Powder Technology 413 (2023) 118054

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.journals.elsevier.com/powder-technology

Optimization of sustainable concrete characteristics incorporating palm oil clinker and nano-palm oil fuel ash using response surface methodology

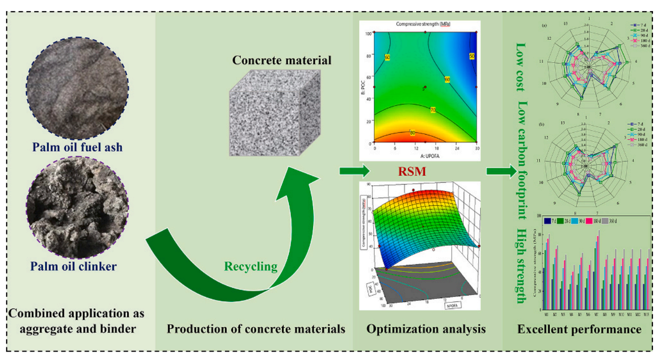
Hussein M. Hamada [a], Alyaa Al-Attar [b], Jinyan Shi [c,*], Fadzil Yahaya [a], Mohammed S. Al Jawahery [d,e], Salim T. Yousif [f]

[a] *Faculty of civil engineering, University Malaysia Pahang, Malaysia*
[b] *Northern technical university, Mosul, Iraq*
[c] *Department of Civil Engineering, Central South University, Changsha, China*
[d] *Highway and Bridges Eng. Dept., Technical College of Eng., Duhok Polytechnic University, Duhok, Iraq*
[e] *Department of Construction Engineering and Projects Management, Al-Noor University College, Nineveh, Iraq*
[f] *Civil engineering department, College of engineering, Nawroz university, Kurdistan, Iraq*

HIGHLIGHTS

- The NPOFA and POC are combined to produce eco-friendly concrete.
- RSM is used to optimally design workability and strengths of sustainable concrete.
- The economic and environmental benefits of NPOFA and POC modified concrete are assessed.

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Nano palm oil fuel ash
Response surface methodology
Palm oil clinker
Concrete
Sustainability

ABSTRACT

The production of concrete by replacing cement and aggregates with biomass materials is a low-carbon footprint and low-cost approach. In this study, the influences of nano-palm oil fuel ash (NPOFA) and palm oil clinker (POC) partially replaced instead of cement (0, 15% and 30%) and coarse aggregate (0, 50%, 100%) into sustainable concrete on workability and compressive strength are investigated using response surface methodology (RSM) methods. The RSM forecasting has presented satisfactory outcomes in optimizing the quantity of POC and NPOFA in the production of concrete with acceptable strength. The peak compressive strength is achieved for the mixture containing 0% POC and 15% NPOFA, and the mixture containing 100% POC and 30% NPOFA has the lowest compressive strength. The optimum condition is successfully predicted using RSM. The use of NPOFA binder enhances the workability and compressive strength of concrete material, in addition to enhancing the sustainability of the concrete industry. Meanwhile, the results of economic and environmental assessments also show that the addition of NPOFA and POC significantly reduces the cost and carbon emissions of concrete, and the effect of NPOFA is even more pronounced. This method might result in the noteworthy consumption of POC

* Corresponding author.
E-mail address: jinyan.shi@csu.edu.cn (J. Shi).

https://doi.org/10.1016/j.powtec.2022.118054
Received 27 August 2022; Received in revised form 15 October 2022; Accepted 25 October 2022
Available online 31 October 2022

and NPOFA in the production of concrete and assist in achieving environmental sustainability by reducing the agricultural and industrial waste by-products.

1. Introduction

Utilization of ordinary Portland cement as binder to produce concrete is not desirable for many reasons, especially the negative impact on the environment through the emission of high quantity of CO_2 to the atmosphere and low durability when used in the acidic and sulphate environments [1,2]. However, the production of cement increases rapidly due to the increasing construction activities all over the world [3,4]. In 2010, the cement consumption was 3270 million ton, expected to reach 4830 million ton by 2030 [5]. This increasing speed will contribute towards negative effects on the environment if not addressed properly. Moreover, the presence of $Ca(OH)_2$ as a cement hydration product, which is not important to increase the concrete strength directly [6]. Therefore, further use of supplementary cementitious materials (SCMs) can both reduce the carbon footprint of concrete and convert calcium hydroxide into gel-like products with high strength gain.

The partial replacement of cement by pozzolanic materials mainly decreases the CO_2 emission effects from cement production, and improves the mechanical properties and reduces the cost of concrete production [7]. Pozzolanic materials are siliceous or siliceous and aluminous materials that react with $Ca(OH)_2$ from cement hydration to produce secondary composites and improves the mechanical properties [8]. There are many types of pozzolanic materials such as, metakaolin, silica fume, fly ash, rice husk ash, and palm oil fuel ash (POFA). In order to reduce carbon emissions, some high-polluting enterprises, such as thermal power plants and steel plants, have been gradually replaced and reduced in number. This means that the reserves of traditional SCMs are gradually decreasing, and high-quality SCMs are often in short supply in some areas. Instead, some biomass power plants and industries dealing with biomass waste have been developed, which has resulted in a gradual increase in the production of biomass waste. POFA is a by-product material results from burning of oil palm residues (nutshells, empty fruit bunches, and fibers) to generate the energy required in the palm oil mills [9]. Presently, the POFA is dumped into open area and landfills without any treatment causing environmental issues [10]. However, POFA may be utilized as cement replacement material because of the high pozzolanic properties [11]. It also enhances, mechanical properties, durability and microstructure of concrete when utilized in low percentages, especially at late curing stages of concrete [12]. Besides, the utilization of POFA in construction industry contributes mainly in the effective management of palm oil waste. Therefore, it has an important role in improving the environmental aspect and enhancing and achieving further sustainable concrete products.

Numerous methods are used to optimize the concrete properties and discover sensible solutions to the problems related the concrete efficiency [13–15]. One of these methods is by enhancing the mix proportions through the statistical or mathematical techniques [16]. Many studies investigated the optimization of concrete and ultra-high-performance concrete [15]. De Larrard and Sedran enhanced the properties of high-strength concrete (HSC) through a response surface method (RSM) as a packing model, and investigated the influence residue volume of paper mill in the performance of normal weight concrete (NWC) [17]. Regarding the POFA utilizations, Aldahdooh et al. also adopted the RSM technique to use the POFA as partial cement replacement to assess the fiber-reinforced UHPC [18]. Furthermore, the RSM is utilized to develop green UHPC comprising ultrafine POFA (UPOFA), which is useful to produce a novel material for enhancing the flexure strength of concrete beam [19]. Recently Hasan et al., used micro and nano-POFA as cement replacement partially to produce HSC [20]. They used central composite design (CCD) under the RSM technique. The results of the experimental runs were utilized to validate the mathematical models. The results indicated that the model forecasting was closely with the experimental results. As mentioned earlier, a perfect approach is required to enhance the properties of HSC related to factors contents. Most of the mix design methods of NWC are multi-variables; furthermore, optimization of concrete mix proportions as used in the traditional way is time consuming, unreliable, and inflexible. Therefore, RSM is an effective tool and widely adopted in different area, such as in physical and chemical aspects for processing and optimization goals. The main objective of RSM utilization is to improve the responses as an effective statistical method for the optimization and modeling of several factors to forecast the optimum performance situations with minimize the experimental trails [21]. RSM technique is a promising tool owing to produce low average error resulted to experimental and modeling validation. The desirability standard factors in RSM will certainly assist researchers in finding the optimum condition. The RSM illustrates the importance of every potential mixture of interaction and square terms. Also, the 3D surfaces created using RSM will assess in imagining the influence of variables on the responses in the whole scope identified. The best procedure is to use the RSM method as an optimization tool. The RSM is widely adopted in different areas, such as chemistry and biology for processing and optimization goals. The CCD within the RSM is usually used to discover the function relationship among the factors and the response and the details of using CCD and RSM applications are existing on the Design-Expert software [21]. Many studies proved that the RSM is one of the best methods to design the concrete mixtures in the construction industry.

In this study, palm oil clinker (POC) is used as coarse aggregate to produce lightweight aggregate (LWA) concrete. POC has resulted from the burning treatment of mesocarp fiber and oil palm shell as a final by-product from is commonly land-filled into the landfills and open areas or utilized as a potholes' cover for the roads [22]. The POC is collected in large chunks from the oil palm mill and is light and large in nature. The crushing process is applied to crushing these large chunks into small particle size to be a suitable LWA, providing an optimum sustainable source of coarse and fine LWA [22]. The previous studies illustrated that the use of palm oil waste as construction materials demand extra investigations [9]. Furthermore, a few studies showed positive the influence of the incorporation two different palm oil waste in the production of concrete [22]. The normal design method is usually adopted to optimize the cement and aggregate content in concrete. Effective recycling of industrial and agricultural solid waste might require extra environmental and economic field investigations. Therefore, a feasible design method was suggested to use the nano-palm oil fuel ash (NPOFA) as cement and POC as coarse aggregate replacement to produce an HSC. Specially, this search aims to study the effect of inclusion both oil palm waste on the concrete properties and optimize the content of NPOFA as cement and POC as aggregate material to achieve the optimum strength and workability using the RSM technique. The results of this study will promote the utilization of POC and POFA to achieve sustainable and eco-friendly concrete using RSM.

2. Experimental program

2.1. Materials and methods

The binder materials include cement (Type I) and NPOFA. The raw POFA was collected from the palm oil mill biomass. Before using, the collected raw POFA was oven-dried in the oven at 110 ± 5 °C for 24 h to remove the absorption water. Then consequently sieve the oven-dried POFA using 300-μm sieve to remove the strange and larger particles, as well as the organic materials. To improve its pozzolanic properties, the sieved POFA was exposed to grinding process for 2 h using ball mill [23]. The main component of NPOFA is silicon dioxide (67.3%). In addition, the summation of SiO_2, Al_2O_3, and Fe_2O_3 of NPOFA is 79.54%, the SO_3 content and loss on ignition (LOI) are 0.535% and 1.4%, respectively. Hereafter, the NPOFA utilized in this study satisfies the requirement of Class F according to ASTM C 618.

The POC results from the burning treatment of 70% fibers and 30% oil palm shell [24]. The heating temperature was increased up 850 °C to produce the required energy to function the palm oil mills and the subsequent waste by-product was obtained as large chunk POC. Therefore, the process of POC obtained at high temperature would allow resisting the elevated temperature in HSC. The POC was washed to remove the organic and dust materials and then dried at oven, crushed and then sieved to get the particle sizes between 4.75 and 10 mm to be utilized as coarse aggregates within this range. The replacements of coarse aggregate by POC are 0, 50%, and 100%. The physical properties and sieve analysis of the coarse aggregates used are presented in Table 1 and Fig. 1, respectively.

According to the test conducted by Hamada et al. the irregular shape of NPOFA might describe its high specific surface area [23]. Natural river sand was used as fine aggregate to produce HSC. The maximum particle size of sand is 1.18 mm, and its water absorption capacity and specific gravity are 2.2% and 2.55, respectively. The potable water supplied to concrete lab was used in the concrete mixtures and for curing purpose. The super-plasticizer (SP) was used in this study to improve the workability of mixture.

2.2. Design of experimental runs using RSM technique

In this search, Design of Expert v12 software was adopted to design modeling and statistical analysis, as well optimizing of responses. The central composite design (CCD) was usually used as design method in RSM technique. In this study, RSM with three-level factorial experimental design as in Fig. 2, were combined to accomplish the optimization by improving the HSC properties at suitable replacement levels of cement and coarse aggregate by NPOFA and POC, respectively.

According to the previous studies, the suitable ranges of POC as coarse aggregate and NPOFA as cement replacement were between 0 and 30% and between 0 and 100%, respectively, as given in Table 2.

While, other concrete components (remains constant) such as total binder content and cement-water ratio to ensure that any changed in the HSC strength occasioned with the replacement levels of the NPOFA and POC aggregate. The CCD method was adopted in this study to calculate the functional relationship between the variables (POC and NPOFA) and the responses (compressive strength and workability). Thirteen experimental runs had been designed using the CCD method (Table 3). Five replication runs were added by the CCD design with the original eight experiments to evaluate pure error. The best condition of the responses (workability and compressive strength) was determined using the optimum predictor quadratic model as presented in Eq. (1).

Table 1
Physical properties of coarse aggregates (POC and Natural) [22].

Properties	POC coarse aggregate	Natural coarse aggregate
Fineness	6.23	–
Aggregate size (mm)	4.7 to 10	4.7 to 10
Bulk density (kg/m^3)	823	1455
Moisture content (%)	0.38	0.29
Aggregate crushing value (ACV, %)	46.5	16.8
Specific gravity (SSD)	1.78	2.65
Water absorption (24 h, %)	5.7	0.74
Los Angeles abrasion value (%)	49.7	23.9
Aggregate impact value (AIV, %)	31.57	–

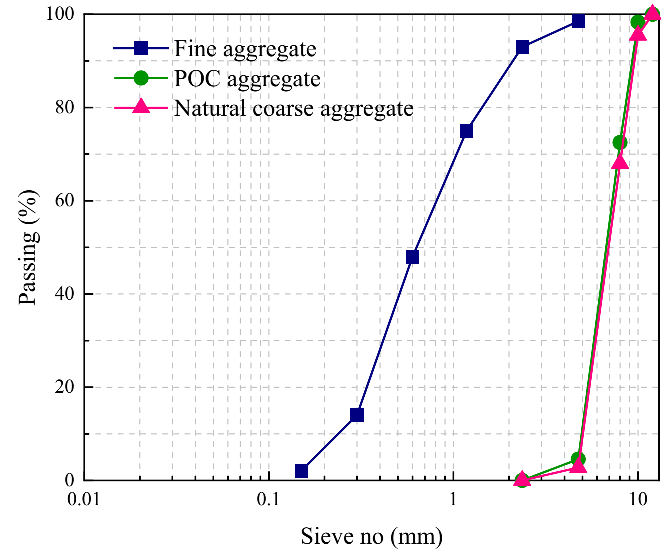


Fig. 1. Sieve analysis of aggregates [16].

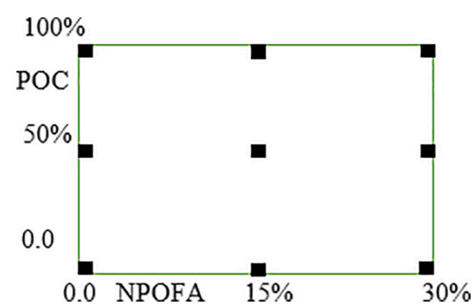


Fig. 2. Points of experimental design.

Table 2
Independent factors, coding values and units of the parameters used.

Variables (factors)	Code	Unit	−1	0	1
NPOFA (A)	NPOFA	%	0	15	30
POC (B)	POC	%	0	50	100

$$Y = \beta_o + \sum_{i=1}^{n} \beta_i x_i + \left(\sum_{i=1}^{n} \beta_{ii} x_i \right) + \sum_{i=1}^{n-1} \sum_{j}^{n} \beta_{ij} x_i x_j + e \quad (1)$$

where, Y is the response (compressive strength or workability), β and i are regression coefficients and linear coefficients, respectively. j is the quadratic co-efficient, $x_i x_j$ are the coded values for the NPOFA and POC, e is the random error, and n is the number of factors.

As observed in Table 3, the cement and coarse aggregate weight changed according to the replacement level of NPOFA and POC except for the control mixture. While the fine aggregates, water/binder ratio, and SP were fixed as a constant weight in all concrete mixtures.

2.3. Analysis, optimization and sample preparation

Analysis of Variance (ANOVA) was utilized to get the relationship between the process variables (POC and NPOFA) replacement levels and the responses (compressive strength and workability), to determine the statistical significance; (*t*-test and *P*-value), and the determination coefficient of R^2. The actual values were used in this research to create the required model. The diagnostic plots, such as the actual value plot versus

Table 3
Proportions of the HSC mixtures according to RSM technique (Kg/m^3).

Mix No.	NPOFA (%)	POC (%)	NPOFA	POC	Cement	Fine aggregate	Coarse aggregate	Water/binder ratio	SP
1	0	0	0	0	450	700	900	0.42	4.5
2	30	0	108	0	315	700	900	0.42	4.5
3	0	100	0	604	450	700	0	0.42	4.5
4	30	100	108	604	315	700	0	0.42	4.5
5	0	50	0	302	450	700	450	0.42	4.5
6	30	50	108	302	315	700	450	0.42	4.5
7	15	0	54	0	382.5	700	900	0.42	4.5
8	15	100	54	604	382.5	700	0	0.42	4.5
9	15	50	54	302	382.5	700	450	0.42	4.5
10	15	50	54	302	382.5	700	450	0.42	4.5
11	15	50	54	302	382.5	700	450	0.42	4.5
12	15	50	54	302	382.5	700	450	0.42	4.5
13	15	50	54	302	382.5	700	450	0.42	4.5

the predicted plot and normal residual for workability and strength were achieved to identify the model suitability. Diagnostic plots assisted in judging the adequacy of model and suitability. Furthermore, 3D response surface plots and perturbation were achieved. All the obtained results were assessed using the Design of Expert v12 software, in numerical and statistical optimization for NPOFA% and POC%. The workability and compressive strength as responses were set within the range. Furthermore, the ramp function diagram was utilized to determine the best section for workability and strength of the HSC to accomplish optimum situation.

The concrete samples were prepared according to BS 1881: Part 131: 1998. The dry materials (cement, fine aggregate, coarse aggregate, NPOFA, POC) were mixed in dry condition for 5 min to achieve a homogeneous mixture. Water was added gradually to the dried-concrete mixture, continuing the mixing process for 6 min. The cube molds were filled in three layers. The samples were removed from the cubic molds after 24 h of casting, and then cured under water till the date of testing. The slump test was conducted according to ASTM: C143/C143M to determine the workability directly after the casting process. The compressive strength was determined through 100 mm concrete cubes with loading rate of 0.60 MPa/s and concrete compression machine with 2000 kN based on BS EN 12390–3. Three specimens for each mixture and of each age (7, 28, 90, 180, and 360 d) were tested.

3. Results and discussions

Based on the Table 3, the HSC mixtures have been divided into thirteen. The mix no. 1 refers to the control concrete mixture as NWC. Whereas the rest twelve mixes were used for NPOFA or POC or both to produce sustainable concrete.

3.1. Workability

The workability of concrete is evaluated using the slump test as shown in Fig. 3. Obviously, the incorporation of POC remarkably decreases the workability of concrete [22]. The slump value is sharply declining with increasing the POC replacement level, while, it increases gradually with an increase in the replacement level of NPOFA. Low workability is always associated with high POC content in concrete mixture. The workability of the concrete has been affected by the high content of the POC aggregate owing to the rough surface and particle shape, besides the spiny broken edges. The irregular shape of POC aggregate leads to the high surface area which increases the request of additional paste volume to obtain better workability.

Compared with POC aggregate, NPOFA has little effect on workability. These effects may be due to the lubrication among the aggregates, while the lubrication by NPOFA is better when compared to that of the POC aggregates. In comparison with the normal concrete (M1), the significant increase of the slump is observed in M2 and M7 mixture which include the NPOFA. This increasing is due to its lower content of the LOI, which referrers to low content of unburned carbon content embedded in POFA particles [9]. Obla et al. reported that the paste must totally fill the pores among the aggregates, and a significant quantity should be left to offer in order to provide better lubrication for the required workability [25]. Reduced workability is related with the content of POC aggregate and the high workability is associated with the content of NPOFA. The high water/binder ratio assists mainly in achieving the necessary slump value, which enhances binding of the aggregate and the binder paste at the interfacial transition zone. From the workability results, the concrete comprising 15%–30% NPOFA and 0% POC significantly enhances the workability.

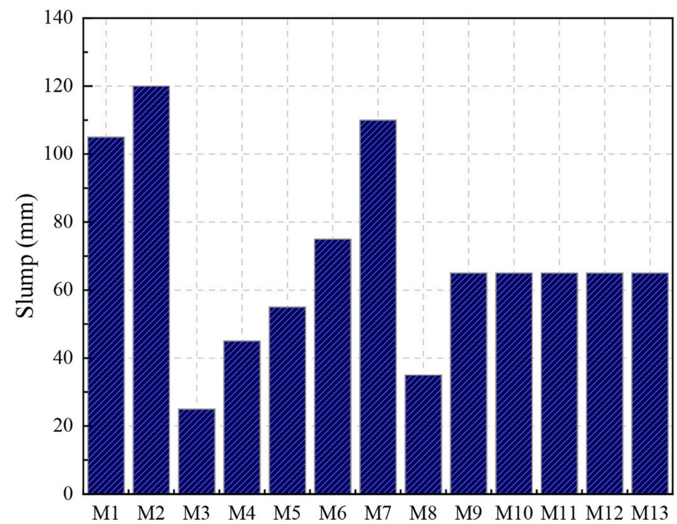


Fig. 3. Slump value of concrete mixtures.

3.2. Compressive strength

The 195 cubes (100 mm) are tested at 7, 28, 90, 180, and 360 d as presented in Fig. 4. The M7 mixture achieves the high compressive strength (85 MPa at 360 d) due to the presence of 15% NPOFA and 0% POC aggregates. The high development in the compressive strength from 7 to 360 d is owing to the reaction between the high silica content in the NPOFA and the calcium hydroxide generates from the hydration process during the mixing. The M4 mixture mixed with 100% POC and 30% NPOFA have the lowest compressive strength (48 MPa at 360 d). The low value and slow development of strength is due the high porosity and presence of voids in the microstructure of POC surface, which make it light and enable to adsorb high water thus leads to decreasing the compressive strength.

The suitable replacement of NPOFA and POC for improving the compressive strength must be ranging between 0 and 15%, and between

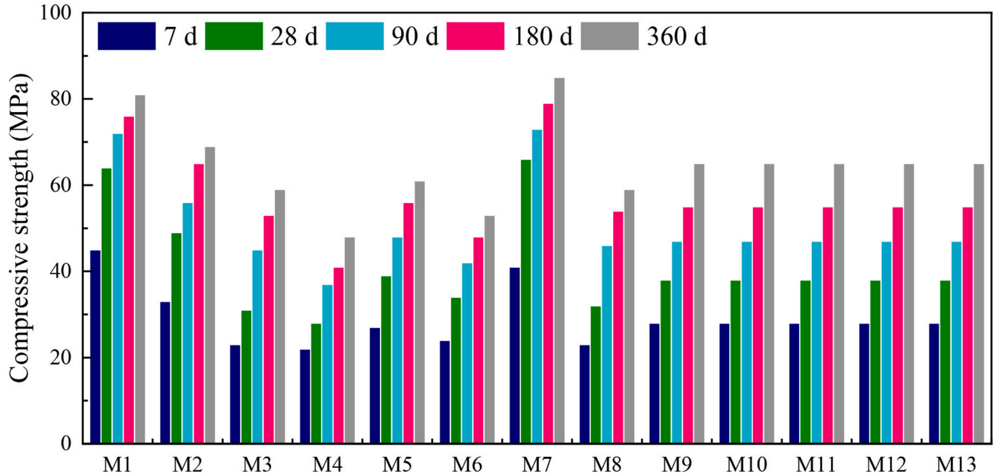


Fig. 4. Compressive strength of concrete.

0 and 50%, respectively. The reduction in the compressive strength may be related to the reduced the bond strength (adhesive strength) between the cement paste and POC aggregates. Abutaha et al. stated that the main reason for the reduced strength of POC concrete could be due to the irregular shape and high content of voids on the POC [26]. The reduction in compressive strength might be resulted by the crushing of POC aggregate. As reported by other study by Kanadasan and Razak, stated that coarse POC had a high crushing value that resulted in the reduced compressive strength by 9.6% and 32.9% at replacement level of 50% and 100%, respectively [27].

3.3. Modeling and statistical analysis

The relationship between the variables (POC and NPOFA) content and the responses required (workability and compressive strength) of HSC mixtures are evaluated through RSM technique. Analysis of variance (ANOVA) is used to analyze the outcomes from the quadratic prediction model, as shown in Table 4.

The model is created based on the coded values from the experimental runs. The equations of the mathematical prediction are established according to the Eq. (1). The responses (predicted results) are assessed as a function of the replacement levels of NPOFA (%) and POC (%). The average of these responses is used when building the prediction models of workability and 360-d compressive strength. The empirical relationship between the factors (NPOFA and POC) and the response (workability and strength) is explained by a second-order polynomial, as illustrated in Eqs. (2) and (3).

$$Workability = +64.83 + 9.17\,A - 38.33\,B + 1.25\,AB + 0.6034\,A^2 + 8.10\,B^2 \quad (2)$$

$$Compressive\ strength = +64.97 – 5.17\,A - 11.5\,B + 0.25\,AB - 7.88\,A^2 + 7.12\,B^2 \quad (3)$$

Table 4 displays the ANOVA outcomes for the workability and strength. As the *P*-values are <0.05 of the data obtained, all the models can be considered as significant at the 95% confidence levels. Moreover, the P-values for all the responses are >0.05 means the association of significant model among the factors and process responses. Therefore, all the *p*-values are <0.05 except the 0.2846 for the A^2 in the workability and the 0.7003 for the AB in the compressive strength case as observed in Table 4.

Table 5 presents the model validation of the workability and compressive strength. The results of ANOVA analysis illustrate that it is a reliable confidence in the approximation of the responses effectiveness (R^2). On the other hand, Ghafari et al. (2019) anticipated a high and close to one R^2 value, a practical agreement with the adjusted R^2 is an

Table 4
ANOVA outcomes for parameters of response surface quadratic model.

	Source	Sum of Squares	df	Mean Square	F-value	p-value	
Workability	Model	9552.45	5	1910.49	2550.11	< 0.0001	Significant
	A-NPOFA	504.17	1	504.17	672.96	< 0.0001	
	B-POC	8816.67	1	8816.67	11,768.44	< 0.0001	
	AB	6.25	1	6.25	8.34	0.0234	
	A^2	1.01	1	1.01	1.34	0.2846	
	B^2	181.36	1	181.36	242.08	< 0.0001	
	Residual	5.24	7	0.7492			
	Lack of Fit	5.24	3	1.75			
	Pure Error	0.0000	4	0.0000			
	Total	9557.69	12				
Compressive strength	Model	1180.20	5	236.04	151.91	< 0.0001	Significant
	A-UPOFA	160.17	1	160.17	103.08	< 0.0001	
	B-POC	793.50	1	793.50	510.69	< 0.0001	
	AB	0.2500	1	0.2500	0.1609	0.7003	
	A^2	171.47	1	171.47	110.36	< 0.0001	
	B^2	140.04	1	140.04	90.13	< 0.0001	
	Residual	10.88	7	1.55			
	Lack of Fit	10.88	3	3.63			
	Pure Error	0.0000	4	0.0000			
	Total	1191.08	12				

Table 5
Model validation of workability and 360-d compressive strength.

Items	Workability	Compressive strength
Santander deviation (SD)	0.8656	2.43
Mean	68.85	37.85
R^2	0.9995	0.9909
Predicted R^2	0.9948	0.9071
Adjusted R^2	0.9991	0.9843
Precision	161.5574	42.27

essential matter [28]. The ANOVA has shown a trustworthy confidence in the estimation of the workability and the 360-d compressive strength (R^2 = 0.9995 and 0.9909, respectively). The predicted R^2 of the workability and compressive strength of HSC (0.9948 and 0.9071, respectively) are in a sensible arrangement with the adjusted R^2 (0.9991 and 0.9843, respectively). The high value of R^2 coefficient refers the acceptable adjustments of the quadratic model. On the other hand, the adequate precision values of 161.5574 and 42.27 for the workability and 360-d compressive strength, respectively, are higher than 4, as desired value, so that the predicted models can be adopted to direct the design space using CCD design.

Based on Table 5, all models can be considered as successful considering the reproducibility. The diagnostic plots, like the normal plot of residual and the actual values versus predicted plot are displayed in Figs. 5 and 6.

The predicted values associated with the actual values obtained from the experimental runs can be summarized as shown in Fig. 6.

The comparative influence of the content of NPOFA and POC on the improvement of the workability and compressive strength are explained by the perturbation plots as presented in Fig. 7. A curvature in POC % appears to be sharper when compared to that of the NPOFA curve in the workability and compressive strength results.

There are two plots (2D and 3D) that can be used to understand the significant models produced from the statistical analysis. The plots illustrate the NPOFA values, referred to as A, and POC referred to as B. These two-plots show the interaction of the NPOFA and POC aggregate in A and B coded to refers to the improvement of the workability and compressive of HSC. The predictive Eqs. (2 and 3) acquired from the regression model are adopted in the 3D response surface plot. Therefore, it can be noted the effects of the combination of NPOFA and POC on the workability and 360-d compressive strength from the contour 2D plot and 3D plot as in Figs. 8 and 9.

Furthermore, the influences of the experimental situations of NPOFA and POC on the workability and compressive strength are established in the 2D and 3D surface response plots as presented in Figs. 8 and 9. The high slump value (120 mm) is noted at 0% POC and 30% NPOFA. As mentioned before, the use of NPOFA can improve the workability of the HSC mixtures. In contrast, the lowest slump value (25 mm) is achieved with M3 mixture which contains from 100% POC and 0% NPOFA. Fig. 8 illustrates that the increase in the content of POC as coarse aggregate prompted to decrease the compressive strength value.

For a better explanation of the influence of the replacement of NPOFA and POC on the workability and compressive strength development, contour plots are created via the established model. Figs. 8 and 9 illustrates the workability and 360-d compressive strength, and the effect of the replacement levels of NPOFA and POC. The results show that the addition of NPOFA increases the workability (increase the slump values), while the presence of 30% NPOFA reduces the 360-d compressive strength of HSC. According to the replacement levels of POC, it is identified to have a negative impact on the workability (especially with high replacement level), as well as, it reduces the 360-d compressive strength to less than that of the NWC. However, the 360-d compressive strength of HSC containing POC can be acceptable as it is >20 MPa.

The factors as well as their responses adopted in this study (NPOFA and POC) are set in the range. The model equations are concurrently solved to discover the process parameters. To achieve the optimum condition, the NPOFA is 15% and the POC is 0% to produce slump of 110 mm and 85 MPa as 360-d compressive strength according to desirability function of 1 as explained in Fig. 2.

3.4. Optimization

A multi-objective simultaneous optimization technique is adopted after analyzing the variables which including RSM as a base to find out the best solution. A response surface experimental plan is utilized to discover the optimum settings for (NPOFA 0%, 10%, 20%, and 30%; POC 0%, 50%, and 100%) as a CCD method. Table 6 illustrates the importance of each factor and response as well as the lower and upper limits of these factors and responses of HSC.

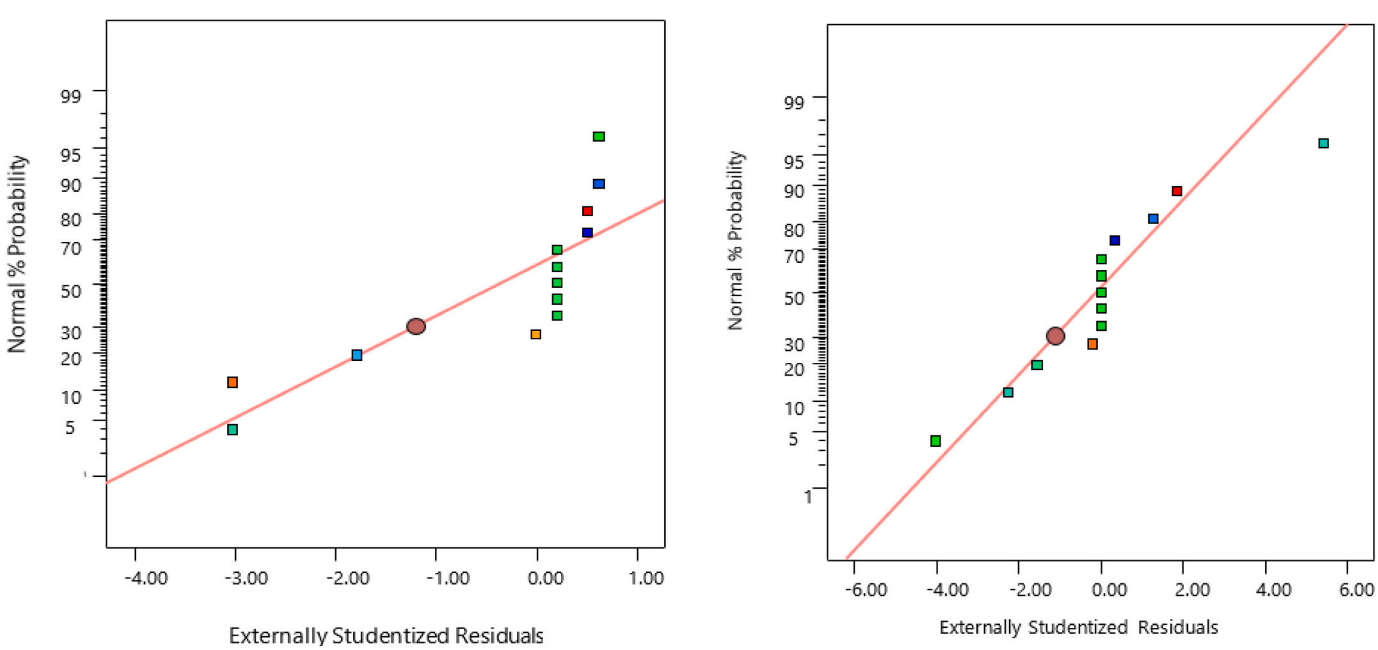


Fig. 5. Normal plot residual for (a) workability and (b) strength of concrete.

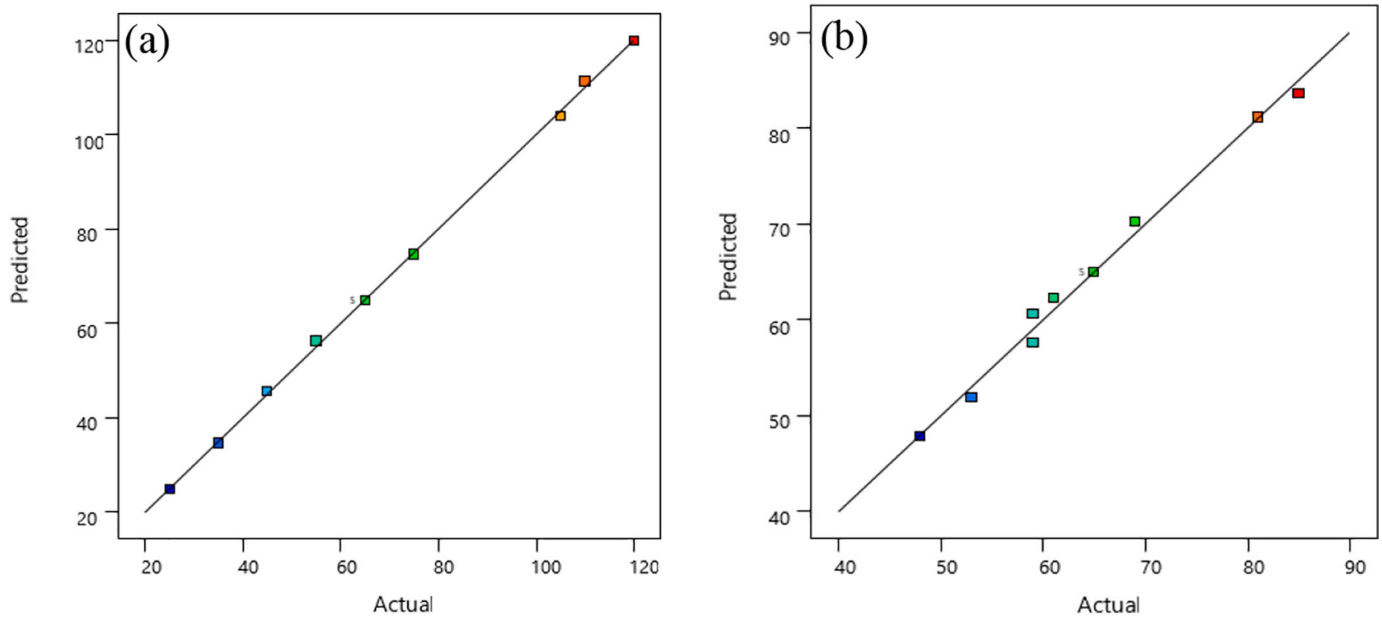


Fig. 6. Actual versus predicted values of (a) workability and (b) strength of concrete.

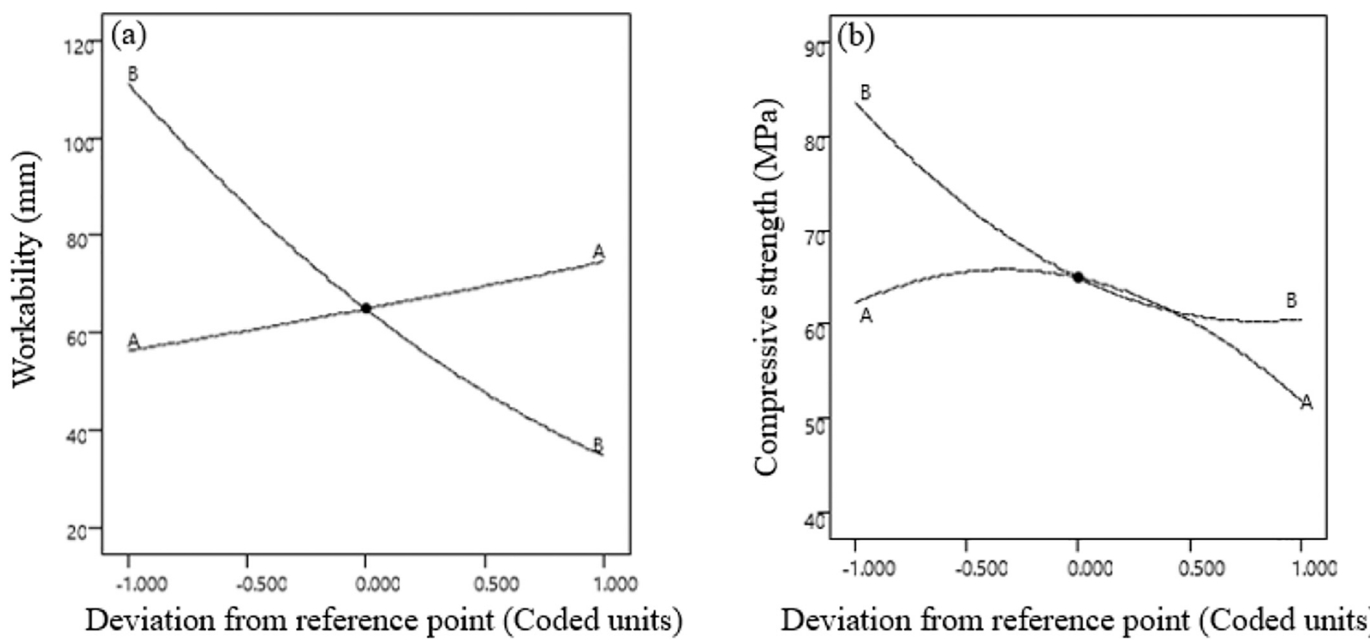


Fig. 7. Division from reference points for (a) workability and (b) compressive strength.

If the optimal settings for each response are in different zones, finding that all responses are satisfied is more complicated. The level of complications increases when these optimal zones are further apart from each other and do not intersect. Therefore, changes in the factor level may enhance one specified response and has a negative influence on the other response. Therefore, a multi-criteria methodology has been used to solve the problem associated with the optimization of several responses at the same time. In this research, the multiple response optimization methods are used to optimize the properties of concrete.

Among mathematical functions, desirability function is one of the important methods of multi-criteria method, which is based on constructing a desirability function for each response. In summary, the responses including the workability and compressive strength are transformed into an individual desirability (di) scale which dimensionless value. The individual desirability values range from 0, for a fully undesirable response, to 1 for a completely desired response. This transformation assists to combine the outcomes acquired from various responses. The two responses of workability and compressive strength of HSC are optimized, and the ideal function is obtained. Desirability variation for the workability and compressive strength of HSC is 0.619 for the variables and responses as in Fig. 10 that shows the graphical ramp for optimized workability and compressive strength.

The multi-objective optimizations of results are 12.42% NPOFA and 11.27% POC aggregates, as shown in Fig. 10. While, the optimum values

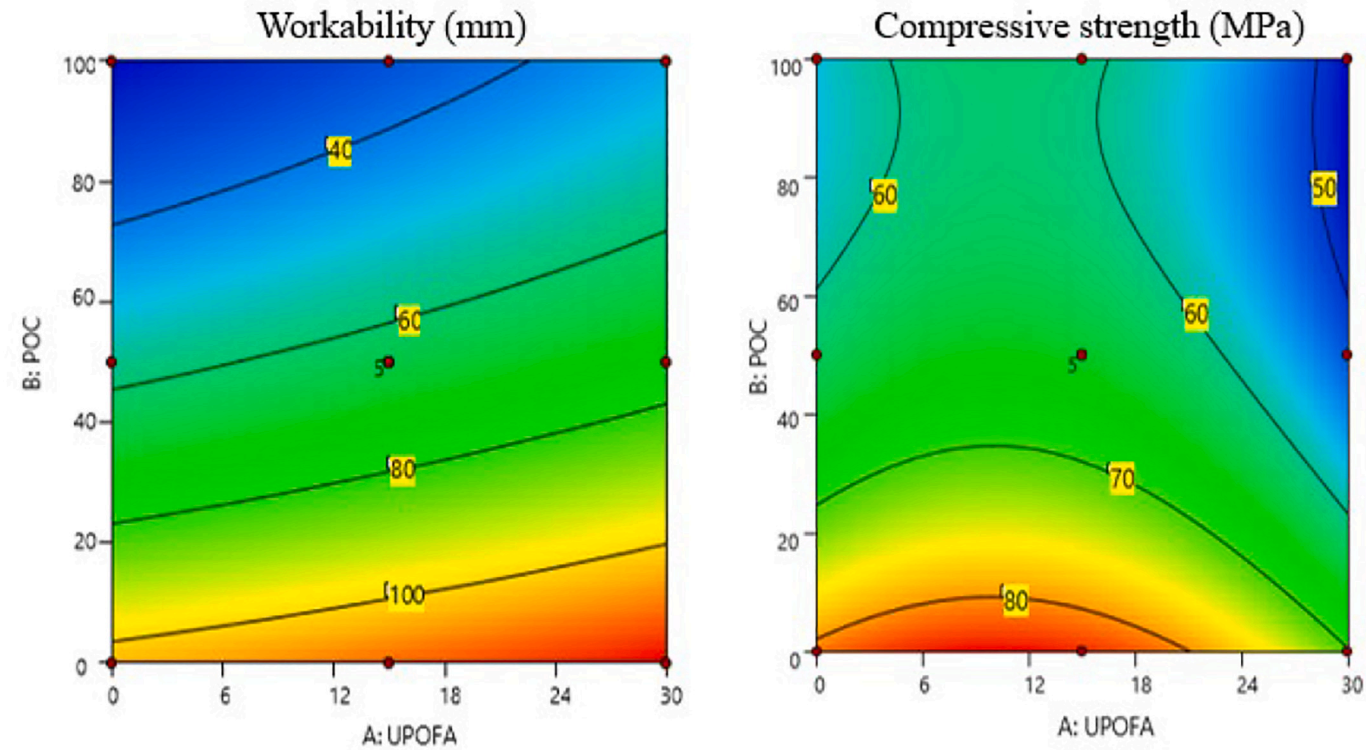


Fig. 8. Response surface 2D plots of workability and compressive strength.

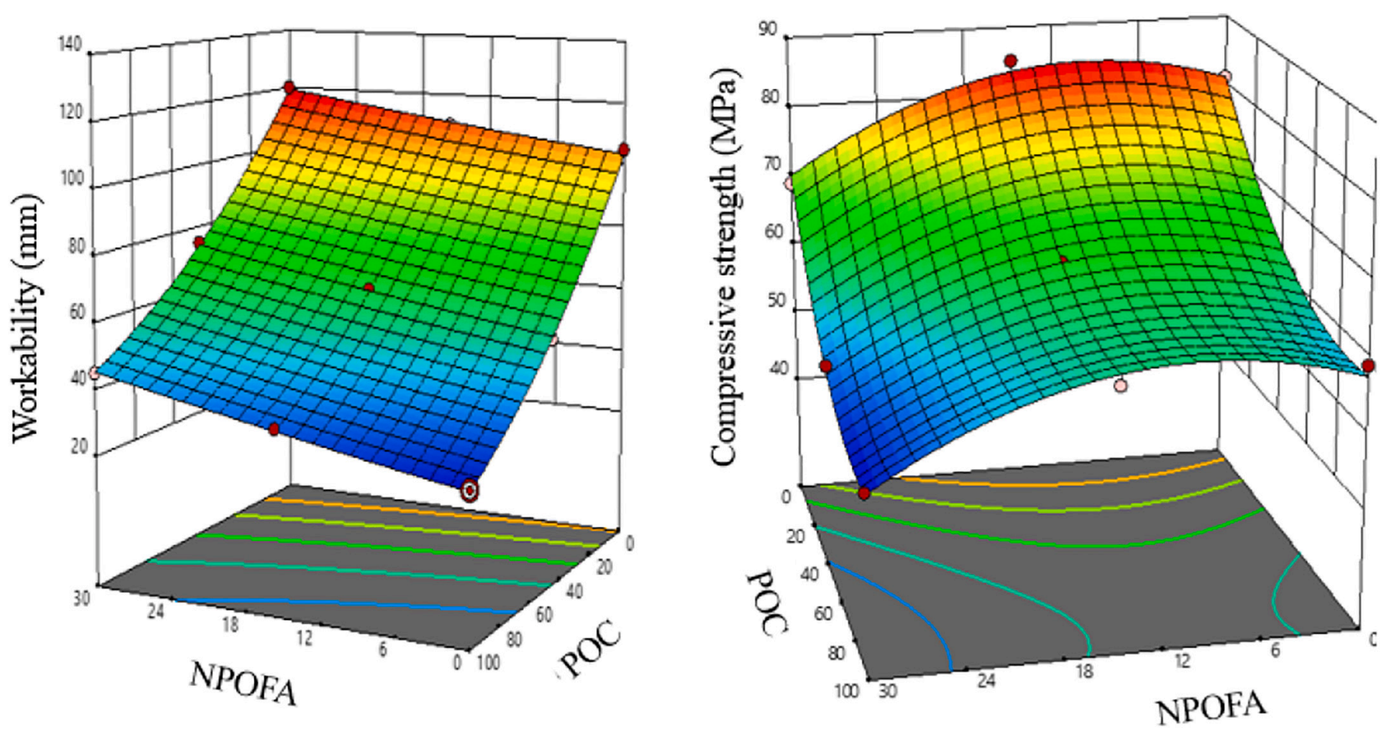


Fig. 9. Response surface 3D plots of workability and compressive strength.

of workability and 360-d compressive strength are 97.98 mm and 78.83 MPa, respectively. The desirability of the optimal solutions is 0.619. The optimization results show that 12.42% NPOFA with an 11.27% POC has achieved the desirability value of 0.619. These variables (NPOFA and POC, %) replacement level are predicted to experience 97.98 mm and 78.83 MPa, respectively.

4. Economic and environmental benefits

4.1. CO_2 emission and cost due to treatment of NPOFA and POC

This study calculated CO_2 emissions and costs from the transportation, grinding and processing of NPOFA and POC collected from

Table 6
Importance and limits of factors and responses.

Name	Goal	Lower Limit	Upper Limit	Importance
A:UPOFA	Is in range	0	30	3
B:POC	Is in range	0	100	3
Workability	Maximize	25	120	5
Compressive strength	Maximize	48	85	5

palm oil mills. In the palm oil mill, NPOFA and POC are wastes, and their initial cost and carbon emissions are set to zero. These wastes are often disposed of in landfills, which are also costly and have potential impacts on the environment surrounding of the landfill. This part of the potential economic and environmental benefits is not calculated because different countries have different treatment policies and costs. For NPOFA, it is successively dried, sieved, ground and calcined, and the electricity consumption produced by this process in the laboratory is calculated in Table 7. Data from the UK Department of Energy and Climate Change show that carbon emissions from power generation and transport are 0.521 and 0.192 kg CO_2/km, respectively. Meanwhile, the distance between the palm oil factory and the laboratory is calculated as 100 km, and carbon emissions are calculated based on the amount of diesel required by the truck. Compared to NPOFA, POC omits the calcination step, and it also does not require grinding. According to industrial electricity policy of China, the cost factor is set to 0.0737 $/kWh. In addition, a truck with a load of 10 tons and a volume of 7.6 × 2.3 × 2.5 (43.7 m^3) is used to transport the material. A single shipment is calculated at 10 tons due to the higher density of POC. For the first 15 km, the transportation cost is 48.6453 $, and until 100 km, the unit cost is 5.5 $/km.

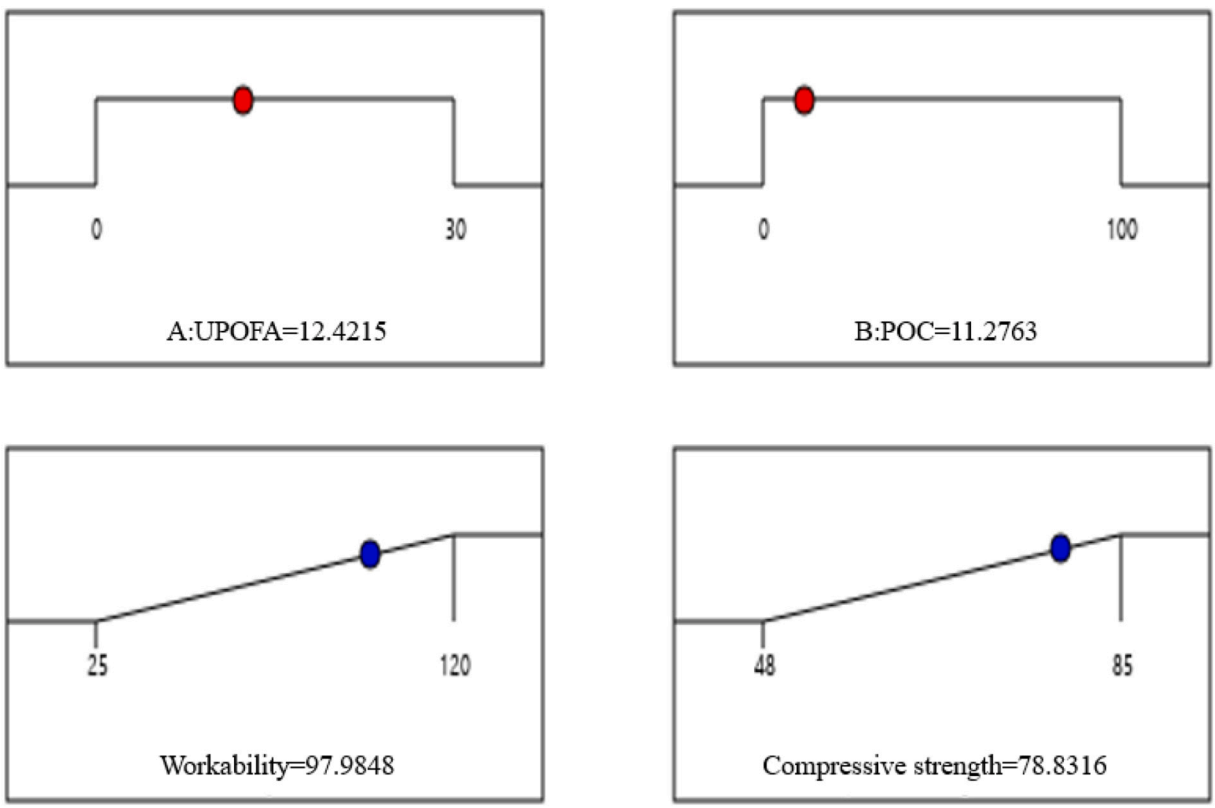


Fig. 10. Graphical ramp assessments for optimized concrete properties.

Table 7
The cost and CO_2 emissions of NPOFA and POC.

Item	Energy requirements for 1000 kg material						Transportation of 1000 kg SCM			Total emission (kg CO_2/kg)	Total cost ($/kg)
	Consumption (kWh)				Emission factor (kg CO_2/kWh)[5]	Cost factor ($/kWh)[6]	Distance (km)[7]	Emission factor (kg CO_2/km)[8]	Cost factor ($/km)[9]		
	Drying[1]	Sieving[2]	Grinding[3]	Calcining[4]							
NPOFA	25	213.5	178.5	141	0.521	0.0737	100	0.192	0.214	0.1837	0.0356
POC	25	5	0	0	0.521	0.0737	100	0.192	0.214	0.0579	0.0028

1. The material is dried in a laboratory oven with the temperature of 110 ± 10 °C for 24 h.
2. To differentiate particle size, aggregates and powders are sieved using a shaker.
3. Grind with a ball mill for 10 h.
4. Calcined in a muffle furnace at 600 °C for 2 h [29].
5. Carbon emissions from electricity generation.
6. Charges for using electricity.
7. Distance between palm-oil mill and laboratory.
8. Carbon emissions from the use of diesel fuel for transport materials.
9. The cost of hiring a means of transport.

Finally, the costs and carbon emissions of NPOFA and POC are calculated. Since NPOFA requires more grinding and calcination processes, its cost and carbon emissions are significantly higher than POC and higher than similar products. Meanwhile, the carbon emissions and cost of other raw materials are also collected from references, as shown in Fig. 11. The carbon footprint of POC is slightly higher than that of natural coarse aggregate, which may be due to the high water content of POC. This makes it take longer time to dry treatment, which increases its carbon footprint. With the reduction of natural resource reserves, the use of solid waste to produce concrete will achieve higher economic and environmental benefits.

4.2. Comparison of cost and CO_2 emission of concrete

Table 8 presents the effect of NPOFA and POC on the overall cost and carbon footprint of concrete. Both NPOFA and COP alone significantly reduces the cost of the mixture. Adding 15% and 30% NPOFA to the concrete reduces the cost of the mixture by 3.73% and 7.47%, respectively. Likewise, replacing aggregate with POC also reduces the cost of the mixture. Adding 50% and 100% POC to concrete reduces the cost of the mixture by 5.03% and 10.07%, respectively. Combining the two in the mixture achieves better cost reduction than using NPOFA and POC alone. When 30% NPOFA and 100% POC are used, the cost of the mixture reaches the lowest (73.081 $/kg) among all mixtures and is reduced by 17.54% relative to the plain mixture. Since the carbon footprint of the binder is much higher than that of the aggregate, the use of NPOFA to replace the cement achieves better environmental gains than the use of POC to replace the coarse aggregate. Binder is a major contributor to the carbon emissions of concrete, which can reach 84%–90% per cubic meter of mixture. When the substitution levels of NPOFA and POC are 30% and 100%, the carbon emission of the mixture is reduced by 22.47% and 2.93%, respectively, relative to the plain concrete. Further combined use of NPOFA and POC reduces the carbon footprint of the mixture to 346.43 kg/kg, which is only 74.6% for plain concrete. Therefore, the use of NPOFA and POC to produce concrete materials is beneficial in reducing the total cost and total carbon footprint of the mixture.

4.3. Economic and environmental efficiency

To facilitate the comparison of the economic and environmental efficiencies of NPOFA and POC for concrete, the ratios of cost and carbon emissions to compressive strength are calculated as shown in Tables 9 and 10. At 7 d, the cost and carbon footprint benefits of concrete are significantly higher due to the low pozzolanic reactivity of NPOFA and the high crush value of POC relative to the reference group. As the strength of the modified concrete increases, the situation is slightly improved at 28 and 90 d. When a small amount of NPOFA is added, the 28-d and 90-d costs of concrete are reduced by 6.65% and 5.05%, respectively, compared with plain concrete. At 7, 28 and 90 d, the carbon emissions of the 15% NPOFA-modified mixture are reduced by 2.58%, 13.93%, and 12.45% compared to the plain concrete. The economic and environmental efficiency of the mixture is further improved as the curing age increases.

Fig. 12 presents the radar chart of mixture-normalized costs and carbon emissions. It is clear that Mix 7 has the most significant gains for cost and carbon emission efficiency. This is mainly due to the low

Table 8
The cost and CO_2 emission per cubic meter of concrete mixed with NPOFA and POC.

Mix No.	Total cost ($/kg)	Total CO_2 emission (kg/kg)
1	88.6212	464.42081
2	82.0035	360.06041
3	79.6987	450.79241
4	73.081	346.43201
5	84.15995	457.60661
6	77.54225	353.24621
7	85.31235	412.24061
8	76.38985	398.61221
9	80.8511	405.42641
10	80.8511	405.42641
11	80.8511	405.42641
12	80.8511	405.42641
13	80.8511	405.42641

Table 9
The cost per MPa of concrete mixed with NPOFA and POC ($/kg·MPa).

Mix No.	7 d	28 d	90 d	180 d	360 d
1	1.96936	1.384706	1.23085	1.166068	1.094089
2	2.484955	1.673541	1.464348	1.261592	1.188457
3	3.465161	2.570926	1.771082	1.503749	1.350825
4	3.321864	2.610036	1.975162	1.782463	1.522521
5	3.117035	2.157947	1.753332	1.502856	1.379671
6	3.230927	2.280654	1.846244	1.615464	1.463061
7	2.080789	1.292611	1.168662	1.079903	1.003675
8	3.321298	2.387183	1.660649	1.414627	1.294743
9	2.887539	2.127661	1.720236	1.47002	1.243863
10	2.887539	2.127661	1.720236	1.47002	1.243863
11	2.887539	2.127661	1.720236	1.47002	1.243863
12	2.887539	2.127661	1.720236	1.47002	1.243863
13	2.887539	2.127661	1.720236	1.47002	1.243863

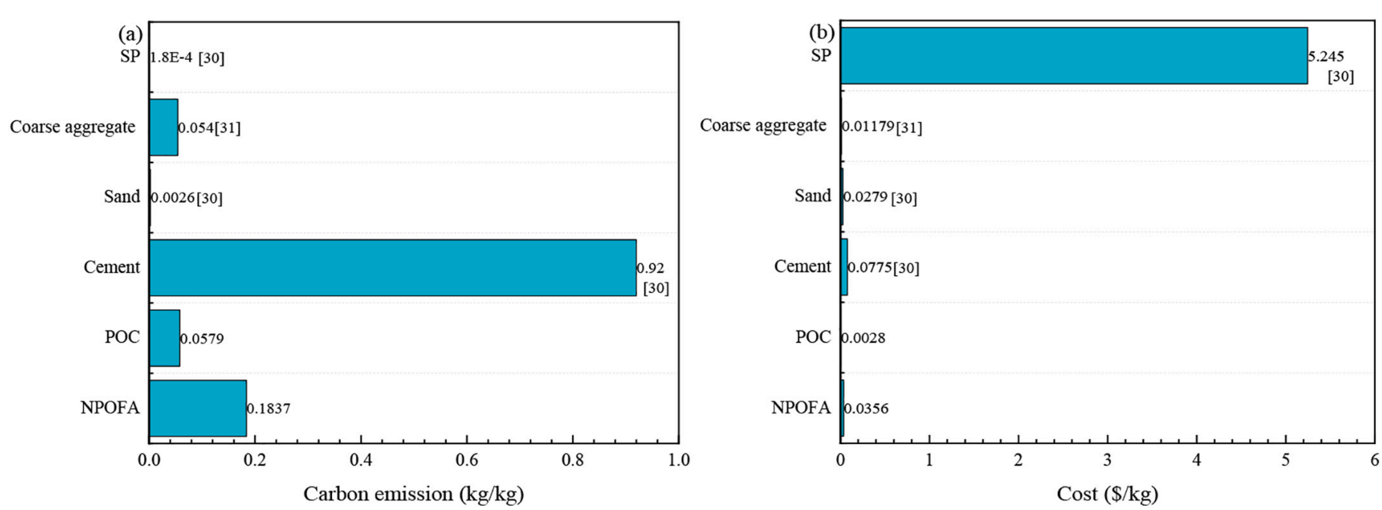


Fig. 11. The carbon emissions (a) and costs (b) of raw materials [30,31].

Table 10
The carbon emissions per MPa of concrete mixed with NPOFA and POC (kg/kg·MPa).

Mix No.	7 d	28 d	90 d	180 d	360 d
1	10.32046244	7.256575156	6.450289028	6.110800132	5.733590247
2	10.91092152	7.348171633	6.429650179	5.539390923	5.218266812
3	19.59967	14.54169065	10.01760911	8.50551717	7.640549322
4	15.74690955	12.37257179	9.363027297	8.44956122	7.217333542
5	16.94839296	11.73350282	9.533471042	8.171546607	7.501747705
6	14.71859208	10.38959441	8.410624048	7.359296042	6.66502283
7	10.05464902	6.246069848	5.647131644	5.21823557	4.849889529
8	17.33096565	12.45663156	8.665482826	7.381707593	6.756139153
9	14.47951464	10.66911605	8.62609383	7.371389273	6.237329385
10	14.47951464	10.66911605	8.62609383	7.371389273	6.237329385
11	14.47951464	10.66911605	8.62609383	7.371389273	6.237329385
12	14.47951464	10.66911605	8.62609383	7.371389273	6.237329385
13	14.47951464	10.66911605	8.62609383	7.371389273	6.237329385

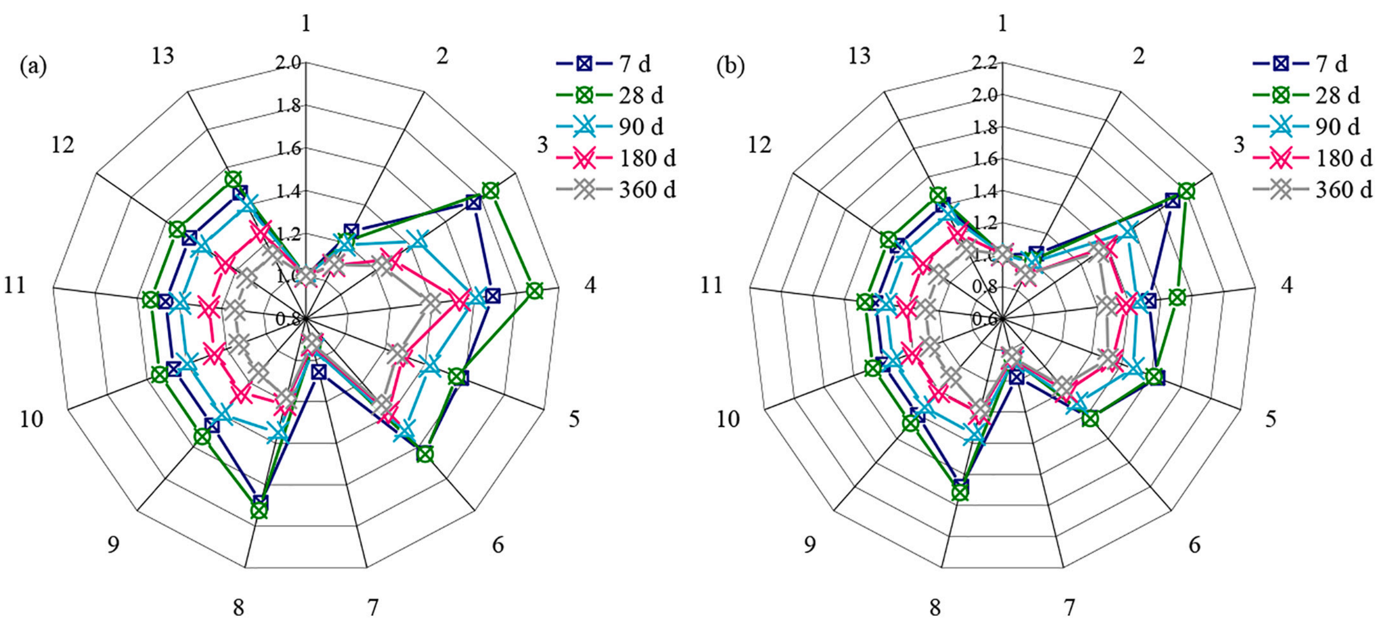


Fig. 12. Economic (a) and environmental (b) efficiency of concrete mixed with NPOFA and POC.

negative effect of adding a small amount of NPOFA on the strength of concrete. Meanwhile, this improvement effect is enhanced, with the increase of curing age.

5. Conclusion

To produce eco-friendly concrete materials, NPOFA and POC are used to replace part of the cement and aggregate, respectively, in this study. Meanwhile, the effect of substitution levels of NPOFA (0–30%) and POC (0–100%) on the workability and compressive strength of concrete is studied by RSM. In addition, the effects of NPOFA and POC on the economic and environmental benefits of concrete are also discussed in detail. The results obtained are listed below.

(1) The addition of NPOFA to the mixture makes its workability improved, however, the workability of concrete incorporating POC is significantly reduced due to the high water absorption and high porosity of the POC particles.
(2) Substituting cement with a small amount of NPOFA increases the compressive strength of the mixture due to its pozzolanic reactivity and filling effect. However, the high crush value of POC results in a significant reduction in the compressive strength of concrete.
(3) The highest compressive strength is achieved for the concrete containing 0% POC and 15% NPOFA, while the lowest compressive strength is achieved for the mixture containing 100% POC and 30% NPOFA.
(4) The effects of substitution levels of NPOFA and POC on the workability and compressive strength of concrete are analyzed by RSM. As a result of RSM analysis, R^2 values for workability and compressive strength are 0.9948 and 0.9909, respectively. The optimum condition is predicted by RSM for the mixture containing 15% NPOFA and the 0% POC.
(5) The results of economic and environmental assessments show that the use of NPOFA and POC to produce concrete significantly reduces the overall cost and carbon emissions of the mixture, and the gains from replacing cement with NPOFA are higher. For cost and carbon emissions per unit strength, mixtures with small amounts of NPOFA (M7) perform best due to their improved compressive strength.

CRediT authorship contribution statement

Hussein M. Hamada: Conceptualization, Writing – original draft. **Alyaa Al-Attar:** Formal analysis. **Jinyan Shi:** Writing – review & editing. **Fadzil Yahaya:** Methodology. **Mohammed S. Al Jawahery:** Writing – review & editing.

Declaration of Competing Interest

None.

Data availability

Data will be made available on request.

Acknowledgments

None.

References

[1] B. Liu, J. Qin, J. Shi, J. Jiang, X. Wu, Z. He, New perspectives on utilization of CO2 sequestration technologies in cement-based materials, Constr. Build. Mater. 272 (2021), 121660.
[2] Ç. Yalçınkaya, O. Çopuroğlu, Hydration heat, strength and microstructure characteristics of UHPC containing blast furnace slag, J. Build. Eng. 34 (2021), 101915.
[3] V. Revilla-Cuesta, M. Skaf, A.B. Espinosa, V. Ortega-López, Multi-criteria feasibility of real use of self-compacting concrete with sustainable aggregate, binder and powder, J. Clean. Prod. 325 (2021), 129327.
[4] Ç. Yalçınkaya, H. Yazıcı, Effects of ambient temperature and relative humidity on early-age shrinkage of UHPC with high-volume mineral admixtures, Constr. Build. Mater. 144 (2017) 252–259.
[5] J. Usman, A.M. Sam, Acid resistance of palm oil fuel ash and metakaolin ternary blend cement mortar, Sustain. Environ. Res. 27 (4) (2017) 181–187.
[6] Z.H. He, M.L. Shen, J.Y. Shi, Ç. Yalçınkaya, S.G. Du, Q. Yuan, Recycling coral waste into eco-friendly UHPC: mechanical strength, microstructure, and environmental benefits, Sci. Total Environ. 836 (2022), 155424.
[7] M.N.A.A. Aeshah, G. Kaplan, Mechanical durability and microstructural properties of sustainable high strength mortars ıncorporated basalt fiber and copper slag: Taguchi optimization, Constr. Build. Mater. 339 (2022), 127815.
[8] C. Ma, G. Chen, J. Shi, H. Zhou, W. Ren, Y. Du, Improvement mechanism of water resistance and volume stability of magnesium oxychloride cement: A comparison study on the influences of various gypsum, Sci. Total Environ. 829 (2022), 154546.
[9] H.M. Hamada, G.A. Jokhio, A.A. Al-Attar, F.M. Yahaya, K. Muthusamy, A. M. Humada, Y. Gul, The use of palm oil clinker as a sustainable construction material: A review, Cem. Concr. Compos. 106 (2020), 103447.
[10] H.M. Hamada, G.A. Jokhio, F.M. Yahaya, A.M. Humada, Y. Gul, The present state of the use of palm oil fuel ash (POFA) in concrete, Constr. Build. Mater. 175 (2018) 26–40.
[11] H. Hamada, B. Tayeh, F. Yahaya, K. Muthusamy, A. Al-Attar, Effects of nano-palm oil fuel ash and nano-eggshell powder on concrete, Constr. Build. Mater. 261 (2020), 119790.
[12] W. Tangchirapat, S. Khamklai, C. Jaturapitakkul, Use of ground palm oil fuel ash to improve strength, sulfate resistance, and water permeability of concrete containing high amount of recycled concrete aggregates, Mater. Design 41 (2012) 150–157.
[13] S. Zuo, Q. Yuan, T. Huang, M. Zhang, Q. Wu, Rheological behaviour of low-heat Portland cement paste with MgO-based expansive agent and shrinkage reducing admixture, Constr. Build. Mater. 304 (2021), 124583.
[14] B. Kursuncu, O. Gencel, O.Y. Bayraktar, J. Shi, M. Nematzadeh, G. Kaplan, Optimization of foam concrete characteristics using response surface methodology and artificial neural networks, Constr. Build. Mater. 337 (2022), 127575.
[15] Y. Sun, R. Yu, Z. Shui, X. Wang, D. Qian, B. Rao, Y. He, Understanding the porous aggregates carrier effect on reducing autogenous shrinkage of ultra-high performance concrete (UHPC) based on response surface method, Constr. Build. Mater. 222 (2019) 130–141.
[16] H.M. Hamada, A.A. Al-Attar, B. Tayeh, F.B.M. Yahaya, Optimizing the concrete strength of lightweight concrete containing nano palm oil fuel ash and palm oil clinker using response surface method, Case Stud. Constr. Mater. 16 (2022), e01061.
[17] F. De Larrard, T. Sedran, Optimization of ultra-high-performance concrete by the use of a packing model, Cem. Concr. Res. 24 (6) (1994) 997–1009.
[18] M.A.A. Aldahdooh, N.M. Bunnori, M.M. Johari, Evaluation of ultra-high-performance-fiber reinforced concrete binder content using the response surface method, Mater. Des. 1980-2015 (52) (2013) 957–965.
[19] M.A.A. Aldahdooh, N.M. Bunnori, M.M. Johari, A. Jamrah, A. Alnuaimi, Retrofitting of damaged reinforced concrete beams with a new green cementitious composites material, Compos. Struct. 142 (2016) 27–34.
[20] W.N.F.W. Hassan, M.A. Ismail, H.S. Lee, M.S. Meddah, J.K. Singh, M.W. Hussin, M. Ismail, Mixture optimization of high-strength blended concrete using central composite design, Constr. Build. Mater. 243 (2020), 118251.
[21] D.C. Montgomery, Design and Analysis of Experiments, John wiley & sons, 2017.
[22] H.M. Hamada, F.M. Yahaya, K. Muthusamy, G.A. Jokhio, A.M. Humada, Fresh and hardened properties of palm oil clinker lightweight aggregate concrete incorporating Nano-palm oil fuel ash, Constr. Build. Mater. 214 (2019) 344–354.
[23] H.M. Hamada, A. Alya'a, F.M. Yahaya, K. Muthusamy, B.A. Tayeh, A.M. Humada, Effect of high-volume ultrafine palm oil fuel ash on the engineering and transport properties of concrete, Case Stud. Constr. Mater. 12 (2020), e00318.
[24] B.S. Mohammed, O.C. Fang, K.M.A. Hossain, M. Lachemi, Mix proportioning of concrete containing paper mill residuals using response surface methodology, Constr. Build. Mater. 35 (2012) 63–68.
[25] K. Obla, H. Kim, C. Lobo, Effect of continuous (well-graded) combined aggregate grading on concrete performance, phase A: aggregate voids content (packing density) (no. project D340), 2007.
[26] F. Abutaha, H.A. Razak, J. Kanadasan, Effect of palm oil clinker (POC) aggregates on fresh and hardened properties of concrete, Constr. Build. Mater. 112 (2016) 416–423.
[27] J. Kanadasan, H.A. Razak, Mix design for self-compacting palm oil clinker concrete based on particle packing, Mater. Design 1980-2015 (56) (2014) 9–19.
[28] S. Ghafari, H.A. Aziz, M.H. Isa, A.A. Zinatizadeh, Application of response surface methodology (RSM) to optimize coagulation–flocculation treatment of leachate using poly-aluminum chloride (PAC) and alum, J. Hazard. Mater. 163 (2–3) (2009) 650–656.
[29] H. Wu, J. Xu, D. Yang, Z. Ma, Utilizing thermal activation treatment to improve the properties of waste cementitious powder and its newmade cementitious materials, J. Clean. Prod. 322 (2021), 129074.
[30] H.B. Hu, Z.H. He, J.Y. Shi, C.F. Liang, T.G. Shibro, B.J. Liu, S.Y. Yang, Mechanical properties, drying shrinkage, and nano-scale characteristics of concrete prepared with zeolite powder pre-coated recycled aggregate, J. Clean. Prod. 319 (2021), 128710.
[31] S. Ni, H. Liu, Q. Li, H. Quan, M. Gheibi, A.M. Fathollahi-Fard, G. Tian, Assessment of the engineering properties, carbon dioxide emission and economic of biomass recycled aggregate concrete: A novel approach for building green concretes, J. Clean. Prod. 365 (2022), 132780.