weight concrete. The authors attributed this to the fact the PS CA concrete had a closed cellular structure with negligible water absorption capacity. Moreover, Choi et al. (2005, 2009) reported an increase in the slump value of concrete with increasing substitution levels of two types of WPLA (FA). According to Choi et al. (2005), this may be attributed to not only the spherical shape with smooth surface but also the absorption capacity (almost zero) of WPLA. Additionally, the problem of segregation may occur when dealing with concrete components characterized by aggregates with different specific weights, especially light aggregates such as PA (Babu and Babu, 2003). To prevent such segregation in the concrete mixes, PA treated with hydrophilic type chemical coating were widely used in the previous studies (Haghi et al., 2006; Lai et al., 1996; Ravindrarajah and Tuck, 1994; Tang et al., 2008; Xu et al., 2012).

3.1.1.2. Effect of PF. Fig. 5 shows the representative results obtained from the existing studies (Han et al., 2005; Hsie et al., 2008; Karahan and Atiş, 2011; Mazaheripour et al., 2011; Nibudey et al., 2013; Nili and Afroughsabet, 2010; Ochi et al., 2007; Pelisser et al., 2012; Sivakumar and Santhanam, 2007; Toutanji, 1999; Wang et al., 2000) on the effect of PF content (C_{PF}) on the slump. Most of the studies indicated that the slump of fresh concrete reduced significantly with increase in C_{PF} (Han et al., 2005; Hsie et al., 2008; Karahan and Atiş, 2011; Mazaheripour et al., 2011; Nibudey et al., 2013; Ochi et al., 2007; Sivakumar and Santhanam, 2007; Toutanji, 1999; Wang et al., 2000). Ochi et al. (2007) reported that there was no significant reduction in the slump when the PET fiber content reached 0.5% as compared to the slump of the conventional concrete. However, when the fiber content was increased to 1.0%, the slump value of fresh concrete was only approximately 25% that of the conventional concrete. However, several groups also observed that the workability improved only when the concrete had small fiber content. When the fiber content increased, the slump of FRC degraded (Nili and Afroughsabet, 2010; Pelisser et al., 2012). Pelisser et al. (2012) observed that the addition of 0.05% of PET fiber to concrete, the slump value increased by approximately 50%, and then decreased upon further addition of fiber.

3.1.2. Unit weight and density

3.1.2.1. Effect of PA. Figs. 6 and 7 show the results of the existing studies (Akçaözoğlu and Ulu, 2014; Babu et al., 2005; Babu and Babu, 2003; Batayneh et al., 2007; Chen and Liu, 2004; Choi et al., 2005, 2009; Elzafraney et al., 2005; Ferreira et al., 2012; Fraj et al., 2010; Ge et al., 2013; Herki et al., 2013; Ismail and Al-Hashmi, 2008; Juki et al., 2013; Kan and Demirboğa, 2009b; Kou et al., 2009; Lai et al., 1996; Laukaitis et al., 2005; Lima et al., 2010; Marzouk et al., 2007; Panyakapo and Panyakapo, 2008; Rai et al., 2012; Ravindrarajah, 1999; Ravindrarajah and Tuck, 1994; Sabaa and Ravindrarajah, 1997; Saikia and de Brito, 2013, 2014; Silva et al., 2013; Tang et al., 2008; Wang and Meyer, 2012; Xu et al., 2012) on the effect of R_{PA} on the density; the sub categories of concrete containing plastic CA (Fig. 6) and FA (Fig. 7) are also shown. The figures show that the density of PA concrete decreases with increasing substitution. Sabaa and Ravindrarajah (1997) reported that the increase in the substitution level of waste EPS

Table 8
Type and substitution level of plastic aggregates used in previous studies.

No.	References	Types of composite	Type of plastic	Types and amounts of substitution
1	Ravindrarajah and Tuck (1994)	Lightweight concrete	EPS	Coarse aggregate, 87% and 100% by volume
2	Lai et al. (1996)	Concrete	EPS	Fine aggregate, 10% total volume
3	Naik et al. (1996)	Concrete	HDPE	Fine aggregate, 0.5–5% total weight
4	Sabaa and Ravindrarajah (1997)	Lightweight concrete	EPS	Coarse aggregate, 30%, 50% and 70% by volume
5	Ravindrarajah (1999)	Concrete	EPS	Coarse aggregate, 10%, 20% and 30% by volume
6	Malloy et al. (2001)	Lightweight concrete	LDPE, HDPE, PS, Mix plastic	–
7	Babu and Babu (2003)	Lightweight concrete	EPS	Coarse aggregate, 21–36.4% total volume
8	Chen and Liu (2004)	Lightweight concrete	EPS	Coarse aggregate, 25–55% total volume
9	Elzafraney et al. (2005)	Concrete	Mix plastic of HDPE, PVC and PP	Coarse aggregate: plastic aggregate = 1: 0.274 by volume
10	Choi et al. (2005)	Concrete	PET	Fine aggregate, 25%, 50% and 75% by volume
11	Babu et al. (2005)	Lightweight concrete	EPS	Coarse aggregate, 16.3–66.5% total volume
12	Laukaitis et al. (2005)	Non-load-bearing lightweight Concrete	PS	Foam cement: foam PS granules as 1:1; 1:2; 1:3 by volume
13	Haghi et al. (2006)	Lightweight concrete	EPS	–
14	Babu et al. (2006)	Lightweight concrete	EPS and UEPS	Coarse aggregate, EPS: 20–50% by total vol/UEPS: 30% by total volume
15	Kumar and Prakash (2006)	Concrete	HDPE	Sand and cement 2%, 4% and 6% by volume
16	Batayneh et al. (2007)	Concrete	Not mentioned	Fine aggregate, 5–20% by volume
17	Marzouk et al. (2007)	Mortar	PET	Fine aggregate, 2–100% by volume
18	Tang et al. (2008)	Concrete	PS	Coarse aggregate, 20–80% by volume
19	Panyakapo and Panyakapo (2008)	Non-load-bearing lightweight concrete	Melamine	Cement: melamine = 1:1–1:4 by volume
20	Ismail and AL-Hashmi (2008)	Concrete	Mix plastic of 80% PET and 20% PS	Fine aggregate, 10%, 15% and 20% by volume
21	Kan and Demirboğa (2009b)	Lightweight concrete	Modified EPS	Coarse and fine aggregate, 25–100% by volume
22	Asokan et al. (2009)	Concrete	Glass fiber reinforced plastic (GRP)	Fine aggregate, 5–50% by volume
23	Choi et al. (2009)	Mortar and concrete	PET	Mortar: fine aggregate, 25–100% by volume Concrete: fine aggregate, 25–75% by volume
24	Albano et al. (2009)	Concrete	PET	Fine aggregate, 10% and 20% by volume
25	Kou et al. (2009)	Lightweight concrete	PVC	Fine aggregate, 5–45% by volume
26	Yesilata et al. (2009)	Concrete	PET	Settle into the surface of concrete
27	Remadnia et al. (2009)	Mortar	PET	Fine aggregate, 30%, 50% and 70% by volume
28	Akçaözoğlu et al. (2010)	Lightweight concrete	PET	Fine aggregate, PET: binder = 0.5:1 by volume
29	Asokan et al. (2010)	Concrete	Glass fiber reinforced plastic (GRP)	Fine aggregate, 5% and 15% by volume
30	Lima et al. (2010)	Lightweight concrete	Ethylene vinyl acetate (EVA)	Coarse aggregate, 25% and 50% by volume
31	Frigione (2010)	Concrete	PET	Fine aggregate, 5% by volume
32	Fraj et al. (2010)	Lightweight concrete	Polyurethane (PUR)	Coarse aggregate, 100% by volume
33	Madandoust et al. (2011)	Lightweight concrete	EPS	Coarse aggregate, 10–30% total volume
34	Galvão et al. (2011)	Concrete	PET and LDPE	Fine aggregate, 0.5–7.5% by volume
35	Ramadevi and Manju (2012)	Concrete	PET	Fine aggregate, 0.5–6% by volume
36	Ferreira et al. (2012)	Concrete	PET	Pc: coarse and fine aggregate, 7.5% by volume Pp and Pf: fine aggregate, 7.5% and 15% by volume
37	Xu et al. (2012)	Lightweight concrete	EPS	Coarse aggregate, 15–25% total vol
38	Wang and Meyer (2012)	Concrete	High impact polystyrene (HIPS)	Fine aggregate, 10%, 20% and 50% by volume
39	Rai et al. (2012)	Concrete	Not mentioned	Fine aggregate, 5%, 10% and 15% by volume
40	Silva et al. (2013)	Concrete	PET	Pc: coarse and fine aggregate, 7.5% by volume Pp and Pf: fine aggregate, 7.5% and 15% by volume
41	Herki et al. (2013)	Lightweight concrete	EPS	Fine aggregate, 60% and 100% by volume
42	Ge et al. (2013)	Mortar	PET	Sand: PET = 1:1, 2:1, 3:1 and 4:1 by volume
43	Juki et al. (2013)	Concrete	PET	Fine aggregate, 25%, 50% and 75% by volume
44	Saikia and de Brito (2013)	Concrete	PET	Pc: coarse and fine aggregate, 5%, 10% and 15% by volume Pp and Pf: fine aggregate, 5%, 10% and 15% by volume
45	Chaudhary et al. (2014)	Concrete	LDPE	Fine aggregate, 0.4–1% total weight
46	Ferrándiz-Mas et al. (2014)	Lightweight mortar	EPS	Fine aggregate, 60% by volume
47	Saikia and de Brito (2014)	Concrete	PET	Pc: coarse and fine aggregate, 5%, 10% and 15% by volume Pp and Pf: fine aggregate, 5%, 10% and 15% by volume
48	Akçaözoğlu and Ulu (2014)	Geo-polymer concrete	PET	Unground slag aggregate 20–100% by volume

Classification: coarse aggregate > 3 mm; fine aggregate < 3 mm.
Pc: large irregular flaky PET plastic.
Pf: small irregular flaky PET plastic.
Pp: regular cylindrical granules.

CA caused almost a linear reduction in the unit weight of concrete. For 70% substitution level of waste EPS, the unit weight reduced by up to 31%. Lima et al. (2010) reported that at 50% substitution level of waste ethylene vinyl acetate (EVA) CA, the fresh wet, air-dried, oven-dried, and hardened densities of concrete all reduced by approximately 26% of the value for the conventional concrete.

3.1.2.2. Effect of PF. Owing to the small volume fraction of the plastic fiber added in the concrete, there is no significant reduction in the density of plastic FRC as compared to the density of conventional concrete (de Oliveira and Castro-Gomes, 2011; Han et al., 2005; Karahan and Atiş, 2011; Kayali et al., 1999; Richardson, 2006; Yao et al., 2003).

Table 9
Type and content of plastic fibers used in previous studies.

No.	References	Types of composite	Type of plastic	Dosage in concrete
49	Wang et al. (1994)	Concrete	PP and nylon fiber	1–2% by volume
50	Sanjuan and Moragues (1997)	Mortar	PP fiber	0.1–0.27% by volume
51	Toutanji et al. (1998)	Concrete	PP fiber	0.1–0.5% by volume
52	Kayali et al. (1999)	Lightweight concrete	PP fiber	0.28–1% by volume
53	Mesbah and Buyle-Bodin (1999)	Recycle aggregate mortar	PP fiber	0.1–1% by volume
54	Toutanji (1999)	Expansive-cement concrete	PP fiber	0.1–0.5% by volume
55	Wang et al. (2000)	Concrete	PP and nylon fiber	0.07–1.4% by volume
56	Yao et al. (2003)	Concrete	PP fiber	0.5% by volume
57	Kayali et al. (2003)	Lightweight concrete	PP fiber	0.28–1% by volume
58	Silva et al. (2005)	Mortar	PET fiber	0.4% and 0.8% by volume
59	Martínez-Barrera et al. (2005)	Concrete	PP fiber	1.5%, 2.0% and 2.5% by volume
60	Han et al. (2005)	High performance concrete	PP fiber	0.05% and 0.1% by volume
61	Song et al. (2005)	Concrete	PP and nylon fiber	0.6 kg/m^3
62	Richardson (2006)	Concrete	PP fiber	Medium: 0.45–1.8 kg/m^3 High: 6–12 kg/m^3
63	Martínez-Barrera et al. (2006)	Concrete	Nylon fiber	1.5%, 2.0% and 2.5% by volume
64	Sivakumar and Santhanam (2007)	Concrete	PP fiber	4.5 kg/m^3
65	Ochi et al. (2007)	Concrete	PET fiber	0.3–1.5% by volume
66	Suji et al. (2007)	Concrete	PP fiber	0.1–0.3% by volume
67	Wongtanakitcharoen and Naaman (2007)	Concrete	pp and PVA fiber	0.1–0.4% by volume
68	Hsie et al. (2008)	Concrete	PP fiber	Staple fibers 0.6 kg/m^3 with monofilament fibers 3–9 kg/m^3
69	Meddah and Bencheikh (2009)	Concrete	PP fiber	0.5–1.0% by volume
70	Khadakbhavi et al. (2010)	Concrete	HDPE fiber	0.6% by volume
71	Kim et al. (2010)	Concrete	PET and PP fiber	0.5–1.0% by volume
72	Nili and Afroughsabet (2010)	Concrete	PP fiber	0.2–0.5% by volume
73	Fraternali et al. (2011)	Concrete	PET and PP fiber	1% by volume
74	Martínez-Barrera et al. (2011)	Concrete	PP fiber	1.0%, 1.5% and 2.0% by volume
75	de Oliveira and Castro-Gomes (2011)	Mortar	PET fiber	0.5–1.5% by volume
76	Karahan and Atiş (2011)	Concrete	PP fiber	0.05–0.2% by volume
77	Mazaheripour et al. (2011)	Lightweight concrete	PP fiber	0.1–0.3% by volume
78	Bagherzadeh et al. (2011)	Concrete	PP fiber	F1, F2: 0.1% by volume F3, F4: 0.3% by volume
79	Pelisser et al. (2012)	Concrete	PET fiber	0.05–0.3% by volume
80	Kakooei et al. (2012)	Concrete	PP fiber	0.5 kg/m^3, 1.5 kg/m^3 and 2 kg/m^3
81	Nibudey et al. (2013)	Concrete	PET fiber	0.5–3% by weight of cement
82	López-Buendía et al. (2013)	Concrete	PP fiber	1% by volume
83	Fraternali et al. (2014)	Concrete	PET fiber	1% by volume

3.1.3. Air content

Few studies have focused on the air content of fresh concrete containing waste PAs. Some of these studies indicated that the incorporation of plastic as an aggregate increased the air content of the resulting concrete; this was because plastic and natural aggregates did not combine mix sufficiently in the concrete matrix, resulting an increasing in porosity of PA concrete, and therefore, the air content of PA concrete increased (Ravindrarajah, 1999; Tang et al., 2008). Ravindrarajah (1999) confirmed that when the PS CA substitution level increased up to 30%, the entrapped air content of the concrete gradually increased to 7 times that of the conventional concrete group. Tang et al. (2008) also reported that the air content increased significantly and almost linearly with the increase in the PS CA content of the mix. However, Choi et al. (2009) reported a reduction in the air content of concrete with increasing WPLA (FA) content. Furthermore, the studies on plastic FRC indicated that PF had no remarkable influence on the air content of concrete (Han et al., 2005; Richardson, 2006; Toutanji, 1999).

3.2. Mechanical properties of concrete containing plastic aggregates and fibers

3.2.1. Compressive strength

3.2.1.1. Effect of PA. The compressive strength of PA concrete depends on many parameters such as the *w/c*, R_{PA}, and the types and shapes of waste plastic. Figs. 8 and 9 show the results of the existing studies (Akçaözoğlu et al., 2010; Akçaözoğlu and Ulu, 2014; Albano et al., 2009; Asokan et al., 2009, 2010; Babu et al., 2006, 2005; Babu and Babu, 2003; Batayneh et al., 2007; Chen and Liu, 2004; Choi et al., 2005, 2009; Elzafraney et al., 2005; Ferrándiz-Mas et al., 2014; Ferreira et al., 2012; Fraj et al., 2010; Frigione, 2010; Galvão et al., 2011; Ge et al., 2013; Haghi et al., 2006; Herki et al., 2013; Ismail and Al-Hashmi, 2008; Juki et al., 2013; Kan and Demirboğa, 2009b; Kou et al., 2009; Kumar and Prakash, 2006; Lai et al., 1996; Lima et al., 2010; Malloy et al., 2001; Marzouk et al., 2007; Naik et al., 1996; Panyakapo and Panyakapo, 2008; Rai et al., 2012; Ravindrarajah, 1999; Ravindrarajah and Tuck, 1994; Remadnia et al., 2009; Sabaa and Ravindrarajah, 1997; Saikia and de Brito, 2013, 2014; Silva et al., 2013; Tang et al., 2008; Wang and Meyer, 2012; Xu et al., 2012) on the effect of R_{PA} on the compressive strength; the sub categories of concrete containing plastic CA (Fig. 8) and FA (Fig. 9) are also shown. The figures show that the compressive strength of PA concrete with the same *w/c* decreases with increasing R_{PA}. The figures also indicate that the compressive strength of concrete containing non-uniformly shaped PA decreases more significantly than that of concrete containing uniformly shaped PA. Furthermore, the use of PAs with a low elastic modulus (i.e. EPA and EVA aggregates) results in a more significant reduction in the compressive strength of the concrete than those result from the use of PAs with a high elastic modulus (i.e. PET aggregates). Previous studies attributed the relatively low compressive strength of concrete containing PAs to the elastic modulus of PAs being lower than that of natural CA or FA; the low bond strength between the surface of the PA and the cement paste; the restrained cement hydration reaction near the surface of PA resulting from the hydrophobic nature of PA; high air content and porosity of PA concrete; and the possible deterioration of PET aggregates exposed to an alkaline environment (i.e. the concrete pore fluid).

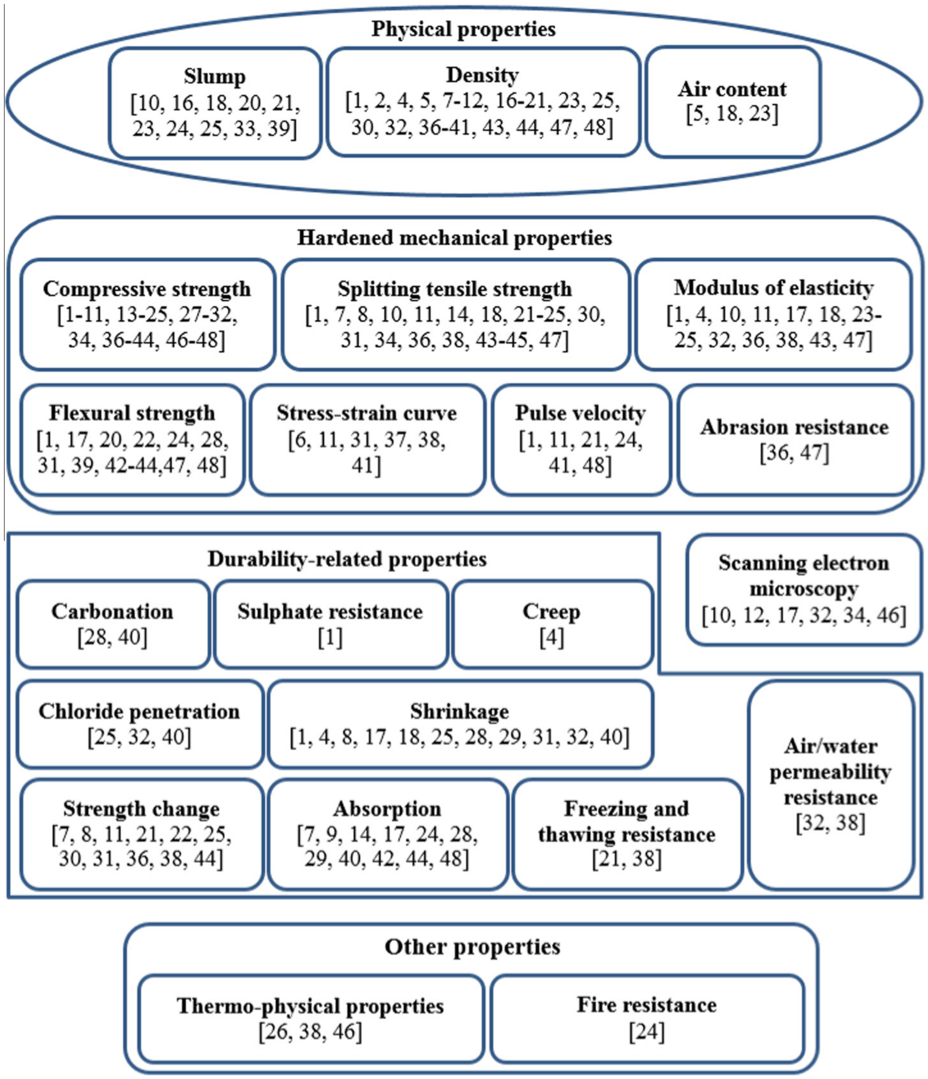

Fig. 2. Studies reported in literature on properties of concretes containing plastic aggregates.

Kou et al. (2009) reported the compressive strength of lightweight concrete containing up to 45% recycled PVC FA. The results showed that at 5% substitution level, the compressive strength reduced by 9%, and then the reduction gradually increased to 47% when the substitution level reached 45%. Wang and Meyer (2012) reported the compressive strengths of mortar prepared with 10, 20, and 50% fine high-impact polystyrene (HIPS) FA; the compressive strength decreased almost linearly with the increase in the substitution level, and the reduction in the strengths of the mortar with 10, 20, and 50% HIPS FA were 12%, 22%, and 49%, respectively, at a curing age of 28 days. In addition, Saikia and de Brito (2014) confirmed that different shape and size distribution of waste PET aggregates resulted in different compressive strengths of concrete with the same substitution levels of PAs. Fraj et al. (2010) reported the compressive strength of concrete with 100% polyurethane (PUR) foam CA. PUR foam CA used in some of the concrete samples were immersed in water for 24 h before mixing. Reductions of 78% and 57% were observed in the compressive strength with and without the immersing procedure, respectively.

3.2.1.2. Effect of PF. Fig. 10 shows the different observations obtained from the existing studies (Bagherzadeh et al., 2011; de Oliveira and Castro-Gomes, 2011; Fraternali et al., 2011, 2014; Han et al., 2005; Hsie et al., 2008; Kakooei et al., 2012; Karahan and Atiş, 2011; Kayali et al., 1999, 2003; Khadakbhavi et al., 2010; Kim et al., 2010; Meddah and Bencheikh, 2009; Nibudey et al., 2013; Nili and Afroughsabet, 2010; Ochi et al., 2007; Pelisser et al., 2012; Ramadevi and Manju, 2012; Song et al., 2005; Suji et al., 2007; Toutanji, 1999; Wang et al., 2000, 1994; Yao et al., 2003) on the effect of C_{PF} on the compressive strength of FRC. Some researchers reported that the compressive strength of concrete improved upon addition of plastic fiber (de Oliveira and Castro-Gomes, 2011; Fraternali et al., 2011; Han et al., 2005; Hsie et al., 2008; Kakooei et al., 2012; Khadakbhavi et al., 2010; Nili and Afroughsabet, 2010; Ochi et al., 2007; Song et al., 2005; Suji et al., 2007; Toutanji, 1999; Yao et al., 2003). Furthermore, Fig. 10 also indicates that the use of recycled plastic fibers with a high ultimate tensile strength (i.e. recycled PP fibers) results in a more significant improvement in the compressive strength of the concrete than that when fibers with a low ultimate tensile strength (i.e. recycled PET fibers) are used. Han et al. (2005) reported that for PP fiber volume fractions of 0.05% and 0.10%, the compressive strength ratio of concrete increased slightly by 1–3%. Song et al. (2005) reported that at a fiber content of 0.6 kg/m^3, the compressive strength of the nylon FRC improved the most by 12.4%, followed by the PP-FRC, which improved by 5.8%. Hsie et al. (2008)

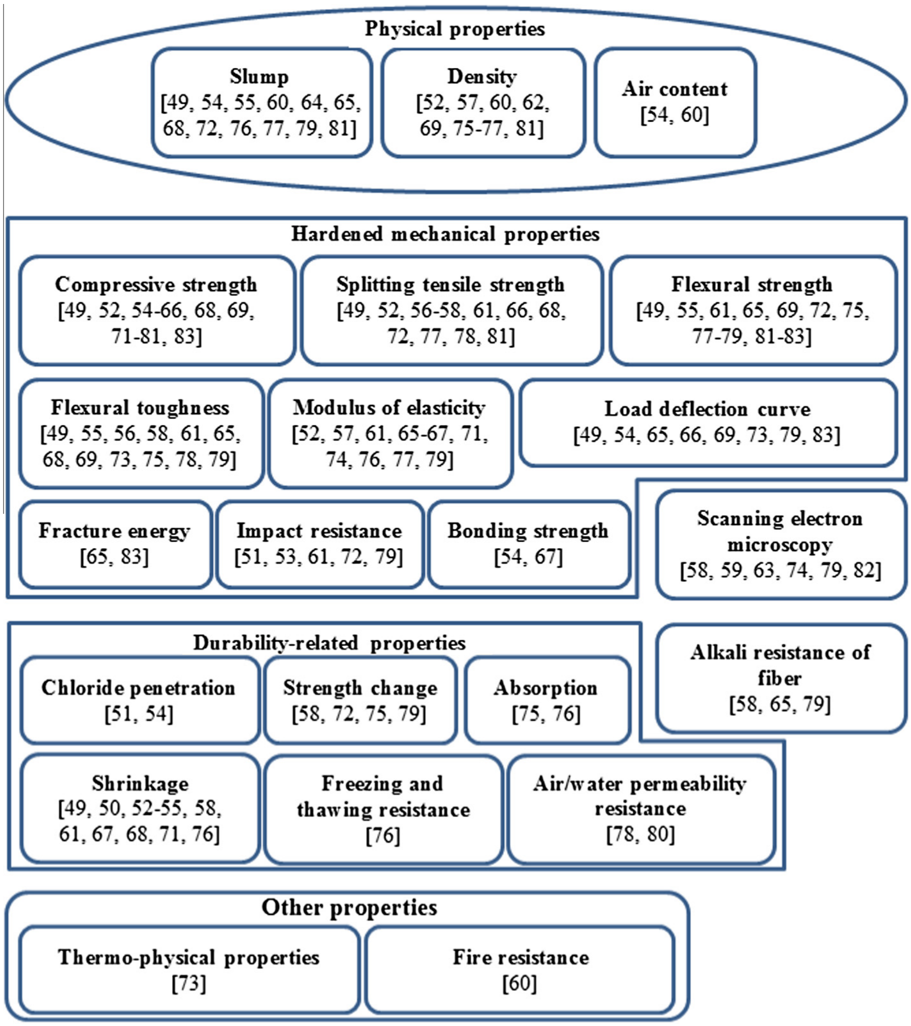

Fig. 3. Studies reported in literature on properties of concrete containing plastic fibers.

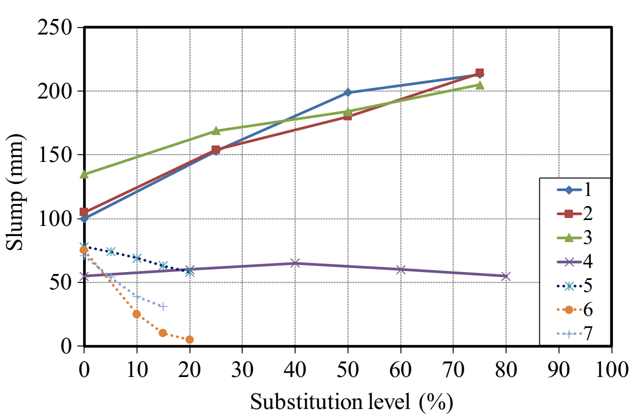

Fig. 4. Variation of slump of concrete with substitution level of plastic aggregates: (1), (2), (3): fine aggregates (Choi et al., 2005); (4): coarse aggregates (Tang et al., 2008); (5): fine aggregates (Batayneh et al., 2007); (6): fine aggregates (Ismail and AL-Hashmi, 2008); and (7): fine aggregates (Rai et al., 2012) [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates].

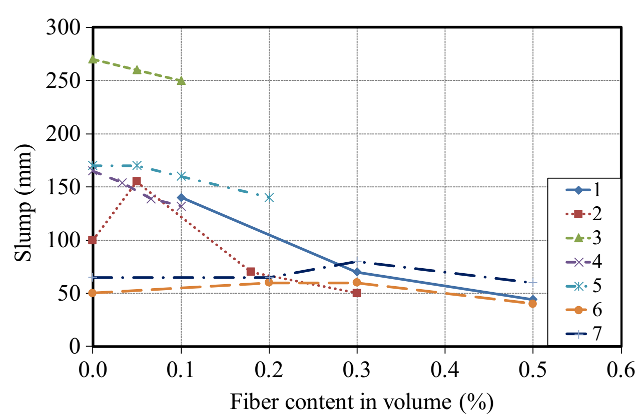

Fig. 5. Variation of slump of concrete with content of plastic fibers: (1): PP fibers (Toutanji, 1999); (2): PET fibers (Pelisser et al., 2012); (3): PP fibers (Han et al., 2005); (4): PP fibers (Hsie et al., 2008); (5): PP fibers (Karahan and Atiş, 2011); and (6), (7): PP fibers (Nili and Afroughsabet, 2010).

reported that with monofilament fiber contents of 3, 6, and 9 kg/m^3, the compressive strength of the PP-FRC improved by 4.65%, 9.12%, and 13.24%, respectively, over the conventional concrete. Moreover, when an additional 0.6 kg/m^3 staple PP fiber was added to the samples with the monofilament fiber, the compressive strength of the concrete increased by 17.31% over the conventional concrete. However, some studies also reported reductions in the compressive strength of concrete containing PF (Fraternali et al., 2014; Kim et al., 2010; Meddah and Bencheikh, 2009; Pelisser et al., 2012).

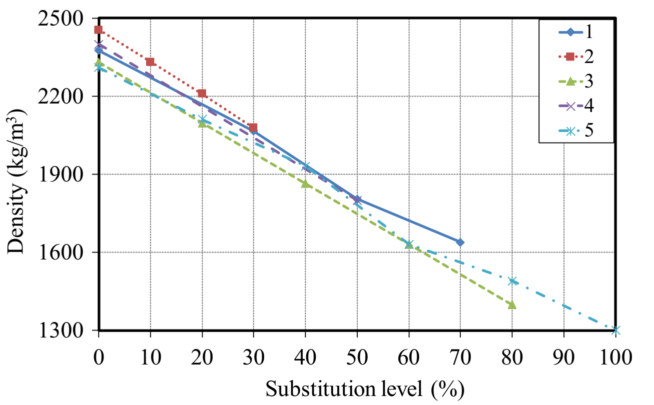

Fig. 6. Variation of density of concrete with substitution level of plastic coarse aggregates: (1): (Sabaa and Ravindrarajah, 1997); (2): (Ravindrarajah, 1999); (3): (Tang et al., 2008); (4): (Lima et al., 2010); and (5): geopolymer concrete (Akçaözoglu and Ulu, 2014).

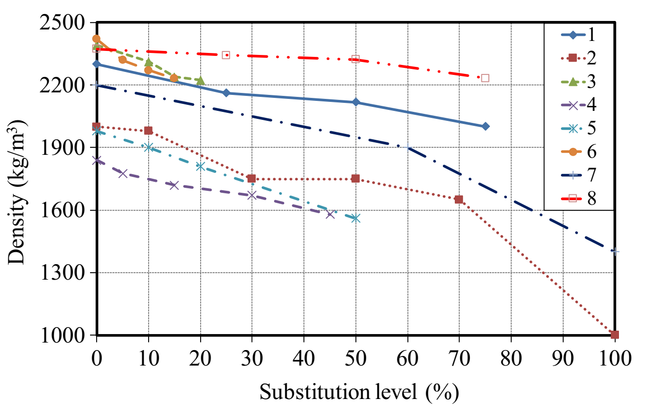

Fig. 7. Variation of density of concrete with substitution level of plastic fine aggregates: (1): (Choi et al., 2005); (2): mortar (Marzouk et al., 2007); (3): (Ismail and AL-Hashmi, 2008); (4): lightweight concrete (Kou et al., 2009); (5): mortar (Wang and Meyer, 2012); (6): (Rai et al., 2012); (7): lightweight concrete (Herki et al., 2013); and (8): (Juki et al., 2013).

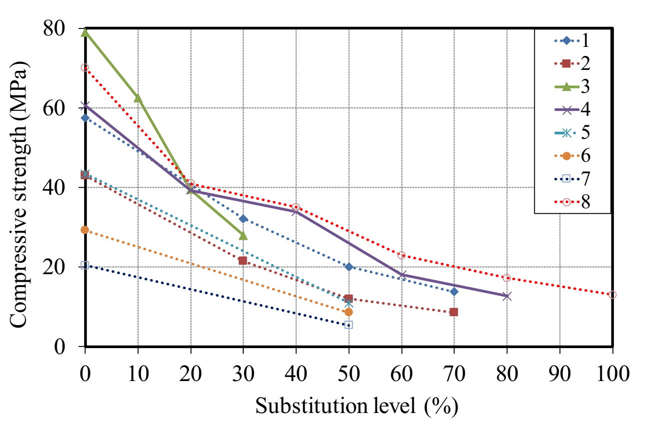

Fig. 8. Variation of 28-day compressive strength of concrete with substitution level of plastic coarse aggregates: (1), (2): EPS (Sabaa and Ravindrarajah, 1997); (3): (Ravindrarajah, 1999); EPS (4): EPS (Tang et al., 2008); (5), (6), (7): EVA (Lima et al., 2010); and (8): PET (Akçaözoğlu and Ulu, 2014); [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates].

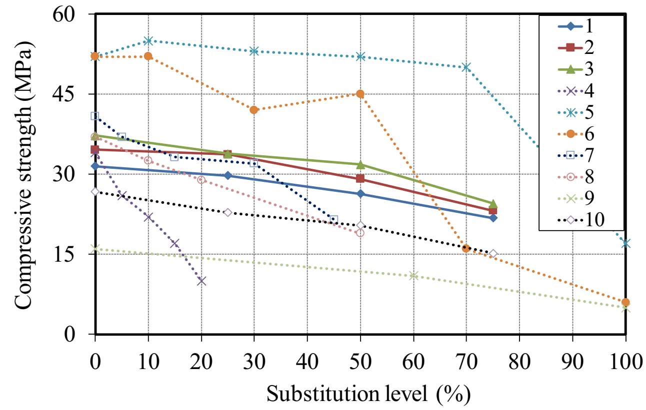

Fig. 9. Variation of 28-day compressive strength of concrete with substitution level of plastic fine aggregates: (1), (2), (3): WPLA (Choi et al., 2005); (4): mixed plastic (Batayneh et al., 2007); (5), (6): PET aggregate mortar (Marzouk et al., 2007); (7): PVC (Kou et al., 2009); (8): HIPS aggregate mortar (Wang and Meyer, 2012); (9): EPS (Herki et al., 2013); and (10): PET (Juki et al., 2013); [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates].

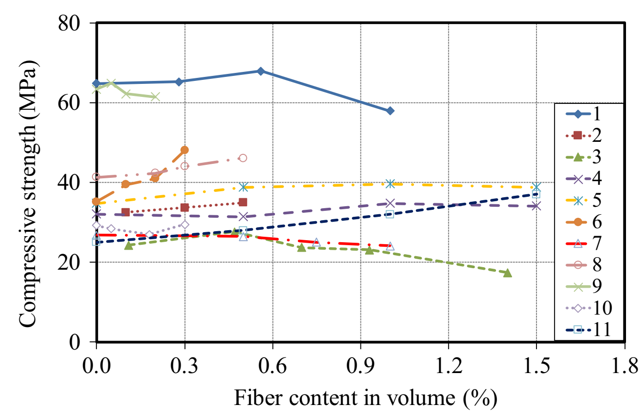

Fig. 10. Variation of 28-day compressive of concrete with content of plastic fibers: (1): PP fibers (Kayali et al., 1999); (2): PP fibers (Toutanji, 1999); (3): PP and nylon fibers (Wang et al., 2000); (4), (5): PET fibers (Ochi et al., 2007); (6): PP fibers (Suji et al., 2007); (7): PET fibers (Kim et al., 2010); (8): PP fibers (Nili and Afroughsabet, 2010); (9): PP fibers (Karahan and Atiş, 2011); (10): PET fibers (Pelisser et al., 2012); and (11): PP fibers (Kakooei et al., 2012).

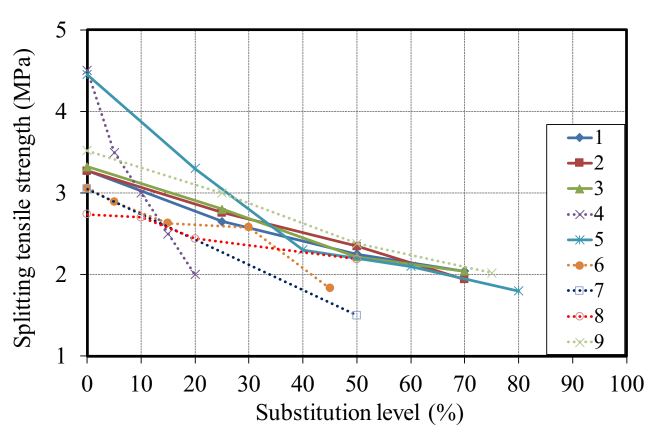

Fig. 11. Variation of 28-day splitting tensile strength of concrete with substitution level of plastic aggregates: (1), (2), (3): WPLA fine aggregates (Choi et al., 2005); (4): mixed plastic fine aggregates (Batayneh et al., 2007); (5): EPS coarse aggregates (Tang et al., 2008); (6): PVC fine aggregates (Kou et al., 2009); (7): EVA coarse aggregates (Lima et al., 2010); (8): HIPS fine aggregates (mortar) (Wang and Meyer, 2012); and (9): PET fine aggregates (Juki et al., 2013); [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates].

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Table 10
Expression proposed in the literature to predict mechanical properties of concrete containing plastic aggregates.

References	Splitting tensile strength (f_{st})	Modulus of elasticity (E_c)
Ravindrarajah and Tuck (1994)		$E_c = 1.146D^{1.1}f_c'^{0.5}$
Babu et al. (2005)	$f_{st} = 0.358f_c'^{0.675}$	
Choi et al. (2009)	$f_{st} = 0.23f_c'^{(1/3)}$	

f_c', f_{st} and E_c are in MPa, D is the air-dried density of concrete in kg/m^3.

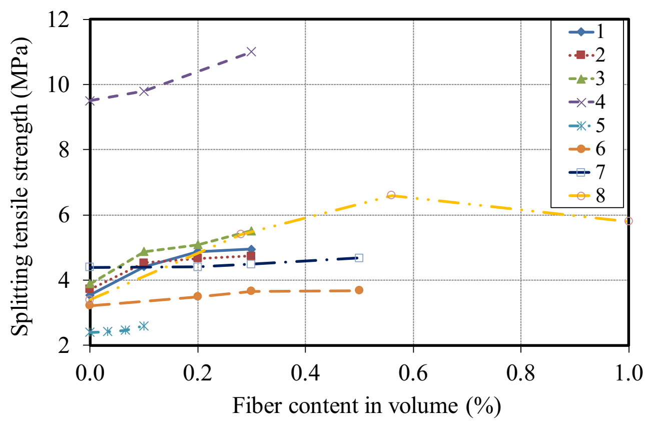


Fig. 12. Variation of 28-day splitting tensile strength of concrete with content of plastic fibers: (1), (2), (3): PP fibers (Suji et al., 2007); (4): PP fibers (Bagherzadeh et al., 2011); (5): PP fibers (Hsie et al., 2008); (6), (7): PP fibers (Nili and Afroughsabet, 2010); and (8): PP fibers (Kayali et al., 1999).

Pelisser et al. (2012) reported that with a PET fiber volume fraction of up to 0.30% in concrete, compressive strength reduced by up to 10%. Fraternali et al. (2014) reported that the compressive strength of concrete containing 13.4 kg/m^3 PET fiber reduced by up to 8.2% compared to the strength of the conventional concrete. Furthermore, several groups also observed that the compressive strength improved only when the concrete had small fiber content. When the fiber content increased, the compressive strength of FRC degraded (Bagherzadeh et al., 2011; Karahan and Atiş, 2011; Kayali et al., 1999, 2003; Nibudey et al., 2013; Ramadevi and Manju, 2012; Wang et al., 2000, 1994). Ochi et al. (2007) reported that compressive strength of concrete increased with increasing PET fiber volume fraction, peaking at 1.0% content—at this content, the compressive strength increased by approximately10%. Thereafter, as the fiber volume fraction increased up to 1.5%, the compressive strength decreased.

The aspect ratio and geometry of fibers also affect the compressive strength of plastic FRC. Khadakbhavi et al. (2010) reported the influence of the aspect ratios of HDPE fibers on the compressive strength of concrete containing 0.6% fiber by volume. The authors observed that fibers with aspect ratios (defined as the ratio of the fiber length to diameter) of 20, 40, 60, and 80 increased the compressive strength by 5%, 8%, 14%, and 3%, respectively, whereas at an aspect ratio of 100, the compressive strength decreased by 6%. Fraternali et al. (2011) investigated the increase in the compressive strength of concrete containing PET and PP fibers with straight, crimped, and embossed geometry with a volume fraction of 1%. The results showed that straight fiber increased the compressive strength mostly by 35.1%. Additionally, Martínez-Barrera et al. (2005, 2006, 2011) reported that modifying the properties of PP and nylon fibers by gamma irradiation can improve the stress transfer between the fibers and cement matrix, so that the compressive strength of FRC can be significantly improved. The results

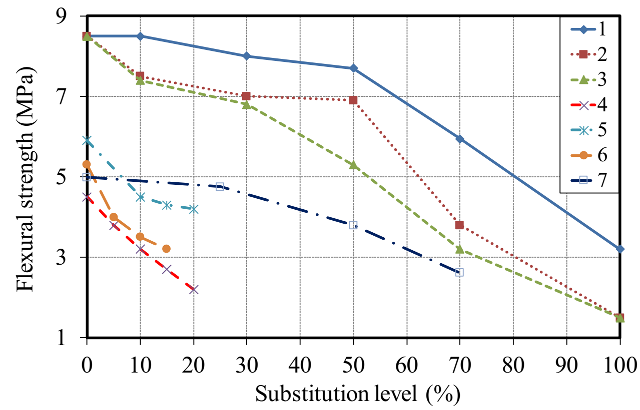


Fig. 13. Variation of 28-day flexural strength of concrete with substitution level of plastic aggregates: (1), (2), (3): PET fine aggregates (mortar) (Marzouk et al., 2007); (4): mixed plastic fine aggregates (Batayneh et al., 2007); (5): mixed plastic (80% PET) fine aggregates (Ismail and AL-Hashmi, 2008); (6): mixed plastic fine aggregates (Rai et al., 2012); and (7): PET fine aggregates (Juki et al., 2013).

showed that highest values of compressive strength (101 MPa) were obtained for irradiated-fibers (10 kGy) and at 1.5% in volume of the fiber; the corresponding strength of conventional concrete was 35 MPa (Martínez-Barrera et al., 2005).

3.2.2. Splitting tensile strength

3.2.2.1. Effect of PA. As it is the case for the compressive strength, the splitting tensile strength of PA concrete is generally less than that of conventional concrete with the same *w/c*. Fig. 11 shows the results obtained from the existing studies (Albano et al., 2009; Asokan et al., 2010; Babu et al., 2006, 2005; Babu and Babu, 2003; Chaudhary et al., 2014; Chen and Liu, 2004; Choi et al., 2005, 2009; Ferreira et al., 2012; Frigione, 2010; Galvão et al., 2011; Juki et al., 2013; Kan and Demirboğa, 2009b; Kou et al., 2009; Lima et al., 2010; Ravindrarajah and Tuck, 1994; Saikia and de Brito, 2013, 2014; Tang et al., 2008; Wang and Meyer, 2012) on the effect of R_{PA} on the splitting tensile strength. The figure shows that the splitting tensile strength of PA concrete decreases with increasing R_{PA}. The figure also indicates that more significant reductions in the splitting tensile strength occur in the concrete containing non-uniformly shaped PAs than that containing uniformly shaped PAs. Furthermore, the splitting tensile

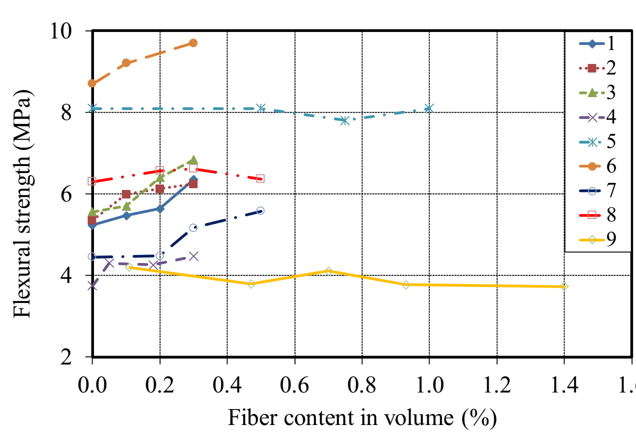


Fig. 14. Variation of 28-day flexural strength of concrete with content of plastic fibers: (1), (2), (3): PP fibers (Suji et al., 2007); (4): PET fibers (Pelisser et al., 2012); (5): PP fibers (Meddah and Bencheikh, 2009); (6): PP fibers (Bagherzadeh et al., 2011); (7), (8): PP fibers (Nili and Afroughsabet, 2010); and (9): PP and nylon fibers (Wang et al., 2000).

strength of PA concrete decreases with a reduction in the elastic modulus of low modulus PAs. Choi et al. (2009) suggested that the test value of the splitting tensile strength of concrete containing WPLA (FA) fitted the expression for lightweight concrete, as shown in Table 10. Kou et al. (2009) observed that the splitting tensile strength of lightweight concrete containing recycled PVC FA had a linear relationship with its compressive strength. Babu and Babu (2003) reported that the failure mode of the splitting tensile test of lightweight concrete containing EPS CA did not exhibit the typical brittle failure normally exhibited by conventional concrete, which was more compressible and the specimens did not separate in two. Babu et al. (2005) also derived an expression, presented in Table 10, for the relationship between the 28-day compressive strength and the splitting tensile strength of concrete containing EPS CA and FA. Tang et al. (2008) also reported that the ratio f_{st}/f'_c increased as the EPS CA content increased and that the concrete specimens containing EPS CA did not exhibit brittle splitting failure.

3.2.2.2. Effect of PF. Fig. 12 shows the different observations obtained from the existing studies (Bagherzadeh et al., 2011; Hsie et al., 2008; Kayali et al., 1999, 2003; Nibudey et al., 2013; Nili and Afroughsabet, 2010; Ramadevi and Manju, 2012; Song et al., 2005; Suji et al., 2007; Wang et al., 1994; Yao et al., 2003) on the effect of C_{PF} on the splitting tensile strength of FRC. Most of the studies reported that the splitting tensile strength of concrete increased upon the addition of PF (Bagherzadeh et al., 2011; Hsie et al., 2008; Nili and Afroughsabet, 2010; Song et al., 2005; Suji et al., 2007). Fig. 12 also shows that the observed improvement increases as a function of the tensile strength of plastic fibers. Song et al. (2005) stated that once splitting occurred and continued, the fibers bridging across the split portions of the matrix acted through the stress transferred from the matrix to the fibers, and thus, gradually supported the entire load. The stress transfer improved the tensile strain capacity of the two FRCs, and therefore, the splitting tensile strength of the reinforced concretes was higher than that of the unreinforced control counterpart. However, Yao et al. (2003) reported a 5% reduction in splitting tensile strength when a 0.5% volume fraction of PP fiber was added to the conventional concrete. Furthermore, several researchers also observed that the splitting tensile strength improved only when the concrete had small fiber content. When the fiber content increased, the splitting tensile strength of FRC degraded (Kayali et al., 1999, 2003; Nibudey et al., 2013; Ramadevi and Manju, 2012; Wang et al., 1994). Kayali et al. (1999) observed that the tensile strength increased when the PP fiber content increased up to 0.56%, and then decreased slightly at a content of 1.0%. Nibudey et al. (2013) observed that the splitting tensile strength of concrete containing PET fiber increased by 18.6% at 1% fiber level, and then reduced by 19% at 3% fiber content. Khadakbhavi et al. (2010) also reported the influence of the aspect ratio of HDPE fibers on the splitting tensile strength of FRC. The authors observed that for fibers with aspect ratios of 20, 40, 60, 80, and 100, the splitting tensile strength increased by 10%, 23%, 37%, 22%, and 5%, respectively.

3.2.3. Flexural strength

3.2.3.1. Effect of PA. Fig. 13 shows the results obtained from the existing studies (Akçaözoğlu et al., 2010; Akçaözoğlu and Ulu, 2014; Albano et al., 2009; Asokan et al., 2009; Frigione, 2010; Ge et al., 2013; Ismail and Al-Hashmi, 2008; Juki et al., 2013; Marzouk et al., 2007; Rai et al., 2012; Saikia and de Brito, 2013, 2014) on the effect of R_{PA} on the flexural strength. As it is the case for the compressive strength, the flexural strength of PA concrete is generally less than that of conventional concrete with the same *w/c*. Juki et al. (2013) reported on the flexural strength of the concrete containing up to 75% PET FA. The results indicated that the flexural strength only decreased by 5% at 25% substitution level, and then decreased by 24% and 48% when the content of PET fine aggregates increased to 50% and 75% levels, respectively. Akçaözoğlu and Ulu (2014) also observed an almost linear decrease in the flexural strength with an increase in the PET FA substitution level from 0 to 100% in alkali activated slag mortar. However, Rai et al. (2012) observed a very slight reduction in flexural strength when the substitution level of plastic FA increased from 0 to 15%. Moreover, Saikia and de Brito (2013) concluded that the effect of plastic CA and FA content on the flexural strength was less than that on the compressive strength.

3.2.3.2. Effect of PF. Fig. 14 shows the representative results obtained from the existing studies (Bagherzadeh et al., 2011; de Oliveira and Castro-Gomes, 2011; López-Buendía et al., 2013; Mazaheripour et al., 2011; Nibudey et al., 2013; Nili and Afroughsabet, 2010; Ochi et al., 2007; Pelisser et al., 2012; Ramadevi and Manju, 2012; Suji et al., 2007; Toutanji, 1999; Wang et al., 2000, 1994) on the effect of C_{PF} on the flexural strength of FRC. Most of the studies observed that the flexural strength of concrete increased upon the addition of PF (Bagherzadeh et al., 2011; de Oliveira and Castro-Gomes, 2011; López-Buendía et al., 2013; Mazaheripour et al., 2011; Nili and Afroughsabet, 2010; Ochi et al., 2007; Pelisser et al., 2012; Ramadevi and Manju, 2012; Suji et al., 2007; Toutanji, 1999). It can also be seen in Fig. 14 that this improvement increases with an increase in the tensile strength of plastic fibers. Ochi et al. (2007) also noted that the flexural strength of concrete containing PET fibers improved by up to 36.1% when the fiber content was increased gradually up to 1.5%. Suji et al. (2007) reported that the flexural strength of concrete mixes containing 0.3% PP fiber in volume increased by 16.6–23.0% as compared to strength of the conventional concrete. On the other hand, several studies observed that the flexural strength improved only when the concrete had small fiber content, and when the fiber content increased above a certain threshold, the flexural strength degraded (Nibudey et al., 2013; Wang et al., 2000, 1994). Nibudey et al. (2013) observed that the flexural strength of concrete containing PET fiber increased by 20% at 1% fiber level, and then reduced by 16.4% at 3% fiber content. Khadakbhavi et al. (2010) confirmed that the influence of the aspect ratios of HDPE fibers on flexural strength of FRC was not as significant as that on compressive and splitting tensile strength. The authors

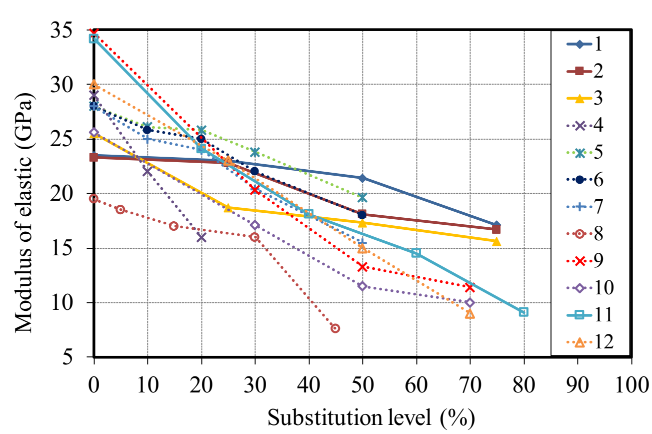


Fig. 15. Variation of 28-day elastic modulus of concrete with substitution level of plastic aggregates: (1), (2), (3): WPLA fine aggregates (Choi et al., 2005); (4): PET fine aggregates (Albano et al., 2009); (5), (6), (7): PET fine aggregates (mortar) (Marzouk et al., 2007); (8): PVC fine aggregates (Kou et al., 2009); (9), (10): EPS coarse aggregates (Sabaa and Ravindrarajah, 1997); (11): EPS coarse aggregates (Tang et al., 2008); and (12): PET fine aggregates (Juki et al., 2013); [solid lines: uniformly shaped aggregates; dotted lines: non-uniformly shaped aggregates].

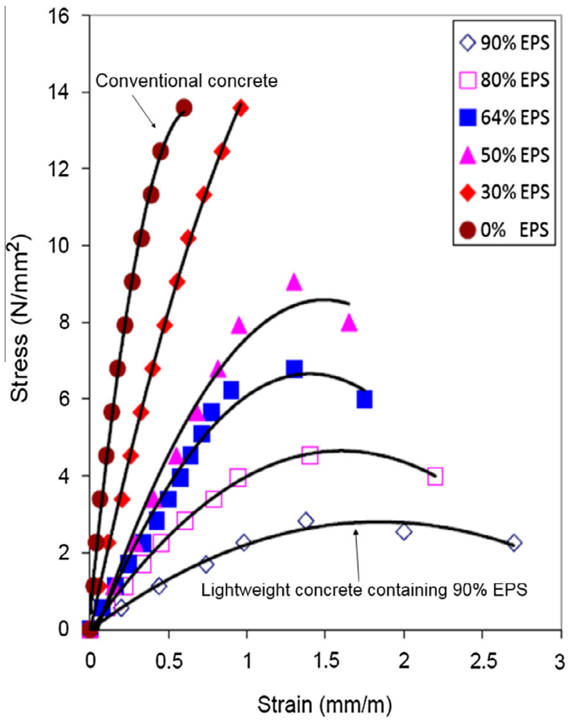


Fig. 16. Variation of stress-strain curves of EPS concretes containing 50% fly ash (Babu et al., 2005).

observed that for fibers with aspect ratios of 20, 40, 60, and 80, the flexural strength increased by 4%, 8%, 12%, and 2%, respectively, whereas at an aspect ratio of 100, the strength decreased by 3%. Meddah and Bencheikh (2009) reported the effects of fiber lengths on the flexural strength of concrete containing PP fibers. When PP fibers of lengths 50 and 60 mm were used, the flexural strength of concrete did not show any significant variation as the fiber content increased from 0 to 1.0% by volume. However, when 30-mm-long fibers were used, the flexural strength of concrete decreased as the fiber content increased; the largest reduction of 44.4%, as compared to the value for the conventional concrete, was seen in the case of the mix with 1.0% fiber volume.

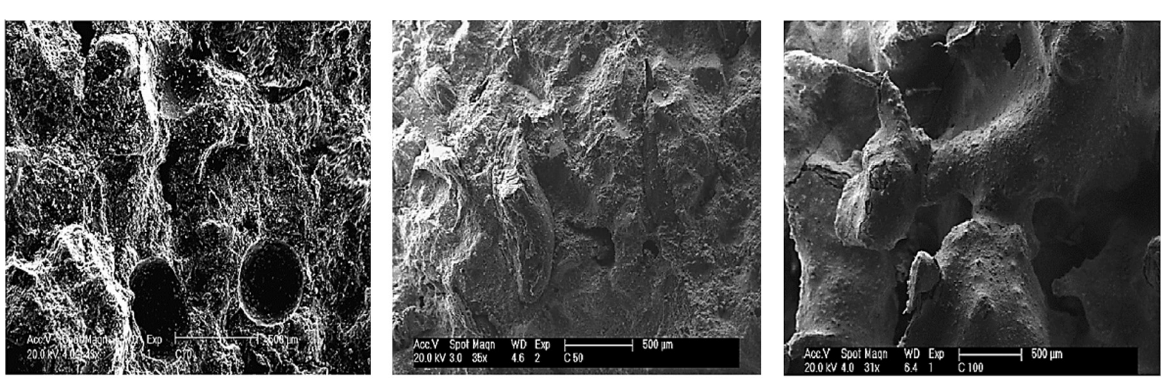
3.2.4. Elastic modulus

3.2.4.1. Effect of PA. The elastic modulus of PA concrete (E_c) depends on a large number of parameters such as *w/c*, R_{PA}, the type of waste plastic, the porosity of the aggregates, and the transition zone characteristics. Fig. 15 shows the results obtained from the existing studies (Albano et al., 2009; Babu et al., 2005; Choi et al., 2005, 2009; Ferreira et al., 2012; Fraj et al., 2010; Juki et al., 2013; Kou et al., 2009; Marzouk et al., 2007; Ravindrarajah and Tuck, 1994; Sabaa and Ravindrarajah, 1997; Saikia and de Brito, 2014; Tang et al., 2008; Wang and Meyer, 2012) on the effect of R_{PA} on E_c. As it is the case for the compressive strength, E_c of PA concrete is generally lower than that of conventional concrete with the same *w/c*. The figure also indicates that the decrease in E_c becomes more significant as the shape of PAs becomes less uniform or the elastic modulus of PAs decreases. Ravindrarajah and Tuck (1994) proposed an empirical expression, presented in Table 10, to fit the measured values for the cylinder strength and E_c of PS CA concrete. Babu et al. (2005) observed that the E_c of concrete containing EPS CA and FA increased with an increase in the cylinder strength, and this observation was in agreement with Ravindrarajah and Tuck's (1994) expression. Tang et al. (2008) also stated that E_c was significantly affected by the properties of EPS CA, cement paste matrix, and transition zone. Because of the negligible elastic modulus of PS aggregates, its increased incorporation in the mix increased the elastic incompatibility between the inclusion and the matrix, which in turn increased the stress concentration at the bond interface.

3.2.4.2. Effect of PF. The results of the existing studies show that the E_c of the plastic FRC does not differ significantly from that of conventional concrete (Karahan and Atiş, 2011; Kayali et al., 1999, 2003; Mazaheripour et al., 2011; Pelisser et al., 2012). In general, E_c is primarily affected by the elastic modulus and volume proportion of each component in concrete. Although PF usually has a lower elastic modulus than conventional concrete (Table 7), this difference only had a minor influence on E_c owing to the low PF content in FRC.

3.2.5. Stress-strain curve

3.2.5.1. Effect of PA. Frigione (2010) reported the stress-strain relationship of concrete containing 5% waste un-washed PET bottles (WPET) as a substitution for FA was similar to that of conventional concrete. Ge et al. (2013) suggested that when the sand to PET ratio increased from 3:1 to 2:1, the initial slope of the curve and the maximum stress decreased whereas the ultimate strain increased. The stress-strain curves given by Frigione (2010) and Ge et al. (2013) indicate that at higher R_{PA}, the peak compressive stress is lower, but the corresponding strain and ultimate strain of concrete are higher. In other words, at high R_{PA}, the ductility behavior will be improved, but the peak compressive stress will be less as compared to conventional concrete. Babu et al. (2005) reported the



(a) (b) (c)

Fig. 17. Field emission SEMs of various mortar containing 2 mm PET aggregates (Marzouk et al., 2007): (a) 30% (magnification: 43×); (b) 50% (magnification: 35×); and (c) 100% (magnification: 31×).

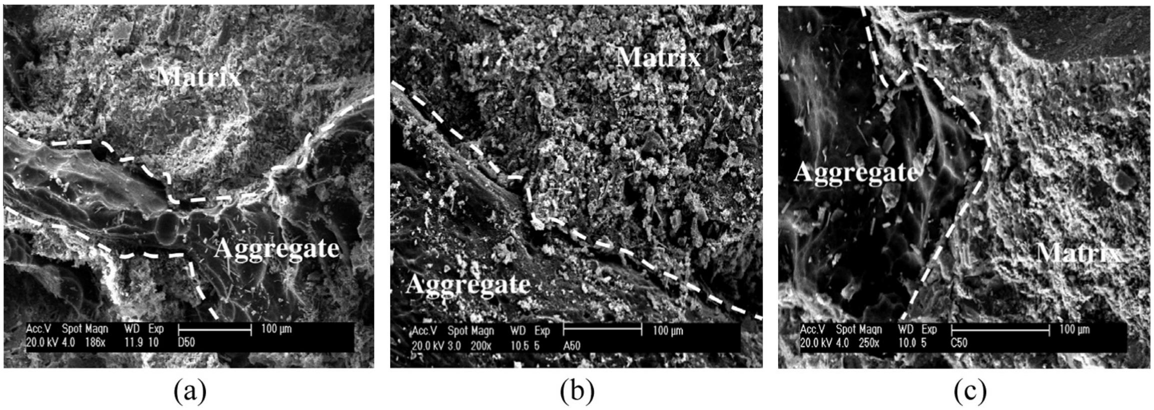


Fig. 18. Field emission SEMs of composites containing type A (5 mm), C (2 mm) and D (1 mm) aggregates (Marzouk et al., 2007): (a) Type A 50% (magnification: 200×); (b) Type C 50% (magnification: 250×); and (c) Type D 50% (magnification: 135×).

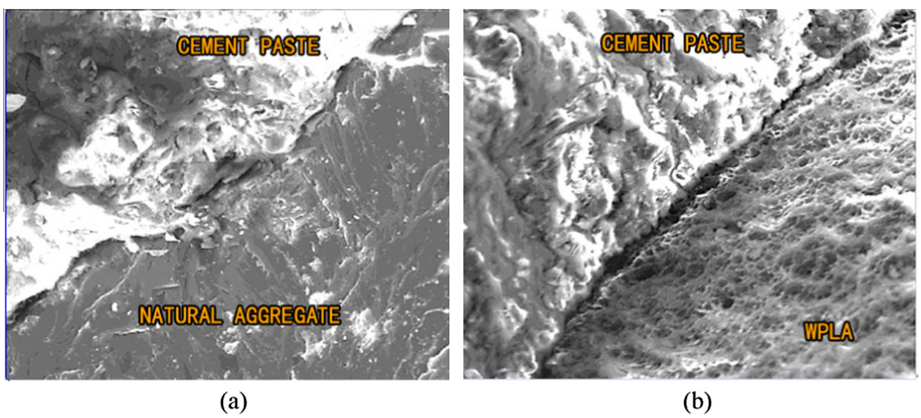


Fig. 19. Transition zone between cement paste and natural aggregate/WPLA in mortar (Choi et al., 2005): (a) natural aggregate (28 days, magnification: 700×) and (b) WPLA (28 days, magnification: 700×).

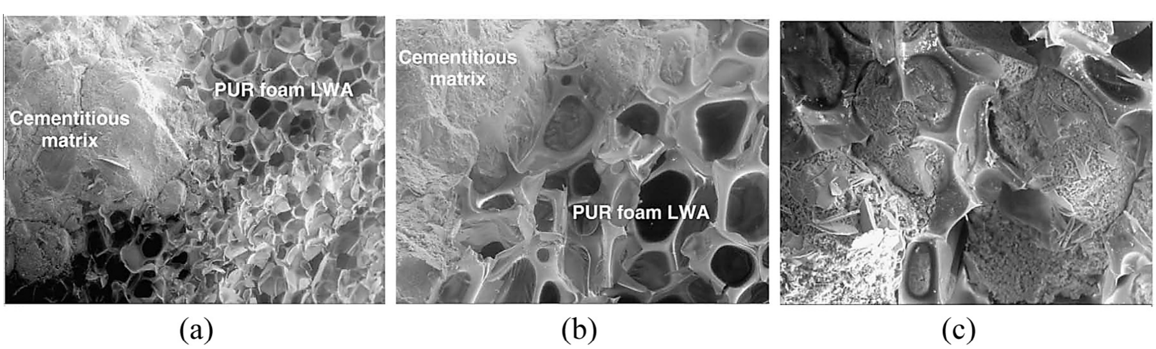


Fig. 20. Field emission SEMs of the interfacial zone between the cementitious matrix and the polyurethane foam aggregates concrete at 28 days (Fraj et al., 2010): (a) magnification: 100×; (b) magnification: 300×; and (c) magnification: 500×.

stress-strain relationship of concrete containing EPS aggregates, which are a substitution for both natural coarse and fine aggregates, and 50% fly ash in cement with slightly different *w/c*, as shown in Fig. 16; their observations agreed with those of Frigione (2010) and Ge et al. (2013). However, the observations made by Xu et al. (2012) differ from those of the above-described works in terms of the stress-strain relationship of the lightweight concrete containing EPS CA, which had the lowest substitution level of EPS and lowest *w/c* and had the highest strain at peak compressive stress with the highest ultimate stress in the entire group. Xu et al. (2012) attributed it to the lack of bonding additives or admixtures in their study; this resulted in poor interfacial bonding performance between EPS particles and cement paste in the specimens when the amount of EPS added into the concrete was increased.

3.2.6. Abrasion resistance

3.2.6.1. Effect of PA. Ferreira et al. (2012) reported that the use of plastic waste CA and FA improved the abrasion resistance of concrete. According to the authors, this behavior could be attributed to the fact that plastic waste aggregates were tougher and had higher abrasion resistance than natural aggregates. Saikia and de

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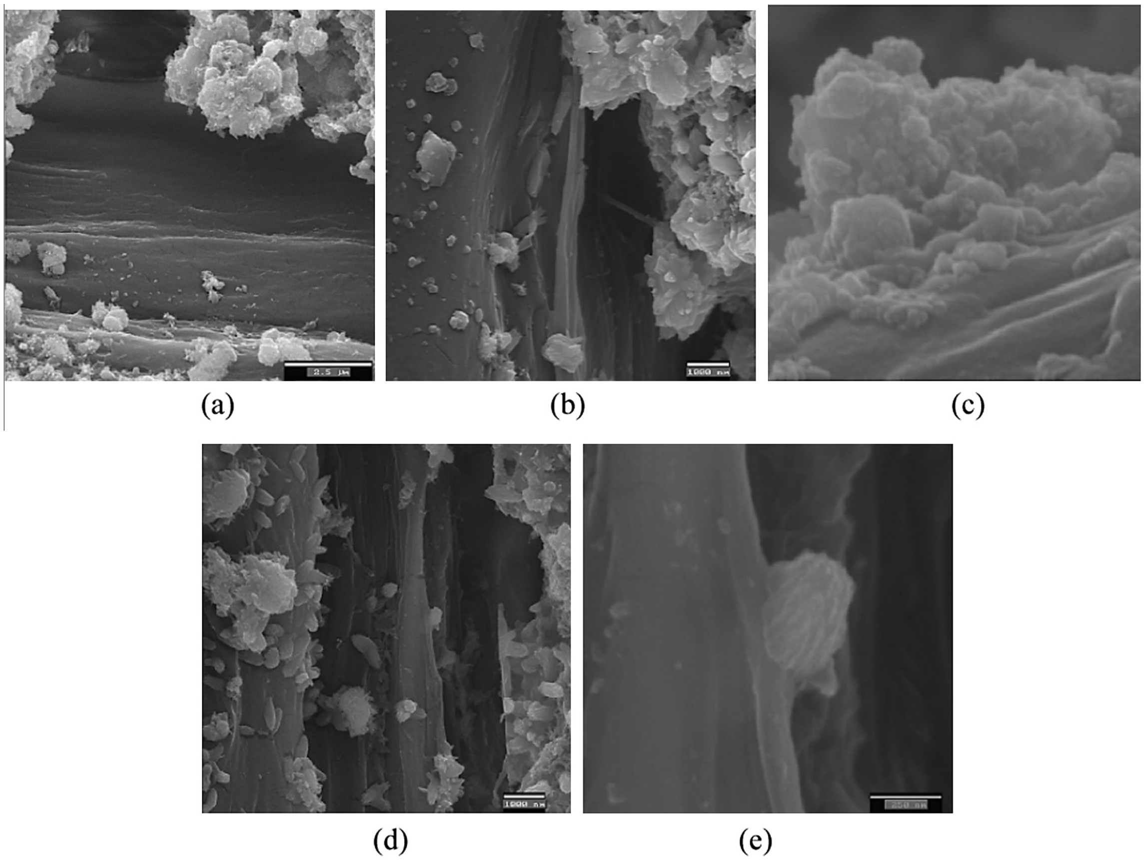

Fig. 21. Field emission SEMs of untreated and surfaced treated PP fibers in concrete matrix (López-Buendía et al., 2013): (a) untreated PP fiber; (b) treated PP fibers; (c) treated PP fiber showing cement crystal growth on the surface of fiber (portlandite morphology); (d) general view of treated PP fiber showing cement crystal growth on the surface of fiber (ettringite morphology); and (e) detail (grain nucleated) of treated PP fiber showing cement crystal growth on the surface of fiber (ettringite morphology).

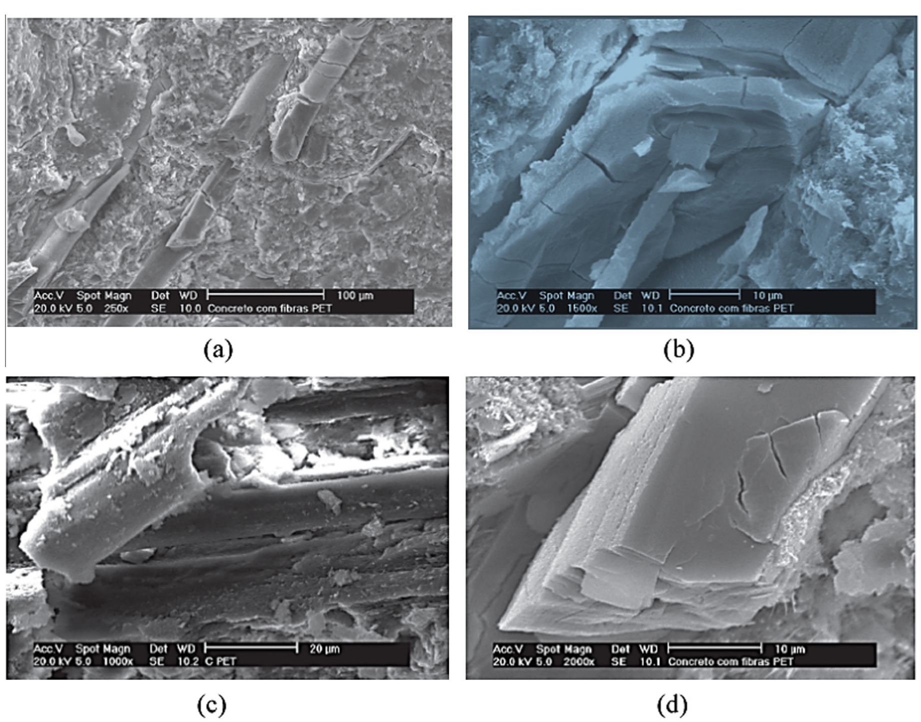

Fig. 22. Field emission SEMs showing the PET fibers in the process of degradation in the alkaline concrete environment (Pelisser et al., 2012): (a) 150 days with magnification of 250×; (b) 150 days with magnification of 1500×; (c) One year with magnification of 1000×; and (d) One year with magnification of 2000×.

Brito (2014) also reported that the abrasion resistance of concrete mixes with the various types of PET CA and FA was better than that of the reference concrete. They also suggested that the abrasion resistance depended on the compressive strength of the concrete and PA properties, including size, shape, and toughness.

3.2.7. Morphology

3.2.7.1. Effect of PA. The morphology of PA concrete is affected by many parameters such as R_{PA} and the type, size, and shape of PAs. Fig. 17 shows the SEM images (Marzouk et al., 2007) of concrete containing 2-mm PET FA with 30%, 50%, and 100% substitution level. The images reveal a high level of compactness in composites when the substituted volume is less than or equal to 50%; on the other hand, the structure appeared more cavernous when the substituted volume exceeded 50%. Such differences in the morphology can explain the observed decrease in the bulk densities and mechanical properties of concrete with increasing level of PAs. On the other hand, Marzouk et al. (2007) also provided the SEM images of concrete containing PET FA of three sizes, from 1 to 5 mm, with 50% substitution level (Fig. 18; the interfacial transition zone (ITZ) has been highlighted by a dashed line). These images show that matrix-aggregate adhesion was good and did not vary with the size of the substituted aggregates. The previous study also showed that the ITZ of PA concrete differed from that of conventional concrete (Choi et al., 2005). Fig. 19 shows the SEM images (Choi et al., 2005) of WPLA concrete, showing the ITZ between the cement paste and the natural aggregates and that between the cement paste and the WPLA in mortar at the age of 28 days. The ITZ between the WPLA and the cement paste was consistently wider than that between the cement paste and natural aggregates. This is attributed to not only the spherical and smooth shape of the PA, but also the hydrophobic nature of PA, which inhibits the cement hydration reaction near the surface of PA by restricting movement of water. Moreover, the anchoring points of PA with the cement matrix are very poor because of the smooth surfaces of the PA. This ITZ forms the weakest link and strength limiting phase in PA concrete because it acts like a wall between the matrix phase and the aggregate phase in concrete; this phenomenon is called the wall effect. Fig. 20 shows the SEM images (Fraj et al., 2010) of concrete containing PUR foam CA. The samples used were obtained from fragments of cylindrical specimens tested under compression, and were investigated without any specific pre-treatment (drying or polishing). The images reveal good adhesion between the cementitious matrix and the PUR foam aggregates: the cement paste penetrated through the surface pores of the lightweight aggregates because the pores were sufficiently large for the cementitious morphology to develop in it. No wall effect was observed at the interface between the pre-wetted or dry PUR foam aggregates and cement mortar.

3.2.7.2. Effect of PF. Fig. 21 (López-Buendía et al., 2013) shows the SEM images of untreated and treated PP fibers in mortar. In the case of the untreated PP fibers, the surface in contact with the concrete matrix was quite smooth with very poor anchoring points. Fig. 21(a) showed a smooth and clean fiber surface with no apparent interaction with the concrete matrix, and this agreed well with commonly observed behavior of concrete containing untreated PP fiber. In the case of the treated fibers, the higher surface roughness appeared to facilitate the anchoring to the matrix (Fig. 21b, c, d, and e). Moreover, crystal growth was detected on the surface of the concrete containing treated PP fibers (Fig. 21c, d, and e). Most morphologies were related to hydrated cement mineral nucleation; portlandite and hydraulic cement crystal morphologies were also seen in some cases. These morphologies were characterized by crystals forming associations of parallel needle-forming sheaves (Fig. 21d and e).

3.3. Durability-related properties of concrete containing plastic aggregates and fibers

3.3.1. Plastic degradation in alkaline environment

Pelisser et al. (2012) observed the SEM micrographs shown in Fig. 22 and observed a high degree of degradation of the PET fiber in the alkaline concrete environment at curing ages of 150 days and one year. This was because PET was easily affected by Ca^{2+}, Na^{+}, K^{+}, and OH^{-} ions in the pore fluid in a highly alkaline concrete environment, as suggested by Silva et al. (2005). Apart from PET, most types of common plastics (i.e. PP, PVC) are not biodegradable and have high chemical stability (Webb et al., 2012). Hence, such polymer products persist for decades, even for centuries in natural environment. Likewise, when added into concrete, most types of plastics (i.e. PP, HDPE) remains stable in this highly alkaline concrete environment (Puertas et al., 2003; Wypych, 1985) and hence their leaching from concrete would not be a concern.

3.3.2. Water absorption

3.3.2.1. Effect of PA. The water absorption characteristics such as the permeable pore volume and connectivity indirectly represent the porosity. In most of the studies, it was observed that increasing the substitution rate of natural sand with plastic FA increases the water absorption; this was because plastic and natural aggregates did not combine mix sufficiently in the concrete matrix, and therefore, the resultant mortar became porous (Akçaözoğlu et al., 2010; Albano et al., 2009; Babu and Babu, 2003; Choi et al., 2009; Marzouk et al., 2007; Saikia and de Brito, 2013; Silva et al., 2013). Saikia and de Brito (2013) reported an increasing water absorption capacity of concrete specimens with various substitution levels of PET CA and FA. Furthermore, it was reported that the coarse flaky aggregates of PET caused larger increase in water absorption capacities than did the PET fine and pellets aggregates. Fraj et al. (2010) also reported increases of 60–159% in the porosity of concrete containing 100% PUR foam CA with different mix proportions. Babu and Babu (2003) also reported that concrete containing higher levels of EPS FA had lower absorption values initially, but that the total absorption value was higher than that of the conventional concrete. However, Babu et al. (2006) reported that the concrete containing un-expanded PS (UEPS) FA had lower absorption capacity than the conventional concrete. According to these authors, the lower absorption capacity of the PA concrete may be due to the non-absorbent nature of UEPS FA.

3.3.2.2. Effect of PF. Few studies have focused on the water absorption capacity of concrete containing PFs. Karahan and Atiş (2011) reported that the water porosity and water absorption capacity of concrete containing 0.05%, 0.10%, and 0.20% PP fiber increased by approximately 6%, 18%, and 28%, respectively, as compared to the corresponding value for the control mixture.

3.3.3. Air/water permeability

3.3.3.1. Effect of PA. The air and water permeability of PA concrete is significantly influenced by the water absorption and porosity of the concrete. Wang and Meyer (2012) reported on the water vapor permeability of mortar containing HIPS FA. Their results indicated that the effect of the HIPS on the water vapor permeability of mortar was not significant. The permeance decreased by 13.7% as the HIPS content increased from 0 to 50%. According to the author, this was attributed to fact that the hydrophobicity of plastics was larger than that of the natural sand. Fraj et al. (2010) also reported that the gas permeability of concrete containing PUR foam CA was much larger than that of the conventional concrete, especially in the case of concrete containing pre-wetted PUR aggregates.

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3.3.3.2. Effect of PF. Bagherzadeh et al. (2011) observed that air permeability did not vary significantly upon the addition of different types PP fibers with increasing dosage. However, Kakooei et al. (2012) reported that concrete containing PP fibers had lower gas permeability than that of concrete without fibers; they attributed this behavior to the fact that the fibers prevent crack growth in concrete by forming bridges across the cracks.

3.3.4. Chloride migration

3.3.4.1. Effect of PA. The chloride migration of PA concrete is influenced by the water absorption, porosity, and water permeability of the concrete, as a more open structure results in more chloride ion penetration. Silva et al. (2013) also reported that the chloride permeability of concrete containing waste PET CA and FA was higher than that of conventional concrete. Moreover, the concrete specimens cured in a laboratory environment had the highest chloride ion penetration, followed by the specimens cured in an outdoor environment, and finally those cured in a wet chamber. Fraj et al. (2010) also reported increases of 44.3–220% in the effective chloride coefficient of concrete containing 100% PUR foam CA with different mix proportions.

3.3.4.2. Effect of PF. Toutanji et al. (1998) reported that the chloride permeability of concrete containing PP fibers increased with an increase in the dosage of fibers. Further, a decrease in the fiber length resulted in a decrease in the permeability of concrete with an equivalent volume fraction. Toutanji (1999) also showed that when the fiber volume fraction was increased from 0.1% to 0.5%, the maximum charge passed increased by 143%.

3.3.5. Carbonation

3.3.5.1. Effect of PA. The carbonation of PA concrete is also influenced by the water absorption, porosity, and water permeability of the concrete. Akçaözoğlu et al. (2010) reported that the carbonation depth of lightweight concrete containing 100% waste PET FA was lower than that containing both PET fine aggregates and sand, and the incorporation of slag in cement increased the carbonation depth significantly. Silva et al. (2013) also studied the carbonation depth of concrete containing waste PET CA and FA in an outdoor environment, a laboratory environment, and a wet chamber. The increase in the carbonation depth of concrete containing PAs was higher than that in the case of conventional concrete. This was so because PET and natural aggregates did not mix sufficiently in the mixture, resulting in porous mortar. Moreover, the carbonation depths were the highest in specimens cured in the laboratory environment, while those cured in the wet chamber had the lowest values. This is because the degree of partial pore filling with water in the wet chamber is higher, which leads to less "open" pores for carbon dioxide ingress and hence slower carbonation.

3.3.6. Shrinkage

3.3.6.1. Effect of PA. Drying shrinkage is another important property of concrete containing PAs. In most of the studies, concrete containing waste plastic as a substitution of natural aggregates has higher drying shrinkage than conventional concrete. This is because of the low stiffness of the plastic aggregates as a result of which, it provides very low resistance to the shrinkage of cement paste (Akçaözoğlu et al., 2010; Chen and Liu, 2004; Fraj et al., 2010; Ravindrarajah and Tuck, 1994; Sabaa and Ravindrarajah, 1997; Tang et al., 2008). Sabaa and Ravindrarajah (1997) also reported that the drying shrinkage of concrete containing crushed EPS waste CA increased as the substitution level increased; 40% of the increase was observed for a substitution level of 70% at 240 days. Chen and Liu (2004) reported the drying shrinkage of concrete containing 0, 25%, 40%, and 55% EPS CA and FA. At 90 days, for the EPS concrete with 55% substitution level, the drying shrinkage was almost twice that of conventional concrete. However, Silva et al. (2013) reported that the drying shrinkage of concrete containing waste PET CA and FA was lower than that of the conventional concrete; this observation was attributed to the fact that the amount of water absorbed by the aggregates was less because of the impervious nature of the plastic aggregates; as a result, more free water was available to hydrate the cement, leading to lower shrinkage values. The tendency of drying shrinkage to decrease when the substitution level of PVC FA in specific lightweight expanded clay aggregate concrete was increased was also investigated by Kou et al. (2009). According to the authors, the PVC granules can be assumed to be impervious, and they did not absorb water. Therefore, the PVC granules did not shrink; hence, the overall shrinkage of concrete was reduced.

3.3.6.2. Effect of PF. In the previous studies, different observations regarding the drying shrinkage of concrete containing PFs were reported. Some researchers reported that the drying shrinkage of concrete was reduced upon addition of PF (Karahan and Atiş, 2011; Sanjuan and Moragues, 1997; Song et al., 2005; Wongtanakitcharoen and Naaman, 2007). Wongtanakitcharoen and Naaman (2007) reported unrestrained early age shrinkage of concrete containing PP fibers. The results indicated that at a volume fraction of 0.1%, PP fibers reduced the unrestrained early age shrinkage by 32.5% in comparison to the shrinkage in conventional concrete. However, the shrinkage corresponding to an increase in the fiber volume fraction from 0.1% to 0.4% was similar to that of 0.1% PP fiber. According to the authors, the drying shrinkage decreased upon incorporation of plastic fibers because fibers restrain shrinkage owing to the shear along the fiber matrix interface when the matrix is subjected to the tensile stresses induced by shrinkage. Karahan and Atiş (2011) also reported that the drying shrinkage of concrete containing 0.05%, 0.10%, and 0.20% PP fibers reduced by 5%, 13%, and 17%, respectively at 210 days. However, Kayali et al. (1999) reported that there was no remarkable change in drying shrinkage when using PP fiber in lightweight aggregate concrete. Mesbah and Buyle-Bodin (1999) reached a similar conclusion when studying recycle aggregate concrete containing PFs. Furthermore, Kim et al. (2010) reported 8–25% higher drying shrinkage than that of the conventional concrete when using up to 1% of recycled PET and PP fiber in concrete. According to the authors, this was attributed to the large volume of air voids resulting from the presence of a large amount of synthetic fibers in the mix.

3.3.7. Creep

3.3.7.1. Effect of PA. Sabaa and Ravindrarajah (1997) reported the creep behavior of concrete containing 30%, 50%, and 70% crushed expanded EPS waste CA. The reference concrete showed significantly lower creep rate than that of PS aggregate concrete. In addition, the initial creep rate increased with an increase in the PS aggregate content. The higher creep potential for PS aggregate concrete was attributed partly to the inability of the low-modulus PS aggregate particles to restrain the creep of the cement paste matrix. Furthermore, the PS aggregate particles were subjected to time-dependent volume changes because of their compressibility.

3.3.8. Freezing and thawing resistance

3.3.8.1. Effect of PA. Kan and Demirboğa (2009b) reported that the compressive strength and relative dynamic elastic modulus of concrete containing MEPS CA and FA decreased significantly after 300 freezing and thawing cycles. Furthermore, the results showed that the coarse lightweight MEPS aggregates were more susceptible than fine lightweight aggregates to the freeze–thaw cycles. The concrete could be expected to exhibit a higher frost resistance and durability when the MEPS aggregate ratio in mixtures was increased. Conversely, Wang and Meyer (2012) showed that the use of HIPS FA as a partial substitution of sand does not affect the mortar's resistance to freezing and thawing.

3.3.8.2. Effect of PF. Karahan and Atiş (2011) reported that the freezing and thawing resistance of concrete containing PP fiber was slightly higher than that of concrete without fibers. This was attributed to the presence of randomly distributed fibers in the former concrete mixture; these fibers restrained the expansion caused by the frozen water in concrete and reduced the freeze–thaw damage incurred by concrete.

3.4. Other properties of concrete containing plastic aggregates and fibers

3.4.1. Thermophysical properties

3.4.1.1. Effect of PA. Yesilata et al. (2009) studied the effect of waste polymeric material addition on the thermal transmission properties of ordinary concrete by using waste PET bottles that were shredded into small pieces of different shapes and lined into fresh concrete before hardening. The test results showed that waste PET pieces remarkably lowered the thermal transmittance of ordinary concrete, resulting in an improvement of 10.27%, 17.11%, and 17.16%, in the insulation performance upon the addition of square, stripped, and irregular PET pieces, respectively, into ordinary concrete. Wang and Meyer (2012) reported that the thermal conductivity of mortar containing HIPS FA decreased to 87%, 69%, and 44% of that of the regular mortar when the HIPS ratio was 10%, 20%, and 50%, respectively. This was attributed to the facts that the thermal conductivity of HIPS was less than that of natural sand, and that the mortar made using HIPS had lower bulk density.

3.4.1.2. Effect of PF. Fraternali et al. (2011) reported that the thermal conductivity of concrete containing PET and PP fibers with 1% volume fraction decreased by 18% and 21.8%, respectively, from that of conventional concrete.

3.4.2. Fire resistance

3.4.2.1. Effect of PA. Albano et al. (2009) studied the flexural strength of concrete containing PET FA through a three-point loading test conducted in a furnace at temperatures of 200, 400, and 600 °C. There were no noticeable changes at 200 °C; at 400 and 600 °C, the degradation process of PET was replaced by the formation of gas products that caused the formation of holes in the specimens, thus decreasing the flexural strength.

3.4.2.2. Effect of PF. Han et al. (2005) reported the residual compressive strength of concrete containing PP fibers after heating the specimens in a furnace to 850 °C for 40 min. The results showed that conventional concrete underwent a severe spalling failure, and thus, it had no residual compressive strength after the fire resistance test. On the other hand, no spalling occurred in concrete specimens containing 0.05–0.1% PP fibers, and PP FRC maintained 70% of its residual compressive strength after the fire resistance test. Furthermore, as the PP fiber content increased, the residual compressive strength also showed a slight increase. The weight reduction of PP FRC specimens after the heating process was less than 10%, while that of conventional concrete was up to 60% because of the spalling failure. Thus, fiber bridging can support the concrete matrix and prevent concrete from undergoing spalling failure caused by the high vapor pressure generated at high temperatures. Meanwhile, PP fibers have a high melting point (i.e., approximately 165 °C), and the vapor pressure is relieved by the time the temperature reaches this temperature.

4. Conclusions

In the past two decades, a great amount of research has focused on understanding the behavior of concrete containing plastic materials. This study has presents a critical review of the 84 published reports on the topic; the reports were reviewed and classified into subcategories depending on whether they considered concrete containing PAs (49 studies) and PFs (35 studies). The material properties of plastics and the influence of plastic materials on the properties of concrete were discussed in detail. Based on this review, the following conclusions can be drawn:

1. The recycling methods for both PA and PF typically involve direct mechanical recycling or melting. The former is an efficient and economical way to obtain recycled PA and PF, whereas the latter yields materials with more uniform size and properties. In general, the use of PA and PF obtained from direct mechanical recycling results in concretes with inferior properties compared to concretes produced with PA and PF obtained using melting treatment.
2. Concrete containing PAs and PFs exhibits lower slump than conventional concrete. The use of high R_{PA} or C_{PF} result in concretes that is stiff and difficult to handle. PAs with a smooth surface and spherical shape have a lower negative influence on the workability of concrete than those with non-uniform shapes.
3. The density of concrete containing PAs is lower than that of conventional concrete, whereas that containing PFs does not differ from conventional concrete in terms of density. Furthermore, the density of concrete containing PAs is directly related to the substitution level of plastic aggregate, and mixes with higher R_{PA} exhibit lower density.
4. The compressive strength, elastic modulus, splitting tensile strength, and flexural strength of concrete containing PA decrease with an increase in R_{PA}. Furthermore, these properties of concrete containing non-uniformly shaped PA decreases more significantly than that of concrete containing uniformly shaped PA. The use PAs with a low elastic modulus (i.e. EPA and EVA aggregates) results in a more significant reduction in these concrete properties than those result from the use of PAs with a high elastic modulus (i.e. PET aggregates). Previous studies attributed these lower properties to the lower elastic modulus of PAs than that of natural aggregate; the low bond strength between the surface of the PA and the cement paste; and the restrained cement hydration reaction near the surface of PA resulting from the hydrophobic nature of PA.
5. Concrete containing PFs has higher compressive, splitting tensile, and flexural strengths than those of conventional concrete, when the concrete has a relatively low fiber content (i.e. less than 1%); an increase in the fiber content beyond this level leads to deterioration in the mechanical properties of concrete. The use of recycled plastic fibers with a high ultimate tensile strength (i.e. PP fibers) results in a more significant improvement in the compressive strength of the concrete than that when fibers with a low ultimate tensile strength (i.e. PET fibers) are used.
6. Concrete containing PAs exhibits higher ductility, but lower peak stress compared to conventional concrete.
7. The morphology of concrete containing PAs is affected by the substitution level, type, and size and shape of PAs. The interfacial transition zone of concrete containing PA or PF differs from that of conventional concrete due to the smooth surface and hydrophobic nature of plastic that results in poor anchoring points to the cement matrix. On the other hand, the morphology of concrete containing PA or PF with high surface roughness shows that roughness on the fiber surface favors interactions and facilitates the anchoring of the plastic to the cement matrix.

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8. The shrinkage of concrete containing PA increases with an increase R_{PA}, as the low stiffness of PA provides very low resistance to the shrinkage of cement paste. On the other hand, the shrinkage of concrete containing PF decreases with an increase C_{PF}, as fibers restrain shrinkage owing to the shear along the fiber matrix interface when the matrix is subjected to the tensile stresses induced by shrinkage.
9. The water absorption and porosity of concrete containing PA increase with an increase in R_{PA}, as plastic and natural aggregates do not mix sufficiently in the concrete matrix, resulting in a porous matrix. The chloride ion penetration and carbonation depth also increases with R_{PA} as a more open structure results in lower resistance to chloride ion migration and carbon dioxide ingress.

A large number of studies reported in recent years on the topic indicate that the use of recycled plastic aggregates and fibers as a construction material is gaining wide spread attention. The findings of this critical review show that the use of recycled plastic fibers in concrete can lead to improved concrete properties; whereas the use recycled plastic aggregates in concrete would not result in such an improvement, and the main motivation in that case is the disposal of plastic waste. Apart from PET, most types of common plastic (i.e. PP, PVC) can persist stably for decades, even for centuries, inside the concrete. Though no studies have been reported to date on the recycling of concrete containing plastics after its service cycle, one attractive option is the use of construction and demolition waste from concrete containing plastics as recycled aggregates in the production of new concretes in future construction applications. Findings of this review indicate that the use of recycled plastic materials in concrete can contribute significantly toward a more sustainable construction industry. Future studies on the environmental aspects, such as long-term behavior of plastic materials in concrete, and the environmental consequences of recycling of concrete containing plastics after its service cycle, are recommended.

5. Definitions and abbreviations

CA	coarse aggregates
C_{PF}	plastic fiber content
EPS	expanded polystyrene
EVA	ethylene vinyl acetate
E_c	elastic modulus of concrete
FA	fine aggregates
FRC	fiber-reinforced concrete
HDPE	high-density polyethylene
HIPS	high-impact polystyrene
LDPE	low-density polyethylene
LLDPE	linear low-density polyethylene
MEPS	modified expanded polystyrene
MSW	municipal solid waste
PA	plastic aggregates
PC	polycarbonate
PF	plastic fibers
PET	polyethylene terephthalate
PLA	poly lactic acid
PP	polypropylene
PS	polystyrene
PUR	polyurethane
PVC	polyvinyl chloride
R_{PA}	substitution level of plastic aggregates
SEM	scanning electron microscopy
WPET	waste un-washed PET bottles
WPF	waste polypropylene fibers
WPLA	waste polyethylene terephthalate lightweight aggregates
w/c	water-cement ratio

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