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RESEARCH

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Meta-analysis on PET plastic as concrete aggregate using response surface methodology and regression analysis

Beng Wei Chong and Xijun Shi*

Abstract

This paper aims to thoroughly analyze the effect of polyethylene terephthalate (PET) plastic aggregate on concrete compressive strength using a meta-analysis. Forty-three datasets for concrete containing PET coarse aggregate and 60 data sets for concrete containing PET fine aggregate were collected. The input variables used were percentage and nominal maximum size of PET aggregate along with the concrete mix proportions. Main effect plots, contour plots, and surface plots of the expressions were presented to demostrate the effect of PET aggregate on the 28-day compressive strength of concrete. The statistical parameters of the regression equations, such as R^2, adjusted R^2 and root-mean-square error (RMSE), indicated that the RSM approach is a powerful tool to describe the change of concrete compressive strength by PET aggregate addition. In addition, the study showed that using PET plastic as a fine aggregate replacement performed better than using it as a coarse aggregate replacement in concrete. At up to 30% replacement, concrete containing PET plastic as a fine aggregate can have satisfactory compressive strength.

Keywords: Polyethylene terephthalate, Concrete, Regression, Response surface methodology, Compressive strength

Introduction

Plastic pollution is one of the leading challenges plaguing all countries across the globe. The usage of plastic is popularised in 1950, and the annual production of plastic has since increased by about 200 times to 380 million tonnes in 2015 [1]. Despite the massive increase in production and consumption, the management of waste plastic has failed to keep up, with most plastic ending up being inefficiently disposed [2]. Generally, developed countries have generated more plastic waste due to higher production capability and spending power, but plastic pollution has caused greater harm to developing countries as those countries are less equipped in technology to manage the waste [3]. As a result, most of these countries have resorted to the landfill when handling plastic waste, which leads to a multitude of problems. In the landfills, plastic leaches into soil and water sources, causing more pollution to the environment. It is estimated that an estimated 8 million tonnes of plastic ended up in the ocean every year due to leakage [4], causing the disruption and degradation of the marine ecosystem. Consequently, microplastic in the ocean enters the human body through our diet. This causes health concerns as plastic particles are known to possess heavy metals [5] and toxins which come from the manufacturing process or absorbed from the environment.

Polyethylene terephthalate (PET) plastic is a type of thermoplastic which is most extensively used in the food and beverage industry. It is also used as the single-use plastic for bottled water that is quickly discarded [6]. Compared to other types of plastic, thermoplastic such as PET is highly recyclable. Well-established process such as multiple forms of chemical hydrolysis, mechanical recycling, and melt processing provide effective means of recycling PET plastic [7, 8]. Yet, the recycling rate of PET plastic is relatively low. According to the PET Resin

*Correspondence: xijun.shi@txstate.edu

Ingram School of Engineering, Texas State University, San Marcos, TX 78666, USA

Association (PETRA) [9], the United States recycle only about 31% of PET waste while Europe recycle about half of the amount generated. Apart from recycling PET plastic through arduous industrial processes, new innovations on reuse of waste plastic have also been attempted to support the effort in combating plastic pollution.

Waste PET plastic sees great potential to be reused in the field of construction. Thus far, research on the application of PET plastic in various construction materials has been undertaken. Waste PET plastic has been utilized to produce mortar [6, 10], bricks and masonry [6, 11], and concrete [12–14]. The introduction of waste plastic as a constituent of cement-based construction materials has a two-fold advantage of not only providing an outlet to reuse or dispose of plastic but also reducing the consumption of non-renewable raw materials such as rocks and sands. Experts have warned that rapid urbanization and the expansion of a massive construction industry will cause a global shortage of sand in the near future [15]. Even today, extensive excavations of sand have been linked to the destruction of the environment and the exacerbation of climate change [16]. This is compounded by the fact that the construction industry is the leading emitter of greenhouse gas, as well as the primary consumer of sand and gravel, taking up to about 40% global usage of stone, sand and gravel [17].

The incorporation of PET plastic into concrete production is a step towards a more sustainable construction. Moreover, the application has the potential to alleviate the brittleness of concrete and enhance the durability of concrete in certain aspects. Saxena et al. [18] studied concrete with up to 20% fine aggregate replaced by PET plastic and concluded that the impact resistance and energy absorption capacity of concrete increased with proportion of replacement. Likewise, Abu-Saleem et al. [19] experimented on concrete with various types of waste plastic and noted that plastic as a coarse aggregate replacement increased the impact resistance of concrete. The specimen with an optimum plastic replacement level of 30% achieved 4.5 times greater impact resistance than the control concrete. In addition, PET plastic concrete has superior abrasion resistance [20], better heat insulation [21], and is more ductile under flexural load [22].

Despite the potential benefits in improving concrete durability, replacement of aggregate with PET plastic in concrete comes with a major challenge – reducing the mechanical strength of concrete. For example, in a study by Bamigboye et al. [23], the 28-day compressive strength of water-cured concrete with 10% PET aggregate is 38% lower than the control concrete. At the 30% PET coarse aggregate replacement level, the strength loss increased to 68%. In another experiment by Islam et al. [24], concrete with 20% PET coarse aggregate lost about 20% to 25% strength depending on different mix designs. To further complicate the matter, different research employed replacement by weight [18, 25] or volume [23, 24] when producing PET aggregate concrete. Application of PET aggregate has also involved the replacement of coarse aggregate [23, 24], fine aggregate [13, 26], and both in different studies.

Design of experiment (DoE) techniques such as response surface methodology (RSM) are gaining popularity on studying the properties of concrete with waste materials. For instance, RSM has been applied to aid the data analysis of a complicated mix design consisting of recycled aggregate, silica fume, and ground-granulated blast-furnace slag [27]. By plotting the contour plot with the replacement materials as primary factors, the trend of strength variation was neatly demonstrated. In another experiment which used a combination of a few admixtures [28], RSM had been similarly utilized for the same purpose. Even for experiment with only one replacement material, Senthil Kumar and Baskar [29] studied the influence of e-waste on 28-day concrete compressive strength by plotting the replacement percentage and w/c ratio together in surface and contour plot. Similar endeavors involving eggshell powder had also been conducted using output from both single [30] and multiple [31] experimental data sets.

Although the statistical analysis in this study was performed based on published works that might contain some unavoidable bias in data collection and presentation, the effect of PET aggregate on compressive strength was thoroughly analyzed, and some general trends were found. The findings from this study could be useful for future studies in this field [29]. Moreover, this study served as a great example on how RSM could facilitate the understanding of material behavior across a broader range of parameters as opposed to some other methods that are limited to the condition of a single experiment set. At present, the state-of-the-art review about PET plastic waste in concrete is available [32, 33]. While the reviews have provided a broad overview of the waste material, an in-depth numerical synthesis and analysis of the influence of PET plastic on the mechanical strength of concrete is still scarce.

In this study, RSM was conducted to formulate the infleunce of PET plastic aggregate on the 28-day compressive strength of concrete. Two mathematical expressions, one for PET plastic as a coarse aggregate replacement and one for PET plastic as a fine aggregate replacement, were analyzed based on data from the gathered literature. The performance of both expresions were evaluated through statistical parameters such as determination coefficient (R^2), adjusted coefficient (R^2 adj) and root mean-square error (RMSE). Finally, the compressive strength index of both sets of data were presented on a single plot for regression analysis and the inflence of PET plastic aggregate on concrete compressive strength was thoroughly discussed.

Materials and methods

PET plastic aggregate

PET is a thermoplastic that is strong, durable and lightweight. It is the most commonly consumed plastic, which can be found from household waste such as bottled drinks [34]. The specific gravity of PET plastic aggregate generally fell between the range of 1.25 to 1.50. Two studies [12, 35] reported the density of PET plastic aggregate as 1225 kg/m^3 and 1340 kg/m^3. PET plastic has a low water absorption, typically below 0.70%. The fineness modulus of PET plastic used as a coarse aggregate replacement is about 6.70. Meanwhile, the other two studies on PET plastic as a fine aggregate replacement reported a fineness modulus of 3.20 and 3.51, respectively. In addition, the melting point of PET plastic is reported to be higher than 250 °C by Sai Gopi et al. [26], which corroborates with the general recognized melting point of PET in other literature [36, 37] Furthermore, a study by Islam et al. [24] that melted waste plastic to produce plastic flakes specified the usage of temperature between 280 °C and 320 °C in the melting process.

Meta-analysis and data curation

Literature search of studies involving PET plastic as a coarse aggregate or a fine aggregate replacement in the production of concrete was conducted. The collected literature spread approximately over a decade, with the earliest literature from 2012 and the latest from 2022. All papers were studied to extract the relevance information such as the physical properties of PET aggregate, replacement proportion, concrete mix design, and compressive strength. While most literature reported a decrease in strength with PET aggregate, the pattern of strength loss varied among different studies. In certain studies, the strength loss was minimum, while in other studies, a significant strength reduction was observed even in lower percentages of replacement. Hence, a meta-analysis was conducted to access the pattern of strength loss, as well as to identify the conditions in which the usage of PET aggregate was most effective. A meta-analysis is defined as a mathematical or statistical study which combines the outcome of multiple independent studies in an effort to form a new, unified conclude on the topic concerned. By gathering a larger amount of data from multiple accounts, the variables which caused the inconsistencies could be isolated and studied. Subsequently, mathematical expressions that could show the trend of change in concrete strength by the PET aggregate addition were developed.

Studies with enough details on both the concrete mix design and 28-day compressive strength were selected, while those with incomplete data or included more than one waste material were excluded. For the concrete mix design, the values presented in ratio format were all converted to a unified presentation under kilogram per cubic meter (kg/m^3). For the compressive strength, data presented in exact numbers were simply extracted. For data presented in figures with incomplete labels, PlotDigitizer software was used to obtain the values through interpolation. A total of 42 data points from six studies were gathered for studies of PET plastic as coarse aggregate replacement by volume. Meanwhile, 60 data points from seven studies of PET plastic as a fine aggregate replacement by volume were collected. The data are presented on Tables 1 and 2, respectively.

For the PET coarse aggregate (PET-CA) expression, the independent variables were percentage of PET replacement, nominal maximum size of PET particles in millimeter, cement content, fine aggregate (FA) content, coarse aggregate (CA) content, and water-cement ratio (W/C). For the size of PET particle, the maximum size specified on the paper was taken. If the size of PET particle was presented as gradation data, then according to the U.S Department of Transportation, Federal Highway Administration (FHWA) [48], the nominal maximum size is defined as the smallest sieve size in which most of the aggregate passes and less than 15% aggregate is retained. Hence, the closest sieve to 85th percentile of the graduation curve was taken as the nominal maximum size. For the PET fine aggregate (PET-FA) however, the size of plastic was not a variable as most studies used the same sieve passing 4.75 mm which was the same as that of sand. Hence, only PET replacement and the content of each constituent of concrete were chosen as independent variables. The outputs of the studies were the 28-day compressive strengths.

Response surface methodology (RSM)

RSM is a DoE method which can assess the effect of multiple independent variables on the dependent variable. In experiments involving multiple independent variables, the conventional method to study the impact of each variable is conducted by changing one variable at a time (OVAT) while keeping the other variables constant. The OVAT method requires a large number of experiment trails and hence a lot of time and resources. Furthermore, OVAT is unable to analyze the combined effect and interaction within the multiple independent variables [49].. Statistical methods such as RSM enable the understanding of the dependant variable using least

Table 1 Literature for PET-CA expression

Source	No.	PET (%)	Size (mm)	Cement (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	W/C ratio	28-day Compressive Strength (MPa)
Abu-Saleem et al., 2021 [35]	1	0	8	302	859	886	0.75	27.46
	2	15	8	302	859	886	0.75	23.63
Abu-Saleem et al., 2021 [38]	3	15	8	302	859	886	0.75	21.37
	4	0	8	327	877	906	0.7	32.00
	5	10	8	327	877	906	0.7	29.20
Bamigboye et al., 2022 [23]	6	0	8	320	1280	640	0.5	26.48
	7	10	8	320	1280	640	0.5	16.43
	8	20	8	320	1280	640	0.5	19.96
	9	30	8	320	1280	640	0.5	8.61
	10	100	8	320	1280	640	0.5	3.59
Bachtiar et al., 2020 [39]	11	0	18	469	604	1122	0.48	18.20
	12	25	18	469	604	1122	0.48	12.73
	13	50	18	469	604	1122	0.48	12.30
	14	75	18	469	604	1122	0.48	10.61
	15	100	18	469	604	1122	0.48	10.18
Islam et al., 2016 [24]	16	0	18	462	1024	534	0.42	33.52
	17	20	18	462	1024	534	0.42	30.28
	18	30	18	462	1024	534	0.42	27.06
	19	40	18	462	1024	534	0.42	25.95
	20	50	18	462	1024	534	0.42	20.47
	21	0	18	449	996.4	519.8	0.48	32.13
	22	20	18	449	996.4	519.8	0.48	27.66
	23	30	18	449	996.4	519.8	0.48	26.44
	24	40	18	449	996.4	519.8	0.48	24.48
	25	50	18	449	996.4	519.8	0.48	19.49
	26	0	18	432	958	500	0.57	31.71
	27	20	18	432	958	500	0.57	24.20
	28	30	18	432	958	500	0.57	24.31
	29	40	18	432	958	500	0.57	22.88
	30	50	18	432	958	500	0.57	17.36
Osubor et al., 2019 [40]	31	0	0	320	1280	640	0.6	21.33
	32	5	3	320	1280	640	0.6	20.45
	33	10	3	320	1280	640	0.6	18.10
	34	15	3	320	1280	640	0.6	16.85
	35	20	3	320	1280	640	0.6	14.97
	36	5	5	320	1280	640	0.6	18.70
	37	10	5	320	1280	640	0.6	17.05
	38	15	5	320	1280	640	0.6	15.65
	39	20	5	320	1280	640	0.6	14.31
	40	5	7	320	1280	640	0.6	17.20
	41	10	7	320	1280	640	0.6	16.75
	42	15	7	320	1280	640	0.6	14.25
	43	20	7	320	1280	640	0.6	13.74

number of experimental trials along with a more efficient data collection [50]. In addition, the enhanced processing power of the DoE approach allows the synthesis of results from multiple similar experiments for a thorough understanding of a particular topic of interest. In this study, PET-CA expression involved 43

Table 2 Literature for PET-FA expression

Source	No.	PET (%)	Cement (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	W/C ratio	28-day Compressive Strength (MPa)
Thorneycroft et al., 2018 [41]	1	0	550	780	780	0.4	53.80
	2	10	550	780	780	0.4	54.40
	3	10	550	780	780	0.4	51.80
	4	10	550	780	780	0.4	51.60
Ohemeng et al., 2014 [42]	5	0	414	1241	828	0.3	38.12
	6	10	414	1241	828	0.3	35.23
	7	20	414	1241	828	0.3	31.14
	8	30	414	1241	828	0.3	26.16
	9	40	414	1241	828	0.3	22.52
	10	50	414	1241	828	0.3	17.55
	11	60	414	1241	828	0.3	14.70
	12	0	414	1241	828	0.35	41.66
	13	10	414	1241	828	0.35	37.14
	14	20	414	1241	828	0.35	33.41
	15	30	414	1241	828	0.35	27.86
	16	40	414	1241	828	0.35	24.11
	17	50	414	1241	828	0.35	19.85
	18	60	414	1241	828	0.35	16.10
	19	0	414	1241	828	0.4	44.50
	20	10	414	1241	828	0.4	41.44
	21	20	414	1241	828	0.4	38.76
	22	30	414	1241	828	0.4	29.30
	23	40	414	1241	828	0.4	25.30
	24	50	414	1241	828	0.4	20.83
	25	60	414	1241	828	0.4	17.30
	26	0	414	1241	828	0.45	47.29
	27	10	414	1241	828	0.45	43.58
	28	20	414	1241	828	0.45	39.83
	29	30	414	1241	828	0.45	31.95
	30	40	414	1241	828	0.45	27.18
	31	50	414	1241	828	0.45	21.89
	32	60	414	1241	828	0.45	18.81
Rai et al., 2012 [43]	33	0	432	1282	469	0.44	42.24
	34	5	432	1282	469	0.44	40.08
	35	10	432	1282	469	0.44	39.31
	36	15	432	1282	469	0.44	38.17
Black, 2020 [44]	37	0	450	1080	630	0.5	47.20
	38	10	450	1080	630	0.5	45.40
	39	20	450	1080	630	0.5	47.40
Ferrotto et al., 2022 [45]	40	0	315	798	735	0.5	18.43
	41	10	315	798	735	0.5	12.90
	42	20	315	798	735	0.5	8.60
Albano et al., 2009 [46]	43	0	320	736	1152	0.5	21.29
	44	10	320	736	1152	0.5	18.25
	45	20	320	736	1152	0.5	12.82
	46	0	407	407	1099	0.6	27.90
	47	10	407	407	1099	0.6	22.45
	48	20	407	407	1099	0.6	18.38

Table 2 (continued)

Source	No.	PET (%)	Cement (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	W/C ratio	28-day Compressive Strength (MPa)
Irwan Juki et al., 2013 [47]	49	0	295	1085	885	0.45	31.23
	50	25	295	1085	885	0.45	27.89
	51	50	295	1085	885	0.45	22.94
	52	75	295	1085	885	0.45	17.02
	53	0	295	1085	885	0.55	26.71
	54	25	295	1085	885	0.55	25.52
	55	50	295	1085	885	0.55	20.35
	56	75	295	1085	885	0.55	15.94
	57	0	295	1085	885	0.65	25.42
	58	25	295	1085	885	0.65	25.31
	59	50	295	1085	885	0.65	19.06
	60	75	295	1085	885	0.65	15.62

data points and six independent variables, while PET-FA had 60 data points and five independent variables. Since the data were collected from various sources, the standard methodologies such as Central Composite Design or Box–Behnken Design were not applied. Instead, uncoded variables was used to perform the RSM. The quality of the mathematical expressions were evaluated based on statistical parameters including determination coefficient (R^2), adjusted coefficient (R^2 adj) and RMSE. The accuracy of the expressions was further accessed by consulting the Patero Chart and residual plot. Subsequently, the effect of the independent variables was studied by referring to the interaction plot. Lastly, the expressions were presented in 2D and 3D plots through the contour plot and surface plot to investigate the impact of PET plastic aggregate on the compressive strength of concrete.

Table 3 RSM of PET-CA expression

Source	DF	Adj SS	Adj MS	F-Value	*P*-Value
Expression	9	1959.35	217.706	66.67	0.000
Linear	5	601.27	120.253	36.83	0.000
CA	1	18.55	18.546	5.68	0.023
FA	1	53.14	53.137	16.27	0.000
W/C	1	121.22	121.218	37.12	0.000
PET(%)	1	186.53	186.534	57.12	0.000
Size(mm)	1	52.10	52.097	15.95	0.000
Square	1	343.39	343.390	105.16	0.000
CA*CA	1	343.39	343.390	105.16	0.000
2-Way Interaction	3	125.62	41.874	12.82	0.000
CA*Size(mm)	1	35.48	35.476	10.86	0.002
FA*PET(%)	1	58.31	58.313	17.86	0.000
FA*Size(mm)	1	38.36	38.356	11.75	0.002
Error	33	107.76	3.265		
Total	42	2067.11			
RMSE		1.583			
R^2		0.9479			
R^2 adj		0.9337			

Regression analysis

Regression analysis is a basic statistical method that is widely used to determine the relationship between a dependent variable and an independent variable. At the most rudimental level, plotting two variables together allows for a closer examination of how one variable influences another. By applying simple regression analysis, the relationship between the variables may be determined. To apply simple regression on the dataset in Tables 2 and 3, the value differences caused by different mix design was eliminated by using the strength index (SI) of the concrete. The definition of SI is as shown in Eq. 1

$$SI = \frac{CSR}{CSC} \tag{1}$$

where CSR is the 28-day compressive strength of concrete with any percentage of PET plastic aggregate, while CSC is the 28-day compressive strength of control mix without any PET. Obviously, all control mix of each data set has a SI of 1.0. For the specimens with

PET aggregate, SI above 1.0 indicates a certain percentage increase in compressive strength and vice versa. The independent variable of the expression is the percentage of PET replacement, and the dependent variable of the expression is the SI of concrete specimens. Based on this, the influence of PET replacement on the compressive strength of concrete may be accessed.

Results and discussion

RSM of PET-CA expression

Backward elimination method with $\alpha = 0.05$ was used in the approach. Figure 1 presents the Pareto Chart for the PET-CA expression. Except for cement content (A), the linear term of all primary variables such as coarse aggregate content (B), fine aggregate content (C), water-cement ratio (D), PET content (E) and size (F) were all significant variables. The quadratic term of coarse aggregate (BB) ranked the highest out of all factors, while three interaction terms, CE, CF, and BF rounded up the expression. Figure 2 shows the residual versus order plot for the expression. The residual versus order plot is used to determine the legitimacy of the expression. Any shift or trend in the plot would be caused by other variables, which was not present in the equation. From Fig. 2, the residuals of the expression were distributed randomly in a zig-zag pattern. Hence, there was no other variable which was not accounted for in the analysis.

Table 3 depicts the analysis of variance (ANOVA) and RSM analysis for the PET-CA expression. The expression had negligibly low *p*-value across the board, with CA content had a higher *p*-value of 0.023 which was still smaller than 0.05 (a commonly used confidence level). Since it was known that the compressive strength of concrete was largely influenced by its mix proportion, all terms in the expression were deemed to be significant. At the same time, the presence of quadratic terms signified that the influence of the factors was not entirely linear. Meanwhile, the interaction terms were included for better computational power and data-fitting. The R^2 value of the PET-CA expression was 0.9479, while the adjusted R^2 value was 0.9337, indicating a strong fitting of the equations. The RMSE of the PET-CA expression was 1.583, which was minor. Hence, the PET-CA expression was deemed to be satisfactory. The expression for 28-day compressive strength of concrete with PET as a coarse aggregate replacement was given in Eq. 2:

$$CS_{28} = -122.3 + 0.311B + 0.020C - 29.77D - 0.383E + 2.232F - 0.000152B^2 - 0.00156BF + 0.000311CE - 0.00138CF \tag{2}$$

Figure 3 shows the interaction plot of the PET-CA expression. The interaction plot was used to check the general relationship between each independent variable in the expression and the dependent variable (i.e., the 28-day compressive strength of concrete). From the interaction plot, the content of coarse aggregate has a curved effect on the compressive strength, while a higher fine aggregate content increases the strength of concrete. The compressive strength of concrete drops with a higher water-cement ratio, which is a fundamental principle in concrete mix design. The PET plastic aggregate replacement caused a linear decrease in compressive strength. The decrease in compressive strength was attributed to the morphology of plastic particles.

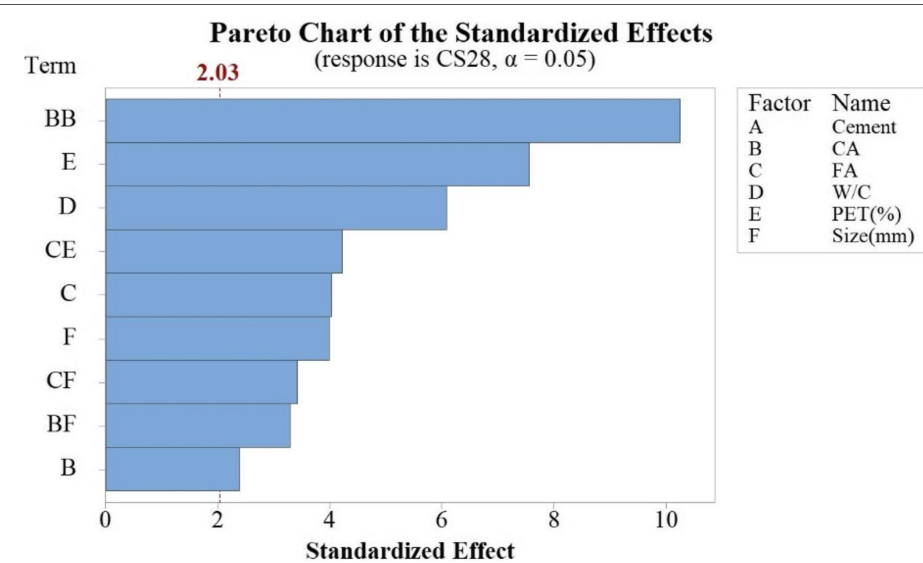

Fig. 1 Pareto Chart of PET-CA expression

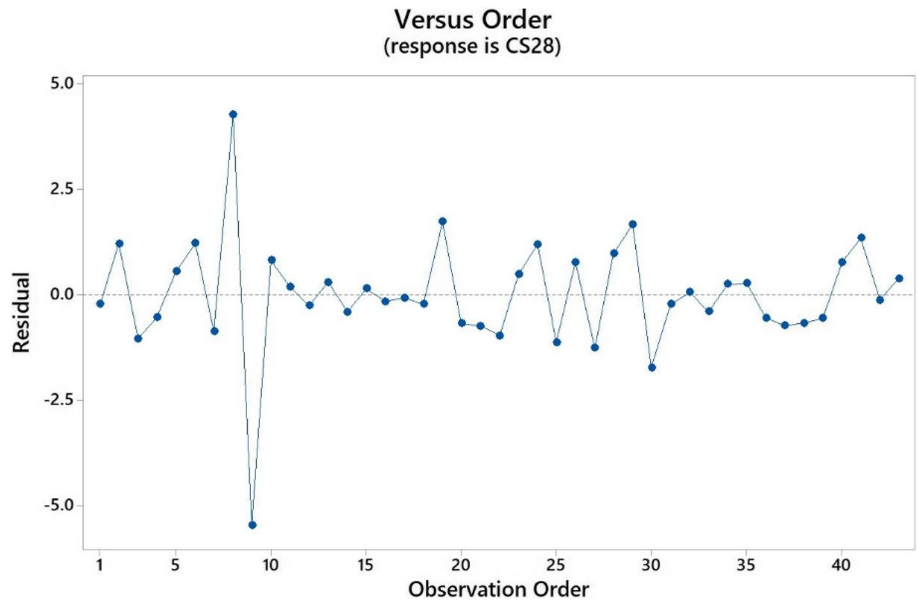

Fig. 2 Residual versus Order Plot of PET-CA expression

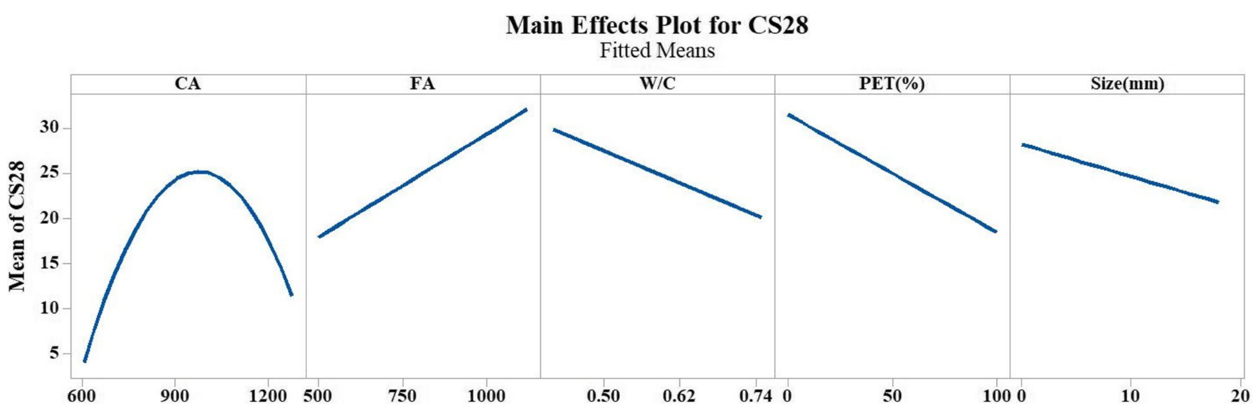

Fig. 3 Residual versus Order Plot of PET-CA expression

Compared with the rough texture of conventional aggregate, the smooth surface of plastic had a poorer adhesion with cement paste [38]. This statement was further elaborated by Islam et al. [24], where they added that the interfacial transitional zone (ITZ) of PET aggregate concrete was compromised due to the non-existent water absorption of PET plastic. This caused the accumulation of water at the ITZ which explained the reason for a weak bond between PET aggregate and cement paste. The gap within the microstructure subsequently became voids which in turn also increased the porosity and water absorption of PET concrete. Finally, the interaction plot postulated that the particle size of PET aggregate had a negative effect on compressive size. Such a relationship between the two variables was partially hinted in the experiment of Saikia and Brito [51], but the effect was not apparent due to limited data and lower replacement proportion. However, the negative effect of particle size was verified by Osubor et al. [40] in detail using three different sizes of PET plastic at up to 20% aggregate replacement. The main cause fell on the surface area of the single particle of the plastic, which increased with particle size. Hence, PET aggregate of greater size caused a greater level of weakness at the ITZ and thus, reducing compressive strength more markedly.

Figure 4 presents the contour plot and surface plot of the PET-CA expression. The contour plot was set to highlight the influence of the replacement level of PET plastic and particle size on the strength of concrete. From the contour plot, the compressive strength reduction caused by higher percentages of PET aggregate replacement was shown by the changing contour along the y-axis. The x-axis represented higher particle size of PET plastic as it moved along the right. For a same percentage of PET replacement, the compressive strength of concrete crossed the diagonal boundary towards a contour of lower strength as the size of PET plastic increased. The information was also presented in the surface plot in a 3D manner, with the surface inclined downward towards higher percentage of PET and bigger PET size. Based on this, the influence of PET-CA on the 28-day compressive strength of concrete was evidently demonstrated.

RSM of PET-FA expression

For the PET-FA expression, the forward selection method with $\alpha = 0.05$ was used to filter out least significant terms as the backward elimination resulted in a overly complex expression. The Pareto Chart and residual versus order plot of the expression are shown

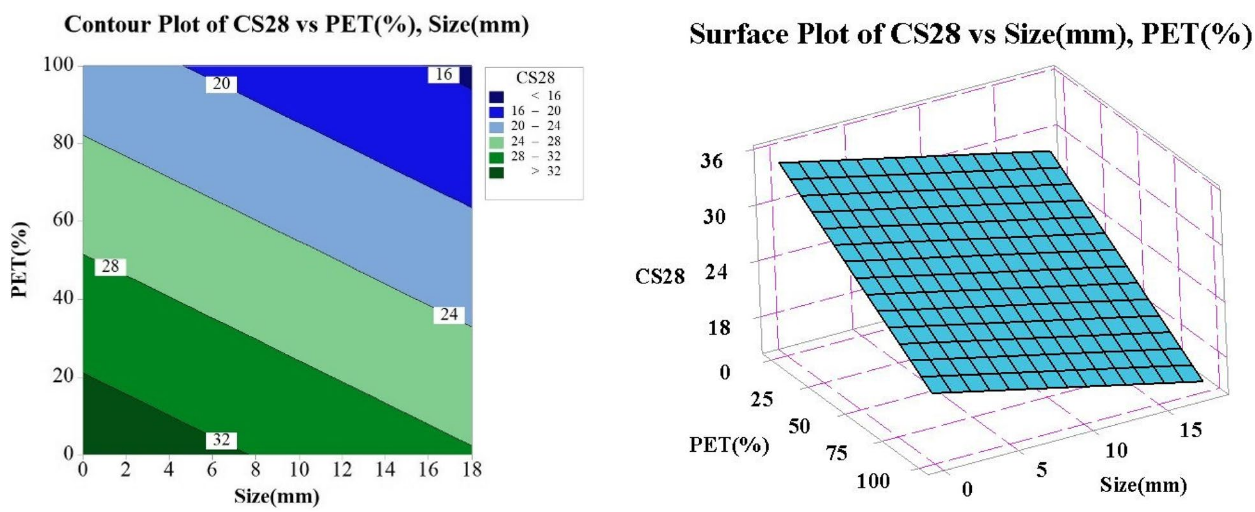

Fig. 4 Residual versus Order Plot of PET-CA expression

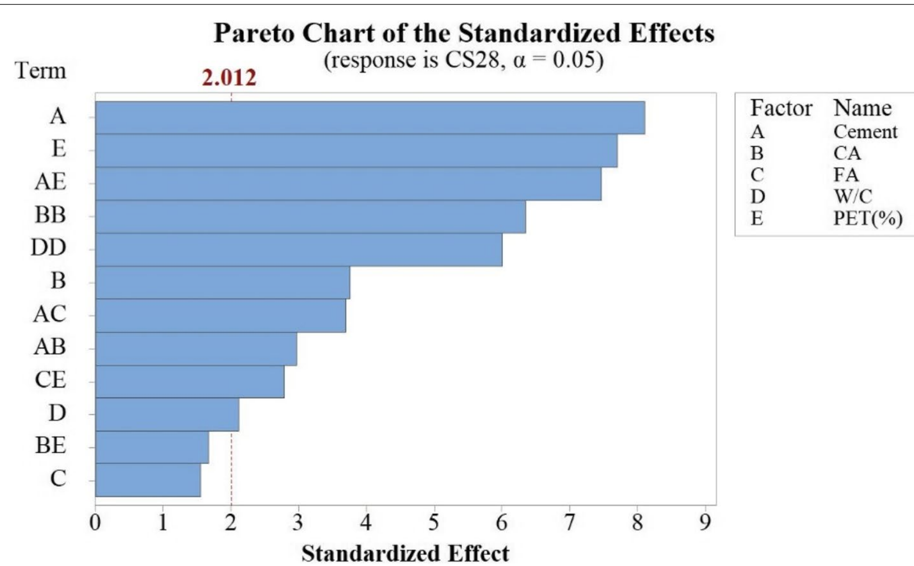

Fig. 5 Pareto Chart of PET-FA expression

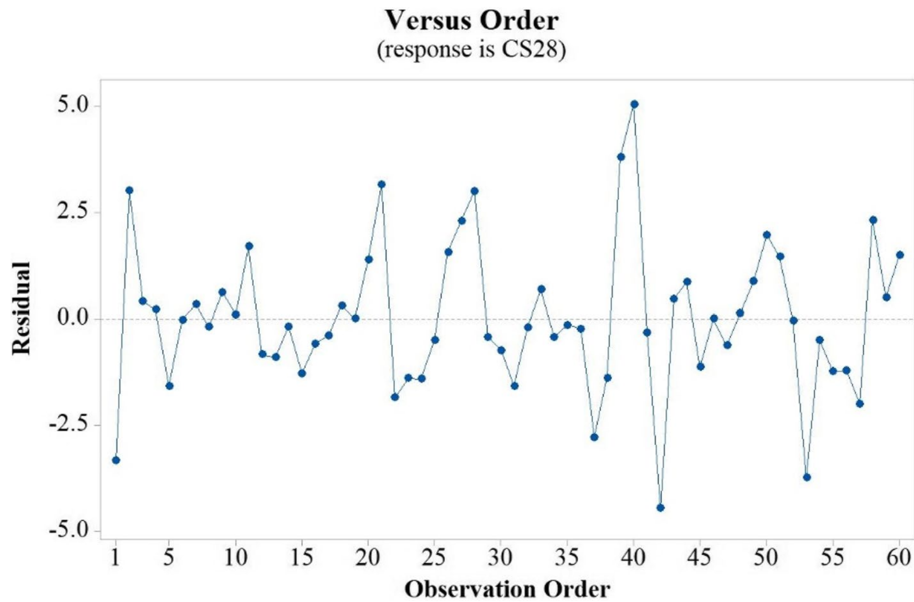

Fig. 6 Residual versus Order Plot of PET-FA expression

in Figs. 5 and 6, respectively. Compared to the PET-CA expression, more terms are present in the PET-FA expression. From the Pareto Chart, all primary terms (A to F) were deemed to be significant, followed by the quadratic terms of coarse aggregate (BB) and water-cement ratio (DD). A total of five interaction terms were added to round up the expression. For the residual versus order plot in Fig. 6, a zig-zag pattern was observed, meaning that the residual of the expression was distributed randomly. This indicates good integrity of the expression with all significant variables being accounted for.

Table 4 depicts the ANOVA and RSM analysis of the PET-FA expression. Most of the terms in the expression had a low *p*-value that is below 0.05. However, a certain degree of multicollinearity was observed in the term CA and CA × PET(%), which shows higher *p*-values of 0.128 and 0.103. However, this was only a minor imperfection on the expression, which occurred due to the complexity of concrete mix design. The primary valuable, the PET(%), which was the major interest in this study, was not affected. Meanwhile, the R^2 value of PET-CA expression was 0.9787 and the adjusted R^2 value was 0.9733, which confirms a strong correlation ($R^2 > 0.80$) of the expression with the dependent variable. Likewise, the RMSE of PET-CA expression was 1.726, which was minor. The expression for the 28-day compressive strength of concrete with the PET as a fine aggregate replacement was given in Eq. 3:

Table 4 RSM of PET-FA expression

Source	DF	Adj SS	Adj MS	F-Value	*P*-Value
Expression	12	8220.25	685.021	180.12	0.000
Linear	5	3737.72	747.544	196.56	0.000
Cement	1	250.43	250.427	65.85	0.000
CA	1	53.75	53.746	14.13	0.000
FA	1	9.13	9.130	2.40	0.128
W/C	1	17.05	17.052	4.48	0.040
PET(%)	1	225.68	225.678	59.34	0.000
Square	2	314.57	157.287	41.36	0.000
CA*CA	1	153.68	153.682	40.41	0.000
W/C*W/C	1	137.42	137.416	36.13	0.000
2-Way Interaction	5	685.42	137.084	36.05	0.000
Cement*CA	1	33.52	33.520	8.81	0.005
Cement*FA	1	51.86	51.864	13.64	0.001
Cement*PET(%)	1	212.39	212.389	55.85	0.000
CA*PET(%)	1	10.53	10.530	2.77	0.103
FA*PET(%)	1	29.69	29.695	7.81	0.008
Error	47	178.74	3.803		
Total	59	8398.99			
RMSE		1.726			
R^2		0.9787			
R^2 adj		0.9733			

$$CS_{28} = -311.4 + 0.44 + 0.288B + 0.0823C + 157.6D + 1.522E - 0.000106B^2 - 156.5D^2 - 0.000109AB - 0.000156AC - 0.002249AE - 0.000299BE - 0.000803CE \quad (3)$$

Figure 7 shows the interaction plot of the PET-FA expression. From the figure, the cement content had a positive effect on concrete strength, which matched the principle of concrete mix design. A curved relation was observed for the coarse aggregate content and water-cement ratio, while a negative effect was reported for the fine aggregate content. For the percentage of PET replacement, an evident decrease in compressive strength was observed at higher proportion of replacements. This is the same as shown in the PET-CA expression. The poor adhesion of the PET plastic with cement paste cited in many studies [42, 43, 52] was the reason for the decrease in strength. The statement was supported by the experimental finding from Black [44] who observed the segregation in concrete matrix and the formation of honeycomb shaped pores and cavities on concrete surface. Bamigboye [13] found the similar phenomenon by observing micropores and honeycombing using the scanning electron microscope (SEM) of PET concrete. Another reason for the strength reduction was proposed by some studies [46, 52], and they pointed out that PET plastic had a lower density and load-bearing capacity compared to river sand.

Figure 8 presents the contour plot and surface plot of PET-FA expression. The water-cement ratio and PET replacement proportion were selected as the variables to be presented in this paper. From the contour plot,

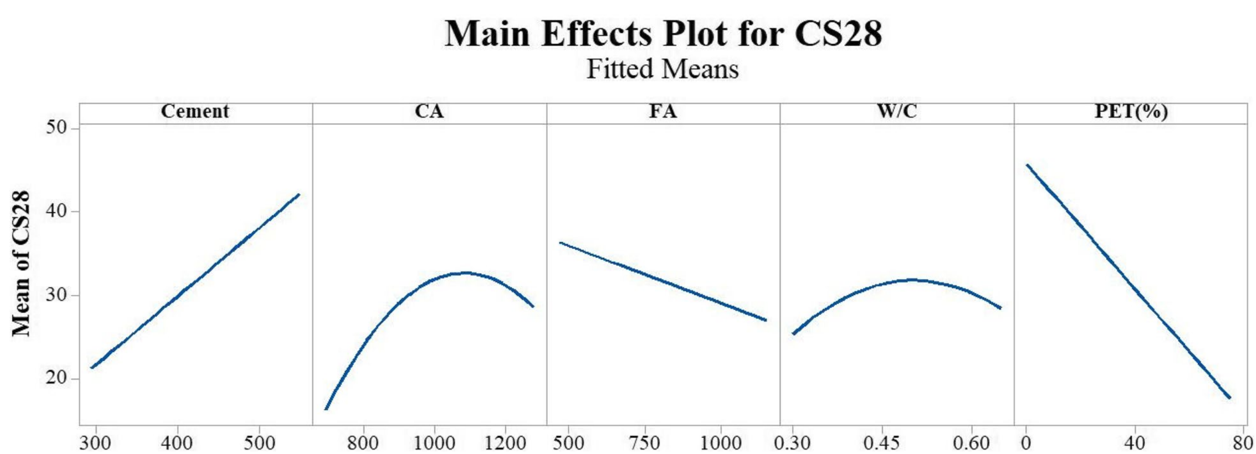

Fig. 7 Main effect plot of PET-FA expression

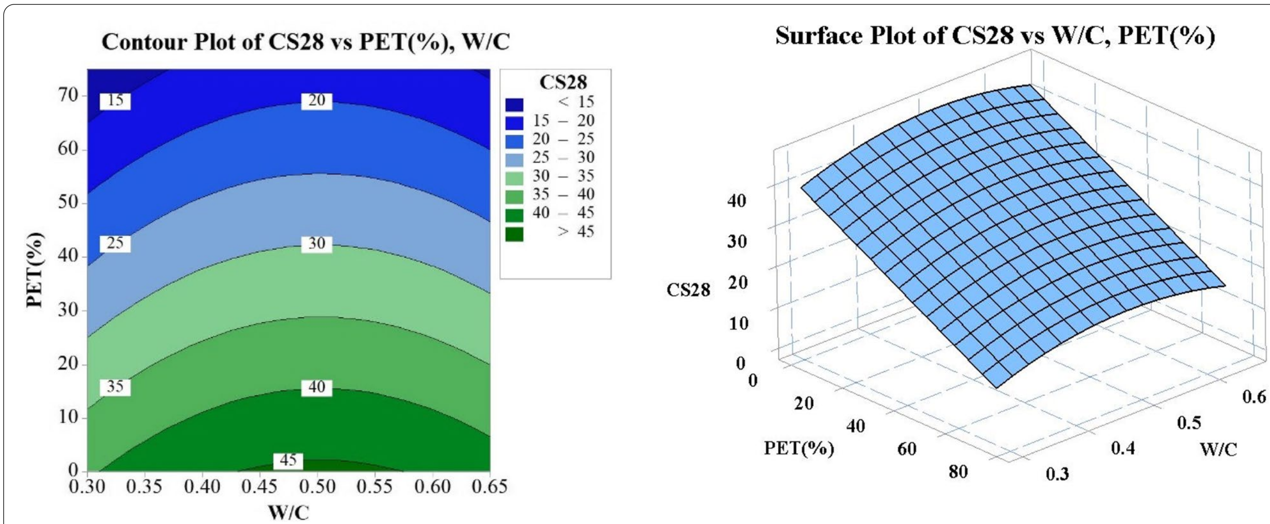

Fig. 8 Contour and surface plot of PET-FA expression

the reduction in compressive strength was displayed by the shifting contours across the axis. At the same time, curved boundaries were observed due to the effect of water-cement ratio. For the surface plot, the drop in the surface displayed a consistent decrease in compressive strength regardless of water-cement ratio of the mix.

Regression analysis

The regression analysis was conducted by plotting the SI of PET concrete versus the percentage of the PET replacement. Both series of data from the PET-CA and PET-FA expressions were plotted together with discernable symbols as shown in Fig. 9. Same as the findings from the RSM, the compressive strength of concrete decreased with increasing percentage of PET replacement in both coarse and fine aggregate replacement cases. The data was scattered across a broad range, which made it difficult to identify a distinct relationship between the variables. Since the compressive strength in the regression output was relative to the control concrete (SI = 1.0), the intercept of the regression was set to be 1.0 to formulate the change in compressive strength with respect to the PET replacement. A quadratic expression was applied to formulate the relationship between the percentages of PET and SI of concrete. The selection of the quadratic equation over a linear expression was made because while the strength of concrete decreased proportionally with percentage of replacement, a higher strength loss was generally seen at higher percentages of replacement. Obviously, there can other equations that can fit the data reasonably well, the quadratic equation was the simplest while still maintaining sufficient accuracy in data fitting. The regression analysis identified a quadratic relation in which the PET-CA expression had a R^2 value of 0.6144 and the PET-FA expression had a R^2 value of 0.7295. However, the correlation for both sets of data was only moderate ($0.60 > R^2 > 0.80$).

Figure 10 presents the separate residual plot for both expressions. The RMSE of PET-CA and PET-FA regression expression was computed to be 0.1175 and 0.1080 respectively. Residual plot showed that the quadratic expression in Fig. 9 was moderately descriptive of the SI of PET aggregate concrete. From the residual versus order plot, most of the predicted SI fluctuated within ±0.10 range. However, several data points showed greater deviations, mainly originating from experiment with very high replacement proportion. For PET-CA expression, the highest deviation was from the study of Bamigboye et al. [23] with replacement up to 100%. In contrast, the deviation in PET-FA expression was caused by variation of results in 10% PET aggregate concrete among different researchers. The variation would become a key point for examination to determine the conditions in which PET aggregate displayed greater strength.

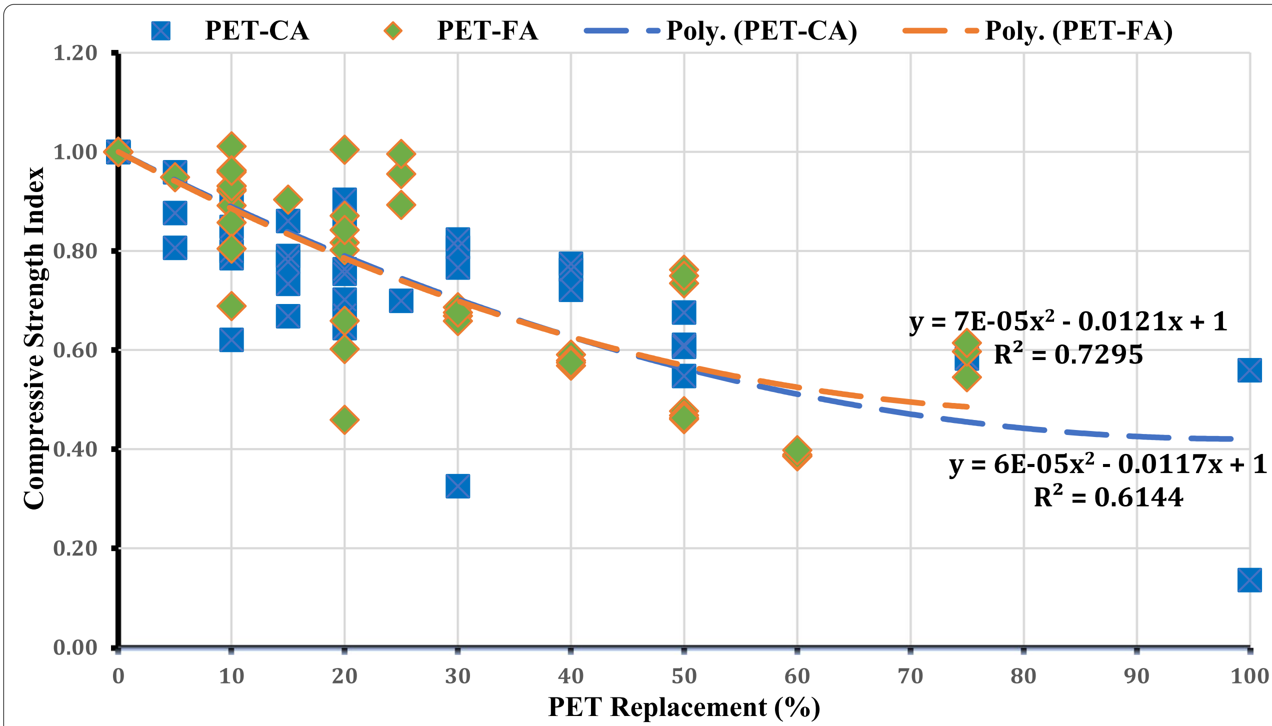

Fig. 9 Regression analysis of PET concrete

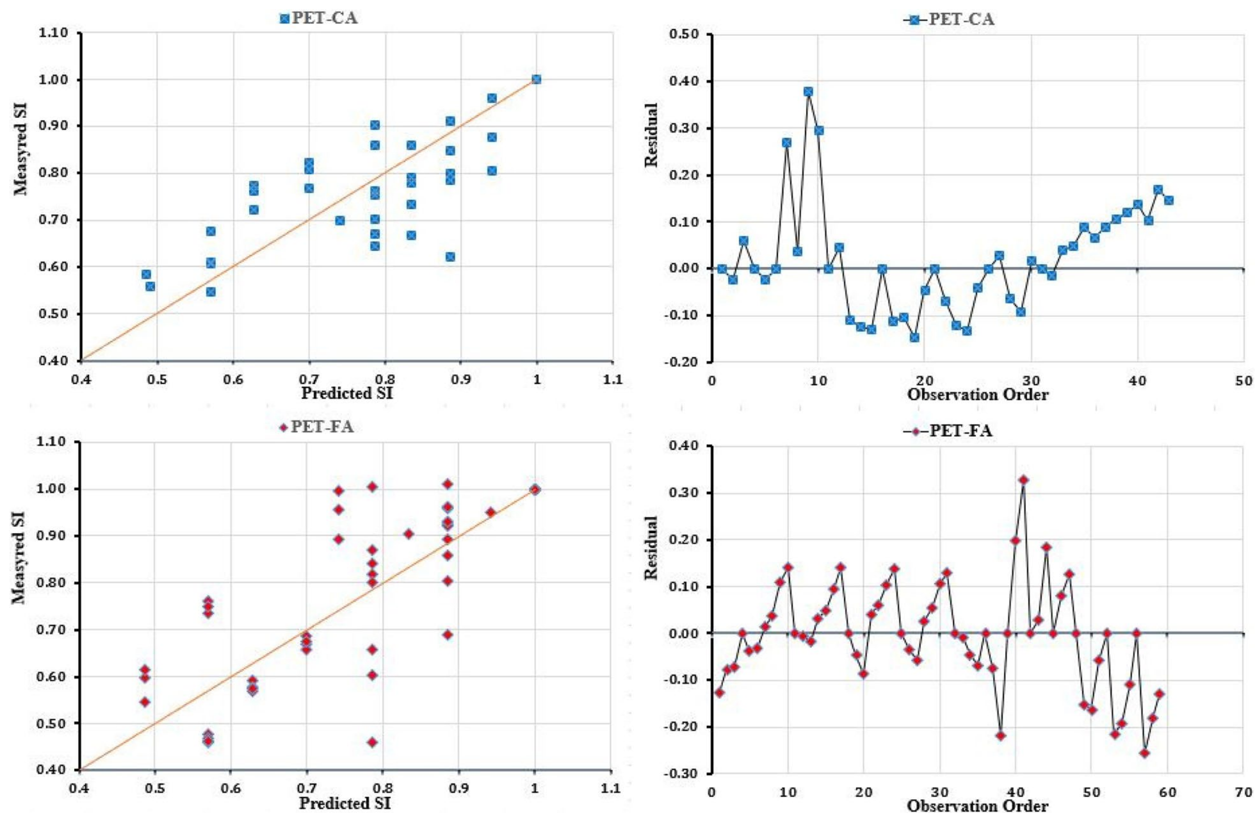

Fig. 10 Residual Plots of Regression expression

It is concluded that the PET aggregate caused a similar trend of decrease in compressive strength for both coarse aggregate and fine aggregate replacement cases, despite the strength decrease for the PET-FA expression was slightly less significant than the PET-CA. More specifically, at up to 20% PET replacement, a significant amount of data points from the PET-FA expression was placed above the PET-CA expression. Moreover, a number of data from the PET-FA expression were closer to the 1.0 line at about 20% replacement. Those data points were from the experiment of Thorneycroft et al. [41] that utilized PET plastic of a small size at 0.5 mm to 2 mm and 2 mm to 4 mm. At the 5% replacement level, a miniscule increase in compressive strength was even observed, while the 10% PET concrete had comparable strength to that of control. The experiment reported that the increased packing due to the smaller PET particles had a positive effect on compressive strength, which helped mitigate the strength loss inherent to PET concrete [41]. In another study by Rai et al. [43], concrete lost only about 10% of its compressive strength at 15% PET as a fine aggregate replacement. It is unknown if the fineness of ground plastic or the use of CONPLAST SP320 superplasticiser was the key to the low strength reduction. In another example [44], the PET plastic that was ground using a granulator was used as a fine aggregate replacement and achieved comparable strength as the control, even at the 20% replacement level. Based on these analyses, it becomes apparent that using PET plastic as a fine aggregate replacement might be a better option due to the less adverse effect on compressive strength. With a proper mix design and a judicious selection of replacement level, it is feasible to use the PET plastic as a fine aggregate source in the production of sustainable concrete with minimum strength reduction.

Conclusion

In this study, the 28-day compressive strength of concrete with PET as either a coarse aggregate or a fine aggregate replacement was analyzed using RSM and regression approaches. The input variables for the regression equations were the percentage of PET replacement, the size of PET aggregate, and other basic concrete mix design parameters such as cement content, coarse aggregate, fine aggregate, and water-to-cement ratio. The main effect plot was examined to confirm that all the variables were significant and played a role in determining concrete compressive strength. At the same time, the contour and surface plots were generated to thoroughly study the influence of PET replacement on concrete compressive strength. From the PET-CA expression, it was concluded that the increase in percentage of PET aggregate reduced the compressive strength of concrete. The reduction in compressive strength occured because PET aggregate had a smooth surface and low bearing capacity which caused weakness in the ITZ. Moreover, PET aggregate of larger maximum nominal size resulted in concrete with even lower compressive strength. From the PET-FA expression, a similar trend of strength reduction was reported with the increase of the PET aggregate replacement level. The results of the RSM showed satisfactory accuracy with R^2 value of 0.9479 for the PET-CA expression and 0.9787 for the PET-FA expression. The RMSE of both expressions was also found to be minimal. Meanwhile, the regression analysis showed that the SI of PET concrete had a moderate quadratic correlation with the percentange of PET aggregate. Comparing both cases, the addition of PET aggregate in concrete yielded less strength reduction when utilized as fine aggregate. Interestingly enough, the experimental data for which PET was ground to fine size below 2 mm showed similar compressive strength between the PET concrete and the control concrete. From this study, it was found that incorporating PET in concrete as a fine aggregate replacement at up to 30% can lead to sustainable concrete with minimum strength reduction.

Abbreviations
ANOVA: Analysis of Variance; CA: Coarse Aggregate; DoE: Design of Experiment; FA: Fine Aggregate; FHWA: Federal Highway Administration; ITZ: Interfacial Transitional Zone; OVAT: One Variable at a Time; PET: Polyethylene Terephthalate; R^2: Determination Coefficient; R^2 adj: Adjusted Coefficient; RMSE: Root-Mean-Square Error; RSM: Response Surface Methodology; SEM: Scanning Electron Microscope; SI: Strength Index; W/C: Water-To-Cement.

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Authors' contributions
BWC conducted the study conception and design. XS aided in the data collection process. BWC performed the analysis and interpretation of results. BWC and XS contributed to draft manuscript preparation. All authors have reviewed the results and approved the final version of the manuscript.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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