



Review Paper

Cementitious materials incorporating waste plastics: a review

Rawa Ahmed Mahmood¹ · Niyazi Ugur Kockal¹

Received: 6 September 2020 / Accepted: 18 November 2020 / Published online: 24 November 2020
© Springer Nature Switzerland AG 2020

Abstract

Plastics in all forms have invaded a large area of our daily life. Increased demand for plastics in the last decades has led to severe environmental issues due to the accumulation of plastic-related waste. This situation has provided scientists with a new research area to work on the properties and study the possible use of recycled plastics as a new generation of construction materials. In recent years, many studies have been conducted regarding the usage of plastic particles. Most of the studies focus on the methods of recycling and disposing of waste plastic materials in an environmentally friendly way. This paper is a review of published research articles on the incorporation of waste plastic materials in cementitious mixtures. Fresh, mechanical, and durability-related properties of composites containing plastic particles have been reviewed based on the current literature.

Keywords Recycled plastic · Cementitious materials · Workability · Mechanical properties · Durability-related properties

Abbreviations

FA	Fly ash
HDPE	High-density polyethylene
HIPS	High-impact polystyrene
HPC	High-performance concrete
HPSCC	High-performance self-compacting concrete
HSC	High-strength concrete
HVFA	High-volume fly ash
LDPE	Low-Density Polyethylene
LLDPE	Linear low-density polyethylene
MEPS	Modified waste expanded polystyrene
MPW	Metalized plastic waste
MSW	Municipal solid waste
PBWF	Plastic bag waste fiber
PC	Polycarbonate
PET	Polyethylene terephthalate
PF	Polypropylene fiber
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
RPF	Recycled plastic fiber
SBR	Styrene-butadiene rubber

SCC	Self-compacting concrete
SCLC	Self-compacting lightweight concrete
SF	Silica fume
UHPC	Ultra-high-performance concrete
UHPCC	Ultra-high-performance cementitious composite
UHSC	Ultra-high strength concrete
W/B	Water-binder ratio
W/C	Water-cement ratio

1 Introduction

The environment is being polluted by various types of plastic wastes that are used in our daily life such as plastics used in packing films, wrapping materials, water bottles, shopping, and garbage bags. Increasing demand for plastic materials is possibly because of plastics advantageous properties such as low density, high strength to weight ratio, and high durability [1]. Reports show that even though plastics are small, but they are considered a significant part of waste products [2]. The biodegradation

✉ Rawa Ahmed Mahmood, rawa.ahmed12@gmail.com | ¹Department of Civil Engineering, Akdeniz University, Antalya, Turkey.



of these plastic waste materials requires thousands of years [3]. This means serious environmental problems caused by burning waste materials or illegal landfilling. Soil productiveness, which is affected by the soil's degree of permeability, is harmed by squandered plastics, which decrease the permeability of soil [4]. Gu and Ozbakkaloglu [1] reported that some plastic wastes pollute the environment by producing toxic components and releasing them to the atmosphere, such as plastics like polyvinyl chloride (PVC) and polycarbonate (PC). In Europe in 2016, plastic consumption reached about 27.1 million tons, 8.42 million tons out of it ended up in recycling. Figure 1 graphically represents the treatment of post-consumer plastics in 2016 [5]. In 2016 for the first time, plastic recycling overtook landfilling. 31.1% of plastic was recycled, 41.6 was energy recovered, and only 27.3% landfilled while in 2012, the recycling rate was 26.3%, and landfilling was 38.1% [5]. The amount of plastics used in Europe was 42.9 million tons in 2012 out of these 25.2 million tons of plastics

resulted in the waste stream [6]. From 1960 to 2012, the waste produced by plastics increased about 80 times, but the recycling of plastics started later at 1980 with a recycling rate of 0.3%, by 2012 this rate increased to 8.8% but still not enough to protect the environment [1]. Table 1 provides a list of types and amounts of plastics in municipal solid waste (MSW) in the USA in 2013 [7]. In the table, many types of plastics and their recovery rates are listed. In total, 32.5 million tons of plastics were produced, and 3 million tons were recycled which accounts for 9.2%, while in 2012 total plastic generated was 31.7 million, and 8.8% of it ended up recycling [7]. Studies of finding different ways of disposing plastics have been conducted to minimize the detrimental effects of plastics since landfilling and incineration have been forbidden in many countries. Landfilling requires a large area, and incineration contributes to climate pollution. Engineers and scientists have started investigating various properties of plastic materials and their use in the construction industry especially in

Fig. 1 Treatment of post-consumer plastics in 2016 by EU28 + NO/CH [5]

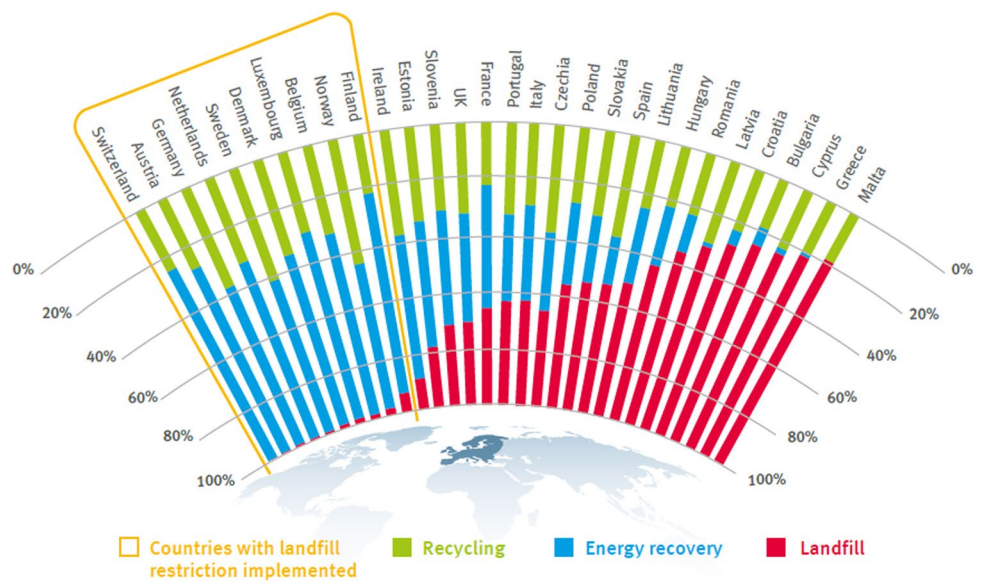


Table 1 Types and quantities of plastics in municipal solid waste (MSW) in the USA in 2013 [7]

Type of plastic	Generation 1000 tons	Recovery		Discards 1000 tons
		1000 tons	% of generation	
PET	4680	930	19.9	3750
HDPE	5580	570	10.2	5010
PVC	900	Neg	Neg	900
LDPE/LLDPE	7460	470	6.3	6990
PLA	50	Neg	Neg	50
PP	7400	40	0.5	7360
PS	2270	30	1.3	2240
Other resins	4180	960	23	3220
Total plastics in MSW	32,520	3000	9.2	29,520

cementitious mixtures as a substitution of fine and coarse aggregate or as fiber reinforcement, for this many types of plastics like polyethylene terephthalate particles (PET) [8–11], high-density polyethylene waste (HDPE) [12, 13], polypropylene (PP) [14, 15], PET bottle fibers [16, 17], polystyrene (PS) [18], e-plastic waste [19–21] and polyvinyl chloride (PVC) [22, 23] were used. Figure 2 shows some different forms of plastic wastes used in the studies as reported in the literature.

This paper provides an overview of the effects of plastic materials on cementitious mixtures by studying the material properties of plastics and used in cementitious mixtures. Physical properties such as workability; mechanical properties such as compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity; durability-related properties such as water absorption, freezing and thawing resistance, shrinkage, and carbonation of mixtures including waste plastic particles by reviewing existing studies in this area.

2 Type and properties of waste plastics used in cementitious mixtures

Plastics are mostly used either as fiber or aggregate replacement in the cementitious mixtures. Tables 2 and 3 list the types and properties of waste plastic materials as reported in the literature. Listed in the tables are types of composites, plastic-type, and type of use. among material properties, physical properties including workability and air content; mechanical properties, including compressive strength, flexural strength, splitting tensile strength and modulus of elasticity of cementitious mixtures containing waste plastics are listed in tables below.

3 Fresh and mechanical properties of waste plastics in cementitious mixtures

3.1 Workability

Figure 3 exhibits the effects of various types of plastic aggregates on the slump of concrete [8, 12, 15, 32] Some studies revealed that using plastic particles as aggregate replacement decreases workability [15], whereas some

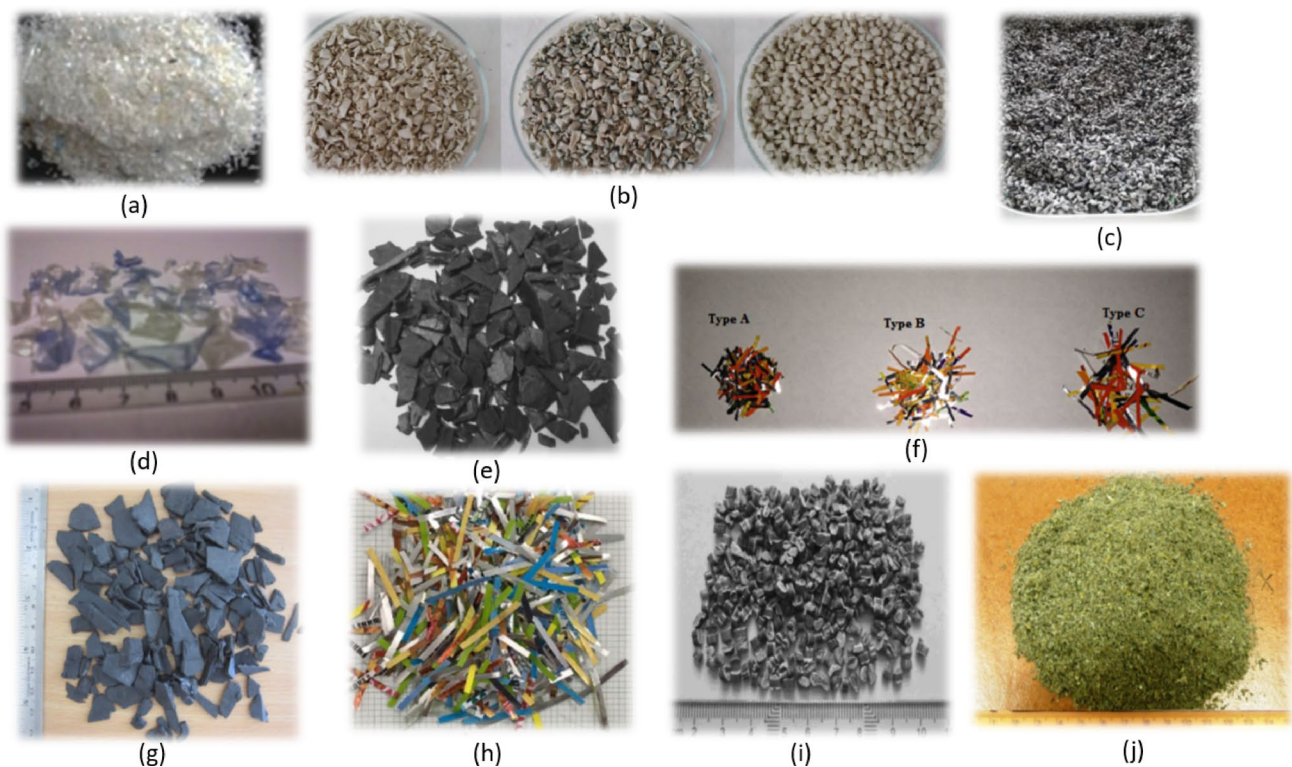


Fig. 2 Different forms of plastic waste: **a** PET aggregate [8], **b** Polypropylene [14], **c** Electronic plastic waste [19], **d** PET aggregate [20], **e** Electronic plastic waste [21], **f** Shredded metalized plastic fiber

[23], **g** High impact polystyrene [24], **h** waste metalized plastic fiber [25], **i** Polypropylene [26], **j** Plastic waste sand [27]

Table 2 Substitution ratio and type of plastics used in previous studies

Ref	Type of composite	Type of plastic	Type of use
[8]	Concrete	PET aggregates	Replaced natural aggregates with PET aggregates by 0%, 7.5%, and 15%
[12]	Concrete	HDPE, LDPE, PET aggregates	Replaced natural coarse aggregate with plastic particles by 0%, 5%, 10%, 15%, and 20% by weight
[18]	Mortar	shredded high impact polystyrene (HIPS) electronic wastes with particle size less than 4 mm	Replaced sand with HIPS by 10%, 20%, and 50% by volume
[19]	Polymer concrete	Electronic plastic waste	Used as filling material in the percentages of 0%, 5%, 15%, and 25% with three different sizes (0/2 mm, 2/4 mm, 4/8 mm)
[20]	Concrete	Shredded flaky and pellet-shaped PET aggregates	Replaced natural aggregates with PET aggregates by 5%, 10%, and 15% by volume
[25]	sustainable concrete	Metalized plastic waste fiber with length of 20 mm long	Mixed in concrete in amounts of 0%, 0.25%, 0.5%, 0.75%, 1% and 1.5% by volume of mix
[27]	Mortar	Recycled Polyolefin (mostly polyethylene and polystyrene) and PET aggregates	Substituted siliceous sand with polyolefin and PET aggregates by 10%, 20%, 30%, 40%, and 50% by weight
[28]	Concrete	Metalized plastic waste fiber with dimensions of 5 mm, 10 mm and 20 mm long	Mixed in concrete in amounts of 0%, 0.5%, 1%, 1.5% and 2% by volume of mix
[29]	Concrete	Electronic plastic waste (High impact polystyrene)	Replaced coarse aggregate with electronic plastic waste by 10%, 20%, 30%, 40%, and 50% per unit volume
[30]	Self-compacting concrete	recycled plastic bag waste fiber and polypropylene fiber	RPBWF content of 1, 3, 5, and 7 kg/m ³ , pp. content of 1 kg/m ³
[31]	Lightweight concrete	Modified expanded polystyrene (MEPS) aggregates with a maximum size of 16 mm	Replaced natural aggregates with MEPS by 0%, 25%, 50%, 75% and 100% by volume
[32]	Lightweight concrete	PVC plastic granules with a particle size of 5 mm	Replaced sand with PVC granules by 0%, 5%, 15%, 30% and 45% by volume

studies reported that by using superplasticizer slump of concrete increases with the addition of plastic aggregates [12]. Silva et al. [8] stated that the shape of the PET plastic aggregate affects the workability of the concrete and to maintain the workability the w/c ratio should be adjusted for each concrete sample. For the concrete samples containing flaky shape plastic aggregate, the w/c ratio was increased to 0.56 and 0.60 for the substitution level of 7.5% and 15% respectively. However, for the samples containing 7.5% and 15% regular shape plastic aggregate, the w/c ratio was reduced to 0.53 and 0.52 respectively. The authors attributed this to the shape of aggregates; flake shape aggregate impaired the workability while the smooth texture and impermeable nature of the regular shape aggregate enhanced the workability. Pirzada et al. [12] replaced natural coarse aggregate with plastic aggregate, which consisted of different kinds of plastics like High-density polyethylene (HDPE), Low-density polyethylene (LDPE), and PET after being passed through heating processes. Natural coarse aggregate was substituted by coarse plastic aggregate at the percentage range between 0 and 20% increase by 5% each time, produced plastic aggregate contained 80% PET, and 20% HDPE and LDPE. The workability of the fresh concrete was

tested using a slump cone. Obtained results showed a decrease in workability as the amount of plastic aggregate increased but with the addition of superplasticizers workability increased. Manjunath [15] made an experimental study on the usage of e-plastic waste particles as partial replacement of fine and coarse aggregate in concrete with the percentage ratio ranging from 10 to 30%. Test results showed that slump and workability values decreased as the percentage of e-plastic in the mix increased. Saika and Brito [20] used different shapes of plastic waste particles. They observed a slight increase in workability with the addition of cylindrical shape plastic particles as partial replacement of aggregate and a significant decrease in workability with shredded shape plastic particles. Bhogayata and Arora [28] used metalized plastic wastes (MPW) which are made from polypropylene (PP) and shredded into fibers to study the workability of concrete. Plastic fibers of lengths 5 mm, 10 mm, and 20 mm were prepared, and they were mixed with concrete at a rate between 0 and 2% by volume of concrete. Slump test results showed a decline in slump values with increasing percentage and length of plastic fibers. For 5 mm long fibers slump reduced by 5%, 8%, 12%, and 16% for fiber contents between 0.5 and 2%, this reduction was higher

Table 3 Properties of plastics used in previous studies

Ref	Type of plastic	Physical properties				Hardened mechanical properties			
		Slump	L-box test	Density	Air content	Compressive strength	Splitting tensile strength	Flexural strength	Modulus of elasticity
[8]	PET	✓	x	✓	x	✓	x	x	x
[9]	PET	x	x	✓	x	✓	✓	✓	✓
[10]	PET	x	x	x	✓	✓	✓	✓	x
[12]	HDPE, LDPE, PET	✓	x	x	x	✓	✓	✓	x
[14]	PP	✓	x	✓	x	✓	x	✓	✓
[15]	E-plastic waste	✓	x	✓	x	✓	✓	✓	x
[16]	PET fiber	x	x	x	x	✓	x	x	x
[17]	PET fiber	✓	✓	✓	x	✓	x	✓	x
[18]	PS	✓	x	✓	x	✓	✓	x	✓
[19]	E-plastic waste	x	x	x	x	✓	✓	✓	x
[20]	PET	✓	x	✓	x	✓	✓	✓	✓
[21]	E-plastic waste	✓	x	x	x	✓	✓	✓	x
[22]	PP	✓	x	✓	x	✓	✓	✓	✓
[23]	PET, PP, and PVC	✓	x	x	x	✓	✓	✓	x
[24]	HDPE	x	x	✓	x	✓	x	✓	✓
[25]	MPW fiber	✓	x	x	x	✓	✓	✓	x
[26]	PP	✓	x	✓	x	✓	✓	✓	✓
[27]	PET and Polyolefin (PP, PE)	x	x	✓	✓	✓	x	✓	x
[28]	MPW fiber (PP)	✓	x	x	x	✓	✓	✓	x
[30]	PF and PBWF	✓	✓	x	x	✓	✓	✓	x
[31]	MEPS	✓	x	✓	x	✓	✓	x	✓
[32]	PVC	✓	x	✓	x	✓	✓	x	✓
[33]	PET	✓	✓	✓	✓	✓	✓	✓	✓
[34]	PVC	✓	x	x	x	✓	✓	x	✓

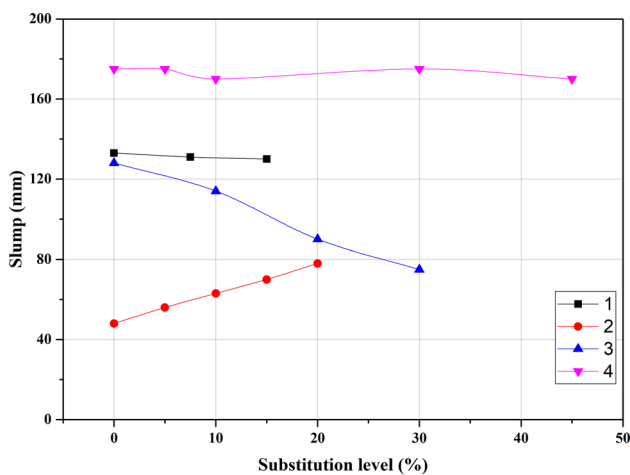


Fig. 3 Variation of slump of concrete with substitution level of plastic aggregates: (1) PET regular shape aggregate [8]; (2) PET, HDPE and LDPE aggregates [12]; (3) E-plastic aggregates [15]; (4) PVC aggregates [32]

for longer plastic fibers, this is because long fibers could not make a homogenous distribution in the mix and caused the formation of a mesh-like structure. Ghernouti et al. [30] performed slump flow sieve stability and L-box tests to study the fresh properties of self-compacting concrete (SCC) containing Plastic bag waste fiber (PBWF) and Polypropylene fibers (PF). Results revealed that addition of PBWF in SCC improve in the slump values for different length and percentages of the fibers, this can be attributed to the smooth surface of these fibers which makes the flow of the concrete easier. It was also reported that PBWF satisfied the slump flow criterion, which was between 650 and 800 mm, but the addition of PF did not meet the slump flow criterion since polypropylene fibers increased the viscosity of SCC. Kou et al. [32] reported that the dosages of superplasticizer required to provide workability close to that of the control concrete in the concrete samples containing PVC granules at the rates of 15%, 30%, and 45% were 2.4%, 12.2%, and 31.7% respectively. The authors attributed this high-required dosage of superplasticizer to the angular shape and greater sizes of the PVC particles to

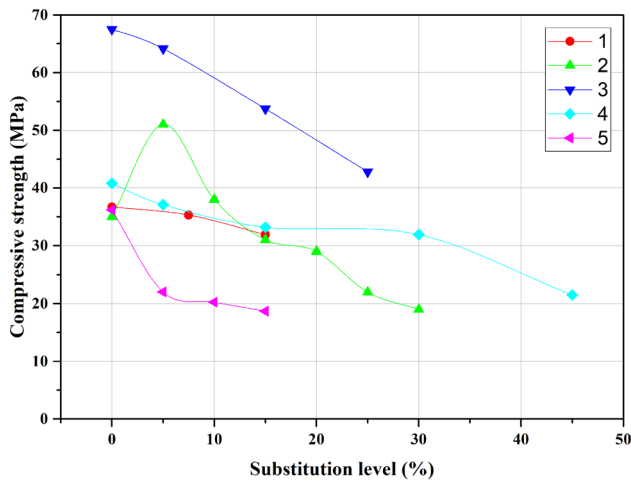


Fig. 4 Variation of 28-day compressive strength of concrete with substitution level of plastic aggregates: (1) PET aggregates [8]; (2): PET aggregates [9]; (3): E-plastic aggregates [19]; (4): PVC aggregates [32]; (5): PET aggregates [33]

that of the river sand. They also revealed that slump values were between 170 and 175 mm.

3.2 Compressive strength

Figure 4 shows the effects of using plastic aggregates on the compressive strength. The figure indicates that the compressive strength of concrete containing plastic aggregates reduces regardless of the type and substitution level of the aggregates [8, 9, 19, 32, 33]. Strength reduction was attributed to many reasons like low modulus of elasticity of the plastic aggregate; weak strength bond between plastic aggregate and cement paste; reduction in the packing level of concrete due to the coarser size of plastic particles [32]. Silva et al. [8] studied the properties of concrete by replacing natural aggregate with plastic PET aggregates in the percentages of 0%, 7.5%, and 15%. The concrete samples were cured in three different curing environments, which were outdoor environment, laboratory environment, and wet chamber. The compressive strength decreased with the increase in the ratio of plastic aggregates. The impermeable nature of the plastic aggregate led to the formation of weak bond strength between the cement paste and PET aggregates. The packing level of concrete was reduced by the coarser particle size of the plastic aggregates. Azhdarpour et al. [9] stated that the compressive strength of concrete produced by replacing aggregates with plastic aggregates increases up to 10% of the replacement level. The compressive strength of concrete increased by 39% and 7.6% for 5% and 10% replacement levels respectively. However, more than 10% replacement caused a decline in the compressive strength.

The authors related this decrease to the existence of the plastic aggregates at the points where failure starts. Won et al. [16] studied the effects of adding recycled PET particles to the fiber-reinforced cement composites. Prepared composite samples were digested in five chemical solution environments, calcium chloride, sulfuric acid, alkali, salt, and sodium sulfate for 30, 60, 90, and 120 days. No changes were noticed for compressive strength of samples in sodium sulfate, calcium chloride, and salt environments which showed the best performance of chemical resistance of recycled PET fiber-reinforced cement composite in these environments. In the case of the alkaline environment a small decrement in the values of compressive strength occurred for samples tested at the age of over 60 days, this means good chemical resistance of samples in alkaline environments. It was concluded that in the sulfuric acid environment compressive strength of recycled PET fiber-reinforced cement composite deteriorated about 24%, so it had low resistance to sulfuric acid environments. Al-Hadithi and Hilal [17] used waste plastic fibers obtained by cutting a beverage bottle to examine the improvements in the properties of self-compacting concrete. Waste plastic fibers were added in the percentages of 0%, 0.25%, 0.5%, 0.75%, 1%, 1.25%, 1.5%, 1.75%, and 2% by volume. The compressive strength values of all samples prepared with waste plastic fibers were measured to be higher than that of the control specimen. The maximum values of compressive strength were 56 Mpa, 68 Mpa, and 79 Mpa for 7, 14, and 28 days respectively as it can be seen in Fig. 5. The reason of increased strength was attributed to prevention of micro crack propagation by the fibers close to the propagation area [17]. Bulut and Şahin [19] used e-plastic wastes which were resulted from the recycling of monitor plastics in the ratios of 0%, 5%,

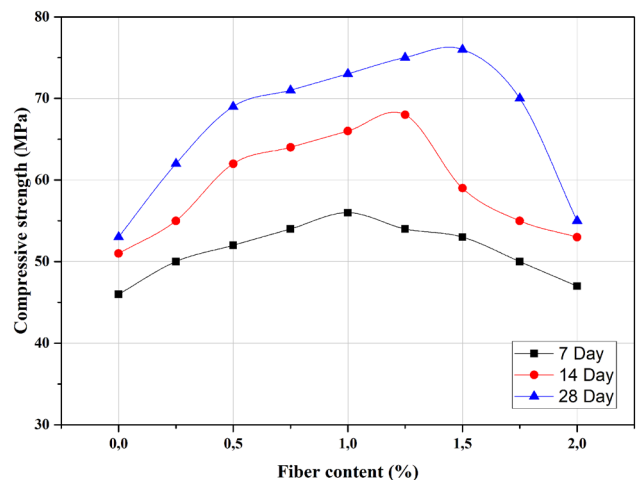


Fig. 5 Variation of compressive strength of concrete with plastic fiber content [17]

15%, and 25% as a part of filling material (quartz sand and gravel) to produce polymer concrete. It was concluded from the compressive strength test results that by increasing the ratio of e-plastic wastes, the compressive strength of the polymer concrete decreased, this decrease in the strength can be related to the reasons such as an increase in the pore holes in the concrete due to the increment in the amount of e-plastic wastes, increasing electronic plastic ratio in the mixture, decreased the volume and amount of aggregate which then lead to the low strength of the polymer concrete. It was also noted that the ideal ratio of e-plastic wastes to be used is 5%. Mohammadhosseini et al. [25] stated that the addition of waste metalized plastic (WMP) fiber into concrete reduced the compressive strength. The compressive strength of concrete was reduced by 6%, 7%, 11% 18%, and 21% with the addition of MPW at the percentages of 0.25%, 0.5%, 0.75%, 1%, and 1.25% respectively. This strength reduction can be related to the increasing of air voids in the matrix by the addition of waste plastic fibers. Kumar and Baskar [29] made an experimental study on the effects of thermal shock and temperature on the concrete made with the incorporation of high impact polystyrene (HIPS) e-plastic waste as a partial substitution of coarse aggregate. HIPS was used at the percentages ranging between 10 and 50% increasing by 10% each time. The compressive strength results showed an incline when the content of HIPS increased. Hence the compressive strength gained the highest value at the 50% replacement of HIPS with coarse aggregate. Kan and Demairboža [31] modified waste expanded polystyrene (MEPS) by heat treatment method to produce artificial lightweight aggregate for use in the production of lightweight concrete. Natural aggregates were replaced by MEPS aggregates by volume in the percentages ranging from 0 to 100% with a 25% increment each time. From the test results, it was concluded that the 28-day compressive strength of MEPS concrete could be categorized under semi-structural lightweight concrete. The authors stated that MEPS aggregates exhibit a 40% higher compressive strength compared to vermiculite and perlite. Kou et al. [32] reported a reduction in the compressive strength of concrete by 9.1%, 18.6%, 21.8%, and 47.3% with the 5%, 15%, 30%, and 45% replacement of PVC plastic aggregate respectively, compared to that of the reference concrete. The weak bonding strength between PVC aggregates and the cement paste and the greater particle size of PVC aggregates, which led to a reduction in the packing level of concrete, can be shown as the reasons of lower strength of concrete. Sadrmomtazi et al. [33] reported a remarkable decline in the strength of concrete due to the utilization of PET plastic aggregates. The 28 days compressive strength of concrete with the 0%, 5%, 10% and 15% content of plastic aggregates was 36.19, 22.03, 20.25 and 18.70 MPa

respectively. The plane shape of the PET particles provide a greater specific surface area for PET particles to that of the natural sand. Greater specific surface area of the PET particles lead to the accumulation of more water in the interfacial transition zone. The authors attributed the strength reduction to the porosity of the interfacial transition zone which causes the formation of a weak microstructure of the cement matrix. Frigione [35] recycled PET bottles and utilized as fine aggregate, test results showed that compressive strength slightly (about 2%) decreased in the comparison to the reference concrete. Ismail and AL-Hashmi [36] stated that this decrease can be explained by the decrease in the adhesive strength between cement paste and surface of the plastic waste. In a study done by Rai et al. [37] waste virgin plastic accompanied with plasticizer used to examine the fresh and hardened properties of concrete. A reduction in the compressive strength was observed with increasing the amount of waste plastic, this was due to low adhesive strength as explained above and increase in the particle size of the plastic waste.

3.3 Flexural strength

Results of flexural strength obtained from the experiments conducted in previous studies with the utilization of plastic aggregates are demonstrated in Fig. 6 [9, 12, 15, 19, 33]. Strength reduction occurred as the substitution level of plastic aggregate increased regardless of the type of plastic aggregate used. According to Azhdarpour et al. [9], the addition of PET plastic particles at low amounts increases the flexural strength; however, at high amounts, the flexural strength tends to show a decreasing trend.

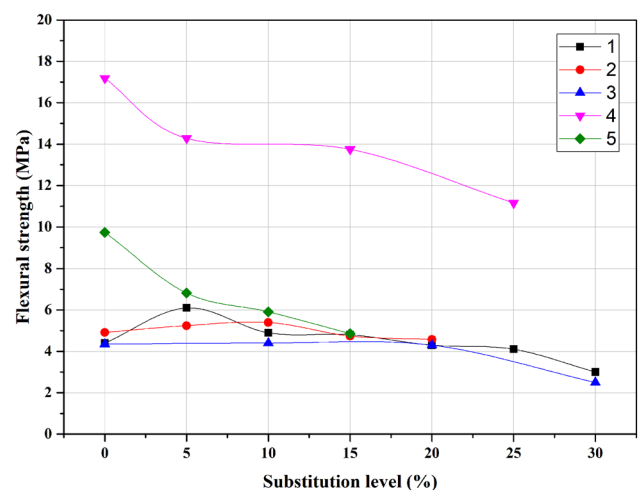


Fig. 6 Variation of 28-day flexural strength of concrete with substitution level of plastic aggregates: (1): PET aggregates [9]; (2): HDPE, LFPE, PET aggregates [12]; (3): E-plastic aggregates [15]; (4): E-plastic aggregates [19]; (5): PET aggregates [33]

Strength incline at low amounts could be attributed to the remarkably high tensile strength of PET particles (60 MPa) which shows up at the point where failure starts. At higher amounts of PET aggregates, the accumulation of PET particles occurs, hence reduces the strength of concrete. An investigation by Akçaözöğlü et al. [10] revealed that mortars containing sand and PET aggregate demonstrated better flexural strength behavior than those containing only PET aggregates. Badche et al. [11] studied the effects of adding high-density polyethylene (HDPE) as a partial substitution of aggregate. Results showed a decrease in the flexural strength with increasing HDPE amount by 0.34, 1.4, 1.4, and 1.77 MPa for 15%, 30%, 45%, and 60% replacement respectively. Pirzada et al. [12] showed that the flexural strength of the concrete was improved up to 10% replacement of plastic aggregate. Záleská et al. [14] concluded that a high amount of plastic aggregate, in this study PP, caused the flexural strength of concrete to decrease. This reduction was attributed to the plastic aggregates' low strength. Manjunath [15] stated that using e-plastic wastes as a partial replacement of aggregate in concrete decreased the flexural strength to a value below the reference concrete specimen. The author also concluded that 20% replacement had the lowest flexural strength value for the 28 days of curing. Al-Hadithi and Hilal [17] concluded that the inclusion of waste plastic fibers improved and increased the flexural strength of concrete up to 1.75% addition of fiber by volume. The maximum increase in the flexural strength values in comparison to the concrete prepared without fiber was recorded at 1.75% inclusion which was 141.4%, 93.3%, and 82.2% for 7, 14, and 28 days of curing respectively. However, the flexural strength decreased at the fiber content of 2%. This reduction was caused by poor bonding behavior of PET fibers and the fact that the high content of plastic causes more free water to be accumulated around the plastic particles which decrease the interface of plastic-paste leading to a zone of big voids and a considerably weak adhesion. Bulut and Şahin [19] reported that using e-plastic waste in the production of polymeric concrete resulted in a lower flexural strength compared to the control sample. Saikia and Brito [20] concluded that using any amount of PET particles as aggregate substitution, decreased the flexural strength of concrete. The authors also pointed out that the specimens prepared with PET flaky coarse aggregate and PET flaky fine aggregate (PF) have improved post cracking strength due to their shape and sizes. The results of the flexural strength of the study conducted by Azhdarpour et al. [9] support conclusions done by Saikia and Brito [20] which state that increasing the amount of PET particles as aggregate replacement reduces the flexural strength. This strength reduction is due to the accumulation of PET particles close to each other, which causes a weak adhesion

between the PET particles and the cement surface. The study done by Kumar and Baskar [21] agrees with Manjunath [15] which states that increasing the percentage of plastic aggregate as partial replacement of coarse aggregate decreases flexural strength. The authors reported that with 50% substitutions, strength loss reached about 37.38%. Yang et al. [26] concluded that up to 15% substitution of sand with recycled PP plastic aggregate, increased the flexural strength of self-compacting lightweight concrete (SCLC). 15% substitution gave the ultimate flexural strength, and then strength decreased as the amount of plastic increased. Iucolano et al. [27] reported that hydraulic mortar prepared with the partial replacement of natural aggregate with recycled plastic waste materials such as PET and PE decreased the flexural strength of the mortar. The flexural strength of the mortar decreased from 2.15 to 1.11 MPa with a 10% substitution. The authors related this strength reduction to the weak bond between the cement paste and the surface of the plastic aggregate. Bhogayata and Arora [28] stated that with increasing plastic fibre content (metalized plastic fibre), the flexural strength decreased. The average reduction recorded was about 9% when compared to the control concrete specimen. The authors also stated that the inclusion of plastic fiber improved the ductility of concrete by showing a sustained deflection up to an extent for a given load value. Concrete reinforced with metalized plastic waste fibre demonstrated a steady increase in the capacity of deformation for a given load, this behaviour is also observed and supported by Dora Foti [13]. Sadrmomtazi et al. [33] investigated the effects of waste PET particles as an aggregate replacement on the properties of self-compacting concrete (SCC) containing silica fume (SF) and fly ash (FA). It was seen from the results that the flexural strength of the specimen containing FA, 5% of PET replacement was decreased up to 14.7% at the age of 28 days. Moreover, as the percentage ratio increased to 10% of PET in specimen containing FA the flexural strength decreased to 34.6%, so it can be concluded that increasing the amount of PET particles decreased the flexural strength of SCC. The authors also indicate that the flexural strength of the concrete samples containing PET plastic aggregates shows a decreasing trend due to the low adhesive strength between PET particles and cement paste. Malagaveli and Patura [38] concluded that adding HDPE fibres up to 3.5% by volume played a good role in increasing flexural strength which could increase it by 17.47% when compared to the reference concrete.

3.4 Splitting tensile strength

Figure 7 shows the effects of different types of plastic aggregates on splitting tensile strength obtained from

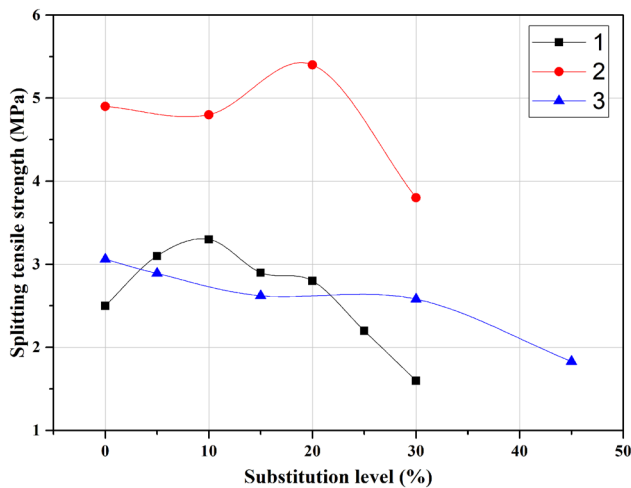


Fig. 7 Variation of 28-day splitting tensile strength of concrete with substitution level of plastic aggregates: (1): PET aggregates [9]; (2): E-plastic aggregates [15]; (3): PVC aggregates [32]

previous studies [9, 15, 32]. Similar observations were reported in the studies that show an increase in the strength up to an optimum substitution level and then a decrease in strength occurs [9, 15]. Strength reduction was reported as the substitution level of plastic aggregates increased [32]. Azhdarpour et al. [9] indicated that up to 10% replacement of aggregate by plastic particles improves tensile strength. This was due to the greater tensile strength of PET particles compared to the other components of concrete. The authors pointed out that at the higher ratios of plastic aggregates, the tensile strength decreased. This reduction is caused by the nonabsorbent property of the PET particles, which does not allow the cement hydration to occur on their surfaces and hence reduces the tensile strength of the concrete. Manjunath [15] showed that the 28 days tensile strength got the maximum value at the 20% replacement of aggregate by e-plastic aggregate. Furthermore, at the 30% replacement, the tensile strength reached the lowest value. Wang and Meyer [18] reported that the addition of recycled high-impact polystyrene (HIPS) as partial replacement of sand in the cement mortar reduced the splitting tensile strength. It was concluded that with high replacement ratios, splitting tensile strength decreased. For the 28 days age, strength was reduced by 1.5%, 11%, and 20% for 10%, 20%, and 50% amounts of HIPS induced mortar. Saikia and Brito [20] stated that like compressive strength, the splitting tensile strength also has a decreasing trend with increasing substitution ratio of shredded PET plastic aggregates. The worst values were reported for plastic coarse aggregate due to a high w/c ratio. The characteristics of the interfacial transition zone have a great effect on the splitting tensile strength of concrete. According to

the authors, the cause of the weak bond between cement paste and plastic aggregate is free water accumulated at the surface of plastic aggregate and the smooth surface of plastic particles. Observations reported by Ozbakkaloglu et al. [22] exhibit a reduction in the splitting tensile strength of concrete with the addition of recycled PP plastic aggregates (RPA). The splitting tensile strength decreased by 2.9% and 4.1% for normal strength concrete (NSC) and high strength concrete (HSC) respectively at PP content of 10%, and 5.8% and 7.4% for NSC and HSC at 20% replacement ratio, and lastly 13.7% and 20.3% for NSC and HSC respectively at PP content of 30%. Bhogayata and Arora [23] reported that a combination of recycled plastic fiber (RPF) and styrene-butadiene rubber (SBR) improved the splitting tensile strength of concrete. Splitting tensile strength increased by 27%, 47%, 45%, and 40% for different percentages of RPF and SBR. The addition of RPF restrains crack propagation and thus reduces the splitting of concrete mass by acting as anchors into the hardened mass. In a study carried out by Mohammedhosseini et al. [25], metalized plastic waste (MPW) fiber, in this case, LDPE, was used in the manufacturing of concrete. It was concluded that increasing the percentage of MPW fiber improved the behavior of the splitting tensile strength. In all percentages splitting tensile strength was higher than the control specimen. The increment in the splitting tensile strength of MPW fibers were 12%, 19%, 17%, 13% and 8% for fiber contents of 0.25%, 0.5%, 0.75%, 1%, and 1.25% respectively. It can be noticed that 0.5% of MPW fiber gave the maximum splitting tensile strength. The authors also concluded that the highest splitting tensile strength values were obtained from the 91 days cured specimens. The findings of Yang et al. [26] show an improvement in the splitting tensile strength of SCLC produced with PP aggregates. The authors reported that the maximum value of splitting tensile strength was obtained at a 15% replacement ratio of sand by PP aggregates. This increment is due to the bridging action developed by plastic aggregates which leads to an improvement in the fracture mechanism. Bhogayata and Arora [28] investigated the usability of metalized plastic waste (MPW) in concrete. MPW was used as fiber in different dimensions like 5 mm, 10 mm and 20 mm long and mixed in concrete from 0 to 2% by volume of the mix. It was noticed that the addition of MPW improved the splitting tensile strength and that the dimension and fraction of MPW affected the resistance to splitting tensile strength. The authors stated that increasing the amount of MPW increased splitting tensile strength and they also concluded that fibers with longer length exhibited significantly better resistance to crack by reducing the elongation of micro-cracks when compared to shorter length fibers. Kou et al. [32] stated that increasing PVC content causes a decline in the splitting

tensile strength. This is due to the accumulation of water around the PVC particles caused by the hydrophobic surface nature of PVC particles which leads to the formation of a weak bond between the cement matrix and PVC particles. In a similar study, Haghghatnejad et al. [34] reported that adding recycled PVC as partial substitution of coarse aggregate reduced the splitting tensile strength of concrete. The 28 days age splitting tensile strength of control specimen concrete was measured to be 3.84 MPa, this value was decreased by 3.5%, 6.7%, 14.1%, and 24.2% with the substitution ratio of 20%, 30%, 40%, and 50% of recycled PVC aggregate respectively. This reduction can be attributed to the lower elastic modulus of recycled PVC than that of the cement paste which leads to the initiation of cracks around PVC particles and hence reduced splitting tensile strength can be noticed.

3.5 Modulus of elasticity

Saikia and Brito [20] revealed a reduction in the elastic modulus of concrete produced with PET particles. This was due to the lower modulus of elasticity of the plastic particles. Kou et al. [32] also stated a reduction in modulus of elasticity with the increasing replacement ratio of PVC aggregates. For PVC contents of 5%, 15%, 30%, and 45% reductions in modulus of elasticity were by 6.1%, 13.8%, 18.9% and 60.2% respectively. Mohammed et al. [39] used PVC waste particles both as coarse and fine aggregate. Elastic modulus reduction was noticed with an increasing amount of plastic aggregate as can be seen in Fig. 8. They concluded that coarse aggregate replacement with PVC aggregates caused more reduction in modulus of elasticity than fine aggregate replacement. This is contributed to the effect of elastic modulus of PVC aggregates on the elastic

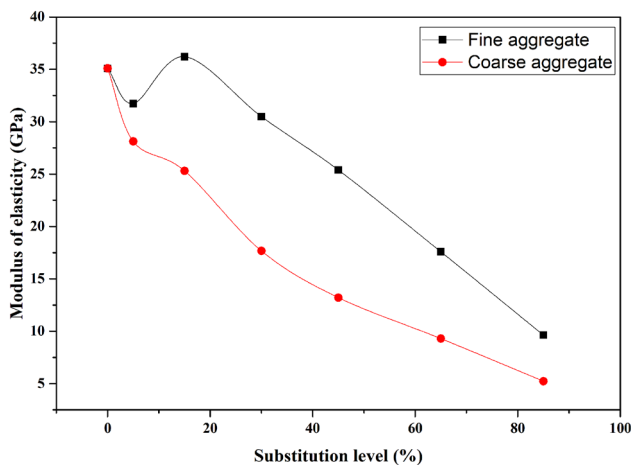


Fig. 8 Variation of modulus of elasticity with plastic PVC aggregates [39]

modulus of concrete; thus, replacement ratio and degree of reduction of elastic modulus of concrete have a linear relationship. The findings of Alqahtani et al. [40] agrees with the works of authors mentioned above, in which they combined LLDPE plastic aggregates with red or dune sand at ratios of 30% and 70% respectively and used as partial replacement of aggregate. The authors reported 58% (11 GPa) loss of elastic modulus in concrete made with plastic aggregate in comparison to the reference concrete.

4 Durability related properties

4.1 Water absorption

Silva et al. [8] observed water absorption behavior of concrete containing plastic aggregate via immersion and capillary in three different environments (outdoor environment, laboratory environment, and wet chamber). Results indicated higher water absorption of concrete specimens cured in an outdoor environment. Water absorption is affected by the relative humidity of the environment. The environment's high relative humidity leads to the greater amount of water in the cement matrix; this means enough water for better cement hydration which optimizes the packing level and porosity of concrete and thus ends up in lower water absorption [41]. It was expected by Silva et al. [8] for the specimens cured in the laboratory environment to have the highest water absorption due to lower relative humidity compared to the other two environments, but results were not as expected. The authors explained this situation by the formation of a thin layer on the exposed layer of the specimens cured in the outdoor environment and wet chamber due to carbonation. Results of water absorption via capillary show that specimens cured in a wet environment had lower water absorption compared to drier environments. Akçaözöğlü et al. [10] concluded that the water absorption ratio for mortars containing PET particles with a PET-binder ratio of 0.5 is 13.4% and 14.8% for different mix proportions.

4.2 Freezing and thawing resistance

Wang and Meyer [18] concluded that no changes happened in the relative dynamic modulus up to 300 cycles which means that HIPS as a partial sand replacement does not affect the mortar's resistance to freezing and thawing. Results from the freezing and thawing test conducted by Kan and Demairboğa [31] demonstrated that after 300 freezing and thawing cycles, compressive strength and relative dynamic modulus of elasticity of concrete produced with MEPS aggregates decreased dramatically. It was also reported that fine lightweight aggregates were

less susceptible to freezing and thawing cycles than coarse lightweight MEPS aggregates. Even though an increase in the amount of MEPS aggregates in mixtures led concrete to show higher resistance and durability, none of the mixtures met the basic requirements of durability. Karahan and Atis [42] reported that concrete produced with PP fiber had a higher resistance to freezing and thawing than concrete without fiber. This was due to the existence of PP fiber which was distributed in the concrete randomly. These randomly distributed fibers block the expansion caused by frozen water in concrete and then decrease the damage of concrete caused by freezing and thawing.

4.3 Shrinkage

Akçaözoğlu et al. [10] reported that using PET plastics as aggregate in mortars provided higher shrinkage values than mortars containing both PET aggregates and sand. At 28 days, length change values for mortars containing only plastic aggregate were 0.17%, however for mortars containing PET aggregates and sand, this value reduced to 0.11%. Lower drying shrinkage of mortars containing both PET aggregates and sand can be seen; this is due to the prevention of shrinkage in the cement paste by sand and PET aggregates. The authors also reported that the cement amount was lower in the mixtures containing both plastic aggregate and sand than those containing only PET aggregates, which is also another reason for having lower shrinkage values since the low amount of cement reduces shrinkage. An investigation done by Kou et al. [32] showed that drying shrinkage decreased as the percentage of PVC plastics as fine aggregate replacement increased. Authors reported a reduction by 18.1%, 31.6%, 48.7% and 72.2% for replacement levels of 5%, 15%, 30% and 45% respectively when compared to the reference concrete. This is attributed to the impervious structure of PVC particles, so they do not absorb water and hence reduce shrinkage of concrete. The results of the study conducted by Sadrmomtazi et al. [33] support the findings of Akçaözoğlu et al. [10] which indicated that using PET plastics as aggregate replacement increased the drying shrinkage of concrete. Shrinkage values of 15% replacement of PET aggregates were 0.31, 0.24, and 0.27 for normal concrete, concrete containing silica fume, and concrete containing fly ash respectively. However, the shrinkage value for reference concrete was 0.18.

4.4 Carbonation

Silva et al. [8] reported that substitution of aggregates by waste plastics increased the carbonation depth of concrete. The authors used three different cured environments such as outdoor environment, laboratory environment,

and wet chamber. It was concluded that specimens cured in the laboratory environment had the highest carbonation depth and those cured in the wet chamber had the lowest value. Akçaözoğlu et al. [10] stated that mortar containing only PET particles as aggregate had a lower carbonation depth than mortar containing both PET and sand. Carbonation depths were 1.2 and 5.0 mm for concrete specimens prepared with 100% PET replacement at 28 and 90 days respectively, while it was 1.4 and 5.9 for concrete containing both PET and sand at 28 and 90 days. This shows that PET particles and sand aggregates do not sufficiently combine and become porous, so more CO₂ penetrates the mortars containing both PET and sand, which leads to a higher penetration depth. The authors also stated that using slag significantly increased the depth of carbonation.

5 Conclusions

This study has provided a detailed review of the utilization of waste plastic particles in the cementitious mixtures. Physical, mechanical, and durability related properties of cementitious materials were discussed in detail, and conclusions are given below:

1. The workability of cementitious mixtures reduces with increasing amounts of waste plastics. The non-uniform shape of plastic particles causes a low flowability. Using high amounts of recycled plastic aggregate and plastic fiber lead to the formation of a stiff matrix and thus reduce the workability.
2. The addition of plastic particles does not improve the compressive strength since the compressive strength of cementitious mixtures containing waste plastic particles decreases with an increasing amount of plastics. This is due to the low adhesive strength between the cement paste and the surface of the waste plastics. The decrease in strength is more pronounced in mixtures containing non-uniformly shaped plastic aggregates than mixtures with the uniformly shaped plastic aggregates.
3. Flexural strength of cementitious mixtures increases with the addition of waste plastic fibers up to a limited percentage, and also the addition of plastic fibers improves the ductility of the mixes. Moreover, plastic fibers with higher tensile strength lead to the formation of a mixture with improved strength. However, waste plastic aggregates reduce the flexural strength.
4. Waste plastic fibers with various lengths and dimensions play a useful role in developing the splitting tensile strength of cementitious mixtures. In contrast,

waste plastic aggregates do not positively affect splitting tensile strength.

5. Replacement of coarse or fine aggregates by waste plastic aggregates reduces the elastic modulus of cementitious mixtures. This reduction is related to the low modulus of elasticity of waste plastics.
6. Higher water absorption values are seen when cementitious mixtures containing waste plastics are investigated. This can be due to the formation of a matrix with an insufficient combination of natural and plastic aggregates.
7. Plastic fibers increase resistance against freezing and thawing; in contrast, plastic aggregates dramatically reduce freezing–thawing resistance or do not affect at all.
8. An increase in shrinkage values has been observed with the addition of plastic aggregates. This can be attributed to the stiffness of plastic aggregates. Plastic aggregates with low stiffness cause the formation of a cement matrix that has meager shrinkage resistance.
9. The carbonation of cementitious mixtures varies for different types of waste plastics. The utilization of recycled plastic aggregates in cement-based materials increases the carbonation depth of the mix due to increased porosity which makes the mix to be less resistant to the ingress of carbon dioxide.

6 Future trends

Many studies have been conducted regarding the use of recycled plastic particles as aggregate and plastic fiber as reinforcement material in cement-based composites. From the outcomes of this review it can be seen that the properties of concrete improve with the use of plastic fiber, however plastic aggregates do not provide enhanced property of the mixture been induced. The reviewed studies mostly incorporate one type of plastic and up to date no studies have been reported on the use of various types of plastic aggregates and plastic fiber together in the same composite. This can be an interesting research topic for the future studies, since the sustainability of cement-based mixture has always been one of the main concerns in the construction industry. Utilization of waste plastic materials as fiber and aggregate helps save the natural reservoirs and also is one of the best ways of disposing these waste materials. It is recommended for the future studies to focus on the long-term behavior of cement-based materials incorporating both waste plastic aggregates and waste plastic fibers.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Gu L, Ozbakkaloglu T (2016) Use of recycled plastics in concrete: a critical review. *Waste Manag* 51:19–42. <https://doi.org/10.1016/j.wasman.2016.03.005>
2. Subramanian PM (2000) Plastics recycling and waste management in the US. *Resour Conserv Recycl* 28:253–263. [https://doi.org/10.1016/S0921-3449\(99\)00049-X](https://doi.org/10.1016/S0921-3449(99)00049-X)
3. Madhavan Nampoothiri K, Nair NR, John RP (2010) An overview of the recent developments in polylactide (PLA) research. *Biore-sour Technol* 101:8493–8501. <https://doi.org/10.1016/j.biortech.2010.05.092>
4. Saikia N, De Brito J (2012) Use of plastic waste as aggregate in cement mortar and concrete preparation: a review. *Constr Build Mater* 34:385–401. <https://doi.org/10.1016/j.conbuildmat.2012.02.066>
5. Plastics-the Facts (2018) An Analysis of European Latest Plastics Production, Demand and Waste Data
6. Plastics-the Facts (2013) An Analysis of European Latest Plastics Production, Demand and Waste Data
7. EPA U (2015) Municipal Solid Waste Generation, Recycling, and Disposal in the United States Detailed Tables and Figures for 2013. US Environmental Protection Agency
8. Silva RV, De Brito J, Saikia N (2013) Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates. *Cem Concr Compos* 35:23–31. <https://doi.org/10.1016/j.cemconcomp.2012.08.017>
9. Azhdarpour AM, Nikoudel MR, Taheri M (2016) The effect of using polyethylene terephthalate particles on physical and strength-related properties of concrete; A laboratory evaluation. *Constr Build Mater* 109:55–62. <https://doi.org/10.1016/j.conbuildmat.2016.01.056>
10. Akçaözöğlü S, Atiş CD, Akçaözöğlü K (2010) An investigation on the use of shredded waste PET bottles as aggregate in lightweight concrete. *Waste Manag* 30:285–290. <https://doi.org/10.1016/j.wasman.2009.09.033>
11. Badache A, Benosman AS, Senhadji Y, Mouli M (2018) Thermo-physical and mechanical characteristics of sand-based lightweight composite mortars with recycled high-density polyethylene (HDPE). *Constr Build Mater* 163:40–52. <https://doi.org/10.1016/j.conbuildmat.2017.12.069>
12. Pirzada RA, Kalra T, Laherwal FA (2018) Experimental study on use of waste plastic as coarse aggregate in concrete with admixture superplasticizer polycarboxylate ether. *Int Res J Eng Technol* 5(03):558–563
13. Foti D (2013) Use of recycled waste pet bottles fibers for the reinforcement of concrete. *Compos Struct* 96:396–404. <https://doi.org/10.1016/j.compstruct.2012.09.019>
14. Záleská M, Pavlíková M, Pokorný J, Jankovský O, Pavlík Z, Černý R (2018) Structural, mechanical and hygrothermal properties of lightweight concrete based on the application of waste plastics. *Constr Build Mater* 180:1–11. <https://doi.org/10.1016/j.conbuildmat.2018.05.250>
15. Manjunath BTA (2016) Partial replacement of E-plastic waste as coarse-aggregate in concrete. *Procedia Environ Sci* 35:731–739. <https://doi.org/10.1016/j.proenv.2016.07.079>
16. Won JP, Il JC, Lee SW, Lee SJ, Kim HY (2010) Long-term performance of recycled PET fibre-reinforced cement composites.

- Constr Build Mater 24:660–665. <https://doi.org/10.1016/j.conbuildmat.2009.11.003>
17. Al-Hadithi AI, Hilal NN (2016) The possibility of enhancing some properties of self-compacting concrete by adding waste plastic fibers. *J Build Eng* 8:20–28. <https://doi.org/10.1016/j.jobe.2016.06.011>
 18. Wang R, Meyer C (2012) Performance of cement mortar made with recycled high impact polystyrene. *Cem Concr Compos* 34:975–981. <https://doi.org/10.1016/j.cemconcomp.2012.06.014>
 19. Bulut HA, Şahin R (2017) A study on mechanical properties of polymer concrete containing electronic plastic waste. *Compos Struct* 178:50–62. <https://doi.org/10.1016/j.compstruct.2017.06.058>
 20. Saikia N, De Brito J (2014) Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Constr Build Mater* 52:236–244. <https://doi.org/10.1016/j.conbuildmat.2013.11.049>
 21. Senthil Kumar K, Baskar K (2015) Recycling of E-plastic waste as a construction material in developing countries. *J Mater Cycles Waste Manag* 17:718–724. <https://doi.org/10.1007/s10163-014-0303-5>
 22. Ozbakkaloglu T, Gu L, Gholampour A (2017) Short-term mechanical properties of concrete containing recycled polypropylene coarse aggregates under ambient and elevated temperature. *J Mater Civ Eng* 29:1–10. [https://doi.org/10.1061/\(ASCE\)JMT.1943-5533.0002046](https://doi.org/10.1061/(ASCE)JMT.1943-5533.0002046)
 23. Bhogayata AC, Arora NK (2018) Workability, strength, and durability of concrete containing recycled plastic fibers and styrene-butadiene rubber latex. *Constr Build Mater* 180:382–395. <https://doi.org/10.1016/j.conbuildmat.2018.05.175>
 24. Kumar KS, Baskar K (2018a) Effect of temperature and thermal shock on concrete containing hazardous electronic waste. *J Hazard Toxic Radioact Waste*. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000387](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000387)
 25. Mohammadhosseini H, Tahir MM, Sam ARM (2018) The feasibility of improving impact resistance and strength properties of sustainable concrete composites by adding waste metalized plastic fibres. *Constr Build Mater* 169:223–236. <https://doi.org/10.1016/j.conbuildmat.2018.02.210>
 26. Yang S, Yue X, Liu X, Tong Y (2015) Properties of self-compacting lightweight concrete containing recycled plastic particles. *Constr Build Mater* 84:444–453. <https://doi.org/10.1016/j.conbuildmat.2015.03.038>
 27. Iucolano F, Liguori B, Caputo D, Colangelo F, Cioffi R (2013) Recycled plastic aggregate in mortars composition: effect on physical and mechanical properties. *Mater Des* 52:916–922. <https://doi.org/10.1016/j.matdes.2013.06.025>
 28. Bhogayata AC, Arora NK (2017) Fresh and strength properties of concrete reinforced with metalized plastic waste fibers. *Constr Build Mater* 146:455–463. <https://doi.org/10.1016/j.conbuildmat.2017.04.095>
 29. Kumar KS, Baskar K (2018b) Effect of temperature and thermal shock on concrete containing hazardous electronic waste. *J Hazard Toxic Radioact Waste* 22:8–13. [https://doi.org/10.1061/\(ASCE\)HZ.2153-5515.0000387](https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000387)
 30. Ghernouti Y, Rabehi B, Bouziani T, Ghezraoui H, Makhloufi A (2015) Fresh and hardened properties of self-compacting concrete containing plastic bag waste fibers (WFSCC). *Constr Build Mater* 82:89–100. <https://doi.org/10.1016/j.conbuildmat.2015.02.059>
 31. Kan A, Demirboğa R (2009) A novel material for lightweight concrete production. *Cem Concr Compos* 31:489–495. <https://doi.org/10.1016/j.cemconcomp.2009.05.002>
 32. Kou SC, Lee G, Poon CS, Lai WL (2009) Properties of lightweight aggregate concrete prepared with PVC granules derived from scraped PVC pipes. *Waste Manag* 29:621–628. <https://doi.org/10.1016/j.wasman.2008.06.014>
 33. Sadrmomtazi A, Dolati-Milehsara S, Lotfi-Omran O, Sadeghi-Nik A (2016) The combined effects of waste Polyethylene Terephthalate (PET) particles and pozzolanic materials on the properties of self-compacting concrete. *J Clean Prod* 112:2363–2373. <https://doi.org/10.1016/j.jclepro.2015.09.107>
 34. Haghghatnejad N, Mousavi SY, Khaleghi SJ, Tabarsa A, Yousefi S (2016) Properties of recycled PVC aggregate concrete under different curing conditions. *Constr Build Mater* 126:943–950. <https://doi.org/10.1016/j.conbuildmat.2016.09.047>
 35. Frigione M (2010) Recycling of PET bottles as fine aggregate in concrete. *Waste Manag* 30:1101–1106. <https://doi.org/10.1016/j.wasman.2010.01.030>
 36. Ismail ZZ, AL-Hashmi EA (2008) Use of waste plastic in concrete mixture as aggregate replacement. *Waste Manag* 28:2041–2047. <https://doi.org/10.1016/j.wasman.2007.08.023>
 37. Rai B, Rushad ST, Kr B, Duggal SK (2012) Study of waste plastic mix concrete with plasticizer. *ISRN Civ Eng* 2012:1–5. <https://doi.org/10.5402/2012/469272>
 38. Malagavelli V, Patura N (2011) Strength characteristics of concrete using solid waste an experimental investigation. *Int J Earth Sci Eng* 4(6):937–940
 39. Mohammed AA, Mohammed II, Mohammed SA (2019) Some properties of concrete with plastic aggregate derived from shredded PVC sheets. *Constr Build Mater* 201:232–245. <https://doi.org/10.1016/j.conbuildmat.2018.12.145>
 40. Alqahtani FK, Ghataora G, Khan MI, Dirar S (2017) Novel lightweight concrete containing manufactured plastic aggregate. *Constr Build Mater* 148:386–397. <https://doi.org/10.1016/j.conbuildmat.2017.05.011>
 41. Toutanji HA, Bayasi Z (1999) Effect of curing procedures on properties of silica fume concrete. *Cem Concr Res* 29:497–501. [https://doi.org/10.1016/S0008-8846\(98\)00197-5](https://doi.org/10.1016/S0008-8846(98)00197-5)
 42. Karahan O, Atiş CD (2011) The durability properties of polypropylene fiber reinforced fly ash concrete. *Mater Des* 32:1044–1049. <https://doi.org/10.1016/j.matdes.2010.07.011>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.