Vol. 6, No. 10, October 2025
E-ISSN:2723 – 6692
P-ISSN:2723– 6595
http://jiss.publikasiindonesia.id/

The Effect of Metal Oxide Content on Ash Fusion Temperature (AFT) and Determination of Coal Slagging and Fouling Indices

Muhammad Fat'hul Rozaq
Universitas Mulawarman, Indonesia
Email: fathulrozaq04@gmail.com

KEYWORDS
Metal oxides; Ash Fusion Temperature; Slagging; Fouling; Coal

ABSTRACT

One of the abundant natural resources on Earth is coal, and one of its main uses is as fuel. The utilization of coal as an industrial fuel produces waste in the form of coal ash. The oxide composition of coal ash significantly influences the fusion temperature of the sample, which, in turn, affects the formation of slagging and fouling. Therefore, it is necessary to investigate the oxide composition of coal ash and its effect on the ash fusion temperature (AFT), as well as to determine the slagging and fouling indices. In this study, coal ash was melted and subsequently analyzed for its oxide composition, tested for ash fusion temperature (AFT), and evaluated for slagging and fouling indices. The results showed that high SiO_2 content combined with low Al_2O_3, Fe_2O_3, CaO, and MgO contents tends to decrease the AFT value. However, when both SiO_2 and Al_2O_3 contents are high and Fe_2O_3, CaO, and MgO contents are low, the AFT tends to increase. Furthermore, if the Fe_2O_3, CaO, and MgO contents are slightly higher than those of SiO_2 and Al_2O_3, the AFT also tends to increase. The calculated slagging and fouling indices indicated that almost all samples fall within the high to very high categories. These findings provide practical guidance for coal-fired power plant operators in Indonesia to predict and mitigate ash-related operational challenges, particularly in boiler design optimization and fuel blending strategies to minimize slagging and fouling occurrences, thereby improving combustion efficiency and reducing maintenance costs.

INTRODUCTION

One of the abundant natural resources found on Earth and widely used as an energy source is coal (Liu et al., 2023; Pang et al., 2024). Coal is a complex solid formed through geological processes, derived from high-level plants such as trees that have been buried beneath the Earth's surface for many years (Harrison, 2023). The classification of coal grades consists of lignite, sub-bituminous, bituminous, and anthracite, which are distinguished based on the length and degree of their geological formation (Smith & Johnson, 2023). Chemically, coal primarily contains carbon, along with other elements such as sulfur, hydrogen, and nitrogen, and in small amounts, it contains metal oxides including silica oxide, iron oxide, calcium oxide, aluminum oxide, and other metallic compounds (Harrison, 2023; Smith & Johnson, 2023).

Indonesia is one of the countries with abundant coal resources in the world (Admi et al., 2022; Ordonez et al., 2022). According to statistical data in 2022, Indonesia had coal reserves of 31.7 billion tons, with the largest reserves located in the provinces of South Sumatra, East

Kalimantan, South Kalimantan, and Riau (Syahril et al., 2023). Based on the calorific value of coal in Indonesia, the type of coal is considered low-grade if it has a calorific value of less than 5,100 calories per gram, and high-grade if it exceeds 7,100 calories per gram (Sembiring, 2022). The country's coal resources are essential not only for energy production but also as an important export commodity (Putra, 2023).

In Indonesia, coal is extensively used as fuel in the Steam Power Plant (PLTU) industry (Muliati & Rosdiana, 2024; Myson, 2025). The use of coal in coal-fired power plants produces several impacts on industrial equipment, including slagging and fouling. Slagging occurs due to the adhesion of molten coal ash to the walls of high-temperature heat conductors near the combustion chamber (furnace), whereas fouling takes place in heat transfer areas (re-heaters), where accumulated melted ash interferes with and inhibits the heat transfer process in the equipment (Prismantoko et al., 2023; Ghazidin et al., 2023; Kuswa et al., 2023). Slagging and fouling can be assessed through initial calculations, known as slagging and fouling indices, by determining the metal oxide content and Ash Fusion Temperature (AFT) value (Monika & Sulistyohadi, 2019; Ghazidin et al., 2024; Efendi et al., 2025; Kuswa et al., 2023).

The metal oxide content has a significant influence on the Ash Fusion Temperature (AFT) value and, consequently, on slagging and fouling behaviour (Yang et al., 2022). Several studies have examined the effect of metal oxide levels in coal ash on AFT values. For instance, Li et al. (2020) found that K_2O and Na_2O reduce the AFT under reduction conditions. According to Zhang et al. (2021), CaO and MgO also tend to lower the AFT. Research by Santoso et al. (2022) shows that AFT is directly proportional to SiO_2 and Al_2O_3 levels. Additionally, AFT increases as the coal slagging index rises (Zhang et al., 2023). Afni (2021) reported that three coal types—lignite, bituminous, and anthracite—demonstrated a correlation between AFT values and medium-category slagging index values.

Based on previous research, it is necessary to conduct a study to determine the effect of metal oxide content on Ash Fusion Temperature (AFT) and the slagging and fouling indices of several coal ash samples from a region in Indonesia. This study differs from earlier works by comprehensively analyzing multi-oxide interactions in Indonesian coal samples and establishing correlations between specific oxide combinations and their synergistic effects on AFT, slagging, and fouling behavior. While earlier studies primarily focused on individual oxide effects or limited coal types, this research examines ten diverse coal ash samples from Indonesian coal resources, thereby providing a more holistic understanding of oxide interaction mechanisms. The novelty lies in systematically correlating multiple oxide compositions (SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, and others) with both AFT measurements and calculated slagging-fouling indices, offering practical predictive tools for Indonesian coal utilization.

The urgency of this research is reinforced by the increasing operational challenges faced by Indonesian coal-fired power plants, where slagging- and fouling-related issues cause significant efficiency losses and higher maintenance costs. Understanding the relationship between ash chemistry and fusion behavior is essential for optimizing fuel selection, boiler design, and operational parameters. The industrial implications are considerable: power plant operators can use these findings to predict ash behavior, implement preventive measures, and develop effective fuel-blending strategies that minimize problematic ash deposition while maintaining combustion efficiency.

METHOD

This research employs an experimental quantitative study design using ASTM-based laboratory methods to characterize coal ash properties and determine slagging-fouling tendencies. Coal samples were collected from various coal-producing regions in Indonesia, representing diverse geological formations and coal ranks. The analytical approach integrates oxide composition analysis, AFT measurements, and index calculations, followed by correlation analysis to identify relationships between oxide composition and AFT values.

Sample preparation is based on the ASTM method, a sample of 4 kg is placed on a tray and dried at a temperature of 40°C in a drying shed, then reduced to a size of 0.25 mm. The coal that has been prepared is then burned in the furnace at a temperature of 500 °C for 1 hour and continued at a temperature of 750 °C for 2 hours.

0.1 grams coal ash with the addition of Lithium Tetraborate (Li2B4O7) as much as 1 gram is heated in the furnace for 15 minutes at a temperature of 1000 °C. The melt is dissolved with a 5% HCl solution by stirring and heating until it dissolves. Then the melted sample was diluted to a volume of 200 mL. For P2O5 analysis, coal ash was decomposed with the addition of concentrated HCl and HF solutions by 3-hour immersion heating, which was then diluted to 100 mL.

The analysis of metal oxide content was carried out using the ASTM method using the Atomic Absorption Spectrophotometer (AAS) instrument for the metals TiO2, SiO2, Al2O3, Fe2O3, CaO, MgO, Na2O, K2O and MnO4, in this analysis using flames from nitrous oxide (N2O), acetylene (C2H2) and free air gases. Cathode lamps with specific wavelengths. The UV-Vis spectrophotometer instrument is used for P2O5 analysis and the sulfur analyzer for SO3 analysis.

AFT testing uses the ASTM method, coal ash samples are printed in a triangular cone which is then analyzed on the AFT device with free air flow in oxidation conditions and CO and CO2 gas flow in reduction conditions, changes in the shape of the sample are observed with a camera connected directly to the computer.

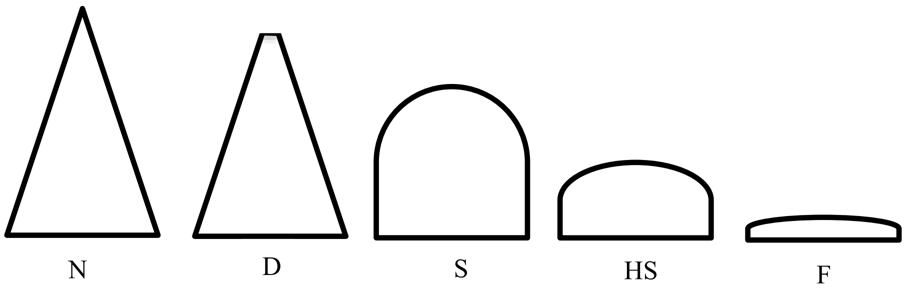


Figure 1. Change in the shape of the AFT test sample

N : Normal
D : Deformation (Loss of Shoots/Tops)
S : Sphere (Tinggi = Lebar Alas)
HS : Hemisphere (Tinggi = ½ Tinggi Alas)
F : Flow (High = 1/3 High HS)

Data analysis techniques include descriptive statistics for oxide composition characterization and correlation analysis to examine relationships between oxide compositions and AFT values. Slagging and fouling indices are calculated using established empirical formulas, and the results are categorized according to standard classification schemes to assess ash behavior tendencies.

For the slagging index using the formula:

$$fs = \frac{4D + HS}{5}$$

For the Fouling index use the formula:

$$fu = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Tio_2 + Al_2O_3} X (Na_2O + K_2O)$$

For the acid-base ratio index use the formula:

$$R\frac{b}{a} = \frac{Fe_2O_3 + CaO + MgO + Na_2O + K_2O}{SiO_2 + Tio_2 + Al_2O_3}$$

For the viscosity index of slag use the formula:

$$SR = 100 X \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO}$$

Table 1. Categories Slagging, Fouling, acid-base and viscosity index

Index	Category			
	Low	Intermediate	High	Very High
Fs	>1343˚C	1232-1343 ˚C	1149-1232 ˚C	<1149 ˚C
Was	<0.6	-	0,6-40	>40
Rb/a	<0.206	0,206-0,4	>0,4	-
SR	>78,8	66,1-78,8	<66.1	-

RESULTS AND DISCUSSIONS

Metal Oxide Analysis

Metal oxide content analysis was conducted using Atomic Absorption Spectrophotometer (AAS) instruments except for P2O5 analysis UV-Vis and SO3 spectrophotometers were used using sulfur analyzers. The results of the metal oxide content analysis in table 2 show various variations in values from the 10 samples tested. Samples with codes T4 and T5 had high SiO2 levels of 54.4% and 54.45%, inversely proportional to Fe2O3 levels of 6.75% for T4 and 11.71% for T5, CaO of 6.75% for T4 and 9.34% for T5 and MgO of 13.55% for T4 and 11.36% for T5. In addition, in contrast to samples with the code T1 where low SiO2 levels were 10.05%, inversely proportional to high levels of Fe2O3, CaO and MgO, which were 21.00%, 17.31% and 22.56%. For SO3 levels, it is relatively low, but there are two samples with levels of more than 10%, namely samples with codes T8 and T9. From the entire sample, the lowest level was P2O5 in the T1 sample of 0.01%.

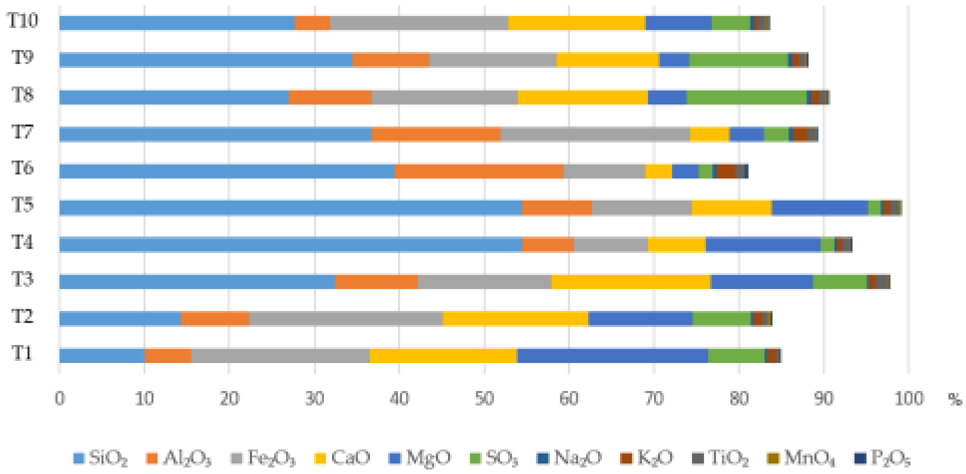
Chart 1 shows the comparison of the composition of metal oxides from ten samples, from the chart it appears that the composition of the sample is dominated by SiO2, Al2O3, Fe2O3, CaO, and MgO and in small amounts consists of Na2O, K2O, TiO2, MnO4 and P2O5

Table 2. Results of metal oxide content analysis

Sample	Metal Oxide (%)										
	SiO2	Al2O3	Fe2O3	Tall	MgO	Na2O	K2O	TiO2	MnO2	P2O5	SO3
T1	10,05	5,50	21,00	17,33	22,56	0,30	0,95	0,32	0,17	0,01	6,60
T2	14,31	8,00	22,80	17,21	12,31	0,32	1,00	0,61	0,40	0,03	6,78

T3	32,51	9,72	18,80	18,80	11,96	0,19	0,84	1,41	0,16	0,06	6,43
T4	54,44	6,14	6,75	6,75	13,55	0,30	0,59	0,91	0,15	0,09	1,56
T5	54,45	8,29	11,71	9,34	11,36	0,24	0,83	1,07	0,17	0,06	1,58
T6	39,50	19,81	9,70	3,16	3,12	0,51	2,17	1,06	0,05	0,44	1,60
T7	36,77	15,15	22,37	4,54	4,04	0,51	1,70	0,98	0,09	0,18	2,96
T8	29,96	9,81	17,19	15,33	4,60	0,47	0,93	0,77	0,24	0,12	14,14
T9	34,50	9,02	15,07	12,00	3,57	0,46	0,83	0,72	0,21	0,13	11,62
T10	27,64	4,23	21,02	16,15	7,78	0,49	0,42	0,93	0,36	0,11	4,43

Chart 1. Comparison of Metal Oxide Composition Ten Samples



Ash Fusion Temperature (AFT) Testing

The results of the AFT test in table 3 show a wide variety of temperature variations from the ten samples. In the reduction condition, the lowest temperature of deformation was 1080°C in the T7 and T8 samples, while the highest temperature of deformation was 1280°C in the T6 sample. Then the lowest flow was in the T8 sample with a temperature of 1120°C and the highest in the T1 sample with a temperature of 1350°C. The oxidation condition showed the lowest deformation temperature of 1165°C in the T5 sample and the highest in the T6 sample with 1340°C, while the highest flow temperature was 1380°C in T6 and the lowest in T10 with a temperature of 1210°C.

The melting point in the sample is influenced by many factors, one of the causes of which is the composition of the metal oxides contained in the sample. The presence of Fe2+, Ca2+ and Na2+ ions will cause a breakdown of the bond between oxygen and silica (Si-O-Si or Si-O-Al) which will cause a decrease in AFT values (Zhou et al, 2023).

Table 3. Ash Fusion Temperature (AFT) analysis results in °C

	Reduction				Oxidation			
	D	S	HS	F	D	S	HS	F
T1	1250	1330	1340	1350	1250	1310	1340	1360
T2	1250	1280	1290	1320	1310	1320	1330	1340
T3	1200	1220	1225	1230	1210	1220	1230	1240
T4	1180	1240	1260	1290	1170	1250	1270	1300
T5	1150	1180	1200	1240	1165	1180	1220	1250
T6	1280	1300	1310	1320	1340	1360	1370	1380
T7	1080	1130	1160	1190	1230	1260	1290	1300
T8	1080	1090	1100	1120	1210	1220	1225	1230

T9	1130	1140	1150	1160	1210	1120	1230	1240
T10	1150	1160	1170	1180	1180	1200	1205	1210

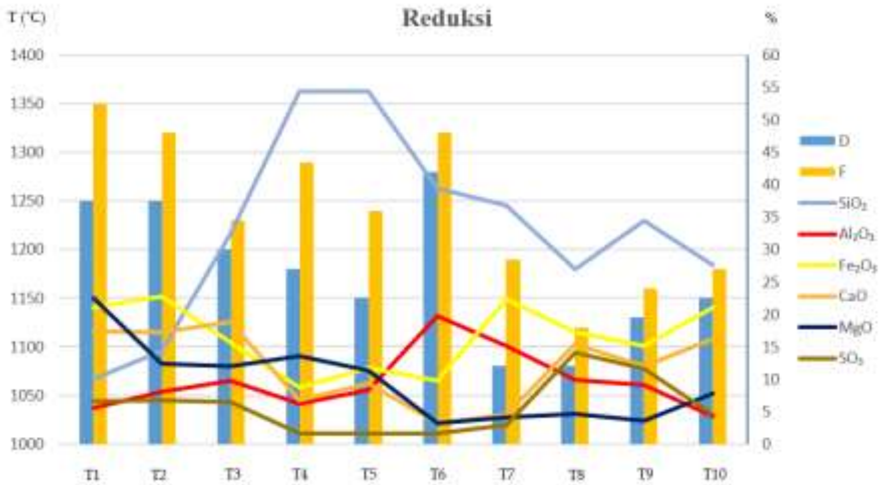
Results of Calculation of Slagging, Fouling, Viscosity and Acid-Base Index

Table 4. Results of Calculation of Slagging, Fouling, Viscosity and Acid-Base Index

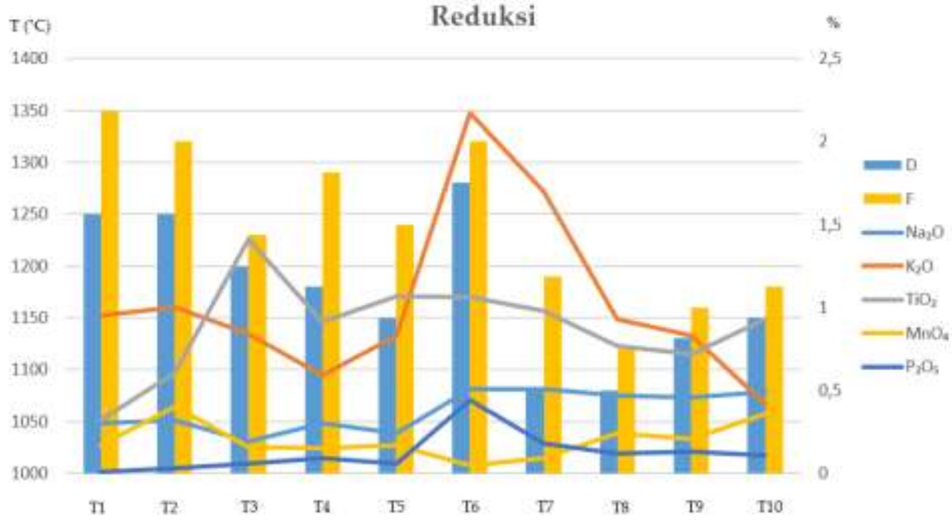
Sample	Index							
	fs		was		Rb/a		SR	
T1	1268	M	4,89	H	3,92	H	14,17	H
T2	1258	M	3,09	H	2,34	H	21,48	H
T3	1205	H	1,12	H	1,09	H	41,17	H
T4	1196	H	0,43	L	0,49	H	65,19	H
T5	1160	H	0,56	L	0,52	H	62,69	H
T6	1286	M	0,83	H	0,31	M	71,20	M
T7	1096	VH	1,39	H	0,63	H	54,30	H
T8	1084	VH	1,44	H	1,03	H	42,07	H
T9	1134	VH	0,93	H	0,72	H	52,96	H
T10	1154	H	1,27	H	1,40	H	38,08	H
	L=Low M=Medium H=High VH=Very High							

Table 4 shows the results of the calculation of the Slagging, Fouling, Viscosity and acid-base indices of the ten samples used. Samples with codes T7, T8 and T9 showed a high category slagging index with the lowest value of 1084°C in the T8 sample so that when viewed from this value the sample was not good enough, for the medium category of 1268°C in the sample with Jode T1, so when viewed from this value the sample was not good enough. Then the sample with codes T4 and T5 showed a low category fouling index of 0.49 and 0.52, so it was a fairly good sample, for the high category of 4.89 in the T1 sample. Then for the acid-base index and viscosity, there is one sample in the middle category, namely T6, which is 0.31 for the acid-base index and 71.20 for the viscosity index, while for the high category with an acid-base index of 3.92 and a viscosity index of 14.17, namely in the sample with the code T1.

Effect of metal oxide content on Ash Fusion Temperature (AFT) value



Graph 1. Correlation of SiO2, Al2O3, Fe2O3, CaO, MgO and SO3 Levels to AFT Values under Reduction Conditions

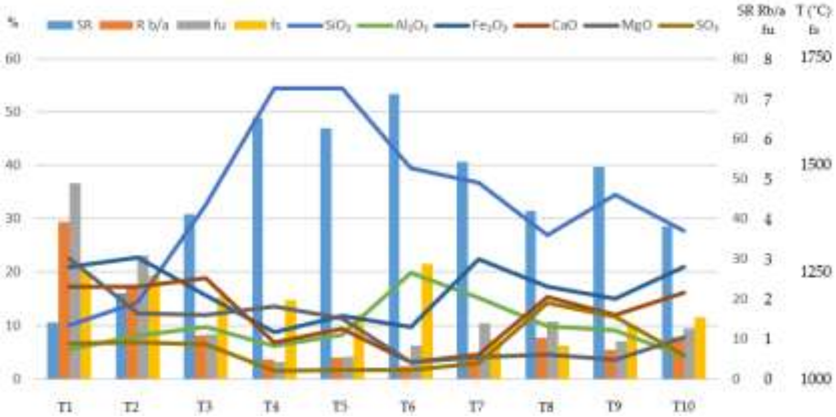


Graph 2. Correlation of Na2O, K2O, TiO2, MnO4 and P2O5 Levels to AFT Values under Reduction Conditions

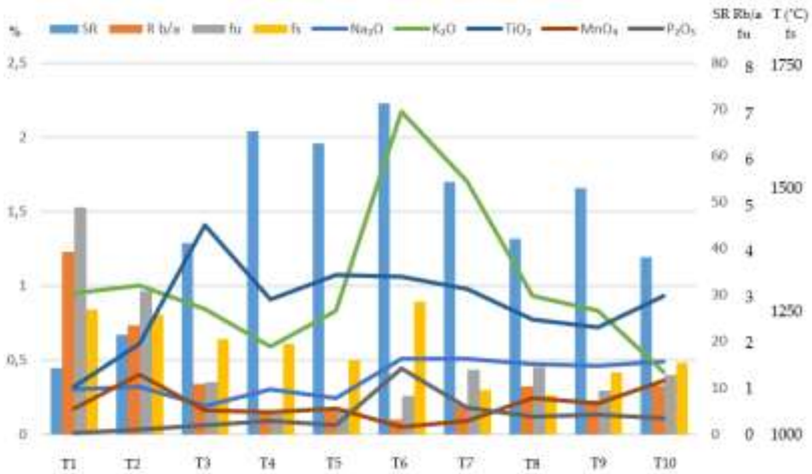
From graph 1, it shows that the T4 and T5 samples have high SiO2 levels inversely proportional to the AFT values which tend to be lower, this is also strengthened by the results of research conducted by (Lachman et al, 2021) that SiO2 levels of more than 40% can reduce the AFT value to less than 1100°C in the deformation state. Meanwhile, in T1 and T2 samples that had relatively low levels of SiO2 and Al2O3 compared to Fe2O3, relatively higher CaO and MgO tended to increase the AFT value. However, if the dominant Fe2O3 level is higher than the others, it will decrease the AFT value due to the formation of the crystalline mineral hematite (Suyatno, 2024). Relatively high levels of MgO will increase the AFT value because Mg will form the mineral $MgAl_2O_4$ which has a stable lattice structure so that it will be difficult to melt (Zhang et al, 2021). Then if a higher CaO level can increase the melting point of the sample due to the formation of Ca2SiO4 compounds (Wang, 2020). Another sample, namely T6, which has high levels of SiO2 and Al2O3, is directly proportional to the increase in AFT values, this is relevant to research that has been conducted by (Zhang et al, 2023) showing that high levels of SiO2 and Al2O3 cause high Ash Fusion Temperature (AFT) values in the deformation state. In the study (Li et al, 2021) it was reported that high levels of K2O and Na2O will reduce AFT values, but in graph 2 above the sample with code T6 has a fairly high level of K2O but does not show a significant decrease in AFT values, this is because the levels of Na2O are not high enough so that they do not have much effect on the decrease in AFT values. The high composition of K2O and Na2O will form the mineral (Na,K)AlSiO4 which will decrease the AFT value, while if the Na2O ratio is lower, it will form the mineral KalSi2O6 which causes an increase in the AFT value (Li et al, 2021).

.

Effect of metal oxide content on slagging, fouling, acid-base and viscosity index values



Graph 3. Correlation of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO and SO_3 Levels to slagging, fouling, acid-base and viscosity indices



Graph 4. Correlation of Na_2O, K_2O, TiO_2, MnO_4 and P_2O_5 Levels to slagging, fouling, acid-base and viscosity indices

Based on graph 3, it can be seen that the SiO_2 level is directly proportional to the viscosity index, in samples with codes T4, T5 and T6 showing that the high SiO_2 level is also in line with the high viscosity index. In samples with codes T4 and T5, it can also be seen that the higher the SiO_2 level, the lower the fouling index. This result is also shown by research conducted by (Listiyowati et al, 2023) relatively high SiO_2 levels will be inversely proportional to the decreased fouling index. Relatively low Fe_2O_3 and SO_3 content will reduce the slagging and fouling index (Prayoga et al, 2025), seen in samples with T5 codes with relatively low Fe_2O_3 and SO_3 levels also reduce the slagging and fouling index. MgO levels also affect the value of the slagging index, in the T1 and T2 samples, it shows that the higher the MgO level, the higher the slagging index, this data is also relevant to what was done by (Suyatno et al, 2024) which shows that MgO levels will be linear with the slagging index. The combination of relatively high SiO_2, K_2O and Na_2O content will form minerals $KNa_3(AlSiO_4)_4$, $NaAlSiO_4$ and $KalSi_3O_8$ which can lower the melting point of the sample thereby increasing the slagging index (Liang, 2025).

The effect of the Ash Fusion Temperature (AFT) value on the value of the slagging index, fouling

From graph 5 shows that the slagging index is always directly proportional to the AFT value and is slightly higher than the AFT value, research conducted by (Listiyowati et al, 2023) also shows that a lower AFT value will tend to lower the slagging index. The graph also shows that the viscosity index is inversely proportional to the fouling and acidity index, an increase in the viscosity index will decrease the fouling index and the acid-base index. The acid-base index tended to follow the AFT value and the slagging index, in the T6 sample showed a high acid-base index also followed by a high AFT value and slagging index.

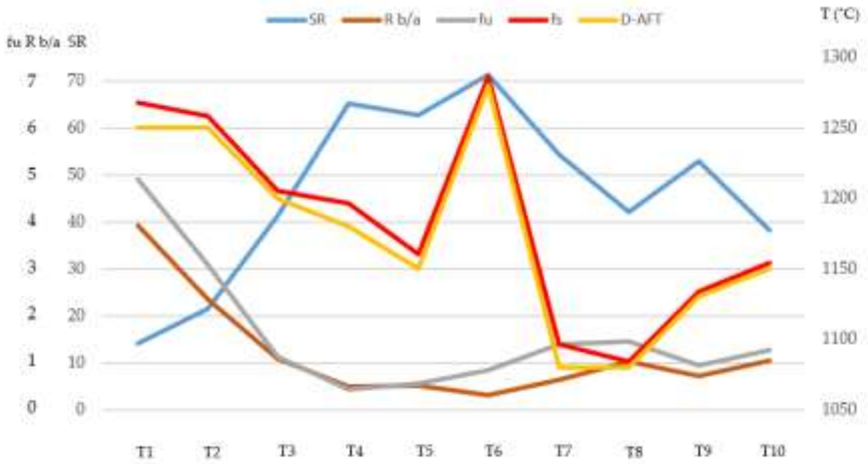


Chart 5. The relationship between AFT values and Slagging, Fouling, acid-base and viscosity Index

CONCLUSION

This study on the effects of metal oxide composition on ash fusion behavior in Indonesian coal highlights complex, concentration-dependent interactions that shape slagging and fouling tendencies. Dominated by SiO_2 (up to 54.45%) and with minimal P_2O_5 (0.01%), the samples exhibit wide AFT variability (1080°C–1380°C) under different atmospheres. Variations in SiO_2, Al_2O_3, Fe_2O_3, CaO, and MgO determine whether stable aluminosilicate networks form to raise AFT or eutectic melts develop to lower it, while moderately elevated flux oxides can increase AFT before reversing at high levels. Most samples fall into High to Very High slagging categories, with fouling indices generally elevated, underscoring the operational need for mitigation measures such as fuel blending and optimized heat management in coal-fired plants. The established correlations between oxide composition, AFT, and operational indices offer predictive value for fuel selection and plant efficiency. Future research should involve pilot-scale combustion trials to validate laboratory outcomes in real-world settings and refine blending strategies to balance ash behavior, efficiency, and emissions compliance.

REFERENCES

Admi, R., Saleh, S., & Fitrianto, G. (2022). The analysis of coal competitiveness and the factors affecting Indonesia's coal exports to main destination countries (a case of 8 destination countries). *Journal of Developing Economies*, *7*(1), 15–28.

Afni, N. (2021). *Analisis potensi pembentukan slagging pada tiga jenis batubara dengan menggunakan AFT di PT Geoservices*. Politeknik AKA Makassar, Makassar.

Efendi, M. A. A., Ghazidin, H., & Suyatno, S. (2025). Product evaluation and analysis of slagging-fouling potential. *Chemical Engineering, 9*(3), 1–12. https://doi.org/10.1016/j.ce.2025.01.001

Ghazidin, H., Suyatno, S., & Darmawan, A. (2024). Slagging, fouling, and corrosion potential during the co-firing of Indonesian coal and solid recovered fuel. *AIP Conference Proceedings, 3069*(1), 020107. https://doi.org/10.1063/5.0092345

Ghazidin, H., Suyatno, S., & Ruhiyat, A. S. (2023). Slagging-fouling evaluation of empty fruit bunch and palm kernel shell co-firing in coal-fired power plants. *Energy Reports, 9*, 1–10. https://doi.org/10.1016/j.egyr.2023.01.001

Harrison, R. (2023). Geological processes and coal formation. Earth Science Journal, 58(3), 112–118.

Kuswa, F. M., Prabowo, & Darmawan, A. (2023). Investigation of slagging fouling aspect of palm fiber and palm leaves waste in drop tube furnace. In *Proceedings of the 6th Mechanical Engineering, Science and Technology International Conference (MEST 2022)* (pp. 15–23). Atlantis Press. https://doi.org/10.2991/978-94-6463-134-0_3

Lachman, J., Baláš, M., Lisý, M., Lisá, H., Milčák, P., & Elbl, P. (2021). An overview of slagging and fouling indicators and their applicability to biomass fuels. *Fuel Processing Technology, 217*, 106804. https://doi.org/10.1016/j.fuproc.2021.106804

Li, J., Chen, X., Wang, B., Zhang, W., Zhang, Y., Guo, J., Zhang, W., Ge, Z., & Sun, Q. (2021). Effects of sodium and potassium on fusion characteristics of petroleum coke ash with high vanadium and nickel. *Fuel, 303*, 122177. https://doi.org/10.1016/j.fuel.2021.122177

Li, X., Zhi, L., Shi, W., Kong, L., Bai, J., Yu, J., Reinmöller, M., Guhl, S., Meyer, B., & Li, W. (2020). Effect of K_2O/Na_2O on fusion behavior of coal ash with high silicon and aluminum level. *Fuel, 265*, 116964. https://doi.org/10.1016/j.fuel.2019.116964

Liu, M., Baisheng, S., Alharthi, M., Hassan, M. S., & Hanif, I. (2023). The role of natural resources, clean energy and technology in mitigating carbon emissions in top populated countries. *Resources Policy*, *83*, 103705.

Liang, H., Yi, J., Yang, Y., Zhang, L., Ma, T., Chen, W., Liu, H., & Che, D. (2025). Study on the mechanism of multiple sodium salts co-loading on ash fusibility and mineral evolution behaviors. *Fuel, 397*, 135397. https://doi.org/10.1016/j.fuel.2025.135397

Listiyowati, L. N., Mubarok, M. Z., Sanwani, E., & Santoso, I. (2023). Study on the slagging behavior of bio-coal ash based on composition, ash fusion temperature, and calculated critical-viscosity-temperature. In *5th International Seminar on Metallurgy and Materials (ISMM2022)* (AIP Conference Proceedings, Vol. 3003, 020060). AIP Publishing. https://doi.org/10.1063/5.0186089

Muliati, M., & Rosdiana, R. (2024). The Impact Of The Construction Of A Steam Power Plant (PLTU) In The Socio-Economic Life Of The Community In Lampoko Village, Balusu District, Barru Regency. *Jurnal Ekonomi*, *13*(03), 1012–1024.

Monika, I., & Sulistyohadi, F. (2019). Ash deposit characteristics of blended coal in coal-fired power plants. Indonesian Mining Journal, 22(1), 49–60. https://doi.org/10.30556/imj.v22i1.675

Myson, M. (2025). Comparative Reaction of Substitution of Diesel-fueled Steam Power Plant and Coal-fueled Steam Power Plant. *International Journal of Technology, Education and Social Humanities*, *3*(2), 71–78.

Nasir, S. (2022). *Pemanfaatan Batubara*. Unsri Press.

Ordonez, J. A., Jakob, M., Steckel, J. C., & Fünfgeld, A. (2022). Coal, power and coal-powered politics in Indonesia 1. In *The Political Economy of Coal* (pp. 281–299). Routledge.

Pang, L., Liu, L., Zhou, X., Hafeez, M., Ullah, S., & Sohail, M. T. (2024). How does natural resource depletion affect energy security risk? New insights from major energy-consuming countries. *Energy Strategy Reviews*, *54*, 101460.

Prayoga, M. Z. E., Putra, H. P., Wargadalam, V. J., Surachman, H., Luktyansyah, I. M., Saudah, S., Darmawan, A., Aziz, M., Prabowo, P., Wang, Y., Vuthaluru, H. B., & Hariana, H. (2025). Thermal characteristics and slagging-fouling analysis in co-combustion of coal and oil palm waste mixtures. *Energy, 319*, 134908. https://doi.org/10.1016/j.energy.2025.134908

Putra, I. B. G. P. (2023). The role of coal resources in Indonesia's energy and economic sector. Journal of Energy and Environmental Sustainability, 14(3), 112–120. https://doi.org/10.1016/j.jees.2023.02.006

Prismantoko, A., Ghazidin, H., Solikhah, M. D., Sugiyono, A., Maulana, I., & Hariana. (2023). Potential for slagging, fouling, and abrasion during co-firing of Indonesian bituminous coal and hardwood waste pellet. International Journal of Application on Sciences, Technology and Engineering, 1(1), 210–216. https://doi.org/10.24912/ijaste.v1.i1.210-216

Santoso Ali, A. M., Syaiful, A. Z., & Gazali, A. (2022). Pengaruh senyawa alumina (Al_2O_3) dan silika (SiO_2) dalam kualitas batubara. *SAINTIS, 3*(1), 1–7.

Sembiring, H. (2022). Classification and quality of coal in Indonesia: A review. Journal of Coal Science, 28(4), 249–256. https://doi.org/10.1016/j.jcs.2022.08.004

Smith, T., & Johnson, P. (2023). The classification of coal grades and their geological significance. International Journal of Earth Sciences, 39(4), 289–295. https://doi.org/10.1016/j.ijes.2023.05.008

Suyatno, S., Ghazidin, H., Prabowo, P., Kuswa, F. M., Putra, H. P., Ruhiyat, A. S., Karuana, F., Soleh, M., Utomo, S. M., Prismantoko, A., Abimanyu, H., Darmawan, A., & Hariana, H. (2024). Investigation of slagging-fouling and mineral contents in low-rank coals for improved combustion performance. *Combustion Science and Technology*. Advance online publication. https://doi.org/10.1080/00102202.2024.xxxxxx

Syahril, F., Putra, I. M., & Nasution, A. H. (2023). Coal mining in Indonesia: Geography, reserves, and sustainability issues. Indonesian Journal of Geology and Energy, 17(2), 67–75. https://doi.org/10.1016/j.ijgeoe.2023.01.003

Wang, Y. (2020). Effect of sodium and calcium on the ash fusion temperatures of Zhundong coal. *Journal of Thermal Analysis and Calorimetry*. https://doi.org/10.1007/s10973-020-09469-2

Yang, L. I., Wei, Z., & Yi-tian, F. (2022). Modification of ash fusion behavior of high ash fusion temperature (AFT) coal by textile dyeing sludge addition and its mechanism. *Journal of Fuel Chemistry and Technology*, *50*(6), 703–713.

Zhang, J., Liu, Z., Li, X., Wang, B., Teng, Z., & Han, K. (2023). Study on slagging characteristics of co-combustion of meager coal and spent cathode carbon block. *Energies, 16*(2), 736. https://doi.org/10.3390/en16020736

Zhang, L., Wang, J., Wei, J., Bai, Y., Song, X., Xu, G., Pan, Y., & Yu, G. (2021). Synergistic effects of CaO and MgO on ash fusion characteristics in entrained-flow gasifier. *Energy & Fuels, 35*(1), 425–432. https://doi.org/10.1021/acs.energyfuels.0c03358

Zhou, Q., Deng, W., Xu, Y., Ma, X., & Gao, N. (2023). Investigation on ash fusion characteristics during the co-gasification of coal and textile dyeing sludge. *Journal of Thermal Analysis and Calorimetry, 148*, 14011–14022. https://doi.org/10.1007/s10973-023-12687-z