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Review

Utilisation of plastic waste as aggregate in construction materials: A review

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HIGHLIGHTS

- Plastic waste is potential to replace the natural aggregate at specific percentages.
- Materials are fulfilling the standard requirement even after the addition of plastic.
- Plastic addition improves the durability and mechanical properties of the materials.
- Plastic waste utilisation provides benefits to the society, economy and environment.
- Future exploration is required to examine other perspectives of plastic waste utilisation.

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ABSTRACT

Plastic waste accumulation in the environment due to huge volumes of plastic waste produced daily with no effective disposal method and waste management have raised public awareness to look for an alternative to replace the current disposal techniques. Waste utilisation or plastic recycling has been regarded as an excellent method to reduce the abundant amount of plastic waste as well as minimising the environmental impacts. In this article, a total of 163 previous studies between 2012 and 2021 had been reviewed to discuss the utilisation of different types of plastic waste as aggregate in construction materials. This paper evaluates on the use of plastic as aggregate in terms of the physical, mechanical and durability properties of the construction materials as well as the environmental and cost analyses. It was found that the mechanical and durability properties of produced materials were altered after the addition of plastic as aggregates; however, the materials are still fulfilling the requirement of construction materials. Besides, a general SWOT analysis to highlight the advantages and disadvantages of plastic waste utilisation was also conducted.

Contents

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1. Introduction

Since 1855, the production of plastic widely used in many applications including consumer and industry products. This versatile polymer was successfully replaced many raw materials such as wood, metal and papers in the manufacturing of multiple products [1]. It may be due to remarkable properties of plastic such as low cost, easy to use, lightweight, durable, strong and long-lasting. Plastics have been used in many industries such as packaging, electronic, automobile as well as in the medical and healthcare sectors [2]. The increasing consumption of plastic in various industries and sectors has led to the generation of a high volume of plastic wastes in the world. In 2018, the global plastic production was almost 360 million tonnes, which increased about 200-fold from 1950 [2]. The increasing amount of plastic waste produced daily has also increased the plastic waste-related issues such as microplastic pollution, food chain contamination, biodiversity breakdown and also economic loss. According to EPA (2019) [3], about 8.4% of the total plastic waste generated was recycled while 75.8% was accumulated in landfills and the environment. Fig. 1 shows the historical trends of cumulative data for plastic waste management and disposal from 1950 to 2015 and data projections till 2050.

Plastic is undeniably a wonderful manmade invention; however, due to its non-biodegradable properties, it has brought to a variety of repercussions to the environment. Plastic pollution has become the most significant threat in the modern civilisation as it has resulted in environmental pollution as well as affected the economy [5]. The high volume of plastic waste accumulated in the environment has threatened many marine lives and the sustainability of the environment. The plastic dumped into the rivers and oceans tends to contaminate the water and led to the degradation of several toxic compounds from the plastic waste after exposing with the extreme sunlight and physical forces by waves [6,7]. The weathering of plastic to small particles also led to the bioaccumulation and biomagnification in the animals and eventually, damaging their health [8,9]. Aside from that, the plastic waste can also disrupt the drainage system and led to the breeding of mosquitos and water-borne diseases [5]. The blocked drainage will also be caused flooding problems [1]. Besides, the large amount of plastic waste is typically to be landfilled instead of being recycled has also become a significant reason to discover proper plastic waste management [10,11]. The high cost and energy required for landfilling process have resulted part of plastic wastes being accumulated or dumped in the aquatic environment [12]. As a result, plastic has contributed to many environmental problems and at the same time posed hazards to the inhabitants due to its low biodegradable properties.

For environmental protection and sustainable development, recycling of plastic is a feasible alternative to manage plastic waste [13]. In the last decades, the use of plastic waste in civil constructions has been studied extensively [11,14]. In the most cases, plastic wastes have been used in concrete or mortars either as fine or coarse aggregate [15,16]. A wide variety of plastic waste materials have been studied, for example, polyethylene terephthalate (PET), high-density polyethylene (HDPE), polyvinyl chloride (PVC), low-density polyethylene (LDPE), polypropylene (PP), polycarbonate, metalized plastic waste (MPW) and also polystyrene (PS). The excellent properties such as durability, lightweight, strong, hardness and high insulation to heat make plastic waste suitable to be used and recycled in the construction industry. Therefore, the

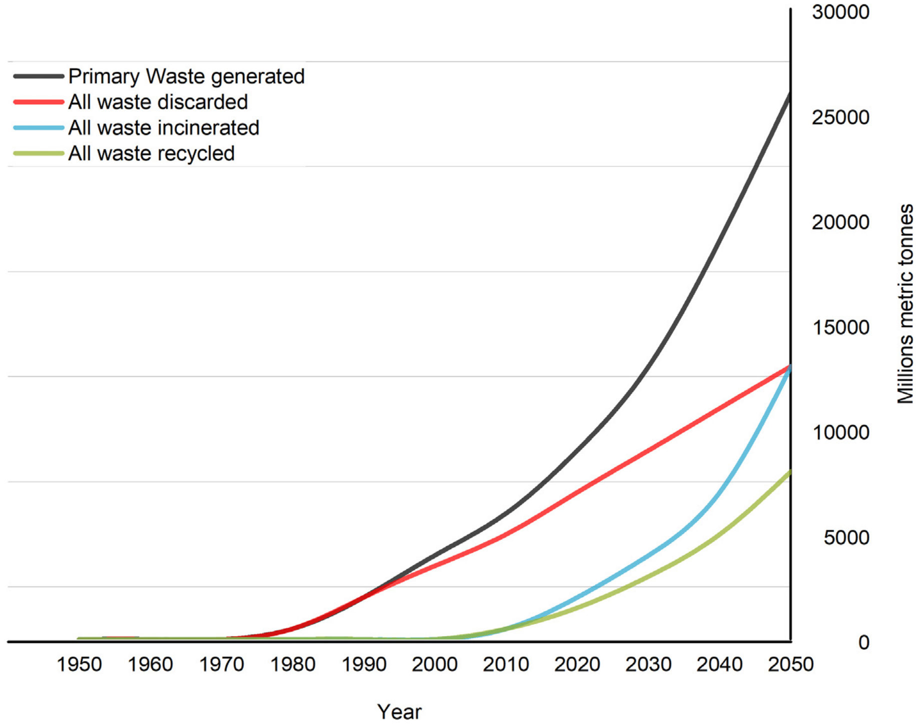

Fig. 1. Cumulative plastic waste generation and disposal (in million metric tonnes) [4].

utilisation of plastic waste in the manufacturing process of construction materials or cementitious composite becomes a great effort to reduce environmental impacts [13]. In fact, replacing natural resources with waste materials will also minimise the environmental damage and the depletion of natural materials caused by quarrying and exploitation of the natural aggregates [17]. Besides, it also provides economic advantage to reduce the cost of conventional materials after replacing a particular portion of aggregate in the concrete or mortar mix.

In this review study, the latest updates on plastic waste utilisation as aggregate in various construction materials are presented. Although plastic waste usage in construction material is advantageous from the environmental perspective, however, the properties of construction materials required further investigation to evaluate plastic waste's potential and feasibility to be used as aggregate. Therefore, the mechanical, physical and durability properties of construction materials containing plastic waste as aggregate are discussed accordingly. Furthermore, this paper discusses a few environmental assessments, such as the leaching potential of plastic additives and plastic aggregate stability in the concrete or mortar mixtures and the relationship between the materials' properties. Moreover, this paper presents a general SWOT analysis covering the economic and sociological potential of this innovative approach of utilising plastic waste in civil engineering applications.

2. Environmental footprints of plastic waste

Plastic benefits human society in numerous ways; however, it also causes a plethora of environmental problems. Plastic has been identified as one of the biggest environmental threats due to its non-biodegradable properties which have made plastic waste as a recalcitrant pollutant in both aquatic and terrestrial environments [18–20]. The slow degradation rate of plastic has majorly eased the plastic to accumulate and widely disperse in the environment. It was estimated about 46,000 pieces of plastic waste have been seen floating on almost every part of the ocean and nearly 8 million tonnes of plastic waste have entered into the oceans annually [5,20,21]. Plastic was found in all major oceanic gyres, polar seas and deep-sea sediments in wide ranges of sizes from macro (≥1 cm), meso (1–10 mm), micro (1–1000 μm) and nano plastics (1–1000 nm) [20,22–24].

Global distribution of plastic waste in the marine environment has induced the interaction of plastic waste with marine fauna as well as increase the tendency of biomagnification of plastics at all trophic levels [10,25,26]. Several broad classes of plastics were frequently found in marine debris, for example, polyethylene, polypropylene, polyethylene terephthalate and polystyrene [27]. These plastic wastes can be entered to the ocean via both land-source and oceanic-source which include fishing and recreational activities, beach litter as well as improper plastic waste management [6,10,21–23]. Approximately 60–90% of plastic debris was found and accumulated in the marine environment, including shorelines, beaches, surface water and seafloor [22].

The increasing of plastic generation and discharge into the environment has led to several environmental burdens especially for the marine environment due to their persistence and harmful effects on the oceans, wildlife and potentially, humans [21,28]. A large amount of plastic waste being washed to the rivers and oceans has created physical hazards to marine lives through entanglement and ingestion where over 690 species of wildlife including marine mammals, turtles and seabirds were affected [29]. Furthermore, the presence of plastic waste in the oceans also led to the degradation of plastic to microplastic in the environment. Plastic can be break down and degraded after being exposed to the environment for an extended period via different mechanisms such as weathering, photodegradation, biodegradation and mechanical forces like turbulence, wave action, and abrasion [6,22,30]. The microplastics have increased the environmental problems since these fragments have a much larger surface area therefore it can be potential to transport and release hazardous substances [29,31].

3. Current plastic waste management

Plastic accumulation keeps increasing from day to day due to the non-degradable properties of plastic waste as well as unsustainable use and disposal methods [32]. Post-consumed plastic waste is usually managed with three common methods which include of landfilling, incineration and recycling [11,33]. However, these methods not giving a significant impact in reducing the amount of plastic waste, thus these methods also not relevant to practice as landfilling and incineration are not environmentally friendly. Various attempts have been made by different stakeholders to replace the current plastic waste management practise. Also, reuse and recycling of plastic waste are more effective than incineration and landfilling, however, the current recycling strategies are unable to mitigate the adverse effects of plastic pollution due to the increasing amount of plastic waste produced daily. Therefore, finding a sustainable application for plastic waste management is highly needed to overcome these issues.

3.1. Landfilling of plastic wastes

Landfilling is an age-old technique in dealing with most of the solid wastes, including plastic waste [34]. It was estimated that between 22% and 43% of plastic waste worldwide is being disposed in landfills [22]. It is the most common practice for non-recyclable plastics by burying into the soil. To date, landfilling of plastic considered as the last resort in managing plastic waste because it requires a vast amount of spaces yet may cause a long-term pollution problem [11]. The cost of operation in landfilling of plastic waste may rather low as compared to the other disposal methods; however, the environmental sustainability of this method is often being questioned. The risk of additives and other potential contaminants to break down from plastic waste and eventually polluting the groundwater system has been a great concern over time [35,36]. A considerable amount of plastic additives and chemical substances can be released from plastic waste and consequently present in landfill leachate [36]. This imply that the plastic additives and monomers are the likely to be released in landfill leachate which may lead in polluting the groundwater system and aquatic environment.

3.2. Incineration of plastic wastes

Incineration is widely used as one of the disposal methods to reduce the volume of solid wastes [37]. This thermal waste treatment is also commonly applied to plastic waste in many countries such as Denmark, Norway and Sweden [38] Incineration is a traditional method in managing plastic waste which significantly reduced the need of plastics landfilling [39,40]. Incineration is capable of reducing about 80–90% of various types of waste, and this has regarded as its advantage [40]. However, incineration has been assessed as an ecologically unacceptable method in the last decade due to the environmental burdens and potential risk to human health [23]. Incineration of plastic waste is a threat to the environment as it may cause atmospheric pollution [23]. The burning of plastic waste gives off toxic fumes, hazardous emissions, harmful substances including particulate matters, carbon monoxide, dioxins and furans; metals, acid gases, volatile chlorinated organic compounds and polycyclic aromatic compounds [23,37,39,41].

3.3. Recycling of plastic wastes

Recycling is the leading practice for plastic waste management in many parts of the world, aside from landfilling and incineration [11,42]. It has always seen as an effective method that can minimise the environmental impact and resource depletion [34,43]. Plastic waste recycling is included with various recycling methods such as mechanical, chemical, and thermal recycling. The plastic wastes were granulated, breakdown into their minor constituent, and reprocessed plastic by the heating process, respectively [14]. Besides, recycling and re-utilisation of materials have many advantages. It can reduce time, cost, energy consumption and virgin material usage per unit of products [44,45]. In that respect, plastic waste utilisation in civil engineering applications recently gained much attention as this approach has considered can remarkably encounter plastic pollution problems. This way, the plastic waste is converted into a construction aggregate where it replaces the conventional aggregate during the production of construction materials. By this method, the plastic waste does not involve any intense recycling treatment. It can be used directly in construction materials as an alternative to conventional aggregate. In this regard, the plastic waste disposes within the hardened construction materials. It prevents a direct return to the environment, unlike landfilling and plastic incineration, which contributed a few environmental consequences through the leaching and heating process [33,46]. Moreover, plastic waste in construction material is also discovered can improve some mechanical and physical properties of the produced materials [47].

4. Review of research on the utilisation of plastic as aggregate

Failure of the proper plastic waste management system becomes the main contributing factor to plastic pollution. The lack of effort in plastic recycling have led to the introduction of plastic waste into the marine and terrestrial ecosystem [10]. The inefficient and non-environmentally-friendly disposal methods such as incineration and landfilling were had indirectly cause the plastic waste ended up in the environment. At present, waste utilisation is considered as one of the most innovative ideas for managing the abundant amount of waste generated as well as reducing the negative impacts on the environment. The utilisation of plastic waste as a partial aggregate replacement has become one of the interesting agenda in the construction sector, and it has been studied extensively in these recent years [13,14,48]. The use of plastic waste in construction helps to reduce the consumption of natural aggregate, which has become one of the important environmental concern nowadays. Many researchers have made remarkable efforts to examine the potential and feasibility of utilising various types of plastic waste such as PET, HDPE, LDPE, PP and PVC in the construction industry [49–51]. A vast of studies have been conducted on different construction applications such as bricks production [52–55], pavement [56–58] and aggregate replacement in concrete [59–66].

Plastic utilisation in the construction industry can be in various forms, and one of them is by incorporating plastic waste as an aggregate. The utilisation of plastic waste as aggregate is generally a substitution of a partial amount of natural aggregate with multiple types of plastic waste. The plastic waste can replace the natural aggregate in two forms either replaced as coarse aggregate (CA) or fine aggregate (FA). Many past studies have been conducted to observe the physical and mechanical behaviour of construction materials with plastic waste as a fine and coarse aggregate replacement [67–70]. The majority of the plastic wastes tested in previous studies were grounded into a small particle which then sieved to obtain the fraction of the suitable sizes [30,71–75]. Then, the small plastic particles were incorporated with various construction materials such as mortar, concrete, brick, pavement and others. However, some studies also used plastic pellets or granulated plastic which had undergone a melting process to pelletised the plastic prior to the

Table 1
Past studies on the utilisation of plastic waste in concrete, mortar, paver block and brick.

Types of composites	Types of plastic	Types of replacement	Percentage of replacement (%)	References
Concrete	EPS	Fine	0, 15, 20, 25	[59]
	–	Fine	0, 5, 10, 15	[79]
	PET	Coarse	0, 0.5, 1, 2, 4, 6	[83]
	HDPE	Coarse	0, 10, 20, 30	[84]
	PET	Coarse	0, 5, 10, 15	[85]
	PS	Coarse	0, 10, 20, 30, 40	[86]
	–	Coarse	100	[60]
	E-plastic	Fine	0, 2, 4, 6, 8, 10	[87]
	PET	Coarse	0, 5, 10, 20	[88]
	HIPS	Fine	0, 10, 20, 30, 40 ,50	[89]
	PET	Fine	0, 1, 2, 3	[90]
	PS	Coarse	0, 45, 67, 73, 82	[91]
	E-plastic	Coarse	0, 10, 20, 30	[61]
	E-plastic	Fine and Coarse	0, 5, 10, 15, 20, 25	[92]
	PS	Coarse	0, 20, 40, 60, 80, 100	[93]
	PP	Fine	0–10	[49]
	Various	Fine and Coarse	0, 5, 10, 15, 20	[94]
	PP	Coarse	–	[68]
	HDPE	Coarse	0, 5, 10, 15, 20	[18]
	PET	Fine	0, 5, 10, 15, 20	[71]
	PET	Fine	0, 2.5, 5, 7.5	[95]
	E-plastic	Coarse	0, 40, 50, 60	[62]
	MPW	Coarse	0, 0.5, 1, 1.5, 2	[96]
	Various	Fine	0, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55	[51]
	Styrofoam	Fine	0, 30, 40, 50	[97]
	PVC	Coarse	0, 25, 50, 75, 100	[98]
	–	Coarse	0, 15, 30	[50]
	HDPE	Fine	0, 10, 20	[99]
	PET	–	0, 1, 3, 5, 7, 10	[100]
	Various	Fine	0, 15, 20, 30, 40, 50	[63]
	E-plastic	Fine	0, 5, 10, 15, 20	[72]
	PP	Fine	0, 10	[82]
	HDPE	Coarse	0, 25, 50	[101]
	E-Plastic	Coarse	0, 5, 10, 15, 18, 20	[64]
	PS	Fine	0, 25, 50, 70, 100	[65]
	PET	Fine	0, 10, 20, 30, 40, 50	[102]
	PVC & PP	Fine	0, 15, 30, 45, 60	[66]
Brick	PET	Coarse	0, 5, 10, 15	[103]
	PET	–	0.5, 1, 1.5, 2	[55]
	E-plastic	Fine	0–10	[104]
	HDPE&LDPE	Fine	0, 5, 10, 15 20, 25	[105]
	HDPE	Fine	0, 10, 20	[106]
	LDPE	Fine	0, 5,10, 15, 20	[75]
	HDPE	Fine	3	[52]
	Various	Fine	10	[107]
	PET	Fine	0, 1, 1.5, 2, 2.5	[19]
	PP	Fine	0, 5, 10, 20, 100	[108]
	EPS	Fine	0, 20, 30, 40, 50	[109]
	PET	Fine	–	[110]
	PET	Coarse	0,1,3, 7	[53]
	LDPE	Fine	0, 20, 25, 30, 50	[111]
	LDPE	Coarse	0, 5, 10, 15, 20	[112]
	Various	Fine and Coarse	0, 50, 100	[77]
	PET	Fine	0, 5, 10, 15, 20	[113]
	PET	Fine	8	[74]
	Polyester	–	0, 10, 15, 20, 30	[54]
Paver block	PET & PP	Coarse	0, 10, 20, 30	[56]
	HDPE	Coarse	0, 2, 4, 6, 8, 10	[57]
	PET	Fine	0, 25, 30	[67]
	HDPE	Coarse	0, 2, 4, 6, 8, 10	[58]
	PVC	Fine	0, 10, 20, 30	[114]
Mortar	LDPE	Fine	0, 10, 20, 30, 50	[115]
	PC	Fine	0, 3, 10, 20, 50	[116]
	PET	Fine	0, 5, 10, 15	[117]
	PET & Polyolefin	Fine	0, 10, 15, 20	[78]
	PP & PE	Fine	0, 10, 25	[76]
	PP & PE	Fine	0, 10, 25	[118]
	PP	Coarse	0, 5, 7.5, 10, 12.5, 15	[69]
	PP	Fine	0, 100, 150, 200	[119]
	Various	Fine	0, 10, 25, 50	[120]

(continued on next page)

Table 1 (*continued*)

Types of composites	Types of plastic	Types of replacement	Percentage of replacement (%)	References
	E-plastic	Fine	0, 2.5, 5, 7.5, 10, 12.5	[73]
	LDPE	Fine	0, 5, 10, 20, 30, 40, 50, 60	[121]
	PET	Fine	0, 2.5, 5, 10, 15, 20	[70]
	PET, POM, ABS, PC	Fine	0, 5, 15, 20	[122]

Note. PET-Polyethylene terephthalate, HDPE-High-density polyethylene, PVC- Polyvinyl chloride, LDPE-Low-density polyethylene, PP-Polypropylene, PS- Polystyrene, PC-Polycarbonate, EPS-Expanded polystyrene, E-plastic- Electronic and electrical plastic and MPW-Metalised plastic waste, POM- Polyoxymethylene, HIPS- High Impact Polystyrene, ABS- Acrylonitrile butadiene styrene.

incorporation of plastic waste aggregate into construction materials [76–78]. Furthermore, modification of plastic waste aggregate by heating and mechanical treatment, mixing with other additives and techniques were also being carried out in the preparation of plastic waste aggregate to improve the quality of the final produced construction materials [66,79–82].

Table 1 indicates that the study of performance in construction materials with plastic as aggregate replacement. A lot of studies have examined the multiple types of plastic waste used as aggregate in various replacement percentages. Most of the findings revealed that the materials produced with plastic aggregate comply with the multiple construction standards and showed positive potential of plastic waste to be used as construction aggregate. For example, Coppola *et al.* [76] found that mortar containing 10% and 25% of plastic aggregate obtained 35.12 MPa and 22.86 MPa of compressive strength respectively, which exceeded the standard requirement of American Concrete Institute (ACI) committee for structural concrete (17.25 MPa). It is also noted that there were several patents for the utilisation of plastic waste as construction aggregate which have been approved (Table 2).

Despite the growing numbers of literature and patents, the commercial production and application of plastic waste as construction aggregate is still limited. The market for the plastic waste aggregate is still yet to be developed, and most of the plastic waste aggregate was applied on a small scale [12,130]. Since the construction materials were produced with plastic waste, few environmental concerns have become the major drawbacks for this utilisation approach to be successfully implemented. According to Zhang *et al.* [130], the potential of waste materials to cause a new contaminant or releasing of few pollutants have adversely influenced the public and industry acceptance on the waste material-based brick or concrete. Contaminants may release during the production process through leaching or any chemical degradation that might cause the construction materials to be unsafe to use. Therefore, environmental impact assessment, such as leaching analysis, should have be conducted to evaluate the properties of construction materials containing plastic waste aggregate [130]. In the following sections, the use of plastic waste as a fine or coarse aggregate replacement was discussed extensively. The physical, mechanical and durability properties along with environmental assessment and cost analysis are also presented.

5. Performance of construction materials containing plastic waste as aggregate

The performance of plastic waste as aggregate was examined to assess its viability to be used in construction industry. There are a lot of essential factors that need to be considered since the addition of plastic waste could affect the performance of composite materials produced. The physical, mechanical and durability properties of made concrete or bricks such as unit weight, density, compressive strength and water absorptivity were investigated accordingly. However, a few pivotal factors such as compressive strength (CS), bulk density (BD) and water absorption (WA) were found to be the most common characteristics that were considered by most of the studies in terms of plastic waste materials performance [131].

5.1. Physical properties of construction materials containing plastic waste

5.1.1. Unit weight and density

In some trials, the unit weight and density of the composite were investigated with the addition of plastic. In most construction materials, plastic replacement includes concrete, mortar and brick, resulting in the production of lightweight construction material, due to the nature of plastic that has low density and very light weight. Hence, several studies found that the weight and density of the materials reduce after the addition of plastic waste as aggregate. Table 3 showed the variation of density recorded in several studies for concrete, mortar and bricks. Rai *et al.* [79] examined the properties of concrete containing mix plastic waste, including fresh and dry density. It was observed that the fresh density decreased after the addition of plastic pellets to the concrete mix. The fresh density for all plastic replacement was notably reduced by 5%, 8.7%, and 10.75% for 5%, 10%, and 15% of plastic percentages, respectively. In addition, with increased plastic content, the dry density of manufactured concrete was also reduced. It was concluded that the drop in concrete density may be due to the low density of plastic pellets used as an aggregate lead in decreasing the concrete density [79].

Chowdhury *et al.* [83] presented an experimental work on the use of polyethylene terephthalate (PET) as an alternative to build construction materials. 0.5%, 1%, 2%, 4% and 6% of conventional aggregate was replaced by PET and mixed with cement to produce the concrete samples. Substantial reduction in bulk density and

Table 2
Patents for the use of plastic waste as aggregate in cementitious composites.

Patent no.	Title	Inventor/Year	Plastic Types	References
US 005422051A	Method for Recycling Plastic into Cementitious Building Products	Sawyers/1995	–	[123]
US 6488766 B2	Aggregate Using Recycled Plastic	Balkum/2002	PVC	[124]
US 006,669,773 B2	Fly Ash/ Mixed Plastic Aggregate and Products Made Therefrom	Malloy *et al.*/2003	–	[125]
US 2006/0106191 A1	PET Artificial Aggregate for the Preparation of Lightened Concrete	Lo Presti and Martines/2006	PET	[126]
US 20120252918	Method and composition for insulative composite building material	Stenger/2012	EPS	[127]
WO 2016/084007 Al	Extruded Plastic Aggregate for Concrete	Barrow *et al.*/2016	–	[128]
US 2017/0088463 A1	Recycled Plastic Aggregate for Use in Concrete	Alqahtani *et al.*/2017	PET	[129]

Table 3
Variation of density of construction materials that were produced with varying proprtions of plastic aggregates.

Types of materials	Plastic proportion (%)	Density without plastic addition (kg/m^3)	Density with plastic addition (kg/m^3)	References
Concrete	0, 5, 10, 15	2400	2300–2225	[79]
Fly ash brick	0.5, 1.0, 1.5, 2.0	2.0	2.1–1.8	[55]
Concrete	0, 5, 10, 15, 20	2365	2336–2221	[18]
Concrete	0, 2.5, 5, 7.5	2350	2340–2310	[95]
Concrete block	0, 5, 10, 15, 20, 100	2350	2250–500	[108]
Mortar	0, 2.5, 5, 7.5, 10, 12	2000	1900–1500	[73]
Concrete	0, 5, 10	2600	2550–2450	[132]
Burnt brick	0, 5, 10	1674	1404–1330	[113]

weight of the concrete were reported in this study. It may be due to directly proportional to the plastic content applied to the concrete mix and indirectly attributable to the plastic's low unit weight. Cadere *et al.* [93] determined the engineering properties of concrete containing polypropylene granules with varying proportions, 20%, 40%, 60%, 80% and 100% of the plastic. The study found that the density of fly ash concrete and polystyrene granules were ranged from 1880 to 2131 kg/m^3, which is lower than the control mix density of 2250 kg/m^3.

Alan *et al.* [55] observed a small reduction of bulk density of fly ash brick prepared with 0%, 0.5%, 1%, 1.5% and 2% of PET strips. The average bulk density reported for all fly ash bricks containing PET was 1.77 kg/m^3, which is less than the density of control brick (2 kg/m3). Ahmad *et al.* [106] used the high-density polyethylene (HDPE) plastic waste to study for cement brick production. The weight of cement brick produced with the replacement of HDPE experienced a reduction which is the average mass of 10% and 20% HDPE bricks was 2.4 kg while the ordinary cement brick was 2.9 kg. The density of the cement brick was also affected after the addition of plastic where 10% HDPE brick and 20% HDPE brick were reduced by 12.96% and 15.78% respectively, compared to the ordinary cement brick with no addition of HDPE.

Rubio-de Hita *et al.* [69] observed the use of mix polypropylene as aggregate in mortars for the production of jack arch floors with timber beams. The density results showed that increasing of plastic waste added in the mortar proportionately reduces the density of the fresh mortar. The same trends also resulted in a hardened density of the mortar containing plastic substitution as the density diminished with increasing plastic percentages. Makri *et al.* [73] found that the density of the specimens exhibited small fluctuations with plastic replacement in mortar. The density of the mortar appeared lower than standard at 2.5%, 5% and 12.5% replacement ratios, whereas the density of the specimens with 7.5% and 10% of plastic were measured slightly higher.

Natural aggregate substituted by plastic flakes or pellets reduces the weight and density of the composite generated due to the difference between plastic density and natural aggregate. According to Rai *et al.* [79], plastic has about 70% much lower density than sand. Therefore, the increasing amount of plastic added into the concrete may result in higher reduction of density. Moreover, Saikia and Brito [85] analysed that density could be influenced by the particle size of plastic or replacement materials. It was found that the cement composite containing larger particles of plastic tend to have lower density compared with the small particles. Hence, it was concluded that the addition of various types and sizes of plastic has led to the reduction in unit weight and density of construction materials [5,11,14].

5.2. Mechanical properties of construction materials containing plastic waste

5.2.1. Compressive strength

Compressive strength is the capacity of material to withstand loads or resist the pressure applied by the compression machine. In order to verify the consistency and efficiency of manufactured concrete, mortar and others, this property is the basic parameter that is extensively tested for most building materials or structural composites. All materials must exceed or meet the basic standard requirements of the structural application in order to be applied or used in any construction activity. The inclusion of plastic in the construction materials is often linked with some deterioration in terms of mechanical properties and engineering properties of the concrete, mortar or brick produced [5,11,14,16,133].

In several previous research, the use of plastic as an aggregate has been found to reduce the compressive strength of building materials such as concrete, mortar, paver block and stone [63,79,105,122,134]. Fig. 2 shows the reported 28-day compressive strength of construction materials containing different plastic types and varying percentages. Generally, the figure shows that the compressive strength was reduced after the conventional aggregate substitution with plastic waste. The increase of plastic content will contribute to the higher reduction in compressive strength of produced materials. The figure also indicates that most of the materials incorporated with plastic waste as aggregate replacement experienced a decline in compressive strength regardless of types of plastic waste added in particular construction material. According to Almeshal *et al.* [14], the use of low elastic modulus plastic as aggregate decreases the compressive strength more significantly than high elastic modulus plastic types.

Wahid *et al.* [103] examined the utilisation of plastic waste as partial aggregate replacement in sand bricks. The study revealed that the value of compressive strength decreases as the ratio of plastic waste increase which may be attributed to the low adhesive strength of plastic to cement paste that led to the decrease of compressive strength in the materials after addition of plastic waste.

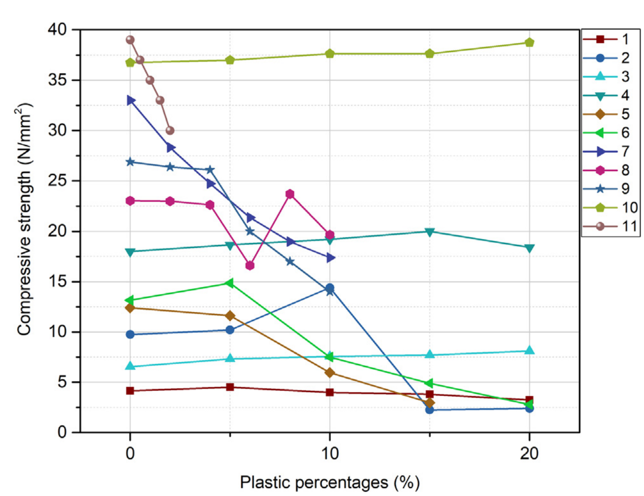

Fig. 2. Variation of 28-day compressive strength of construction materials with varying plastic replacement percentages. (1) HDPE and LDPE brick [105], (2) PET concrete [71] (3) LDPE brick [75], (4) LDPE brick [112], (5) PET brick [103], (6) PP brick [108], (7) PC brick [104], (8) PP concrete [49], (9) HDPE paver block [58], (10) Mix plastic concrete [51], (11) MPW concrete [135].

The brick containing 5%, 10% and 15% of plastic waste obtained a compression value of 11.61 N/mm^2, 5.96 N/mm^2 and 2.98 N/mm^2 respectively. The control brick (without plastic replacement) showed the highest compressive strength at 12.40 N/mm^2. Hence, it was concluded that the reduction in compressive strength might be responsible for the weak bond strength between plastic and cement paste as well as the hydrophobic nature of plastic which inhibited the hydration reaction. Hossain *et al.* [88] investigated the use of PET as a constituent material in concrete. It was observed that there is a decrement in compressive strength after the inclusion of PET in the concrete. However, the concrete containing 10% of PET exhibited a similar compressive strength with the reference concrete at 28 days (16.55 MPa). According to American Concrete Institute (ACI) Committee (1987), the compressive strength of a lightweight structural concrete at 28 days should be within 15.2–17.2 MPa [88].

Coppola *et al.* [76] demonstrated the utilisation of lightweight plastic aggregate (LWA) as natural aggregate replacement which was manufactured from the extruding process that combined two types of PP and PET plastic wastes. It was observed that the mechanical properties of produced concrete decreased with increasing LWA content. The average compressive strength of mortar with plastic aggregate replacement at 10% and 25% were obtained at 35.12 MPa and 22.86 MPa, respectively. However, the compressive strength of mortar obtained after plastic inclusion exceeded the standard requirement of American Concrete Institute (ACI) committee for structural concrete (17.25 MPa). Purnomo *et al.* [68] studied the influence of uncoated plastic and sand coated plastic aggregates on the strength properties of concrete. The results revealed that the compressive strength of concrete containing sand coated plastic aggregate was higher than the uncoated plastic aggregate. The highest compressive strength of the concrete with uncoated plastic aggregate was obtained at 14.25 MPa while the concrete with sand coated plastic aggregated resulted at 18.16 MPa. The concrete with sand coated aggregate achieved a better compressive strength and exceeded the minimum requirement (17.5 MPa) as defined by the Indonesia National Standard SNI 03–2847-2002. This is possibly due to the sand coated aggregate which has rough surface as compared to the uncoated aggregate that has smooth surface and hydrophobia characteristics which disturbed the hydration process during the production of concrete [68].

Bhogayata *et al.* [96] studied the strength properties of concrete with replacement of metalised plastic waste (MPW). In this study, two sizes of plastics, 1 mm and 5 mm of MPW were added in varying percentages (0%, 0.5%, 1.0%, 1.5% and 2%) by volume of concrete mix. It was reported that a reduction trend was observed in the compressive strength with the increased dosage of plastic waste. The larger dimensions of plastic are also likely to cause a decrease in compressive strength. Mahzuz and Tahsin [101] used the high-density polyethylene (HDPE) to replace coarse aggregate in cement bricks. They replaced a partial amount of coarse aggregate using stone chips with HDPE by 0%, 25% and 50%. It was discovered that both compressive strength and unit weight were reduced as the plastic percentage increases in all mix ratios. The highest compressive strength was recorded at 20.62 MPa (1:1:1 with 25% of plastic replacement) which has surpassed the brick classification for first-class brick as per stated in LGED 2005 (Local Government Engineering Department, Bangladesh).

Hamsavathi *et al.* [64], studied on the use of recycled cathode ray plastic tube panel in concrete for concrete beams and other structural applications. It was observed that a reduction in compressive strength after the addition of e-plastics in concrete where the highest compressive strength of 19 MPa was obtained in comparison with the reference concrete (30 MPa). Nonetheless, the study concluded that 15% of plastic aggregate replacement is reasonable as it delivers a good compressive strength and exhibits equal strength while compared to the conventional used concrete beams in a structural application.

From the gathered findings, it can be concluded that the incorporation of plastic as aggregate is indeed causing some form of deterioration in strength of the produced materials. The strength of the construction materials containing plastic aggregate can be affected with several potential factors such as (1) the hydrophobic properties of plastic which inhibited the cement hydration process to fully occur on the surface of plastic aggregates; (2) low surface energy of plastic added to the concrete which has negatively affected the mechanical bond between the plastic waste and cement matrix; (3) the inclusion of plastic waste has created several voids and resulted in high porosity and air content; (4) low elastic modulus of plastic aggregates as compared to natural aggregate and (5) the possible deterioration of materials by several environmental factors such as plastic degradation in an alkaline environment. The hydrophobic property of plastic is seen as the main factor that associated to the reduction in compressive strength where the addition of higher plastic replacement often resulted in a higher content of bleeding water around aggregates and created weaker bonding between concrete lattice and waste plastic aggregate (WPA) [44,68,103]. Besides, Saikia and Brito [85] found that the shape and particles size of plastic added as aggregates could also result in different compressive strengths of construction materials. Waroonkun *et al.* [71] studied the plastic inclusion in concrete with three different sizes of large (4.75–9.53 mm), medium (2.38–4.75 mm) and small (1.19–2.38 mm). The findings revealed that the cement blocks containing the small plastic flakes have the highest levels of compressive strength. Akinwumi *et al.* [53] found that the smaller size of shredded plastic added in the mix of compressed earth brick obtained higher compressive strength as compared to brick containing larger particles of plastic aggregates. The larger particles of plastic created more slip surfaces within the bricks and could cause strength failure [53].

The significant reduction in the compressive strength of concrete and brick have gained attention from many researchers to evolve and adopt different methodologies to improve the current methods of transforming plastic waste into aggregate as construction materials. Rai *et al.* [79], Jaivignesh *et al.* [94] and Correa *et al.* [82] have suggested on the use of admixtures or additives to improve the chemical bond between plastic wastes and cement mixture. Rai *et al.* [79] revealed that the compressive strength of concrete was increased in about 5% after the addition of superplasticiser. Meanwhile, Jaivignesh *et al.*, [94] found that the addition of 0.3% metal fibre can improve the compressive strength of concrete produced. Similarly, Velayutham and Cheah [136] found the same finding in terms of compressive strength after the inclusion of steel fibre in the concrete mix with various volume fractions (0.5%, 1.0%, 1.5%, 2.0% and 3.0%). Concrete which has the maximum volume of steel fibre (3%) obtained the highest values of 70.7 MPa and 11.45 MPa for compressive strength and flexural strength respectively.

Besides, Correa *et al.* [82] also examined the surface treatment method by using surfactant for polypropylene (PP) flakes before the addition to the concrete mix. The concrete samples containing treated PP flakes showed an increase of 16% in the compressive strength and of 8.9% in stiffness as compared to the untreated samples. The results showed improvement on the chemical interaction between the plastic flakes and cement mixture after TS2 (surfactant 2) surfactant treatment was applied to PP flakes. Furthermore, it was found that the application of gamma irradiation on plastic waste has a positive effect on the mechanical properties of concrete as it helps to modify and reorganise the molecular structure of polymers [81]. The application of radiation technology helps in improving the adhesion and bond linking of fibre and matrix

[137]. These treatments are significant in avoiding the diminishment of the strength property of the construction materials containing plastic waste. However, a comprehensive assessment has to be conducted to examine the feasibility of applying the treatments to the plastic waste prior addition as aggregates as these several treatments might create impacts to the environment and increase the overall cost of the materials.

5.2.2. Flexural strength

Flexural strength refers to as the ability of concrete to resist any deformation under heavy load. It is also known as bending strength or modulus of rupture. The effects of flexural strength were also studied on various composites made from the plastic aggregate. Fig. 3 presents the results of the flexural strength of concrete and mortar containing multiple amounts of plastic aggregate. The figure shows that most construction materials experienced a reduction in flexural strength after addition of plastic waste as aggregate. Alqahtani *et al.* [60] found that the flexural strength of the concrete with the addition of recycled plastic aggregate is decreased linearly with the increasing plastic proportions and it was observed that the concrete made with plastic aggregate have the flexural strengths ranging between 3.5 and 4.5 MPa.

Similarly, Bhogayata *et al.* [96] recorded about 9% reduction of flexural strength as compared to the reference concrete. Besides, Rai *et al.* [79], Habib *et al.* [18], Akinyele *et al.* [108] as well as Ohemeng and Ekolu [121] also reported that the use of plastic as aggregate has marginal influence in the reduction of flexural strength in concrete and mortar. Similar to the case of compressive strength, the weak adhesion could be the possible cause of reduction in flexural strength between plastic aggregate and cement matrix [79,138]. The weak resistance at the interfacial transition zone (ITZ) between plastic aggregate and cement paste has reduced the flexural strength [138]. According to Kapoor *et al.* [44], the deterioration of flexural strength can also be linked with the hydrophobic nature of plastic waste which restricts the hydration of cement.

In contrast with the conclusions made by Alqahtani *et al.* [138] and Kapoor *et al.* [44], Hameed and Ahmed [100] observed an increase of flexural strength in concrete with PET replacement at 1%, 3% and 7%. The results showed the flexural strength was increased by 23.11%, 25.59%, 37.93% for 1%, 3% and 7% plastic proportions, respectively. The increment in flexural strength might be due to the reduction of crack propagation, as plastic can hinder the crack growth after adding a certain amount of plastic in concrete [100]. Besides, plastic waste as the aggregate was found can interlock within the mixtures due to its shapes and flexibility, which prevent failure [139,140]. However, the flexural strength of concrete containing higher plastic dosage tends to decrease due to some defects such as voids, decreasing its strength. In this regard, the flexural strength may increase with the limited addition of plastic waste in construction materials. Hamsavathi *et al.* [64] monitored the concrete containing 15% of plastics (e-waste) exhibited an equal strength as compared to conventional concrete where the use of plastic (e-waste) reported to improve the ductility of concrete as the plasticity nature of the e-waste materials have improved the strength of matrix. However, the addition of e-waste beyond 15% is expected to result in a decremental trend of the flexural strength. In this case, the addition of plastic waste can improve the flexural strength for particular dosages. However, the addition of plastic to building materials can also cause defects and reduce the strength of the material. [64,100].

5.2.3. Split tensile strength

Tensile strength is one of the parameters that often being assessed to evaluate the material's ductility. It also determines the load-bearing behaviour of the produced material [141]. The split tensile strength test is often carried out as one method to determine the tensile strength of the produced material. Similar to the compressive strength, the incorporation of plastic aggregate in most construction materials often lower the materials' tensile strength. Substantial reduction of splitting tensile strength was observed in various past studies [18,87,88] on the use of plastic as aggregate in construction materials. Fig. 4 presents the results on the splitting tensile strength for various construction materials containing plastic aggregate. The figure indicates that most of the previous research found that the addition of plastic waste as aggregate affects the split tensile strength of the construction materials. Based on Fig. 4, most of the split tensile strength of concrete containing plastic waste as aggregate were reduced.

Aslani *et al.* [65] analysed the split tensile strength property of polystyrene incorporated with geopolymer concrete. The result shows that, with increasing plastic proportions applied to the concrete, the tensile strength appears to decrease. The split tensile strength values obtained in this study ranged from 0.95 MPa to

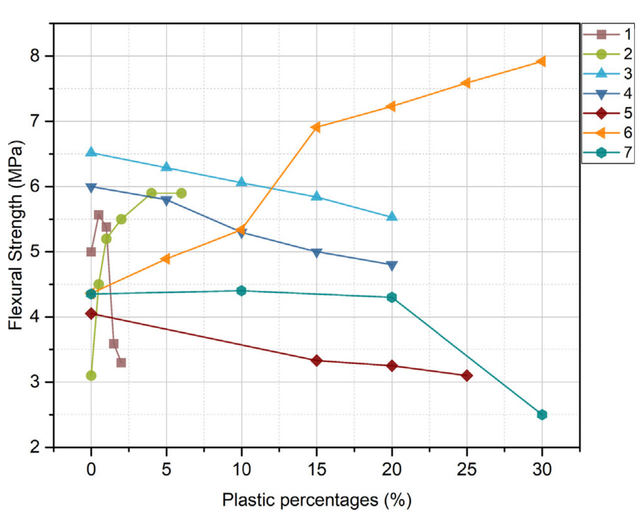

Fig. 3. Variation of 28-day flexural strength of concrete with substitution level of plastic aggregates. (1) PET brick [55], (2) PET concrete [83], (3) E-plastic concrete [72], (4) HDPE concrete [18], (5) Mix plastic concrete [94], (6) Mix plastic concrete [51], (7) E-plastic concrete [61].

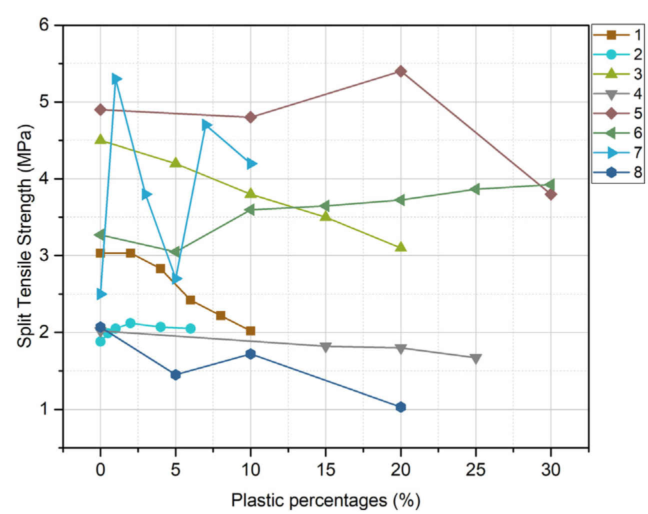

Fig. 4. Variation of 28-day split tensile strength with different replacement ratios and types of plastic aggregates. (1) E-plastic concrete [87], (2) PET concrete [83], (3) HDPE concrete [18], (4) Mix plastic concrete [94], (5) E-plastic concrete [61], (6) Mix plastic concrete [51], (7) PET concrete [100], (8) PET concrete [88].

1.82 MPa, compared to 2.26 MPa for controlled concrete. Habib *et al.* [18] also reported that the inclusion of plastic in concrete decreases the tensile strength. The test result showed that the tensile splitting strengths were decreased from 6.7% to 30% for concrete containing 5% to 20% of HDPE respectively. Cadere *et al.* [93] reported that the highest tensile strength for concrete made with 80% of polystyrene granules at 1.47 MPa, which is closer to the value of tensile strength for the control concrete. Alqahtani *et al.* [138] demonstrated that the tensile strength of concrete was decreasing after the inclusion of recycled plastic aggregate. The split tensile strength of concrete mix containing recycled plastic aggregate was ranged from 1.8 to 2.3 MPa while the reference concrete obtained 2.6 MPa. These results also have a broad agreement with the findings reported by Jaivignesh *et al.* [94], Das *et al.* [87], Al- Azzawi and Shalal [98] and González-Montijo *et al.* [77].

Important research has shown that, with the increasing amount of plastic added, the split tensile strength decreases. Similar to the reason given for the decrease in compressive and flexural strengths, the effect of tensile strength is divided by several previously described variables. The factors include (1) the properties of the interfacial zone (ITZ) between the mixes and plastic aggregates [14,41,60,85], (2) low elastic modulus of plastic aggregates [11] and (3) increase porosity after addition of plastic into the mix [5]. The smooth and hydrophobic surface of plastic has caused the accumulation of free water which led to the weaker bonding of plastic in the cement paste or mix [15,44,85,138]. According to Kou *et al.* [142], the plastic aggregate in the concrete mix was debonded after performing the splitting tensile strength test. This portrayed the weaker bond between plastic aggregates and cement paste yet it also confirmed that the 28-day of splitting tensile strength has a positive correlation with the 28-day compressive strength [142].

Despite to the prior findings, there were a few studies which found contradict outcomes on the split tensile strength. Khatab *et al.* [143] observed an enhancement of splitting tensile strength of concrete containing plastic waste fibres found that the splitting tensile strength increases significantly, and crack development has been restricted. Similar findings also observed in Bhogayata *et al.* [96] where the metalised plastic waste (MPW) was added into the concrete has also improved the split tensile strength in which concluded that the fibres of MPW have contributed to restrict crack development. The improvement of split tensile strength that recorded in both studies might have a relation with the plastic sizes and forms that added in the composites mix. Khatab *et al.* [143] and Bhogayata *et al.* [96] used the plastic fibres-type and found different responses towards split tensile strength and several mechanical properties [11]. According to Alfahdawi *et al.* [133], the fibre-types plastic tends to improve the splitting tensile strength as it was found that many reinforced-fibre concretes have less occurrence to crack. Khatab *et al.* [143] explained that the improvement in splitting tensile strength in the concrete was attributed to the improved bonding after plastic fibres addition into the concrete. The fibres worked and operated with a concept similar to the reinforcement method and resulted in a strong crack-resistant strength with concrete strengthened by ductility.

5.2.4. Thermal conductivity

Thermal conductivity is one of the great properties that have been explored to investigate heat transfer in the materials [144]. From several past studies, it was observed that the thermal conductivity of the construction materials with the inclusion of plastic waste had reduced linearly with the plastic proportions [144–146]. Mondal *et al.* [104] reported that the thermal conductivity of lightweight brick containing polycarbonate was reduced with an increasing amount of plastic added into the bricks. Brick specimens with 10% of plastic have resulted in 0.43 $Wm^{-1}K^{-1}$ while control bricks (with no addition of plastic) obtained 0.84 $Wm^{-1}K^{-1}$ of thermal conductivity. Similarly, Sayadi *et al.* [91] found that the specimens with 82.22% of EPS exhibited the lowest thermal conductivity of 0.0848 $Wm^{-1}K^{-1}$as compared to specimens that contained 45% of plastic (0.1566 $Wm^{-1}K^{-1}$). The reduction in thermal conductivity of bricks after plastic inclusion is mainly attributed to the lower thermal capacity of EPS as compared to conventional aggregate [91]. These findings have a broad agreement with several studies [120,147], which they reported that the thermal conductivity tends to decrease after the addition of plastic into cement composites. The behaviour can also be explained due to the plastic waste has five times lower thermal conductivity than silica [148].

Moreover, Záleská *et al.* [145] investigated the thermal transport and storage properties of lightweight concrete incorporate with expanded polypropylene (EPP) aggregate. It was found that the concrete containing EPP aggregates demonstrated an enhanced thermal insulation property. A substantial reduction in thermal conductivity was observed at concrete containing EPP aggregate. The replacement of silica sand by EPP aggregates of 60% in volume results in a 63% reduction in the thermal conductivity compared to the reference material. Besides, the study's findings also showed that the thermal diffusivity were very low in concrete containing EPP aggregates. Similarly, Záleská *et al.* [119] also found the similar effect in the magnesium oxychloride cement (MOC) composites containing EPP aggregate. These results indicate that the use of plastic aggregate enhances the thermal insulation property of the construction materials. Similarly, Halim, Taib and Aziz [146] also found that the reusing of PET in concrete has gradually decreased the thermal conductivity and lower the heat transfer capacity in developed concrete. The addition of plastic waste has increased the air voids inside the composites, resulting in the declining thermal conductivity values of the produced composites [11,15,44,149]. In short, relative to traditional building materials, plastic waste's inclusion into construction materials has dramatically enhanced the insulating properties.

5.2.5. Fire resistance

The fire resistance of concrete or mortar containing plastic waste is also an essential aspect of the feasibility study where plastic waste might be degraded under extreme temperature and harsh conditions. Coppola *et al.* [76] observed a weight reduction in the mortar prepared with lightweight plastic aggregate after exposing it to high temperature. Sayadi *et al.* [91] investigated the fire resistance of the concrete made up of expanded polystyrene (EPS) and found that the foamed concrete has improved the fire resistance property due to its porous structure. However, a high amount of EPS has led to low thermal stability. Besides, increasing the density of concrete also results in satisfactory performance of fire resistance. The concrete specimen of 250 kg/m^3 reached the insulation threshold (>160) after 1 h 56 min of heating. At the same time, the specimens that were having low density (150 kg/m^3 and 200 kg/m^3) resulted in low fire endurance where both specimens reached the insulation threshold after 17 min and 60 min of heating, respectively. The higher density of concrete specimens tends to have greater fire endurance due to higher paste content and low amount of EPS beads. The ratio of Al_2O_3/CaO also affects the fire resistance of cement composites as they act as a flame retardant [54,91]. In order to determine the thermal stability of the bricks, Barros *et al.* [54] performed a flammability test on the prepared ecological brick specimens that were made of polyester and limestone. For ecological bricks that have 90/10 (polyester/limestone), no flame propagation was observed, whereas the bricks with 100% polyester resin were burned to completion. Due to the presence of limestone in the specimen that can cause flame interruption during the flammability test, the fire resistance of 90/10 (polyester/limestone) can be enhanced [54].

5.2.6. Post-Fire mechanical behaviour

Besides, the thermo-mechanical behaviour of the construction materials that incorporated with plastic waste was also explored. This assesment was used to investigate the structural response of any construction materials at higher temperatures. Saxena *et al.* [150] determined residual compressive strength of concrete containing 5%, 10%, 15% and 20% of plastic waste as fine and coarse aggregate. It was shown that the concrete containing plastic aggregate had a reduction in compressive strength after exposure to elevated temperatures of 300 °C and 600 °C. Both concrete containing the highest replacement ratio (20%) of fine and coarse aggregate were having 59.26% and 50.72% at 300 °C, while 64.81% and 69.57% at 600 °C of reduction percentage in compressive strength. Hence, it was concluded that the higher plastic percentages added to concrete led to the higher residual compressive strength. The above finding is consistent with several past studies [46,47], which also found that incorporating plastic waste as aggregate in construction material has led to reduced post-fire compressive strength. Moreover, Moushavimer and Nematzadeh [33] demonstrated that plastic waste as aggregate replacement in the concrete mixture degraded the flexural properties at increasing temperatures. The concrete specimens containing 15% of plastic waste had a flexural strength of 4.43 MPa and showing a decline of 18.56% compared to reference concrete. The flexural strength was then furthered declined after the specimens were subjected to 250 °C and 500 °C. The reason underlying the declining mechanical properties of construction materials containing plastic waste was discussed in previous studies [33,46,47].

In general, the higher temperature that was subjected to the specimens might cause the evaporation of the free water in the concrete mixtures and lead to microcracks and internal stress [33,47]. Besides, Saxena *et al.* [150] assumed that plastic polymers' thermal degradation might happen during the heating process in which the ester links were degraded to their monomer constituent. This has led to the plastic mass loss and reduction in the materials' porosity and, consequently, higher heat transfer in concrete volume [47]. Moreover, Moushavimer and Nematzadeh [33] found that the reduction in compressive strength and flexural strength was more pronounced in concrete containing plastic waste than concrete containing rubber waste. Therefore, it can be assumed that there are a few changes in the chemical and physical composition of plastic waste in concrete and consequently affected the concrete's post-fire mechanical behaviour.

5.3. Durability performance of construction materials containing plastic waste

5.3.1. Water absorption

Water absorption is another important parameter for durability testing that required by various standards (Table 4). Water absorption is carried out to observe the composite or material's water absorption rate and indirectly measures the water-permeable pore space. The porosity of construction materials such as concrete, mortar and brick can be determined by water saturation, where water molecules can enter spaces in the microstructure [15]. In most research, water absorption has been found to decrease after a rising amount of plastic waste has been added. Fig. 5 illustrates the variations of water absorption in various construction materials containing plastic waste as aggregate. The results revealed that most of the plastic made brick are still within the range of allowable limits by the standard requirements, as shown in Table 4.

Akinyele and Toriola [108] investigated the effects of using polypropylene in the production of sandcrete blocks by adding it

Table 4
ASTM specification requirement for water absorption.

Standard Specification	ASTM designation	Type/Grade	Maximum water absorption (%)
Loadbearing Concrete Masonry Units	C90-16a	Lightweight	18
		Medium	15
		Normal	13
Non loadbearing Concrete Masonry Units	C129-17	–	No limit
Building Brick	C62-10	SW	17
		MW	22
		NW	No limit
Pedestrian and Light Traffic Paving Brick	C902-07	SX	8
		MX	14
		NX	No limit

Note:
SW, SX- Severe weathering, Severe exposure.
MW, MX- Moderate weathering, Moderate exposure.
NW, NX- Negligible weathering, Negligible exposure.

with varying percentages of 0%, 5%, 10%, 20%, and 100%. The water absorption characteristics of the produced block have been found to decrease with increasing plastic content. The highest water absorption was recorded for control brick (no plastic addition) at 16.95%, while water absorption for 100% of plastic additives decreased to 0.67%. The water absorption obtained in this study were lowered than the recommended 17% water absorption level by ASTM C90. It was attributed that the behaviour to the plastic properties of having less affinity for water, and the presence of plastic has reduced the void formation as well as reducing the retention of water in the block materials [108]. The voids formed in the matrix which are supposed to retain water in the system were occupied by the plastic waste. Thus, the more the plastic was added to the mix, the less the void left for water to occupy.

Kamarulzaman *et al.* [109] examined the water absorption properties of cement brick with a partial replacement of expanded polystyrene beads (EPS). It has been shown that after the substitution of plastic waste as an aggregate, water absorption decreases. Compared to the water absorption value obtained by the control brick (11.23%), the cement brick containing the highest EPS content (50%) had a lower water absorption value (4.37%). The authors

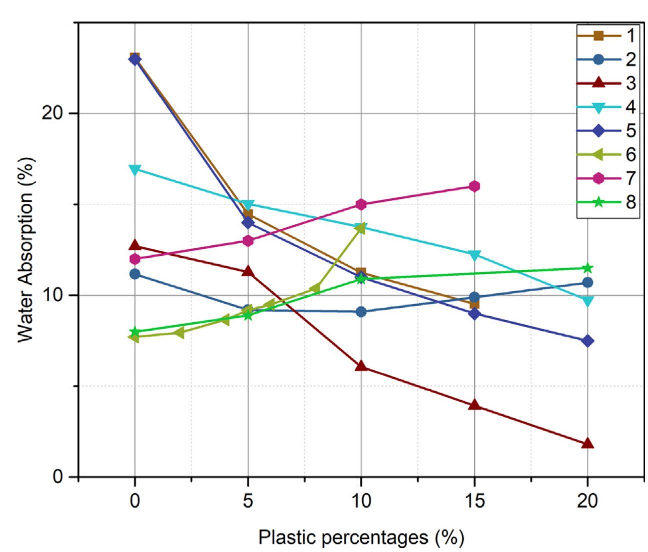

Fig. 5. The water absorption of brick and concrete produced with plastic waste. (1) PET brick [103], (2) HDPE and LDPE brick [105], (3) LDPE brick [75], (4) PP brick [108], (5) LDPE brick [112], (6) PC brick [104], (7) PET concrete [85], (8) PET concrete [88].

concluded that brick with higher EPS has less void as compared to bricks without EPS replacement [109]. Al-Hadithi and Al-Ani [95] reported that the concrete with the addition of PET aggregate (0%, 0.5%, 5% and 7.5%) exhibited continuous reduction with increasing plastic contents. The water absorption recorded to be relatively low between 2.2% and 3.4%. The effects of continuous hydration are ascribed to this action, and because silica fume was used in this analysis, the capillary pores were reduced as the cement paste was filled with mineral admixtures [95]. Therefore, the capillary voids of the produced concrete were decreased proportionately.

However, the decreasing trend in water absorption after plastic addition is inapplicable to many other studies [55,97,104,105,121] as the increasing water absorption was observed subsequent to the plastic addition. Alan *et al.* [55] reported that the bricks with plastic waste (0%, 0.5%, 1%, 1.5%, 2%) obtained higher water absorption as compared to the control brick which has no addition of plastics. The highest water absorption was recorded at 11.5% for plastic replacement of 1.5% and 8.78% on the seventh and 28th days of curing, respectively. On the other hand, the control sample recorded 7.49% and 6.01% of water absorption on the seventh and 28 days of curing, respectively.

Kumar and Gomathi [105] also found a similar trend that 20% of plastic replacement could gain up to 10.7% of water absorption where the increasing water absorption values were observed from 5% to 20% of plastic contents. In contrast, brick with 5% of plastic replacement only gained 9.2% of water absorption. The increase of water absorption with an increasing amount of plastic added can be assumed due to insufficient mixing and inclusion of heterogeneities by plastic into a homogenous cement matrix which has likely to make the materials to be more porous [11,148]. Ohemeng and Ekolu [121] found that there is a rising of water absorption in mortars containing LDPE. Besides, the water absorption was also observed to rise along with the increment in the water-cement ratio (w/c). For instance, at 20% LDPE content, the water absorption was 2.71%, 2.85%, 3.01%, and 3.14% for 0.45, 0.50, 0.55, 0.60 w/c, respectively. It was concluded that for each plastic replacement, the expanding water absorption value could be due to the effects of LDPE plastic inclusion that may lead to higher porosity that is resulted from the poor bond between LDPE particles and cement paste. In addition, inadequate mixing has made the concrete or mortar more brittle for both traditional aggregate and plastic aggregate [11,14].

Due to the difference in findings for water absorption of construction materials, a few intensive studies were conducted to confirm the morphology of construction materials with plastic waste as aggregate [118,148]. Záleská *et al.* [148] found that the higher natural aggregate replacement in lightweight concrete has led to the increasing water transport in the concrete. It was assumed that the rising water transport was due to the concrete's open porosity after adding a higher amount of polypropylene. This was confirmed by observing the microstructure of the produced concrete and concluded that the addition of bigger particles of plastic aggregates has led to the opening of the path for water transport along the boundaries of cement matrix and polypropylene particles. Similarly, Coppola *et al.* [118] also observed an increasing water absorption at a growing amount of plastic aggregates due to the increased open porosity. The higher amount of plastic aggregate was observed to cause a coarsening of porous structure in the interfacial transition zone between cement paste and plastic aggregates [118]. However, the morphology of concrete or mortar containing plastic aggregate can be affected by the substitution level, type, size and shape of used plastic aggregates [11]. This is supported by Záleská *et al.* [148], which revealed that the lower porosity was observed at concrete containing granulated plastic aggregate compared to the crushed plastic aggregate. This has consequently resulted in a lower water absorption capacity of the concrete. In addition, Saikia and De Brito [140] also found the differences in size, shape and texture of plastic aggregates have a significant influence on both fresh and hardened concrete properties. Hence, this might explain the inconsistency of findings for water absorption parameters as the difference in the physical properties of plastic aggregate may result in different outcomes. In addition, Záleská *et al.* [148] observed that the water and water vapor transport parameters of the analyzed concretes increased with the increasing amount of plastic aggregates, but their water vapor adsorption capacity mostly decreased. Therefore, Záleská *et al.* [148] suggested that the hygric performance of developed construction materials should be assessed case by case.

5.3.2. Freeze and thaw resistance

Hannawi and Prince-Agbodjan [151] evaluated the durability of mortar containing polycarbonate aggregate by conducting the freezing and thawing durability test. The addition of plastic aggregate as sand replacement has been stated to have caused a reduction in the mechanical properties of the composites. After successive freezing and thawing cycles, the compressive strength, flexural strength and ultrasonic properties of the mortar have been decreased. It was deduced that the reduction in the mechanical property after the freeze and thaw cycles might ascribe from the formation of crack and voids in the composite due to repeated differential thermal contraction and dilatation of the materials. Nevertheless, the compressive strength obtained after the freeze and thaw durability test are still within the standard for bearing materials as according to International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM LC2) lightweight concrete classification.

5.4. Environmental analysis

5.4.1. Plastic stability in alkaline environment

Cementitious composites such as mortars, concrete and cement brick are highly alkaline which can affect the morphological and chemical of plastic polymers. Portland cement contains calcium silicate and aluminates where it will react with water to form calcium hydroxide [Ca $(OH)_2$] which led to the formation of strongly alkaline solution with pH of 10–13 [152]. Most of the polymers and fibres are chemically inert and highly stabilised in alkaline environment. However, there are few types of polymers such as PET which is susceptible to degradation after exposing it to alkaline environment. Most polymers that have pure carbon backbones appear to have better tolerance to the alkaline environment compared to polymers that have heteroatoms in the backbones [153]. Therefore, in order to analyse the suitability of plastic waste to be used as an aggregate in building products, the resilience of plastic in cement composites has been examined.

Pelisser *et al.* [154] compared the porosity of the PET-fibre-reinforced concrete samples at 28, 150 and 365 days and found a considerable increase in the concrete porosity after one year and portrayed signs of PET degradation in the concrete samples. Moreover, the scanning electron microscopy (SEM) observations of the PET fibres have revealed a high degree of fibre deterioration degradation. Likewise, Fernandez *et al.*, [155], also found changes in PET and HDPE's surface structure after exposing it to the alkaline solution and cement pastes for 270 days. It was seen that the plastic fibres have degraded due to the scissions at polymer chains by hydrolysis of ester bonds in alkaline conditions [156]. On the other hand, the study also found that HDPE plastic has shown higher alkali resistance than PET fibre. Similarly, Silva *et al.* [157] also observed low alkali resistance of PET in cement-based materials as the PET-fibre-reinforced mortar's toughness decreased linearly over time. This may attribute due to the degradation of PET due to the alkaline environment that leads to depolymerisation reaction that breaks the polymer chain [157].

Interestingly, Fernandez *et al.* [155] found that the degradation process of plastic in the cement composites may reduce with the addition of other pozzolan materials. Pozzolans materials such as rice husk ash (RHA), waste of fluid catalytic cracking catalyst (FCC), fly ash (FA), sewage sludge ash (SSA), and ceramic brick residue (CBR) can reduce the presence of portlandite and hydration products of Portland cement which reduce the pH of the mixtures and consequently enhance the durability of the plastic fibres [155]. Despite the degradation process that was observed in the studies mentioned above, the materials produced, such as concrete and mortar, were still showing good behaviour in terms of mechanical and physical properties [154,155]. The degradation of plastic in an alkaline environment or cementitious materials is a prolonged process [154]. Also, most polymers, including HDPE and PP, have high chemical stability and good resistance to the alkaline environment [153,155,158]. Hence, these polymers are not biodegradable and may persist for decades or even centuries in the natural environment [11]. Likewise, the incorporation of plastic in concrete is expected to result in a similar manner in which the plastic remains stable in an alkaline environment [11,158].

5.4.2. Leaching potential of plastic additives from construction materials containing plastic waste

Potential of plastic waste to release any hazardous chemical substances or additives after incorporated with construction materials was also investigated by carrying out leaching analysis. Kumar *et al.* [89] assessed the leaching of heavy metals from concrete that made up of e-plastics by conducting the toxicity characteristics leaching procedure (TCLP). It was found that the heavy metals, such as Cd, Cu, Zn, and Pb concentrations in the concrete samples were below the regulatory level set by the United States Environmental Protection Agency (USEPA) and Resource Conservation and Recovery Act (RCRA). The results also showed that the leaching is decreasing with the increase number of curing days. This has portrayed that the chemical substances or heavy metals can be stabilised in the cement matrix over the time. According to Gu and Ozbakkaloglu [11], the plastic properties which are not able to degrade in short period of time has made it resistant to certain types of chemical and thermal reactions. Therefore, the leaching from the concrete containing plastic waste would not be a concern.

5.5. Cost analysis

The substitution of sand with plastic waste in most construction materials have also been investigated in terms of the economic perspective. Several attempts have been made to evaluate on how the use of plastic waste as aggregate could affect the overall cost of the materials [18,90,107]. Lasiyal *et al.* [90] acquired the cost of the raw materials which are needed to produce 1 m^3 of concrete for 1%, 2%, and 3% of PET replacement. It was found that there are slight decrements in the cost for concrete with plastic aggregates as compared to the cost of the production for 1 m^3 of conventional concrete. The use of 1%, 2% and 3% of PET replacement in the concrete was revealed to minimise the total cost of production of 1 m^3 concrete by 4.7246 Rs (USD 0.064), 9.449 Rs (USD 0.13) and 14.1378 Rs (USD 0.19), respectively. Similarly, Yaseen *et al.* [107] have also found that 10% of plastic replacement in fly ash brick could also reduce about 21.5% total cost for one brick.

Despite to the prior findings by Lasiyal *et al.* [90], Habib *et al.* [18] found a contradict findings as the cost to produce 1 m^3 of concrete with plastic replacement is higher as compare to the conventional concrete. Habib *et al.* [18] revealed the estimated cost of using 15% of plastic as aggregate in concrete was in about USD 340. The cost is much higher when comparing to the standard price of 1 m^3 of conventional concrete USD 185. According to Zhao *et al.* [48], substituting waste materials in the production of construction materials could reduce the production cost, however, there is also some cases that demonstrated higher cost of production upon waste replacement. The increasing in the production cost may affected from the treatments used, the rate of plastic replacement and several other factors that could give rise on the overall cost of the produced material [48]. Future studies are therefore encouraged to determine the cost specifically before mixing with the composites for the different rate and treatment applied to the plastic waste. In order to provide insights into environmental and economic benefits, a comprehensive life cycle review needs to be performed. In general, given the benefits of this recycling method in reducing the problems of plastic contamination, investing in this type of project may be especially worthwhile for waste management and the environment.

6. SWOT analysis on the use of plastic waste as aggregate

SWOT analysis is an assessment tool which analyses the information of a system or plan in terms of its strengths, weaknesses, opportunities and threats. The SWOT analysis, specifically for waste management, is used to understand the internal and external conditions as well as to discover the potentials and ways to implement a system or programme successfully. Notably, the internal conditions are related to the strengths and weaknesses, and the external conditions often refer to the opportunities and threats. Identified SWOTs were obtained from the results of reviewing the plastic utilisation related literature and recent solid waste management reports. A general SWOT analysis for the utilisation of plastic waste as an aggregate replacement was performed, as shown in Table 5.

6.1. Strengths

6.1.1. S1: Improve the performance of construction materials

Previous studies on the use of plastic aggregates in various construction materials has shown exciting results on the performance of the materials containing plastic aggregates. Construction materials including concrete, mortar, brick and paver block that containing plastic aggregates showed higher durability as compared to the conventional construction materials [88,104]. As the proportion of plastic increases, the voids of the produced composite will increase. The increasing of voids in the materials have made the construction materials containing plastic waste to be more porous which increase the water absorption, reduce the thermal conduc-

Table 5
SWOT analysis of plastic waste utilisation as aggregate replacement in construction materials.

Strengths (S)	Weaknesses (W)
• S1: Improve the performance of construction materials • S2: Creating an alternative for aggregate materials in construction industry • S3: Lower cost of construction materials	• W1: Unsuitable for certain applications • W2: Varying proportions and types of plastic aggregates • W3: Lack of understanding on the long-term performance of the plastic aggregates
Opportunities (O)	**Threats (T)**
• O1: Establishment of recycling centres • O2: Promotion of sustainable waste management in the construction industry • O3: Circular economy through plastic recycling	• T1: Economical constraints • T2: Absence of appropriate standard and regulation for recycling plastic as aggregate • T3: Local market for plastic aggregate is yet to be developed

tivity and making it suitable for sound insulation [70,91,159]. Besides, the addition of plastic waste is also observed to slightly enhanced the ductility of the construction materials due to the structure and shape of plastics [160]. The incorporation of plastic waste as aggregate in various construction materials could produce a lightweight material which decrease the dead weight of the buildings. Ultimately, the plastic waste aggregate could minimise the risk from earthquakes as the force of earthquakes depends linearly on the dead weight of a building [14].

6.1.2. S2: Creating an alternative for aggregate materials in construction industry

The extensive extraction of natural aggregate for construction activities has contributed to several environmental issues such as alteration of the river structure, degradation of water quality and harming the ecological systems [161–163]. Several excellent properties of plastic such as lightweight, high melting point and good insulators to electricity, heat and chemicals have attracted many studies on the feasibility of using plastic waste as the conventional aggregate replacement [164,165]. It was found that plastic waste is a prospective material to replace the natural aggregate at specific dosages [64,100,101]. The use of plastic waste in the construction industry can be one of the best alternatives for natural aggregates as it minimises the environmental issues such as plastic pollution and ecological impacts which involved in the mining phase of natural aggregates.

6.1.3. S3: Lowering the cost of construction materials

Reusing plastic wastes as construction substitute materials also helps in reducing the total cost of construction materials production. Generally, plastic wastes are considered as unwanted post-consumer products which, estimated to have lower monetary and economic values. Additionally, plastic wastes are produced abundantly and readily available, thus the use of plastic waste as construction materials will eliminate the cost involved in the production of conventional building materials and will reduce the overall cost of construction. The use of plastic waste for construction will result in substantial cost savings as this recycling approach enable to reduce the natural aggregate extraction and manufacturing activities.

6.2. Weaknesses

6.2.1. W1: Unsuitable for certain applications

The use of low-density materials in the construction industry may give advantages to produce lightweight material; however, it also affects the mechanical properties of the produced materials. The hydrophobic surfaces of plastic waste have reduced the adhesive strength between plastic waste and cement paste [52,103]. The decline in compressive strength is mainly resulted by the weak bond that was produced between plastic surfaces and cement matrix [64,73,121]. The impact on the mechanical properties of plastic waste building materials has rendered the materials unsuitable for use in specific applications where high toughness and elasticity modulus are required [12]. As a result, this has restricted the extensive use of plastic aggregate in building materials.

6.2.2. W2: Varying proportions and types of plastic aggregates

In contrast to the other types of construction materials such as steel, plastic waste is made up of different grades and types which might result in a non-isotropic performance when used as construction materials. The physical and chemical differences of every kind of plastics have become the challenges in this plastic utilisation method. A comprehensive study should be conducted to understand the effects of different types of plastic waste that will be used as construction aggregates. Besides, the optimum proportions of plastic aggregates that will replace the conventional aggregates in construction materials are still yet to be confirmed as most of the previous studies have found different optimum plastic proportions for various construction materials. At present, there is still no standard plastic proportions that can be used to replace the partial amount of natural aggregates for construction materials [12].

6.2.3. W3: Lack of understanding on the long-term performance of the plastic aggregates

Furthermore, the long-term performance and environmental impacts from the utilisation method are still not well understood by public and contractors since there are limited use and acceptance of plastic aggregates in different construction applications [12]. In addition, there are still lack of scientific studies to examine the long-term behaviour of construction materials containing plastic waste as it may influence the governmental and industrial supports for this recycling approach. Accordingly, a comprehensive life cycle assessment on the construction materials with partial replacement of plastic aggregate is urgently required to assess the advantages and disadvantages of the construction materials made from plastic waste in term of ecological, economic and material properties.

6.3. Opportunities

6.3.1. O1: Establishment of recycling centres

The plastic waste utilisation method such as reusing plastic waste as aggregate require public participation and governmental support to ensure the plastic waste supply is in self-sufficient amount. The utilisation of plastic wastes in the construction industry may increase public awareness through plastic recycling and improve plastic waste management [166,167]. The emergence of more recycling centres for waste sorting and segregation will ease the plastic waste collection before converting the plastic to plastic aggregates. Hence, an integrated system for plastic waste management with transfer stations, processing, recovery and recycling facilities can be established to improve the overall plastic recycling process.

6.3.2. O2: Promotion of sustainable waste management in the construction industry

Plastic recycling in the construction industry has been seen as one of the feasible methods for overcoming the issue of plastic waste, reducing reliance on natural resources, ensuring future green construction projects, and enhancing the development of the country 's economy [168]. This form of utilisation not only ensures the safe disposal of plastic waste, but also helps to minimise the use of natural aggregates in construction activities. Sustainable plastic waste management and a sustainable building industry can be practised by applying this approach in the future.

6.3.3. O3: Circular economy through plastic recycling

The recovery of valuable resources from discarded waste for the production of new products could minimise the waste generation and beneficial to the economic development [166,169]. The possible use of plastic waste will add monetary value to materials that have been deemed as wastes which subsequently create an additional source of revenue for various stakeholders interested in the waste recycling materials and plastic manufacturers [12]. Hence, the sustainable management of plastic waste is utmost crucial as it will lead to a positive growth of circular economy and social development.

6.4. Threats

6.4.1. T1: Economical constraints

Recycling in some types of plastic may require advanced technology which could be expensive at the moment; thereby, this could be significant drawbacks in the plastic recycling process [12]. There are few factors including the cost of transportation, the technology required and energy consumption that have to be considered if compared with the production of conventional construction materials. A detailed economy analysis has to be conducted to examine how the utilisation of plastic waste for construction affects the production cost.

6.4.2. T2: Absence of appropriate standard and regulation for recycling plastic as aggregate

Currently, there is no standard which supports the use of plastic waste for construction applications. Despite the number of studies that have been carried out on the use of plastic waste as aggregate replacement in construction materials, this application is still not well received commercially [12]. The establishment of appropriate standard and guidelines in terms of the adopted methods including cleaning and crushing the plastic waste, plastic percentages used, and types of plastic waste that can be utilised as aggregate are crucial specifically in selecting the plastic waste from various sources. Plastic waste is heterogeneous, dirty and highly contaminated, therefore a uniform standard procedure to convert plastic waste aggregate into construction materials is essentially needed for immediate implementation [170].

6.4.3. T3: Local market for plastic aggregate is yet to be developed

Despite the extensive research on the plastic aggregate that has been conducted, the commercial production of construction materials containing plastic aggregate is still minimal. The possible reasons are linked to a lack of understanding of the performance of the products manufactured and the slow acceptance by industry and the public of plastic waste-based products [12,130]. The lack of enforcement of methods and standards for the manufacture of plastic building materials and the possible contamination of the plastic waste used have also led to this hazard [12,130].

7. Conclusions

The reuse and recycling of plastic waste in construction materials has been one of the main research topics of interest in recent decades due to the increasing concern about environmental problems caused by the abundant amount of plastic waste. In order to determine the viability and efficiency of cement composites and construction materials containing plastic waste, a myriad of research studies have been carried out. Different kinds of plastic waste were tested and used as building materials in different amounts to replace the standard aggregate. The properties of construction materials incorporating various types of plastic waste, including unit weight, density, mechanical and durability properties were thoroughly reviewed in this paper. As a result, the following conclusions can be drawn:

1. Construction materials containing plastic waste exhibited lower unit weight and density as compared to the materials without plastic replacement. This has reported that the lower density of produced composite is ascribed due to the low density of plastic waste and the higher porosity of the materials produced.

2. The mechanical properties of construction materials containing plastic decrease with increasing of plastic waste added into the mixture. It was attributed that low adhesive strength between plastic waste and cement paste could cause a reduction in compressive strength. Due to the hydrophobic nature of plastic, the weak interfacial bonding between plastic aggregates with a cement matrix has impeded the process of cement hydration on the plastic surface.

3. Two distinct findings were obtained for water absorptivity of construction materials containing plastic waste. Several studies have shown that the increasing degree of plastic substitution has contributed to a decrease in the absorption of water due to the reduction of material capillary voids, as plastic has less water affinity. However, some studies indicated contradict findings in which the water absorption of the materials was observed to increase with increasing plastic waste added into the concrete or brick mixture due to the increase in porosity.

4. A rigorous feasibility analysis and life cycle evaluation should be conducted in order to study and to provide a more detailed understanding of environmental effects as well as other properties, such as fire resistance, frost resistance and the release of toxic smoke during burning.

8. Future research

The utilisation of plastic waste as aggregate in construction materials has dramatically impacted on the construction sector. This paper has successfully provided new insight into recent research for the utilisation of plastic waste in construction materials and the properties of construction materials containing plastics. More information on the mechanical properties and other durability properties such as porosity and bond strength would help to establish a greater degree of accuracy on the plastic waste construction material. Besides, there is also a limited study on the environmental consequences of the construction materials containing plastic waste for civil applications. It is expected to provide remarkable insights on the ecological perspectives, like long-term performance of plastic materials in the concrete as well as environmental evaluations, such as leachability of plastic additives into construction materials and release of toxic smoke during combustion. Besides, the study on physical and chemical characteristics, ecological consequences of construction and demolition waste from concrete containing plastic waste are also recommended. Therefore, further studies on environmental aspects should be carried out as this study will be significant to lighten the ecological burden of plastic waste as well as creating a sustainable future in the construction industry.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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