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Article

Management and Utilization of Fly Ash Containing High Free-Lime and Sulfur Trioxide Contents

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Abstract. This study focuses on managing fly ashes with elevated free lime and sulfur trioxide contents, which are produced at a coal-fired power plant. Two techniques are employed for this purpose. The first technique involves pre-combustion, where correlations between coal and fly ash properties are established to estimate the properties of the resulting fly ash. Statistical analysis was performed on six years' worth of data on coal and fly ash properties provided by the power plant, including coal ash and fly ash analyses, to establish these correlations. These relationships not only help to produce fly ash with desired properties but also help to separate, collect, and manage the off-standard fly ash with undesired properties. The second technique is a post-combustion approach, specifically fly ash blending. An extensive experimental program was conducted to investigate the effects of blending high-free lime fly ash with low-free lime fly ash to be able to utilize the fly ash with high free lime content in the concrete industry. Three types of fly ashes were derived from 2 sources, and free lime was added up to increase the free lime content in these fly ashes. Subsequently, six blended fly ashes were prepared by mixing low and high-free lime fly ashes to evaluate their properties. Various tests, including water requirement, setting times, compressive strength, autoclave expansion, expansion due to alkali-aggregate reaction, and sulfate expansion, were conducted on the blended fly ash mixtures. When compared with the results of a previous study, the performance of the mixtures with the blended fly ashes fell between those of the mixtures containing high and low-free lime fly ashes. This finding indicates that the blending technique holds promise in addressing the issue of high-free lime fly ash effectively.

Keywords: Blending, coal ash, coal combustion, durability, free lime, fly ash, sulphur trioxide, waste management.

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1. Introduction

Coal plays a crucial role in the global energy system, serving as one of the primary sources of fuel for electricity generation. Approximately 40% of the world's electricity production is derived from coal, and this proportion is expected to remain significant in the coming decades [1]. As a by-product of coal burning, various materials are produced, including coal ashes, boiler slag, and flue gas desulphurization by-products [2–5]. Among these, fly ash, an industrial residue resulting from coal combustion, constitutes a major component of coal ash and has found extensive use as a partial substitute for cement for concrete production.

Numerous aspects of power plants influence the properties of fly ash, including the type, chemical compositions, and source of the coal, as well as boiler type, burning process, temperature, and emission control procedures. Due to the variations in these factors, the properties of the resulting fly ashes fluctuate significantly. As a consequence, the direct application of different international standards becomes challenging.

The primary source of fly ash production in Thailand is the Mae Moh power plant, operated by the Electricity Generating Authority of Thailand (accounting for approximately 90% of the country's total national production [6]. Recently, the fly ash from the Mae Moh power plant has exhibited elevated levels of free lime and sulfur trioxide, which can result in undesirable volumetric expansion when used as a binder in concrete mixtures.

Standards such as ASTM C618 [7] impose a limit of 5% for the SO_3 content in fly ash, but no specific limit is mentioned for the free lime content in ASTM and several other standards. However, EN 450 [8] sets a maximum allowable free lime content of 1% for fly ash. In cases where fly ashes contain up to 2.5% free lime content, it is advisable to conduct the autoclave expansion test to assess the volumetric expansion of the cement-fly ash mixtures. This test helps in understanding the potential impact of free lime content on the behavior of the concrete mixture.

In separate research studies, Kaewmanee et al. [9] and Nawaz et al. [10] extensively investigated the utilization of fly ashes with high free lime contents in fly ash mixtures.

Kaewmanee et al. [9] reported that even high-free lime fly ashes, with a free lime content of 4.51%, exhibited satisfactory performance when incorporated into cement-fly ash mixtures.

Conversely, Nawaz et al. [10] focused on the influence of fly ashes with high free lime and elevated SO_3 contents on the performance of fly mixtures. They found that fly ashes containing SO_3 content below 5% and free lime contents up to 4.23% showed adequate performance. For fly ashes with higher SO_3 content, specifically between 5% and 10%, Nawaz et al. [10] recommended reducing the acceptable limit of free lime content to 3.73%. This adjustment ensures optimal performance in fly ash mixtures.

These valuable findings offer crucial insights into the behavior of high-free lime fly ashes and their interaction with cement in various mixtures, providing essential guidance for engineers and researchers in effectively utilizing these materials in concrete applications.

Indeed, the studies conducted by Kaewmanee et al. [9] and Nawaz et al. [10] proposed specific limits for free lime content in the fly ashes. However, the amounts of free lime and SO_3 in Mae Moh fly ash occasionally exceed these suggested limits. Such very high free lime and high SO_3 contents in fly ash can discourage its usage as a binder in concrete leading to the wastage of the fly ash. Consequently, these unacceptable fly ashes end up being disposed of in landfills, posing potential threats to the environment.

To address this issue, effective management of fly ash containing high free lime and SO_3 contents becomes essential. Finding ways to make such fly ash valuable for the concrete industry would be highly beneficial and preferable. This could involve implementing suitable treatment or blending techniques to modify the fly ash properties, making it suitable for use in concrete and minimizing its environmental impact. Proper management strategies would not only reduce environmental concerns but also optimize the utilization of this industrial by-product, contributing to sustainable practices in the construction sector.

In this study, two techniques are proposed to address the management of Mae Moh fly ash with high free lime and high SO_3 contents. The first method involves a pre-combustion analysis technique, which aims to establish correlations between the coal properties and the resulting fly ash. This allows for the estimation of fly ash properties before the coal combustion process takes place. At the power plant, data on both coal and resulting fly ash properties are periodically collected. However, these valuable datasets have not been effectively utilized to optimize coal and fly ash management practices. By developing correlations between coal and fly ash properties, the pre-combustion analysis technique enables power plant operators and managers to predict the properties of the produced fly ash based on the properties of the coal. This predictive capability can be beneficial for planning and decision-making, as it provides valuable insights into the quality and characteristics of the fly ash that will be generated during the combustion process. Moreover, this technique aids in producing desired fly ash characteristics and managing off-standard fly ashes at power plants for better quality control and management. As a result, the proper utilization of this technique can contribute to more efficient management of coal and fly ash resources and facilitate their appropriate application in concrete and construction industries, thereby minimizing waste and environmental impact.

The second technique involves blending the fly ash having high free lime content with the fly ash having low free lime content for use in the concrete. However, the properties of concrete with blended fly ash haven't been studied yet. Therefore, it's crucial to investigate the effects of blended high-low-free lime fly ash on the properties of blended fly ash concrete mixtures. By combining pre-combustion and post-combustion analysis techniques, all fly ashes from the power plant can be fully utilized instead of being discarded as waste.

2. Research Methodology

2.1. Method 1: Pre-Combustion Analysis Technique

In this method, six-year data (2008-2013) from the Mae Moh thermal power plant in Thailand was analyzed. The data includes the used coal properties and the resulting fly ash properties (see Table 1). The statistical data on the properties of coal and fly ash were provided by the Electricity Generating Authority of Thailand. The coals were stored at different stocking locations and were fed to the power plant through four different conveyor belts (lines 1 to 4). These four lines serve ten power plant units (1 to 10). For a visual representation, refer to Fig. 1 showing the diagram of the conveyors, power plant units, and the resulting fly ash.

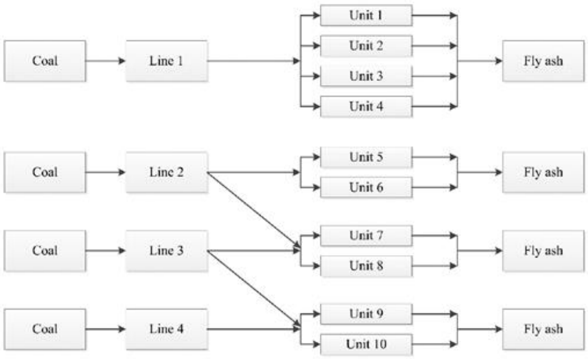


Fig. 1. Diagram of conveyors, power plant units, and fly ash.

From Fig. 1 it is noted that:
- Line 1 fed coal to Units 1 to 4.
- Line 2 fed coal to Unit 5 and Unit 6
- Line 3 fed coal to Unit 7 and Unit 8
  whereas Line 2 fed coal when Line 3 could not feed.
- Line 4 fed coal to Unit 9 and Unit 10 whereas Line 3 fed coal when Line 4 could not feed.

To establish connections between coal and fly ash properties, a synchronization process was undertaken for coal and fly ash data on a daily and shift basis, encompassing all conveyors and power plant units. As can be seen, the fly ash properties produced from Units 1 to 4 were paired with the coal properties from Line 1 for each day. Statistical analysis software was employed to derive correlations between the properties of coal and fly ash.

2.2. Method 2: Post-Combustion Analysis Technique

In this method, high-free lime and low-free lime fly ashes were blended and incorporated into cement-fly ash mixtures. The basic and durability properties of the mixtures were then tested to analyze the effects of blending these fly ashes. The fly ashes were used to replace cement partially at 20% and 40% levels. The performance of the blended fly ash mixtures was compared to a previous study by Nawaz [11] that investigated the performance of high-free lime and low-free lime fly ash mixtures separately.

Materials: Ordinary Portland cement type I (OPC) conforming to ASTM C150 [12] and TIS 15 [13] and 3 original fly ashes, F(A) and F(C) from the Mae Moh power plant, and F(R) from the BLCP power plant were used in this research. Table 2 displays the chemical compositions of these binders.

F(R) was classified as Class 2a, which is low CaO fly ash, while F(A) and F(C) were categorized as Class 2b, which is high CaO fly ash according to TIS 2135 [14]. Additionally, F(C) had an SO_3 content that exceeded the maximum limit of 5% as per TIS 2135 [14]. Two more fly ashes, F(A10) and F(C10) were prepared by adding external free lime to F(A) and F(C), respectively, resulting in a total free lime content of 10%. Table 3 presents the physical properties of the materials used. River sand with a specific gravity of 2.60, following ASTM C33 [15] standards, was used as the fine aggregate.

Table 1. Coal and fly ash analysis data provided by the Mae Moh power plant.

Analysis	Descriptions
Coal analysis	- Moisture content, sulfur, ash, volatile - Chemical composition: SiO_2, CaO, Al_2O_3, Fe_2O_3, SO_3 - Ash fusion temperature
Fly ash analysis	- Fineness, wet sieve fineness (# 325), and specific gravity - Chemical compositions: SiO_2, CaO, Al_2O_3, Fe_2O_3, Free lime, SO_3

Table 2. Chemical compositions of fly ashes and cement used in the study.

Chemical compositions %	OPC type I	Fly ash A	Fly ash C	Fly ash R
SiO_2	18.93	35.71	25.22	61.46
Al_2O_3	5.51	20.44	13.88	20.27
Fe_2O_3	3.31	15.54	17.39	5.56
CaO	65.53	16.52	26.25	1.73
MgO	1.24	2.00	2.38	0.96
Na_2O	0.15	1.15	1.40	0.73
K_2O	0.31	2.41	1.92	1.36
SO_3	2.88	4.26	9.44	0.38
LOI	-	0.49	0.56	5.38
Free lime	0.75	1.71	3.06	0.03
Equivalent sodium oxide (Na_2O + 0.658 K_2O)	0.35	2.74	2.66	1.62

Table 3. Physical properties of materials.

Materials	Specific gravity	Specific Surface area (cm^2/g)
OPC	3.15	3100
F(A)	2.21	2867
F(A10)	2.26	2904
F(C)	2.57	2722
F(C10)	2.61	2790
F(R)	2.17	2723
Free lime	2.96	3749

Table 4. Blended proportions and designation of the blended fly ashes.

Designation	Percentage of fly ash with low free lime content	Percentage of fly ash with high free lime content	Total free lime (%)	Total SO_3 (%)
F(A-C)	95%F(A)	5%F(C)	1.77	4.52
F(A-A10)	95%F(A)	5%F(A10)	2.12	4.26
F(A-C10)	95%F(A)	5%F(C10)	2.12	4.52
F(R-C)	95%F(R)	5%F(C)	0.18	0.83
F(R-A10)	95%F(R)	5%F(A10)	0.53	0.57
F(R-C10)	95%F(R)	5%F(C10)	0.53	0.83

The six blended fly ashes were prepared by combining low-free lime fly ashes with high-free lime fly ashes. The blended fly ashes consist of 5% high-free lime fly ashes (F(C), F(A10), or F(C10)) mixed with 95% low-free lime fly ashes (F(A) or F(R)).

Table 4 presents the designation and details of the fly ash blended proportions. For instance, F(A-C10) indicates a mixture of 95% F(A) with 5% F(C10), while F(R-A10) represents a combination of 95% F(R) with 5% F(A10).

The proportioning of low-free lime and high-free lime fly ashes in the blended fly ashes was carefully done to ensure that the SO_3 content of the blended fly ashes adhered to the ASTM C618 [7] limit of 5%, and the free lime content remained below the EN 450 [8] limit of 2.5% for all blended fly ashes (as shown in Table 4).

Experimental setup and sample designation: Various tests were conducted on the blended fly ash mixtures, including water requirement, setting times, strength index, autoclave expansion, expansion due to alkali-aggregate reaction, and expansion due to sulfate solutions. The corresponding test standards for each test are shown in Table 5. The details of mix designations and the proportions of binders, free lime, and SO_3 contents of each fly ash are shown in Table 6. For example, C80F(R-C10)20 means the mixture consists of 80% cement and 20% F(R-C10), where F(R-C10) consists of 95% F(R) and 5% F(C10).

3. Results and Discussions

3.1. Pre-Combustion Analysis Techniques

3.1.1. Relationship between coal and fly ash properties

In Section 2, it was mentioned that four coal lines (1-4) supply coal to ten power plant units (1 to 10). Fig. 1 provides a schematic diagram depicting the arrangement of the conveyors, power plant units, and the resulting fly ash. This diagram illustrates the flow of coal and the generation of fly ash from the power plant units.

Table 5. Test details.

Properties	Fly ash ratio	Standard
Compressive strength	20% and 40%.	ASTM C109 [16]
Setting time		ASTM C191 [17]
Water requirement		ASTM C311 [18]
Autoclave expansion		ASTM C151 [19]
Expansion due to alkali-aggregate reaction		ASTM C1260 [20]
Expansion due to sodium sulfate		ASTM C1012 [21]
Expansion due to combined sodium sulfate+magnesium sulfate solutions		ASTM C1012 [21]

Figures 2 to 4 present a comparison of collected coal data for each conveyor before transportation to the burning unit. These figures demonstrate fluctuations in the coal properties for all conveyors. Furthermore, the chemical compositions of fly ashes including SO_3, and free lime contents from each unit were measured. Figure 5 illustrates an example of the chemical compositions of fly ash, produced from the same set of coals but received at different power plant units. This figure highlights variations in the fly ash properties resulting from different power plant units receiving the same set of coals.

Figure 5 indicates that the chemical compositions of fly ash produced by units 1 to 4 are closely clustered together, whereas the properties of fly ash produced by units 5 to 10 show a similar pattern. It is evident that there are distinct differences between the properties of fly ashes from these two groups of units.

Table 6. Mix designation of the tested fly ash mixtures.

Mix designation	Free lime in fly ash (%)	SO_3 in fly ash (%)
C100	-	-
C80F(A)20	1.71	4.26
C60F(A)40	1.71	4.26
C80F(C)20	3.03	9.44
C60F(C)40	3.03	9.44
C80F(R)20	0.03	0.38
C60F(R)40	0.03	0.38
C80F(A10)20	10	4.26
C60F(A10)40	10	4.26
C80F(C10)20	10	9.44
C60F(C10)40	10	9.44
C80F(A-C)20	1.77	4.52
C60F(A-C)40	1.77	4.52
C80F(A-A10)20	2.12	4.26
C60F(A-A10)40	2.12	4.26
C80F(A-C10)20	2.12	4.52
C60F(A-C10)40	2.12	4.52
C80F(R-A)20	0.18	0.57
C60F(R-A)40	0.18	0.57
C80F(R-A10)20	0.53	0.57
C60F(R-A10)40	0.53	0.57
C80F(R-C10)20	0.53	0.83
C60F(R-C10)40	0.53	0.83

Note: C = Cement, F = Fly ash

However, some fluctuations in properties can still be observed within each group. These variations may be attributed to several factors, such as source, type, and chemical compositions of coal, boiler type, burning procedure, temperature, and age of boiler units. Units 1 to 4 are older [22] and have a capacity of 150 MW while units 5 to 10 are newer with a higher production capacity of 300 MW. These differences in the age and capacity of the units can contribute to the variations in the properties of the fly ash they produce.

It is noted that only the chemical compositions of the used coal are considered due to the unavailable data on each power plant unit characteristics to develop the relationships between the coal properties and the resulting fly ashes.

3.1.2. Correlation of different variables

In the analysis, various coal and fly ash properties, such as chemical compositions of coal ashes and fly ashes, coal ash content, fusion temperatures, are considered as variables for correlation. From these variables, coal properties that exhibit significant correlations with the properties of fly ash are identified as the independent variables. These variables are then utilized to find their effects on the dependent variables, which are the properties of the fly ash, as demonstrated in Table 7. For the correlation analysis, a simple linear regression method is employed to establish relationships between the independent variables and the dependent variables. The coefficient of determination (R^2 value) is used to assess the strength of the influence of each independent variable on each dependent variable.

Figure 6 presents the simple regression analysis results for different dependent variables (fly ash properties) in terms of R^2 values. The variability of each dependent variable (e.g., oxides in the fly ash) is mainly correlated with the corresponding oxide in the independent variables (coal properties). For instance, in the case of CaO_{FA} (Fig. 6(a)), the highest R^2 values are derived when correlated with CaO_{CA} for all power plant units. A similar pattern is observed for other dependent variables as well.

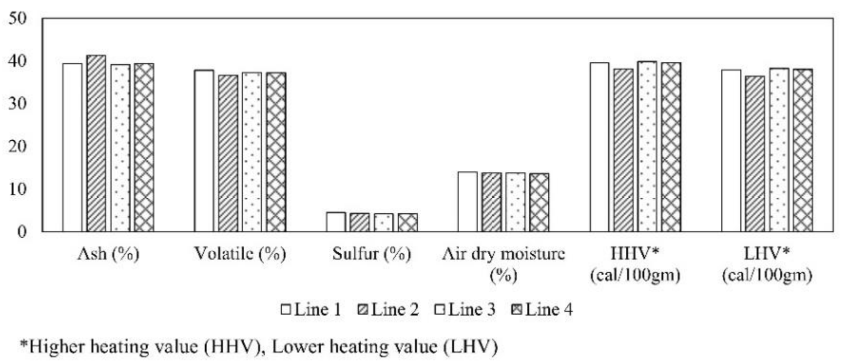


Fig. 2. Analysis results of coals collected from different conveyors.

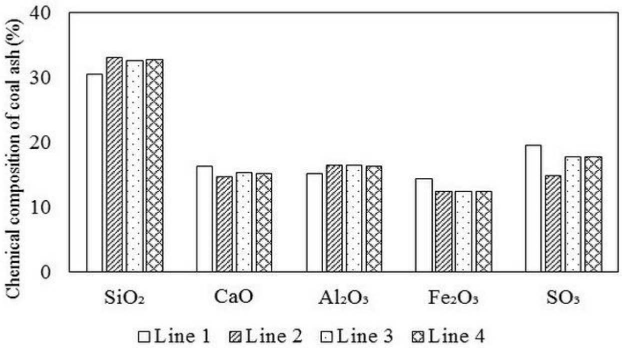


Fig. 3. Chemical compositions of coal from different conveyors.

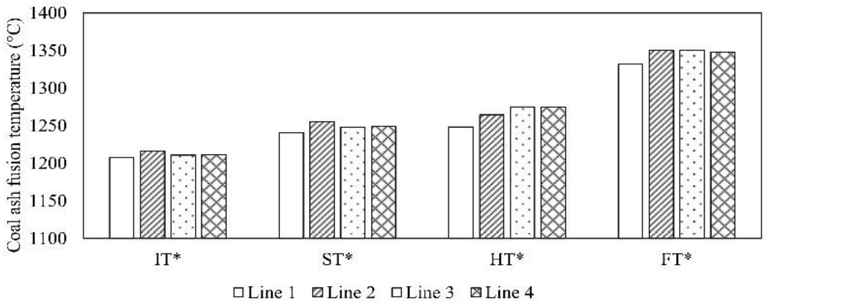
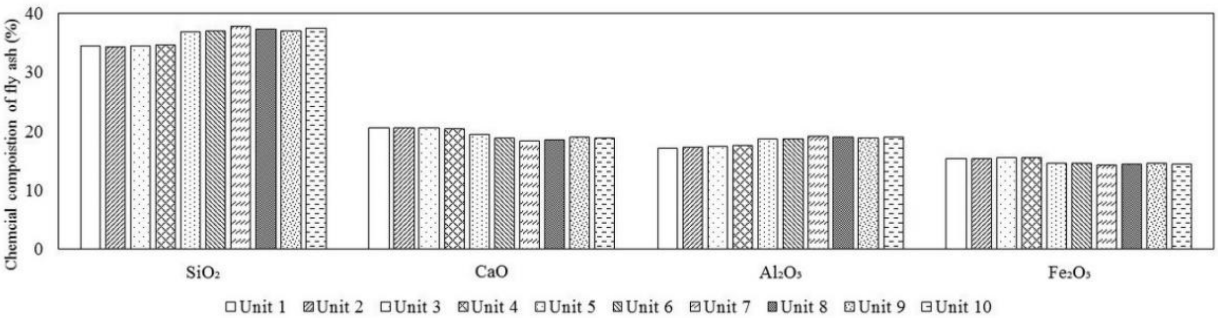
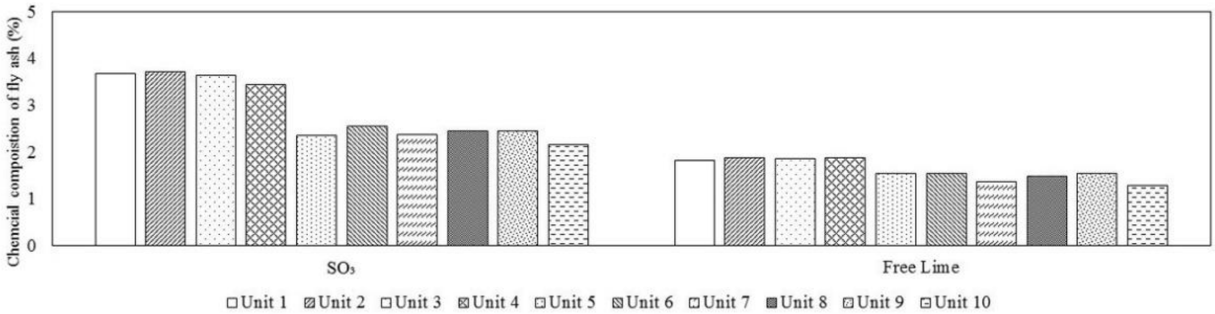


Fig. 4. Fusion temperatures of coal from different conveyors.

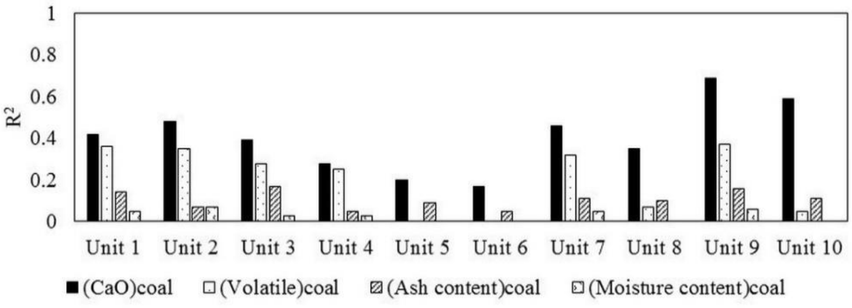


(a)

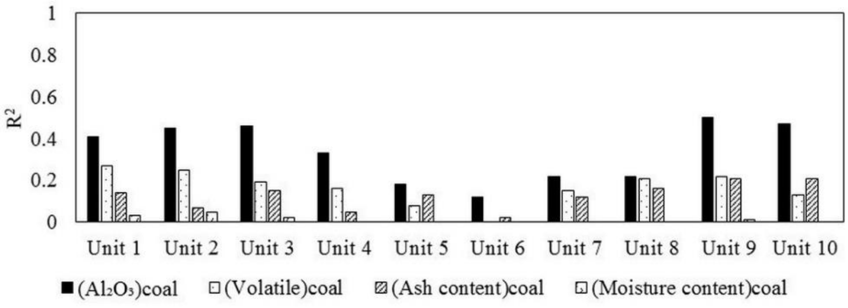


(b)

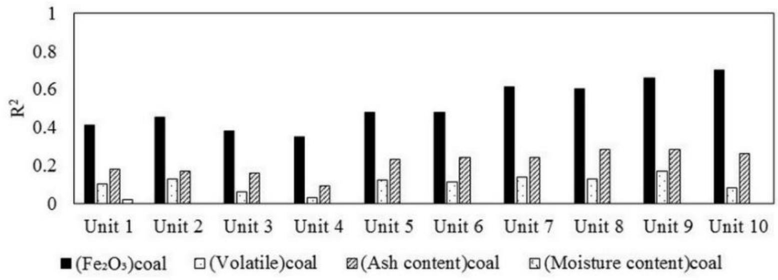
Fig. 5. Chemical compositions of fly ashes collected at different conveyors, (a) SiO_2, CaO, Al_2O_3, and Fe_2O_3 contents, (b) SO_3 and free lime contents.



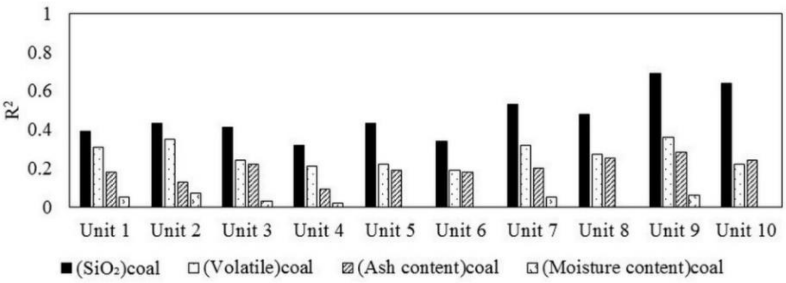
(a) CaO_{FA}



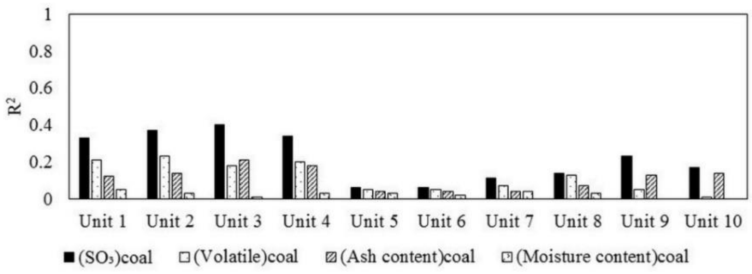
(b) $Al_2O_{3\ FA}$



(c) $Fe_2O_{3\ FA}$

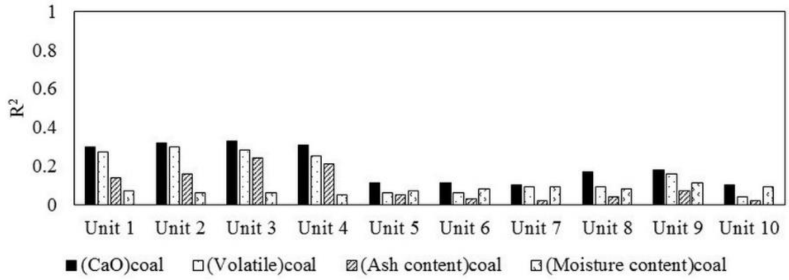


(d) $SiO_{2\ FA}$



(e) $SO_{3\ FA}$

Fig. 6. R^2 values of simple linear regression of (a) CaO_{FA}, (b) $Al_2O_{3\ FA}$, (c) $Fe_2O_{3\ FA}$, (d) $SiO_{2\ FA}$, (e) $SO_{3\ FA}$, (f) FL_{FA}, on independent variables.



(f) FL_{FA}

Fig. 6. R^2 values of simple linear regression of (a) CaO_{FA}, (b) Al_2O_3 $_{FA}$, (c) Fe_2O_3 $_{FA}$, (d) SiO_2 $_{FA}$, (e) SO_3 $_{FA}$, (f) FL_{FA}, on independent variables (continued).

Table 7. Details of different variables.

Variable types	descriptions
Dependent (fly ash properties)	SiO_2, CaO, Al_2O_3, Fe_2O_3, SO_3, Free lime
Independent (coal properties)	SiO_2, CaO, Al_2O_3, Fe_2O_3, SO_3, Volatile, Ash content, Sulfur, Moisture content

Table 8. Correlations between CaO_{FA} and CaO_{CA}.

Variable	Powerplant Unit	Line	CaO_{FA}	R^2	CaO_{FA} at 95% interval
CaO	1 to 4	1	1.2701 CaO_{CA}	0.34	1.6465 CaO_{CA}
	5 to 6	2	1.2991 CaO_{CA}	0.12	1.7683 CaO_{CA}
	7 to 8	2 to 3	1.2480 CaO_{CA}	0.36	1.6440 CaO_{CA}
	9 to 10	3 to 4	1.2420 CaO_{CA}	0.58	1.4833 CaO_{CA}

3.1.3. Relationship between coal and fly ash properties

From the linear regression, it was found that the dependent variables (e.g., oxides in fly ash) are highly reliant on the corresponding oxides in the independent variables (coal properties). To establish relationships between properties of coal and fly ash for each power plant unit, only the corresponding oxides in coals and fly ashes are considered as independent and dependent variables, respectively. For example, CaO in the fly ashes is linearly correlated with CaO in the coals.

Fig. 7 illustrates the relationship between CaO in the fly ashes (CaO_{FA}) and CaO in the coals (CaO_{CA}) for different units of the same coal line. Using statistical analysis software, a line of 95% prediction interval is generated, indicating that 95% of the data are under this line. The 95% prediction interval lines for different units are depicted in Fig. 7. This interval helps to assess the variation and reliability of the relationship between the CaO in fly ash and CaO in coals for each power plant unit.

Only the upper limit is of interest for three compositions, CaO_{FA}, free lime, and SO_3, because they must be controlled to be not too high for quality control of fly ash. Table 8 shows the equations of regression lines and their R^2 values as well as the equations of 95% prediction interval lines for CaO_{FA}. Similarly, relationships between the properties of coals (CaO_{CA} and SO_{3CA}) and two other properties of the resulting fly ashes (free lime and SO_{3CA}) are depicted in Figs. 8 to 9 whereas Table 9 and Table 10 show the equations of regression lines and R^2 values as well as the equations of 95% prediction interval lines for the mentioned properties. The relationships between coal and fly ash properties such as CaO, SO_3, and free lime content are only shown here since those properties are the most concerned properties contributing to undesired expansion and volume instability problems as compared with the other properties.

3.1.4. Correlation between the properties of coal and fly ash for controlling and managing fly ash properties

The linear relationship between different properties of coal and fly ash can be established in the form of regression equations. Hence, the properties of fly ash can be forecasted and managed. By using the equations, fly ash with undesirable properties can be separated and removed from the stockpile.

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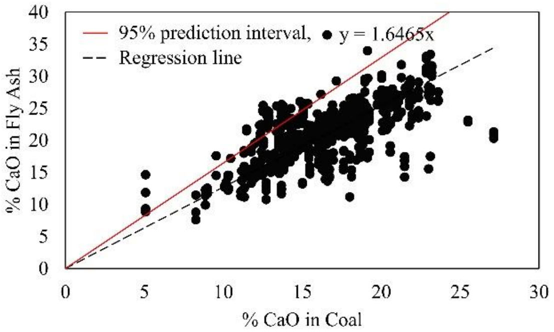
Table 9. Correlations between $SO_{3\,FA}$ and $SO_{3\,CA}$.

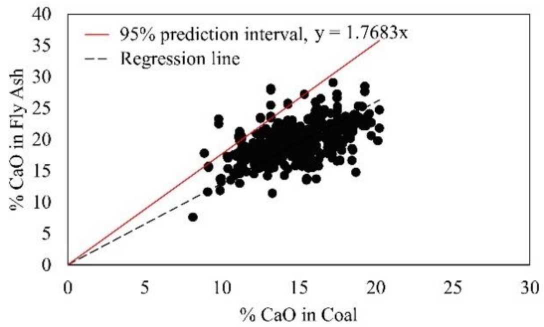
Variable	**Powerplant Unit**	**Line**	**$SO_{3\,FA}$**	**R^2**	**$SO_{3\,FA}$ at 95% interval**
SO_3	1-4	1	0.1860 $SO_{3\,CA}$	0.36	0.2818 $SO_{3\,CA}$
	5-6	2	0.1617 $SO_{3\,CA}$	0.01	0.2500 $SO_{3\,CA}$
	7-8	2 to 3	0.1339 $SO_{3\,CA}$	0.05	0.2015 $SO_{3\,CA}$
	9-10	3 to 4	0.1294 $SO_{3\,CA}$	0.17	0.1770 $SO_{3\,CA}$

Table 10. Correlations between FL_{FA} and CaO_{CA}.

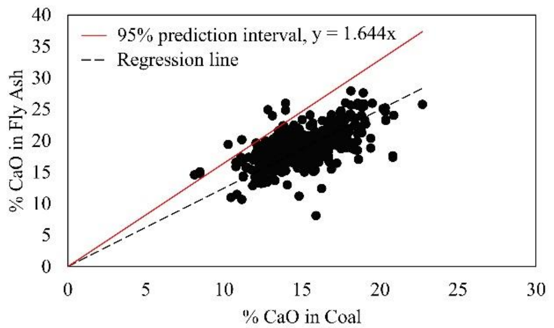
Variable	**Powerplant Unit**	**Line**	**FL_{FA}**	**R2**	**FL_{FA} at 95% interval**
Free lime	1-4	1	0.1145 CaO_{CA}	0.31	0.1882 CaO_{CA}
	5-6	2	0.0878 CaO_{CA}	0.07	0.1554 CaO_{CA}
	7-8	2-3	0.0938 CaO_{CA}	0.14	0.1882 CaO_{CA}
	9-10	3-4	0.0933 CaO_{CA}	0.13	0.1882 CaO_{CA}



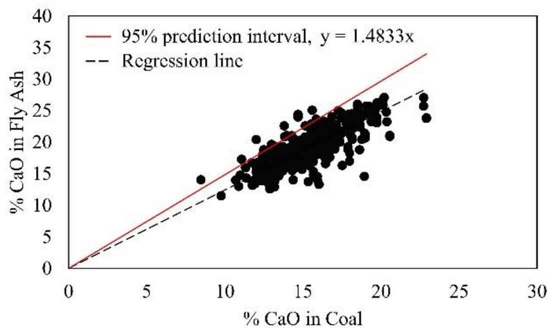
(a) Units 1-4



(b) Units 5-6



(c) Units 7-8



(d) Units 9-10

Fig. 7. Correlation between CaO_{FA} and CaO_{CA} for units with same conveyer (a) Unit 1 to 4, (b) Unit 5 to 6, (c) Unit 7 to 8, (d) Unit 9 to 10.

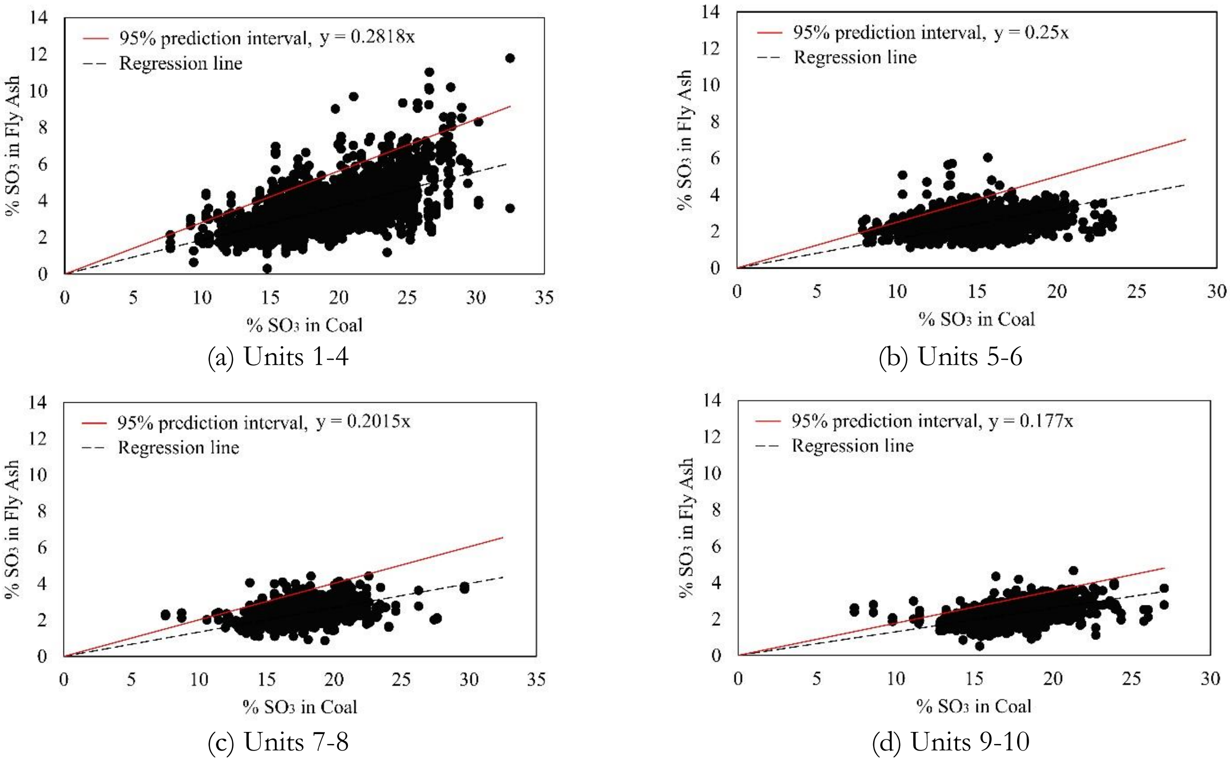


Fig. 8. Correlation between $SO_{3\,FA}$ and $SO_{3\,CA}$ for units with same conveyer, (a) Unit 1 to 4, (b) Unit 5 to 6, (c) Unit 7 to 8, (d) Unit 9 to 10.

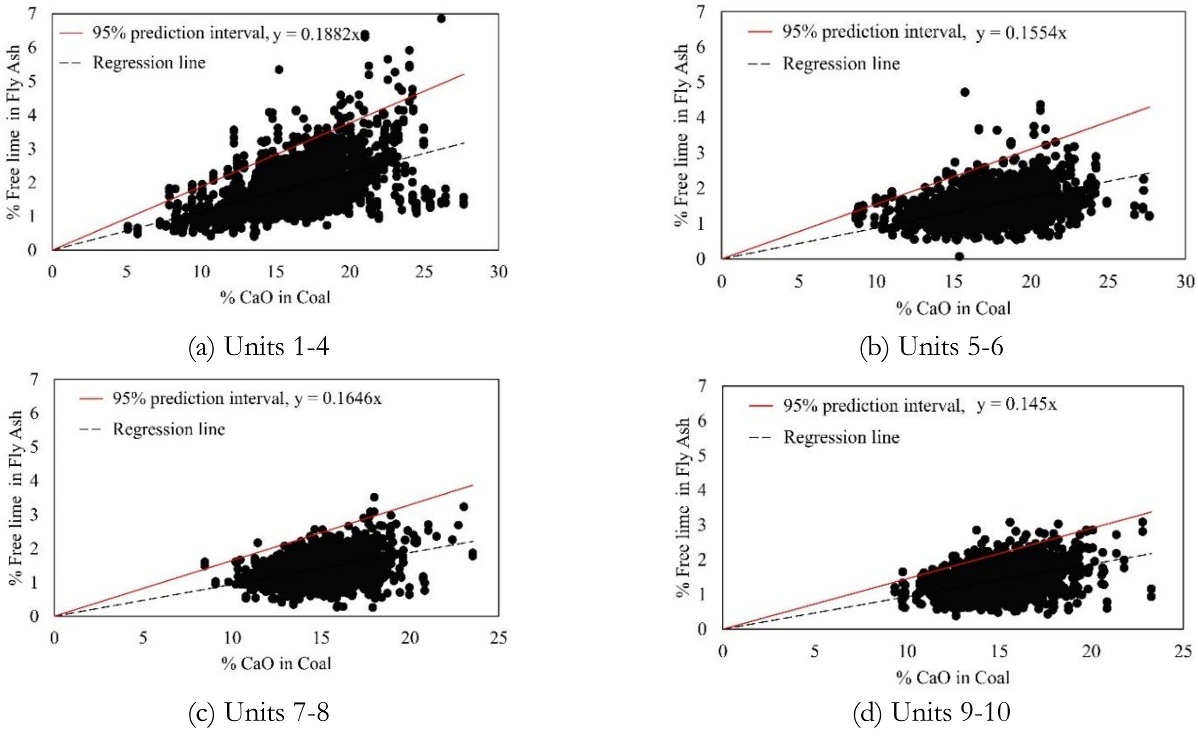


Fig. 9. Correlation between FL_{FA} and CaO_{CA} for units with same conveyer, (a) Unit 1 to 4, (b) Unit 5 to 6, (c) Unit 7 to 8, (d) Unit 9 to 10.

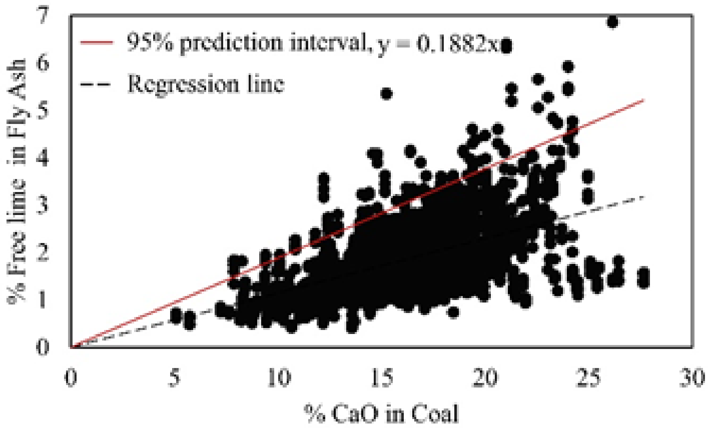


Fig. 10. Correlation between FL_{FA} and CaO_{CA} for Units 1 to 4 receiving coal from Line 1.

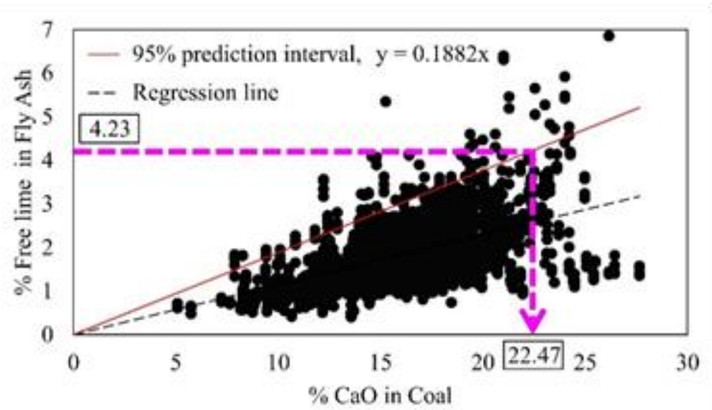


Fig. 11. Application of relationship between FL_{FA} and CaO_{CA}.

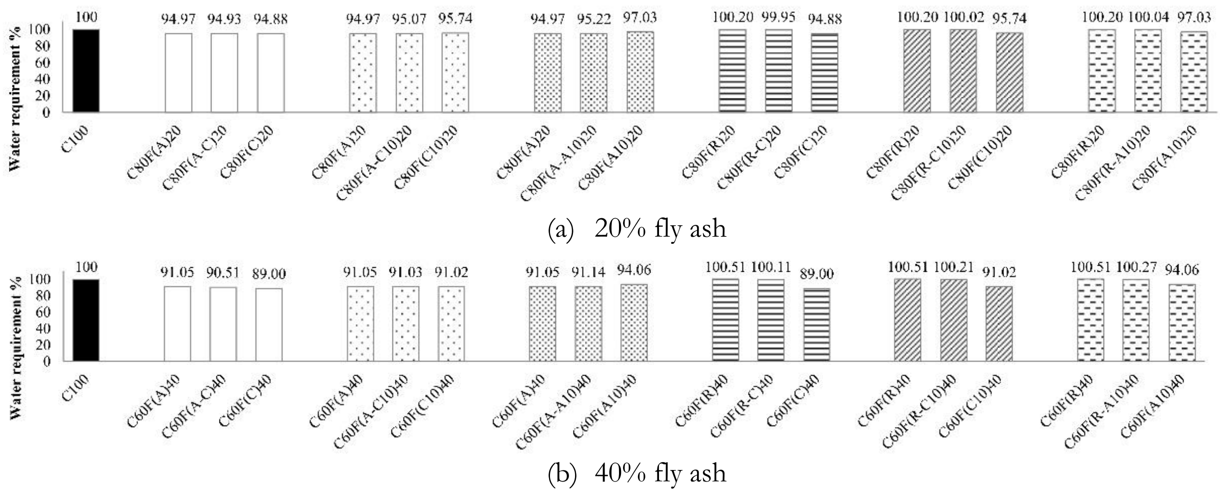


Fig. 12. Water requirement of mortar mixtures containing high-free lime fly ashes, low-free lime fly ashes, and blended fly ashes, (a) 20% fly ash (b) 40% fly ash.

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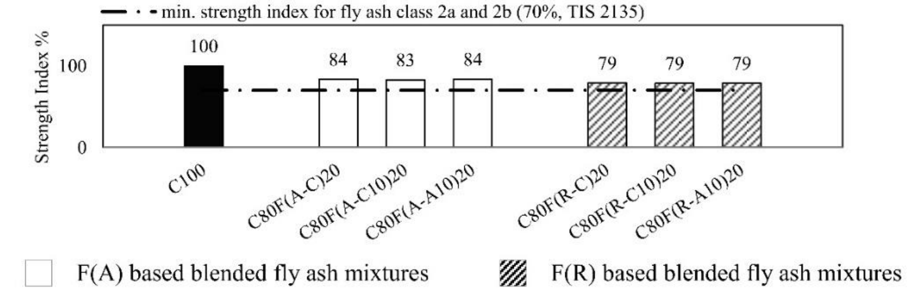
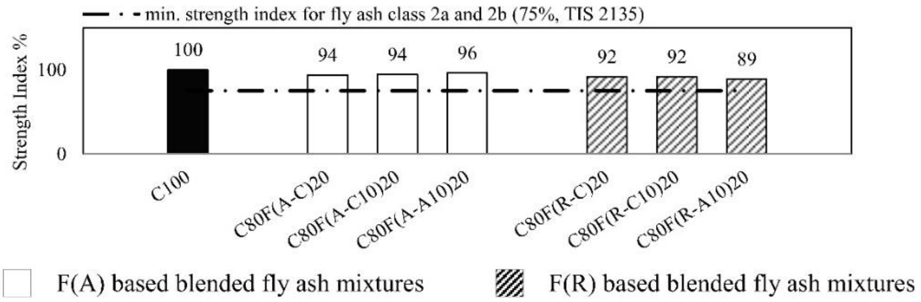
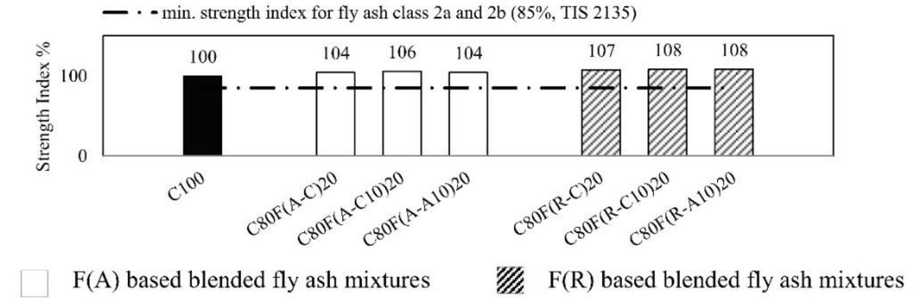


(a) 7 days

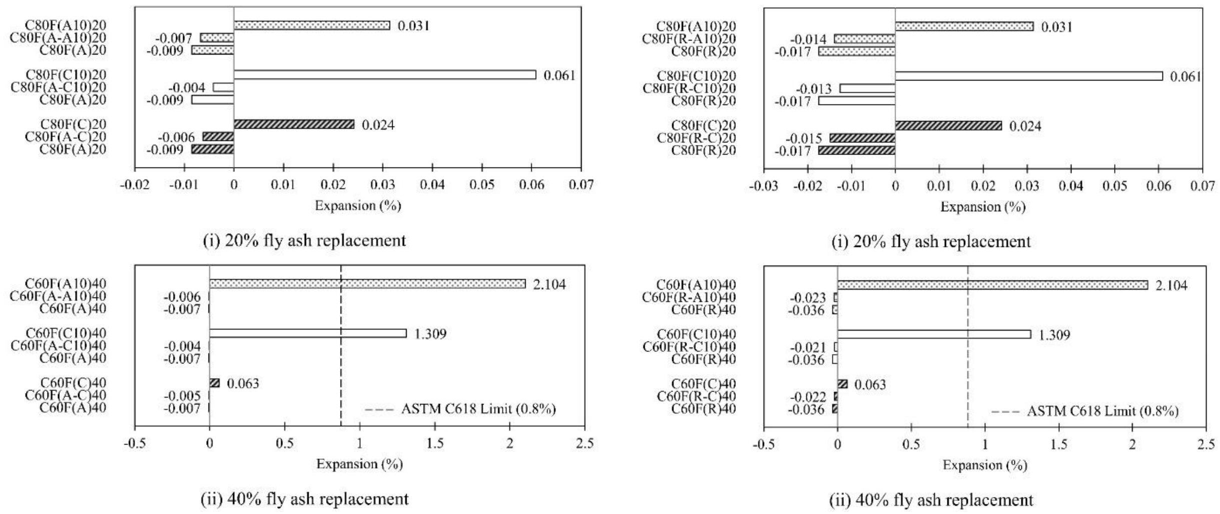


(b) 28 days



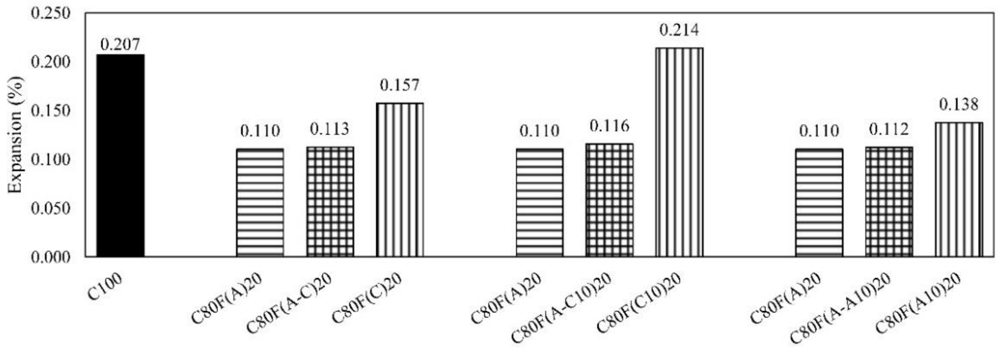
(c) 91 days

Fig. 13. Strength index of mortars containing blended fly ashes, (a) 7 days, (b) 28 days, (c) 91 days.

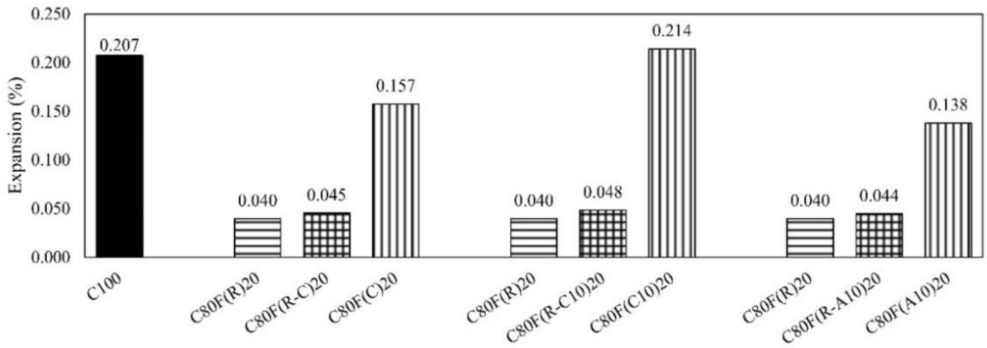


(a) F(A) based blended fly ash mixtures (b)F(R) based blended fly ash mixtures

Fig. 14. Autoclave expansion of pastes containing blended fly ashes, (a) F(A) based blended fly ash (b) F(R) based blended fly ash.

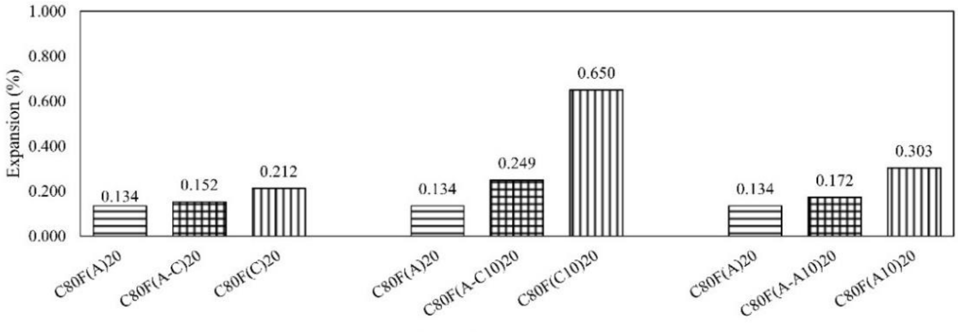


(a) FA based blended fly ash

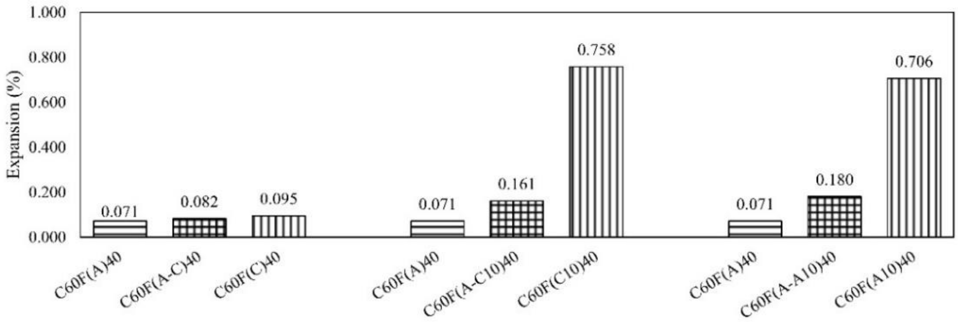


(b) F(R) based blended fly ash

Fig. 15. Expansion due to alkali-aggregate reaction of mortars, (a) F(A) based blended fly ash (b) F(R) based blended fly ash.



(i) 20% fly ash replacement



(ii) 40% fly ash replacement

(a) F(A) based blended fly ash

Fig. 16. Expansion at 224 days in Na_2SO_4 solution of mortars containing blended fly ashes (a) F(A) based blended fly ash (b) F(R) based blended fly ash.

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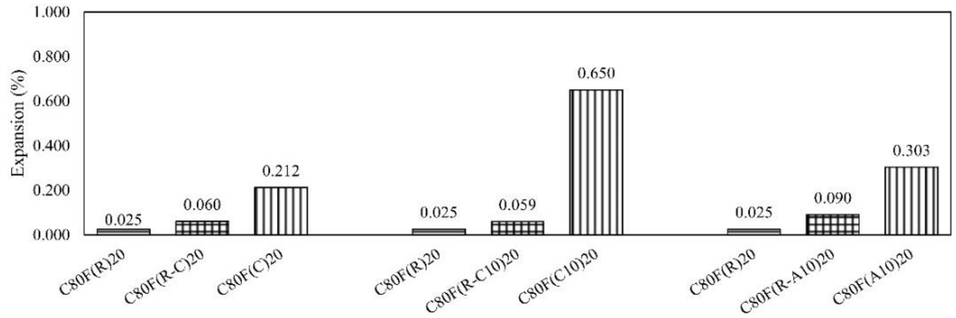
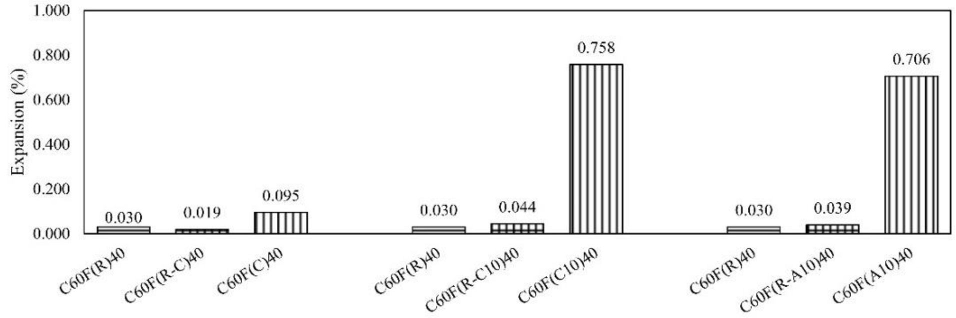


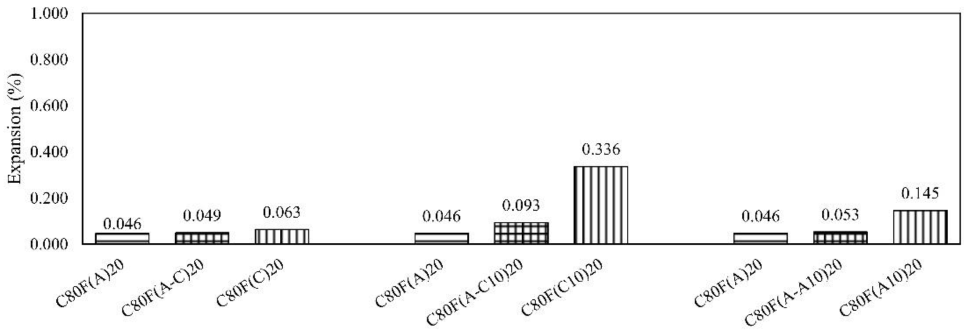
(i) 20% fly ash replacement



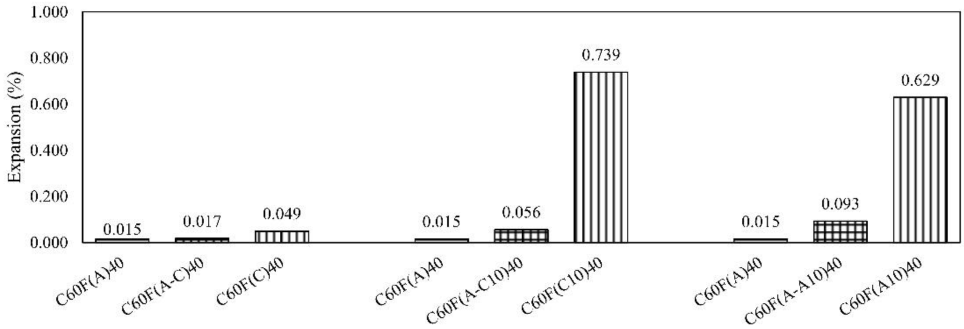
(ii) 40% fly ash replacement

(b) F(R) based blended fly ash mixtures

Fig. 16. Expansion at 224 days in Na_2SO_4 solution of mortars containing blended fly ashes (a) F(A) based blended fly ash (b) F(R) based blended fly ash (Continued).



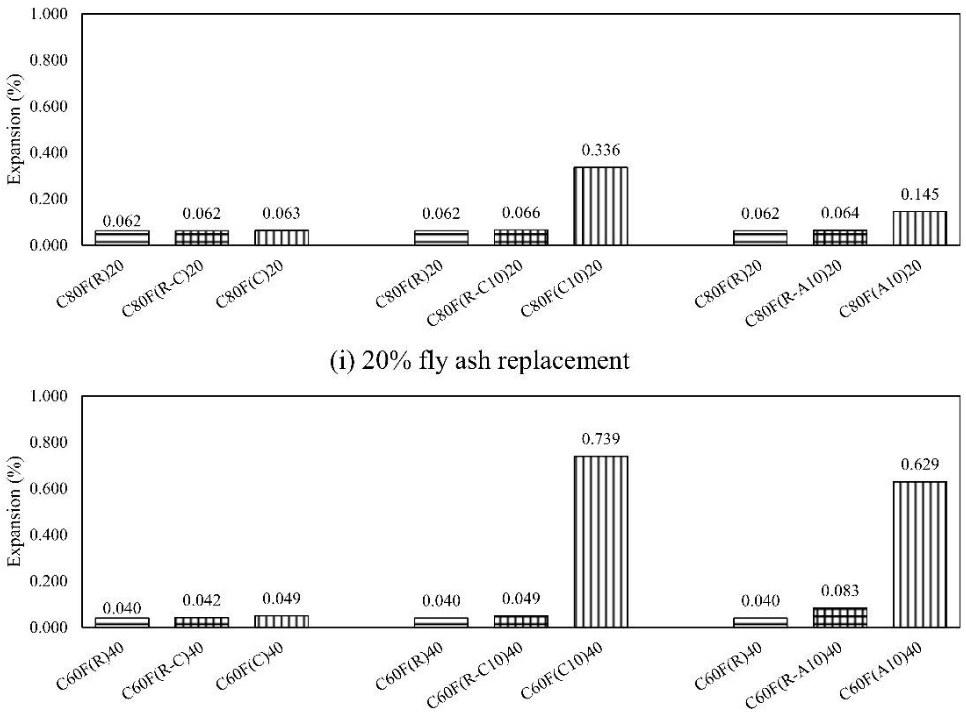
(i) 20% fly ash replacement



(ii) 40% fly ash replacement

(a) F(A) based blended fly ash

Fig. 17. Expansion at 224 days in Na_2SO_4-$MgSO_4$ combined solution of mortar containing blended fly ashes (a) F(A) based blended fly ash mixtures, (b) F(R) based blended fly ash mixtures.



(ii) 40% fly ash replacement

(b) F(R) based blended fly ash mixtures

Fig. 17. Expansion at 224 days in Na_2SO_4-$MgSO_4$ combined solution of mortar containing blended fly ashes (a) F(A) based blended fly ash mixtures, (b) F(R) based blended fly ash mixtures (Continued).

To produce fly ash with the desired quality and minimal deviation from the standard, it is beneficial to predict the fly ash properties while mixing coals with different characteristics. As can be seen, the R^2 values of regressions give low value. This is because of the scattered data. This results in prediction errors in the cases of free lime as well as SO_3 contents. To minimize the errors for controlling the fly ash quality, the utilization of a 95% prediction interval equation is useful. The 95% prediction interval line implies that 95% of total existing data is under this line.

As discussed earlier in section 1, Mae Moh fly ash demonstrates higher contents of free lime and SO_3, therefore it is critical to determine the maximum amount of these components in the resulting fly ash. By applying the upper limit of 95% prediction line, it is possible to control free lime and SO_3 contents in the fly ash so that about 95% of the produced fly ash will have free lime and SO_3 contents within the limits in the standard.

Considering the relationship between FL_{FA} and CaO_{CA}, Fig. 10 illustrates the relationship between FL_{FA} and CaO_{CA} for Units 1 to 4 (also in Fig. 9(a)). If it is required to acquire fly ash from Units 1 to 4 to have free lime in fly ash not more than 4.23% (free lime limit mentioned by Nawaz [10]), the equation of 95% prediction interval line, as illustrated in Fig. 11, is adopted. The maximum CaO content in the coal used for burning can be determined as follows.

$$\text{Free lime}_{FA} = 0.1882\ CaO_{CA}$$

$$\therefore CaO_{CA} = (4.23/0.1882) = 22.47\% \quad (1)$$

Therefore, when CaO_{CA} is higher than 22.47%, that coal should be mixed with another coal having lower CaO content. Fig. 11 illustrates the procedure to obtain the maximum allowable CaO_{CA} in coal to obtain fly ash with a free lime content less than 4.23% by using the regression equation.

3.2. Post-Combustion Technique (Fly Ash Blending)

3.2.1. Mechanical properties

Figures 12 to 13 illustrate the performance comparison on basic properties including water requirement and strength index of the blended high-free lime and low-free lime fly ash mixtures. In case of mixtures containing F(A), F(C). The reduced water requirement for fly ash mixtures can be seen as compared to the control mix. This reduction can be attributed to the spherical shape of the fly ash particles as observed in the past studies [23–27]. On the contrary, in case of F(R) mixtures, the higher water requirement is caused by the irregular shape, porous particles, and high LOI of F(R) [10]. The water requirement of the mixtures for both 20% and 40% fly ash replacements are in between those of the mixtures containing high-free lime and low-free lime fly ashes. As blended fly ashes consists of 95% low-free lime fly ash and only 5% high-free lime fly ash, the mechanical properties of the blended fly ash mixtures are nearer to that of low-free lime fly ash mixes. Mehta and Monteiro [28] also observed that the incorporation of low-calcium fly ash tends to result in reduced water demands in concrete mixes.

In addition, as illustrated in Fig. 13, the strength activity indices of blended fly ash mixtures with F(R). F(A) and F(C) are higher than 70%, 75%, and 85% of that of the cement-only (C100) mixture at 7, 28, and 91 days, respectively. Hence, all the blended fly ashes satisfied the requirement of TIS 2135 [14] regarding strength. Furthermore, although the fly ash mixtures exhibited lower strength values at an early age, the strength of these mixtures surpassed that of the control mix at a later age. This can be attributed to the delayed pozzolanic reaction of the fly ash, as indicated by several past studies [29–32].

3.2.2. Durability properties

Figures 14 to 17 illustrate various durability performances including autoclave expansion, expansion caused by alkali aggregate reaction, and sulfate expansion of the mixtures with blended fly ash compared to the performances of high-free lime and low-free lime fly ash mixtures. In cases of 20% and 40% replacements, the durability performances of the blended fly ash mixes are in between those of the low-free lime and high-free lime fly ash mixtures. Since the blended fly ashes mixtures contain only 5% high-free lime fly ash, their properties are close to that of low-free lime fly ash mixtures. Furthermore, the fly ash mixes with higher free lime content exhibited higher expansion, due the presence of free lime content that can cause soundness problems in cement mixtures [33, 34], as observed in the literature [11, 35, 36].

Based on the tested mechanical and durability properties, high-free lime with low-free lime fly ash blending is an effective solution to utilize very high-free lime fly ashes for partial cement replacement in concrete.

It should be noted that the fly ash properties depend not only on the chemical composition of the coal but also several more factors including the type of emission control procedure, temperature, burning process, boilers etc. of the power plants. By considering these additional factors it will be helpful to enhance the accuracy of the prediction of the resulting fly ash properties.

4. Conclusions

1) The properties of the produced fly ash can be forecasted by utilizing the developed relationships between coal properties and fly ash properties. It is helpful in quality control of the fly ash by managing the properties of the input coal.

2) By combining high-free lime fly ash with a low-free lime fly ash, it is possible to make use of the high-free lime fly ash. The resulting blended fly ash mixtures behave in a manner that is in between that of mixtures made using high-free lime and those made with low-free lime.

3) The results of the study are useful for coal and fly ash management at the Mae Moh power generating plant to maximize the utilization of fly ash in the concrete industry.

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Adnan Nawaz, photograph and biography not available at the time of publication.

Parnthep Julnipitawong, photograph and biography not available at the time of publication.

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