**Development of Thermal Insulating Materials from Coal Fly Ash: A Case Study from PLTU Kaltim Teluk**

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**Abstract.** This research investigates the development of thermal insulating materials by repurposing coal fly ash (CFA), a byproduct of coal combustion from PLTU Kaltim Teluk, as a sustainable alternative to conventional fire clay. Several compositions were prepared by combining water, CFA, and commercial fire clay in different proportions. Among these, the 2–40 composition exhibited the most promising performance, achieving the lowest thermal conductivity values of 0.1327 W/m·K. The physical and chemical properties of the samples were systematically evaluated, with particular emphasis on thermal conductivity and compressive strength. The results demonstrate that, with appropriate processing and treatment, coal fly ash can be transformed into an environmentally friendly and economically viable insulating material, offering significant potential for scalable applications in industrial furnaces and energy-efficient building systems.

# introduction

Insulation materials play a crucial role in a multitude of industries, serving as the backbone for high-temperature processes in sectors such as petrochemicals, iron and steel production, power generation, as well as ceramics and glass manufacturing. These materials are essential for operations that involve extreme heat and are pivotal in safeguarding equipment from thermal damage. This focus is driven by the need to enhance efficiency, reduce costs, and minimize the environmental impact of high-energy-consuming processes. As such, the strategic use of refractory materials is not only a matter of operational necessity but also a key component of sustainable industrial practices[1]. Several Commercial Thermal Insulation Materials that are widely used are based on cellular plastic materials, mineral wool, glass wool, cotton wool, wood wool, aerated concrete, and clay brick with various thermal conductivity [2].

In recent years, the development of thermal insulation materials from industrial by-products such as ferronickel slag [3], secondary raw materials red mud and waste glass [4], and waste iron tailings [5] have attracted increasing attention due to their cost-effectiveness and environmentally friendly properties. Such innovations not only reduce the environmental burden of industrial waste but also improve resource utilization. Coal fly ash (CFA), a byproduct of coal combustion, has also been widely investigated for applications in construction and thermal insulation. For instance, CFA combined with waste glass, borax, and calcium carbonate has been used to fabricate glass–ceramic foams through calcination at 800 °C, producing compressive strengths above 5 MPa and thermal conductivities around 0.36 W/m·K. However, these processes often require additional chemical agents, which increase both complexity and production costs [6].

In this study, CFA was directly utilized as a partial substitute for commercial fire clay without the use of chemical additives. The CFA used in this work was sourced from PLTU Kaltim Teluk, a power plant located in Balikpapan - East Kalimantan, Indonesia, which produces approximately 150 tons of CFA per day [7]. To date, this material has primarily been used in low-value applications such as soil subgrade, concrete, paving, and bricks, meaning its economic potential remains underutilized. The CFA from PLTU Kaltim Teluk is classified as Class F, with a CaO content of 8.59% and a total pozzolanic oxide content (Fe₂O₃, Al₂O₃, and SiO₂) of 75.97% [8]. The main objective of this study is therefore to develop new thermal insulating materials from CFA as an eco-friendly and low-cost substitute for commercial fire clay. By emphasizing direct utilization without additives, this work aims to demonstrate a practical and sustainable pathway for the valorization of local industrial by-products into functional thermal insulation.

# research methods

## Materials

Commercial Fire Clay (CFC) and CFA were used in this research. The CFA was sourced from the PLTU Teluk Balikpapan, a power plant located in the Kariangau Industrial Estate, Balikpapan, East Borneo, Indonesia. Crystalline phases of CFA and fire clay were characterized using X-ray diffraction (XRD, Bruker D8 ADVANCE ECO.

## Preparation of Specimen

Specimen pastes were prepared by manually mixing water and binder according to the compositions specified in Table 1. The mixing was carried out for approximately 10 minutes to ensure homogeneity. Each mixture was then moulded into two different shapes: rectangular blocks (11 cm × 6 cm × 2 cm) for thermal conductivity testing and cylindrical specimens (5 cm in height and 2.5 cm in diameter) for compressive strength testing. The moulded samples were cured under ambient laboratory conditions for 3 days.

After curing, compressive strength was measured using a Universal Testing Machine (UTM, Automax Multitest – Controls) for cylindrical specimens. Rectangular blocks specimens were calcinated by direct combustion using an open flame in air atmosphere. The heating process was maintained for 48 hours with maximum temperature is 1100oC to ensure sufficient thermal treatment. This method represents a practical approach to simulating high-temperature exposure without the use of an electric furnace, and the calcination environment was therefore atmospheric air. Thermal conductivity was determined using a heat flow method (Conductometer QTM-500) at 200oC.

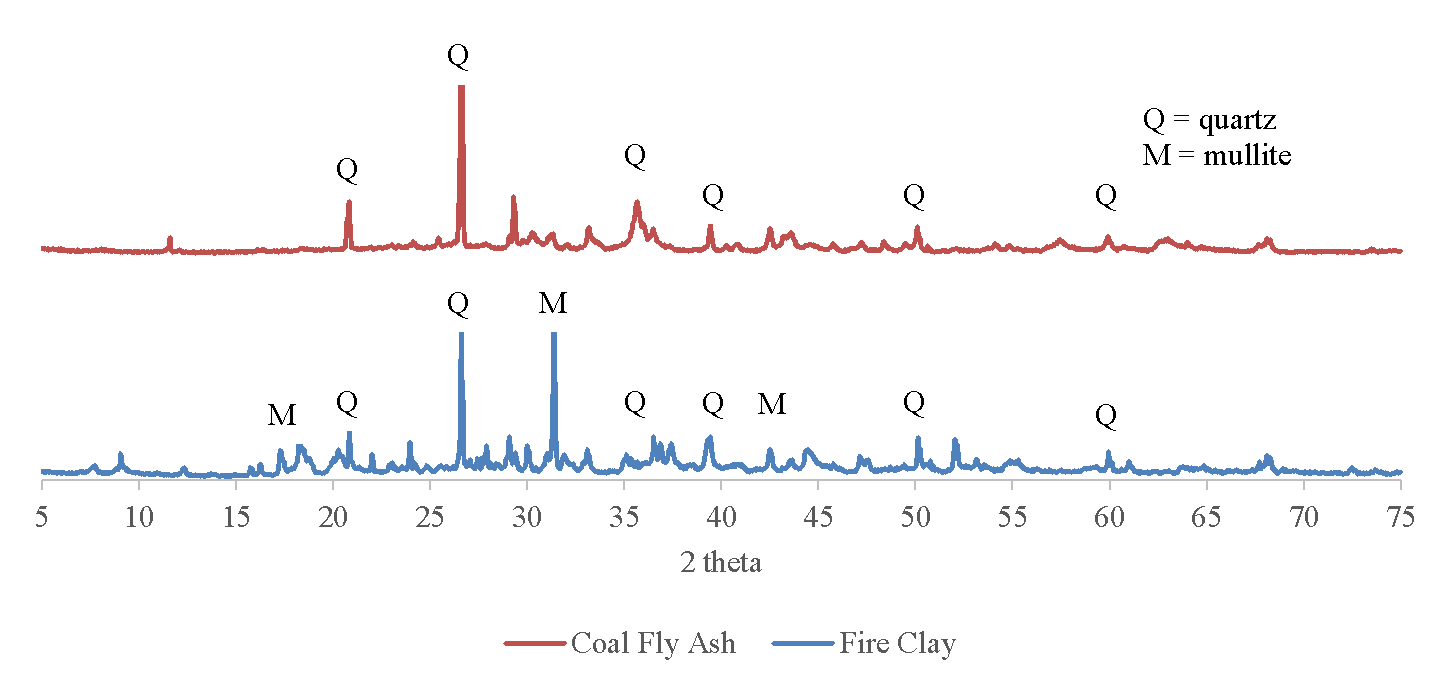
**TABLE 1.** Composition of Specimen

| Code of Specimen | Water | Fire Clay | CFA |
| --- | --- | --- | --- |
| 1-30 | 67% | 23,10% | 9,90% |
| 1-35 | 67% | 21,45% | 11,55% |
| 1-40 | 67% | 19,80% | 13,20% |
| 2-30 | 60% | 28,00% | 12,00% |
| 2-35 | 60% | 26,00% | 14,00% |
| 2-40 | 60% | 24,00% | 16,00% |

# RESULT AND DISCUSSION

## XRD Characterization

The result of XRD Characterization is shown in Figure 1. The presence of the mullite phase is the difference between CFA and Fireclay as observed from the diffractogram results. Mullite has received extensive attention in the fields of refractory materials and engineering ceramics because of its high mechanical strength, good creep resistance, and low thermal expansion coefficient [9]. By mixing CFA and fireclay, an alternative thermal insulation material can be formed that has low thermal conductivity and is more economical.



**FIGURE 1**. X-ray diffractogram of Coal Fly Ash and Fire Clay

## Compressive Strength

Samples were tested for compressive strength at 3 days of age, and the results are shown in Figure 2. Compressive strength increased with increasing fly ash content, with the highest values obtained for sample 1-40 (0.14 MPa) and 2-40 (0.10 MPa). These values are relatively low compared to conventional insulating materials such as aerated concrete from solid waste incinerator bottom ash (4.48±0.28 MPa) [10]. However, it is important to note that the present study is based on paste formulations, consisting only of binder and water, without the inclusion of aggregates. As a result, the mechanical strength is inherently lower than that of mortar or concrete composites.

Despite the limited compressive strength, the material demonstrates potential for non-load-bearing thermal insulation applications, such as protective coatings on pipelines, walls, or roofs in high-temperature environments. The relatively low strength may also be influenced by the short curing period (3 days) and low hydraulic activity from CFA.

**FIGURE 2**. Compressive Strength of Specimen Thermal Insulator Materials

## Thermal Conductivity

Thermal conductivity is a key parameter for evaluating the performance of insulating materials, as it directly influences energy conservation and the environmental impact of high-temperature systems. The results of thermal conductivity measurements at 200 °C are presented in Table 2. The best performance was observed in sample 2–40, which exhibited values of 0.1980 W/m·K before calcination and 0.1327 W/m·K after calcination.

These values are notably lower than those of several commercial and alternative insulating materials. For example, fired bricks typically exhibit a thermal conductivity of 0.48 W/m·K, fired clay bricks with recycled cigarette butts reach 0.880 W/m·K 11, and agro-industrial aerated concrete shows values around 0.50 W/m·K [12]. This comparison highlights the competitive insulation performance of CFA-based formulations, even without chemical additives.

The reduction in thermal conductivity after calcination indicates that heat treatment enhances the insulating capability of the material. This effect can be attributed to several factors: (i) the initial formation of mullite through the reaction between SiO₂ and Al₂O₃, which has intrinsically low thermal conductivity; (ii) the generation of microcracks during high-temperature reactions, which produce micropores that hinder heat transfer; and (iii) the evaporation of residual water within the specimen, which further contributes to pore formation and increases the overall porosity. Together, these mechanisms reduce the effective thermal conductivity of the material, confirming that calcination plays a crucial role in improving its insulation performance.

**TABLE 2**. Thermal Conductivity of Specimen (W/m.K)

| Code of Specimen | Before Calcination | After Calcination |
| --- | --- | --- |
| 1-30 | 0,2585 | 0,1551 |
| 1-35 | 0,3376 | 0,1566 |
| 1-40 | 0,2181 | 0,1649 |
| 2-30 | 0,2894 | 0,1377 |
| 2-35 | 0,3618 | 0,1345 |
| 2-40 | 0,1980 | 0,1327 |

# COnclusion

Coal fly ash (CFA) from PLTU Kaltim Teluk can be used as a partial substitute for commercial fire clay in the development of thermal insulating materials. The lowest thermal conductivity result was achieved by specimen 2–40, consisting of 60% water, 24% fire clay, and 16% CFA, which exhibited a value of 0.1327 W/m·K after calcination. This performance demonstrates that CFA-based formulations have the potential to serve as eco-friendly and cost-effective alternatives to conventional insulating materials.

Given their relatively low compressive strength, these materials are most suitable for non-load-bearing applications, such as coatings on pipelines, walls, or roofs in high-temperature environments. Future research should focus on evaluating the mechanical strength, durability, long-term heat exposure, and thermal cycling resistance of the developed materials, as well as exploring scalable production methods for practical industrial applications.

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