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RECYCLING OF PET BOTTLES INTO DIFFERENT TYPES OF BUILDING MATERIALS: A REVIEW

In this globalized era, building materials play an essential role in the civil engineering field. Nowadays, with the increase in population, the demand for construction activities is also increasing. Polyethylene (PET) bottles are among the most widely used materials and cause an abundance of non-degradable waste, at about 0.94 million tonnes in Malaysia. One of the alternatives to reduce this waste's environmental impact is to incorporate it inside building materials such as brick and concrete. As PET bottles' recycling is highly promoted, the physical and mechanical properties of building materials made from PET bottles have also been reviewed. The data analysis shows that the compressive strength, flexural strength, split tensile strength and density of building materials decreases as the percentage of PET waste increases. However, other properties such as water absorption, initial absorption rate, and firing shrinkage increase proportionally with the PET waste. Besides, heavy metals in these building materials comply with the United States Environmental Protection Agency (USEPA) standards. It can be concluded that the percentage of PET waste incorporated into brick and concrete must be less than 5% and 2%, respectively, to produce suitable materials to provide alternatives in reducing and recycling PET waste.

Keywords: PET bottles; waste recycling; fired clay brick; concrete; environmental management

1. Introduction

Plastic is commonly used in many sectors such as electric and electronic, automotive, household, and packaging. Amongst these sectors, packaging is the most popular sector in Malaysia that contributes to the high amount of plastic waste. As these industries continue to grow year by year, many plastic wastes have contributed to plastic pollution. Furthermore, Malaysia has been rated as one of the world‘s worst countries in plastic pollution. Only 2% of the waste was recycled in 2013, while the remaining were dumped and burnt [1]. This situation happens due to a lack of awareness of recycling‘s importance among related companies and communities. An incident proved this at Jenjarom, Kuala Langat, where plastic waste was recklessly burnt by illegal plastic recycling plants [2]. The open burning of plastic waste is harmful because these activities could release toxic gas and carbon monoxide that cause nearby residents to experience breathing difficulty, itchiness, coughing and fatigue. In Malaysia, the most commonly used plastic is polyethylene, and it has been dominating the packaging market [3]. Nowadays, landfills are no longer able to accommodate the increasing amount of PET bottles [4]. One of the current methods to utilize this plastic waste is by incorporating it into several building materials.

Currently, the incorporation of plastic waste into building materials is being investigated by many researchers. For example, plastic waste is replaced as fine aggregate [5], and PET fibres are incorporated into concrete to improve compressive strength and PET bottles are filled with soil [6-7]. Incorporating plastic waste in building materials has positively effects on various material properties such as compressive strength, density and water absorption. Therefore, this overview paper‘s gap provides essential information on incorporating PET bottles waste into fired clay brick as an alternative disposal method and providing low-cost material for brick manufacturing.

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2. Methodology

Generally, the literature reviews studies' main objectives are to give an overview of a research area and highlight future research needs. Secondly, the previous review's importance is to enclose a research area's scientific literature against theories and knowledge [8]. A systematic literature review (SLR) consists of works to provide a brief article, such as related article collection, selecting relevant articles for the write-up, verification of data and information from the selected articles. Therefore, a simple Bibliometric analysis was used in this study to measure the impact of published articles statistically and the inclusion of the intermediate search paper with clear contributions and the validity of data among the documented forms in the initial search [9]. The VOSviewer software was used, which is a software to attain the visualization of highly cited published articles and subsequently to map the citations to indicate their impact on future research

3. Bibliometric Analysis Related to Brick and Concretes

The alternate search was carried out to screen and identify relevant and irrelevant papers to the review. Papers with consistent contributions and the data validity of data among the published papers in the initial search are the criteria for inclusion in the intermediate search. This phase aims to extract papers, search for conditions to find important papers, and exclude those who were not. Therefore, in this section, some analysis types may converge in identifying scientific gaps and research trends.

A total of 108 papers were selected out of 677 documents in the database for keywords PET bricks. Figure 1a shows the Bibliometric data extracted by Scopus related to research involving PET into bricks by countries. It can be seen that United States, China, India, Australia, and Thailand are the most countries that were doing research related to PET bricks. Meanwhile,

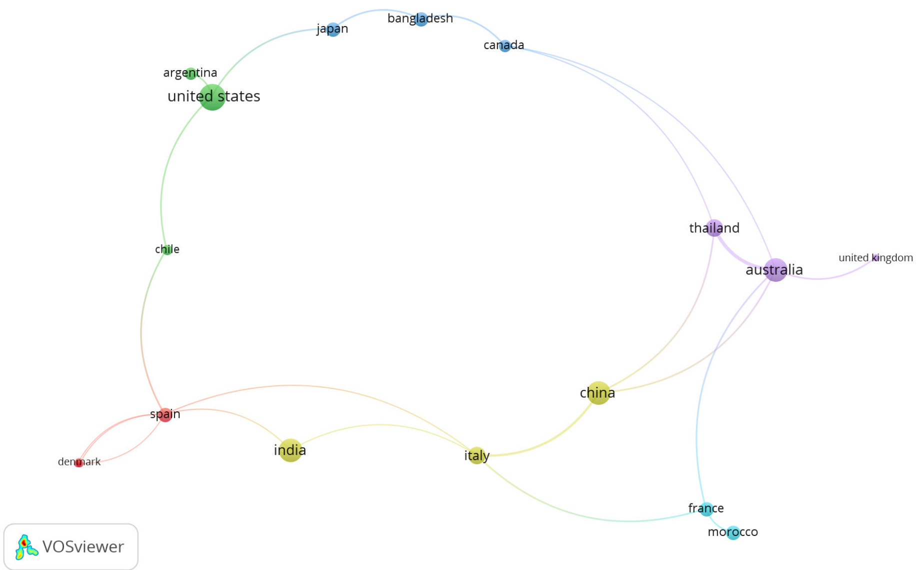

Fig. 1a. A Bibliometric analysis of PET Brick based on countries

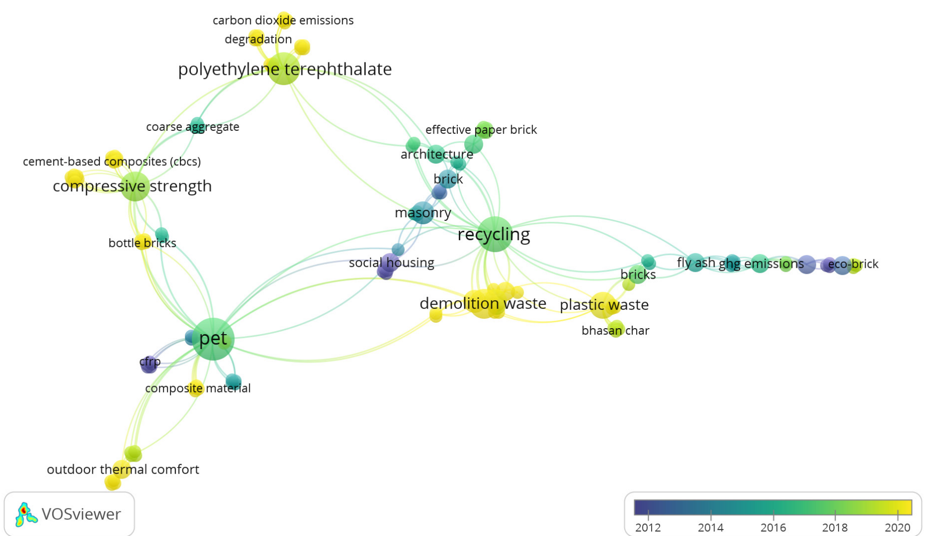

Fig. 1b. A Bibliometric analysis of PET Brick based on keywords

Figure 1b shows the total number of papers for each keyword for PET, recycling, polyethylene terephthalate from 2012 to 2020.

On the other hand, 455 out of 677 documents were selected involving keywords PET and concrete. From Figure 2a, the United States is the highest country doing research on PET and concrete, followed by India, Switzerland and Canada. Meanwhile, Figure 2b depicts the most keywords used, such as concrete, PET, polyethylene terephthalate, PET waste from 2005 to 2020.

4. Properties and Heavy Metal Leachability of Bricks and Concretes

The types of building materials discussed in this paper are bricks, and concretes are selected because of they have been used worldwide. Moreover, brick is the human-made building materials that has been used since the early age of civilization. The bricks and concrete were broadly used for construction, engineering works and landscape design. The quality of brick usually depends on the composition of raw materials, compressive strength, initial rate of absorption, firing shrinkage and many more [10].

5. Compressive strength

Compressive strength is the maximum stress of the building materials under crushed loading. By referring to BS 3921:1985, every type of brick has its strength [11]. Engineering bricks are the densest and strongest bricks. It can be classified into two classes; class A and class B. However, for the compressive strength of concrete, the value can vary from 2500psi to 4000psi [12].

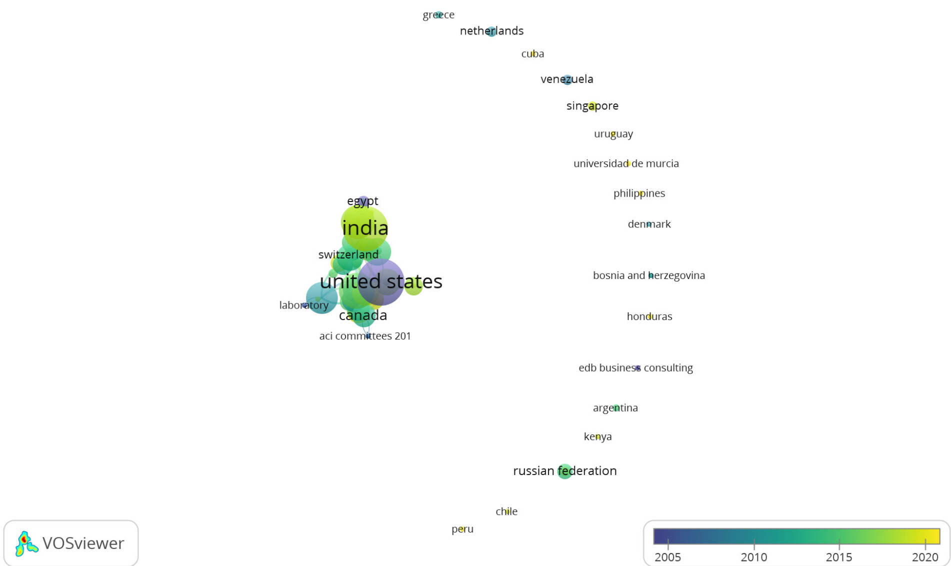

Fig. 2a. A Bibliometric analysis of PET Concrete based on countries

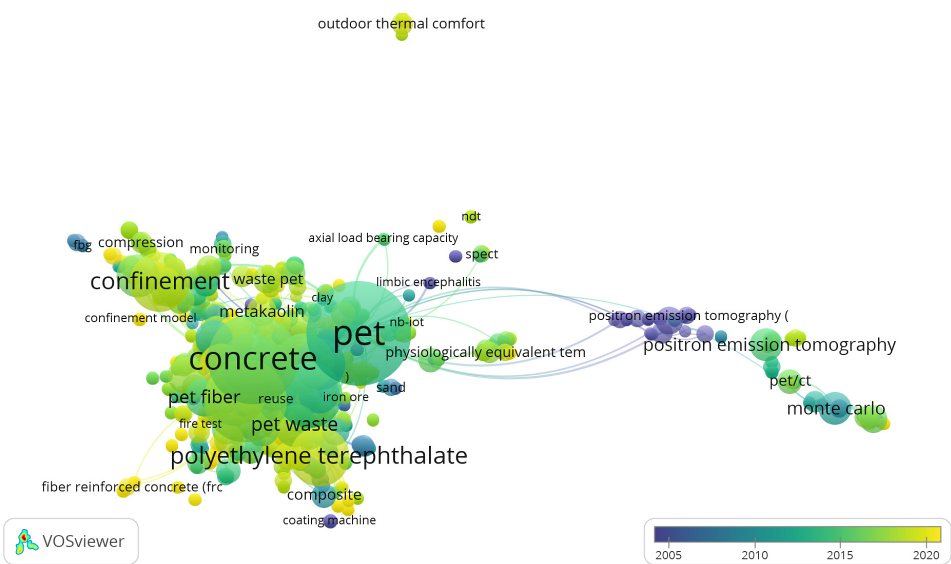

Fig. 2b. A Bibliometric analysis of PET Concrete based on keywords

6. Initial rate of absorption (IRA)

The initial absorption or IRA rate is defined as the amount of water absorbed from the brick bed area in one minute over 30 square inches [13]. The acceptable value ranges between 10 grams and 30 grams. A dry brick should be wetted before laying it with an IRA above 30 grams. A more straightforward test for measuring IRA is to put 20 drops of water on a brick in a quarter-sized area and then time its absorption. The water absorbed in less than one and a half minutes before the laying, and the brick should be wetted. If a brick is a too dry, too much water will be absorbed by the applied mortar.

7. Firing shrinkage

Firing shrinkage is a comparative indicator of the degree of vitrification. After the firing process, specimens were picked and measured randomly from the furnace. According to Lin et al. (2003), the firing shrinkage must be less than 8% [14].

8. Water absorption

According to ASTM D570, water absorption can be defined as the quantity of water absorbed under a given condition [15]. Several factors affecting water absorption are; temperature, duration of exposure and additives used. The average percentage of water absorption is between 12% to 20%.

9. Flexural strength

Flexural strength can be described as the strength of materials before it yields. Usually, the value of flexural strength is about 10% to 20% of its compressive strength. However, this value depends upon the size, type, and volume of coarse aggregate used [16]. The typical value for flexural strength in concrete is between 3MPa to 5MPa.

10. Split tensile strength

Tensile strength is an essential parameter of concrete where it affects the extension of cracking in concrete. Therefore, determination tensile strength is crucial to deciding the maximum load at which the concrete may crack. Typically, split tensile strength is conducted using ASTM C496 standard [17], and the value of tensile strength in concrete varies from 2 MPa to 5 MPa.

11. Leachability

The process of extracting minerals or heavy metals is called leachability. The solids dissolved into a liquid form naturally or by hand. From previous studies, several methods were used to determine the presence of hazardous waste elements. All the requirements are based on the United States Environment Protection Agency (USEPA) and the Environment Protection Agency (EPA).

12. Overview on The Physical and Mechanical Properties of Building Materials Incorporated with PET bottles

As PET bottles' recycling is highly promoted, each researcher reviewed the production of building materials made from PET bottles according to their effects on physical and mechanical properties.

The production of clay bricks with PET waste has shown an increasing trend among many researchers. In particular, Akinyele et al. (2020) have attempted to recycle five different weigths percentages of PET waste in fired clay bricks (0% to 20% of PET) [18]. In this study, thirty bricks with 290 mm × 140 mm × 100 mm were manufactured and used for several testings. The bricks' determination of properties that consist of 15% and 20% PET cannot be tested because the bricks disintegrated at high temperatures (900°C). The results show that some properties such as compressive strength, water absorption, and density reduced as the percentage of PET increased. However, the firing shrinkage of clay bricks with 0%, 5%, and 10% PET increased by 2.11%, 2.18%, and 2.28%, respectively. Fortunately, all the values were within the safe and acceptable limits for industrial production.

In another study by Limami et al., (2020), they used 0%, 1%, 3%, 7%, 15% and 20% of PET with three different grain-sizes ($\delta \leq 1$ mm; 1 mm < $\delta \leq 3$ mm and 3 mm < $\delta \leq 6$ mm) [19]. As for the manufacturing process, brick samples with 160 mm × 40 mm × 40 mm were prepared according to the New Mexico standards NM EN 772-16 and NM EN 772-20. The results indicated that all the specimens tested can be categorized as lightweight bricks because the value of density did not exceed 1.75 g/cm^3. The initial absorption and compressive strength in the bricks consist of the smallest grain size ($\delta \leq 1$ mm), showing an improvement by almost 17% and 28%, respectively, compared to the largest grain size.

A similar study by D Alighiri et al. (2019), 66%, 69%, and 75% in PET waste volume, was used in this study [20]. Bricks of two different sizes were manufactured (50 mm × 110 mm × 230 mm and 52 × 115 × 240 mm) according to the Indonesian National standards SNI 15-2094-199. For the first stage of the manufacturing process, the sand was dried in an oven at 110°C. After that, the stability of plastic mortar was tested at a temperature from 30°C to 90°C. Next, PET was heated at a temperature between 280°C to 290°C. Other than that, the compressive strength of PET concrete bricks increased as the amount of PET additive increased. Also, the percentage of water absorption was relatively low due to the low porosity of PET material. The low value of water absorption indicated that the quality of the bricks was good.

Another study reviewed was conducted by Basil & Sadiq (2018), who studied the potential of producing lightweight clay bricks with different PET waste percentages [21]. The percentages were valued at; 0%, 2%, 4%, 6%, 8% and 10%. A vacuum extruder was used to form the samples with 38 mm × 25 mm × 75 mm for the sample formation. All methods that were used in this research were based on the Iraqi specifications IQS 25/1988. The compressive strength and density of clay bricks were reduced by (0.4%-2.3%) and (3.5%-25.1%) respectively, while the patterns of water absorption and firing shrinkage increased by (3-43.5%) and (0.6%-20.2%) respectively. All the changes depended upon the percentages of PET and of grain that were incorporated into the samples. It revealed that the smallest grain size would produce the smallest pores when fired, resulting in the smallest firing shrinkage value.

As for Azmi et al. (2018), their bricks measuring 215 mm × 103 mm × 65 mm were manufactured according to the British standards BS 5628-3 design method [22]. In this research study, RCA and PET were mixed. Two mixed design ratios, which were 1:4 and 1:5, were used with a water-cement ratio of 0.6. Each material was prepared with three different weight percentages (RCA: 25%; 50% and 75%) and (PET: 1.0%; 1.5%; 2.0% and 2.5%) of natural sand. The results of water absorption increased from 3.4% to 5.1% in 7 days. Meanwhile, water absorption results for 28 days showed an increase from 4% to 6.1%. However, the water absorption for PET1.0%RCA50% slightly decreased because it was less permeable than other samples. Samples that consisted of 75% RCA absorbed more water than samples with RCA 25% and RCA 50%. Besides, the strength for both mix design ratios decreased as the PET composition increased.

In their research studies, Misal et al. (2019) used PET waste and sand with two different particle sizes of 600 μm and 4.75 mm [23]. The size of the bricks that were used in this study was 22 cm × 10 cm × 7.5 cm. Besides that, two types of concrete bricks were prepared, with one of the bricks providing a 14 cm × 4 cm × 1 cm frog size. The compressive strength for bricks without a frog passing through 600 μm was similar for the ratio of 1:3 and 1:5 (3.344 MPa), and for the ratio 1:4, the result obtained was 6.641MPa. As for bricks that passed through 4.75 mm, tests were not run on them. However, the compressive strength test conducted only for bricks with the frog had the ratio of 1:3, 1:4, and 1:5. The compressive strength values were 2.449 MPa, 6.688 MPa and 3.455 MPa, respectively. These studies also identified that water absorption decreased for the bricks for bricks with a balance of 1:4. The ratio of 1:4 was used because it led to comparatively better results.

Besides that, in a study conducted by F.S. Khalid et al. (2018), recycled concrete aggregate (RCA) and PET waste were used as a replacement for fine aggregates in concrete bricks [6]. This study used three different percentages of RCA (25%; 50% and 75%) and three different percentages of PET waste (0.5%; 1.0% and 1.5%). The samples containing PET (0.5%) and RCA (75%) possessed the highest value of the studies' compressive strength. However, the compressive strength is reduced when PET volume increases from 1.0% to 1.5%. This result showed that the increased volume of PET additives reduces the strength of materials. Also, the results of water absorption increased from 3.4% to 5.1% in 7 days.

Meanwhile, the water absorption result after 28 days showed an increase from 4% to 6.1%. However, water absorption for PET1.0%RCA50% slightly decreased because it was less permeable compared to other samples. The results also revealed that the density of concrete bricks decreased as the PET composition increased. Table 1 shows the overview of the physical and mechanical properties of brick by incorporating PET bottles.

PET waste was also incorporated into concrete, as shown in Table 2. According to Ramadevi & Manju (2012), PET with percentages of 0.5%, 1%, 2%, 4%, and 6% were used to replace fine aggregate in concrete [24]. Three types of specimens were used in this study (cube: 150 mm × 150 mm × 150 mm, cylinder: 150 mm diameter and 300 mm height, and prism: 100 mm × 100 mm × 500 mm). The compressive strength in the concrete cube and split tensile strength in the cylinder concrete increased

TABLE 1

Overview of the physical and mechanical properties of brick by incorporating PET bottles

Researcher	Types	Sieve size (mm)	Mixing percentage (%)	Properties					
				Compressive strength (MPa)	Water absorption (%)	IRA (g.cm^2.min$^{0.5}$)	Density (g/cm^3)	Shrinkage (%)	Curing period Day(s)
1	2	3	4	5	6	7	8	9	10
Akinyele (2020)	Clay brick	—	0	5.15	10.29	—	1.67	2.11	
		—	5	2.30	9.43	—	1.40	2.18	
		—	10	0.85	6.57	—	1.33	2.88	
Limami et al., (2020)	Clay brick	—	0 (control brick)	5.62	—	—	1.78	—	—
		≤ 1	1, 3, 7, 15, 20	4.50-2.82	—	27.95-46.83	1.71-1.53	—	—
		1-3		4.15-2.55	—	27.95-56.13	1.69-1.49	—	—
		3-6		3.52-1.72	—	27.95-60.12	1.63-1.44	—	—
D. Alighiri et al., (2019)	Concrete brick		66, 69, 75 (by volume)	26-75	0.008-0.003				
Basil &Sadiq (2018)	Clay brick		0	12.4	21.66		1.67	1.58	
		2.36	2, 4, 6, 8, 10	11.03-7.41	23.71-31.1		1.59-1.25	1.62-1.90	
		1.18		11.66-7.84	23.09-29.12		1.60-1.26	1.61-1.82	

TABLE 1. CONTINUED

1	2	3	4		5		6		7	8	9	10
Azmi et al., (2018)	Concrete brick (design ratio 1:4)	—	0		30		4.1					
			RCA (25%)	PET (1.0%, 1.5%, 2.0%, 2.5%)	31-28		4.15-4.4					28
			RCA (50%)		24-17		4.4-5.9					28
			RCA (75%)		16-15.6		6.2-7.6					28
	Concrete brick (design ratio 1:5)	—	0		0		4.2					
			RCA (25%)	PET (1.0%, 1.5%, 2.0%, 2.5%)	28-24		4.25-5.1					28
			RCA (50%)		23-20		4.9-6.1					28
			RCA (75%)		15.8-15		6.2-6.9					28
Misal et al., (2019)	Concrete brick		0(control brick)		1.685		23.79					
			Ratio PET: sand		Without frog	With frog	Without frog	With frog				
			1:3		3.34		2.79					
			1:4		6.46	6.02	1.31	1.36				
			1:5		3.34		1.83					
			1:3			2.45		3.35				
			1:4			6.69		2.43				
			1:5			3.46		5.37				
F.S Khalid (2018)	Concrete brick	—	0		13.1		3.4		—	2.16	—	7
					14.1		4.0		—	2.17	—	28
			RCA (25%)	PET (0.5%, 1.0%, 1.5%)	7.17-23.5		3.7-4.0		—	2.14-2.07	—	7
					8.7-24.2		5.0-5.1		—	2.16-2.09	—	28
			RCA (50%)		20.6-21.6		4.1		—	2.05-2.0	—	7
					22.2		5.2-5.5		—	2.06-2.02	—	28
			RCA (75%)		22.2-19.5		4.8-5.1		—	1.98-1.95	—	7
					24.9-23.6		5.8-6.1		—	2.0-1.95	—	28

TABLE 2

Overview of the physical and mechanical properties of concrete by incorporating PET bottles

Researcher	**Type of building material**	**Mixing percentage (%)**		**Properties**				
				Compressive strength (MPa)	**Split tensile strength (MPa)**	**Flexural Strength (MPa)**	**Density (g/cm^3)**	**Curing period Day(s)**
Ramadevi & Manju, (2012)	Concrete	0		21	—	—	—	7
				31	1.88	3.1	—	28
		0.5, 1, 2, 4, 6		23-25	—	—	—	7
				33-38	1.99-2.05	4.5-5.9	—	28
Choi et al., (2005)		W/C (45)	PET (0%, 25%, 50%, 75%)	28.8-20.7	—	—	—	3
				31.3-24.8	—	—	—	7
				37.2-24.9	3.32-2.04	—	2.3-1.94	28
		W/C (49)		19.0-15.8	—	—	—	3
				27.8-21.6	—	—	—	7
				34.6-23.2	3.27-1.94	—	2.3-2.0	28
		W/C (53)		18.4-14.8	—	—	—	3
				24.0-19.2	—	—	—	7
				31.5-21.8	3.27-2.04	—	2.3-2.01	28

when the PET reached 2%, however, it started to reduce when the percentage exceeded 2%. The prism concrete's flexural strength increased gradually as the percentage of PET replacement increased by 2% and began to be constant at the percentage of 4% and 6%. The results showed that 2% of PET waste was the most suitable percentage to be incorporated into concrete because it gave the highest value for all tested samples.

In a study by Choi et al. (2005), used three different percentages of water-cement ratio (45%, 49, and 53%) and PET aggregate (25%, 50%, and 75%) [25]. All specimens were cast in a compacted mould with a diameter of 100 mm × 200 mm. Cling film was used to ensure no water loss from the mould after the casting and curing process. All the specimens were cured in water at 23±2°C for 3, 7, and 28 days. The results implied that the compressive strength for the water-cement ratio of 45% with 75% of PET aggregate reduced to 24.9 MPa from 37.2 MPa of the control concrete. A reduction in split tensile strength and density was also obtained in this study.

13. Overview on The Leaching Behaviour of Building Materials Incorporated with PET bottles

A recent study that has been conducted by S. Perera et al. (2019) used Australian Standard Leaching Procedure (ASLP) to determine the value of heavy metals and AS 4439.3-1997 standards to indicate the total concentration of crushed brick and concrete aggregate blended with PET [26]. Marginally acidic leaching fluids, acetate (pH 5.0), alkaline and tetraborate (pH 9.2), were used in this study as a leaching buffer. The results indicated a slight difference in the heavy metals concentration between the recycled concrete aggregate (RCA)/PET blends and crushed brick (CB)/PET blends. The total concentration of barium in RCA/PET was 80mg/kg of dry weight, less than CB/PET. However, the total concentration of chromium in RCA/PET was higher than CB/PET, 18mg/kg of dry weight. The concentration of selenium in CB/PET was 20mg/kg, which was higher than the concentration in RCA/PET. Other than that, using acetate and tetraborate in ASLP testing resulted in only a slight difference for the leachate value of barium at (0.1 mg/L) and (0.2 mg/L), respectively. The results of other contaminants for both RCA/PET and CB/PET were the same. The study also claimed that all the value of total concentration (TC) and ASLP testing could be considered non-hazardous filling materials because all contaminants‘ value was below the maximum concentration. Table 3 shows the results of the leachability test for RCA/PET blends and CB/PET blends.

14. Conclusion

Based on the literature review, the utilization of PET in several types of building materials shows positive results. The increasing pattern in water absorption, firing shrinkage, and most researchers obtained the initial absorption rate. They also agreed that this pattern is due to the increase of grain size that causes higher porosity of materials. Theoretically, the high value of porosity in materials might increase the water absorption rate and firing shrinkage. Besides that, the utilization of PET in building materials revealed that the density of brick reduced as the volume of PET additive increased. It is due to the reduction of mass in the bricks as the specific gravity of PET is significantly low. Since these observed concrete results made with plastic revealed an increased in compression and tensile strength, PET bottle fibre replacements can increase demand as a partial replacement for fine aggregates. Besides that, the leachability results change to indicated that the concentration of heavy metals in both RCA/PET and CB/PET was considered non-hazardous. The level of concentration of heavy metals was below the maximum level as stated in the EPA guidelines. Therefore, the future project aims to develop the correct formulation to recycle plastic bottle waste into fired clay bricks as an alternative disposal method and produce an environmentally friendly product. In conclusion, the data obtained from previous studies revealed that PET waste is suitable ot h incorporated into building materials as it can produce lightweight materials and reduce the disposal cost of waste materials.

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TABLE 3

Heavy metals in construction materials [23]

Contaminant	RCA/PET blends			CB/PET blends		
	TC (mg/kg)	ASLP (mg/L)	ASLP (mg/L)	TC (mg/kg)	ASLP (mg/L)	ASLP (mg/L)
Arsenic	<5	<0.1	<0.1	<5	<0.1	<0.1
Barium	80	0.1	<0.1	90	0.2	0.2
Cadmium	<1	<0.05	<0.05	<1	<0.05	<0.05
Chromium	18	<0.1	<0.1	<13	<0.1	<0.1
Lead	8	<0.1	<0.1	8	<0.1	<0.1
Selenium	<5	<0.05	0.05	20	<0.05	0.05
Silver	<2	<0.1	<0.1	<5	<0.1	<0.1
Mercury	<0.1	<0.001	<0.001	<0.1	<0.001	<0.001

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