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Assessing the optimal compressive strength of eco-friendly bricks using full factorial design

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Abstract

Eco-friendly brick is one of the innovations that can be developed to reduce plastic waste. Plastic waste is mixed using clay and epoxy resin to be united into Eco-friendly brick. This research was conducted to understand the interactions between the parameters of the eco-friendly brick mixing process through the Full Factorial Design (FFD) approach. Two variables were observed: epoxy resin-clay ratio (30-50%) and PET particle (1-5mm). FFD with 22 replications resulted in a total of 8 experimental sets. Design Expert was used to optimize the compressive strength response produced as a variable of the prepared eco-friendly brick. From the results of Design Expert, it is found that the optimum processing parameters are in the condition of 37.78% ratio, and 3.58 mm for PET particle size which will produce the maximum compressive strength of 78.65 MPa with a coefficient of determination R2 of 0.9720. Overall, this study has significance in facilitating processing in the manufacture of eco-friendly bricks. Research and implementations involving mixes of PET particles and epoxy resin in producing environmentally friendly bricks have demonstrated the significant potential for these materials to enhance the compressive strength of sustainable brick.

Keywords: FFD, Brick, Epoxy, PET

1. Introduction

Environmental issues, particularly waste, have become pressing global concerns [1]–[3]. The rise in population and economic development directly correlates with increased waste generation, posing significant environmental challenges [4]. This surge in waste affects both developed and developing nations, emphasizing the critical need for effective waste management strategies. Efficient waste utilization can significantly reduce environmental waste [5].

The use of PET (Polyethylene Terephthalate) has escalated dramatically due to its application in manufacturing beverage bottles, cosmetics, food containers, and other products [6], [7]. PET is favored for its lightweight, strength, and recyclability [8]. Proper handling of PET waste is crucial to preventing environmental pollution, and recycling is an effective method to mitigate the negative impacts of increasing PET waste and reducing landfill accumulation.

PET plastic waste is being innovatively used to create brick composites or permeable bricks, presenting a sustainable waste management solution [9]. The construction industry predominantly uses clay bricks, leading to land degradation due to extensive clay extraction. Substituting traditional bricks with those made from PET plastic can conserve natural resources and provide additional benefits such as heat reduction, noise absorption, and improved anti-skid performance. Various types of plastics, including PET, LDPE, and HDPE, are commonly used in producing plastic bricks [10], [11].

Many regions in Indonesia produce red bricks, one of which is the Bojonegoro area. Based on data from the Department of Industry and Trade (Disperindag), there are 207 red brick craftsmen [12]. The red brick craftsmen are spread across the banks of the Bengawan Solo River, from Padangan District to Bureno District. One of the Bojonegoro areas famous for producing red bricks is located in Ledok Kulon Village. In this village, hundreds of residents from outlying villages make their living by working as red brick craftsmen. Every day, there are around 5 to 10 people who work in each of the red brick industries. Every month, craftsmen can produce 15,000 ready-to-sell red bricks for 500 rupiah per seed during the dry season and 600 rupiah per seed in the rainy season because production is difficult. Additionally, water is typically used as a binding agent in brickmaking, but epoxy resin offers an alternative due to its excellent tensile strength and versatility in construction applications. Epoxy resin is known for its durability, weather resistance, and flexibility [13].

The full two-level factorial design with kk factors (FD,2) is an experimental approach that decreases the number of experiments needed without sacrificing result quality, aiming for optimal process optimization [14]–[16]. This technique simultaneously utilizes all data to determine the impact of each factor and their interactions. The full factorial design requires observing every possible combination of factor levels, with each combination known as a treatment combination [17]. This design ensures greater accuracy in estimating the main effects and interactions of various factors. In a full factorial design, each factor level is paired with every level of all other factors [18]. It identifies the effect of each factor on the response and how these effects vary with changes in the levels of other factors.

Post-use polymer waste, particularly PET, HDPE, and LDPE, forms a significant part of solid waste due to its resistance to degradation. Recycling these plastics into new products, such as eco-bricks, can alleviate environmental burdens. For instance, in China, most PET bottle waste is recycled into fiber through a deposit refund system (DRS), significantly reducing greenhouse gas emissions and pollutants [19]. The global demand for construction materials, including bricks, is rising with population growth. Regions like China, India, Canada, and Indonesia have seen increased brick production, leading to the rapid depletion of natural clay resources. Therefore, using waste materials for brick production is essential for sustainability [20], [21].

Incorporating plastic waste into construction, particularly in making eco-bricks, has become a contemporary trend toward sustainability. Adding plastic to concrete mixtures enhances product characteristics. Epoxy resin, derived from PET waste, can be used as an adhesive and binder in brickmaking, improving compressive strength and durability. Studies indicate that adding PET increases porosity, resulting in a more porous surface compared to HDPE and LDPE.

2. Research method

2.1. Materials

In this research, the material used is PET bottle waste. The PET bottle waste is then washed and dried then cut into small pieces. The clay used for brickmaking comes from local brick craftsmen [22]. This research also uses epoxy resin as a curing agent. Epoxy resin is obtained from chemical companies that have a composition of more than 85% epoxy resin, bisphenol diglyceryl ether (E-44 and E-51), produced using bisphenol A (BPA) and epichlorohydrin (ECH). Hardener is also used in this study in accordance with the instructions for the use of epoxy resin, namely 1:1 ratio between epoxy resin and hardener. The characteristics of epoxy resin can be seen in Table 1.

Table 1. Physico-chemical characteristics of epoxy resin

Type	Viscosity (Mpas)	Density (g/cm3)	Epoxy number (mol/100g)	Molecular weight (g/mol)
Bisphenol A epoxy resin	30.000	1.17	0.49	450

2.2. Experimental setup

For the preparation of eco-friendly brick samples, a pre-experiment plan was designed using Design Expert software. A full factorial design was used in this experiment. A 22 full factorial design for 2 independent variables with two replications was applied in this study resulting in a total of 8 experimental sets. The independent variables of eco-friendly brick-making are ratio (A) and particle size (B). The factor levels in this study can be seen in Table 2. For the manufacture of eco-friendly brick samples, a pre-experiment experimental design was designed using Design Expert software. A full factorial design was used in this experiment. A full factorial design for 2 independent variables with two replications was applied in this study resulting in a total of 8 experimental sets. The independent variables of eco-friendly brick-making are ratio (A) and particle size (B).

Table 2. The factor levels

Ratio (X1; Epoxy resin)	Size particles (X2, mm)
30 (minimal)	1 (minimal)
50 (maximal)	5 (maximal)

The factorial design of the experiment for all parametric combinations can be seen in Table 3. The dependent variable tested in this study focused on compressive properties. The compressive strength measurement was carried out with ASTM C109-11 standard with a sample cube size of 100x100x100 mm. The test was conducted after the drying process for 7 days and continued the combustion process. The compressive test was conducted using a universal testing machine. Sample eco-friendly bricks were obtained by mixing clay, PET, and epoxy resin. Epoxy resin was mixed with hardener in a ratio of 50:50 (epoxy: hardener). The resin mixture was then mixed with PET and clay molded on brick molds and allowed to stand at ambient temperature for 7 days.

Table 3. The number of runs in the FFD experiment

Run	Coded value	
	A	B
1	50	5
2	50	1
3	10	1
4	10	5
5	10	1
6	50	5
7	50	1
8	10	5

2.3. Full factorial design (FFD)

The full factorial design is extensively used in experiments due to its advantages [23]. It is important to note that only factors impacting the response should be selected [24]. Design Expert was used to run FFD based on the set of ranges in Table 1. FFD analyzes the data from the experiments to fit the first-order polynomial shown in Equation (1).

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i X_i \quad (1)$$

Where Y is the response value, β0 is the constant coefficient, k is the number of variables, βi is the linear parameter coefficient, and Xi is the interaction parameter coefficient. Based on FFD, 8 experiments were obtained with each experiment repeated twice to reduce errors. Full factorial design with k factors (2k) is a design experiment method that can reduce the number of experiments without having to reduce the quality of experimental results that can be used to achieve an optimal process. The full factorial design assumes that the response (in this case, compressive strength) is a linear function of all factors. Factors and coded levels can be seen in Table 4.

Table 4. Factors and coded levels used in the FFD experiment

No	Factors	Coded	Types of factors	Actual value of coded levels	
				-1	+1
1	Ratio	A	Numerical	10	50
2	Size particles	B	Numerical	1	5

3. Results and discussion

This research has been made with 8 set point data with FFD. The set point design in this study includes 2 variables and 1 response. In planning the experiment using Design Expert, the entire experimental data set and the predicted experiment after the compression test can be seen in Table 5.

Table 5. Experimental results

Run Order	Factors		Response Compression Test (MPa)		Residual
	1 (ratio)	2 (size)	Experiment	Predicted	
1	50	5	74.50	74.12	0.38
2	50	1	89.20	88.33	0.87
3	10	1	77.07	76.53	0.54
4	10	5	79.55	78.07	1.48
5	10	1	75.99	76.53	-0.54
6	50	5	73.74	74.12	-0.38
7	50	1	87.46	88.33	-0.87
8	10	5	76.59	78.07	-1.48

Analysis of variance (ANOVA) was used to interpret the correlations between factors and responses and to estimate statistical parameters [25]. The ANOVA result of this research is shown in Table 6. F-values were used to assess the statistical significance of the regression equation, while p-values were used to determine the significance of individual coefficients. The model yielded an F-value of 46.63, accompanied by a p-value of 0.0015. This indicates that the majority of the variation in the response can be explained by the regression equation, making the model significant. In addition, the probability value ($p < 0.0015$) further indicates that the model is significant. Based on Table 6, A, B, and AB are considered significant and have a substantial impact on the manufacture of eco-friendly bricks.

Table 6. ANOVA Analysis results

Source	Sum of Squares	df	Mean Square	F-value	p-value
Model	235.11	3	78.73	46.63	0.0015
A-Epoxy resin	30.81	1	30.81	18.21	0.0130
B-PET	80.26	1	80.26	47.45	0.0023
AB	124.03	1	124.03	73.32	0.0010
Pure Error	6.77	4	1.69		
Cor Total	241.87	7			

Based on Analysis of Variance (ANOVA), it is described as a linear model. The resulting regression equation can be illustrated in Equation 2.

$$\text{y (compression)} = 235.11 + 30.81X_1 - 80.26X_2 - 124.03X_1X_2 \quad (2)$$

Table 7 presents the summary statistics obtained from the data acquired during the experiment. The R2 value, as determined through ANOVA, serves as an indicator of how closely the data aligns with the regression line. An R^2 value that exceeds 90% signifies a good model fit. In this study, the R^2 value was 0.9720 indicating that the model's ability to accurately predict the values closely matched the experimental data. Figure 1 further illustrates this excellent correspondence by displaying the linear correlation between the predicted and actual compressive strength data.

Table 7. Statistic summary of the experiment

Property	Value
Std.Dev	1.30
Mean	79.26
C.V.%	1.64
R2	0.9720
Adjusted R2	0.9510
Predicted R2	0.8881
Adeq Precision	15.4509

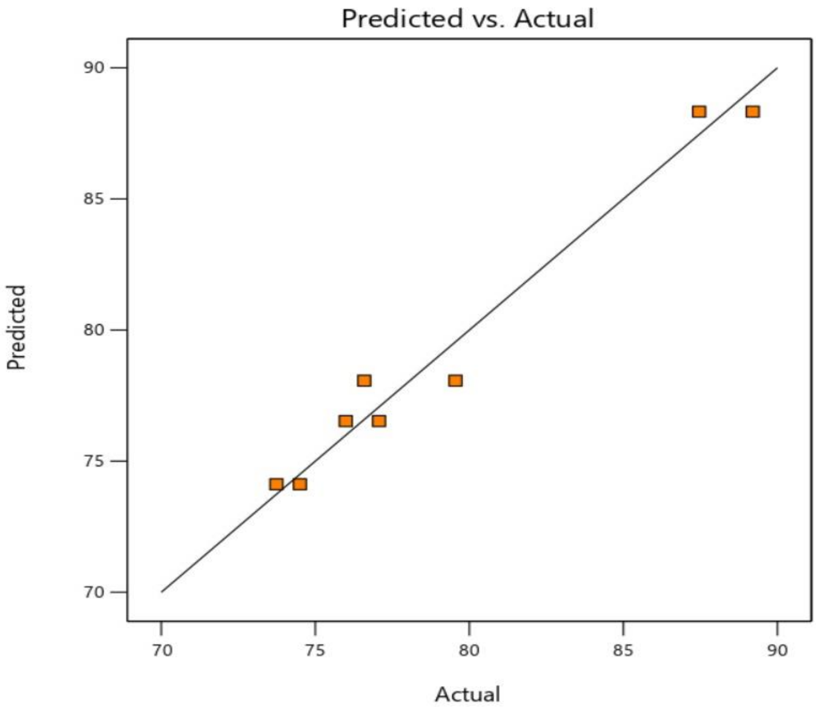

Figure 1. Comparison of predicted and actual

Figure 2 shows a comparison of the actual value and predicted value of the compression test results at 7 days of hardening; the actual value and predicted value have similar values. The statistical model results show that the actual value and predicted value data have a high coefficient of correlation.

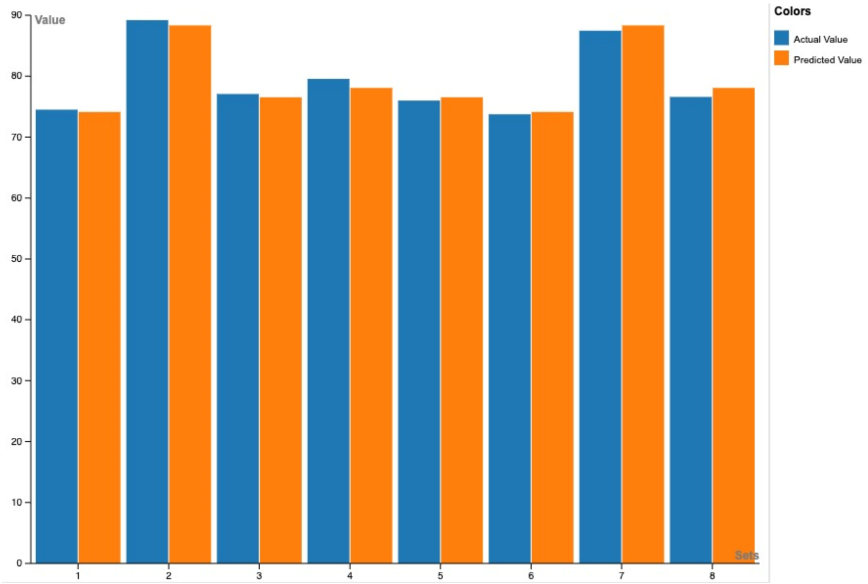

Figure 2. Comparison of actual value and predicted value for compressive strength

Referring to the data presented in Table 7, the adequacy precision ratio stood at 15.4509, exceeding the threshold of 4, thus indicating satisfactory signal quality. In addition, the R^2 predicted 0.8881, indicating that the experimental data for the compression test matched the values in the model. The standard deviation shows 1.30 which indicates that the model can match the expected response value.

One of the main objectives of the screening process is to identify the key factors that have the most influence on the manufacture of eco-friendly bricks. In Figure 3 different colors are given. Factors producing positive effects are represented by orange color while factors having negative effects have blue color. In the Pareto diagram, the arrangement and height of the bars provide information about the order of effect and the magnitude of influence on compression strength. The length of each bar corresponds to the t-value associated with the relevant estimated effect. These t-values are derived from the square root of the F-values obtained from the ANOVA.

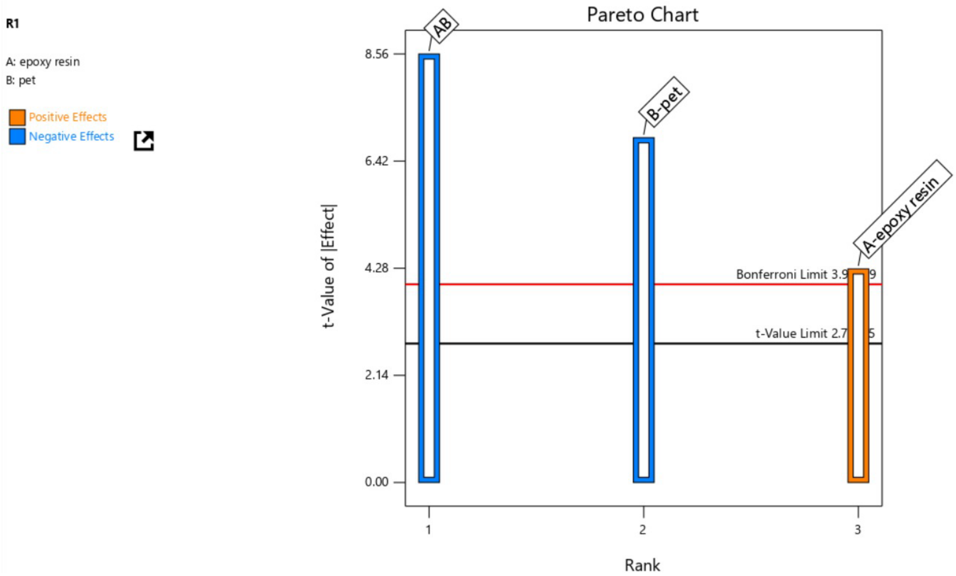

Figure 3. Pareto chart effect of various factors during FFD screening

The half-normal plot with the compressive strength response resulting from the factorial design is depicted in Figure 3 below. From the results of the (factorial) effect, it can be seen that factors A (epoxy resin), B (PET size), and the interaction between AB are outside the straight line, which indicates the significant factors of this experiment.

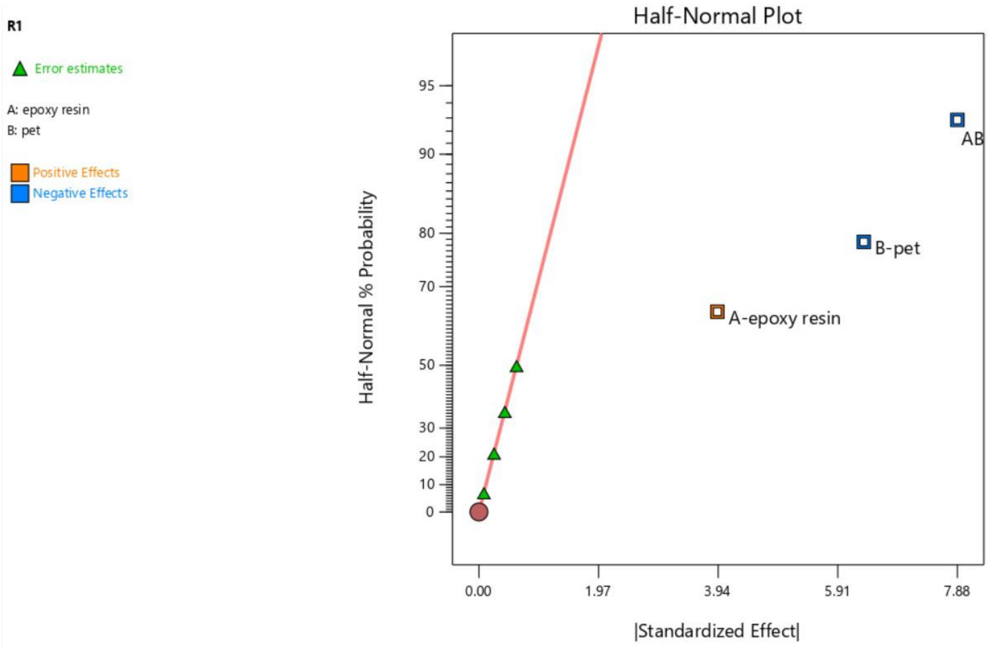

Figure 4. The half-normal plot of eco-friendly bricks compression strength response

Three-dimensional response surface contour plots were used to interpret and evaluate the resulting statistical model as depicted in Figure 5. The graph shows that the larger the compressive strength response value, the smaller the value of the size variable and the larger the value of the ratio variable. Figure 5 shows that larger PET particles have lower compressive properties. Therefore, eco-friendly bricks should be made with very small particles to provide greater compressive strength.

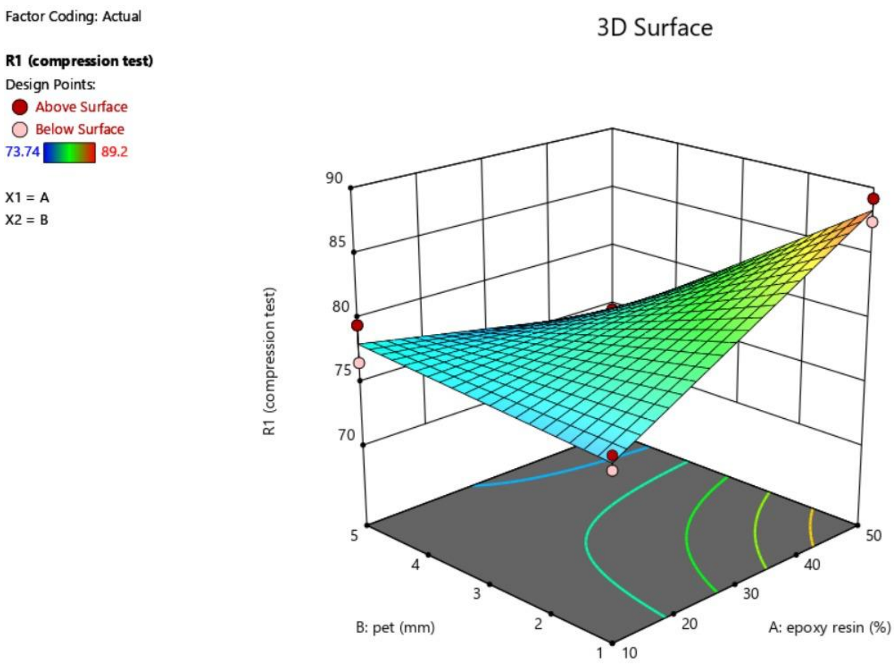

Figure 5. 3D response surface for compressive strength response

The optimization recommended by the DOE software is formulated in Table 8. Based on Table 8, these factors were optimized to obtain maximum compressive strength. The optimization target was set to the parameters Ratio and Size of PET particles. Meanwhile, the response parameter in the form of compressive strength is set to maximum. Based on the optimization results in Figure 6, the selected solution is 37.78% ratio and 3.58 mm for PET particle size. The desirability results are also close to the unity value of one, which means that all factors analyzed are fully significant. Several studies have also discussed the use of PET in the manufacture of sustainable brick [26]-[30]. This shows that the addition of PET can increase the compressive strength in the manufacture of sustainable brick.

Table 8. Optimization results of RSM on sustainable brick

Parameters	Goals	Level		Optimization Result
		Lower	Upper	
Ratio (%)	In range	30	50	37.78
Size (mm)	In range	1	5	3.58
Compressive strength (MPa)	Maximize	73.74	89.2	78.65

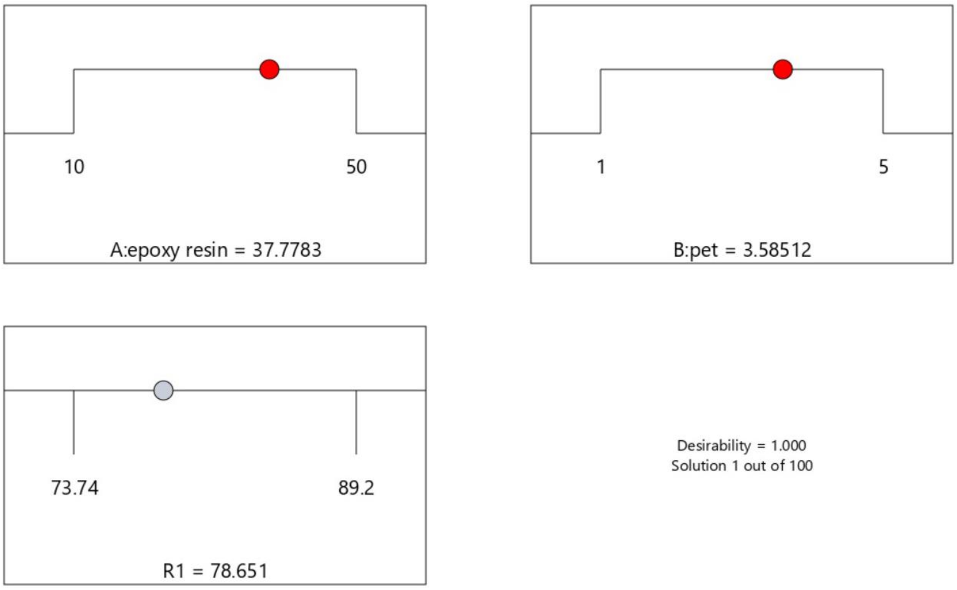

Figure 6. Optimization results in ramps graphical view

Figure 7 shows the desirability results, the histogram shows that each factor and response individually. Combining all factors can produce the maximum value, thus showing the interaction between factors.

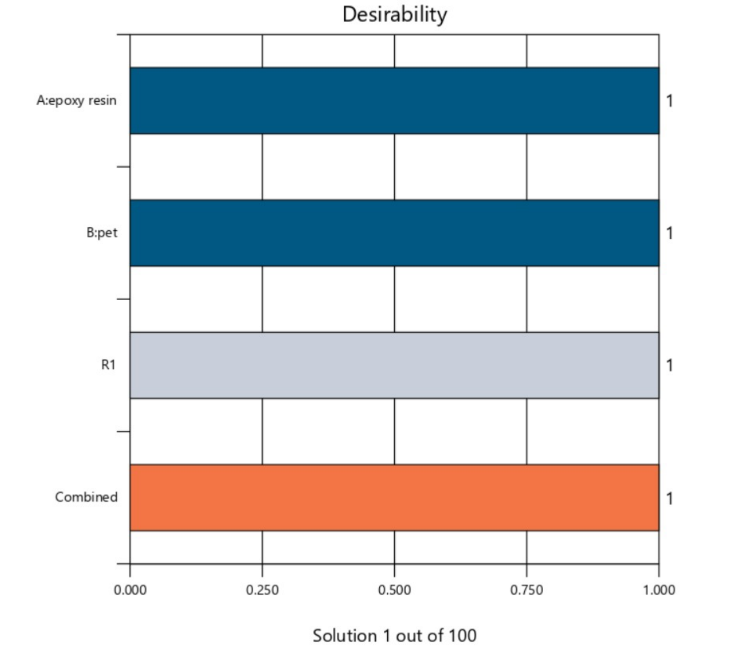

Figure 7. Graphical view of desirability

4. Conclusions

The manufacture of eco-friendly Bricks using a mixture of clay, epoxy resin, and PET has been investigated with FFD. Based on the analysis, the factor ratio between epoxy resin-clay and PET particle size has a significant influence on compressive strength. The designed experiment identified the optimum condition of 37.78% ratio and 3.58 mm for PET particle size that will produce maximum compressive strength of 78.65 MPa. The R2 value is close to one (1.00) which means the results are very adequate to represent the proposed linear regression model in predicting the optimum interaction parameters for compressive strength response. In addition, this study also showed the effectiveness of FFD in assessing the impact of various factors on the process efficiently with minimal experimentation.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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Author contribution

The contribution to the paper is as follows: Okka Adiyanto, Farid Ma’ruf, Abdul Hopid: study conception and design; Okka Adiyanto, Farid Ma’ruf: data collection; Okka Adiyanto, Farid Ma’ruf: analysis and interpretation of results; Okka Adiyanto, Farid Ma’ruf, Abdul Hopid: draft preparation. All authors approved the final version of the manuscript.

Ethical approval statement

Ethical approval is not applicable to this research.

Informed consent

Informed consent for the publication of personal data in this article was obtained from the participant(s).

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