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# Reuse of incinerated ash from industrial sludge-derived fuel

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## HIGHLIGHTS

- Adding industrial sludge-derived fuel incinerated ash (FIA) can increase hydration heat and shorten setting time.
- FIA is a very suitable mineral admixture for controlled low-strength materials (CLSMs).
- Optimum proportion of FIA to cement paste is 10–20%.
- Pore size of FIACPs mainly was >1 μm.

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## ABSTRACT

The demand for alternative fuel derived from industrial sludge has substantially increased. Therefore, sustainable methods for disposal of industrial sludge-derived fuel incinerated ash (FIA) are urgently needed. This study evaluates the feasibility of using FIA as an admixture for either pozzolanic material or concrete and proposes strategies for FIA reuse. Experiments showed that FIA cement paste (FIACP) was characterized by early setting and high hydration heat because of its high calcium chloride content and high alkalinity, which reduced the initial setting and final setting times by 60.47% and 45.42%, respectively. Therefore, FIA had the characteristics of a set-accelerating agent and is a very suitable mineral admixture for controlled low-strength materials (CLSMs). At mixing proportions of 10% and 20% FIA in Portland cement, minimum curing ages for FIACP were 28 days and 60 days, respectively, and the pozzolanic strength activity index (SAI) exceeded 75%. Thus, the optimum ratio of FIA to cement paste is 10–20%.



## 1. Introduction

According to the Taiwan Environmental Protection Administration, the reuse of general industrial waste-derived fuel has increased from 103,000 metric tons in 2005 to 939,000 metric tons in 2010. The Ministry of Economic Affairs has also reported that the sludge yields by the paper industry and textile industry have reached as high as 18.1 million tons and 4.1 million tons, respectively. Studies by the Ministry of Economic Affairs show that pulp industry sludge and textile industry sludge contain insulation raw materials, refractory materials, brick kilns or cement kilns, and boiler auxiliary fuels. Therefore, the use of pulp sludge and textile sludge as fuels has increased annually.

In a moist environment, pozzolanic materials, which contain silica and alumina, have a hydration reaction with cement hydration products, such as calcium hydroxide (CH). The resulting C–S–H gels can be used to fill pores in cement pastes to improve water permeability and strength [1,2]. Common pozzolanic materials such as coal ash, furnace slag, and rice husk ash [3], sewage sludge incinerated ash [4,5], cow dung incinerated ash [6], blast furnace slag [7], waste bricks [8], silica manganese slag [9], pulp and paper sludge incinerated ash [10–12], bagasse ash [13,14], and waste glass [15,16] have varying pozzolanic activity. Therefore, pozzolanic materials have been widely used in cement materials to achieve the performance requirements of environmental protection, low hydration heat, and high strength and durability. The optimum condition for transforming pulp sludge into pozzolanic materials is heating at 700 °C for at least 2 h [17]. Palm oil fuel ash is considered an excellent pozzolanic material due to its fineness [18] and its lower water consumption compared to rice husk ash [19].

As pulp sludge and textile sludge can reach calorific values approaching 9.46 MJ/kg and 15.25 MJ/kg, respectively, they have potential use as fuels, especially since they comply with environmental laws and regulations. Therefore, this research team developed a fuel mixture derived from pulp sludge and textile sludge to replace heavy oil for use as a fuel source for heating kitchen wastes.

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**Table 1**
Oxide and compound compositions of industrial sludge-derived fuel incinerated ash (FIA).

| Oxide | $SiO_2$ | $Al_2O_3$ | $Na_2O$ | $K_2O$ | MgO | CaO | $TiO_2$ | LOI |
|---|---|---|---|---|---|---|---|---|
| FIA (%) | 11.46 | 17.76 | 4.23 | 0.56 | 1.91 | 45.21 | 0.25 | 0.75 |

Portland cement (PC); industrial sludge-derived fuel incinerated ash (FIA); LOI: loss on ignition.

Because industrial sludge has a high incinerated ash content, sustainable ways to dispose of industrial sludge-derived fuel incinerated ash (FIA) are urgently needed to improve its potential use as an alternative energy source. Many Asian countries, including Taiwan, China, Japan, Korea, Vietnam, Indonesia, are gradually establishing waste-derived fuel plants to treat wastes and to resolve energy shortage problems. Thus, this study analyzes the basic physical and chemical properties and pozzolanic activity of FIA to assess the feasibility of FIA reuse strategies. Throughout the study, wastes were used to achieve the goal of "Recycling-Based Society" and "Zero Waste Policy".

## 2. Methodology

### 2.1. Experimental materials

This study analyzed industrial sludge-derived fuel containing 70% pulp sludge and 30% textile sludge. Calcium hydroxide was added to the industrial sludge-derived fuel to a total weight percentage of 10% to inhibit the generation of chlorine-containing compounds, which are major pollutants. The fuel was transformed into FIA by burning at 600–700 °C for 2 h followed by a pre-treatment process of drying, crushing, and sieving. Finally, the basic properties of FIA were analyzed. The Type I Portland cement (PC) used in the experiment met the ASTM C150 "Portland Cement" specifications and had a fineness of 300 $m^2$/kg as measured by Blaine Air Permeability Method (ASTM C204) and a specific gravity of 3.15. Portland cement was used as the primary material in mixtures containing varying ratios of FIA, which were used to produce 25 mm cubes of FIA cement paste (FIACP) under the condition of standard fluidity. The FIACPs were then cured in saturated lime water.

### 2.2. Experimental design

Because of the high calcium chloride ($CaCl_2$) content in industrial sludge-derived fuel incinerated ash (FIA), cement paste with incinerated ash sets quickly with high hydration heat. This limited the amount of FIA added to the cement paste. Portland cement with weight ratios of 100%, 90%, 80%, and 70% was mixed with industrial sludge-derived fuel incinerated ash (FIA) at ratios of 0%, 10%, 20%, and 30% and coded as FIACP mixing ratios PC100FIA0 (defined as control specimen), PC90FIA10, PC80FIA20, and PC70FIA30, respectively. Adaptive reuse strategies and the effects of mixing ratios and curing ages of FIA on the pozzolanic effect of cement paste were also studied.

The FIA analyses included chemical composition (by Inductively Coupled Plasma, ICP), pH, water-soluble chloride ion (by the chemical titration method, AASSTO T260), XRD patterns (by X-ray diffractometer), and the pozzolanic material strength activity index (SAI) (ASTM C311-07) [20].

The analyses of the freshly mixed FIACP included consistency (ASTM C187, ASTM C230), setting time (ASTM C191), and hydration heat (ASTM C186-05); the analyses of the hardened FIACP included compressive strength (ASTM C109), pulse velocity (by plus ultrasonic tester, ASTM C597), chemical corrosion resistance (0.5 N hydrochloric acid solution, 1.0 N sulfuric acid solution, 1.5 N sodium hydroxide solution), calcium hydroxide content (by chemical titration method), hydroxide ions (by chemical titration method) concentration, XRD patterns (by X-ray diffratometer), microstructures (by scanning electronic microscopy, SEM), and pore structures (by surface area and porosity analyzer).

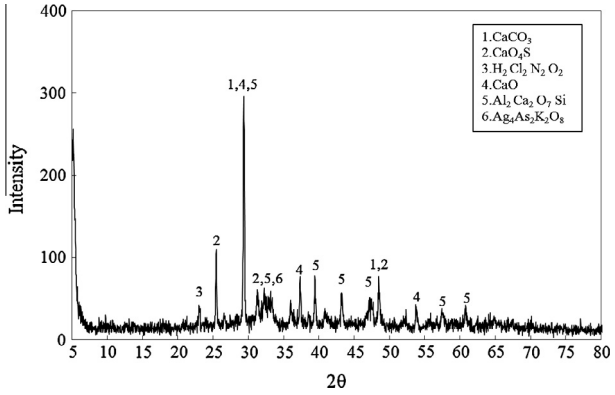


**Fig. 2.** XRD patterns of industrial sludge-derived fuel incinerated ash (FIA).

**Table 2**
Consistency and strength development of industrial sludge-derived fuel incinerated ash cement pastes (FIACPs).

| Properties | | PC100FIA0 | PC90FIA10 | PC80FIA20 | PC70FIA30 |
|---|---|---|---|---|---|
| Water to cement ratio | | 0.35 | 0.40 | 0.47 | 0.55 |
| Fluidity values (%) | | 110 | 113 | 114 | 115 |
| Initial setting time (min) | | 172 | 136 | 127 | 68 |
| Final setting time (min) | | 207 | 178 | 173 | 113 |
| Strength activity index of Pozzolans | 3 days | – | 65.59 | 31.20 | 23.10 |
| | 7 days | – | 69.70 | 36.55 | 24.43 |
| | 28 days | – | 88.21 | 68.30 | 33.35 |
| | 60 days | – | 99.24 | 77.47 | 38.82 |
| | 90 days | – | 99.40 | 85.80 | 42.75 |
| Compressive strength (MPa) | 3 days | 10.42 | 6.52 | 3.25 | 2.41 |
| | 7 days | 11.66 | 8.12 | 4.26 | 2.85 |
| | 28 days | 13.02 | 11.49 | 8.90 | 4.34 |
| | 60 days | 13.91 | 13.80 | 10.78 | 5.40 |
| | 90 days | 15.11 | 15.02 | 12.96 | 6.46 |

Portland cement (PC); industrial sludge-derived fuel incinerated ash (FIA).

## 3. Results and discussion

### 3.1. Characteristics of FIA

#### 3.1.1. Chemical composition

Table 1 shows the chemical composition of FIA. The main components were CaO, $Al_2O_3$, and $SiO_2$, which comprised 45.21%, 17.76%, and 11.46%, respectively, followed by $Na_2O$, MgO, $K_2O$, and $TiO_2$, which comprised 4.23%, 1.91%, 0.56%, and 0.25%, respectively. Loss on ignition (LOI) was 0.75%. Because 10% lime ($Ca(OH)_2$) must be added to the industrial sludge-derived fuel to

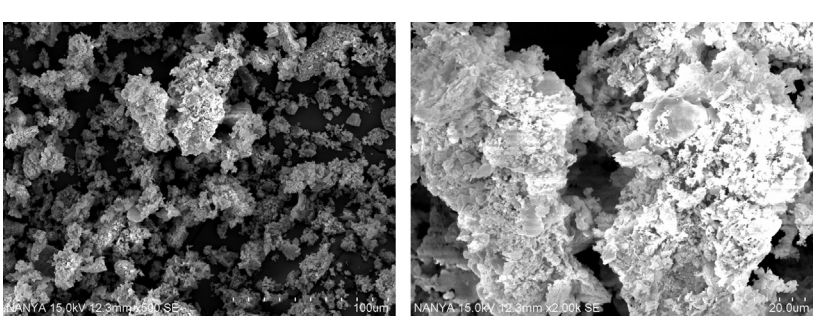

**Fig. 1.** SEM micrographs of industrial sludge-derived fuel incinerated ash (FIA).