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Optimization of Sugarcane Bagasse Ash Utilization for Concrete Bricks Production Using Plackett-Burman and Central Composite Design

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ABSTRAK

PT. Industri Gula Glenmore (PT. IGG) setiap tahunnya memproduksi 14.300 ton abu ampas tebu (AAT) sebagai hasil samping pembakaran *boiler* yang belum dimanfaatkan secara maksimal. Menariknya, AAT memiliki kandungan silika tinggi yaitu 68,5% yang dapat ditingkatkan nilainya sebagai substitusi parsial semen dalam pembuatan bata beton. Oleh karena itu, pada penelitian ini komposisi dan ukuran partikel AAT dioptimalkan dalam pembuatan bata beton. Optimasi dilakukan dengan menggunakan *Response Surface Methodology* (RSM) untuk memahami perilaku faktor-faktor signifikan yang mempengaruhi kuat tekan bata beton. RSM ditentukan dengan menggunakan *software* Design-Expert V11. Bata beton dibuat dengan perbandingan semen dan pasir menggunakan perbandingan 1:6 dengan variasi AAT 5% sampai 25% dari berat normal semen. Hasil pengujian di *Workshop* menunjukkan bahwa penggunaan *Fly Ash* dan kapur sebagai bahan pengikat untuk menggantikan sebagian semen dengan variasi 23, 26, 28, 30, dan 33% menghasilkan kuat tekan berturut-turut sebesar 56, 52, 49, 40, dan 34 kg/cm^2. Dengan demikian, bata beton pada penelitian ini termasuk dalam mutu tingkat 3 berdasarkan SNI 03-0349-1989. Inovasi ini merupakan solusi untuk meningkatkan nilai tambah AAT dan menjadi peluang bisnis baru bagi PT. IGG di masa depan.

***Kata kunci*:** Abu Ampas tebu, Bata Beton, Kuat Tekan, Response Surface Methodology

ABSTRACT

PT. The Glenmore Sugar Industry (PT. IGG) annually produces 14,300 tons of Sugarcane Bagasse Ash (SCBA) as a by-product of boiler combustion that has not been fully utilized. Interestingly, SCBA has a high silica content of 68.5%, which can be valorized as a partial substitution of cement in the manufacture of concrete bricks. Therefore, in this study the composition and particle size of SCBA were optimized in the manufacture of concrete bricks. Optimization was carried out by using Response Surface Methodology (RSM) to understand the behavior of significant factors affecting the compressive strength of concrete bricks. RSM was determined using the Design-Expert V11 software. Concrete bricks were made with a ratio of cement and sand using a ratio of 1:6 with a variation of bagasse ash 5% to 25% of the normal weight of the cement. The test results showed that the use of fly ash and lime as a binder to replace some cement with variations of 23%, 26%, 28%, 30%, and 33% resulted in a compressive strength of 56 kg/cm^2, 52 kg/cm^2, 49 kg/cm^2, 40 kg/cm^2, and 34 kg/cm^2, respectively. Thus the concrete brick in this study was included in the quality level 3 based on SNI 03-0349-1989. This innovation is a solution to increase SCBA's added value and a new business opportunity for PT. IGG in the future.

***Keywords*:** Bagasse Ash, Compressive Strength, Concrete Brick, Response Surface Methodology

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1. INTRODUCTION

Glenmore Sugar Industry Ltd. produces sugarcane bagasse ash (SCBA) of 2% of the total raw material of 14,300 tons per year [1]. Unfortunately, SCBA accumulated around the factory area pollutes the environment. In fact, this SCBA contains inorganic minerals and metal elements which is potential as concrete bricks material [2]. It is well known that SCBA contains minerals in the form of SiO_2, K, Ca, Ti, V, Mn, Fe, Cu, Zn and P. The largest content of these minerals is silica (SiO_2) [3]. SCBA obtained from the combustion residue of a sugar factory also contains silicate (SiO_2), aluminate (Al_2O_3), Ferrite (Fe_2O_3) which are the main ingredients for the formation of Portland cement and are included as pozzolans. These silica compounds can react with $Ca(OH)_2$ when cement is mixed with water producing adhesive substances such as cement [4], [5]. Therefore, the use of SCBA as an additional material for concrete bricks makes it possible to produce high-quality concrete bricks in terms of compressive strength without compromising the economic aspect [6].

Concrete brick is an alternative material for making building walls that are cheap and relatively strong [7]. The physical properties of hard, strong, and stable concrete bricks at high temperatures are influenced by their additive composition. The composition of concrete bricks is generally composed of sand, cement, and water in a ratio of 75:20:5 [8]. Utilization of SCBA as an additional material for concrete bricks will result a high-quality compressive strength of concrete bricks. This will be achieved, if the use of SCBA is carried out with an optimum composition [9].

The problem in using SCBA as an additional material for concrete brick is its significant effect on compressive strength. This is because there is a maximum limit on the addition of SCBA composition [10]. The more SCBA added to the concrete brick mixture, the lower the compressive strength of the concrete brick [11]. For this reason, it is necessary to find the best SCBA composition for the utilization of cheap and abundant waste basic materials which has not been used optimally [12]. Beside the addition of SCBA, the addition of lime is also very influential for supporting the compressive strength of concrete bricks because the constituents of Portland cement are 60-65% consisting of lime or CaO [13]. Lime has adhesive properties, so the addition of lime in the manufacture of concrete bricks can increase the compressive strength [14].

Response surface methodology (RSM) is the most used statistical tools for optimizing, analyzing, and developing models between the observed factors (independent variables) and the responses (dependent variables). RSM is used in almost all fields including in concrete bricks production [15]. In this area, RSM has been employed to determine the optimum proportion of the mixture and evaluate the mechanical and durability properties of concrete [16], [17]. RSM consists of two steps, namely factor screening and optimizing. During the screening step, the most considerable variables affecting responses are identified. This step can reduce the number of factors that will facilitate further investigation for optimization [18], [19]. Then, the optimization step is carried-out to provide the important independent factors, interactions among factors, and optimal conditions for maximizing the responses of concrete bricks production from SCBA [20]. Although there is an opportunity for SCBA to be one of the concrete brick's materials, from the literature study, there has never been a study reported on the optimization of the addition of SCBA and lime for the production of concrete bricks.

From this background, this study aims to optimize the use of SCBA as a substitute for cement in the manufacture of concrete bricks. In this present work, Plackett-Burman design using Design Expert software is applied for screening step. Optimization was carried out using the Face Centered Central Composite Design (FC-CCD) model towards the compressive strength of concrete bricks. In the literature, FC-CCD has been commonly used due to its rotatability and high robustness features.

2. RESEARCH METHODS

In this study, the Plackett-Burman design (PBD) was used to identify the significant factors affecting the compressive strength by using Design-Expert® V-11 (Demo version, Stat-Ease Inc., Minneapolis, MN, USA). Five independent variables, namely sand, cement, ash, lime-stone and ash size were determined in 12 trials. Each variable was assessed at 2 different concentrations (i.e., high (level + 1) and low (level -1)) to determine the significant change in compressive strength, as shown in Table 1. The experiment was conducted in duplicate and the average value was taken as the response. Variables with a significant effect on response were selected using regression analysis, as described in previous work [21]. According to the PBD these five factors, at two levels, can be efficiently combined in eight runs, as reported in Table 2.

Table 1. Concentration ranges of the variables used in the Plackett–Burman design.

Factors	Actual levels of coded factors	
	-1	+1
Sand (kg)	10	12
Cement (kg)	1	1,5
Ash (kg)	0	0,5
Limestone (kg)	0,4	0,6
Ash Size (Mesh)	100	200

The research was conducted at the Waste Water Treatment unit of Glenmore Sugar Industry Ltd., Banyuwangi, Indonesia. The raw material used was bagasse ash from the combustion residue of the boiler with particle sizes passing between 100 and 200 mesh sieves. Screening of 100 and 200 mesh was carried out to reduce the SCBA particle size and produce a uniform particle size.

The composition of lightweight concrete bricks is an aggregate material based on sludge, sand, and cement as an adhesive matrix. This study used fine aggregate (sand), coarse aggregate (gravel), Portland cement (Semen Gresik Ltd., Indonesia), clean water, and building lime 50 Kg.

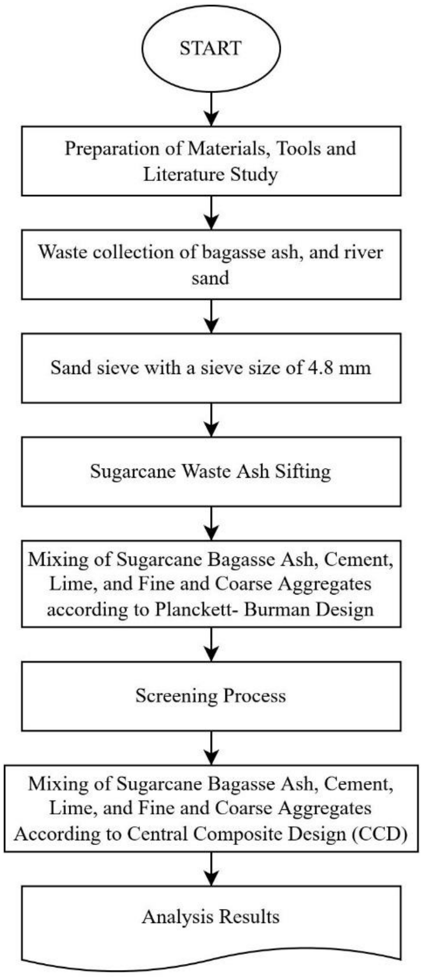

Figure 1. Research procedure for making concrete bricks from sugarcane bagasse

The tools were concrete brick molds in the form of blocks, a sand sieve with a sieve size of 4.8 mm, and a 50 ton hydraulic press compressive strength test machine. Concrete bricks were dried under the sun for 5-7 days. Concrete bricks were made with a ratio of cement and sand of 1:6. The research procedure started from the preparation of raw materials and tools, making concrete bricks, and testing. The printing process was carried out for 1 day, and dried with the help of the sun for 7 days. The sand used in each experiment was 11 Kg. The stages of this research are shown in Figure 1.

The research design using a combination of Plackett-Burman and CCD has shown excellent results in previous studies [22]–[26]. In this study, the research design using Plackett-Burman Design was applied by varying the variables of cement, sand, ash, lime and SCBA size, as shown in Table 2. Variable screening was used to find the three most significant variables. The research design with CCD was applied by varying the variables of cement, ash, and lime according to Table 3.

The compressive strength of concrete brick was the compressive strength value obtained from the application of an external force in the form of a compressive force to the cross-sectional area [27]. The compressive strength of concrete brick was the magnitude of the load per unit area, which caused the concrete brick test object to crumble when it was loaded with a certain compressive force, which is produced by the press machine. To determine the strength of the concrete brick made from a mixture of SCBA which was dried for 5-7 days, the next step was to test the compressive strength using a 50 ton hydraulic press. The compressive strength test of the concrete brick was carried out by loading the test object until it was broken and the value of the collapse load was obtained. Calculation of the compressive strength of concrete bricks wasdone by Equation 1.

$$P = \frac{F}{A} \tag{1}$$

Where the compressive strength (P) with units (Kg/cm^2) was calculatedby the quotient between the maximum compressive load (F) with units (Kg) and the surface area of the test object (A) with units (cm^2). The results of the compressive strength test can be used as a reference to determine the quality level of concrete bricks. Concrete bricks must meet the physical requirements according to SNI 03-0349-1989.

Table 2. Plackett-burman design for variable screening

Run	Sand	Cement	Ash	Lime-stone	Ash Size
1	12	1	0,5	0,4	200
2	12	1,5	0	0,4	0
3	10	1	0,5	0,4	200
4	10	1,5	0	0,6	0
5	12	1	0,5	0,6	100
6	12	1	0,5	0,6	200
7	10	1	0,5	0,4	100
8	10	1	0,5	0,4	100
9	10	1	0,5	0,4	200
10	10	1	0,5	0,6	200
11	12	1	0,5	0,6	100
12	12	1	0,5	0,4	100

Table 3. Central composite design for optimization

Run	Ash	Limestone	Cement
1	0,65	0,85	0,8
2	0,8	0,7	1
3	0,8	1	0,6
4	0,65	0,85	0,8
5	0,8	0,7	0,6
6	0,4	0,85	0,8
7	0,5	1	1
8	0,8	1	1
9	0,5	0,7	0,6
10	0,65	0,85	0,8
11	0,65	0,85	0,8
12	0,65	0,85	0,8
13	0,65	0,85	0,6
14	0,65	0,6	0,8
15	0,65	0,85	0,8
16	0,9	0,85	0,8
17	0,5	1	0,6
18	0,65	0,85	1
19	0,65	1	0,8
20	0,5	0,7	1

Table 4. Test results of variable screening with the Plackett-Burman for concrete bricks production

Run Order	Sand (Kg)	Cement (Kg)	Ash (Kg)	Lime (Kg)	Ash Size (*Mesh*)	Cement (%)	Lime (%)	Ash (%)	Compressive Strength (kg/cm^2)
1	12	1	0,5	0,4	200	53	21	26	36,51
2	12	1,5	0	0,4	0	79	21	0	72,72
3	10	1	0,5	0,4	200	53	21	26	36,39
4	10	1,5	0	0,6	0	71	29	0	83,63
5	12	1	0,5	0,6	100	48	29	24	56,37
6	12	1	0,5	0,6	200	48	29	24	58,18
7	10	1	0,5	0,4	100	53	21	26	35,62
8	10	1	0,5	0,4	100	53	21	26	35,57
9	10	1	0,5	0,4	200	53	21	26	36,51
10	10	1	0,5	0,6	200	48	29	24	58,09
11	12	1	0,5	0,6	100	48	29	24	56,11
12	12	1	0,5	0,4	100	53	21	26	35,29

3. RESULTS AND DISCUSSION

The selection of the factors demonstrating significant effects on compressive strength was carried out using Plackett-Burman with 12 trials. The results of the screening with Plackett-Burman are shown in Table 4. Based on the results in Table 4, it is known that the greatest compressive strength was found in the composition of the material without the addition of SCBA (compressive strength 83.63 and 72.72 kg/cm2 in Experiments 4 and 2). The addition of ash has a negative effect on the compressive strength. The addition of SCBA as cement filler had a significant effect on the compressive strength characteristics of concrete bricks ($P < 0.05$). The addition of SCBA with a smaller content became a filler between the particles that form the concrete brick. So, with the SCBA, the porosity of the concrete brick would be smaller [28], [29]. Meanwhile, the decrease in compressive strength was due to SCBA, which was physically black and resembled charcoal, had a high water absorption capacity (hydrophilic). The hydrophilic nature contained in the SCBA was possible to interfere with the aggregate binding reaction by cement [30], [31]. SCBA is classified as an active pozzolan, so if portland cement, water, pozzolan and aggregate are mixed in the concrete brick, a hydration reaction occurs from the cement compounds and hydration of the mineral component of pozzolan with calcium hydroxide produced by the hydration of Portland cement. [32], [33]. The addition of filler in the cement content reduced the compressive strength of the concrete brick.

The addition of ash above the optimum limit caused the compressive strength to decrease. The value of compressive strength with the addition of relatively high ash (about 58 kg/cm2, quality level III according to SNI 03-0349-1989) was obtained at a percentage of 24% (see Tables 3 experiments 6 and 10). This relatively large compressive strength was possible due to the addition of lime. This could happen because the addition of lime indirectly helped to glue fine and coarse aggregates [34]. When compared with previous studies, mixing 10% SCBA can only produce a compressive strength of 29.12 MPa. Without the addition of lime, a decrease in compressive strength occurs [11].

It is known that the addition of lime and cement variables significantly affected the compressive strength of concrete bricks ($P<0.05$) while the ash particle size was not significant ($P>0.05$). The results of the Plackett - Burman method also provide a prediction that with the addition of 24% and 26% ash, it was still possible to do optimization. The optimum condition of the addition of SCBA was then determined using the Central Composite Design

Table 5. Compressive strength results with central composite design

Run Order	Ash (Kg)	Lime (Kg)	Cement (Kg)	Cement (%)	Lime (%)	Ash (%)	Compressive Strength (Kg/cm^2)
1	0,65	0,85	0,8	35	28	37	49,31
2	0,8	0,7	1	40	32	28	34,74
3	0,8	1	0,6	25	33	42	38,41
4	0,65	0,85	0,8	35	28	37	49,31
5	0,8	0,7	0,6	29	38	33	34,76
6	0,4	0,85	0,8	39	20	41	56,88
7	0,5	1	1	40	20	40	56,94
8	0,8	1	1	36	29	36	56,88
9	0,5	0,7	0,6	33	28	39	34,76
10	0,65	0,85	0,8	35	28	37	49,31
11	0,65	0,85	0,8	35	28	37	49,31
12	0,65	0,85	0,8	35	28	37	49,31
13	0,65	0,85	0,6	29	31	40	49,31
14	0,65	0,6	0,8	39	32	29	34,76
15	0,65	0,85	0,8	35	28	37	56,88
16	0,9	0,85	0,8	31	35	33	38,41
17	0,5	1	0,6	29	24	48	56,88
18	0,65	0,85	1	40	26	34	56,88
19	0,65	1	0,8	33	27	41	56,90
20	0,5	0,7	1	45	23	32	38,42

Optimization was carried out according to the Plackett - Burman Design screening variable where the variables tested are lime, cement and ash as shown in Table 5. Based on the results in Table 5, it is known that the highest compressive strength (56.94 kg/cm^2, quality level III) was obtained in the 7th experiment where the addition of Cement, Lime, and Ash with a ratio of 1: 1: 0.5. These results are strongly influenced by the addition of lime which can increase the compressive strength [35]. SCBA contains a lot of SiO2. If SCBA was mixed with $Ca(OH)_2$ lime, a hydration reaction between cement and water and a $C_3S_2H_3$ compound is formed which functions the same as cement as an adhesive [36].

The results of the analysis of variance (ANOVA) to result Mathematical equation models to predict significant variabels with P-values less than 0.05. ANOVA results also showed that each component, namely the bagasse ash, lime, and cement had a significant effect on the response. Lack of Fit F-value yield response with a P-value greater than 0.05 indicates that Lack of fit is not significant. The insignificant Lack of fit value is a prerequisite for a good model because it shows the suitability response data with the model [37].

After getting the results of the compressive strength test, then the optimum response variable value needs to be calculated using the Derringer method. The Derringer method is used to determine the optimal conditions for developing the compressive strength of concrete bricks using the optimum composition of lime, cement and bagaase ash as shown in Figure 2. In Figure 2, it is presented that the optimum compressive power of 56.9 kg/cm^2 was obtained at conditions of 0.57 kg SCBA, 0.96 kg lime, and 0.88 kg cement.

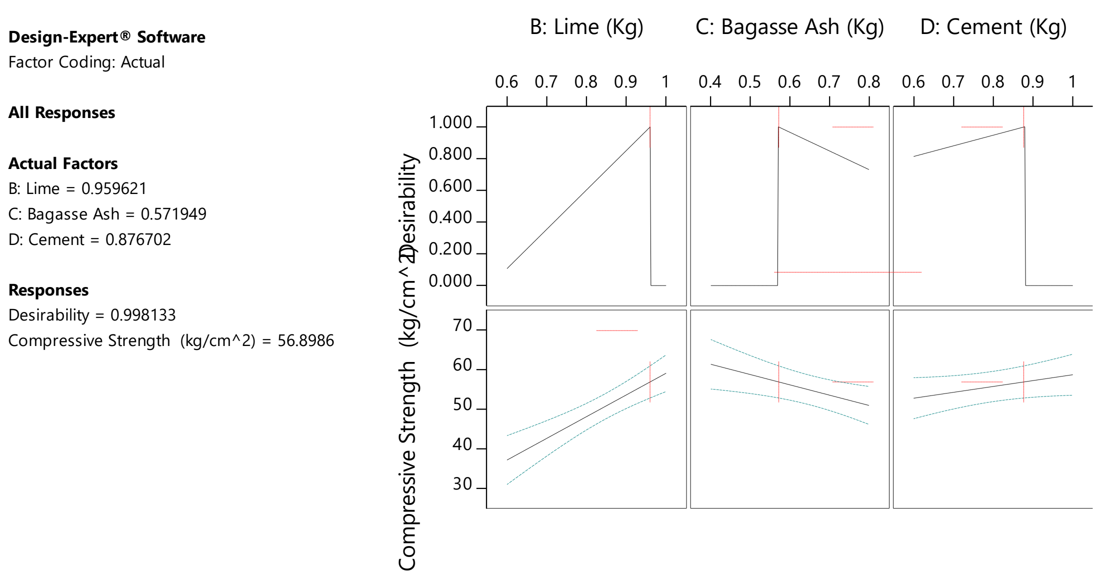

Figure 2. Derringer's desirability graph

Table 6. Summary of R^2 value of models for the compressive strength response

Source	Std. Dev.	R^2	Adjusted R^2	Predicted R^2	PRESS	
Linear	**5.23**	**0.7144**	**0.6608**	**0.4946**	**775.48**	**Suggested**
2FI	5.23	0.7681	0.6611	-0.3329	2045.16	
Quadratic	4.39	0.8746	0.7618	-0.2049	1848.75	
Cubic	3.09	0.9689	0.8817		*	Aliased

Table 7. Summary of P-value of models for the compressive strength response

Source	Sum of Squares	df	Mean Square	*F*-value	*P*-value Probe>*F*	
Linear	**390.46**	**11**	**35.50**	**3.72**	**0.0793**	**Suggested**
2FI	308.06	8	38.51	4.03	0.0706	
Quadratic	144.64	5	28.93	3.03	0.1246	
Cubic	0.0000	0				Aliased
Pure Error	47.75	5	9.55			

Table 6 and 7 exhibit the model summary of statistics for the compressive strength response. As shown in Table 6, the linear model is most suitable model for predicting the compressive strength of concrete bricks. The fit summary for response shows preference for the special linear model with R-squared, adjusted and predicted R-squared of 0.7144, 0.6608 and 0.4946, respectively. The lack of fit test results showed the value of the sum of squares, mean square, and P-value were 390.46, 35.50, and 0.0793, respectively (see Table 7). Higher significant lack of fit p-value was selected and used as the response predictor [38].

The cook's distance test is commonly used for the determination of the data point influence when carrying out ordinary least square regression analysis. The influential points which are particularly worth for validity checks and also to show planes of the feasible experimental design space where better performance can be achieved. The cook's distance vs. experimental run plot for the two response cases are shown in Figure 3. The plotted result indicates that the cook distance score for the response are mostly within 0 and 1 [39].

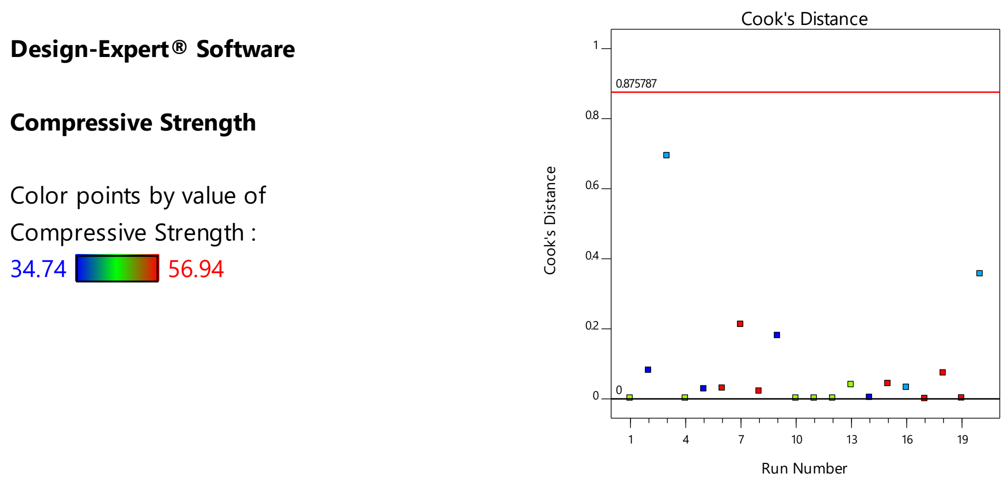

Figure 3. The Cook's Distance Plot

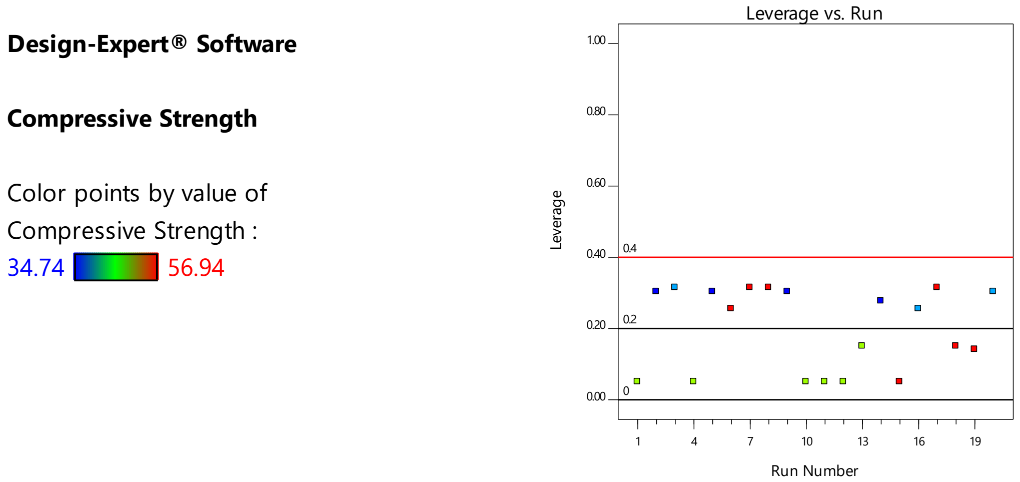

Figure 4. Leverage vs. Run plot

Leverage test measures how much each point infuences the model fit. If a point has a leverage of 1.00, then the model exactly fits the observation at that point. Experimental run with leverage greater than 2 times the average is generally regarded as having high leverage, such runs have few other runs near them in the factor space [40]. The average leverage is the number of terms in the model divided by the number of experimental runs in the design and the plot for CBR is presented in Figure 4.

Based on Table 8 ANOVA test results, the P-value of the quadratic model of 0.002 indicates the model used has a significant effect. Based on Table 8, the P-values of ash, lime, and cement are 0.008, 0.001, and 0.058, respectively, which means that they had a significant effect. The value of R^2 (coefficient of determination) of 0.8746 shows the data that supports the model of 87.46%. The factors that affect the compressive strength were lime, cement and SCBA. The quadratic model equation for the optimization of the conditions of the concrete brick is shown in Equation 2.

Equation 2 shows that the compressive strength response will increase directly proportional to the increase in the variable. The ANOVA results show that each component, namely cement, lime, and SCBA, has a significant effect on the compressive strength response.

The response surface graphs and contour plots of the model were used to assess the interactions between the significant factors. The shape of the interaction surface between the various components is shown in Figure 5. From Figure 5, it is known that the addition of a high lime concentration combined with a low ash concentration will produce optimum compressive strength. This happened because the nature of lime which resembled cement was able to glue ash and sand better, with a lower concentration of ash. When compared with previous studies, the addition of lime was used as a stabilizer for sand stabilization. In traditional construction, lime is added to increase the performance and durability of the construction material [41].

$$\text{Compressive Strength } (\text{Kg/cm}^2) = -107{,}5 + 104{,}3\ \text{Ash} + 236\ \text{Lime} + 14\ \text{Cement} - 84{,}1\ \text{Ash*Ash} - 106{,}1\ \text{Lime*Lime} - 57{,}1\ \text{Cement*Cement} - 82{,}5\ \text{Ash*Lime} + 61{,}4\ \text{Ash*Cement} + 62{,}0\ \text{Lime*Cement} \quad (2)$$

Table 8. Analysis of variance (ANOVA) for compressive strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value	
Model	9	1341,96	149,107	7,75	**0,002**	Significant
Linear	3	920,26	306,754	15,94	**0,001**	
Ash	1	207,17	207,169	10,77	**0,008**	
Lime	1	624,65	624,646	32,47	**0,001**	
Cement	1	88,45	88,447	4,60	0,058	
Square	3	163,42	54,472	2,83	0,093	
Ash*Ash	1	49,82	49,817	2,59	0,139	
Lime*Lime	1	45,05	45,047	2,34	0,157	
Cement*Cement	1	22,70	22,702	1,18	0,303	
2-Way Interaction	3	82,40	27,467	1,43	0,292	
Ash*Lime	1	27,57	27,565	1,43	0,259	
Ash*Cement	1	27,12	27,122	1,41	0,263	
Lime*Cement	1	27,71	27,714	1,44	0,258	
Error	10	192,40	19,240			
Lack-of-Fit	5	144,64	28,929	3,03	0,125	Not Significant
Pure Error	5	47,75	9,551			
Total	19	1534,36				

Note: The values in bold are statistically significant (95 % significance level)

The contour plot graph in Figure 6 was similar to the three-dimensional graph comparing the combined effects of lime and SCBA. The low area (dark blue) indicates a low concentration value, while the high area (dark red color) indicates a high concentration value. From Figure 5 and 6, it is known that a high concentration of lime mixed with a low concentration of ash will produce optimum compressive strength. Compared with previous studies, in this study there was an increase in the compressive strength value where the influence of SCBA was able to increase the compressive strength of concrete bricks compared to the one without the addition of SCBA. This was because the silicate in SCBA reacted with lime and cement which was able to glue fine and coarse aggregates. The increase in SCBA can reduce water absorption because the material has a high density [42].

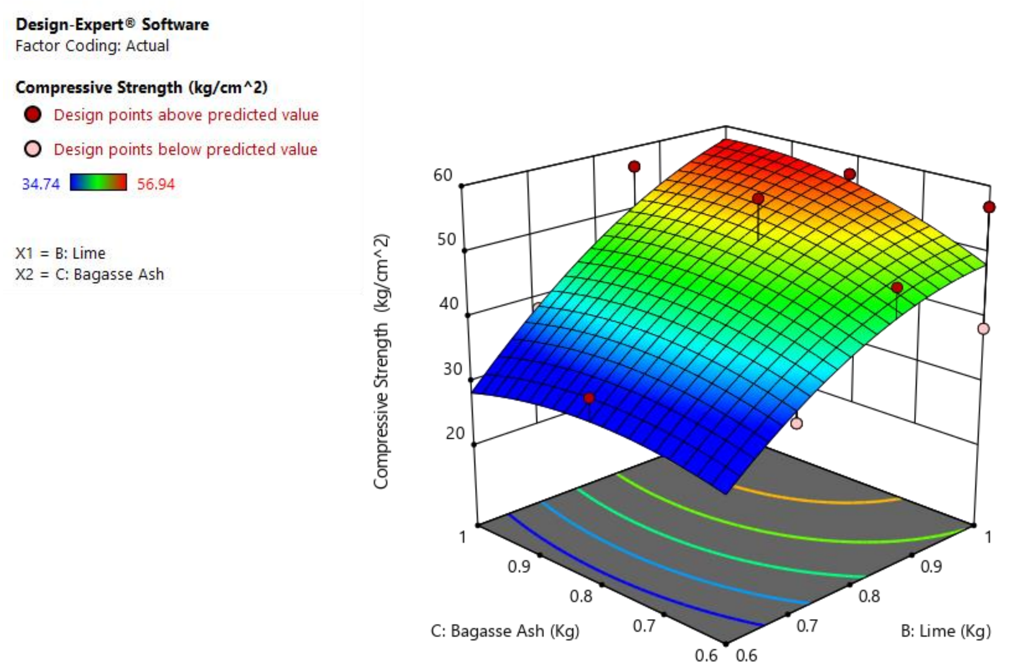

Figure 5. Surface response of the effect of lime and SCBA on compressive strength

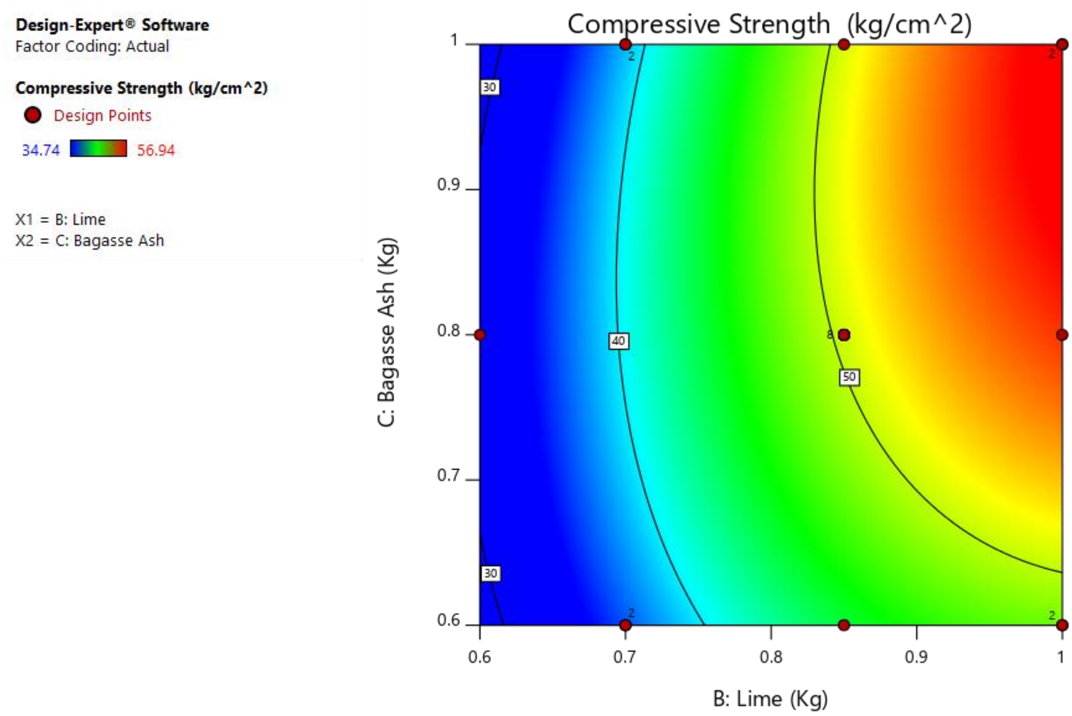

Figure 6. Contour plot of the effect of lime and SCBA on compressive strength

4. CONCLUSION

From this research, it is concluded that the addition of ash greatly affects the compressive strength. The addition of lime helps increase the compressive strength of the concrete brick. Optimization of concrete brick utilization using Plackett-Burman and CCD with the addition of low ash (24%) produces a compressive strength of 56.88 kg/cm^2.

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