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Green Infrastructure

Materials and Applications

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Preface

This book highlights green infrastructure materials and their applications along with their limitations in contributing towards green industries. It starts by discussing modifications in concrete design by adding recycled polyethylene terephthalate bottles as partial replacement of aggregates, mortar, ordinary Portland cement, alternative binder for paving blocks and others. This mixed concrete can be used as sustainable wall panels and concrete blocks. These types of sustainable wall panels can be used to construct green buildings and to save the environment through reduction of waste plastic bottles at landfills.

The initial chapters discuss the repair and retrofitting of concrete structure by using palm oil fly ash (POFA) which is the byproduct of palm oil industries as alkaline and physical activated POFA cement paste. A review of concrete performance on tin slag polymer concrete as green structural material for sustainable future and its study on the effect of waste paper sludge ash (WPSA) in addition to fresh and hardened ultra-high-performance concrete are explained and elaborated.

Chapters "Flexural Performance of Strengthened Glued Laminated (GLULAM) Timber Beam Using Glass Fibre-Reinforced Polymer (GFRP)"–"Analysis of the Flexural Strength of Reinforced Beam with Bamboo by Empirical Modeling Using Statistical Model" present the physical and mechanical properties of timber as one of the green material that contributes to green infrastructure construction and sustainability. The experimental results on flexural performance of strengthened glued laminated (glulam) timber beam using glass fibre reinforced polymer (GFRP); overview on bending and rolling shear properties of cross laminated timber (CLT), together with delamination test for Mengkulang timber species using method A and C are presented. Further analysis on flexural strength of reinforced beam with bamboo by empirical modelling using statistical model is also presented in the book.

The two following chapters in this book discuss road pavement materials and their testing and evaluation. It includes innovative new and waste materials which can be recycled to prolong the life span of road pavements. In order for the pavement to withstand the ever-increasing loadings from vehicles in terms of intensity and axle applications, pavement materials must have adequate strength to withstand these loads and must also be durable to withstand the effects of environment, namely moisture and temperature. Chapter "Application of Pavement Evaluation for Road Maintenance and Rehabilitation" describes the process of pavement evaluation and the application of its results for use in the maintenance and rehabilitation of roads. Meanwhile, chapter "Performance Evaluation of Stone Mastic Asphalt Containing Steel Fibre as Additive" presents the findings of a study on addition of steel fibre in stone mastic asphalt (SMA) application. SMA is a gap-graded asphalt mixture that consists of a large proportion of coarse aggregate, a high percentage of asphalt binder and a substantial amount of filler which provides a durable surface course.

Chapters "Post-construction Complexity Factors Impacting Infrastructure Project Performance in Malaysia"–"Governance Practices in Poverty Alleviation Projects: Case Study from Stewardship-Driven Perspective and Sustainability Context" present the post-construction complexity factors that impact the infrastructure project performance in Malaysia, followed by the SWOT analysis of green technology application for the development of low carbon cities and a sharing of a case study from stewardship-driven perspective and sustainability context through governance practices in poverty alleviation projects.

Discussion on interception loss of tree canopy as green infrastructure and an evaluation of parameters for sustainability assessment of green infrastructure in the urban water system are presented in chapters "Interception Loss of Tree Canopy as Green Infrastructure" and "Evaluation of Parameters for Sustainability Assessment of Green Infrastructure in the Urban Water System", respectively. This contemporary book also covers a green community-based social enterprise (CBSE) for B40 in Sabah, through a sharing of freshwater lobster production-green Aquaponics Perennial System (flp-gaps) in chapter "Freshwater Lobster Production-Green Aquaponics Perennial System (FLP-GAPS): A Green Community-Based Social Enterprise (CBSE) for B40 in Sabah". Last but not least, chapter "An Edible Cutleries Using Green Materials: Sorghum Flour" presents the use of sorghum flour as one of the green materials in a form of edible cutleries performance.

This comprehensive book entitled "Green Infrastructure Materials and Applications" is suitable for engineering students to develop competency in theory, practical and communication skills. It presents a framework for engineers to add on different materials into practice. The chapters in the book also present the link between materials and the application processes. The various engineering materials presented in this book will inspire and stimulate discussions in academia and industry to develop and promote green infrastructure materials and their applications for the future.

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Summary

This book explains the meaning of green infrastructure and limits its attention to the contribution of materials and applications since green infrastructure is varied and diverse. The development of green infrastructure is gathering momentum internationally both in theory and policy, and there is development agreement that green infrastructure provides an attractive opportunity for the delivery of significant environmental, social and economic benefits. This chapter of the book covers four perspectives on green infrastructure. First, the exploration of contested green infrastructure materials that include concrete, wood and pavement. Second, the discussion of opposition to the ambiguity of managing construction green infrastructure is based on a broader debate on the application and process of construction impact. Third, an examination of the relevant concepts and factors that contribute to the application towards green infrastructure in nature. Finally, contributions related to how the study of bread cutters used using sorghum flour will also provide implications for defining green infrastructure explicitly given its ever-changing and disputed nature will be critically examined. Therefore, this contribution is by no means certain, except in an effort to provide a separate and holistic perspective on the concept of "green infrastructure" of engineering.

Contents

Recycled Plastic Bottles as Sustainable Materials

N. H. Hamid and M. M. H. Shamsudin

Abstract Recycle Polyethylene Terephthalate (PET) plastic bottles can be used as partial replacement of aggregates to form plastic bricks, silica plastic blocks and PET bricks. By replacing from 0.5 to 5% of PET recycled plastic as partial replacement of fine and coarse aggregate into concrete mixture can be moulded as silica plastic blocks, colour plastic bricks, RePlast bricks and burnt brick to construct a single-storey house and temporary shelters. Furthermore, by adding 0.5–1.5% of recycled PET fibre in concrete with water cement ratio of 0.65 can increase the compressive strength of concrete. The advantages of using recycled bottles as green construction materials can reduce landfill pollution, conserve natural resources, improve the environment and save sea life from dying. Furthermore, the bottle houses are bioclimatic in design which means it is cold outside and warm inside or vice versa. It can be concluded that by substituting recycled plastic bottles into concrete mixture and transforming into green recycled bricks, they can be used to construct the houses in rural or slump areas where the cost of construction materials are very expensive and limited.

Keywords Recycle plastic bottle · Recycled polyethylene terephthalate · Burnt brick · Green recycled bricks · Green infrastructure material

1 Introduction

In Malaysia, about 40% of the income households are categorized under the B40 group where their incomes are less than RM4, 850 per month. Most of them cannot afford to buy terrace houses ranging between RM490,000 and RM750,000 in Klang

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Valley which is the highest population area in Malaysia. Thus, the Malaysian government needs to build low-cost houses for the B40 group ranging from RM 72,000 to RM 150,000. Waste minimization is common in the construction project site in Malaysia where 73% of the waste materials such as plastic waste is used and recycled. The net benefit of reusing and recycling of plastic waste is estimated at 2.5% of the total project budget (Beguma et al. 2006). The contractors and builders need to search for the lowest cost of sustainable green materials for the construction of these types of houses. Significantly, by 2018, Malaysia produces more than 0.94 million tons of mismanaged plastic waste per year (Chen et al. 2021). At the same time, Malaysia also became a top importer of plastic waste where a total of 105 thousand tons of plastic was imported in 2017 with an increase of 68% from 2016 (Periathamby et al. 2009). Thus, one of the alternative ways is to use recycled plastic bottles for the construction of wall panels, brick, joist, ceiling and columns of the houses. The first bottle house was constructed in 1902 by William F. Peck in Tonopah, Nevada using 10,000 alcohol bottles (Jalaluddin 2017). Andreas Froese is a German social entrepreneur and environmentalist who has developed ECOTEC technology which transforms the reuse of plastic bottles to recycle bricks to erect dwelling houses (Patel et al. 2016). He also constructed the first house in Africa using plastic bottles bound together with string in the Yelwa Village, Nigeria (Hemraj et al. 2018). PET bottles are filled with sand, soil or even rubble to give some firmness and they are placed one by one, creating a house based on a simple and functional design of a building structure. Due to poor soil fertility as a result of the presence of plastic bottles and polythene bags, Butakoola Village Association for Development (BUVAD) in Uganda constructed a bottle house in 2010. Then, Mr. Arthur Huang from Taiwan had built a boat-shaped exhibition hall known as Eco-Ark using 1.8 million recycled plastic bottles. After that, Samarpan Foundation constructed a primary school in New Delhi, India using hundreds of used PET bottles instead of conventional bricks in May 2011 (Jalaluddin 2017).

2 Physical and Chemical Properties of Pet Bottles

Polyethylene terephthalate (PET) is created by two combinations of monomers which are purified terephthalic and modified ethylene glycol (Faraca et al. 2019). PET is the most common thermoplastic polymer resin of the polyester family and is used in fibres for clothing, containers for liquids and foods and thermoforming for manufacturing. It consists of polymerized units of the monomer ethylene terephthalate, with repeating ($C_{10}H_8O_4$) units (Faisal et al. 2016). It is normally used for cereal box liners, microwave food trays, plastic vessels and for implantation in medicinal and plastic bottles. Plastic is heat resistant, chemically stable, resistant against acid, base, some solvents, oils and fats. The tests of physical properties of PET bottles washing include hygroscopic, transient and total moisture, as well as specific and bulk density. Table 1 shows physical properties of PET bottles after burning in a furnace and tested in the laboratory (Department of the Environment and Energy

Table 1 Physical properties of PET bottle ashes (Beata et al. 2019)

Quantity	Unit	Value
Hygroscopic moisture	%	43.7 ± 1.5
Transient moisture	%	6.0 ± 0.76
Total moisture	%	45.1 ± 4.03
Analytical moisture	%	12.1 ± 1.5
Bulk density	kg/m^3	602.3 ± 63.2
Specific density	kg/dm^3	1.27 ± 0.14

Table 2 The composition of inorganic substance in PET bottle ash (Beata et al. 2019)

Component	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O	MgO	K_2O	P_2O_5	TiO_2	SO_3	MnO	LOI
Weight (%)	10.32	4.49	3.13	16.0	0.67	1.32	0.3	0.69	0.07	0.27	0.11	61.2

2018). Meanwhile, Table 2 shows the chemical composition of inorganic substances in PET bottle ash (Beata et al. 2019).

According to Van Krevelen (1990), PET is a polymer that has tensile modulus elasticity and flexural modulus elasticity of 2.9 MPa and 2.4 MPa, respectively. Correspondingly, the characteristics of PET are high chemical resistance and have melting points approximately up to 260 °C. However, the issue concerned is the basic properties of PET such as wetting tension and alkali resistance to ensure the performance of PET itself is suitable to be used in concrete or mortar. Wetting tension value is used to evaluate the adhesion or bonding between PET and concrete or mortar matrix. Likewise, the durability of PET is measured through the alkali resistance to perform well in reacting with cement that contains a high concentration of alkali.

Ochi et al. (2007) have created an understanding of determining properties of PET and comparing it with Polypropylene (PP) and polyvinyl alcohol (PVA). It was found that the wetting tension of PET is 40 mN/m which is slightly higher than PP 35 (mN/m) but this value is lower than PVA (45 mN/m). Furthermore, PET was immersed in an alkali solution (sodium hydroxide) and the tensile strength was tabulated in Table 3. The experimental result revealed that the characteristic of PET

Table 3 Result for alkali resistance of PET by measure tensile strength (Ochi et al. 2007)

Fibre	Diameter (mm)	Length (mm)	Tensile strength (MPa)		Strength ratio[a] %
			Before exposure	After exposure for 12 h	
PET	0.75	30	352	348	99
PP	0.21	30	170	147	86
PVA	0.71	30	360	202	56

[a]Strength after exposure/strength before exposure

is sufficient for alkali resistance which experiences only minor deterioration through tensile strength after immersion as compared to PP and PVA.

3 Plastic Waste as Potential Construction Material

According to Azhdarpour et al. (2016), PET recycled plastic bottles as a building material has gained popularity in the recent decades. Polyethylene Terephthalate (PET) is categorized as a form of plastic that is mostly being thrown away right after a single use (Saxena et al. 2018). In Malaysia, the usage of plastic in various industries is increasing gradually day by day. This phenomenon happens due to urbanization at the same time resulting in an enormous amount of plastic wastes and causes significant environmental problems like pollution, flooding, climate change and diseases. In 2020, the estimated value of annual food plastic packaging consumption in Malaysia amounted to 148,000 metric tons and the annual per capita plastic packaging consumption in Malaysia was equal to 16.78 kg (Müller 2021). According to the study done by Wahab et al. (2007), the rate of plastic consumption in Malaysia was 4.6 tons/day for PET. However, these figures are expected to increase in the future.

Most of the plastic bottles which are considered as solid wastes are dumped at landfills as shown in Fig. 1. The massive proportion of the PET is harmful because it is not being composed readily by nature due to the slow biodegradation phenomenon

Fig. 1 Plastic bottles as solid waste are dumped at landfill

(Ghernouti et al. 2015). These plastic wastes will take more than 100 years to biodegrade inside the soils. Developed countries like Australia generated around 67 million tons of waste in 2016–2017 and only 37 million tons (55%) were recycled (Department of the Environment and Energy 2018). Contradictorily, it was reported that one of the biggest cities, Beijing, China produces 25,000 tons of rubbish in a day (Guo et al. 2020). Various methods of disposing of plastic wastes were introduced such as burning, landfill and dumping wastes into the oceans. Despite recycled plastic bottles, the majority are sent out to landfill which have negative impacts on the environment, social and economy. Furthermore, harmful gases that are being produced from the process of incineration to dispose of PET waste can also disrupt human health (Ghernouti et al. 2015). Many studies have shown that more than 15% of a building's energy consumption and carbon emissions are from virgin materials (Sandanayake et al. 2018, 2020; Huang et al. 2019). Furthermore, excessive usage of virgin materials in building materials results in depleting natural resources and leads to additional environmental burden (Meyer 2009; Hossain and Poon 2018). Therefore, by replacing virgin materials with waste products addresses key issues, excessive waste generation and save virgin material usage.

The use of plastic as one of the construction materials is an environmentally friendly method of disposal. Mixing plastic in construction materials can also absorb desirable properties in the finished products making favourable economic sense. For example, the usage of PET as construction material which can reduce the need for fine aggregate, improve corrosion resistance and makes the concrete lighter.

The construction industry area that produced high consumption capacity is likely to be the most suitable industry to reuse PET waste (Saxena et al. 2018). A lot of research work had been conducted by putting recycled plastic bottles in concrete and mortar as replacement of aggregates and fibre reinforcement (Saikia and De Brito 2012; Usman et al. 2018; Merli et al. 2019). Currently, the impacts of plastic and rubber aggregates on the physical, mechanical, durability and functional properties of concrete are studied (Li et al. 2020) and the state-of-the-art on the fresh and hardened properties of self-compacting concrete containing PAs and PFs (Faraj et al. 2020). According to research conducted by Mahdi et al. (2013) and Jo and Park (2006), recycled PET was used as a binder in concrete by depolymerizing the PET using the glycolysis process to produce unsaturated resin to replace cement. Figure 2 shows the recycled PET use as replacement of aggregates, meanwhile Fig. 3 shows the PET waste was transformed fibre by previous researchers.

There are also applications of recycled plastic waste especially on PET in concrete structures' components such as beams, slabs, precast concrete panels and concrete footpaths. Foti and Paparella (2014) investigated the dynamic behaviour of concrete reinforced with waste PET plastic by cutting drinking bottles and arranged in a grid structure to reinforced concrete slabs subjected to shock and impact loading. Bending tests were performed on concrete beams with PET bars placed at the bottom of the beams under two points load (Foti 2016) with advantages against corrosion. Adding a circular ring of plastic bottle with 5 mm thickness or 10 mm thickness to the reinforced concrete beams did not lower the deflection behaviour as compared with control reinforced concrete beam specimens. During the cracking stage, concrete

Fig. 2 Recycled PET use as replacement of aggregate (Islam et al. 2016)

Fig. 3 Recycled PET use as fibre (Alfahdawi et al. 2019)

beams containing ring plastic bottles with 10 mm showed that the strength of the first crack improved by 32.3% as compared to normal concrete beams (Khalid et al. 2018). Cracking due to drying shrinkage was delayed in the PET fibre-reinforced concrete beams as compared to such cracking in non-reinforced specimens without fibre reinforcement which indicates crack controlling and bridging characteristics of the recycled PET fibres (Kim et al. 2010). Short fibres from recycled PET bottles proved to be an excellent alternative to restrain plastic shrinkage in concrete and building cements materials (Pelisser et al. 2010). Dai et al. (2011) investigated the behaviour of concrete confined by fibre-reinforced polymer (FRP) jackets formed with polyethylene naphthalate (PEN) and PET fibres derived from post-consumer bottles. Besides that, PET is said to be suitable to be utilized in concrete and mortar because the characteristics of PET itself which have high tensile strength, high alkali resistance and high value of wetting tension are believed to further result in good bonding with concrete matrix (Ochi et al. 2007).

4 Performance of Recycled PET Fibre in Concrete

The use of recycled PET as concrete-reinforcing fibre has been steadily developed for a decade. In order to overcome the shortcoming of the concrete in the construction field especially on tensile strength and resistance of crack, recycled PET were used (Borg et al. 2016; Kim et al. 2010). However, the level of performance of fibre as concrete reinforcing depends on various factors such as type, amount and quality of the fibre. Besides that, the shape and dimension of the fibre also have a significant effect on the bonding between the materials in the concrete mix as well (Borg et al. 2016). The shape, amount and dimension of recycled PET fibre lead to various findings on the concrete performance. Table 4 shows the characteristics of the PET fibre and its findings from previous researchers (Ochi et al., 2007; Kim et al., 2010; Fraternali et al., 2011; Foti 2011; Irwan et al., 2013; Shamsudin et al., 2021).

The straight shape of plastic fibres typically does not provide enough ability to resist crack due to poor bonding contact within concrete materials. The smooth form and sides of waste plastic is a significant problem due to its adhesion with the concrete mix (Saxena et al. 2018). Therefore, transforming the shape of fibre to several patterns such as crimped, embossed and twisted can improve the bond strength between the recycled PET fibres and concrete matrix (Kim et al. 2010). Figure 4 until Fig. 7 show the various shapes of fibre which had been used by previous researchers (Borg et al.,

Table 4 Summary of previous research on shape of PET fibre

Researcher	Percentage of PET fibre (%)	The shape of PET fibre	Water cement ratio	Compressive strength of concrete
Ochi et al. (2007)	0.50, 1.00, 1.50	Monofilament	0.55, 0.60, 0.65	Increase
Kim et al. (2010)	0.50, 0.75, 1.00	Strip	0.41	Decrease
Fraternali et al. (2011)	1.00	Straight and crimp	0.53	Increase
Foti (2011)	0.26	Strip and circular	0.70	Decrease
Irwan et al. (2013)	0.50, 1.00, 1.50	Irregular	0.65	Increase
Shamsudin et al. (2021)	0.5, 1.0, 1.5	Straight	0.53	Increase

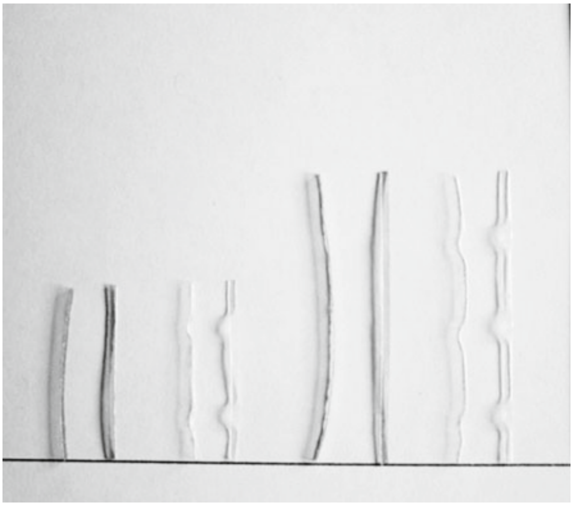

Fig. 4 Embossed and straight fibre shape with length 30 and 50 mm (Borg et al. 2016)

2016; Kim et al., 2010; Foti, 2011; Fraternali et al., 2011). Embossed fibres show the highest bond strength as compared with crimped and straight ones as shown in Fig. 4. The circular fibre shape had been tested by Foti (2011) as shown in Fig. 6. Fraternali et al. (2011) found in his study that the crimp shape of PET fibre can improve the compressive strength and ductility of the concrete as compared to concrete with straight fibre shape as shown in Fig. 7. In addition, the bonding strength of fibre can be enhanced through the coating process. Kim et al. (2010) treated the PET fibre by coating with maleic anhydride grafted polypropylene to produce a rough surface as shown in Fig. 5.

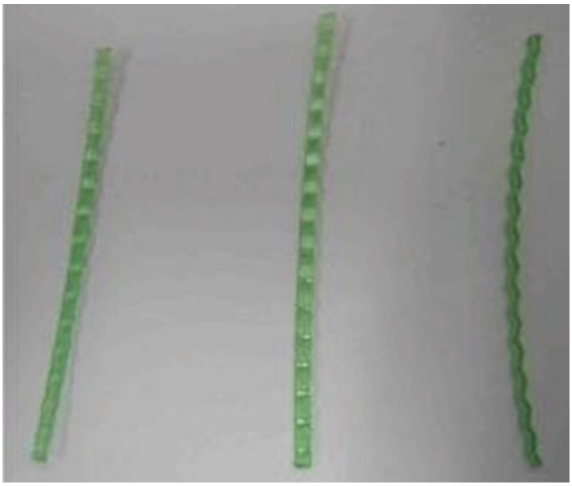

Fig. 5 Crimped fibre shape (Kim et al. 2010)

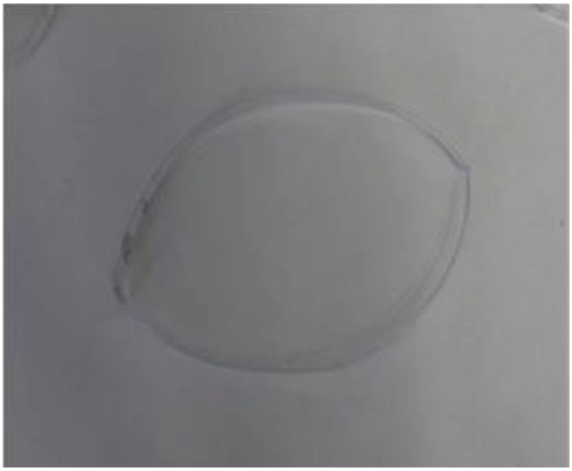

Fig. 6 Circular fibre shape (Foti 2011)

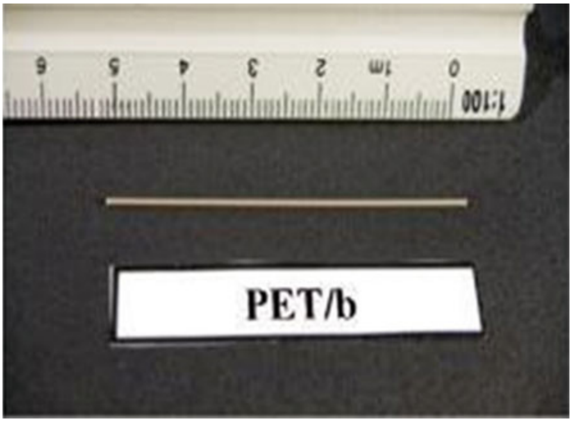

Fig. 7 Straight fibre shape (Fraternali et al. 2011)

Based on experimental work conducted by Irwan et al. (2013) using 0.5% of recycled PET fibre in concrete, it shows better performance as compared to plain concrete in 28 days. However, its performance was dropped by utilizing more than 1.0% to 1.5% volume fraction of PET in the concrete. This study showed that a vast amount of PET can reduce the strength of the concrete. Therefore, it is concluded that the fibre content will affect the strength of the concrete causing difficulty during the mixing process which affects poor compaction, poor workability, fibres did not distribute uniformly and lead to an increase of void volume (Khalid et al. 2018).

5 Recycled Plastic Bottle as Plastic Bricks

Nowadays, recycled material is widely used in the construction industry to promote green construction in order to overcome the pressing issue on the environment as well as enhancing performance of structure. Some of the advantages of using recycled plastic bottles are lower amount of waste, lower greenhouse gas emissions, lower pollution rates, saves on energy, uses less resources, saves money in waste management and maintains sustainability of resources. Plastic shows various benefits through its qualities such as do not corrode, lighter, chemically inert, good in plastic shrinkage cracking resistance and easy to mix with concrete and mortar matrix (Foti 2011). Furthermore, it can reduce the emission of CO_2 to the atmosphere, save energy in producing bricks in the factory and reduce air pollution after burning bottles at damping sites. Furthermore, it also can contribute to conserving natural resources, protecting ecosystems and wildlife, reducing demand for raw materials and can stop disastrous climate change. On top of that, recycled plastic bottles can be processed to become plastic bricks as replacement for conventional bricks. They are thinner, lighter, have superb heat insulating properties and insulating against noise as compared with conventional bricks. Each brick helps rid the world of discarded plastic and is cheaper and more fuel efficient to manufacture than conventional bricks. It is also less energy intensive than recycling the plastic into other forms. The shape and size of bricks from recycled plastic bottles will be discussed in the following topics.

There are a lot of studies that have been conducted on using recycled plastic bottles as plastic bricks. The plastic bottles with 500 mL were used to create voids at equal distance between them in the masonry units and analysed the compressive strength. The experimental results showed 57% difference in the strength by using plastic bottles as compared with local concrete blocks and it can be used as plastic bricks for the construction of houses (Sina and Amani 2016). Rhino Machines is the India-based company that has launched the Silica Plastic Blocks which is a sustainable building brick that is made from recycling foundry dust/sand waste (80%) and mixed plastic waste (20%) (Juliana 2021). Figure 8 shows the hollow Silica Plastic Blocks which were used for the construction of houses in India.

A young Kenyan material engineer, Nzambi Matee decided to invent recycled plastic bits mixed with sand into sustainable bricks and building materials through the company known as Gjenge Makers Ltd. The company gets the plastic waste from packaging factories or other plastic recyclers and mixes with sand as the binder. The extruder machine does the mixing of plastic waste with sand at very high temperatures and then compresses it. This company converts high density polyethylene, low density polyethylene and polypropylene plastics into solid bricks with different colours and sizes. This plastic brick is five times stronger than normal brick due to plastic being fibrous in nature and has excellent properties. This company produces 1000 to 1500 plastic bricks per day. Figure 9 shows some examples of plastic bricks with different shapes and colours which are produced using recycled plastic bits

Fig. 8 Silica plastic blocks produced by Rhino Machines (Jo and Park 2006)

Fig. 9 Different shapes and colours of plastic bricks produced by Gjenge Makers Ltd. (Juliana 2021)

and sand. These plastic bricks are used for the construction of houses, walls, pavement and driveways (Juliana 2021). The PET bricks were developed and patented by the National Council of Scientific and Technological Research (CONICET) using recycled PET bottles, cement and various additives. These bricks have the same properties as common ceramic bricks, but are lighter and have better insulating and sound-proofing properties (Bricks Made from Recycled PET Bottles 2018). Figure 10 shows the PET bricks made from recycled PET bottles patented by CONICET which can be used for the construction of houses (Bricks Made from Recycled PET Bottles 2018). RePlast bricks were developed and created by Peter Lewis under the company called ByFusion in New Zealand. The RePlast brick has the same size as a standard concrete block and is made from different kinds of scrap plastics that do not end up being a waste again. The RePlast system does not require the plastic to be washed or sorted and the permanent nature of construction helps to prevent the plastic from simply ending up in the oceans again (Neha 2016). Figure 11 shows RePlast bricks are produced from different kinds of plastic waste by ByFusion Company.

Fig. 10 PET bricks were made from recycled plastic PET bottles in Cordoba, Argentina (Bricks Made from Recycled PET Bottles 2018)

Fig. 11 RePlast bricks are produced from different kinds of plastic waste by ByFusion Company which is located in New Zealand (Neha 2016)

6 Construction of Houses Using Plastic Bricks

The plastic bricks as described above are used to construct single-storey houses especially in third world countries because the construction materials such as reinforcement bars, cements, concrete binders and others are very expensive and difficult to buy. Figure 12 shows a single-storey house and temporary shelters were constructed in Colombia using plastic bricks which were made from recycled plastic bottles. Plastic bricks are produced using an extrusion process where the plastic is melted and emptied into a final mould by creating a 3 kg brick similar in size as standard brick. This house is thermo-caustic and earthquake-resistant, satisfying the current seismic code of practice of Colombia. The total cost of this house is 20 million Colombian pesos (RM28, 291) per unit and was constructed in 5 days only. The temporary shelters were built using plastic bricks in 28 days at Guapi, Southwest of Colombia for 42 families displaced by armed conflict (Nicolás 2017). Figure 13 shows two single-storey houses built using recycled PET plastic bottles filled with sand. The PET plastic bottles were filled with sand, sealed and then paste them with a mixture made of earth, clay, sawdust and a little cement to provide additional strength

Fig. 12 A single-storey house and temporary shelters were built in Guapi, Colombia (Nicolás 2017)

Fig. 13 Single-storey houses were constructed using recycled plastic bottles refilled and compacted with sand and capped (Keiren 2020)

and durability. This house is an eco-friendly, sustainable and ecological environment which was constructed using 8000 PET bottles with composting toilets and a solar water heating system. The name of the entrepreneur who constructed these types of houses is Andreas Froese and the founder of "ECO-TEC" who built more than 50 eco-friendly projects in Honduras, Columbia and Bolivia.

7 The Manufacturing Process of Plastic Brick

The manufacturing process of the plastic brick blocks involves a modular platform which is portable and removable from one place to another place which is designed to operate using gas or electricity. The plastic trashes which are collected from factories and households are transported to the site or factory by lorry. The shredder is used to reduce the size of plastic bottles and trashes into smaller pieces before compacting them into plastic brick. The plastic bottles and wastes did not require sorting or washing. It is just enough to compress these small pieces of plastic into the plastic brick or block using a water boiler and compactor. The super-heated water and compression machine is used to fuse plastic pieces into plastic blocks. This process is non-toxic and did not use any adhesives during the construction process. Rebar steel rods, metal plate and tape are used during construction of non-load bearing walls, retaining walls and road pavements.

8 The Performance of Plastic Brick

Burnt brick is a vital building material that is widely used throughout the world. Compressed earth and burnt brick technology can be traced to the ancient Egyptian and Babylonian empires. Materials including straw, broken ceramic tiles, broken blocks and waste concrete have all been utilized to either strengthen, or act as a filler in clay bricks. Guettalal et al. (2016) came out with a study on the effects of cork granules in compressed earth bricks on the mechanical properties of bricks. This investigation concluded that with the increasing content of cork granules, the compressive and tensile strengths of cement-stabilized compressed earth blocks decrease. However, the compressive and tensile strength are still seen as acceptable when the cork's minimum mass content was used.

The previous studies on the utilization of waste materials in both compressed and burnt bricks are being reviewed by Zhang (2013). The materials that were investigated with bricks were Class F fly ash, Hematite tailings, Municipal solid waste incineration sludge, Granite sawing waste, Gold mill tailing, Paper production residue, Rice husk ash, Cigarette butt, Waste tea, River sediment, Saw dust, Waste marble powder, Foundry sand by products waste, Kraft pulp production residue, Sugarcane bagasse waste and Petroleum effluent treatment plant sludge. From his review, it can be deduced that one of the useful methods of recycling waste materials is to use it in building materials such as bricks. Despite the fact that the commercial production of bricks from waste products is still limited, the inclusion of these materials in bricks will be beneficial if there is standardization and commercialization being set according to their usage.

Akinyele et al. (2020) studied the possibility of using various proportions of PET as an additional material in burnt bricks. Figure 14 shows PET burnt brick before firing shrinkage test and Table 5 indicates the result of the utilization of various PET percentages in burnt brick including of 0%, 5% and 10% of PET in terms of firing shrinkage, water absorption, dry density and compressive strength. It was observed through the findings that PET material melted during firing due to its low melting point of 250ºC. Samples containing more than 10% PET content have been investigated and collapsed during the firing process. In contrast, samples containing less than 10% PET content did not collapse but are deformed in shape. Furthermore, the compressive strength of the bricks containing PET was also low but samples comprising more than 5% of PET content have better performance in terms

Fig. 14 Burnt brick before firing (Akinyele et al. 2020)

of structural efficiency when compared with control samples. This finding deduced that bricks that consist of 5% PET or less may perform well and further detailed research is needed. The main reason causing the poor performance of PET bricks under loading is revealed through microstructure properties. From the findings and observations, it indicates that the use of PET content of less than 5% can be utilized as a substitute in burnt bricks, aside from well-monitoring of the temperature during the firing process.

A separate research was carried out by (Akinyele and Toriola 2018), with the utilization of crushed plastic (PET) as a replacement of fine aggregate in Sandcrete bricks at 0, 5, 10, 15 and 20% content. All of the brick samples were subjected to mechanical and water absorption tests. Both compressive and flexural strength tests revealed that brick samples containing 5% PET outperform all other brick samples, including the control mix. In addition, it has lower density and water absorption in comparison to the control sample. The research work concluded that shredded PET can be used in Sandcrete bricks if it is less than 5% replacement.

9 Future and Challenges of Using Pet Plastic Bottle as Plastic Bricks in Malaysian Construction Industry

Many researchers found out that the recycled plastic aggregate and fibre as partial replacement can improve the concrete properties. However, there are several challenges regarding using PET plastic bottles as plastic bricks in Malaysian construction industries. One of the biggest challenges is separating and grading the recycle bottles from household waste which are collected by garbage truck. Furthermore, the mentality and discipline of Malaysian citizens to segregate the recycled plastic bottle from other waste materials is still low as compared with developed countries such as Japan, United Kingdom and others. Another challenge is the construction industries in Malaysia are reluctant to recycle plastic bricks manufactured locally

Table 5 Experiment result (Akinyele et al. 2020)

Proportion of PET (%)	Firing Shrinkage (%)	Water absorption (%)	Dry density (kg/m^3)	Compressive strength (N/mm^2)	Modulus of rupture (N/mm^2)	Structural efficiency (× 10^3 m)	Bending stress (N/mm^2)	Shear stress (N/mm^2)
0	2.11	10.29	1674	5.15	13.20	3.08	20.42	14.12
5	2.18	9.43	1404	2.30	11.96	1.64	18.64	12.86
10	2.28	6.57	1330	0.85	8.53	0.64	13.28	9.22

because the clients have many choices of bricks in the market for them to choose for their houses. Due to very low demand for plastic bricks, the cost of setting up the factory, producing plastic bricks and transportation are very expensive. Thus, it can be concluded that the construction industries in Malaysia are not ready to produce and use plastic bricks for the construction of houses, apartments and commercial buildings.

10 Conclusions

Based on the following explanation and discussion on recycled PET plastic bottles as construction materials, the following conclusions and recommendations are as listed below:

a. PET bottle itself consists of good physical and mechanical properties, in which it is non-corrosive, lighter; has high tensile strength, high alkali resistance, high value of wetting tension; and is chemically inert, good in plastic shrinkage cracking resistance and easy to mix with concrete and mortar matrix.
b. The utilization of plastic bottles as one of the construction materials can help to prevent catastrophic impacts, particularly on environmental issues such as climate change, contaminated soil caused by leachate, human health and extinction of aquatic life. Furthermore, this method has the potential to reduce a significant amount of plastic waste generated each year in Malaysia.
c. The construction cost of houses can be reduced in comparison to conventional houses, making it affordable particularly for B40 income households as the cost of material being utilized is much lower due to the use of recycled bottles.
d. Performance of 5% recycled PET bottles in brick due to fire shrinkage, compressive strength and flexural strength outperforms other proportions and controls. This result demonstrates that PET bottles can be used as an additional material in brick.

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Performance of Alkaline-Activated Cement Paste Toward Repairing and Rehabilitation on Concrete Structure

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Abstract The incorporation of waste products as an additive or replacement in concrete is tremendously growing in the world of construction. The use of Palm Oil Fuel Ash (POFA) as a partial replacement in cement paste can contribute to improving the conventional repair and rehabilitation work as it enhances some particular properties of the cement paste. Three different mixes were prepared; plain cement paste, POFA cement paste with and without alkaline activator. POFA is used to partially replace cement with the inclusion of sodium silicate. The test conducted in this study includes the quality of concrete tests such as the ultrasonic pulse velocity test and mechanical properties tests such as the compression test. This study shows the presence of POFA tends to improve the compressive strength of cement paste. However, with the presence of an alkaline activator, the cement paste tends to have adequate compressive strength but improvement in setting time and indicates good quality and continuity of the filling material with the cube. On the other hand, POFA cement with an alkaline activator can be used as repair and rehabilitation material due to improvement in setting time, which still provides adequate compressive strength.

Keywords POFA · Cement replacement · Alkaline activator · Repair · Patching

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