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Performance Improvement of Coal Dust Briquettes: Application of Taguchi Design and Pareto Analysis for Optimizing Key Processing Variables

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ABSTRACT

The main challenge in the briquette-making process is selecting the appropriate and proportionate reinforcement or adhesive. The chosen adhesive must not only provide strong adhesion but also be compatible with other components. Briquettes are alternative fuels in solid form, made from carbon-containing materials with a high calorific value, allowing them to burn for an extended period. Coal is one of the alternative materials that can be used for briquettes. The choice of adhesive type and composition directly influences the compressive strength, thermal stability, and durability of briquettes in various environmental conditions. This study aims to investigate how process parameters affect the compressive strength of briquettes produced from coal powder reinforced with molasses, to improve the efficiency of the briquette production process. The methodology used in this study is the Taguchi method. The process parameters include four factors, each with three levels, tested with three replications: the percentage of reinforcement or adhesive at levels of 10%, 12.5%, and 15%; pressure at levels of 8 MPa, 10 MPa, and 12 MPa; temperature at levels of 70 °C, 90 °C, and 110 °C; and heating time at levels of 60 minutes, 90 minutes, and 120 minutes. To enhance the comprehensiveness of the study, several factors, including the moisture content of the briquettes, have also been examined. The results indicate that the temperature during the drying process is the most significant factor influencing the production of these briquettes.

Keywords: *coal, efficiency, moisture content, Taguchi*

1. INTRODUCTION

In the mining and energy industries, coal remains one of the main energy sources widely used across various sectors. However, during the transportation process from mining sites to distribution or utilization points, physical abrasion or erosion often occurs, resulting in fine particles known as coal fines. The presence of these fines not only reduces the usable volume of coal but also presents significant challenges in industrial solid waste management.

Coal fines generated during handling and transportation processes are generally regarded as residual materials with low economic value. As a result, this waste is often not utilized optimally and merely accumulates, posing logistical and environmental burdens. If not properly managed, the accumulation of coal fines can pollute the environment, increase the risk of fire, and raise waste management costs for companies.

In fact, with the right technological approach—such as the briquetting process, which involves compacting fine particles into solid forms that are easier to handle and use—coal fines have the potential to be processed into high-value products. This process not only allows the reuse of waste materials but also contributes to resource efficiency, reduces environmental impact, and enhances the economic value of the entire coal supply chain.

Coal is a solid mineral material found underground, formed from the deposition of plants/organic matter over millions of years. Coal dust can be utilized through the briquetting process. In the briquetting process, the use of a binder plays a crucial role. Binders serve to bond the fine coal particles together, allowing them to form a strong, solid structure. Binders are classified into three categories: inorganic binders, organic binders, and composite binders [1]. The type and amount of binder used in the briquette manufacturing process significantly influence the mechanical properties of the final product, including compressive strength. Selecting the appropriate and proportional binder is a major challenge, as the binder must not only provide good adhesion but also be compatible with the properties of coal and not interfere with its final application [2]. An increase in moisture content can reduce the bonding coefficient and increase porosity [3].

In this process, the binder plays a key role in uniting coal particles to form briquettes with good mechanical properties. The choice of binder type and amount directly affects the compressive strength, thermal stability, and durability of briquettes under various environmental conditions. Several studies have been conducted, including one that found oven drying to be more efficient and faster than sun drying due to its higher effectiveness [4]. Briquettes made from filter cake with 15% molasses binder showed high calorific value and produced the most optimal burning temperature [5]. Variations in molding pressure significantly affect the combustion rate of briquettes—the higher the pressure, the lower the combustion rate [6]. The optimal molasses binder content and drying time were found to be 30% and 7 hours, respectively, due to the lowest moisture content and the production of durable, high-quality briquettes during combustion [7]. A pressure of 100 N/cm^2 and 10% binder were found to be the most optimal for manufacturing water hyacinth briquettes [8].

Several methods, including the Taguchi method and Response Surface Methodology (RSM) with variance analysis, can be used to identify an optimal process. The Taguchi method involves using the Signal-to-Noise (SN) Ratio and Analysis of Variance (ANOVA) within a Taguchi orthogonal design. This approach helps determine the optimal process parameters that significantly influence the response [9,10].

Therefore, it is essential to study and develop coal fines processing methods—particularly through briquetting technology—as an environmentally friendly and economical solution to address the challenges of coal waste management.

2. METHODOLOGY

This study aims to investigate the impact of various process variables on the quality of coal briquettes, specifically in terms of compressive strength. The research was conducted through a series of systematic stages, starting from the determination of the experimental design, preparation of tools and materials, briquette manufacturing process, and mechanical property testing.

The initial stage involved selecting an experimental design using the Taguchi method. This method was chosen because it efficiently identifies the optimal combination of multiple factors with a limited number of experiments. The factors examined in this study include: molasses percentage as a binder, compaction pressure, drying temperature, and heating time. Each factor consists of three levels. The experimental design used is an orthogonal array L27(3×4), with three replications to enhance data validity.

The tools and materials used in this study include: coal fines as the main material, molasses as the binder, a mixing machine for homogenizing the mixture, briquette molds and a pressing machine for the forming process, an oven for drying, and a compression testing machine to measure the briquette's compressive strength.

After the briquettes were formed and dried according to the parameter combinations determined in the experimental design, each sample was tested for compressive strength. The test data were then analyzed using analysis of variance (ANOVA) to determine the effect of each factor on the response and to identify the combination of parameters that yielded the best results. Through this approach, the optimal formulation and process conditions can be identified for producing coal briquettes with high compressive strength and good mechanical properties.

3. RESULTS AND DISCUSSION

Moisture zontent testing in coal (anthracite) is conducted as an initial step to assess the condition of the raw material before it is mixed with a binder or adhesive. Anthracite samples are heated in an oven at a temperature of 105°C for 60 minutes, with an initial heating time from room temperature to 105°C for 30 minutes. The test results show an average moisture Content in coal of 2.91% as shown in Table 1. This relatively low moisture Content indicates that anthracite is in good condition to be used as a base material for briquettes, as a high moisture Content can adversely affect the mixing process with the binder and the quality of the resulting briquettes.

Table 1. Water content of sample

No	Before drying (g)	After drying (g)	Water content (%)
1	49.500	47.847	3.34
2	49.502	48.112	2.81
3	49.501	47.869	3.30
4	48.125	46.875	2.81
5	48.125	46.875	2.60
6	48.125	46.775	2.60

Next, three variations of binder percentages were used: 10%, 12.5%, and 15%, with a total sample weight of 55 grams. The binder used was a mixture of molasses and water, with predefined compositions as shown in Table 2. Molasses was chosen due to its high sugar content, which offers good adhesive properties, while water serves as a mixing medium and binder activator. This combination was expected to form briquettes with good mechanical properties, high durability, and ease of handling.

Table 2. Sample composition

Water (g)	Molasses (g)	Anthracite (g)
2.0	3.500	49.500
2.5	4.375	48.125
3.0	5.250	46.750

The experimental design employed was the Taguchi method with an L27 (3^4) orthogonal array, which involved testing 27 parameter combinations. The four primary factors considered were: binder percentage, compaction pressure, drying temperature, and heating time shown in Table 3. Each factor had three levels, and each combination was replicated three times for reliability.

Table 3. Factors and Levels

Binder (%)	Compaction pressure (MPa)	Drying temperature (°C)	Heating time (Minute)
10.0	8	70	60
12.5	10	90	90
15.0	12	110	120

Based on the orthogonal array involving four factors—binder content (10%, 12.5%, 15%), pressure (8 MPa, 10 MPa, 12 MPa), temperature (70°C, 90°C, 110°C), and heating time (60, 90, 120 minutes)—a comprehensive analysis can be conducted to understand the impact of each variable on the resulting compressive strength values.

Generally, it is observed that the compressive strength significantly increases under high-temperature conditions (110°C), particularly when combined with a binder content of 12.5% and moderate pressures (10 MPa or 12 MPa). For instance, sample number 15, which had a binder composition of 12.5%, a pressure of 10 MPa, a temperature of 110°C, and a heating time of 60 minutes, produced the highest compressive strength value of 1403. A similar trend was noted in samples 17 and 18 (with 12.5% binder and a temperature of 110°C), which yielded compressive strength values of 1303, reinforcing the conclusion that a temperature of 110°C significantly influences strength.

Moreover, the effect of pressure becomes more pronounced when paired with the appropriate binder content; pressures of 10 MPa or 12 MPa tend to produce higher values than 8 MPa, which often results in compressive strength values below 300 (as observed in samples 1, 4, 7, and 19). The heating time also plays a role, with 90- and 120-minute durations typically leading to higher compressive strength values. However, there are exceptions, such as the cases at a high temperature of 110°C, where 60 minutes can still lead to very high compressive strengths, as seen in samples 15 and 18.

The binder content significantly influences the results: 12.5% binder yields more samples with compressive strength values above 1000 than either 10% or 15% binder. In contrast, the 15% binder content shows less consistent results; while it can produce high compressive strengths (e.g., 1152 in sample 20), it also results in lower values in other cases (e.g., 204 in sample 25 or 230 in sample 19). This variability indicates that increasing binder content does not always correlate directly with increasing strength.

Overall, the optimum combination suggested by this data trend appears to be: 12.5% binder, pressures of 10–12 MPa, a temperature of 110°C, and heating times of 60–120 minutes, which consistently yield compressive strength values above 1000. Conversely, combinations involving low temperature (70°C), low pressure (8 MPa), and short heating times tend to result in very low compressive strength values (often below 200), highlighting the importance of controlling these variables within optimal ranges.

These findings are consistent with materials engineering principles, which propose that proper thermal and pressure treatments can strengthen interparticle bonds, increase material density, and reduce porosity, all of which contribute to the final mechanical strength of the material.

To determine the factors that most influence the output quality (based on Signal to Noise Ratio) and to filter out insignificant factors for more efficient optimization, a variance analysis is performed. The results of the analysis can be found in Table 4.

Table 4. Analysis of variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Binder	2	25.96	25.96	12.978	1.19	0.332
Pressure	2	3.29	3.29	1.644	0.15	0.861
Temp	2	1131.66	1131.66	565.829	52.10	0.000
Time	2	26.37	26.37	13.187	1.21	0.326
Binder x Pressure	4	43.00	43.00	10.749	0.99	0.445
Residual error	14	152.05	152.05	10.861		
Total	26	1382.32				

The ANOVA analysis of the Signal-to-Noise (SN) Ratio indicates that temperature (°C) is the most significant variable affecting process quality. This conclusion is supported by an F-value of 52.10 and a very low P-value of 0.000, which demonstrate that the impact of temperature on quality variations is highly statistically significant. A high F-value suggests that changes in temperature significantly affect performance differences between treatments, while a low P-value indicates that the likelihood of this effect occurring by chance is extremely minimal. In contrast, factors such as binder content, pressure (MPa), process time (minutes), and the interaction between binder and pressure yield P-values greater than 0.05. This suggests that these factors do not significantly influence the output results. Although it is essential to monitor these factors to maintain stable operations, they are not the primary focus for quality optimization. Pursuing optimization of parameters with minimal influence may lead to wasted resources without achieving meaningful improvements in quality.

Therefore, maintaining optimal and consistent temperature control is crucial for enhancing the quality of the output from the analyzed process. Effective temperature regulation can reduce result variability, increase process efficiency, and produce products with stable characteristics. Consequently, the most strategic initial step for improving quality and efficiency is to ensure that the temperature remains at the optimal level for the specific process requirements, both in laboratory and production environments.

Figures 1 and 2, along with Table 5, display the main effects plot, interaction plot, and response table for the SN ratio. Based on the three graphs and tables presented—specifically, the Main Effects Plot for Signal to Noise (SN) Ratios, the Interaction Plot for SN Ratios, and the Response Table for SN Ratios—we can conclude that temperature (Temp) is the most influential factor in improving process quality, as measured by the SN Ratio value. In the context of the Taguchi method, the SN Ratio is used to evaluate the stability and resilience of the process against external disturbances, with higher values indicating a more stable process and more consistent results.

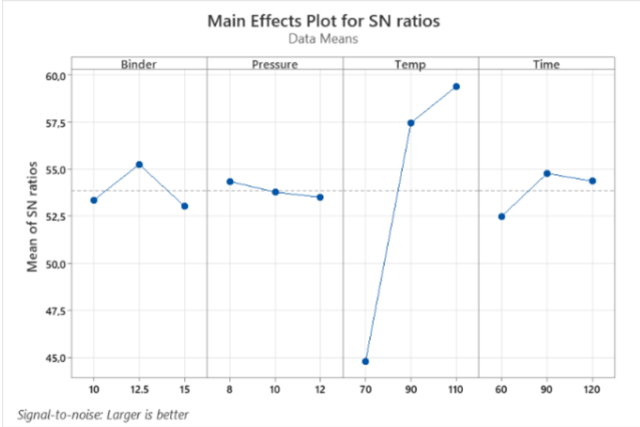

Figure 1. Main effects plot for SN ratios

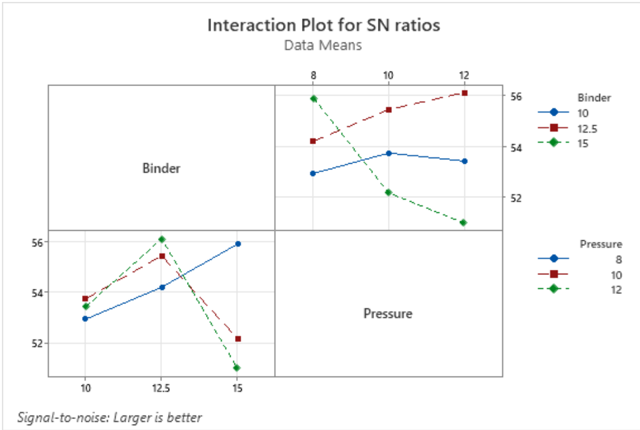

Figure 2. Interaction plot for SN ratios

Table 5. Response table for SN ratios (larger is better)

Level	Binder	Pressure	Temp	Time
1	53.36	54.34	44.79	52.49
2	55.24	53.78	57.45	54.76
3	53.01	53.50	59.39	54.36
Delta	2.23	0.84	14.60	2.27
Rank	3	4	1	2

The Main Effects Plot shows that the temperature factor results in a significant increase in the SN Ratio as the temperature rises from 70°C to 110°C. This finding suggests that process quality is heavily influenced by temperature, likely due to physical or chemical phenomena involved, such as thermal reactions, drying, or material binding.

In contrast, the factors of Binder, Pressure, and Time exhibit only minor fluctuations without any significant trends, indicating that they do not strongly influence the increase in SN Ratio. This conclusion is supported by the Response Table, which reveals that temperature has the highest Delta value (14.60), far exceeding that of the other factors, and is ranked first in terms of impact on output. Binder and Time are ranked second and third, with Delta values of 2.27 and 2.23, respectively, indicating a moderate influence, albeit not as substantial as that of temperature. Pressure ranks last, with a Delta of only 0.84, suggesting a very minimal effect.

However, the Interaction Plot indicates that while Pressure does not have a significant impact on its own, its interaction with the binder may influence the SN Ratio results. For instance, at a pressure level of 8 MPa, increasing the binder from 10% to 15% increases the SN Ratio. In contrast, at a pressure of 12 MPa, the SN Ratio decreases as the binder percentage increases. This suggests that the combination of factors, under certain conditions, can produce unexpected effects on quality output, despite the individual factors not being significant in isolation.

Therefore, in the optimization strategy, it is important to analyze not only the direct influence of each factor but also the interactions between them. Based on the highest SN Ratio values for each factor, the optimal combination of process parameters is as follows: Binder at level 2 (12.5%), Pressure at level 1 (8 MPa), Temperature at level 3 (110°C), and Time at level 2 (90 minutes). This combination is expected to yield the highest SN Ratio, indicating the best quality and stability against external disturbances.

In conclusion, the primary recommendation for the development and optimization of this process is to prioritize temperature control, while maintaining the binder and time at their identified optimal levels. Although Pressure shows a minimal effect, its interaction with the binder should still be monitored to ensure consistency in results. By implementing this strategy, both process efficiency and quality can be significantly enhanced.

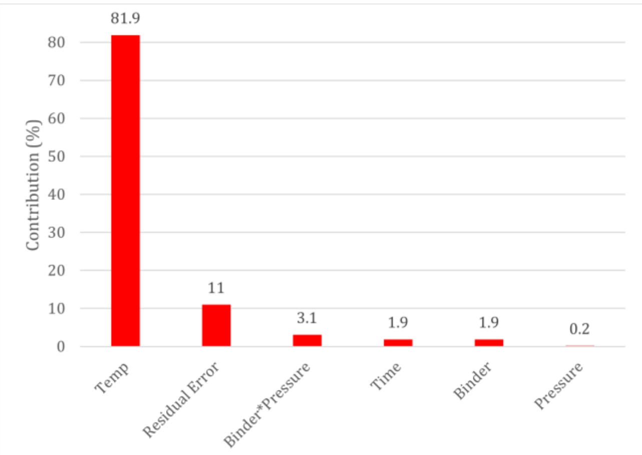

Figure 3. Pareto diagram - Contribution factors for SN ratios

The Figure 3 is a Pareto diagram that illustrates the relative contribution of each factor in the experiment to the Signal-to-Noise (S/N) Ratio, based on the ANOVA data from Table 3. This analysis uses the Taguchi method, which aims to improve the quality and consistency of the process by identifying the factors that have the most significant impact on the results.

This Pareto diagram illustrates the contribution of each factor as a percentage of the total variation in the Signal-to-Noise (SN) Ratio. In the context of the Taguchi method, the SN Ratio is an essential indicator because it combines the average response with its variability, reflecting the stability of the system against disturbances (noise). The contributions of each factor are calculated based on the Adjusted Sum of Squares (Adj SS). The factor with the highest contribution is deemed the most significant in influencing process quality.

The Pareto diagram indicates that temperature (°C) contributes 81.9%, significantly surpassing the contributions of all other factors. This contribution is notably high, even exceeding the combined impact of other variables. Additionally, this finding aligns with the F-ratio value of 52.10 and a P-value of 0.000 from the ANOVA analysis, which demonstrates that temperature is the only statistically significant factor ($P < 0.05$). Practically speaking, temperature is likely to influence the rates of chemical reactions, evaporation, or drying in the production process—for instance, in the manufacture of compost or other materials—making it a crucial factor that must be precisely controlled.

The factors of binder, pressure, time, and the interaction between binder and pressure have minimal contributions, each accounting for less than 5% and having a P-value greater than 0.05 in the ANOVA results. These results indicate that these factors are not statistically significant, meaning that changes in them do not significantly affect the final quality of the process or the stability of the output. However, while these factors may not be significant, they should not be ignored entirely. It is important to control them to prevent unexpected disturbances, but resources for optimization should not be concentrated on these factors.

The 11% contribution of the Residual Error indicates variability that cannot be accounted for by the factors tested. This residual error may stem from measurement errors, operator inconsistencies, or other environmental factors that were not included in the model. An 11% residual value falls within a reasonable range for industrial experiments. However, it also suggests that there is room for improvement in the experimental design or in controlling external sources of noise.

4. CONCLUSION

This study reveals that the combination of process parameters has a significant impact on the compressive strength of anthracite coal briquettes, with drying temperature being the most influential factor. Although to a lesser extent, the binder percentage, heating time, and compaction pressure also contribute to the briquette's mechanical performance. By applying an appropriate experimental design and optimizing these parameters, the compressive strength can be substantially improved. The findings of this study serve as a valuable reference for industries that require high-strength briquettes to ensure efficiency and reliability in their production processes.

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