Innovative Infrastructure Solutions (2022) 7:183
https://doi.org/10.1007/s41062-022-00786-z

CASE STUDY

Optimisation of mixed proportion for cement brick containing plastic waste using response surface methodology (RSM)

Nur Hanis Zulkernain[1,3] · **Paran Gani**[2,3] · **Chuck Chuan Ng**[4] · **Turkeswari Uvarajan**[1,3]

Received: 20 October 2021 / Accepted: 20 February 2022

Abstract

Plastic waste is a significant environmental problem for almost all countries; therefore, protecting the environment from the problem is crucial. The most sensible solution to these problems is substituting the natural aggregates with substantial plastic waste in various building materials. This study aimed to optimise the mixed design ratio of cement brick containing plastic waste as aggregate replacement. Plastic cement brick mixtures were prepared by the incorporation of four different types of plastic waste such as polyethylene terephthalate (PET), high-density polyethylene, low-density polyethylene and polypropylene into cement bricks with different cement contents (150, 300 and 450 g) and plastic replacement percentages (0, 3 and 6%). Compressive strength and water absorption of the plastic cement bricks were analysed using a statistical model through the response surface methodology. It revealed the optimum cement brick mixed design is C3-1% PET with the compressive strength of 27.50 MPa and water absorption of 1.16%. The optimised plastic cement brick also satisfied the general ASTM C62-17 requirements for building bricks despite the higher porosity observed by the scanning electron microscopy. The results from Fourier transform infrared spectroscopy analysis also showed that the addition of the plastic waste into cement brick was unlikely to modify the chemical compound within the cement brick mixtures. Thus, the proposed mathematical model can predict the required hardened properties of plastic cement bricks and could lead to greater utilisation of plastic waste in building materials.

Keywords Plastic waste · Aggregate · Cement bricks · Optimisation · Response surface methodology

Introduction

The use of various plastics in consumer products such as food and beverage packaging, detergents, toiletries, kitchenware and even medical supplies has become prevalent due to its materials, simplicity, and applicability for all kinds of products. Higher plastic products and packaging consumption have eventually led to the rapid growth of post-consumer plastic waste and caused several environmental hazards. Besides, landfilling and burning plastic waste have been seen as the last resort in plastic waste management, considering both procedures created another series of environmental consequences. Hence, the resultant pollution from the abundant amount of plastic waste has heightened the need for a sensible solution to protect the environment and safely dispose of plastic waste.

The ineffectiveness of the current plastic waste management system has motivated many research scientists to look for a long-term solution to efficiently manage plastic waste without contributing to a new wave of plastic waste pollution. At present, plastic waste utilisation is regarded as one of the most inventive solutions for managing the abundant amount of plastic waste produced while also lowering the negative impacts on the environment [1]. Aside from the different recycling management techniques, reusing and recycling plastic wastes in construction materials have provided

---

✉ Nur Hanis Zulkernain
hanisnain@gmail.com

[1] School of Postgraduate Studies, Research and Internationalisation, Faculty of Integrated Life Sciences, Quest International University, Ipoh, Perak Darul Ridzuan, Malaysia

[2] School of Applied Sciences, Faculty of Integrated Life Sciences, Quest International University, Ipoh, Perak Darul Ridzuan, Malaysia

[3] Centre for Research and Innovation, Quest International University, Ipoh, Perak Darul Ridzuan, Malaysia

[4] China-ASEAN College of Marine Sciences, Xiamen University Malaysia, Selangor Darul Ehsan, Malaysia

many benefits to both environment and the construction industry [2, 3]. The utilisation of plastic waste as construction materials ensures that plastic waste is properly disposed of without directly returning to the environment [4]. More significantly, the recovered plastics can replace natural construction materials, which are relatively expensive, while also reducing the need for mining activities that have several negative effects to the environment [5, 6].

One of the most commonly used methods is substituting natural aggregates with recycled plastic waste in various formulations of cementitious materials such as mortar, concrete and cement brick [5, 7]. In recent decades, plastic waste utilisation as construction materials has been one of the major interesting research topics, leading to multiple studies investigating the viability of using plastic waste as building materials. Consequently, many researchers have studied the ability of different types of plastic waste to be used as an aggregate replacement such as PET [8–11], HDPE [12, 13], LDPE [14, 15], PP [16, 17] and others [18, 19]. However, these studies have been focused solely on the single types of plastic waste, with no simultaneous examination of the impacts of different types of plastic waste on brick properties using the same mix ratios and plastic replacement percentages. Besides, the performance of each type of plastic waste used as construction aggregate in various construction materials is also not well understood. Among the diverse types and grades of plastic, various plastic wastes might result in non-isotropic performance when used for construction purposes [20]. The physical and chemical differences of every type of plastic have become the challenges in this plastic utilisation method. Hence, this present study was conducted to evaluate the effects of different types of plastic waste which consist of polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP) as partial aggregate replacement in the production of cement bricks.

Moreover, the literature elucidates that no standard specification was established regarding the use of non-traditional construction materials like plastic waste in cement composites [20, 21]. In fact, traditional methods such as trial-and-error tests or fully experimental methods had been used to optimise the plastic content in cement composites [21, 22]. Therefore, the optimisation of mix design for cement brick containing plastic waste using mathematical modelling is highly required. Yet it can assist in exploring the influence factor on the performance of the cement brick precisely. Response surface methodology (RSM) is an efficient mathematical and statistical technique for modelling and analysing problems in which several variables influence the response of interest [23]. RSM has been widely used for optimising the mixed proportions of raw materials and additives in the formulation of construction materials [24–26]. However, there is limited application of the RSM technique to optimise the mix design of cement brick or plastic waste replacement ratios in cement composites to substitute the natural aggregates [21]. Hence, response surface methodology (RSM) was used in this study to optimise the cement brick mix design containing plastic aggregate with different cement content, plastic percentages and types of plastic.

Moreover, several researchers have addressed the technical viability of incorporating various plastic wastes into cement composites [27–29]. It was found that the inclusion of plastic waste has resulted in varied effects on the mechanical and durability properties of the materials. The incorporation of plastic waste into cement composite reduces the mechanical strength of the materials, which attributed to the weaker adhesion between cementitious matrix and plastic aggregates [5, 30, 31]. Besides, it also results in high water absorption due to the higher porosity of the composites after the addition of plastic aggregate [15, 32]. However, less reliable evidence on the microscopic characteristics of the materials, specifically cement brick containing plastic waste, supports the attributions made in prior investigations [7, 33]. Therefore, a detailed examination of the hardened cement brick is needed to evaluate the microscopic properties of this newly constructed material. In addition, a chemical assessment of the chemical compounds available in the materials is also essential as several plastic polymers may be susceptible to degradation due to exposure to the high alkaline condition of cement pastes [34–36]. Thereby, this present study aims to investigate the effect of four (PET, HDPE, LDPE and PP) different proportion types of plastic waste (%) and cement content (g) as independent variables in optimising the mix design of cement brick containing plastic waste via response surface methodology (RSM). In addition, scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) analysis were also performed accordingly to investigate the hardened properties of cement brick containing plastic aggregate.

Research significance

Reusing and recycling waste products such as plastic waste as a partial aggregate replacement in construction materials is a mutual option for solid waste management and the construction industry. It can help reduce the amount of plastic waste generated on a daily basis by offering a safe disposal mechanism for plastic waste and promoting the use of green bricks in sustainable construction. As a result, the outcomes of this study will point to strategies to make effective use of plastic waste by optimising plastic percentages, types of plastic and cement content. The research was also conducted to show that plastic waste may be recycled and reused as construction materials.

Materials and methods

Materials

This study used the ordinary Portland cement (OPC), type CEM 1 to prepare the cement brick specimens. Natural river sand was used in this study as fine aggregate, which has a maximum size of 4.75 mm. Four different types of plastic waste are polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP) obtained from the local plastic recycling factory in Ipoh, Perak Darul Ridzuan, Malaysia. The crushed plastic waste with size of less than 5 mm in shape was used in preparing the cement brick specimens.

Experimental design and data analysis

Design-Expert® 13.0 (Sat-Ease Inc., Minneapolis, USA) was employed for data analysis as well as for the mathematical and statistical design of the experiments. The face-centred central composite design (FCCCD) of RSM was applied to optimise the mix proportion of cement brick containing plastic aggregate. Before designing the experimental trials, a preliminary experimental study was initiated for determining the reasonable ranges of the cement content (g) and plastic replacement percentages (%) by four different types of plastic. Accordingly, each independent variable was varied over three levels between − 1 and + 1 at the determined ranges based on a set of preliminary findings (Table 1). The experiment has three different cement contents (150, 300 and 450 g) of bricks, and three plastic replacement percentages (0, 3 and 6%) were set up in RSM. Besides, four different types of plastic waste selected in this study include polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE) and polypropylene (PP). The compressive strength and water absorption of the cement brick were denoted as dependent factors (response) in this optimisation analysis.

Table 1 Independent variables of central composite design (CCD) design

Level of value	Numerical factors		Categorical factor
	Cement content (g)	Percentage of plastic aggregate (%)	Types of plastic aggregate
− 1	150 (C1)	0	PET, HDPE, LDPE, PP
0	300 (C2)	3	
+ 1	450 (C3)	6	

A total of 48 experiment trials of the FCCCD experimental design and responses executed are shown in Table 2. The programme suggested a quadratic model equation (Eq. 1) to determine the optimum condition of the responses.

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j X_j + \sum_{j=1}^{k} \beta_{jj} X_j^2 + \sum_{i} \sum_{<j=2}^{k} \beta_{ij} X_i X_j + e_i \quad (1)$$

From the equation, Y is the response; Xi and Xj are the variables; β is the regression coefficient; k is the number of factors studied and optimised in the experiment; and e is the random error. The coded points, actual points, and their corresponding values are described in Table 2. The interaction and relationship between the process factors, cement content (g) and plastic replacement percentages (%) and the responses (compressive strength and water absorption) were obtained from the analysis of variance (ANOVA). Besides, several model terms such as the coefficient of determination (R^2), the probability value (p-value) and F-value were determined at a 5% significance level to evaluate the statistical significance of the proposed model. Moreover, the ramp function graph and three-dimensional (3D) response surface graph were used to identify the optimum region at the end of the procedure.

Mixture proportions

The mixed proportions of cement brick were designed using the FCCCD whereby three plastic replacement percentages (0, 3 and 6%) with three cement contents (C1, C2, and C3) were applied to study the performance and the effect of different plastic waste in cement bricks. The sand was partially replaced by the four different types of crushed plastic waste (PET, HDPE, LDPE and PP) to form two mixes containing 3% and 6% by volume of plastic aggregates, respectively. The mixed design of various plastic cement bricks is shown in Table 3.

Specimen preparation

The brick specimens were prepared according to local standard procedure MS 27:2005, where 1:6 (cement:sand) mixture proportions and a constant water-cement ratio of 0.80 w/c were used in this study. The plastic waste materials were incorporated into different ratios and mixed with cement and sand to produce a homogenous of dry material and mixed with the water. After the mixing process, the mixture of cement, sand, plastics and water was placed into a mould sized 220 mm (l) × 100 mm (w) × 65 mm (h) to form bricks (Fig. 1). The sample bricks were allowed to air-dry and de-moulded after 24 h. On the following day after

Table 2 Actual design with experimental factors and response values for single type of plastic bricks

Run	Factor 1		Factor 2		Factor 3
	A: Cement content		B: Plastic percentages		C: Types of plastic
	Actual	Coded	Actual	Coded	Actual
1	300	0	0	−1	PET
2	300	0	3	0	LDPE
3	300	0	6	+1	PET
4	300	0	6	+1	LDPE
5	150	−1	6	+1	HDPE
6	300	0	3	0	HDPE
7	300	0	6	+1	PP
8	300	0	0	−1	HDPE
9	300	0	3	0	HDPE
10	450	+1	6	+1	LDPE
11	450	+1	3	0	PP
12	450	+1	6	+1	PET
13	300	0	3	0	LDPE
14	300	0	3	0	HDPE
15	450	+1	0	−1	LDPE
16	300	0	0	−1	LDPE
17	150	−1	6	+1	PET
18	150	−1	0	−1	HDPE
19	150	−1	3	0	PP
20	450	+1	0	−1	PP
21	300	0	3	0	PET
22	450	+1	3	0	LDPE
23	300	0	3	0	PET
24	450	+1	3	0	HDPE
25	150	−1	0	−1	PET
26	150	−1	6	+1	LDPE
27	300	0	3	0	LDPE
28	300	0	3	0	PET
29	450	+1	6	+1	HDPE
30	300	0	3	0	PP
31	150	−1	3	0	LDPE
32	150	−1	3	0	HDPE
33	300	0	3	0	LDPE
34	150	−1	0	−1	PP
35	300	0	3	0	PP
36	450	+1	3	0	PET
37	450	+1	6	+1	PP
38	300	0	3	0	PP
39	300	0	0	−1	PP
40	450	+1	0	−1	HDPE
41	150	−1	0	−1	LDPE
42	450	+1	0	−1	PET
43	300	0	3	0	PET
44	300	0	3	0	PP
45	150	−1	3	0	PET
46	150	−1	6	+1	PP
47	300	0	3	0	HDPE
48	300	0	6	+1	HDPE

casting, the bricks were kept in a curing tank and cured for 28 days (Fig. 2). After the curing process was completed, the sample bricks were subjected to several tests.

Bricks characterisation

Several tests were performed to optimise the mix design of cement brick containing various plastic waste as partial aggregate replacement.

Compressive strength test

The compression strength test was carried out on the specimens with a compression machine of a maximum load of 2000 kN, according to the standard procedure by BS EN 772-1: (2000). The axis of the specimen was carefully aligned with the centre of the lower pressure plate of the compression testing machine, after which an upper-pressure plate was lowered until the distance between the pressure plate and the top surface of the specimen was achieved. The load was gradually applied at the rate of 40 kN/min until the specimen got crushed. The maximum load was applied to the samples, and the appearance of the brick was recorded. All testing measurements were taken from three samples, and the average of three samples was presented and discussed in the study. Besides, all results were compared with the American Standard for Testing and Materials (ASTM C62: 2017) and other international standards such as British Standard (BS 3921: 1985) and Malaysian Standard (MS 76: 1972). Besides, it was also analysed using RSM to identify the optimum mix design that produced the maximum compressive strength of the cement brick.

Water absorption test

To determine the water absorptivity of the cement brick samples, 28 days of cured cement brick specimens were dried in an oven for 24 h at 110 °C, until the mass became constant where this weight was noted as the dry weight (W1) of the block. After that, the specimen was immersed in water at room temperature for 24 h and this obtained weight was

Table 3 Various proportions of plastic and cement content for the production of cement brick containing four different types of plastic

Cement content	Cement (g)	Sand (g)	Types of plastic (g)				Sample name
			PET	HDPE	LDPE	PP	
C1	150	1892	59	–	–	–	C1-3% PET
	150	1892	–	59	–	–	C1-3% HDPE
	150	1892	–	–	59	–	C1-3% LDPE
	150	1892	–	–	–	59	C1-3% PP
	150	1833	117	–	–	–	C1-6% PET
	150	1833	–	117	–	–	C1-6% HDPE
	150	1833	–	–	117	–	C1-6% LDPE
	150	1833	–	–	–	117	C1-6% PP
C2	300	1746	54	–	–	–	C2-3% PET
	300	1746	–	54	–	–	C2-3% HDPE
	300	1746	–	–	54	–	C2-3% LDPE
	300	1746	–	–	–	54	C2-3% PP
	300	1692	108	–	–	–	C2-6% PET
	300	1692	–	108	–	–	C2-6% HDPE
	300	1692	–	–	108	–	C2-6% LDPE
	300	1692	–	–	–	108	C2-6% PP
C3	450	1600	50	–	–	–	C3-3% PET
	450	1600	–	50	–	–	C3-3% HDPE
	450	1600	–	–	50	–	C3-3% LDPE
	450	1600	–	–	–	50	C3-3% PP
	450	1551	99	–	–	–	C3-6% PET
	450	1551	–	99	–	–	C3-6% HDPE
	450	1551	–	–	99	–	C3-6% LDPE
	450	1551	–	–	–	99	C3-6% PP

Fig. 1 The casting process of cement brick containing plastic aggregate

Fig. 2 The prepared cement bricks were cured in the water for 28 days

referred as the wet weight (W2) of the block. The purpose of this test method is to compare the relative water absorption tendencies between several cement bricks that containing different types of plastic aggregate. The standard method of ASTM C140-11b [37] was reviewed to conduct the water absorption test.

$$\text{Water absorption}(\%) = \left(\frac{W2 - W1}{W1}\right) \times 100\% \tag{2}$$

where $W1$ = oven-dry weight of block in grams, $W2$ = after 24 h wet weight of block in grams.

Microstructure observation of cement brick specimen by the scanning electron microscopy (SEM)

A scanning electron microscopy (SEM) test was also conducted to explore the interface between cement mixture and aggregates or the so-called interfacial transition zone of cement and plastic aggregate. Field emission scanning electron microscopy (FE-SEM, Leo Supra 50 VP, Carl Zeiss, Oberkochen, Germany) with a back-scattered detector (QBSD) was used for this study. At the preparation of the experiment, the samples were placed on carbon conductive tape. The morphology of cement composites' characterisation was then performed at 6 mm of working distance using a 10 kV of accelerating voltage. The morphological characteristics of cement brick containing plastic waste were identified and observed at the end of the test.

Fourier transform infrared spectroscopy (FTIR) analysis of cement brick specimen

The FTIR spectroscopy test was carried out to identify the functional group of chemical compounds in the optimised plastic cement bricks. In the transmission mode (Tr), sample pellets were prepared by mixing 1 g of potassium bromide (KBr) with 0.01 g of cement brick hardened fractures [38]. All scans were recorded over the range of 4000–400 cm^{-1} using the Alpha Bruker FTIR spectrometer. The background spectrum was collected using a pure KBr pellet, and the spectra of samples were corrected with a linear baseline. The sample specimen was placed on the sample holder of the FTIR machine, and a spectrogram was obtained at the end of this test.

Statistical analyses

Statistical analysis was carried out to determine the statistical significance of the data obtained and to optimise the cement brick mix design at the end of the experiment. Factorial analysis of variance (ANOVA) was employed to compare means between the different types of plastic aggregate used in terms of compressive strength and water absorption. Furthermore, one-way ANOVA with post hoc comparison using Tukey's honestly significant difference (HSD) test was analysed at the significant level of $p < 0.05$, to compare the means of compressive strength and water absorption cement brick in this study. The homogenous group were obtained from the analysis and reported in this study. Besides, the Design-Expert® 13.0 software was used for the statistical design of experiments and data analysis for the optimisation analysis. A FCCCD through RSM was applied to optimise the relationship between the variables (cement content, plastic replacement percentages and types of plastic) and responses (compressive strength and water absorption). The statistical analyses were conducted using the IBM SPSS Statistics 20 software package and Design-Expert® 13.0 (Sat-Ease Inc., Minneapolis, USA).

Results and discussion

Compressive strength of cement bricks

Figure 3 shows the cement brick's compressive strength with various plastic aggregate types with different cement contents (150, 300, and 450 g) and plastic replacement percentages (0, 3 and 6%). Based on the analysed data, most of the cement bricks containing plastic aggregate have satisfied the MS 76: 1972 (5.2 MPa), BS3921:1985 (7.0 MPa) and ASTM C62: 2017 (15.2 MPa) standards except for a few bricks that were found to obtain lower compressive strength. It was found that most of the cement brick had higher strength at higher cement content; meanwhile, cement brick containing higher plastic aggregate percentages had a relatively lower compressive strength. The control sample prepared with different cement contents (C1, C2 and C3) had a relatively higher compressive strength of 7.0 MPa, 16.4 MPa and 32.7 MPa as compared to the cement brick containing 3% and 6% of the plastic aggregate, respectively. The highest compressive strength recorded for cement brick containing a single plastic aggregate was recorded at C3-3% PET (28.7 ± 3.32 MPa), whilst C1-3% LDPE (1.7 ± 1.16 MPa) was recorded as the lowest compressive strength.

The three-way ANOVA analysis showed significant interaction ($p < 0.05$) in all three independent variables studied; cement content, plastic percentages and types of plastic aggregate. It was found that interactions of cement content and plastic percentages with compressive strength of all plastic cement brick showed significant differences ($p < 0.05$), whereby the higher cement content significantly increased the compressive strength of cement brick. Meanwhile, increasing plastic percentages added to the cement brick significantly reduced ($p < 0.05$) the compressive strength of the cement brick. Furthermore, there were no significant differences ($p > 0.05$) between plastic types and compressive strength in most cement brick prepared except for all C2 and C3 cement brick containing 6% of the plastic aggregate. Similarly, the post hoc analysis by Tukey's HSD also found that C2 and C3 cement brick's compressive strength had significant differences ($p < 0.05$) among four different types of plastic such as C3-6% PET with C3-6% LDPE (Table 4).

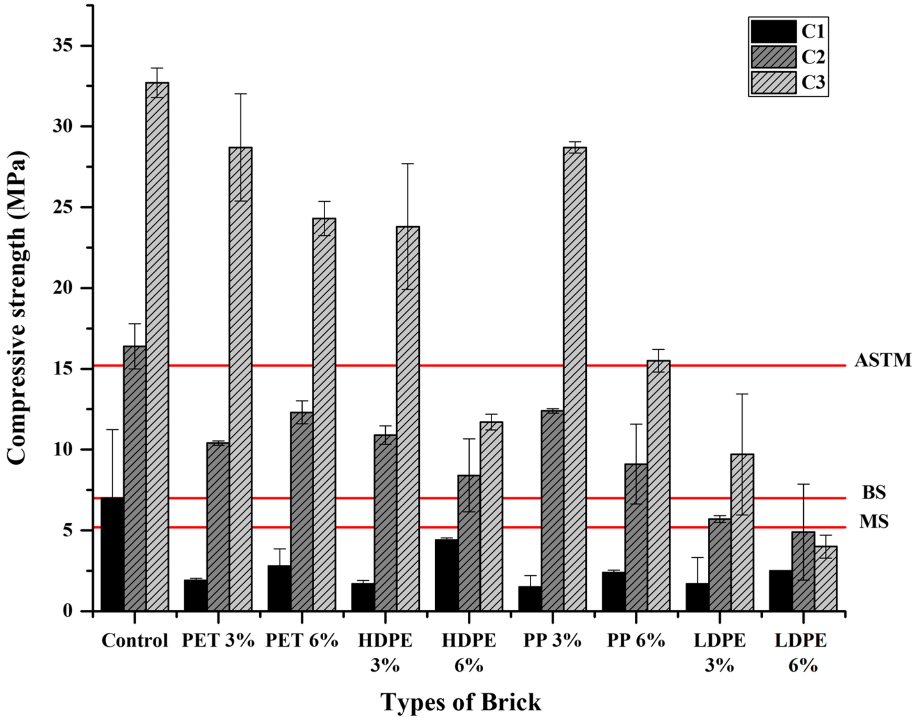


Fig. 3 Compressive strength of cement brick with various plastic aggregate percentages

The substantial increment in compressive strength of cement brick at higher cement content could be associated with the substantial amount of calcium-silicate-hydrate (C–S–H) gel bonds created after reaction with the water [39–41]. Hence, the increase in cement volume in the brick enhances the compressive strength due to cement gel bonds produced in the composite. Besides, a significant reduction in compressive strength of all cement brick after incorporating four different types of plastic at 3% and 6% plastic replacement could be associated with the hydrophobic properties of plastic. The nature of plastic being a hydrophobic material was seen to be the primary cause of the reduction in compressive strength of cement bricks. Thus, it has inhibited the cement hydration process from completely occurring at the surface of plastic aggregate [3]. Due to the incomplete hydration of cement on the surface of plastic aggregate, the adhesive strength and the van der Walls force between cement paste and plastic aggregate have decreased, resulting in low compressive strength of cement brick [33, 42, 43].

Furthermore, other potential factors have been identified in previous studies which reduced the compressive strength of cement brick such as (1) low surface energy of plastic added to the concrete has negatively affected the mechanical bond between the plastic waste and cement matrix; (2) the inclusion of plastic waste has created several voids and resulted in high porosity and air content; (3) low elastic modulus of plastic aggregates as compared to natural aggregate and (4) the possible deterioration of materials by several environmental factors such as plastic degradation in an alkaline environment [3, 20, 33, 35].

Despite the reduction observed in the compressive strength observed in all cement bricks containing plastic aggregate, the majority of the compressive strength of the cement bricks met the standards requirements as specified in the MS 76: 1972 (5.2 MPa), BS3921:1985 (7.0 MPa) and ASTM C62: 2017 (15.2 MPa), with the exception of a few bricks that had lower compressive strength (Fig. 3). In this study, LDPE brick exhibited the lowest compressive strength for cement content in C1 (1.3 ± 0.35 MPa) and C3 (4.0 ± 0.71 MPa) at 6% plastic replacement ratio which failed to meet the general requirement for the building brick based on the MS, BS and ASTM standards. The lower compressive strength obtained by the LDPE brick could be attributed to the physical structure of LDPE plastic aggregate, which has a coarser particle size that reduces particle packing in the cement brick mixtures [5, 44]. Therefore, it can be concluded that different types, grades or sizes of plastic may have variable impacts on the cement brick's mechanical properties, as suggested by Awoyera and Adesina [20] and Saikia and De Brito [45].

Water absorption of cement bricks

Figure 4 illustrates the variations of water absorption of cement brick containing plastic waste as aggregate that were prepared with different cement content and plastic replacement percentages at a constant water-cement ratio (0.8 w/c).

Table 4 Tukey's HSD homogenous groups for compressive strength of cement brick sample

Sample name	Compressive strength (MPa)	Homogenous groups
C1-Control	7.00 ± 1.24	abcdef
C1-3% PET	1.90 ± 0.14	abcd
C1-3% HDPE	1.70 ± 0.21	abc
C1-3% LDPE	1.70 ± 0.21	ab
C1-3% PP	1.50 ± 0.71	abc
C1-6% PET	2.80 ± 1.06	ab
C1-6% HDPE	4.40 ± 0.14	a
C1-6% LDPE	2.50 ± 0.10	ab
C1-6% PP	2.40 ± 0.14	ab
C2-Control	16.40 ± 0.85	hi
C2-3% PET	10.40 ± 0.14	efghi
C2-3% HDPE	10.90 ± 0.57	efghi
C2-3% LDPE	5.70 ± 0.21	efghi
C2-3% PP	12.40 ± 0.14	fghi
C2-6% PET	12.30 ± 0.71	fghi
C2-6% HDPE	8.40 ± 2.26	bcdefg
C2-6% LDPE	4.90 ± 1.97	cdefg
C2-6% PP	9.10 ± 2.47	defg
C3-Control	32.70 ± 0.92	l
C3-3% PET	28.70 ± 3.32	kl
C3-3% HDPE	23.80 ± 3.89	jk
C3-3% LDPE	9.70 ± 3.75	efgh
C3-3% PP	28.70 ± 0.35	kl
C3-6% PET	24.30 ± 1.06	jk
C3-6% HDPE	11.70 ± 0.49	fghi
C3-6% LDPE	4.00 ± 0.71	abcde
C3-6% PP	15.50 ± 0.71	ghi

Mean ± Standard deviation. Similar letters in homogenous group are not significantly different at the 95% level of confidence by Tukey's HSD

The standard requirement of building brick (ASTM C62-10) stated that the water absorption of good quality bricks should be within 20% [46, 47]. The results revealed that most cement bricks are still within the range of allowable limits by the standard requirements. It was shown that the lower cement content of cement brick had a greater water absorption, whereby all cement brick that was prepared with the lowest cement content of C1 (150 g), had higher water absorption values starting from 10%. In contrast, cement brick prepared with the highest cement content of C3 (450 g) obtained very low water absorption values ranging from 1.21 to 5.31%. Besides, a minor decrease in water absorption was observed for PET, HDPE and PP cement bricks after adding plastic waste as aggregate at 3% and 6% of plastic replacement. Incorporating LDPE into cement bricks, on the other hand, has increased the brick's water absorption.

In this study, there is significant interaction ($p < 0.05$) in all three independent variables studied; cement content, plastic percentages and types of plastic aggregate. The higher cement content significantly decreased ($p < 0.05$) the water absorption of cement brick containing different plastic types and percentages. Meanwhile, the increasing plastic percentages added to the cement brick significantly reduced ($p < 0.05$) the compressive strength of the cement brick that was prepared with C1 and C2 cement content. However, there were no significant differences ($p > 0.05$) in the water absorption of C3 cement brick containing 3% compared to 6% of the plastic aggregate. Furthermore, the mean of water absorption in C3 cement brick was found to have no significant differences ($p < 0.05$) among different types of plastic except for C3-6% LDPE, which had a slightly higher water absorption than the other plastic cement brick (Table 5). This implies that different forms or types of plastic aggregate have varying effects on the cement brick's water absorption property.

The lower water absorption in cement brick that was prepared with the highest cement content may be due to the increasing rate of the cement hydration process. The use of high cement content might enhance the paste-aggregate zone of cement mixtures due to the additional C–S–H gel formation [48]. It also improved the cement bricks' interfacial structure, which caused the bricks to have a lower amount of void [41]. Therefore, it can be assumed that the cement brick's permeability would become lower after using high cement content, thus reducing the water absorptivity and water retention in the cement brick.

Besides, two distinct observations were examined for water absorption in this study. The cement brick containing PET, HDPE and PP had a relatively lower water absorption than control brick. Meanwhile, LDPE brick experienced a significant increment ($p < 0.05$) in the water absorption after adding plastic at both plastic replacement percentages (3 and 6%). Several studies have shown that the increasing degree of plastic substitution has contributed to a decrease in the water absorption due to the reduction of material capillary voids and plastic with a low water affinity [42, 49, 50]. However, some previous studies have found that increasing the amount of plastic waste added to concrete or brick mixture increases the water absorption of the materials due to an increase in porosity [15, 32, 51, 52].

A significant increase ($p < 0.05$) in water absorption observed in LDPE brick could be ascribed to the effects of LDPE plastic inclusion that may lead to higher void content created by the cement brick [15]. The increasing porosity in cement bricks could explain the increasing water absorption observed in cement brick containing LDPE plastic aggregate [50]. Besides, it was reported that LDPE plastic has led to the coarsening of the porous structure and increasing macropores within the cement brick [53]. Thus, the higher

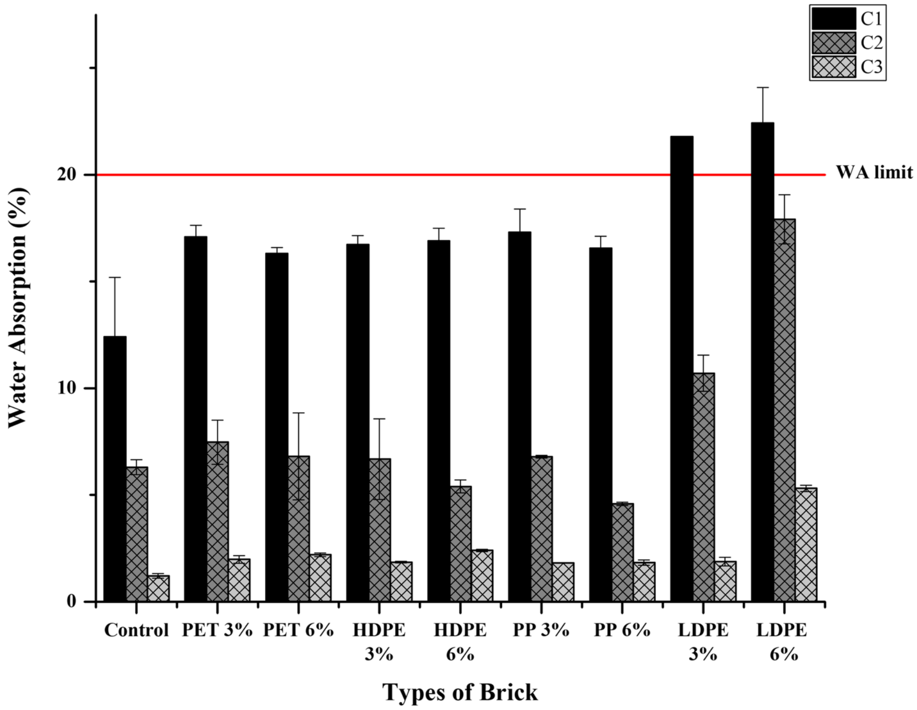


Fig. 4 Water absorption of cement brick containing four different types of plastic aggregate at different cement contents and plastic replacement percentages

void content by the plastic inclusion in cement brick has increased the water absorption, where the cement bricks have a higher ability to absorb more water within the bricks. Hence, this explained the higher water absorption observed in LDPE bricks after adding 3% and 6% plastic aggregate. This study discovered that different types of plastic aggregate can have distinct effects on brick properties, such as water absorption. This could be due to the differences in size, shape and physical qualities of the plastic aggregates employed in this investigation [45].

Analysis of face-centred central composite design (FCCCD)

The compressive strength (MPa) and water absorption (%) responses have been considered to develop the optimised mix design of cement brick containing plastic aggregate. These are the two standard parameters which are extensively assessed in various building bricks requirements [47]. The entire data set and the corresponding experimental data are presented in Table 6. In order to find a good model to describe the interaction of each factor (cement content, plastic replacement percentages and types of plastic) and response (compressive strength and water absorption) that was investigated in this study, the analysis of variance (ANOVA) was applied to all results obtained (Table 7). The data illustrated that all models were statistically significant at the 95% of confidence level. The full quadratic model was adopted as the best-fitted model for the obtained results as expressed below:

$$\begin{aligned}\text{Compressivestrength(MPa)} &= 9.78 + 10A - 5.39B + 1.73C(1)\\ &+ 0.158C(2) - 3.30C(3) - 3.26AB\\ &+ 2.58AC(1) - 0.254AC(2) - 3.50AC(3) + 2.35BC(1) - 0.446\\ &BC(2) - 2.26BC(3) + 2.12A^2 + 2.12B^2\end{aligned} \tag{3}$$

$$\begin{aligned}\text{Waterabsorption(\%)} &= 8.66 - 7.11A + 1.45B-\\ &0.81C(1) - 0.71C(2) + 2.55C(3) - 0.98AB + 0.37\\ &AC(1) + 0.35AC(2) - 0.93AC(3) - 0.72BC(1)\\ &- 0.83BC(2) + 2.67BC(3) + 1.09A^2 - 0.96B^2\end{aligned} \tag{4}$$

The model validation of responses such as correlation coefficient (R^2), probability value (p-value), F-value and lack-of-fit probability value is presented in Table 8. The F-value of compressive strength (42.15) and water absorption (41.84) for plastic cement brick indicated that the models obtained are statistically significant ($p < 0.05$). The model terms were considered significant when the values of the p value are less than 0.05 [54]. The values of correlation coefficient (R^2) of 0.9470 and 0.9467 obtained for compressive strength and water absorption responses have indicated a good relationship between the predicted and observed values. The good fit model should have a minimum correlation coefficient of 0.80 as explained by Amr et al. [55]. Moreover, the high correlation coefficient of the dependent variable shows a good correlation that considered 95% of the measured values; thus, it can be applied for the predicted model [56].

Furthermore, the adequate precision of 24.75 and 27.49 for compressive strength and water absorption obtained for

Table 5 Tukey's HSD homogenous groups for water absorption of cement brick samples

Sample name	Water absorption (MPa)	Homogenous groups
C1-Control	12.41 ± 2.79	f
C1-3% PET	17.09 ± 0.55	h
C1-3% HDPE	16.74 ± 0.29	gh
C1-3% LDPE	21.78 ± 0.10	hi
C1-3% PP	17.31 ± 1.08	h
C1-6% PET	16.31 ± 0.29	gh
C1-6% HDPE	16.90 ± 0.60	h
C1-6% LDPE	22.43 ± 1.66	ij
C1-6% PP	16.56 ± 0.56	gh
C2-Control	10.79 ± 0.35	ef
C2-3% PET	7.47 ± 1.03	cde
C2-3% HDPE	6.68 ± 1.89	cd
C2-3% LDPE	10.70 ± 0.85	ef
C2-3% PP	6.79 ± 0.06	cd
C2-6% PET	6.81 ± 2.04	bc
C2-6% HDPE	5.40 ± 0.3	bc
C2-6% LDPE	17.92 ± 1.15	h
C2-6% PP	4.58 ± 0.08	abc
C3-Control	1.21 ± 0.11	a
C3-3% PET	1.98 ± 0.18	ab
C3-3% HDPE	1.85 ± 0.04	ab
C3-3% LDPE	1.88 ± 0.20	ab
C3-3% PP	1.81 ± 0.01	ab
C3-6% PET	2.20 ± 0.09	ab
C3-6% HDPE	2.40 ± 0.06	ab
C3-6% LDPE	5.31 ± 0.15	bc
C3-6% PP	1.83 ± 0.13	ab

Mean ± Standard deviation. Similar letters in homogenous group are not significantly different at the 95% level of confidence by Tukey's HSD

the plastic cement brick model is greater than four, demonstrating an adequate signal of the model [26, 57, 58]. Hence, this result indicated that the predicted models are desirable and confirmed that the models could be utilised to navigate the design space defined by FCCCD [21, 26]. This was also supported by the determination of not significant lack of fit ($p > 0.05$) in the models where the lack-of-fit value was 2.43 and 1.78 for compressive strength and water absorption responses, respectively. The lack of fit for each response resulted in p-values that much greater than 0.05, indicating that the models accurately fit with the data [26, 54, 59]. The RSM model developed to predict the compressive strength and water absorption of plastic cement brick was found to be reasonable based on the findings.

Besides, the diagnostic plots such as normal probability and predicted plots versus actual value of compressive strength and water absorption were obtained to determine the model's adequacy and satisfactoriness [21, 55]. The normal distribution plots shown in Fig. 5a, b for compressive strength and water absorption, respectively, have indicated that the data used were normally distributed. The points of both compressive strength and water absorption responses were in a straight line. Likewise, all models' predictions were also in a satisfactory match with the experimental value. The points are well accorded with each other as shown in Fig. 6a, b for both compressive strength and water absorption of plastic cement brick, respectively. Accordingly, the selected models used in this study have considered providing an adequate approximation of the responses.

Interpretation of the interaction between variables

The comparative effects of three factors: cement content (g), plastic replacement percentages (%) and types of plastic aggregate (PET, HDPE, LDPE and PP) on optimising the compressive strength and water absorption are clarified by the perturbation plots as shown in Figs. 7 and 8, respectively. The perturbation plots revealed a significant influence between cement content (A) and plastic replacement percentages (B) for both compressive strength and water absorption responses. The increasing cement content in cement brick has remarkably promoted the cement brick's strength in all cement bricks containing different types of plastic aggregate. The perturbation plots also showed that the curvature for cement content (A) factor in PET and PP bricks was notably sharper than the other plastic cement bricks, indicating that the compressive strength was more sensitive in PET and PP bricks at higher cement content.

Besides, the perturbation plots were also compared to assess the relationship between the plastic replacement percentages (B) and compressive strength. Plastic substitution percentages, unlike cement content, have had a negative impact on the compressive strength of cement bricks. A high amount of plastic added as an aggregate replacement into the cement brick has reduced the compressive strength of the cement bricks in this study. These findings corroborate with the previous research that shows that increase of plastic replacement percentages in cement composites reduces the compressive strength dramatically [32, 60–63]. The perturbation plots in Fig. 7 show that plastic replacement percentages were observed to significantly influence the compressive strength for all prepared cement bricks containing plastic aggregate. A higher reduction of compressive strength was observed in cement brick containing the highest percentage (6%) of plastic aggregate. From Fig. 7, it was also observed that both curvatures (A) and (B) have a sharper curve, indicating that the compressive strength is sensitive towards the changes in cement content and plastic replacement percentages. Accordingly, it also displays

Table 6 Experimental data of actual and predicted compressive strength and water absorption for plastic cement bricks

SD	Run	Independent variables			Dependent variables (Responses)			
		Factor 1	Factor 2	Factor 3	Response 1		Response 2	
		A: Cement content	B: Plastic percentages	C: Types of plastic	Compressive strength (MPa)		Water absorption (%)	
					Actual	Predicted	Actual	Predicted
1	25	150	0	PET	7.00	2.94	12.41	13.02
2	42	450	0	PET	32.70	34.63	1.21	1.50
3	17	150	6	PET	1.30	3.40	16.31	16.43
4	12	450	6	PET	24.30	22.04	2.20	1.00
5	45	150	3	PET	1.90	1.05	17.09	15.69
6	36	450	3	PET	28.70	26.22	1.98	2.21
7	1	300	0	PET	16.40	16.67	7.33	6.17
8	3	300	6	PET	12.30	10.60	6.81	7.63
9	28	300	3	PET	10.30	11.51	8.20	7.86
10	21	300	3	PET	10.50	11.51	6.74	7.86
11	23	300	3	PET	7.80	11.51	6.30	7.86
12	43	300	3	PET	10.40	11.51	8.50	7.86
13	18	150	0	HDPE	7.00	7.00	12.41	13.25
14	40	450	0	HDPE	32.70	33.02	1.21	1.67
15	5	150	6	HDPE	1.00	1.86	16.9	16.45
16	29	450	6	HDPE	11.70	14.83	2.40	0.97
17	32	150	3	HDPE	1.70	2.31	16.74	15.81
18	24	450	3	HDPE	23.80	21.81	1.85	2.28
19	8	300	0	HDPE	16.40	17.89	7.33	6.37
20	48	300	6	HDPE	8.40	6.22	5.40	7.62
21	14	300	3	HDPE	11.30	9.94	8.02	7.95
22	6	300	3	HDPE	10.50	9.94	5.35	7.95
23	9	300	3	HDPE	9.30	9.94	8.28	7.95
24	47	300	3	HDPE	10.90	10.90	10.32	7.95
25	41	150	0	LDPE	7.00	8.61	12.41	14.29
26	15	450	0	LDPE	32.70	28.13	1.21	0.17
27	26	150	6	LDPE	1.30	-0.17	22.43	24.48
28	10	450	6	LDPE	4.00	6.31	5.31	6.45
29	31	150	3	LDPE	1.70	2.10	21.78	20.34
30	22	450	3	LDPE	12.30	15.10	1.88	4.27
31	16	300	0	LDPE	16.40	16.25	7.33	6.14
32	4	300	6	LDPE	4.90	0.95	17.92	14.37
33	13	300	3	LDPE	10.30	6.48	11.30	11.21
34	2	300	3	LDPE	5.30	6.48	10.10	11.21
35	27	300	3	LDPE	3.50	6.48	11.30	11.21
36	33	300	3	LDPE	3.80	6.48	12.38	11.21
37	34	150	0	PP	7.00	6.01	12.41	13.37
38	20	450	0	PP	32.70	34.91	1.21	1.51
39	46	150	6	PP	1.30	2.47	16.56	16.00
40	37	450	6	PP	15.50	18.31	1.83	0.23
41	19	150	3	PP	1.50	2.13	17.31	15.64
42	11	450	3	PP	28.70	24.49	1.81	1.83
43	39	300	0	PP	16.40	18.34	7.33	6.35
44	7	300	6	PP	9.10	8.28	4.58	7.02
45	35	300	3	PP	10.30	11.19	6.75	7.64
46	44	300	3	PP	12.50	11.19	6.83	7.64

Table 6 (continued)

SD	Run	Independent variables			Dependent variables (Responses)			
		Factor 1	Factor 2	Factor 3	Response 1		Response 2	
		A: Cement content	B: Plastic percentages	C: Types of plastic	Compressive strength (MPa)		Water absorption (%)	
					Actual	Predicted	Actual	Predicted
47	30	300	3	PP	12.30	11.19	7.71	7.64
48	38	300	3	PP	12.40	11.19	8.18	7.64

Table 7 Analysis of variance (ANOVA) for response surface quadratic model plastic cement brick

Responses	Source	Sum of squares	df	Mean square	*F*-value	*p* value	Remarks
Compressive strength	Model	3791.62	14	270.83	42.15	<0.0001	Significant
	A—CC	2402.00	1	2402.00	373.79	<0.0001	
	B—PP	696.60	1	696.60	108.40	<0.0001	
	C—Types of plastic	190.83	3	63.61	9.90	<0.0001	
	AB	170.30	1	170.30	26.50	<0.0001	
	AC	122.32	3	40.77	6.34	0.0016	
	BC	65.91	3	21.97	3.42	0.0285	
	A^2	47.88	1	47.88	7.45	0.0101	
	B^2	47.88	1	47.88	7.45	0.0101	
	Residual	212.06	33	6.43			
	Lack of fit	171.63	21	8.17	2.43	0.0580	Not significant
	Pure error	40.43	12	3.37			
	Cor total	4003.68	47				
	$R^2=0.9470$, Adjusted $R^2=0.9246$, Predicted $R^2=0.8558$, Adequate Precision = 24.7515						
Water absorption	Model	1465.15	14	104.65	41.84	<0.0001	Significant
	A—CC	1213.53	1	1213.53	485.11	<0.0001	
	B—PP	50.61	1	50.61	20.23	<0.0001	
	C—Types of plastic	104.38	3	34.79	13.91	<0.0001	
	AB	15.33	1	15.33	6.13	0.0186	
	AC	6.95	3	2.32	0.9267	0.4387	
	BC	57.37	3	19.12	7.64	0.0005	
	A^2	12.75	1	12.75	5.10	0.0307	
	B^2	9.79	1	9.79	3.91	0.0563	
	Residual	82.55	33	2.50			
	Lack of fit	62.53	21	2.98	1.78	0.1510	Not significant
	Pure error	20.02	12	1.67			
	Cor total	1547.70	47				
	$R^2=0.9467$, Adjusted $R^2=0.9240$, Predicted $R^2=0.8733$, Adequate Precision = 27.4950						

CC—Cement content; PP—Plastic replacement percentages

that the suitable ranges of cement content (g) and plastic replacement percentages (%) for enhancing the compressive strength should be within 300–450 g and 0–3%, respectively. In addition, it also shows that the highest compressive strength (32.7 MPa) was observed at 450 g of cement content with 0% of plastic replacement percentages.

Furthermore, the combined effect of cement content (A) and plastic replacement percentages (B) in response to the water absorption is also clarified by the perturbation plots, as shown in Fig. 8. A precise observation was observed in the curvature (A) of cement content which is sharper than the curvature (B), indicating that cement content factor had a remarkable effect on the water absorption. Based on Fig. 8, the lower water absorption is generally associated with the higher cement content used while casting the cement brick with different types of plastic aggregate.

Table 8 Model validation of compressive strength and water absorption responses

	Compressive strength (MPa)	Water absorption (%)
Standard deviation	2.53	1.58
Mean	11.90	8.73
Correlation coefficient, R^2	0.9470	0.9467
Predicted R^2	0.8558	0.8733
Adjusted R^2	0.9246	0.9240
Coefficient of variance	21.30	18.11
PRESS	577.41	196.17
Adequate precision	24.75	27.49

Moreover, the perturbation plots also revealed that the increase in cement content and plastic replacement percentages had resulted in decreased water absorption. However, this trend has only occurred in PET, HDPE and PP cement bricks as water absorption of cement brick containing LDPE was significantly increased ($p < 0.05$) after adding 3% and 6% of the plastic aggregate. The curvature (B) in LDPE plastic brick seems to be much sharper than PET, HDPE and PP, indicating that the water absorption of cement brick containing LDPE was more sensitive to higher plastic replacement percentages than to different types of plastic aggregate. Figure 8 shows that the suitable ranges of cement content (g) and plastic replacement percentages (%) for achieving desirable water absorption should be in the range of 150–450 g and 0–3%, respectively. In addition, Fig. 8 shows that the highest water absorption (21.4 MPa) was observed in C1-6% LDPE brick which prepared with the lowest cement content (C1, 150 g) and highest plastic replacement percentages (6%).

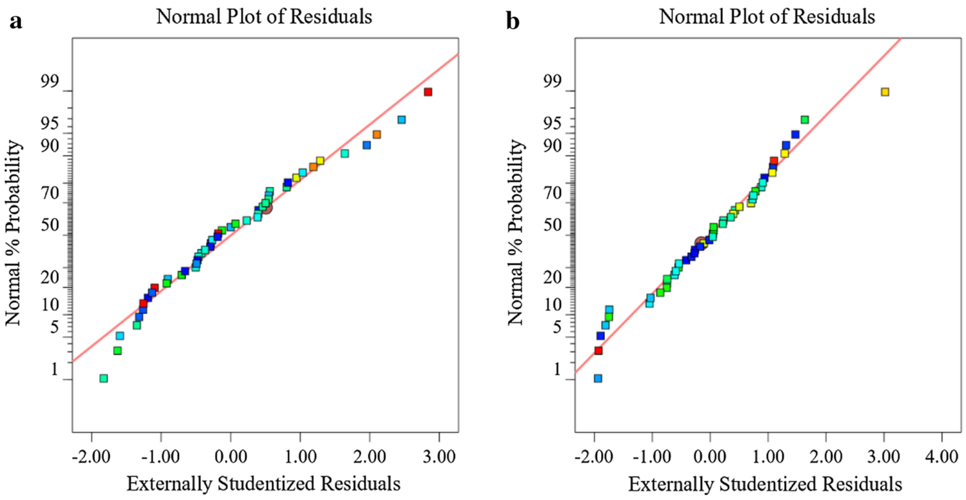


Fig. 5 Normal probability plots for compressive strength and water absorption for plastic cement brick models (**a**) compressive strength and (**b**) water absorption responses

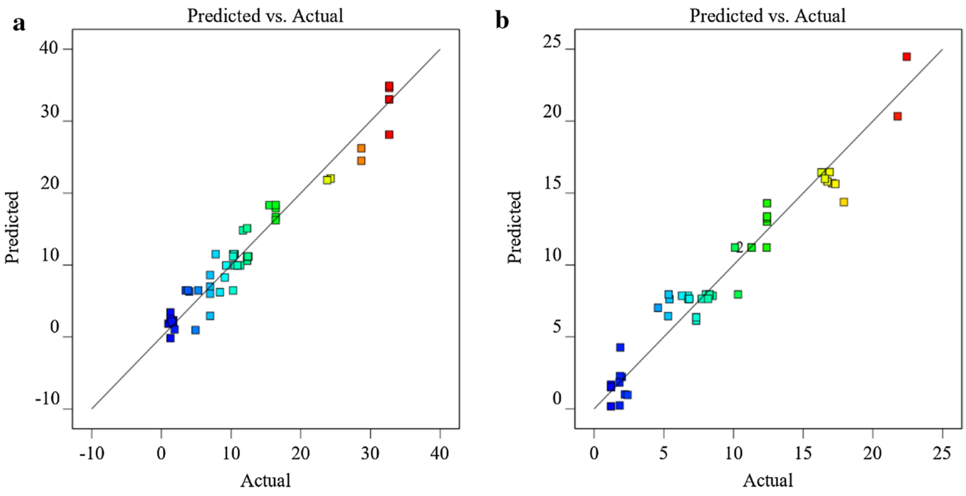
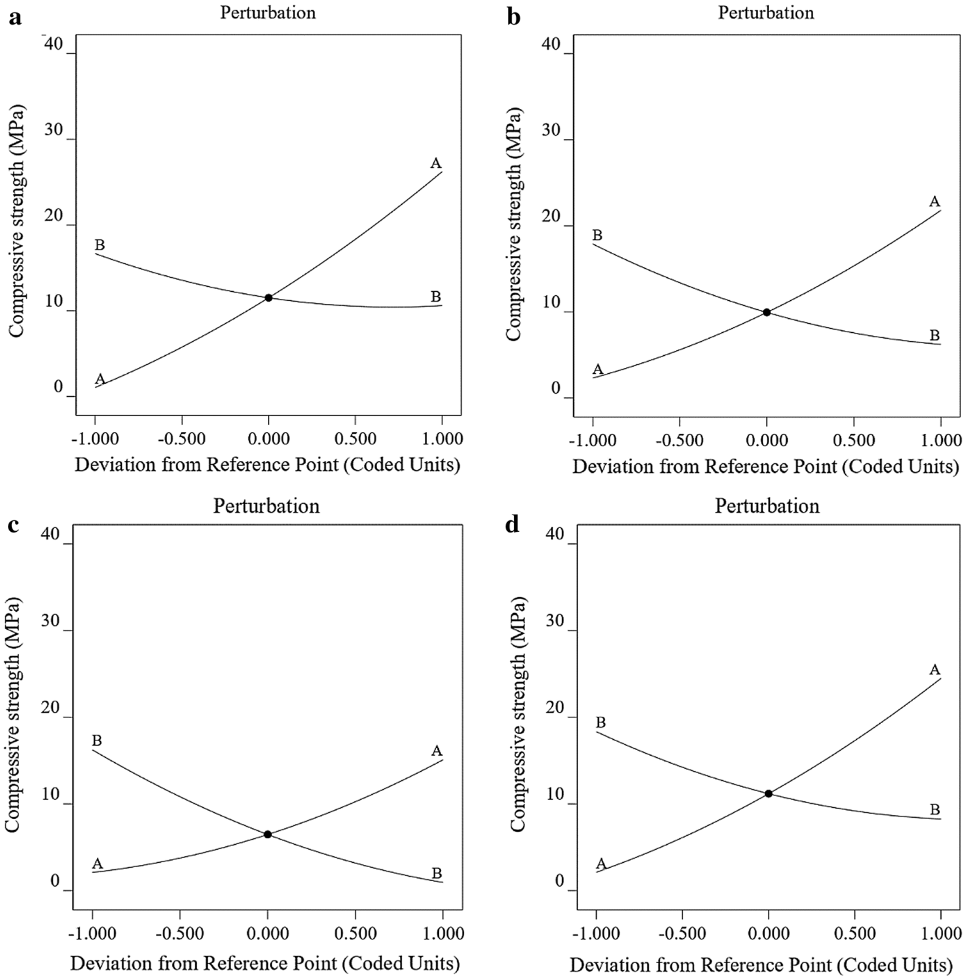


Fig. 6 Predicted versus actual values plots for compressive strength and water absorption for plastic cement brick models (**a**) compressive strength and (**b**) water absorption responses

Fig. 7 Perturbation plots of compressive strength in response to changes in cement content (*A*) and plastic replacement percentages (*B*) for (**a**) PET, (**b**) HDPE, (**c**) LDPE and (**d**) PP



Optimisation of mixed design plastic waste cement bricks

Using the desirability function method in Design Expert (version 13) software, the optimisation process was carried out to develop an optimum mix design of cement brick containing plastic waste as aggregate replacement. A specific criterion has been proposed to optimise the present study's responses (Table 9). In this study, all the operational variables (cement content, plastic replacement percentages and types of plastic aggregate) were defined as 'in range'. Besides, the responses for compressive strength were defined as 'maximum' to achieve the highest cement brick performance. In contrast, the water absorption response was defined as 'in range' to achieve a desirable water absorption below 20%, as stated in the local and international standards [46, 47]. The programme combines the individual desirability into a single number and then search to optimise this function based on the response goal [55]. Accordingly, the optimum mix design for plastic cement brick has been established, and the results are presented in Table 10.

From the optimisation process, about 32 solutions suggested by the Design Expert software as the optimised mixed design of cement brick containing four different types of plastic aggregate. However, the highest desirability values were chosen as the optimum condition, as the desirability values of 0.80–1.00 are regarded as acceptable and excellent [64]. Therefore, the cement brick mixed design for plastic cement brick was optimised at 31.36 MPa with a desirability of 0.959. The highest compressive strength of cement brick containing plastic aggregate was found in the cement brick containing 1% of PET with 450 g of cement content as described in Fig. 9. Besides, the contour plot and three-dimensional (3D) response surfaces were also depicted from the software to visualise the compressive strength and water absorption at the optimum mix design in terms of cement content, plastic replacement percentages and types of plastic aggregate (Figs. 10, 11).

Verification of the final equation model was conducted to ensure the accuracy of the predicted response values in the validation set. A series of experiments on the optimised conditions were performed under the predicted optimal condition to verify the optimisation results. The mean

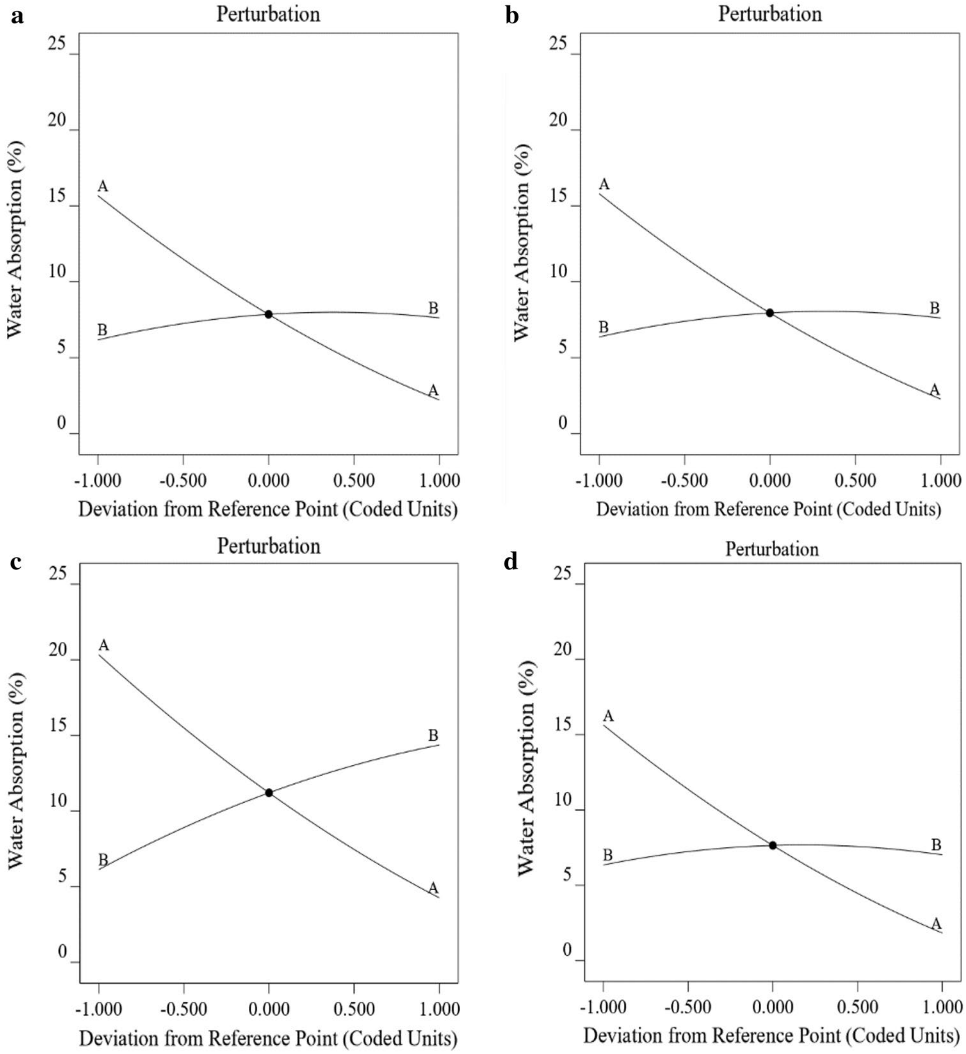


Fig. 8 Perturbation plots of water absorption in response to changes in cement content (*A*) and plastic replacement percentages (*B*) for (**a**) PET, (**b**) HDPE, (**c**) LDPE and (**d**) PP

Table 9 Constraints of numerical optimisation

Name	Goal	Lower limit	Upper limit
Variables constraints			
Cement content (g)	In range	150	450
Plastic replacement percentages (%)	In range	1	6
Types of plastic	In range	PET, HDPE, LDPE, PP	
Responses constraints			
Compressive strength (MPa)	Maximize	15.2	32.7
Water absorption (%)	In range	0	20

Table 10 Optimum operational variable obtained

Cement content (g)	Plastic replacement percentages (%)	Types of plastic	Compressive strength (MPa)	Water absorption (%)	Desirability
450	1.0	PET	31.36	1.95	0.959

of the validation samples for compressive strength and water absorption was 27.50 MPa and 1.16%, respectively. Based on the obtained findings, there is only a minor difference between the experimental (27.50 MPa and 1.16%) and predicted (31.35 MPa and 1.95%) results for compressive strength and water absorption, respectively. Accordingly, the FCCCD model has considered the applicability

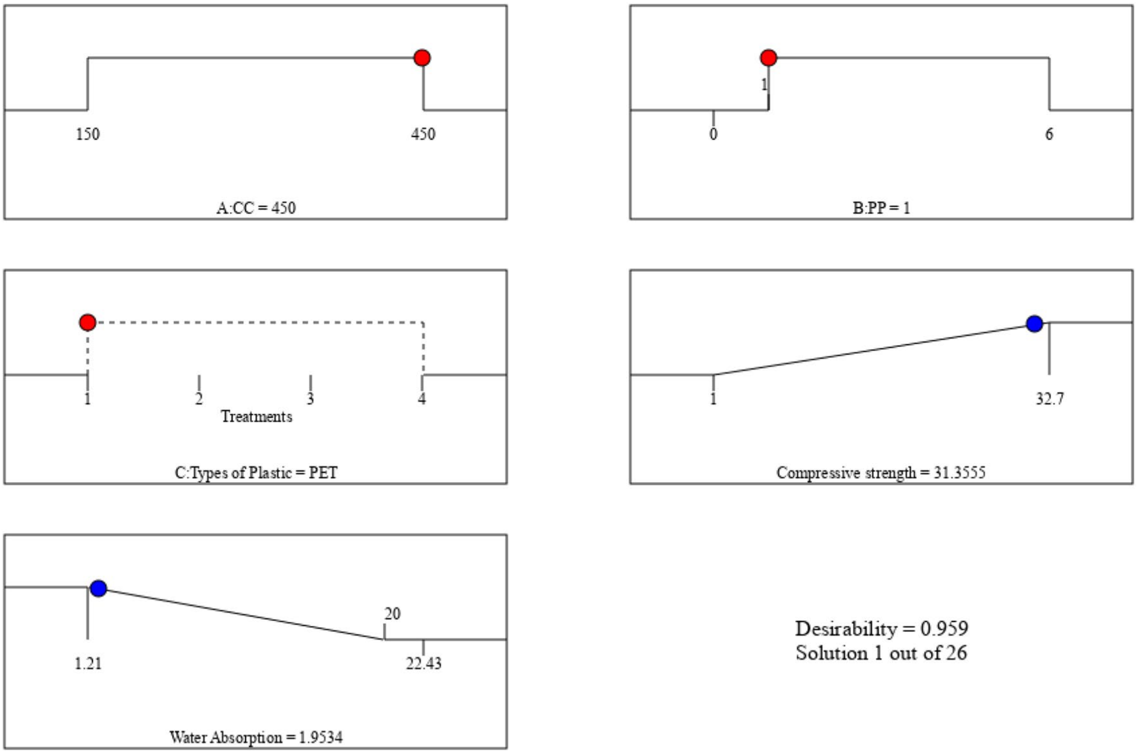
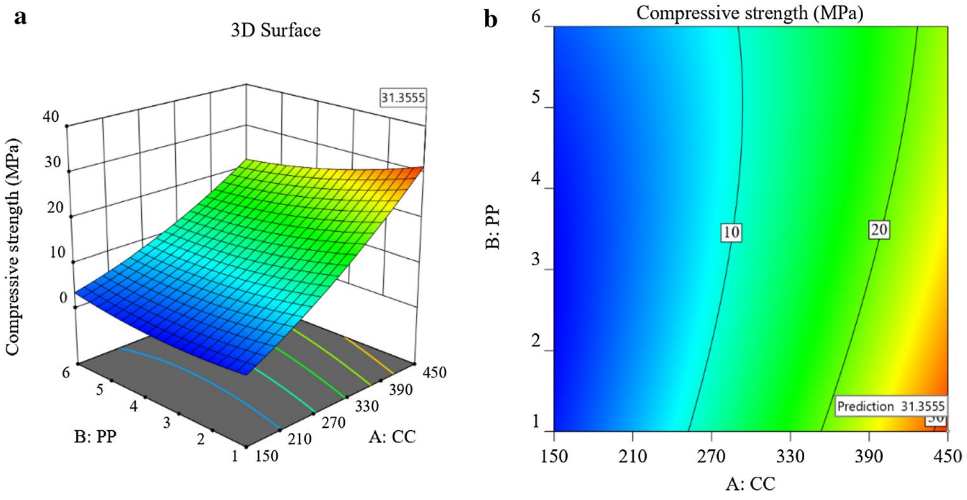


Fig. 9 Ramp function graph for optimum mix design of plastic cement bricks

Fig. 10 The (**a**) three-dimensional (3D) and (**b**) contour plots for the compressive strength of plastic cement bricks on cement content and plastic percentages



for optimisation mix design of cement brick containing a single type of plastic aggregate. Therefore, the optimised mix design for cement brick containing plastic aggregate is shown in Table 11 and Fig. 12.

In addition, the optimum response for cement brick containing plastic aggregate obtained in this study was compared with several past studies. Table 12 summarises the findings reported for the optimum plastic replacement percentages on compressive strength and water absorption of the brick. It was observed that various optimum plastic replacement percentages were reported in previous studies, ranging from 1 to 25%. Besides, it was shown that the cement brick in this present study had achieved a higher compressive strength than the other plastic-incorporated brick in the previous studies. This may be due to the application of higher cement content during the casting of cement brick in this study. However, it is essential to note that there are diversities of the mix design used in these studies.

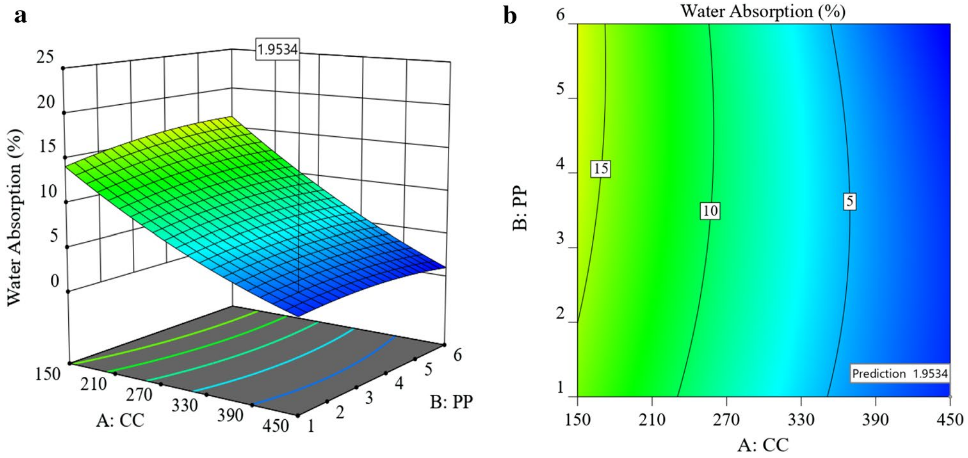


Fig. 11 The (**a**) three-dimensional (3D) and (**b**) contour plots for the water absorption of plastic cement bricks on cement content and plastic percentages

Table 11 Optimum mix design and model validation of compressive strength and water absorption from numerical optimisation

Model	Cement content (g)	Plastic replacement percentages (%)	Types of plastic	Compressive strength (MPa)		Water absorption (%)	
				Actual	Predicted	Actual	Predicted
Plastic cement brick	450	1	PET	27.50	31.35	1.16	1.95

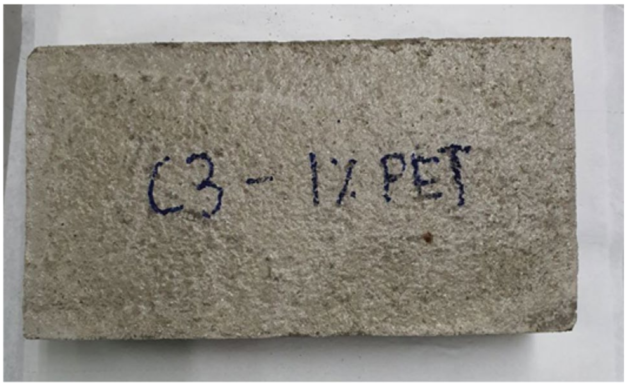


Fig. 12 C3-1% PET has been optimised from the RSM optimisation analysis

Table 12 Comparison of optimum plastic replacement percentages of plastic-impregnated brick observed in seven different studies with the present study

Types of plastic aggregate	Optimum plastic replacement (%)	Compressive strength (MPa)	Water absorption (%)	References
PET	1	18.56	7.46	[51]
PET	1	27.50	1.16	This study
HDPE	10	6.3	–	[65]
HDPE	5	11.61	14.46	[66]
HDPE	3	15.90	2.17	[67]
PP	5	14.85	15.03	[42]
Mixed	24	20.10	–	[21]
Mixed	1	29.19	7.79	[19]

Microstructure observation by the scanning electron microscopy (SEM)

Following the optimisation procedure, the optimised plastic cement brick was evaluated for microscopic and chemical characteristics of cement mixtures. In this study, the porosity of the optimised plastic cement brick, micro-crack distribution, homogeneity of the cement mixtures and the cross-linking bridges at the interfacial zone (ITZ) between the cement mixtures and plastic aggregate were investigated (Fig. 13). From Fig. 13b, it was observed that the homogeneity of cement mixtures has lessened after the addition of plastic waste as aggregate. The SEM images showed many open pores in the cement mixture of optimised plastic cement brick (C3-1% PET). On the other hand, the control brick with no addition of plastic waste had a homogenous surface and texture (Fig. 13a). The number of open pores was lower in the cement mixtures for control brick, and it portrayed that the mixtures of sand and cement were mixed and packed well in the control brick as compared to cement brick containing plastic aggregate.

The higher number of open pores in cement brick incorporated with plastic waste may be due to the irregular shape and non-uniform sizes of plastic aggregate added to the mixtures [29]. The surface roughness of various types of

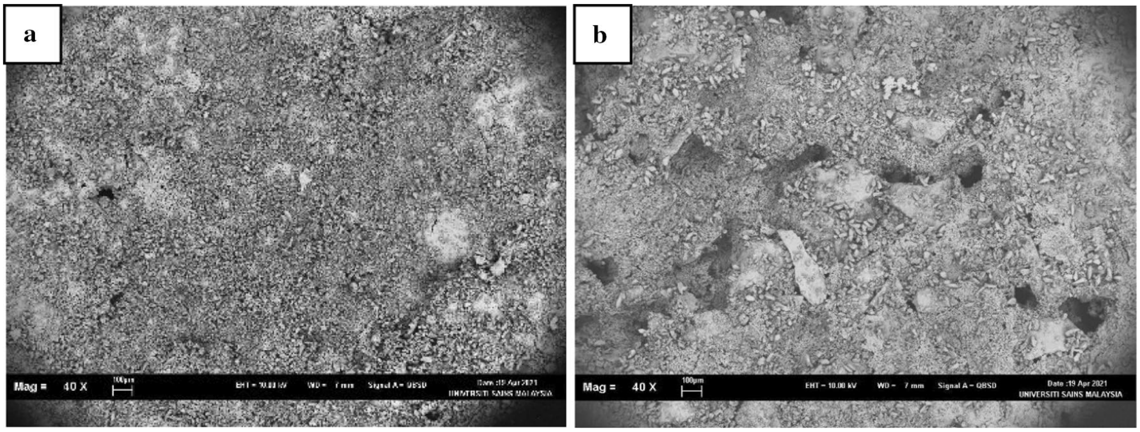


Fig. 13 SEM images of (**a**) control brick and (**b**) plastic cement brick at 40× magnification with 100 µm spatial resolution

plastic waste inhibited the cement mixtures from mixing well with the other raw materials such as sand and cement [5, 68]. Besides, it was also observed that the optimised plastic cement brick has a micro-crack formation within the cement mixtures. The microscopic images shown in Fig. 14 indicate that plastic waste as aggregate in cement brick has caused significant crack formation within the cement brick mixtures. According to Alqahtani et al. [69], the major crack formation that occurred within the cement mixtures may be attributed to the weaker adhesion between the plastic aggregates and cement mixtures.

Hence, the microscopic observation on the interfacial zone between plastic aggregates was also performed for optimised plastic cement brick. The SEM analysis revealed a weaker adhesion at the interfacial zone of plastic aggregates and cement matrix (Fig. 15). These SEM images of optimised plastic cement brick were also compared with the control brick, which found that the control brick has a dense and packed cement paste, unlike the optimised plastic cement brick (Fig. 16).

Following the microscopic observation of both control and optimised plastic cement brick, the SEM analysis has confirmed that the addition of plastic waste has increased the brick's porosity, reduced the homogeneity and increased the formation of micro-crack in the cement paste. These phenomenal occurred due to the weaker adhesion of plastic aggregate with cement mixtures, which can be related to the hydrophobic properties of plastic [68, 70]. The hydrophobic nature of plastic has inhibited the water-cement reaction at the surface of plastic aggregate, which eventually increases the water content between the interface and created a layer that prevents the plastic aggregate from having a good bonding with cement paste [5, 69]. Hence, this might explain the compressive strength reduction and structural deterioration in the cement brick after adding plastic waste as aggregate. The higher reduction in compressive strength

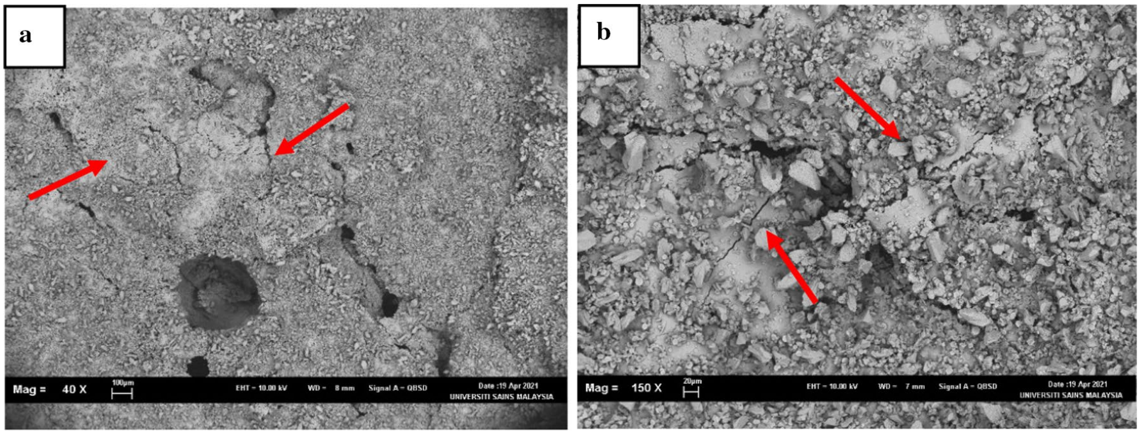


Fig. 14 Micro-crack formation in cement matrix after addition of plastic aggregate (**a**) 40× magnification with 100 µm spatial resolution and (**b**) 150× magnification with 20 µm spatial resolution

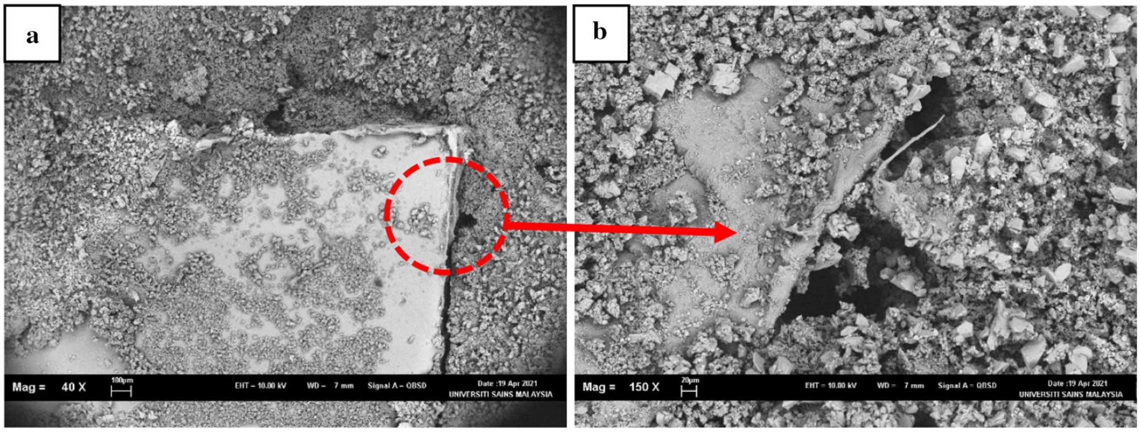


Fig. 15 Interfacial zone between plastic aggregate and cement paste (**a**) 40× magnification with 100 µm spatial resolution and (**b**) 150× magnification with 20 µm spatial resolution

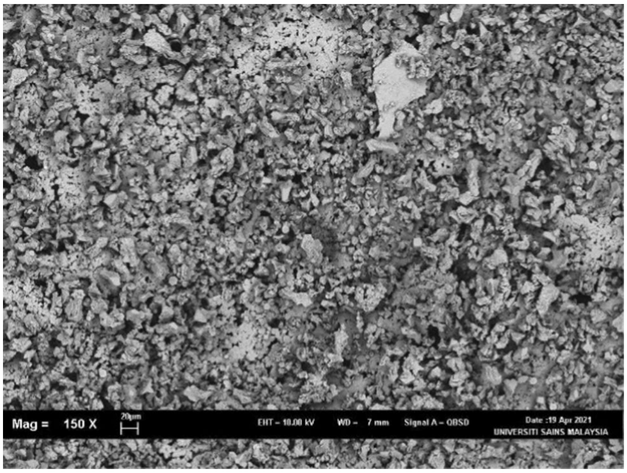


Fig. 16 SEM image of the cement mixture of control brick

was observed in the cement brick with higher plastic aggregate amount that could also be credited to the greater stress transfers produced between the plastic aggregate and cement components, and consequently led to the structure deteriorations through a few plastic aggregate detachments from the cement paste and cracks formation in the mixtures [29]. Moreover, the higher porosity observed in the optimised plastic cement brick (C3-1% PET) has confirmed that the addition of plastic waste as aggregate in cement brick did not increase the water absorption of the plastic cement brick. This is consistent with the findings from several previous studies by Akinyele and Toriola [42], Al-Hadithi and Al-Ani [50] and Kamarulzaman et al. [49], which also showed a reduction in water absorption after the addition of plastic aggregate into cement mixtures.

The deterioration of mechanical properties such as compressive strength of cement bricks due to weaker adhesion at the interfacial zone of plastic aggregate and cement paste has prompted many researchers to develop new methods to improve the conversion of plastic waste into aggregate to be used as a construction material. Rai et al. [60], Jaivignesh et al. [71] and Correa et al. [72] have suggested the use of admixtures and additives such as superplasticizer and metal fibre to improve the chemical bond between plastic wastes and cement mixture. Besides, chemical treatment on the surface of plastic aggregate can also improve the bonding between the cement paste and plastic aggregate added into the cement brick [5, 73, 74]. These treatments are significant in avoiding the diminishment of the strength property of the construction materials containing plastic waste. Therefore, adding admixtures and applying chemical treatment could be a good option in improving the chemical bond of plastic aggregates with cement paste and reducing the internal damage within the cement brick, which leading to strength deterioration.

Fourier transform infrared spectroscopy (FTIR) analysis of the optimised cement brick specimen

An infrared spectrum test with scanned absorption bands from 400 to 4000 cm^{-1} was conducted to examine the main functional groups in the optimised cement brick containing plastic aggregate (C3-1% PET) as well as to compare the plastic cement brick with control brick in term of the chemical composition of the cement brick mixtures. From Fig. 17, the pattern and absorption bands obtained for all samples for control brick and optimised plastic cement brick (C3-1% PET) are quite similar and parallel with each other. Besides, there is no unique peak observed in the spectrum obtained by the cement brick containing plastic aggregate as compared to the spectrum bands of control bricks. Hence, it can be assumed that the addition of plastic waste as aggregate replacement in the cement brick might not have many differences in terms of the chemical composition of the cement brick containing plastic aggregate.

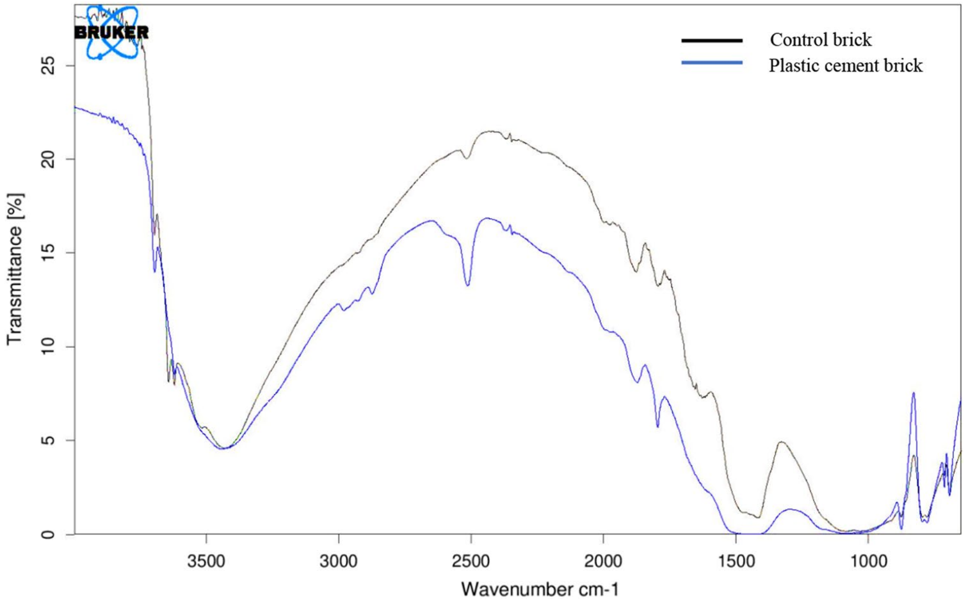
A strong and broad absorption peak was obtained in all cement brick samples between 3436.05 and 3436.48 cm^{-1} representing O–H stretching vibration, which may be due to the presence of calcium hydroxide in the cement brick mixtures. Calcium hydroxide is the main by-product formed in the cement hydration process [75]. Tricalcium silicate in cement powder is responsible for calcium hydroxide whereby in the hydration reaction, tricalcium silicate reacts with water to release calcium ions, hydroxide ions and heat [76]. Therefore, the free calcium (Ca^{2+}) and hydroxide (OH^{-}) ions are attracted to each other; hence, calcium hydroxide was formed and highly available in the cement brick mixtures.

Besides, the C–H stretching absorption bands were slightly present at the wavenumber between 2850 and 3000 cm^{-1} in the FTIR spectra of optimised plastic cement bricks. These peaks that appeared in plastic cement brick might occur due to alkanes and alkyls. However, these peaks were not available in the control brick, and it was more intense in cement brick with the addition of plastic waste as it could be due to the presence of plastic waste in the cement brick, which consist of a substantial number of alkanes and alkyl groups [72, 77].

Furthermore, the peaks observed at 1422.25 cm^{-1} for optimised plastic cement brick and 1479.32 cm^{-1} in the control brick could be due to the stretching bond of C-O of a carbonate ion. Besides, the presence of carbonate ion (CO_3^{2-}) was confirmed with the narrow bands found at 875.10 cm^{-1} and 779.96 cm^{-1} for plastic cement brick and control bricks, respectively [38, 77]. The presence of carbonate ions in the cement brick mixtures might be due to the calcium carbonate salt formed after the reaction of calcium hydroxide with the atmospheric carbon dioxide [75]. Furthermore, the bands observed between 970 and 1100 cm^{-1} in the cement brick sample for control and optimised plastic cement brick acted as an indicator of the presence of calcium silica hydrate (C–S–H) within the cement brick [38]. The signals at 1082.63 cm^{-1} and 1082.64 cm^{-1} for plastic cement brick and control bricks were attributed to the asymmetric vibrations of Si–OH in the formation of calcium silica hydrate (C–S–H) [78].

The bands or peaks of FTIR spectra discussed above are compared with several previous studies [72, 77]. It was found that similar compounds such as alkane, alkyl, carbonates and hydroxides were reported to be within the cement composite containing recycled plastic aggregate. Overall, no unique bands were observed in the optimised single and mixed plastic brick. Furthermore, the compounds found in this study were also reported to be similar to the standard hydrated cement paste [38, 75]. Therefore, it can be concluded that the addition of plastic aggregate into the cement brick as an aggregate replacement is unlikely to modify the chemical compound within the cement brick significantly.

Fig. 17 The IR-spectra obtained for control brick (black) and optimised plastic cement brick (blue)



Conclusions

This present study optimises the mix design of cement brick containing plastic waste using response surface methodology (RSM) with three independent variables (cement content, plastic replacement percentages and types of plastic). Overall, the results indicated that plastic waste possess great potential as an efficient partial aggregate replacement in cement bricks with considerable potential of excellent cement brick properties.

1. All three controlled variables (cement content, plastic waste replacement ratio and types of plastic aggregate) have a significant relationship ($p < 0.05$) with the cement brick properties (compressive strength and water absorption).
2. Response surface methodology via the FCCCD has statistically proven ($p < 0.05$) that the second-order polynomial (quadratic) function fit well with the experimental results.
3. The optimum cement brick mix design was observed at C3-1% PET and C3-1% MIX for single and mixed plastic brick with compressive strength of 27.50 MPa and 24.00 MPa and water absorption of 1.16% and 2.14%, respectively.
4. Microstructure observation by scanning electron microscopy (SEM) revealed a higher porosity and weaker adhesion at the interfacial transition zone (ITZ) between plastic aggregate and cement mixtures. Hence, the impacts observed in the microstructure properties explained the reduction of compressive strength in almost all cement brick incorporated with plastic aggregate.
5. The FTIR analysis showed a similar pattern of spectrum band among the optimised plastic brick with the control brick. Therefore, it was concluded that the addition of plastic aggregate into cement brick did not considerably change the chemical structure of the cement brick.

Future research

This study has effectively provided new insight into plastic waste utilisation as construction materials and the characteristics of plastic cement brick. Considerably more work will need to be done to determine other mechanical and durability properties such as flexural strength, thermal conductivity and masonry failure mechanism. Furthermore, the environmental perspectives of the plastic cement brick should be evaluated to uncover the environmental impacts of plastic waste utilisation. Plastic stability in cement mixtures, microplastic contributions and leaching potential of plastic additives from plastic aggregate are among the potential topics that are yet to be explored by many researchers. Finally, a comprehensive life cycle assessment (LCA) on plastic cement brick can be conducted in the future to analyse the potential environmental impacts associated with the entire process involved from the production, use and disposal phases.

Acknowledgements The authors are grateful to the QI Group of Companies (CRI/QIUP/FST/PG/2018) for the financial support and Quest International University Perak (QIU) to provide the comprehensive research facilities to carry out this study.

Declarations

Conflicts of interest The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. T. Rodrigues, A. Rangel, G. De Azevedo, D. Cecchin, Application of plastic wastes in construction materials : a review using the concept of life-cycle assessment in the context of recent research for future perspectives (2021)
2. Kamaruddin MA, Abdullah MMA, Zawawi MH, Zainol MRRA (2017) Potential use of plastic waste as construction materials: recent progress and future prospect. IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/267/1/012011
3. Gu L, Ozbakkaloglu T (2016) Use of recycled plastics in concrete: a critical review. Waste Manag 51:19–42. https://doi.org/10.1016/j.wasman.2016.03.005
4. Nematzadeh M, Shahmansouri AA, Fakoor M (2020) Post-fire compressive strength of recycled PET aggregate concrete reinforced with steel fibers: optimization and prediction via RSM and GEP. Constr Build Mater 252:119057. https://doi.org/10.1016/j.conbuildmat.2020.119057
5. Belmokaddem M, Mahi A, Senhadji Y, Pekmezci BY (2020) Mechanical and physical properties and morphology of concrete containing plastic waste as aggregate. Constr Build Mater 257:119559. https://doi.org/10.1016/j.conbuildmat.2020.119559
6. Syah PRI, Hartuti P (2018) Land use and river degradation impact of sand and gravel mining. E3S Web Conf 31:2–5. https://doi.org/10.1051/e3sconf/20183109034
7. Zulkernain NH, Gani P, Chuck Chuan N, Uvarajan T (2021) Utilisation of plastic waste as aggregate in construction materials: a review. Constr Build Mater 296:123669. https://doi.org/10.1016/j.conbuildmat.2021.123669.
8. Paihte PL, Lalngaihawma AC, Saini G (2019) Recycled aggregate filled waste plastic bottles as a replacement of bricks. Mater Today Proc 15:663–668. https://doi.org/10.1016/j.matpr.2019.04.135
9. Akinwumi II, Domo-Spiff AH, Salami A (2019) Marine plastic pollution and affordable housing challenge: shredded waste plastic stabilized soil for producing compressed earth bricks. Case Stud Constr Mater 11:e00241. https://doi.org/10.1016/j.cscm.2019.e00241
10. Akinyele JO, Igba UT, Adigun BG (2020) Effect of waste PET on the structural properties of burnt bricks. Sci Afr. https://doi.org/10.1016/j.sciaf.2020.e00301
11. Chow MF, Rosidan MAK (2020) Study on the effects of plastic as admixture on the mechanical properties of cement–sand bricks.

IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/713/1/012016.

12. Ali N, Din N, Khalid FS, Shahidan S, Abdullah SR, Abdul Samad AA, Mohamad N (2017) Compressive strength and initial water absorption rate for cement brick containing high-density polyethylene (HDPE) as a substitutional material for sand. IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/271/1/012083
13. Nursyamsi N, Indrawan I, Theresa V (2018) Effect of HDPE plastic waste towards batako properties. IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/309/1/012013
14. Nursyamsi N, Indrawan I, Ramadhan P. The influence of the usage of Idpe plastic waste as fine aggregate in light concrete bricks. In: MATEC Web of Conferences 2019, Vol 258, p 01006. EDP Sciences
15. Ohemeng EA, Ekolu SO (2019) Strength prediction model for cement mortar made with waste LDPE plastic as fine aggregate. J Sustain Cem Mater 8:228–243. https://doi.org/10.1080/21650373.2019.1625826
16. Khazaal SM, Mohammed SK, Wadi KJ (2020) Recycle of waste plastic materials (Polyvinyl chloride (pvc) and polypropylene (pp)) as a fine aggregates for concrete. Int J Adv Sci Technol 29:911–918
17. Záleská M, Pavlíková M, Studnička J, Pavlík Z (2018) Effect of waste expanded polypropylene-based aggregate on mechanical and thermal properties of lightweight concrete. IOP Conf Ser Mater Sci Eng. https://doi.org/10.1088/1757-899X/371/1/012002.
18. González-Montijo MA, Soto-Toro H, Rivera-Pérez C, Esteves-Klomsingh S, Suárez OM (2019) Design and characterization of concrete masonry parts and structural concrete using repurposed plastics as aggregate. J Mech Behav Mater 28:81–88. https://doi.org/10.1515/jmbm-2019-0010
19. Mondal MK, Bose BP, Bansal P (2019) Recycling waste thermoplastic for energy efficient construction materials: an experimental investigation. J Environ Manage 240:119–125. https://doi.org/10.1016/j.jenvman.2019.03.016
20. Awoyera PO, Adesina A (2020) Plastic wastes to construction products: status, limitations and future perspective. Case Stud Constr Mater 12:e00330. https://doi.org/10.1016/j.cscm.2020.e00330
21. Aldahdooh MAA, Jamrah A, Alnuaimi A, Martini MI, Ahmed MSR, Ahmed ASR (2018) Influence of various plastics-waste aggregates on properties of normal concrete. J Build Eng 17:13–22. https://doi.org/10.1016/j.jobe.2018.01.014
22. Ahmad S, Alghamdi SA (2014) A statistical approach to optimizing concrete mixture design. Sci World J. https://doi.org/10.1155/2014/561539
23. Montgomery DC (2013) Design and Analysis of Experiments—Douglas C. Montgomery—Google Books. https://books.google.com.my/books?hl=en&lr=&id=Py7bDgAAQBAJ&oi=fnd&pg=PA1&ots=X7r3q-QR36&sig=O7GHZ6E-QdV-mupHTdGOn-ZMEP8&redir_esc=y#v=onepage&q&f=false. Accessed July 6, 2021
24. Rahmatika A, Hariyadi H, Fajrin J (2019) The application of response surface methods (RSM) to study the effect of partial Portland cement replacement using silica fume on the properties of Mortar. Int J Civ Eng Technol 10:133–141
25. Cibilakshmi G, Jegan J (2020) A DOE approach to optimize the strength properties of concrete incorporated with different ratios of PVA fibre and nano-Fe_2O_3. Adv Compos Lett 29:1–16. https://doi.org/10.1177/2633366X20913882
26. Awolusi TF, Oke OL, Akinkurolere OO, Sojobi AO (2019) Application of response surface methodology: predicting and optimizing the properties of concrete containing steel fibre extracted from waste tires with limestone powder as filler. Case Stud Constr Mater 10:e00212. https://doi.org/10.1016/j.cscm.2018.e00212
27. Górak P, Postawa P, Natalia Trusilewicz L, Łagosz A (2021) Lightweight PET based composite aggregates in Portland cement materials—microstructure and physicochemical performance. J Build Eng 34:101882. https://doi.org/10.1016/j.jobe.2020.101882
28. Park JK, Kim MO (2020) Mechanical properties of cement-based materials with recycled plastic: a review. Sustain 12:1–21. https://doi.org/10.3390/su12219060
29. Martínez-López M, Martínez-Barrera G, Salgado-Delgado R, Gencel O (2021) Recycling polypropylene and polyethylene wastes in production of polyester based polymer mortars. Constr Build Mater 274:121487. https://doi.org/10.1016/j.conbuildmat.2020.121487
30. Tamrin JN (2021) The effect of recycled hdpe plastic additions on concrete performance. Recycling 6: 1–19. https://doi.org/10.3390/recycling6010018
31. Abu-Saleem M, Zhuge Y, Hassanli R, Ellis M, Rahman M, Levett P (2021) Evaluation of concrete performance with different types of recycled plastic waste for kerb application. Constr Build Mater 293:123477. https://doi.org/10.1016/j.conbuildmat.2021.123477
32. Kumar PK, Gomathi M (2017) Production of construction bricks by partial replacement of waste plastics. IOSR J Mech Civ Eng 14:09–12. https://doi.org/10.9790/1684-1404020912
33. Almeshal I, Tayeh BA, Alyousef R, Alabduljabbar H, Mustafa Mohamed A, Alaskar A (2020) Use of recycled plastic as fine aggregate in cementitious composites: a review. Constr Build Mater 253:119146. https://doi.org/10.1016/j.conbuildmat.2020.119146.
34. Pelisser F, Montedo ORK, Gleize PJP, Roman HR (2012) Mechanical properties of recycled PET fibers in concrete. Mater Res 15:679–686. https://doi.org/10.1590/S1516-14392012005000088
35. Fernández ME, Payá J, Borrachero MV, Soriano L, Mellado A, Monzó J (2017) Degradation process of postconsumer waste bottle fibers used in portland cement-based composites. J Mater Civ Eng 29:04017183. https://doi.org/10.1061/(asce)mt.1943-5533.0002007
36. Rostami R, Zarrebini M, Mandegari M, Mostofinejad D, Abtahi SM (2020) A review on performance of polyester fibers in alkaline and cementitious composites environments. Constr Build Mater 241:117998. https://doi.org/10.1016/j.conbuildmat.2020.117998
37. American Society for Testing and Materials (ASTM) (2017) C140 standard test methods for sampling and testing concrete masonry units and related units. Am Soc Test Mater 04:1–10
38. Pradhan S, Kumar S, Barai SV (2020) Understanding the behavior of recycled aggregate concrete by using thermogravimetric analysis. Front Struct Civ Eng 14:1561–1572. https://doi.org/10.1007/s11709-020-0640-5
39. Hossain K, Rashid MA, Karim R (2015) Effect of cement content and size of coarse aggregate on the strength of brick aggregate concrete. DUET J 2:20–24
40. LeBow C (2017) Effect of cement content on transport in concrete. Thesis Univ Arkansas 50:339–351. https://doi.org/10.1680/macr.1998.50.4.339
41. Megahed F, Sharaky I, Badawy A, Seleem M (2017) The role of cement content on controlling the compressive strength and water absorption of nano silica concrete. J Al-Azhar Univ Eng Sect 12:1417–1426. https://doi.org/10.21608/auej.2017.19135
42. Akinyele JO, Toriola IO (2018) The effect of crushed plastics waste on the structural properties of sandcrete blocks. Afr J Sci Technol Innov Dev 10:709–713. https://doi.org/10.1080/20421338.2018.1496614
43. Almeshal I, Tayeh BA, Alyousef R, Alabduljabbar H, Mohamed AM (2020) Eco-friendly concrete containing recycled plastic as partial replacement for sand. J Mater Res Technol 9:4631–4643. https://doi.org/10.1016/j.jmrt.2020.02.090
44. Kou SC, Lee G, Poon CS, Lai WL (2009) Properties of lightweight aggregate concrete prepared with PVC granules derived

from scraped PVC pipes. Waste Manag 29:621–628. https://doi.org/10.1016/j.wasman.2008.06.014
45. Saikia N, De Brito J (2014) Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. Constr Build Mater 52:236–244. https://doi.org/10.1016/j.conbuildmat.2013.11.049
46. Zhang L (2013) Production of bricks from waste materials—a review. Constr Build Mater 47:643–655. https://doi.org/10.1016/j.conbuildmat.2013.05.043
47. Al-Fakih A, Mohammed BS, Liew MS, Nikbakht E (2019) Incorporation of waste materials in the manufacture of masonry bricks: an update review. J Build Eng 21:37–54. https://doi.org/10.1016/j.jobe.2018.09.023
48. Soto-Pérez L, López V, Hwang SS (2015) Response surface methodology to optimize the cement paste mix design: time-dependent contribution of fly ash and nano-iron oxide as admixtures. Mater Des 86:22–29. https://doi.org/10.1016/j.matdes.2015.07.049
49. Kamarulzaman NA, Adnan SH, Mohd Sari KH, Osman MH, Ahmad Jeni ML, Abdullah MS, Ang PSE, Yahya NF, Yassin NI, Wahee Anuar MNA (2018) Properties of cement brick containing expanded polystyrene beads (EPS) and palm oil fuel ash (POFA). J Sci Technol 10:41–46. https://doi.org/10.30880/jst.2018.10.04.008
50. Al-Hadithi AI, Fawzi Al-Ani M (2019) Effects of adding waste plastics on some properties of high performance concrete. In: Proceedings of international conference on development ESystems engineering DeSE, pp 273–279. https://doi.org/10.1109/DeSE.2018.00055
51. Alan S, Sivagnanaprakash B, Suganya S, Kalaiselvam A, Vignesh V (2015) A study on mechanical properties of fly ash brick with waste plastic strips a study on mechanical properties of fly ash brick with waste plastic strips
52. Solikin M, Ikhsan N (2018) Styrofoam as partial substitution of fine aggregate in lightweight concrete bricks. AIP Conf Proc. https://doi.org/10.1063/1.5042961
53. Záleská M, Pavlíková M, Pokorný J, Jankovský O, Pavlík Z, Černý R (2018) Structural, mechanical and hygrothermal properties of lightweight concrete based on the application of waste plastics. Constr Build Mater 180:1–11. https://doi.org/10.1016/j.conbuildmat.2018.05.250
54. Behera SK, Meena H, Chakraborty S, Meikap BC (2018) Application of response surface methodology (RSM) for optimization of leaching parameters for ash reduction from low-grade coal. Int J Min Sci Technol 28:621–629. https://doi.org/10.1016/j.ijmst.2018.04.014
55. Abu Amr SS, Aziz HA, Bashir MJK (2014) Application of response surface methodology (RSM) for optimization of semi-aerobic landfill leachate treatment using ozone. Appl Water Sci 4:231–239. https://doi.org/10.1007/s13201-014-0156-z
56. Alqadi ANS, Bin Mustapha KN, Naganathan S, Al-Kadi QNS (2012) Uses of central composite design and surface response to evaluate the influence of constituent materials on fresh and hardened properties of self-compacting concrete. KSCE J Civ Eng 16:407–416. https://doi.org/10.1007/s12205-012-1308-z
57. Aldahdooh MAA, Muhamad Bunnori N, Megat Johari MA (2013) Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method, Mater Des 52:957–965. https://doi.org/10.1016/j.matdes.2013.06.034.
58. Roselan MA, Ashari SE, Faujan NH, Faudzi SMM, Mohamad R (2020) An improved nanoemulsion formulation containing kojic monooleate: optimization, characterization and in vitro studies. Molecules https://doi.org/10.3390/molecules25112616.
59. Aldahdooh MAA, Muhamad Bunnori N, Megat Johari MA (2013) Development of green ultra-high performance fiber reinforced concrete containing ultrafine palm oil fuel ash. Constr Build Mater 48:379–389. https://doi.org/10.1016/j.conbuildmat.2013.07.007
60. Rai B, Rushad ST, Kr B, Duggal SK (2012) Study of waste plastic mix concrete with plasticizer. ISRN Civ Eng 2012:1–5. https://doi.org/10.5402/2012/469272
61. Vanitha S, Natarajan V, Praba M (2015) Utilisation of waste plastics as a partial replacement of coarse aggregate in concrete blocks. Indian J Sci Technol 8:211–218. https://doi.org/10.17485/ijst/2015/v8i12/54462.
62. Pooja P, Vaitla M, Sravan G, Reddy MP, Bhagyawati M (2019) Study on behavior of concrete with partial replacement of fine aggregate with waste plastics. Mater Today Proc 8:182–187. https://doi.org/10.1016/j.matpr.2019.02.098
63. Kaur G, PaviaS (2020) Physical properties and microstructure of plastic aggregate mortars made with acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC), polyoxymethylene (POM) and ABS/PC blend waste. J Build Eng. https://doi.org/10.1016/j.jobe.2020.101341
64. Masoumi HRF, Basri M, Samiun WS, Izadiyan Z, Lim CJ (2015) Enhancement of encapsulation efficiency of nanoemulsion-containing aripiprazole for the treatment of schizophrenia using mixture experimental design. Int J Nanomedicine 10:6469–6471. https://doi.org/10.2147/IJN.S89364
65. Ahmad R, Baharudin KS, Chin JL, Nam KM (2017) HDPE Cement Brick, pp 72–75
66. Wahid SA, Rawi SM, Desa N (2017) Utilization of plastic bottle waste in sand bricks utilization of plastic bottle waste in sand bricks (2017)
67. Ali N, Mohd Yusup NF, Sheikh Khalid F, Shahidan A, Abdullah SR (2018) The effect of water cement ratio on cement brick containing high density polyethylene (HDPE) as sand replacement. 03010: 4–8
68. Coppola B, Courard L, Michel F, Incarnato L, Di Maio L (2016) Investigation on the use of foamed plastic waste as natural aggregates replacement in lightweight mortar. Compos Part B Eng 99:75–83. https://doi.org/10.1016/j.compositesb.2016.05.058
69. Alqahtani FK, Ghataora G, Khan MI, Dirar S (2017) Novel lightweight concrete containing manufactured plastic aggregate. Constr Build Mater 148:386–397. https://doi.org/10.1016/j.conbuildmat.2017.05.011
70. Spósito FA, Higuti RT, Tashima MM, Akasaki JL, Melges JLP, Assunção CC, Bortoletto M, Silva RG, Fioriti CF (2020) Incorporation of PET wastes in rendering mortars based on Portland cement/hydrated lime. J Build Eng 32:101506. https://doi.org/10.1016/j.jobe.2020.101506
71. Jaivignesh B, Sofi A (2017) Study on mechanical properties of concrete using plastic waste as an aggregate study on mechanical properties of concrete using plastic waste as an aggregate (2017)
72. Correa PM, Santana RMC, Guimarães D, Graeff AG (2019) Post-consumer PP as partial substitute of sand: effect of surface treatment PP with surfactant on concrete properties. Compos Interfaces 00:1–14. https://doi.org/10.1080/09276440.2019.1702858
73. Usman A, Sutanto MH, Napiah M (2018) Effect of recycled plastic in mortar and concrete and the application of gamma irradiation—a review. E3S Web Conf. https://doi.org/10.1051/e3sconf/20186505027
74. Patel M, Morrell PR, Murphy JJ, Skinner A, Maxwell RS (2006) Gamma radiation induced effects on silica and on silica–polymer interfacial interactions in filled polysiloxane rubber. Polym Degrad Stab 91:406–413. https://doi.org/10.1016/j.polymdegradstab.2005.03.015
75. Nigri G, Cherait Y, Nigri S (2017) Characterization of eco-substituted cement containing waste ground calcined clay brick. Can J Civ Eng 44:956–961. https://doi.org/10.1139/cjce-2016-0537
76. Shetty MS (2006) Concrete Technology by M S Shetty, pp 1–443
77. Verdolotti L, Iucolano F, Capasso I, Lavorgna M, Iannace S, Liguori B (2014) Recycling and recovery of PE-PP-pet-based fiber polymeric wastes as aggregate replacement in lightweight mortar:

evaluation of environmental friendly application. Environ Prog Sustain Energy 33:676–680

78. Sanaeishoar H, Sabbaghan M, Mohave F (2015) Synthesis and characterization of micro-mesoporous MCM-41 using various ionic liquids as co-templates. Microp Mesop Mater 217:219–224. https://doi.org/10.1016/j.micromeso.2015.06.027