Jurnal Polimesin
Department of Mechanical Engineering
State Polytechnic of Lhokseumawe
http://e-jurnal.pnl.ac.id/polimesin

e-ISSN	: 2549-1999	No.	: 1	Month	: February
p-ISSN	: 1693-5462	Volume	: 24	Year	: 2026

Processing dates: received on 2025-08-05, reviewed on 2025-09-20, accepted on 2026-02-11 and online availability on 2026-02-28

Experimental study on the effect of coal composition on the activation energy of sponge iron reduction

Sabuki, Khairil, Sarwo Edhy Sofyan*
Department of Mechanical Engineering, University of Syiah Kuala, Banda Aceh 23111, Indonesia
*Corresponding Author: sarwo.edhy@usk.ac.id

Abstract

The increasing demand for steel in Indonesia necessitates the development of efficient and sustainable ironmaking technologies. Direct reduction has emerged as a promising alternative to conventional blast furnace processes due to its lower operating temperature and reduced carbon emissions. This study examines the effect of coal composition on the reduction kinetics and activation energy of iron ore briquettes produced from locally sourced raw materials. Briquettes were prepared using Lhoong iron ore (93.88 wt% Fe_2O_3), sub-bituminous coal from Nagan Raya, and natural rubber latex as a binder. Four composition ratios were investigated: 80:15:5, 75:20:5, 70:25:5, and 60:35:5 (iron ore:coal:binder), each with a total mass of 60 g. Reduction experiments were conducted at 800 °C, 900 °C, and 1000 °C in an LPG-fired furnace. Mass loss was continuously monitored at 2-minute intervals using a digital balance connected to data acquisition software.

The results demonstrate that increasing coal content significantly enhances reduction performance. The highest mass loss of 46.75% and the maximum reduction rate constant of 3.2084 s^{-1} were achieved by the 60:35:5 composition at 1000 °C. Arrhenius analysis confirmed a linear relationship between ln k and 1/T, indicating temperature-dependent kinetic behavior. The calculated activation energy ranged from 7.378 to 9.010 $kJ \cdot mol^{-1}$ and increased with coal content, suggesting a shift in the controlling reduction mechanism. These findings highlight the critical role of coal composition in optimizing direct reduction kinetics and support the utilization of local resources for sustainable sponge iron production.

Keywords:
Iron ore, coal, direct reduction, activation energy

1 Introduction

Indonesia's steel demand is projected to reach 100 million tons annually by 2045, in line with the acceleration of national development and the achievement of the Golden Indonesia 2045 Vision [1]. This projection reinforces the strategic role of the steel industry in supporting economic growth and transforming the manufacturing sector. Simatupang and Sunitiyoso [2] highlights that dependence on imported raw materials, such as slabs and iron ore, remains a major challenge for industry players in achieving long-term self-sufficiency and sustainability. Strengthening the national supply chain is therefore essential to meet the growing demand [3].

In response to the growing demand for steel in the nation, it is increasingly important to choose ironmaking technologies that are efficient, economically viable, and environmentally sustainable. The quality of steel is closely tied to the raw materials used in its production, with iron being a crucial component. Therefore, the process of producing iron is a vital step in the steel industry. [4]. As a result, the process of producing iron becomes a crucial step in the steel industry [5]. Generally, there are three main methods for iron production: blast furnace, direct reduction, and smelting reduction [6]. The blast furnace remains the most widely used method worldwide, where iron ore is reduced using coke at high temperatures to produce pig iron. However, this process generates high CO_2 emissions and faces cost challenges related to coke production [7]. In contrast, direct reduction occurs at lower temperatures without melting the iron ore. This method uses reducing gases, such as natural gas or hydrogen, to produce sponge iron, resulting in better energy efficiency and lower emissions. Smelting reduction is a newer technology that eliminates the need for pelletizing and coke. It offers substantial environmental benefits, with the potential to reduce CO_2 emissions by up to 50% compared to the traditional blast furnace process [8][9]. Smelting reduction, on the other hand, is a newer technology that eliminates the need for pelletizing and coke. It offers significant environmental benefits, with the potential to reduce CO_2 emissions by up to 50% compared to the traditional blast furnace process [10].

In direct reduction technology, the characteristics of the reducing agent in iron ore briquettes are crucial for controlling reduction behavior and reaction kinetics. The addition of coal to these briquettes is essential for generating carbon monoxide (CO) during the heating process, as it reacts with CO_2. This CO gas serves as the primary reducing agent, speeding up the conversion of iron oxides into metallic iron. The effectiveness of this reduction process is significantly influenced by the carbon source used. For instance, biomass-based carbon has lower activation energy than conventional materials like coke and charcoal, indicating higher reactivity [11]. The gasification of carbon serves as a key mechanism in this system [12], while physical factors such as ore particle size also influence the magnitude of activation energy required during the reduction process [13] Therefore, understanding the kinetic behavior of the reduction process and the influence of coal composition is essential for optimizing direct reduction performance while utilizing locally available resources. Previous studies have emphasized the importance of coal composition in controlling reduction behavior and kinetic parameters in iron ore–coal systems. A comprehensive review by Mishra [12] reported that variations in coal content significantly influence mass loss, reduction extent, and reaction kinetics, highlighting the dominant role of carbon availability in direct reduction processes. Furthermore, Zhou et al. [14] demonstrated that differences in reducing agents and operating temperatures may lead to comparable reduction trends but result in different kinetic parameters, particularly activation energy. These findings indicate that coal composition can alter the controlling reduction mechanism, even when similar reduction behavior is observed under different experimental conditions.

This study investigates the kinetic behavior of the reduction process in iron ore briquettes. It focuses on three key aspects: the mass loss rate during reduction, the impact of coal composition variation on the reduction rate constant, and the determination of activation energy. Understanding these parameters will help achieve an effective reduction process with minimal energy consumption. Ultimately, this research aims to promote the use of local resources for industrial applications.

2 Methods

2.1 Materials

This study used three main materials: iron ore, sub-bituminous coal, and natural rubber latex. The iron ore was sourced from the Lhoong region in Aceh Besar District, and the coal came from Nagan Raya District, both located in Aceh Province, Indonesia. Table 1 presents the chemical composition of the iron ore, while Table 2 displays the ultimate and proximate analyses of the coal.

Table 1. Main chemical composition of Lhoong iron ore based on X-Ray Fluorescence (XRF) analysis [16]

No	Compound	Concentration (wt%)
1	Fe_2O_3	93.88
2	SiO_2	3.43
3	MnO	0.55
4	Al_2O_3	0.43
5	K_2O	0.38
6	P_2O_5	0.33
7	SO_3	0.29
8	Nd_2O_3	0.27
	Total	99.56

Table 2. Proximate and ultimate analyses of Nagan Raya coal [8]

Proximate analysis (wt%, wet basis)		Ultimate analysis (wt%, wet basis)	
Moisture content (%)	5.8	C (%)	60.65
Ash content (%)	5.4	H (%)	5.75
Fixed carbon (%)	42.7	O (%)	27.34
Volatile matter (%)	46.0	N (%)	0.48
Calorific value (Cal/g)	5904	S (%)	0.38

Both the iron ore and coal were initially in lump form. They were manually crushed and ground with a mortar and pestle until fine powders were produced. The resulting powders of iron ore and coal are shown in Fig. 1 and Fig. 2, respectively. To achieve a uniform particle size, both materials were sieved using a 5-mesh screen (equivalent to 4 mm). Natural rubber latex was used as a binder in liquid form. To preserve its quality during storage and transportation, the latex was pre-mixed with stabilizing agents to prevent coagulation. This binder was crucial for enhancing interparticle cohesion and strengthening the mechanical structure of the resulting briquettes [15].

Fig. 1. Ground iron ore

Fig. 2. Ground coal

2.2 Briquette preparation

Briquettes were prepared with a total mass of 60 grams, using four different composition ratios: 80:15:5, 75:20:5, 70:25:5, and 60:35:5 (iron ore : coal : binder) by weight percentage. Each material was weighed according to the specified composition and mixed manually until homogeneous. The mixture was then placed into a cylindrical mold with a diameter of 4 cm and compacted using a hydraulic press applying a pressure of 10 tons. The pressing process is illustrated in Fig. 3. The formed briquettes were subsequently air-dried at room temperature for 24 hours before the reduction stage. Before the reduction process, mechanical durability tests were conducted on all briquette compositions. The durability evaluation was performed using the drop test method, in which four iron ore briquettes with different coal compositions were subjected to impact from a fixed height onto a hard surface. The results indicate that the durability values of all compositions were below 0.1, demonstrating that the briquettes possessed sufficient mechanical strength for subsequent reduction experiments.

Fig. 3. Iron ore briquette

Briquettes produced with all composition ratios were evaluated for mechanical durability before the reduction process (see Fig. 3). The durability test was conducted using the drop test method, which utilized a shatter box measuring 28 inches (711 mm) in length, 18 inches (457 mm) in width, and 15 inches (381 mm) in depth. The box was dropped from a height of 1.8 meters onto a solid surface. The average drop test values for all briquette compositions were found to be less than 1%, indicating that the briquettes exhibited strong resistance to physical impact and met industrial durability standards [17].

2.3 Reduction process

The reduction process used the direct reduction method in an LPG-fired (CH_4) furnace equipped with an air compressor. First, the furnace was preheated to the target temperature. In this setup, LPG served as the main source of thermal energy, while compressed air from the compressor supported combustion. Flow rates of both gas and air were controlled using flow meters, and the internal temperature of the furnace was continuously monitored with a thermocouple connected to a digital display.

A K-type thermocouple was installed through an opening in the outer wall of the furnace. The opening's diameter was adjusted to fit the thermocouple junction, which was positioned near the briquette holder at the same level, ensuring no direct contact. This placement allowed the thermocouple to monitor the furnace chamber temperature close to the briquette during the reduction process. The thermocouple could operate at a maximum temperature of 1200 °C, with a measurement tolerance of approximately ±15 °C.

Once the desired temperature of 800 °C, 900 °C, or 1000 °C was reached, a briquette was placed in a specially designed holder suspended by a wire and connected to a digital balance. The experimental setup is shown in Fig. 4.

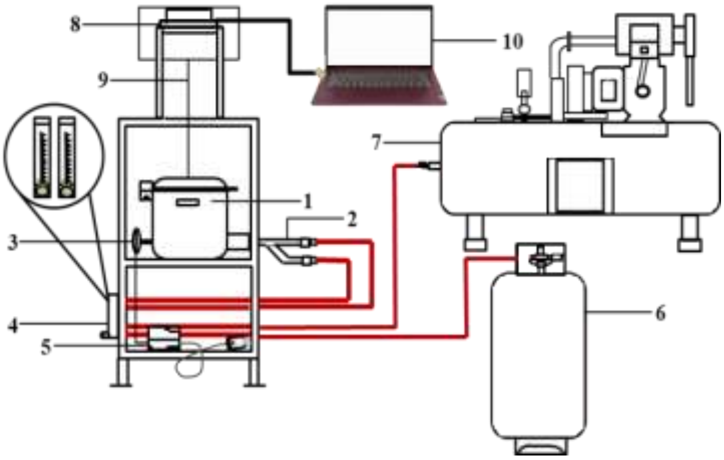

Fig. 4. Experimental setup

The digital balance was linked to a computer and synchronized with the RsKey software, allowing for real-time data logging into

Microsoft Excel. This setup enabled continuous and accurate monitoring of mass changes throughout the reduction process. The experiment concluded when the briquette's mass stabilized, indicating that no further significant reduction took place.

The experimental setup used in this study is shown in Fig. 4. The system comprises several components that function together to support the reduction process. A melting furnace (1) serves as the main chamber and is equipped with a burner (2) as the primary heat source. Temperature inside the furnace is monitored using a thermocouple (3), with readings displayed through a digital thermocouple monitor (5). The flow of LPG gas is regulated by a flow meter (4), while the combustion process is supported by compressed air supplied via an air compressor (7). LPG fuel (6) serves as the main energy source. Positioned above the furnace is a digital balance (AND EK-2000i) (8), connected to a sample holder (9) that suspends the briquette during the reaction. This configuration allows for continuous mass measurement throughout the process. All data are recorded and processed in real time using a computer (10) connected to the balance.

2.4 Analysis parameters

In this study, the independent variables were the coal composition in the briquettes and the reduction temperature. The dependent variables included the reduced mass fraction, unreduced mass fraction, reduction rate constant, and activation energy. Parameters such as briquette diameter, initial briquette mass, binder ratio, and reduction duration were kept constant throughout the experiments.

2.4.1 Mass loss rate

The reduction progress was evaluated by measuring the loss in briquette mass during the reaction. The reduced mass fraction was calculated using Eq. (1).

$$f = \frac{(m_0 - m_t)}{m_0} \times 100\% \tag{1}$$

where m_0 is the initial mass of the briquette (gr), and m_t is the mass at a specific time t (minutes).

2.4.2 Reduction rate

The reduction rate constant was determined by performing a linear regression between the unreduced mass fraction and time. The mathematical relationship for the unreduced fraction is given by Eq. (2)

$$F = 100\% - f \tag{2}$$

where F represents the unreduced mass fraction, and f is the reduced mass fraction. The linear form derived from the regression is expressed as Eq. (3).

$$y = -mx + c \tag{3}$$

where $-m$ corresponds to the slope of the regression line and represents the reduction rate constant (k). The early stage of reduction (typically 0–6 minutes) was used for this calculation, as the reaction proceeds rapidly and exhibits near-linear behavior in that interval.

2.4.3 Activation energy

The activation energy (E_a) required to initiate the reduction reaction was estimated using the Arrhenius equation (Eq. (4)).

$$\ln k = \ln A - \frac{E_a}{R_u T} \tag{4}$$

where k is the reduction rate constant (s^{-1}), A is the pre-exponential factor, E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol·K), and T is the absolute temperature (K). A linear plot of $\ln k$ versus $1/T$ was constructed for each composition, and the slope of the resulting line was used to calculate E_a.

3 Results and discussion

3.1 Effect of coal composition on reduced mass

Mass loss during reduction was observed using a digital balance connected directly to the sample, with data recorded every 2 minutes. The reduced mass fraction was calculated using Eq. (1). The trend of mass reduction over 60 minutes is shown in Fig. 5.

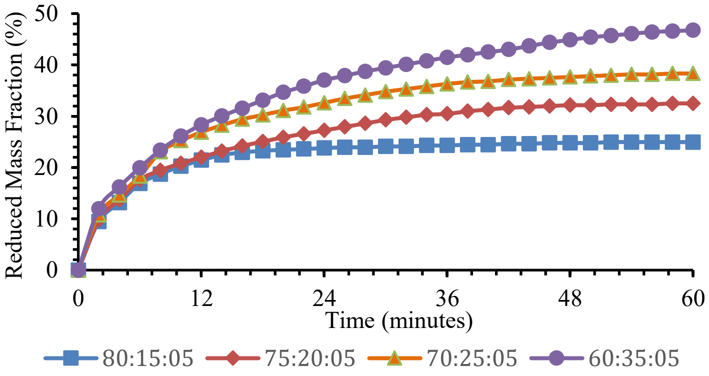

Fig. 5. Effect of coal composition on the reduced mass fraction at 1000°C

Fig. 5 illustrates the effect of reduction time and coal composition on mass reduction at 1000 °C. For all compositions, mass reduction increases progressively with increasing reduction time, indicating continuous advancement of the reduction reaction. However, the extent of mass reduction differs among compositions. The 60:35:5 composition exhibits the highest mass reduction, reaching 46.75%, whereas the 80:15:5 composition, which contains the lowest coal fraction, results in a lower mass reduction of 24.95% under the same conditions. This trend indicates that coal content plays an important role in determining the extent of mass reduction during the reduction process. A comparable trend was reported by Mahendra [18] , who observed a maximum reduction of 23.66% at 750 °C with a 30% coal composition, despite the difference in reduction temperature.

Fig. 6 presents the variation in mass loss for briquettes with different coal compositions at 1000 °C. The results show that increasing coal content leads to higher mass loss, with the 60:35:5 composition exhibiting the highest mass loss of 46.75% after 60 minutes, while briquettes with lower coal content display smaller mass losses. After 60 minutes, the mass loss tends to stabilize, indicating that the reduction process approaches a steady condition under the applied experimental parameters. Comparable mass-loss values have been reported under different experimental conditions, such as by Hakim [19], who observed a 46.54% mass loss at 1250 °C for a 55:40:5 composition, and by Adhitya [20], who reported a 33% mass loss at 1050 °C for the same composition, indicating that coal content plays a dominant role in controlling mass loss despite differences in reduction temperature.

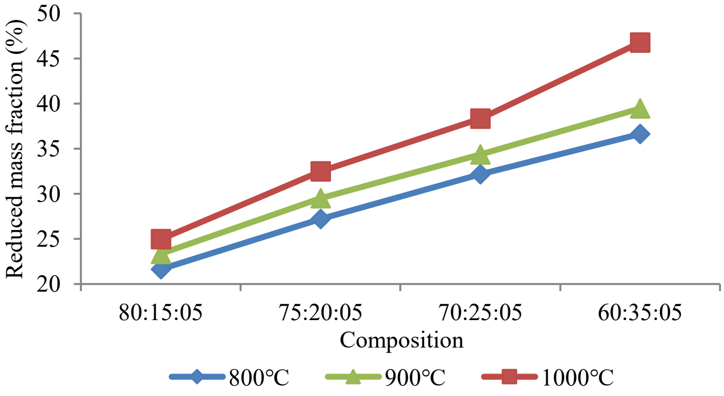

Fig. 6. Effect of coal composition on mass loss across all compositions

3.2 Effect of coal composition on unreduced mass

The unreduced mass fraction (F) was calculated using Eq. (2), where F equals 100% minus the reduced mass fraction. Fig. 7

illustrates that higher coal content and longer reduction times result in a lower unreduced mass fraction. At a reduction temperature of 1000 °C, the unreduced mass fraction is 75.04%. In contrast, at 800 °C, it rises to 78.36%, indicating that higher temperatures enhance the reduction process. This phenomenon can be explained by the increased availability of reducing gas and faster reaction kinetics at elevated temperatures, which lead to more effective removal of oxygen from iron oxides. Previous studies have reported similar trends, showing that higher reduction temperatures and increased carbon content also lead to lower unreduced mass fractions. This confirms that temperature and coal content are crucial factors affecting the reduction completeness of iron ore briquettes.

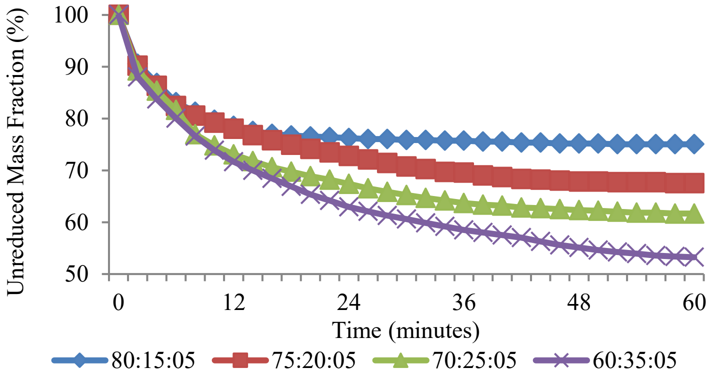

Fig. 7. Effect of coal composition on the unreduced mass fraction at 1000°C

Fig. 8 shows that increasing coal content leads to a lower unreduced mass fraction. At a reduction temperature of 1000 °C, the 60:35:5 composition exhibits the lowest unreduced mass fraction of 53.24%, indicating a higher degree of reduction compared to compositions with lower coal content. This behavior can be attributed to the increased availability of carbon, which enhances the formation of reducing gas within the briquette and promotes more effective oxygen removal from iron oxides. Similar behavior has been reported in previous studies, where higher carbon content resulted in lower unreduced mass fractions, confirming that coal content plays a critical role in improving the reduction extent of iron ore briquettes.

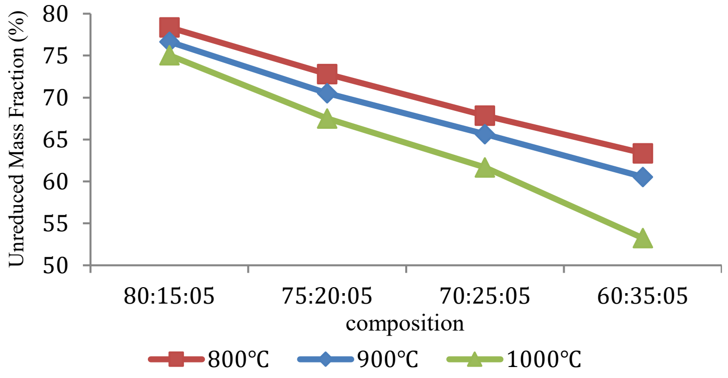

Fig. 8. Effect of coal composition on the unreduced mass fraction across all compositions

3.3 Effect of coal composition on reduction rate

The reduction rate constant (*k*) was obtained through regression analysis of unreduced mass versus time data, particularly from the initial phase of reduction (t = 0–6 minutes), during which the reaction proceeds rapidly, and the trend can be approximated as linear.

The reduction rate constant increases with higher coal content and reduction temperature, as shown in Fig. 9. This indicates faster reduction kinetics under these conditions. At 1000 °C, briquettes with a higher coal content show larger rate constant values, with the 60:35:5 composition displaying the highest reduction rate constant among the samples studied. This behavior suggests that increased coal content enhances the availability of reducing gas at the reaction interface, thereby accelerating gas-solid reduction reactions, especially in the early stages. A similar trend was reported by Rifqi [21], who noted that higher carbon content leads to increased rate constants at elevated reduction temperatures. This indicates that both carbon availability and temperature control the reduction kinetics of iron ore briquettes.

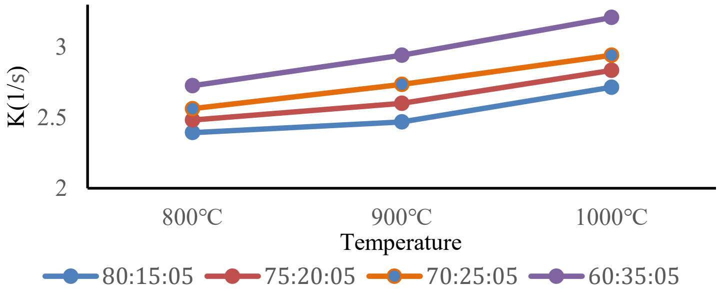

Fig. 9. Effect of coal composition on the reduction rate constant

3.4 Activation energy

The minimum energy required to initiate the reduction reaction was calculated using the Arrhenius equation. Table 3 presents the reduction rate constants (k), the corresponding ln k values, and the reciprocal temperature (1/T) for all briquette compositions at different reduction temperatures. These data serve as the basis for the kinetic analysis using the Arrhenius approach. The results show that the reduction rate constant increases with increasing temperature and coal content, indicating enhanced reaction kinetics under these conditions. The higher k values suggest that greater carbon availability promotes the formation of reducing gases, thereby accelerating the gas–solid reduction reaction.

Table 3. Presents the rate constants, ln *k*, and 1/*T* values for all compositions at different temperatures

Temperature (K)	Rate Constant	ln k	1/T
80:15:5			
1073	2.3935	0.872757	0.00093
1173	2.4704	0.90438	0.00085
1273	2.715	0.998792	0.00078
75:20:05			
1073	2.483	0.909468	0.00093
1173	2.6017	0.956165	0.00085
1273	2.8342	1.04176	0.00078
70:25:05			
1073	2.5635	0.941374	0.00093
1173	2.7357	1.006387	0.00085
1273	2.9412	1.078818	0.00078
60:35:5			
1073	2.7257	1.002725	0.00093
1173	2.9417	1.078988	0.00085
1273	3.2084	1.165772	0.00078

Fig. 10 illustrates the Arrhenius plots (ln k versus 1/T) for each briquette composition. The linear relationship observed confirms that the reduction process follows Arrhenius behavior within the investigated temperature range.

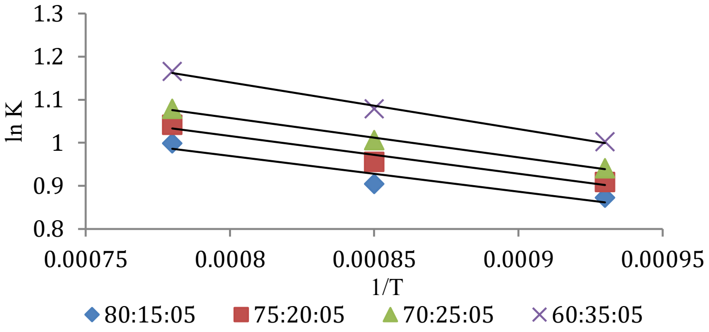

Fig. 10. shows the Arrhenius plots (ln *k* vs 1/*T*)

The slope of each line was used to determine the activation energy for the respective compositions. Differences in slope indicate variations in the dominant reduction mechanism as the coal composition increases, reflecting changes in reaction kinetics and energy requirements

As shown in Table 4, the activation energy increases with increasing coal content. The activation energy values for coal compositions of 15%, 20%, 25%, and 35% are 7.378, 7.557, 7.708, and 9.010 kJ/mol, respectively. This increase does not indicate a slower reduction process. Instead, it indicates a change in the controlling reduction mechanism. At higher coal contents, the reduction process is mainly governed by reduction by CO gas, which requires higher initial energy than simple surface reactions. Consequently, the activation energy calculated from the Arrhenius analysis increases, even though the overall reduction rate becomes faster.

Table 4. Summarizes the calculated activation energies

No.	Composition	Activation energy (kJ/mol)
1	80:15:5	7.378
2	75:20:5	7.557
3	70:25:5	7.708
4	60:35:5	9.010

4 Conclusion

The addition of coal to iron ore briquettes significantly affects reduction performance, impacting mass loss rate, reduction rate constant, and activation energy. The briquette with a composition of 60:35:5 achieved the highest mass reduction of 46.75% at 1000 °C and produced the highest rate constant of 3.2084 s^{-1}. Additionally, activation energy increased with coal content, reaching a peak of 9.010 kJ/mol at the highest coal proportion. These results indicate that while a higher coal content accelerates the reduction rate, it also requires more activation energy to initiate the reaction.

References

[1] "IISIA : The Indonesian Iron & Steel Industry Association." https://www.iisia.or.id/news/chairman-iisia-kebutuhan-baja-indonesia-diperkirakan-akan-mencapai-100-juta-ton-pada-tahun-2045 (diakses Okt 30, 2024).

[2] T. Hamonangan Simatupang dan Y. Sunitiyoso, "Developing The Strategy for Steel Sales by Scenario Planning Approach," J. World Sci., vol. 2, no. 10, hal. 1703–1722, 2023, doi: 10.58344/jws.v2i10.452.

[3] M. A. Mohammadi, A. R. Sayadi, M. Khoshfarman, dan A. Husseinzadeh Kashan, "A systems dynamics simulation model of a steel supply chain-case study," vol. 77, hal. 60, 2022, doi: 10.1016/j.resourpol.2022.102690.

[4] J. Park, E. Kim, I. K. Suh, dan J. Lee, "A short review of the effect of iron ore selection on mineral phases of iron ore sinter," Minerals, vol. 12, no. 1, 2022, doi: 10.3390/min12010035.

[5] I. H. Gonzalez dan J. Kamiński, "The iron and steel industry: a global market perspective," Gospod. Surowcami Miner. - Miner. Resour. Manag., vol. 27, no. 3, hal. 5–28, 2011.

[6] A. Hasanbeigi, M. Arens, dan L. Price, "Alternative emerging ironmaking technologies for energy-efficiency and carbon dioxide emissions reduction: A technical review," Renew. Sustain. Energy Rev., vol. 33, hal. 645–658, 2014, doi: 10.1016/j.rser.2014.02.031.

[7] K. Abdel Halim, "Future of Ironmaking: Review," Int. J. Mater. Technol. Innov., vol. 0, no. 0, hal. 0–0, 2022, doi: 10.21608/ijmti.2022.164452.1059.

[8] Khairil, Buku Ajar Bahan Bakar dan Tanur. Banda Aceh: Syiah Kuala University Press, 2018.

[9] D. Spreitzer dan J. Schenk, "Reduction of Iron Oxides with Hydrogen—A Review," Steel Res. Int., vol. 90, no. 10, 2019, doi: 10.1002/srin.201900108.

[10] J. Van Boggelen, H. Meijer, C. Zeilstra, H. Hage, dan P. Broersen, "HIsarna - Demonstrating low CO2 ironmaking at pilot scale," SteelVIA, no. April 2023, 2018, [Daring]. Tersedia pada: https://www.researchgate.net/publication/358826593_HIsarna_-_Demonstrating_Low_CO2_Ironmaking_at_Pilot_scale.

[11] X. Yuan, F. Luo, S. Liu, M. Zhang, dan D. Zhou, "Comparative study on the kinetics of the isothermal reduction of iron ore composite pellets using coke, charcoal, and biomass as reducing agents," Metals (Basel)., vol. 11, no. 2, hal. 1–11, 2021, doi: 10.3390/met11020340.

[12] S. Mishra, "Review on Reduction Kinetics of Iron Ore–Coal Composite Pellet in Alternative and Sustainable Ironmaking," J. Sustain. Metall., vol. 6, no. 4, hal. 541–556, 2020, doi: 10.1007/s40831-020-00299-y.

[13] Y. Man, J. X. Feng, F. J. Li, Q. Ge, Y. M. Chen, dan J. Z. Zhou, "Influence of temperature and time on reduction behavior in iron ore-coal composite pellets," Powder Technol., vol. 256, no. 7, hal. 361–366, 2014, doi: 10.1016/j.powtec.2014.02.039.

[14] W. Zhou et al., "Kinetics of Reduction of Iron Ore Powder by Industrial Lignin from Pulping and Papermaking Waste Biomass Energy," 2025.

[15] G. Zhang, Y. Sun, dan Y. Xu, "Review of briquette binders and briquetting mechanism," Renew. Sustain. Energy Rev., vol. 82, no. September 2017, hal. 477–487, 2018, doi: 10.1016/j.rser.2017.09.072.

[16] A. Rahwanto, M. Yahya, dan Z. Jalil, " Magnetic Behavior of Natural Fe_2O_3 from Lhoong Iron Ore Mining Area, Aceh Province, Indonesia ," J. Min., vol. 2013, hal. 1–4, 2013, doi: 10.1155/2013/212803.

[17] A. M. Bizhanov dan S. A. Zagainov, "Tests of Briquettes for Mechanical Strength," Metallurgist, vol. 65, no. 3–4, hal. 247–256, 2021, doi: 10.1007/s11015-021-01154-5.

[18] N. Ali, Khairil, dan M. Saputra, "Reduction Behavior of Briquette of Iron Ore and Low-Grade Coal from Aceh," J. Rekayasa Kim. dan Lingkung., vol. 13, no. 1, hal. 51–59, 2018.

[19] T. H. Al Furqan, "Experimental Study on the Effect of Low-Rank Coal Blending on the Reduction Behavior of Iron Ore Briquettes at High Temperature," ETD Unsyiah, 2019, [Daring]. Tersedia pada: https://etd.unsyiah.ac.id/index.php?p=show_detail&id=60932.

[20] A. Adhitya, Khairil, Sarwo Edhy S., "Experimental Study on the Strength of Reduced Iron Ore Briquettes Produced with Low-Rank Coal Using the Hot Briquetted Iron (HBI) Method," J. Tek. Mesin Unsyiah, vol. 8, no. 1, 2020.

[21] M. Rifqi, Khairil, dan S. Edhy, "Experimental Analysis of the Reduction Behavior of Iron Ore Briquettes from Lhoong Blended with Coal at Elevated Temperatures," J. Tek. Mesin Unsyiah, vol. 11, no. Juni, hal. 1–6, 2023.