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REVIEWS

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A brief review on polyvinyl chloride plastic as aggregate for construction materials

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Abstract

Recycling plastic waste in construction applications is a common concept for innovative concrete development. Enormous studies have been conducted for the past three decades. Yet, there is a need in understanding the behavior of the plastic, its effects on cement composite, and the possible approaches for extending the usage of plastic waste to be an alternative resource component of cement composites. For the first section, the types of plastic and its characteristic as well as the overview on the plastic production and waste generated are discussed briefly. Further, the paper is focused on the relevant information on the plastic waste in cement composites and the polyvinyl chloride (PVC) plastic as plastic aggregate in cement composites. The review also includes the factors that influence PVC aggregate on cement composites which are physical characteristics of PVC plastic aggregate, the effect on mechanical and permeation properties of cement composites. The paper also examines the possible approaches in improving the PVC plastic aggregate characteristics, which can enhance the usage of PVC plastic aggregate for sustainable construction material.

Keywords: Plastic, Waste, Waste management, Recycling, PVC aggregate

Introduction

Incorporating recycled waste is a common concept for the innovation in concrete development. The adoption of the concept is well accepted in the development of concrete provided that the incorporation of the waste did not impair the concrete properties. In the view of recycling, the concept drives through the idea of managing the waste and solving the environmental issue. The latest emerging waste, which has become a globally major concern, is plastic waste. The plastic waste generated reflects the demand on the plastic product, where the plastic production increases with the population growth particularly at developing countries. About 50.1% plastic products is produced in Asia, which implied Asia as the largest region of plastic producer as indicated in Fig. 1 [1, 2].

Recent data published indicates a rapid growth in plastic production globally, with the plastic production increased about 39 million tons between 2015 to 2018 (see Fig. 2), and a further increase is expected in the next 20 years [1]. Figure 2 depicts that the global plastic production mainly generated from the packing industrial, where the production increased from 36 to 40% at 2015 and 2018, respectively [2]. In addition, the COVID pandemic also contributes to the increase of plastic waste because most

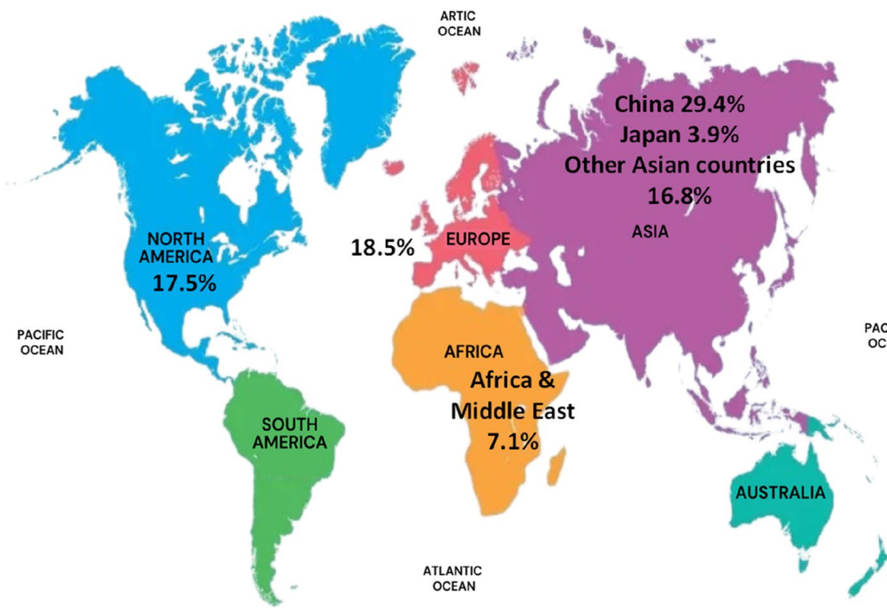

Fig. 1 Global plastic production [2]

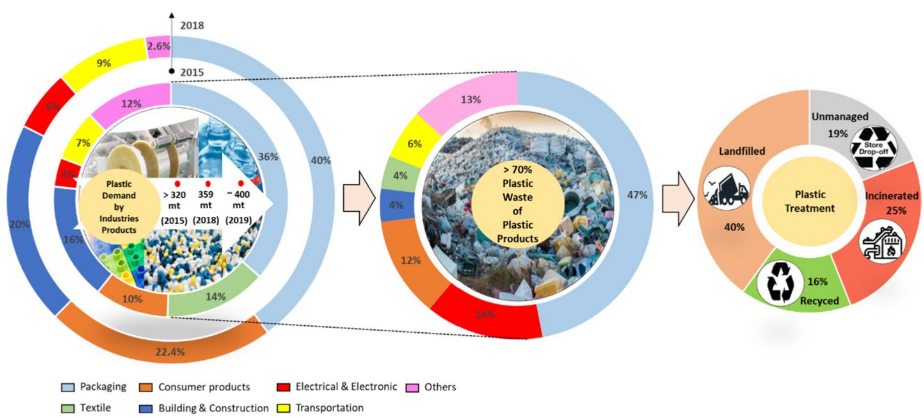

Fig. 2 Industrial plastic products from 1950 to 2018; industrial plastic waste generated and plastic waste treatment (reproduce with modification to Soong, et al. [1, 3, 5])

personal protective equipment is made up from various types of plastic. Consequently, this results in a piling of plastic waste with its non-biodegradable characteristics that will cause a serious environmental problem. Figure 3 shows that the plastic waste generated is dominant by developing countries mainly China and India where the waste produced about more than 20 million tons. The accumulation of plastic waste is responding to the plastic production which mainly dominant by the Asia region. It is estimated that about 70% plastic waste are generated from the global plastic product and the greatest volume of plastic wastes is produced from packaging industrial. About 47%, 14%, and 12% of plastic waste were produced by packaging, electrical and electronic, and consumer product industries, respectively [3]. As mentioned earlier, a massive plastic production results in accumulation of plastic waste and, consequently, gives a negative impact to the environment. Thus, the plastic waste managements are expected to handle the plastic

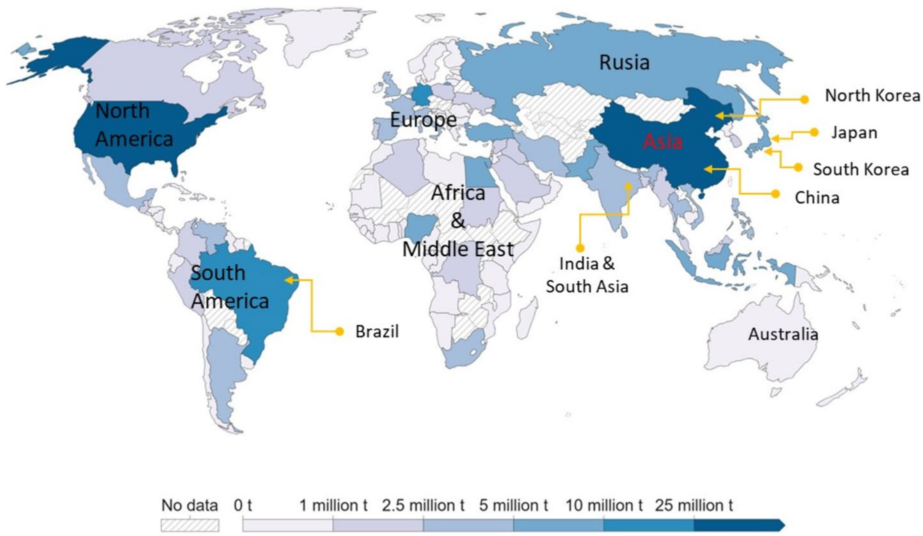

Fig. 3 Global plastic waste generation [6]

waste with the intention to minimize the problematic issues. Data presented in Fig. 2 shows that approximately 40% of plastic waste is disposed in the landfilled. Yet, globally, only 16% of plastic waste is recycled, and 19% is unmanaged according to data for 2015. However, according to Plastic Europe [1], the amount of plastic recycled had doubled from 2006 to 2018. The changes trend on the plastic waste management also found to decrease the plastic waste dumping issue by 1.1% [1]. Though there is positive movement on the trend of plastic recycling, the plastic waste management is still a challenge particularly in developing countries as improper waste collection system, low technology, and financial availability [4].

Furthermore, literature indicates that many works such as agreements, policies, and legislative initiatives had been introduced in improving the waste management system and increasing the rate of recycling [4]. Also, an extensive study on recycling plastic waste into construction application has been done over the three decades (see Fig. 4) [5]. Despite all plastic waste management initiatives and so much work has been published, it is anticipated that the recycling technologies and the unmanaged waste are still at lower rate and remaining a concern that need to be resolved. Therefore, the needs to mitigate the negative impact of plastic to environment is urgent particularly with the increases of plastic production era. At present, a vast amount of review articles on plastic waste management and its potential usage in concrete are available. Yet, there are several properties on the type of plastic waste that may potentially use in construction application that are not well discussed due to the lack availability of information. Therefore, this paper summarizes the generation of plastic wastes and the previous work on the most recycled of plastic type, polyethylene terephthalate (PET), in the cement composite. A thorough review on the potential of polyvinyl chloride plastic waste as component in cement-based composite is also presented. Ultimately, this paper may highlight the benefits of various plastic waste for sustainable alternative material as component of material for construction industry and also extend the possible approaches to enhance the recycled plastic waste.

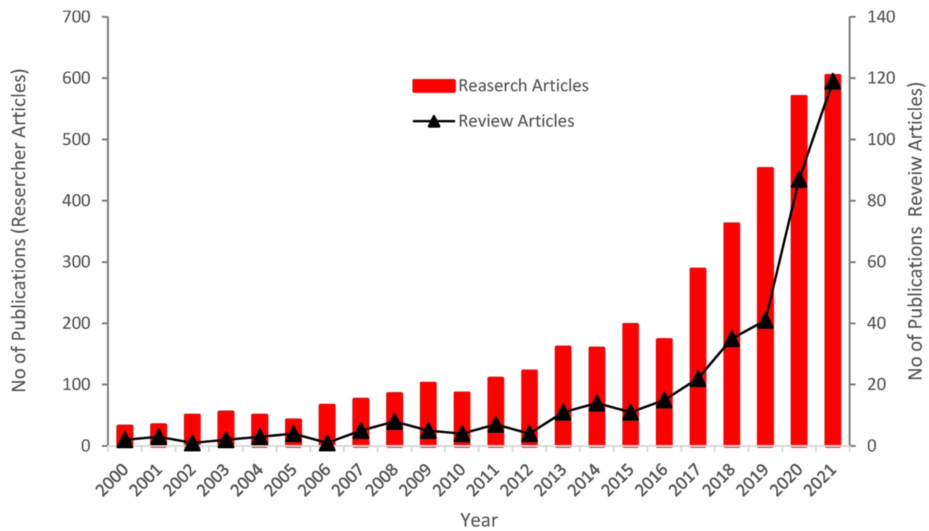

Fig. 4 Publication from 2000 to 2021 on recycling plastic waste [5]

Global plastic waste trend

General

Plastic is also classified as a polymer. Plastic basically can be classified into thermoplastics and thermosets (thermosetting) plastic. In the case of thermoplastic, the plastic can be heated and shaped or molded, and the process can be done repeatedly. The plastic retains the shape once it cooled. In contrast, thermosets plastic will chemically change once the heat is applied, and it cannot be remolded, which mostly is not recyclable [7, 8] Table 1 summarizes the type of plastic according to the plastic's thermal behavior and its characteristic. Among all types of plastic, polypropylene (PP) is the most type of plastic used for plastic production (see Fig. 5) [9]. In term of common plastic properties, PP has lower tensile strength (25–40 MPa) compared to other types of plastic except polyethylene (PE) [10]. Polyethylene terephthalate (PET) (55–80 MPa) and polyvinyl chloride (PVC) (50–60 MPa) possess high tensile strength which about double tensile strength of PP. According to Almeshal et al. [10], the good tensile performance of plastic may be beneficial to concrete properties, as the plastic characteristic is better compared to other concrete's component.

Although recycling is one of waste treatment option, this treatment is not sustainable, and yet landfill is the most chosen method practically [13, 16]. Figure 6 shows the distribution of plastic waste according to plastic type and the recycling rate for plastic waste. The plastic production and the plastic waste generated are majorly by polypropylene (PP) and low density polyethylene (LDPE) [17, 18]. On the recycling point of view, polyethylene (PE), polypropylene (PP), and polyvinyl chloride (PVC) are classified as the easily recyclable plastics and other types of plastic is classified as non-recyclable plastic waste (see Fig. 7) [4, 19]. In contrast, PP and LDPE are categorized as not commonly for recycled treatment according to data collected in 2015 [17, 18]. It is expected that the evolution developed in recycled technology has wider the range of plastic type for recycling. Despite the major classification on the type of plastic waste plastic, plastic waste also categorized by the size of plastic waste. The classification is applicable to all type of

Table 1 Type of plastic and its characteristics

Class	Type	Characteristic	Common uses	References
Thermoplastic polymer	Polyethylene terephthalate (PET)	Tough/hard, clear/transparent. high strength, stiffness, resistance against heat and chemical attacks	Water bottle drink and mineral bottles, dispensing containers for cleaning fluids, biscuit trays	[7, 11]
	Low density polyethylene (LDPE)	Easy process ability, low density, soft, flexible plastic, good chemical resistance, poor abrasion and stretch resistance, milky white color unless a pigment added	Lids of food containers, garbage bags, and rubbish bins	[7, 11]
	High density polyethylene (HDPE)	Easy processing, balance of rigidity, high impact strength, good chemical resistance and waterproofing	Puckered shopping bags, milk storage bags, bottle caps (freeze)	[7, 11]
	Polyvinyl chloride (PVC) - Unplasticized (UPVC) - Plasticized (PPVC)	Versatility, durability, fire resistance Hard rigid plastic, clear Flexible, clear, elastic	Sanitary piping, plumbing pipes and fittings, garden hose, shoe soles, blood bags and tubing	[7, 11, 12]
	Polypropylene (PP) Polyethylene (PE)	Low density, excellent chemical resistance, environmental stress resistance, high melting point, good process ability, dielectric properties, low cost, creep resistance	Ice-cream containers, potato crisp bags, stools and chairs	[7, 11, 13]
	Polymathic methacrylate (PMMA)	High UV light and chemical resistant, transparency, durability	Motorized lamp covers, or for specific applications	[8, 14]
	Expanded polystyrene (EPS)	Glossy, clear in nature, Stiff but brittle plastic Lightweight, foamed, thermal insulation and energy absorbing	Cheap, transparent kitchen ware, light fittings, bottles, toys, and food containers Hot drink cups, insulated food packaging, protective packaging for fragile items	[7, 10, 11]
	Polycarbonate (PC) Acrylic polycarbonate	Transparency, strong, thermal stability, stiff, hard, tough and very rigid	Automotive, glazing, electronic, business machine, optical media and medical, lighting	[10]
	Polylactic acid (PLA); polyhydroxyalkanoates (PHA); acrylonitrile butadiene styrene (ABS)			[10, 15]
Thermosets	Epoxy resins; polyurethanes; phenolic; polyester resins			[8]

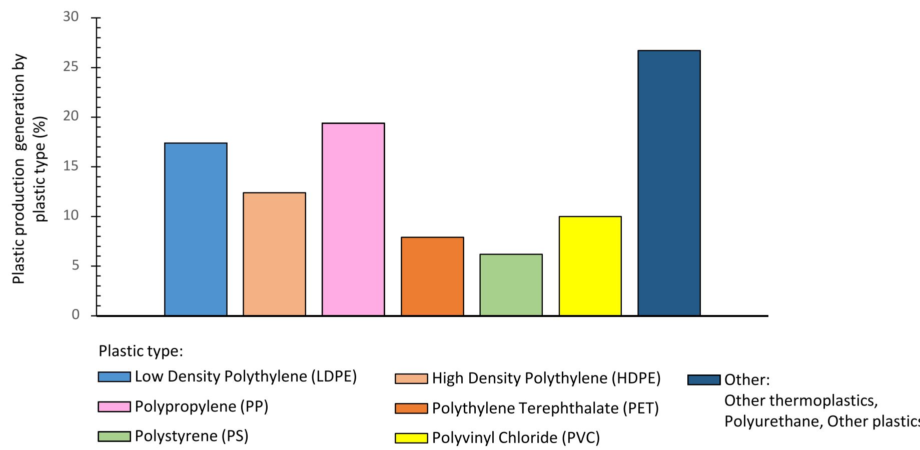

Fig. 5 Global plastic production by the type of plastic in 2019 [9]

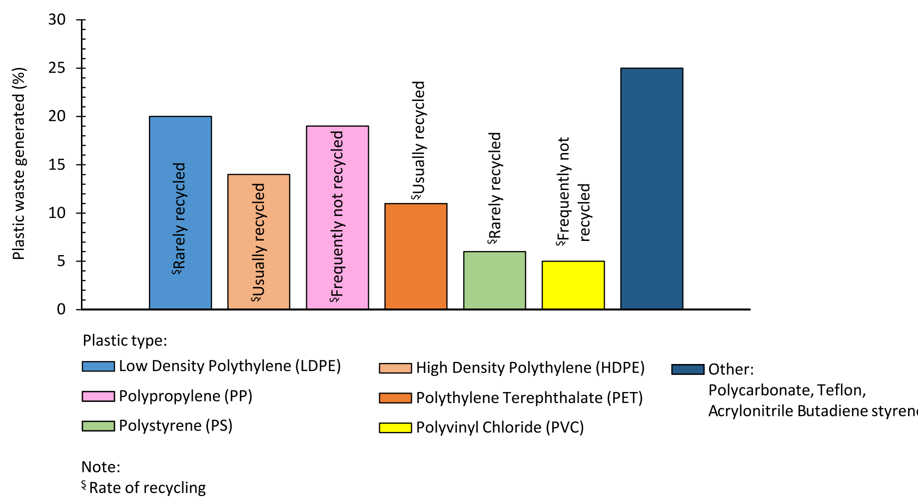

Fig. 6 Global plastic waste generated by the type of plastic in 2015 (reproduce with modification to Issifu et al. [17, 18])

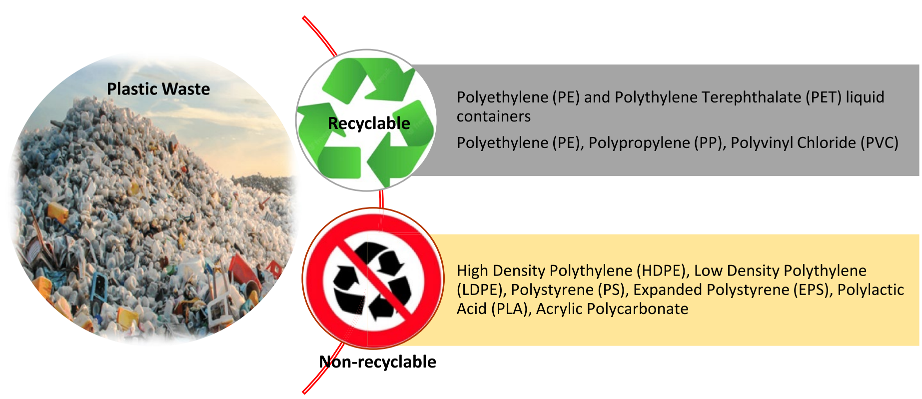

Fig. 7 Plastic waste management process [4, 19]

plastic waste, and this may ease the process for recycling and determining the potential sector for the reuse of recycling plastic waste.

One of particular sectors that has been identified as appropriate option for the reuse of plastic waste is building and construction sectors. This recycling option not only tackling the environment issues and yet, but it also offers an alternative sustainable cement-based composites [13]. However, at present, no cement-based composites are utilized and available although a lot of case studies demonstrated positive and promising findings. This is due to the lack of standardization and commitment (or takers) by authorities and industries, respectively [16]. Nevertheless, information collected on the research activities indicates that the common application of plastic waste in the cement composite is either as (1) polymeric fibers, (2) plastic aggregate, or (3) polymer modified. For the latter application, the recycled plastic can be either in powder or liquid form, which then it is mixed with fresh cement mixture, whereas shredded or fiber form is applicable for the others usage Table 2.

Plastic waste applications

It is well noted that a lot of effort has been done on recycling plastic as an alternative component to replace the traditional component of cement composites particularly as aggregate [20, 21]. Literature also discovers that various studies on plastic waste transformed to alternative resources for mortar and concrete with the focused on hardened properties had been discussed [22, 23]. Many studies approaches are adopted such experimental and simulation methods in producing a sustainable cementitious composites using recycling plastic without compromise its strength properties behavior in general. Furthermore, studies on the use of recycling plastic in cement composites also covered various type of concrete such as lightweight concrete and self-compacting concrete [24–26].

Despite a vast of work has been done on the reuse of plastic waste in cement composites, the selection on which type of plastic waste has better to offer for recycling purposes also need to be considered. Generally, two criteria are used which include the characteristic of the plastic waste and its effect on the environmental. Among various type of plastic, polyethylene terephthalate (PET) has been studied mostly by researchers [27, 28]. Referred to the earlier discussion, PET plastic type is not the major contributor in plastic waste generated. Yet, most of the researchers work with PET, which

Table 2 Classification of plastic waste according to waste size [4]

Class	Size range	Transport pathways	
		Low density plastic (specific density < sea water density)	High density plastic (specific density > sea water density)
Macro plastic	> 25 mm	Floatation	Sedimentation
Mesoplastic	5–25 mm	Floatation	Suspension
Microplastic (MP)	< 5 mm	Floatation	Suspension
Large microplastic (LMP)	1–5 mm	Suspension	Aggregation-sedimentation
Small microplastic (SMP)	< 1 mm 0.2–1 mm	Aggregation-sedimentation	Sedimentation
Nano plastic	< 1 µm	Suspension	Aggregation

they claimed that the PET availability is one of the reasons on the attention of PET in recycled discovery. In 2007, it has been reported that worldwide consumption of PET is about 10 million tons [29] and after 10 years, it has been increasing to 17.8 million tons [30, 31]. Despite the environmental aspect, the major criteria is PET physical characteristic which is one of hard plastic product that has potential for construction purposes, as for possible application shown in Table 3.

On other point of view, it is observed that polyvinyl chloride (PVC) is one of most type of plastic used in plastic production after polypropylene (PP) and polyethylene (PE) plastic types (see Fig. 5). It has been reported that there is an increase in consumption of PVC products [33]. In response to the waste generated, PVC plastic waste also found to be second contributor after polypropylene (PP) and polyethylene (PE) plastic types. However, literature shows that PVC recycling rate is low in practice (see Fig. 6) even it may seriously affect the environment. There is an existence of chlorine in the chemical structure of PVC, which according to Mohammed et al. [33], the risk to environment is higher than others plastic. This may cause major issue to land and water pollution. Yet, very few works found dealing with PVC waste in construction application particularly as plastic aggregate.

Given the background on the application of plastic in the cement-based composites, two interesting points trigger the interest of research. First, it is well accepted that PET is more favorable to reuse in cement composites, and secondly, there are still gaps on the exploiting PVC for alternative sustainable resources in construction industry. Therefore, the intention of this paper is to focus on reviewing work done on the use of recycled PVC waste in cement composites. Furthermore, potential areas and limitation of recycling PVC waste for construction applications are also discussed.

Polyvinyl chloride waste

General

Products made from polyvinyl chloride (PVC) materials have numerous applications in human daily life, and their importance cannot be overstated. In relation to this, result in an increase in PVC waste may risk to the environment. Generally, recycling plastic waste to alternative resources such as plastic aggregate is not only tackling environmental issue but also preserving natural resources of concrete's components [34]. Although extensive work has been done on the plastic aggregate, data on PVC waste specifically are quite scattered Table 4 shows research conducted using PVC waste as a component in cementitious based by some researchers. The summary highlights that most of the studies

Table 3 Physical properties and possible construction application of recycled plastic type [32]

Plastic composition	Physical properties	Possible construction application
High density polyethylene (HDPE)	Rigid	Plastic lumber, table, chairs
Low density polyethylene (LDPE)	Flexible	Bricks and blocks
Polypropylene (PP)	Hard and flexible	Aggregates in asphalt mixture
Polystyrene (PS)	Hard and brittle	Insulation material
Polyethylene terephthalate (PET)	Hard and flexible	Fibers in cementitious composites
Polycarbonate (PC)	Hard and rigid	Aggregates in cementitious composites

Table 4 Overview on work done on polyvinyl chloride in cementitious based by past researchers

References	Type of composite	Type of PVC	Type of substitute	PVC form, size and content
Manjunatha et al. [35]	Concrete	Pipes	Cement	Powder 5, 10, 15, 20, 25, 20% wt
Hu et al. [36]	Concrete	Soft board	Coarse aggregate	5, 10, 15, 20, 30%
Merlo et al. [34]	Mortar	Cables and wires	Fine aggregate	Shredding to granule 63 µm–4 mm 5, 10, 15, 20% vol
Belmokaddem et al. [37]	Concrete	Tubes for underground protection, U-pipe for road drainage system	Fine and coarse aggregate (combined)	Fragmented to granule Fine 0–3 mm Medium 3–8 mm 25, 50, 75% vol
Mohammed et al. [33]	Concrete	Shredded sheet of roofing or wall covering	Fine and coarse aggregate (separated)	Crushing and grinding Max size 9.5 mm 5, 15, 30, 45, 65, 85
Bolat and Erkus [38]	Concrete	-	Fine aggregate	Powder 0–0.25 mm Granule 2–4 mm 10, 20, 30% vol
Haghighatnejad et al. [39]	Concrete	Scrapped pipe	Fine aggregate	Max. size 5 mm 20, 30, 40, 50%
Senhadji et al. [40]	Concrete	Scrapped pipe	Fine aggregate	Graded 0–3 mm and 3–8 mm 30, 50, 70%
Kou et al. [24]	Lightweight concrete	Scrapped pipe	Fine aggregate	Scrap to granular Passing 5-mm sieve 5, 15, 30, 45% vol

were conducted on the recycling PVC waste as aggregate and to evaluate the optimum replacement level with minimum detrimental effect on the properties of the composites. Furthermore, the literature also indicates that various types of formations are used in discovering the potential of PVC aggregate.

Properties of concrete incorporating PVC aggregate

Effect of PVC aggregate on fresh properties

It is well noted that the quality of fresh state influences the properties of hardened state of cementitious composites. Also, it is well noticed that aggregate is one of key factors that govern the workability of the cement mixture, which this relates with size, shape, texture, grading of aggregate, etc. As mentioned earlier, several researchers have investigated various forms of PVC aggregate in cement composite. The results from the works by the researchers are presented and discussed in this section.

Work done by Hu, et al. [36] on using PVC coarse aggregate in normal concrete and considered 5%, 10%, 15%, 20% and 30% replacement level. The researchers recycled PVC waste from PVC soft board, where the board was crushed to flaky particles and then sieved for well-graded particles with the size between 4.75 and 14mm. The finding indicates that the slump decreased with increasing PVC aggregate content, but the trend of decrement is not obvious. The researchers claimed that the flaky and irregular shape of the PVC aggregate affect the workability of the concrete. Also, the increase in specific surface area of PVC aggregate required more cement coating/slurry surrounding the particle. The slump achieved by the researcher is between 161 and 181mm with low slump for high PVC aggregate content (CA5% achieved 181mm). Although there is a decrease in slump, the slumps required for concrete used in road engineering and shotcrete are around 140–160mm and 160–180mm, respectively. Referring to this, the result obtained is within the suggested slump range.

In a study by Belmokaddem et al. [37], concrete mixes were prepared by plastic waste aggregate (HDPE and PP plastic types), and one of the wastes was PVC aggregate for both sand and coarse aggregate for the replacement at 25, 50, and 75%. The finding clearly observed that both, fresh and hardened, densities of concrete decreased with increasing plastic aggregate content regardless of plastic waste types. The researchers stated that the density reduction definitely attributed to the low density of plastic aggregate and porosity increase within the fresh concrete mixture. Furthermore, the researchers found that the concrete with plastic waste aggregate more than 50% can be classified as lightweight concrete due to its hardened concrete density was below 1920kg/m^3, which is the limit of lightweight concrete according to ACI.

In the same manner of replacement approach (but mixing separately) that was investigated by Mohammed et al. [33], the results obtained for the effect of PVC fine aggregate indicated that the slump slightly decreased at 45% PVC, sudden slump drop at 65% PVC, and sticky mix for 85% PVC. A similar trend of slump reduction was observed on the concrete with PVC coarse aggregate. Due to the fact that PVC is granule and the concrete consists of a high proportion of fine particles or powder where the total surface area to weight ratio increases, then it is necessary for an increase in water content to surround the particles [33]. This helps in improving the workability of the mixture. Moreover, the researchers reported that fine aggregate replacement with PVC aggregate did not significantly affect the density of concrete except for 85% PVC (maximum reduction of 16%). In contrast, the density loss is about two times for concrete with PVC coarse aggregate compared to the PVC fine aggregate replacement. The low reduction is due to the high density of PVC aggregate used in the study and particle packing effect due to the physical characteristics of particles (size and shape).

Bolat and Erkus [38] used PVC aggregate in powder (0–0.25mm) and granules (2–4mm) as fine aggregate replacement by 10%, 20%, and 30%. The study reported that the slump significantly affected 10% PVC but slightly better with replacement beyond 10% regardless of PVC aggregate formation. The finding contradicts other researchers' results. Nevertheless, Saikia and Brito [23] reported that a similar behavior was observed by some researcher in the studies of concrete using PET aggregate. The improvement in slump is due to the existence of free water due to no water absorption during mixing. Furthermore, for the powder form, the spherical shape, also the slippery texture, decreased the internal friction between mixture. Besides, Haghighatnejad et al. [39] reported that PVC aggregate affects the slump of concrete. The slump decreased from 75 to 52mm for concrete with PVC aggregate between 20 and 50%. The study evaluated the use of fine PVC aggregate, but according to the grading results, the PVC aggregate used was coarser than sand. Furthermore, the researchers claimed that the workability reduction was due to the sharp edges of PVC aggregate. In the author opinion, the slump reduction obtained is due to the physical characteristics of PVC aggregate, which are larger size and sharp shape.

Kou et al. [24] investigated on PVC plastic granules aggregate to replace river sand by 5%, 15%, 30%, and 45%. The intention of the study is to prepare lightweight concrete with PVC aggregate. The results indicate that the superplasticizer content increased with increasing PVC aggregate to maintain the slump between 160 and 180mm (see Table 5). Despite the high slump range, the mixture of concrete with PVC aggregate was homogenous, but the mixture became less consistent for concrete with 30% PVC aggregate. More than 30% PVC aggregate results in harsh and bleeding concrete mixture. The researchers claimed that physical characteristics of PVC aggregate, which are angular and large size, influenced the loss in workability. A similar trend of slump increases with increasing PVC aggregate that is observed by Senhadji et al. [40]. The slump increased about 82–128% with increasing PVC aggregate between 30 and 70%. For the slump range between 35 and 85mm, no superplasticizer was used in the study. According to Senhadji et al. [40], the hydrophobic nature of plastic aggregate results in more free water, which improve the workability of concrete mixture. Yet, no bleeding and segregation were observed in the concrete mixture.

Kou et al. [24] also highlighted the decrease in concrete density with replacing various percentages of PVC aggregate. The presence of PVC aggregates resulted in a lower hardened density of around 1580 kg/m^3, while the density of concrete with only river sand was recorded at around 1840 kg/m^3. The hardened density of concrete for the mix design is in the range between 1000 and 2000 kg/m^3, as opposed to the normal concrete hardened density of 2400 kg/m^3. In another study on PVC lightweight concrete, the researchers also observed a similar trend of density reduction with increment of PVC aggregate replacement (30–70%) in both fresh and dry densities [40]. Furthermore,

Table 5 Fresh properties of lightweight concrete with PVC aggregate

Type of concrete	**Kou et al. [24]** Lightweight concrete					**Senhadji et al. [40]**			
PVC replacement (%)	0	5	15	30	45	0	30	50	70
Density properties (kg/m^3)									
Wet density	1795	1740	1660	1590	1530	2403	2270	2139	1862
Oven-dried density	1690	1570	1550	1540	1460	2413	2134	1990	1751
Air-dried density	1750	1730	1620	1600	1540				
Hardened density	1840	1775	1720	1670	1580				
Limit of lightweight concrete	1920								
Workability properties									
Slump (mm)	175	175	170	175	170	35	64	75	85
Visual observation	Consistent and homogeneous		Homogenous	Homogeneous but less consistent	Harsh with bleeding	No bleeding or segregation			

the study also found that the density of concrete with high PVC aggregate (≥ 50%) was within the range of lightweight concrete density, as shown in Table 5. The study agrees with Belmokaddem et al. [37]. The findings contribute to useful information for recycling PVC waste in lightweight concrete mixes. The lightweight concrete can benefit to reduce the weight of the structure building, which may reduce the size of structural elements and also lower the risk of earthquake impact.

In general, most researchers agree that workability decreases with increasing PVC aggregate regardless of aggregate components and physical characteristics (shape, size, etc.). Nevertheless, in the author's opinion, the reduction in workability can also be highlighted due to plastic hydrophobic characteristics where more cement paste/slurry mixture is required to ensure that the plastic aggregate is well coated with cement binder. Furthermore, the shredded or flaky form of PVC aggregate affects the workability which similarly to PVC granules effect. In the former PVC aggregate shape, the particle required water to surround, which decreased effective w/c ratio and workability. While for fine PVC granules, as basic principle where a high amount of fine particles increased the surface area which required high water demand for a better workability. Also, the shape and size governed the particle packing of the mixture which influenced the density of concrete. The authors agreed with Mohammed et al. [33] where the slump measurement only is not sufficient in measuring the fresh state of concrete with PVC plastic aggregate, which has various physical characteristics. On the other hand, the author also discovers that limited publication is related with the deeper discussion on properties of fresh concrete involving PVC aggregate in concrete. Thus, the author suggests that an observation on the mixture characteristic should also be carried out for better understanding on the behavior of the concrete incorporating PVC aggregate during its fresh state.

Effect of PVC aggregate on hardened properties

In employing the sustainable concept by incorporating plastic aggregate in concrete, it is important to ensure that the properties of the hardened state of concrete are not detrimental. In the following section, the paper will present the results and discuss the findings from past researchers.

Mechanical properties

Belmokaddem et al. [37] reported that the concrete containing PVC aggregate exhibits a compressive strength that meets the minimum strength requirement of lightweight concrete at 28 days (17MPa). On the other hand, the compressive strengths of 25% PVC and 50% PVC were around 26MPa and 21MPa, respectively, which was within the limit of standard moderate strength of concrete (between 21 and 30MPa) [28]. Yet, the strength of concrete with PVC aggregate was decreased about 23% for 25% PVC and 67% for 50% PVC in comparison to control concrete. The strength reduction can be associated with the fact that the plastic aggregate nature is not comparable to natural aggregate. The smooth texture of plastic aggregate affects the cohesion between cement matrix and plastic aggregate. Nevertheless, PVC aggregate exhibited the best strength performance compared to other types of plastic waste aggregates (PP and PE). This can be attributed to PVC granule particle formation and the particle distribution that is similar to natural sand, which is coarser than fine aggregate limit but smaller than lower limit of coarse aggregate. As a consequence, the aggregate grading improves the fine particle packing matrix within the concrete and enhances the strength of concrete.

Mohammed et al. [33] reported that PVC aggregate can be used up to 30% as fine or coarse aggregate replacement with the mechanical properties of concrete achieving the acceptable strength range (30–40MPa). Beyond 45% replacement level, the strength reduction of concrete with PVC coarse aggregate was higher compared to those with PVC fine aggregate. The strength reduction of concrete with 85% PVC aggregate was about 60% and 80% for fine and coarse aggregate, respectively. The main reason for the strength loss is due to physical characteristics of PVC particles, which is not smaller than 45%, flaky shape, and thickness. Despite the physical characteristics of PVC aggregate, the type of PVC plastic used also influences the properties of plastic aggregate. This can be observed in the work done by Senhadji et al. [40], where the strengths reduction were about 27% and 49% for 50% and 70% PVC aggregate from the scrapped PVC pipe, respectively. The strength reduction obtained was lower than findings by the earlier researcher, which used shredded PVC sheets for the plastic aggregate. Referring to these studies, it shows that different sources of PVC result in different physical characteristics of PVC aggregate, which influences the properties of concrete.

Figure 8 shows the compressive strength of concrete with PVC plastic, which partially substitute either cement or aggregate. The findings suggested that the use of 10–20% PVC plastic could achieve strength of about 30MPa and above provided the minimum cement content which is 350 kg/m^3. Although it is well noted that the strength decreased with increasing PVC plastic content, the characteristics of plastic aggregate need to be also considered. Size and shape of the plastic aggregate are among of important characteristics that are responsible to strength reduction. Furthermore, the plastic major characteristic, which smooth surface and hydrophobic nature also play major role in strength degradation. A combination effect of size and plastic surface nature results in low capability of plastic particle being coated with cement paste. This affects the packing of concrete microstructure, which leads to void formation within the cement matrix and finally affect the strength development. On the other point, it is also observed that concrete with PCV plastic has a potential for load bearing and non-load bearing applications as

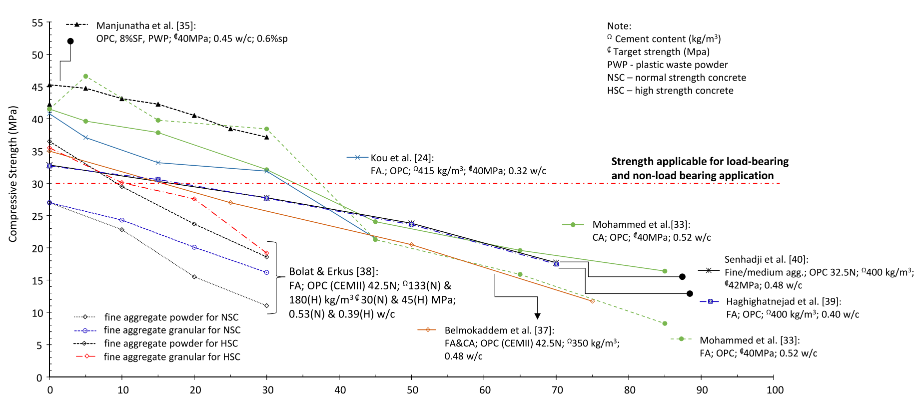

Fig. 8 Compressive strength of concrete with PVC plastic waste at 28 days

the strength obtained able to achieve 30MPa. Furthermore, the strength performances between concrete with PVC plastic and other type of plastic are shown in Fig. 9. It is clearly observed that below 30% of plastic aggregate results in concrete strength at minimum of 25MPa regardless the type of plastic. Also, the is a potential to extent the usage of plastic waste beyond 30%, which a further enhancement should be determined in minimal the adverse effect on the strength.

On the other hand, Merlo et al. [34] claimed that PVC aggregate did not contribute to mechanical strength of the concrete. The researchers discovered that the presence of PVC aggregate weakened the structure within concrete due to its availability, which increased the porosity of the concrete. The findings also observed that poor adhesion between PVC aggregate and cement matrix, which creates pores surrounding PVC particles and consequently, affects the mechanical properties of concrete which include compressive and flexural strengths.

It is well accepted that there is a strong relation between splitting tensile and compressive strengths. Mohammed et al. [33] observed splitting tensile strengths reduction with increasing PVC aggregate content, which is similar to the trend of compressive strength of concrete with PVC aggregate. However, the study discovered that there is no significant difference in splitting tensile strength with the use of either fine or coarse PVC aggregate. Haghighatnejad et al. [39] also found PVC aggregate lowering the splitting tensile strength. In comparison to splitting tensile strength of 3.48MPa for control concrete, the tensile strength decreased about 3.5%, 6.7%, 14.1%, and 24.2% for 20%, 30%, 40% and 50% PVC aggregate, respectively. The researchers concluded that the low interfacial bond strength between PVC aggregate and cement matrix causes the loss of splitting tensile strength. Similar reason was also claimed by Merlo et al. [34]. Furthermore, the low elastic modulus of PVC aggregate causes initiation of cracks surrounding PVC aggregate particles, which consequently affect the strength.

A similar trend to that observed on compressive and splitting tensile strengths, increasing aggregate replacement with PVC aggregate, reduces the elastic modulus of concrete. Mohammed et al. [33] found that for concrete with 5–45%PVC aggregate, the

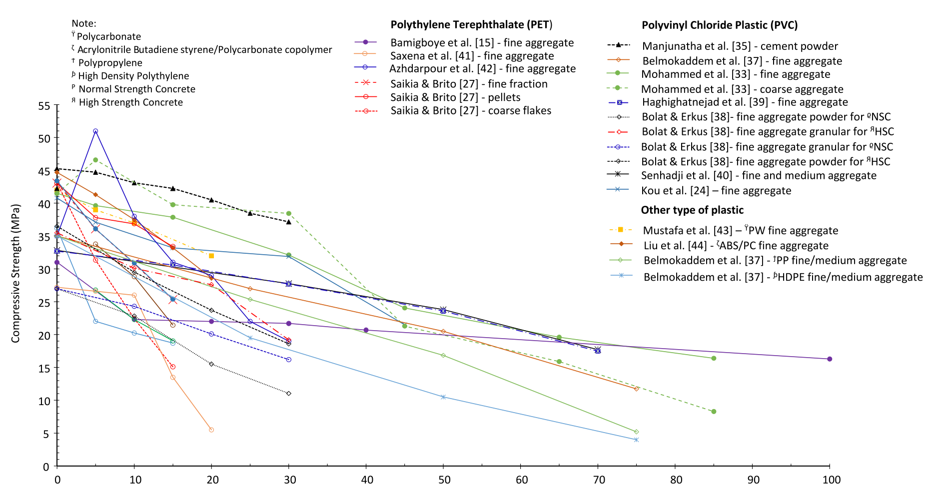

Fig. 9 Compressive strength of concrete with various type of plastic at 28 days

elastic modulus decreased about 9.5–13% and 20–50% for fine and coarse aggregate replacement, respectively. The findings show that the coarse aggregate replacement has affected the elastic modulus pronouncedly. Nevertheless, this behavior is expected as the low elastic modulus of plastic aggregate definitely affects the elastic modulus of concrete. Similar findings are observed by Haghighatnejad et al. [39], but the loss of elastic modulus for 45% PVC aggregate is lower than obtained by Mohammed et al. [33]. Similar reasons as discussed for compressive and tensile strengths are also supporting the finding on elastic modulus.

Mohammed et al. [33] also investigate the behavior of concrete with PVC aggregate by ultrasonic pulse velocity (UPV) measurement. The study also found that increasing PVC aggregate decreased the UPV results, but the UPV reduction was less than 16% for those concrete with PVC aggregate less than 45% (either fine or coarse aggregate replacement). A higher UPV loss was observed for those concrete with PVC aggregate content beyond 45%, and the UPV loss reached about 30% for concrete with 85% PVC aggregate. The finding also observed that the reduction in UPV is much greater for the coarse aggregate replacement since this increases the pores and honeycombing within the matrix of concrete. On further analysis in comparison between various plastic aggregates using UPV measurement with work done by Albano et al. [28] and Akçaözoğlu et al. [41], the researchers conclude that the PCV aggregate based on sheet is not as effective as that of scrapped PVC pipe and PET.

Permeation properties

Mohammed et al. [33] discovered that there is no significant difference for initial and final absorption of concrete using PVC aggregate either as fine or coarse PVC aggregate with the content below 45%. Yet, the researchers claimed that the concrete's absorption obtained in their study was high compared to others work, which was due to the flaky PVC particle that caused poor transition zone and macro-cracks within the concrete matrix.

In contrast, Bolat and Erkus [38] through their research work reported that it is possible to use plastic aggregate in resisting water absorption of concrete provided that the strength of concrete is not adversely affected. The authors found that the capillary water absorption of concrete containing PVC aggregate decreased with increasing PVC aggregate content (10–30%) particularly for PVC in powder form. Bolat and Erkus [38] noted that PVC aggregate (powder and granule formation) decreased the density and strength, but the presence of those aggregate enhances the permeation performance. From the study, Bolat and Erkus [38] concluded that the contradict performance in absorption measurement is due to the combined effect of plastic aggregate characteristics, which are hydrophobic nature, that water repelling and filling of the capillary pores due to its powder form, which can disturb the continuity within capillary pores. Furthermore, the authors also suggested that concrete with plastic aggregate can also be applied for kerbs and gutters, pavements, parks, gardens, and coverings for water-retaining structures that are all possible applications despite lightweight concrete applications.

A similar trend of absorption reduction for concrete with PVC aggregate was also obtained by Haghighatnejad, et al. [39]. The researchers found that the initial absorption of concrete with 20–50% PVC aggregate was between 0.21 and 0.26%, where the concrete can be classified as good concrete according to CEB-FIP (absorption value of 0–3%). For the final water absorption, it was observed that the absorption was relatively low as the range of absorption was within 0.39–0.85% for all concrete. Furthermore, the study also found low water absorption with higher PVC aggregate content, which is similar to other findings.

Enhancement method on PVC aggregate

Blended cement binder

The mechanical properties of cement composites containing plastic aggregates can be improved with the enhancement on cement binder. Principally, the low strength of plastic aggregate can be compensated by the strength of cement paste. Furthermore, the enhancement in cement binder will also improve the matrix bonding between plastic aggregate and cement paste.

Several works have been done to achieve the goal in incorporating plastic aggregate in concrete without affecting its mechanical properties. Manjunatha et al. [35] studied on the green concrete which was prepared with PVC waste powder (PWP) (at 15–20% PWP and fixed contents of ground granulated blast slag (GGBS)). The results showed that the mechanical properties (compressive, split tensile, and flexural strengths) of concrete increased with the presence of GGBS. In 2021, Manjunatha et al. [42] discovered that PWP combining with concrete blended with 8% silica fume showed a promising performance on mechanical properties of concrete. The presence of GGBS or silica fume, which is classified as pozzolana, possesses the pozzolanic reactivity. By having the pozzolanic reactivity, the cement matrix is improved with the additional cement gel. Furthermore, the weakness at the interfacial zone between plastic aggregate and cement matrix also decreased with the presence of additional cement gel. In consequence, the enhancement of the cement matrix results in mechanical strength improvement. The study also demonstrated that PVC waste concrete made with blended cement (GGBS and silica fume) significantly reduces environmental damage due to the usage of cement replacement which reduces the CO_2 production by reducing cement usage.

Punitha et al. [43] also observed the strength improvement on concrete with HDPE plastic waste with the inclusion of metakaolin (MK). The study investigated the strength of concrete with varying ranges of HDPE plastic (5–30%). The finding shows that the inclusion of 10% MK improved the strength of concrete with HDPE content not more than 15%. The result also shows that 15% HDPE with 10% MK is the optimum combination that results in higher strength than control concrete. Beyond 15% HDPE, the strength obtained decreases with increasing HDPE content. Based on this finding, the study suggests that MK did not fully chemically react as pozzolanic with the higher HDPE content. The strength achieved could be due to the physical characteristic of MK, which react as the filler that dense the cement matrix microstructure. Overall, the improvement of cement matrix is one of the methods to enhance the performance of concrete with plastic aggregate. However, there is a limitation with using pozzolan at high plastic aggregate content, which may react chemically and physically or physically only. The latter role of pozzolan may help the performance of concrete with plastic aggregate but not surpass the performance of concrete without plastic aggregate.

Plastic aggregate surface treatment

Another method of enhancement is on the modification of PVC aggregate, where the treatment is applied on the PVC aggregate. The treatment applied is commonly to modify the surface texture of the PVC aggregate. Improving the surface texture, enhancing the bonding between PVC aggregate and cement paste. As a result, this improves the microstructure and the strength of cement composites.

Pan et al. [44] also conducted research to find methods of improving the mechanical properties of PVC waste concrete. The researchers' study on modification of PVC waste particles, where the plastic aggregate surface was pre-treated with encapsulated silane coupling agents (SCA) to improve the mechanical properties of PVC waste concrete properties. The findings showed that the compressive strength reduction of concrete with PVC aggregate is less with the SCA modified recycled PVC, where the SCA modification of PVC surface improved the bonding between PVC particles and cement matrix. The finding also indicated that with the SCA modification, 10% PVC aggregate gave the best compressive strength performance. The researchers concluded that the pretreatment of PVC waste with silane coupling agents (SCA) effectively improves the bonding issue between PVC aggregate and cement matrix.

Conclusions

Several works have been done on incorporation of PVC plastic aggregate from various PVC plastic resources into cement composite. In general, there is a potential for PVC plastic to be an alternative aggregate replacement. Based on this overview, the following conclusions can be drawn:

1. The physical characteristics of plastic aggregates play a major role in governing the workability performance and microstructure of the cement composite containing plastic aggregate including PVC plastic aggregate. Size and shape of plastic aggregate gave a major effect on the performance of fresh state and influenced the formation of pores within the cement matrix. Flaky, shredded, granule, powder potentially can be applied into the cement composite provided the proper size is used.
2. The PVC plastic aggregate can be applied to replace coarse aggregate at low content level, which is less than 30%.
3. PVC plastic in powder form can be used if the strength is not the major concern for the concrete application such as for concrete infrastructure application for moderate strength (21-30MPa).
4. The PVC plastic aggregate can be strengthened by using modification methods, which improve the bonding characteristic within the cement matrix. Furthermore, the enhancement on cement binder can also be done to compensate for the low strength of plastic aggregate.
5. There is lack of review document on PVC plastic for sustainable component as alternative resources for construction application. Also, there is little report particularly on the permeation performance of concrete containing PVC plastic aggregate. Furthermore, most existing data indicated that the absorption rate considerably increased with the presence of plastic aggregate, which due to availability of pores. Nevertheless, there also potential finding indicated that the hydrophobic characteristic of plastic aggregate potentially improves the absorption behavior of concrete. Given this, more studies are required for a clear idea on the improvement factors for these properties.

Abbreviations

HDPE	High density polyethylene
LDPE	Low density polyethylene
PP	Polypropylene
PS	Polystyrene
PET	Polyethylene terephthalate
PC	Polycarbonate
PVC	Polyvinyl chloride
SCA	Silane coupling agents
PWP	PVC waste powder

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Authors' contributions
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Availability of data and materials
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Declarations

Competing interests
On behalf of all authors, the corresponding author states that there is no conflict of interest.

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