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JOURNAL INDUSTRIAL SERVICESS

journal homepage: http://jurnal.untirta.ac.id/index.php/jiss

eISSN 2461-0631

Original research article

Optimization of compressive strength for Aceh Besar traditional bricks using Box-Behnken design

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ARTICLE INFO

Article history:
Received 15 November 2024
Received in revised form 18 May 2025
Accepted 27 May 2025
Published online 30 May 2025

Keywords:
Brick
Clay
Box Behnken Design
Response Surface Methodology
Optimization

Editor:
Bobby Kurniawan

Publisher's note:
The publisher remains neutral regarding jurisdictional claims in published maps and institutional affiliations, while the author(s) bear sole responsibility for the accuracy of content and any legal implications

ABSTRACT

Traditional brick production in Aceh Besar remains inconsistent in quality, particularly regarding compressive strength, which often does not meet the minimum requirement set by the Indonesian National Standard (SNI 15-2094:2000). This inconsistency is mainly due to the absence of standardized raw material formulations and controlled production methods. This study aims to determine the optimal combination of production variables to improve the compressive strength of traditional bricks. To solve this problem, the Response Surface Methodology (RSM) with a Box Behnken Design was employed to examine five key factors: clay, sand, water, drying time, and firing duration. A total of 46 experimental trials were conducted based on the design matrix. The results show that clay and water significantly affect compressive strength, while sand, drying time, and firing duration do not significantly impact. The optimal combination—1600 grams of clay, 600 grams of sand, 600 ml of water, 15 days of drying, and 94 hours of firing—produced a compressive strength of 76.141 kgf/cm². These findings contribute to improving traditional brick production by offering a data-driven approach to achieving higher quality and compliance with national standards.

1. Introduction

Bricks are among the most common construction materials used in communities today, generally categorized into manufactured and traditional fired bricks. Bricks are essential construction materials widely used worldwide. In Aceh Besar, traditional bricks remain a primary choice for housing and small-scale infrastructure construction. However, the quality of conventional bricks is often inconsistent and fails to meet the Indonesian National Standard (SNI 15-2094:2000), raising concerns about building strength and durability. According to SNI 15-2094:2000, brick quality standards include compressive strength tests, with acceptable quality categorized into three levels ranging from 60 to over 100 kgf/cm². This research aims to address these issues by optimizing the production process of traditional bricks, enhancing local construction quality, and supporting the sustainability of conventional practices.

Compressive strength in bricks refers to the maximum compressive force per unit area that a brick surface can withstand. Higher compressive strength values indicate better brick quality [1]. Traditional bricks, widely produced by local industries in Aceh Besar, generally lack standardized compressive strength requirements. Testing of traditional brick samples has shown compressive strength values between 45 and 55 kgf/cm², which do not meet SNI standards. Additionally, production results indicate a defect rate of 10–15%, with cracks frequently found in bricks, rendering them unsuitable for consumer distribution. This issue primarily stems from the absence of standardized raw material composition in traditional brick production, which often relies on manual experience and lacks consistency in the manufacturing process.

The production chain for traditional bricks typically involves three main stages: mixing raw materials (clay, water, and sand), drying, and firing. Interviews with producers revealed significant variations in the

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http://dx.doi.org/10.62870/jiss.v11i1.29638

duration of each production stage among producers. Therefore, improvements are necessary to enhance the compressive strength of bricks by optimizing the production process using Response Surface Methodology (RSM).

Previous research has focused on enhancing brick compressive strength by incorporating industrial waste, such as fly ash and glass cullet, or additives like plastics and construction waste. However, research on optimizing compressive strength in traditional bricks by focusing on key production variables—material composition, drying time, and firing time—is limited, particularly for case studies in Aceh Besar. This research aims to fill this gap by applying Response Surface Methodology (RSM) and Box-Behnken Design (BBD) to determine the optimal combination of variables.

Unlike previous studies, this research focuses on optimizing the compressive strength of traditional bricks in Aceh Besar using RSM and BBD without additives. This approach is crucial because it enables local producers to improve product quality using existing resources, avoiding reliance on materials that may be difficult to obtain or expensive. The practical implications of these findings are significant, providing a feasible and cost-effective method for local producers to enhance product quality and meet national standards. This research contributes to improving construction quality in Aceh Besar, supporting the sustainability of traditional practices and the optimal utilization of local resources.

While traditional optimization methods like OFAT [2], [3]—which struggle with variable interactions—and Monte Carlo simulation [4], [5]—often computationally expensive—exist, this study employs RSM with a Box-Behnken Design [6]. This approach enables efficient optimization with limited experimental runs, a critical factor given the resource constraints of traditional brick production. RSM distinguishes itself by enabling visualization of response surfaces, providing valuable insights into the relationships between input variables (clay, sand, water, etc.) and the desired output (compressive strength). In the context of traditional Aceh Besar brick production, this data-driven optimization represents a significant innovation, moving away from reliance on often inconsistent, experience-based manual methods that have historically dominated the industry. Furthermore, the research integrates experimental design principles with a deep understanding of brick production processes, allowing precise identification of key factors that most significantly impact compressive strength, ultimately offering a novel pathway to improve product quality, consistency, and adherence to national standards.

RSM is a statistical method used in experimental design to evaluate the performance of a response influenced by independent variables [7]. It aims to develop, improve, and optimize processes by identifying the optimal formulation point [8]. By employing RSM, it is possible to estimate optimal conditions or visualize the optimal response generated in the process [9].

RSM includes two main experimental designs: Central Composite Design (CCD) and Box-Behnken Design (BBD). The primary distinction lies in the experimental levels employed. CCD explores response values beyond the predetermined lower and upper levels, whereas BBD confines experiments to levels within the defined bounds.

Previous studies utilizing RSM in brick-making experiments with brick powder and rubber tire waste demonstrated optimal compressive strength with a combination of 5% brick powder and 6.87% rubber tire waste, achieving a maximum compressive strength of 276 kgf/cm² [10]. Further research examining the impact of brick powder and rubber tire waste on bricks, with energy consumption as a response variable, indicated no significant effect on compressive strength [11]. Studies employing RSM in brick production using construction waste, with factors such as molarity, alkaline ratio, and curing temperature analyzed through BBD, revealed significant effects [12]. Another study enhancing brick compressive strength using PET plastic waste and cement achieved a maximum compressive strength of 27.5 MPa [13]. Research utilizing fly ash and glass cullet as compositional factors showed improvements in brick strength, achieving values exceeding 17.2 MPa [14].

Other studies have focused on enhancing brick compressive strength by incorporating additional factors, such as plastic, construction, and rubber tire waste. However, this research seeks to optimize the traditional brick-making process by refining the main production variables—raw material composition, drying time, and firing time—without introducing new additives. This study uses RSM, particularly BBD, to achieve optimal compressive strength according to the Indonesian National Standard (SNI 15-2094:2000).

2. Material and method

2.1. Design experiment

This study aims to determine the optimal combination of factors to achieve maximum compressive strength in traditional bricks. Traditional bricks lack standardized raw material compositions, necessitating the identification of critical factors and their respective levels. The factors and levels considered in this study are shown in Table 1. These factors and levels were selected based on preliminary research and their relevance to compressive strength outcomes. The clay used in this study was sourced from Aceh Besar and has a predominant mineral composition. The sand used had a specific particle size distribution. The clean water used met drinking water standards. The mixing process followed this sequence: first, the clay was gradually mixed with water for 15 minutes using a mixer. Then, sand was added incrementally while stirring continued for an additional 10 minutes until the mixture was homogeneous. The mixing process was conducted at room temperature (25–28°C) with a relative humidity of 70–80%.

Table 1
Design experiment.

No	Factor	Level 1	Level 2
1	Clay	1400 gram	1600 gram
2	Sand	500 grams	600 grams
3	Water	500 ml	600 ml
4	Curing time	13 days	15 days
5	Burning time	94 hours	96 hours

Table 2
Experiment data.

No	Clay (gram)	Sand (gram)	Water (ml)	Curing (day)	Burning (hours)
1	1500	500	550	14	94
2	1500	550	550	14	95
3	1500	550	600	15	95
4	1500	550	500	14	94
5	1600	550	550	14	94
6	1400	550	550	14	96
7	1600	550	550	15	95
8	1400	550	550	13	95
9	1400	500	550	14	95
10	1500	500	550	14	96
11	1600	550	600	14	95
12	1400	550	500	14	95
13	1500	550	550	13	94
14	1500	550	500	15	95
15	1500	550	550	14	95
16	1400	550	550	14	94
17	1500	500	600	14	95
18	1500	500	550	15	95
19	1400	550	600	14	95
20	1500	550	550	14	95
21	1600	550	550	14	96
22	1500	550	550	15	94
23	1600	500	550	14	95
24	1500	600	550	13	95
25	1500	550	550	13	96
26	1500	500	550	13	95
27	1500	550	600	13	95
28	1500	550	550	14	95
29	1600	600	550	14	95
30	1400	600	550	14	95
31	1500	600	550	14	96
32	1500	600	500	14	95
33	1600	550	500	14	95
34	1500	550	600	14	96
35	1500	500	500	14	95
36	1500	550	500	13	95
37	1400	550	550	15	95
38	1500	600	550	15	95
39	1600	550	550	13	95
40	1500	550	550	14	95
41	1500	550	550	14	95
42	1500	550	500	14	96
43	1500	550	550	15	96
44	1500	600	600	14	95
45	1500	550	600	14	94
46	1500	600	550	14	94

By employing the Box-Behnken Design (BBD) within the Response Surface Methodology (RSM), this study systematically investigates the interactions among these factors to identify optimal conditions for maximizing brick strength according to SNI standards.

The results from Table 2 indicate that 46 experimental trials will be conducted using five selected factors, with each brick produced at varying levels. Only one brick will be created for each experimental setup, as the controlled Box-Behnken Design (BBD) structure is conducted under consistent environmental conditions to minimize external variables. Each brick is produced using the same procedures and tools and tested in the same laboratory to ensure consistency.

Table 3
Brick standard according to SNI 15-2094-2000.

No	Brick level	Average compressive strength	
		kgf/cm²	N/mm²
1	Grade I	> 100	>10
2	Grade II	80–100	8-10
3	Grade III	60-80	6-10

The BBD was selected for its efficiency in evaluating parameters with a limited number of trials. Previous studies have successfully applied the BBD with one sample per treatment combination, particularly when optimizing process parameters and controlling variability through standardized procedures [15, 16]. Upon completion of brick production, compressive strength testing will be performed in the laboratory to evaluate each brick's strength.

2.2. Compresive strength testing

The compressive strength of red bricks refers to the maximum compressive force that can be applied to a brick per unit area of its surface. This strength is calculated using Eq. (1) provided in the referenced source [1],

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

where P denotes compresive strength, F is force applied to brick (kgf), and A denotes the cross-sectional area of the brick (cm²).

Table 4
Compressive strength result.

No	Clay (gram)	Sand (gram)	Water (ml)	Curing (day)	Burning (hours)	Strength (kgf/cm2)
1	1500	500	550	14	94	40.91
2	1500	550	550	14	95	39.75
3	1500	550	600	15	95	41.21
4	1500	550	500	14	94	50.94
5	1600	550	550	14	94	59.30
6	1400	550	550	14	96	42.11
7	1600	550	550	15	95	60.40
8	1400	550	550	13	95	29.75
9	1400	500	550	14	95	48.52
10	1500	500	550	14	96	53.17
11	1600	550	600	14	95	63.14
12	1400	550	500	14	95	44.19
13	1500	550	550	13	94	35.72
14	1500	550	500	15	95	41.24
15	1500	550	550	14	95	47.47
16	1400	550	550	14	94	41.21
17	1500	500	600	14	95	35.98
18	1500	500	550	15	95	37.05
19	1400	550	600	14	95	42.58
20	1500	550	550	14	95	40.61
21	1600	550	550	14	96	52.43
22	1500	550	550	15	94	46.43
23	1600	500	550	14	95	52.26
24	1500	600	550	13	95	47.31
25	1500	550	550	13	96	40.04
26	1500	500	550	13	95	36.12
27	1500	550	600	13	95	28.70
28	1500	550	550	14	95	44.87
29	1600	600	550	14	95	46.63
30	1400	600	550	14	95	37.08
31	1500	600	550	14	96	34.94
32	1500	600	500	14	95	41.22
33	1600	550	500	14	95	52.24
34	1500	550	600	14	96	31.01
35	1500	500	500	14	95	47.27
36	1500	550	500	13	95	57.53
37	1400	550	550	15	95	40.48
38	1500	600	550	15	95	47.09
39	1600	550	550	13	95	47.47
40	1500	550	550	14	95	46.76
41	1500	550	550	14	95	41.71
42	1500	550	500	14	96	47.13
43	1500	550	550	15	96	41.54
44	1500	600	600	14	95	45.61
45	1500	550	600	14	94	39.06
46	1500	600	550	14	94	40.04

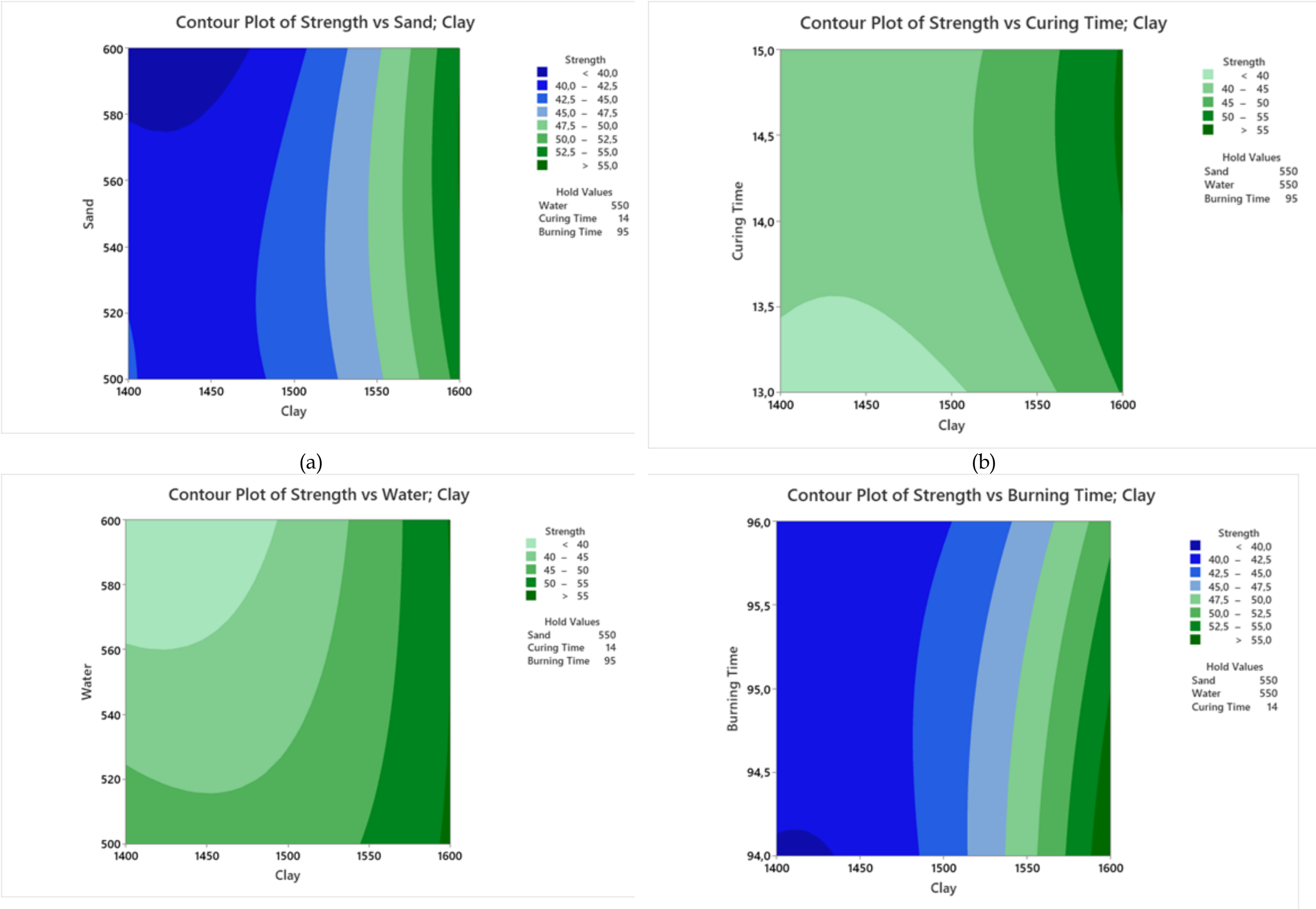

Fig. 1. Countour plot of: (a) strength vs sand. (b) strength vs curing. (c) strength vs water. and (d) strength vs burning time.

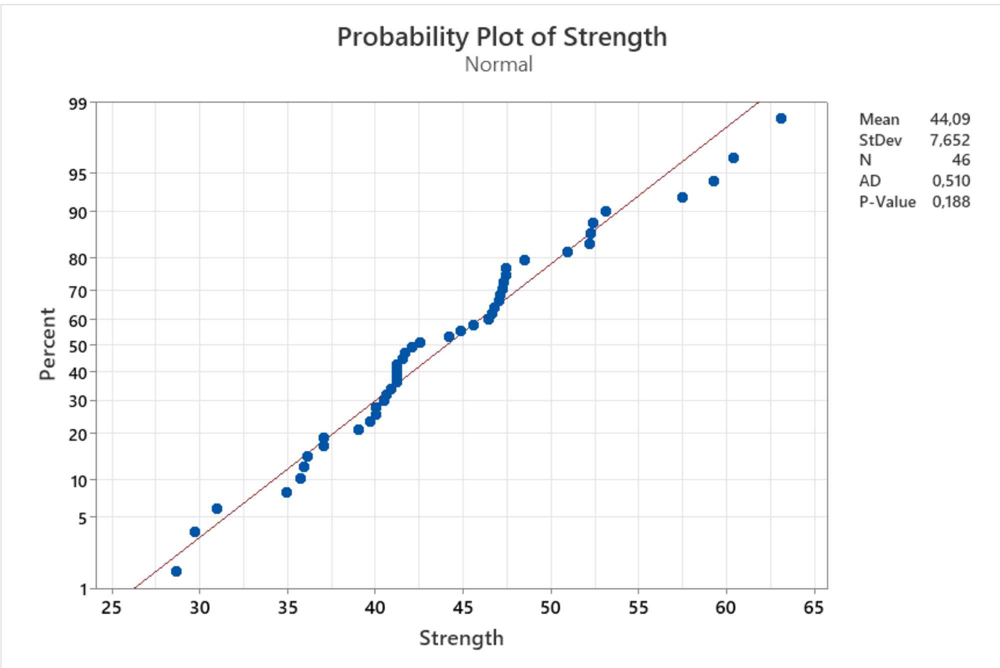

Fig. 2. Normality test.

Based on SNI 15-2094-2000. bricks are classified into three levels. as shown in Table 3. Table 3 indicates that the higher the compressive strength of a brick. the better its quality. Bricks classified as Level III represent the lowest grade and are typically used for temporary construction or partition walls where they are not subjected to heavy loads. Level II bricks are generally used for residential wall construction and exterior work where plastering is applied. Meanwhile. Level I bricks are the highest grade and are used exclusively for structural work and floor construction [17].

Table 5
ANOVA.

Source	p-value	Results
Model	0.014	Significant
Linier	0.001	Significant
Clay	0.000	Significant
Sand	0.635	Non-Significant
Water	0.029	Significant
Curing time	0.176	Non-Significant
Burning time	0.638	Non-Significant
Clay * Sand	0.627	Non-Significant
Clay * Water	0.299	Non-Significant
Clay * Curing time	0.853	Non-Significant
Clay * Burning time	0.516	Non-Significant
Sand * Water	0.195	Non-Significant
Sand * Curing time	0.923	Non-Significant
Sand * Burning time	0.153	Non-Significant
Water * Curing time	0.022	Significant
Water * Burning time	0.722	Non-Significant
Curing time * Burning time	0.442	Non-Significant

2.3. Response Surface Methodology

Response Surface Methodology (RSM) is a collection of statistical and mathematical techniques to improve. develop. and optimize processes. RSM is frequently applied in industry to analyze the impact of input variables (independent variables) on performance metrics. product quality characteristics. and methods. which are referred to as response variables [7]. In RSM. the response variable is influenced by several independent variables. By utilizing this methodology. it is possible to estimate optimal conditions or visualize the optimal response that can be achieved [7], [9].

3. Results and discussions

3.1. Results and analysis

After the brick products are produced. the next step is to conduct testing in the laboratory to determine the compressive strength of the bricks. Table 4 shows the results of the compressive strength tests performed on the brick samples. The results of 46 experimental trials indicate that the highest compressive strength achieved was 63.14 kgf/cm². with the following composition: 1600 g of clay. 550 g of sand. 600 mL of water. a 14-day drying time. and a 95-hour firing time. Conversely. the lowest compressive strength recorded was 28.70 kgf/cm². with a composition of 1500 g of clay. 550 g of sand. 600 mL of water. a 13-day drying time. and a 95-hour firing time.

Response Surface Methodology (RSM) can provide optimal results by illustrating the relationships between the factors used through surface plots. An example of a surface plot generated to visualize the optimal conditions is shown on Fig. 1. This visualization illustrates how variations in the two independent factors influence compressive strength. offering insight into which combinations yield the highest or lowest strengths. The color gradient facilitates easy identification of optimal and suboptimal conditions. with colors corresponding to different levels of compressive strength.

3.1. Normality test

Normality testing was conducted to assess the distribution pattern of the compressive strength data obtained from the brick samples. The data is considered normally distributed if the p-value exceeds 0.05. The test results (see Fig. 2) show a p-value of 0.150. which is greater than 0.05. indicating that the data is normally distributed. Additionally. the data points align along a linear trend. further supporting normality. This suggests that the compressive strength values follow a normal distribution. making them suitable for further statistical analysis and modeling.

3.2. Experiment results

The compressive strength test results were analyzed using ANOVA (Analysis of Variance) to identify the factors that significantly affect the compressive strength of traditional bricks. The results of ANOVA test are shown in Table 5. The results from Table 5 indicate that clay content and water content significantly affect the compressive strength of bricks. with p-values less than 0.05. In contrast. sand content. drying time. and firing time do not significantly influence compressive strength. Subsequently. a model evaluation was conducted using the coefficient of determination (R^2) to assess the model's fit to the data. The coefficient of determination (R^2) indicates that the factors of clay. sand. water. drying time. and firing time account for 67.04% of the variation in compressive strength. However. 32.96% of the variance remains unexplained. suggesting that other factors not included in the model may also influence the compressive strength of the bricks. Following the results of the ANOVA and determination tests. the next step is to identify the optimal combination of factors to achieve maximum compressive strength.

The optimization results for the compressive strength of the bricks using Response Surface Methodology (RSM) indicate that the maximum compressive strength achieved is 76.141 kgf/cm². This result corresponds to the optimal combination of 1600 grams of clay. 600 grams of sand. 600 mL of water. 15 days of curing time. and 94 hours of burning time.

3.2. Discussions

The results of this study indicate that the optimal raw material formulation—1600 grams of clay. 600 grams of sand. 600 mL of water. 15 days of drying. and 94 hours of firing (see Fig. 3)—significantly enhances the compressive strength of the bricks. This outcome addresses the research question regarding how to improve the quality of traditional bricks. Furthermore. these findings support the hypothesis that optimizing the raw material formulation can produce bricks with compressive strength that meets SNI standards.

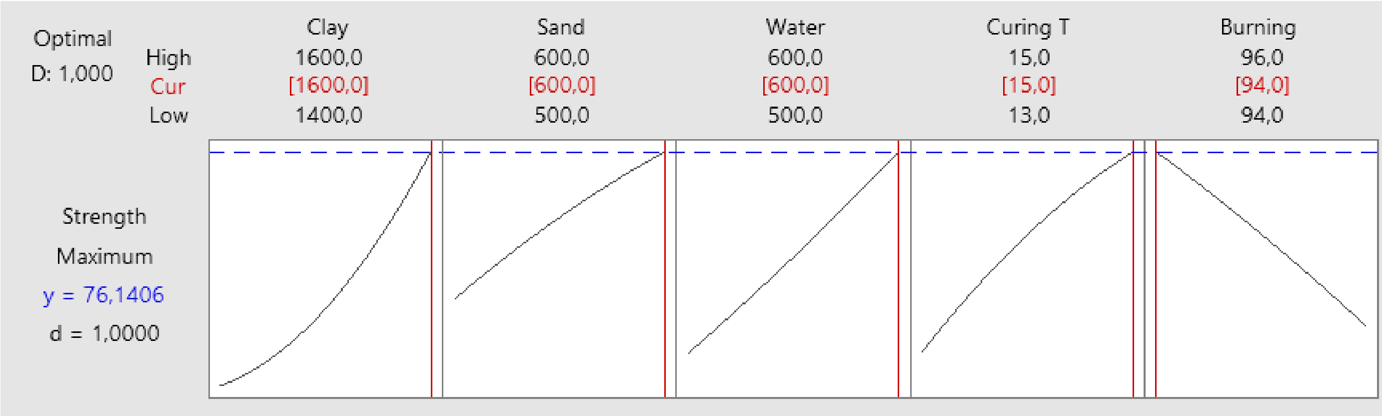

Fig. 3. Optimum design.

These findings are consistent with Subedi's research [18] on the characteristics of bricks in Kathmandu. Nepal. which also found that factors in the brick-making process significantly affect brick quality. However. this study further demonstrates that using the Box-Behnken method to optimize the composition of raw materials (clay. sand. and water) and production parameters (drying time and firing duration) can result in higher compressive strength in traditional Aceh Besar bricks. The following is a description of each factor and the corresponding test results.

The experimental results indicate that clay and water content influence the compressive strength of traditional bricks. Clay is the primary component in brick production due to its silica and alumina content. which contribute to hardening and strength [19]. The effect of clay on compressive strength has also been observed in studies involving recycled clay bricks. ceramic wall tiles. and concrete. where clay significantly influenced the final strength [20]. Increasing the amount of clay. within certain limits. can enhance compressive strength. as clay acts as a binder. providing structural integrity to the bricks [21].

Sand plays a role in reducing shrinkage during the molding and firing processes [22]. A study aiming to improve brick quality using cement. drying time. sand. and rice husk as additional factors—analyzed through the Taguchi method—conducted eight trials. The results showed that 92.7% of the variation in compressive strength could be explained; however. the sand content did not significantly impact compressive strength [23]. Another study similarly found that the addition of sand to brick composition does not always have a significant effect on compressive strength [24].

Water is essential for forming a workable mixture of clay and sand. Without water. it is difficult to mold the clay into bricks. In this study. water content was found to influence the compressive strength of bricks. A comparative study of bricks made using groundwater and wastewater revealed that bricks produced with wastewater had higher compressive strength. attributed to the mineral content in the wastewater. which enhanced strength [25]. Other research has also shown that an appropriate water content improves the bonding between clay particles. leading to a more uniform particle distribution and. consequently. stronger bricks [26].

Curing time plays a critical role in preventing cracks. If not properly managed. insufficient curing can lead to defects [27]. In this study. curing time was found to have no significant effect on compressive strength. This is supported by other research suggesting that curing time does not always have a linear correlation with compressive strength. Instead. curing temperature plays a more critical role: higher temperatures can accelerate drying and increase strength [28]. It is likely that the curing time in this study did not contribute to significant strength improvements because the material rapidly reached its maximum hardening level at a given temperature [29].

The firing process transforms the bricks' internal structure. increasing density and strength when performed at the appropriate temperature and duration [30]. In this study. firing time did not positively affect compressive strength. Other studies have also shown that firing duration does not always significantly impact strength. The optimal firing duration typically ranges from 48 to 192 hours. and beyond this range. further firing may not enhance compressive strength [30]. Prolonged firing may even reduce strength due to overly uniform distribution of particle. which may negatively affect the internal structure of the brick [31].

ANOVA analysis revealed a significant interaction between water content and drying time on compressive strength (p = 0.022). Higher water content extends evaporation time; if drying is inadequate. this can result in porosity or cracking. Conversely. high water content combined with sufficient drying time allows for gradual. even evaporation. which improves particle bonding and results in higher compressive strength. For instance. at a water content of 600 mL. increasing drying time significantly improves strength. In contrast. at 500 mL. drying time has little effect. Therefore. a synergistic relationship between high water content and adequate drying time is essential for achieving optimal compressive strength. Understanding this interaction is important for adjusting water content relative to drying time in traditional brick production [32].

The optimization results using Response Surface Methodology (RSM) showed that the highest compressive strength achieved was 76.141 kgf/cm². using 1600 grams of clay. 600 grams of sand. 600 mL of water. 15 days of drying. and 94 hours of firing. This result meets the criteria for SNI 15-2094-2000 Class III (60–80 kgf/cm²). Although this is the lowest classification within the SNI standard. it represents a substantial improvement over the initial compressive strength of traditional bricks in Aceh Besar. which ranged from 45 to 55 kgf/cm². This improvement is practically significant. as it allows the bricks to be more appropriately used in secondary construction. such as boundary walls. Improved strength can also reduce production defects and waste. thereby increasing efficiency and minimizing raw material loss.

Furthermore. achieving this level of compressive strength opens opportunities for greater market penetration. Traditional bricks are often overlooked in the local market due to concerns about their inability to meet technical standards [33]. By adopting the formulation proposed in this study. local producers can improve their product value without investing in expensive production technologies [34]. However. it is important to note that SNI Class III is still the lowest category. and further development is needed to achieve Class II or even Class I standards. This may be accomplished through improvements in material composition. the use of additives. or tighter control over temperature and humidity during production.

Practically. the findings of this study can help traditional brick producers in Aceh Besar manufacture bricks of more consistent quality that meet SNI standards. Applying the optimized formulation can enhance local product competitiveness and reduce reliance on imported materials. Theoretically. this study offers new insights into factor combinations and their impact on brick performance. providing a basis for future research.

4. Conclusions

This study identified clay and water as the two most significant factors affecting the compressive strength of traditional clay bricks. with significance values of 0.029 and 0.000. respectively. Using the Response Surface Methodology with a Box Behnken Design. an optimal combination of production variables was determined—1600 grams of clay. 600 grams of sand. 600 ml of water. 15 days of drying. and 94 hours of firing—resulting in a compressive strength of 76.141 kgf/cm². which exceeds the minimum threshold set by the Indonesian National Standard (SNI 15-2094:2000).

From a practical perspective. these findings offer an experimentally based formulation approach that small-scale traditional brick producers can readily adopt. This approach can improve product quality consistently and reduce the proportion of defective units caused by low compressive strength. Theoretically. the study contributes to the existing body of knowledge by highlighting the role and interaction of fundamental production parameters. such as raw material ratios and processing time. which are often overlooked in research focusing on material substitution or additive use.

These findings address the issue of quality inconsistency in local brick production and pave the way for the development of standardized and efficient production protocols for the traditional brick industry. Furthermore. this research opens opportunities for future studies on uncontrolled environmental variables (noise). brick placement during the firing process. and microstructural analysis using Scanning Electron Microscopy (SEM) to deepen the understanding of the relationship between processing parameters and the mechanical performance of bricks.

Declaration statement

Riski Arifin: Conceptualization. Methodology. Writing – review and editing. **Sri Rahmawati**: Writing-Original Draft and Supervision. **Sitti Annisa**: Collecting Data. Validation. Visualization.

Acknowledgement

The author would like to sincerely thank the brick factory for its kind cooperation in facilitating the experimental study on enhancing brick strength. Gratitude is also extended to the Universitas Syiah Kuala for its institutional support throughout this research. Special acknowledgment is reserved for the research team members for their invaluable assistance and contributions to this study.

Disclosure statement

The authors explicitly state that no conflicts of interest. financial or otherwise. influenced the design. execution. or reporting of this research.

Funding statement

This work was supported by an Institutional Research Grant from Universitas Syiah Kuala. grant number 1702/UN11/KPT/2024. The author would like to thank Universitas Syiah Kuala for their generous support and resources.

Data availability statement

All data generated or analyzed during this study are included in this published article and its supplementary information files. Additional data can be requested from the authors at email: riskiarifin@usk.ac.id.

AI Usage Statement

Generative AI and AI-assisted tools were used to enhance the language and readability of this manuscript. The authors have reviewed and revised all AI-generated content to ensure its accuracy and alignment with the research. The authors remain fully responsible for the work's scientific content. conclusions. and integrity. and disclose the use of AI to ensure transparency and adherence to publisher guidelines.

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