Development of Green Concrete for Mining Roads using Incineration Residue Ash

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ABSTRACT

This study explores the potential of incorporating Incineration Residues Ash (IRA) as a partial replacement for Portland Composite Cement (PCC) in cement production at a mining site in Ceria Indotama Nugraha, Indonesia. Concrete mixtures with different percentages of IRA-0%, 25%, 50%, 75%, and 100%- were evaluated for workability and compressive strength under extreme conditions. The results show that replacing up to 50% PCC with IRA leads to compressive strength values similar to those of traditional concrete (30 MPa), with 25% IRA being the optimal percentage. Additionally, Life Cycle Assessment (LCA) analysis revealed that the environmental impact of concrete can be reduced with IRA replacement, especially regarding CO_2 emissions. These findings suggest that using incineration residues in concrete production can be a sustainable and possible alternative for mining road constructions.

Keywords-incineration residue; green technology; compressive strength; concrete mix; mining roads

I. INTRODUCTION

Mining roads are necessary for carrying heavy equipment and extracted minerals over large and isolated areas. However, this kind of infrastructure can be degraded by environmental factors, such as unstable temperatures, high humidity, and exposure to corrosive ingredients, leading to increased maintenance and operational costs [1]. This is attributed to traditional construction materials like Portland Composite Cement (PCC) that cannot deal these conditions, thus it is important to develop more durable materials. One capable approach is the integration of incineration residues -obtained from waste incineration processes- in concrete production as a partial substitute for cement, providing an effective use for industrial and municipal waste [2-6]. Calcium, silicon, and aluminum oxides are some the key components of incineration residues, which include chemical properties that make them a potential alternative cementitious material. These alternatives help in the mitigation of CO_2 production, which is a major contributor to greenhouse gas emissions, as well as in the promotion of green technology [7, 8].

Over the years, researchers have explored the ability of waste materials, such as Fly Ash (FA), Ground Granulated Blast-Furnace Slag (GGBFS), and silica fume, as parts of cement in concrete, with the findings indicating that mechanical properties, such as compressive strength and durability have been improved [9, 10]. Authors in [11] proposed that the addition of fly ash in cement production cannot exceed 30% of its content in order to maintain its strength. Another study by authors in [12] indicated that the equivalent substitution of bottom ash for cement reduced the compressive strength of concrete, thus the maximum ratio of bottom ash was 15% and this binder was suitable for application in low strength concrete. However, the utilization of incineration residues, in extreme environments like mining roads, has gained little attention. Regarding mining road construction, researchers in [13] researched the employ of mining wastes as alternative aggregates for concrete production, focusing only on traditional cementitious materials without studying incineration residues. These gaps highlight the need for evaluating the application of incineration residues in concrete during extreme conditions, as well as exploring key mechanical properties, such as compressive strength, and durability over time.

II. RESEARCH SCOPE

This research focuses on the creation of a sustainable concrete mix replacing PCC with different proportions of incineration residues (0%, 25%, 50%, 75%, and 100%) to estimate their impact on the compressive strength of the concrete. This property is tested at 3, 7, and 28 days at mining sites, considering the challenges occurring by heavy loads, unpredictable temperatures, and high humidity levels.

III. MATERIALS AND METHODS

This study aims to evaluate the mechanical properties of concrete by replacing PCC with Incineration Residue Ash (IRA) under extreme laboratory conditions that are as close to real mining environments. Additionally, a Life Cycle Assessment (LCA) is performed to estimate the environmental impact of this material.

A. Materials and Mix Design

- Cement: PCC. Portland Composite Cement (PCC) is a finely ground material designed to meet the needs of modern construction. The average particle size of PCC lies in the range of 25 μm. The chemical composition of PCC is engineered to provide optimal cementitious properties. Its physical and chemical characteristics collectively ensure that PCC delivers high early and long-term strength, durability, and compatibility with supplementary cementitious materials, making it a foundational material in construction.
- Incineration residue: IRA replacing 0%, 25%, 50%, 75%, and 100% of PCC by weight. IRA particles are irregularly shaped with rough surfaces. These surface characteristics facilitate enhanced bonding with the cement matrix. The average particle size of IRA typically has a size of 37 μm, which is similar to other pozzolanic materials like fly ash. The chemical composition of IRA presents a significant presence of oxides essential for pozzolanic reactivity.
- Aggregates: Crushed coarse aggregate (10–20 mm) and natural river sand as fine aggregate were considered.
- Water: Potable water for hydration.
- Admixtures: High-range water reducers.

Table I presents the laboratory testing plan of this research.

TABLE I. LABORATORY TESTING PLAN

Mix Proportions	Percentage of PCC Replacement	Target Workability (Slump)	Curing Period
Mix-1	0%	75-100 mm	3, 7, 28 days
Mix-2	25%		
Mix-3	50%		
Mix-4	75%		
Mix-5	100%		

B. Laboratory-Simulated Extreme Conditions

Various extreme conditions were simulated in the laboratory approaching the mining road environments. The first harsh condition was thermal cycling, which represented the daily temperature variations that occur at mining sites. Concrete specimens were exposed to high temperatures of 50 °C for 12 hours, followed by low temperatures of 10°C for another 12 hours over a 28-day period. The second situation involved water saturation and drying cycles, where simulations of mining roads exposure to water and their drying under harsh sunlight took place. In this case, mixtures were alternately submerged in water for 24 hours and air-dried at 35 °C for another 24 hours over a 14-day cycle, providing information about the moisture variations on concrete strength. To replicate the heavy vehicle loads high load simulation was performed. This methodology involved static load testing with compressive forces equal to 25% of the ultimate load capacity applied for 1000 cycles on cured specimens. The last simulation was about the exposure to acidic environments from mining waste or water, where specimens were immersed in a 5% sulfuric acid (H_2SO_4) solution for 28 days, with periodic checking of weight loss and surface degradation.

C. Evaluation Parameters

The performance of concrete was assessed through its mechanical properties, including compressive strength and workability. Compressive strength tests were conducted at 3-, 7-, and 28-days following ASTM C39 standards under different replacement levels. Slump test was completed according to ASTM C143 to evaluate the workability of concrete mixtures, ensuring that the replacement of PCC with incineration IRA does not adversely affect the fresh properties of the concrete.

IV. RESULTS AND DISCUSSION

A. Mixture Design

Table II presents the mix design of concrete incorporated with IRA instead of PCC, with a compressive strength of 30 MPa. In concrete without IRA, PCC provides the whole amount of cement needed (350 kg/m^3), whereas in a 50% IRA mixture, PCC and IRA provide 175 kg/m^3 each. To keep the concrete volume stable, the coarse-to-fine aggregate ratio remains constant. In order to reach a concrete quality of $f'c$ = 30 MPa, the water-cement factor should be at 0.50. For all modifications, the water content stays at 175 kg/m^3. Since the behavior of combustion ash might change the process efficiency, 2 kg/m^3 of superplasticizer is added to the mixture.

TABLE II. MIXTURE DESIGN

Component	0% IRA	25% IRA	50% IRA	75% IRA	100% IRA
PCC (kg/m^3)	350	262.5	175	87.5	0
IRA (kg/m^3)	0	87.5	175	262.5	350
Fine aggregate (kg/m^3)	750				
Coarse aggregate (kg/m^3)	1000				
Water (kg/m^3)	175				
Water-cement ratio (w/c)	0.50				
Superplasticizer (kg/m^3)	2				

B. Slump Test

To check the workability of concrete, slump test was calculated for all concrete mixes. This procedure is valuable for projects that involve specific performance conditions, evaluating the concrete's flow across the reinforcement and the mold’s filling equally. The slump test helps achieving the proper strength, durability, and structural stability of reinforced concrete by keeping its workability within the desired limits, thus ensuring the success of infrastructure projects [14-15]. Figure 1 illustrates the results of the slump test carried out for all variations of test objects.

It is clear that all specimens range within the acceptable limits of 75-100 mm, suggesting a good workability for structural concrete applications. Specifically, the test that includes only PCC (0% IRA), exhibit a slump value of 85 mm - moderate workability- leading to consistent flow behavior due to homogeneous cement particles. The slump increases at a low rate for specimens with 25% and 50% IRA, probably because of the finer particle size of the material compared to PCC. This improves the paste's ability to coat aggregates and enhance flow. In 75% and 100% IRA incorporation, a decrease in slump is observed, which is related to the high replacement levels of PCC, resulting in lowered cementitious properties and possible moisture absorption by these particles. Concrete with moderate IRA replacement levels (25%-50%) enhances the covering density, improving workability, while excessive replacement (75%-100%) creates heterogeneity, restricting flow. At higher IRA levels, water demand is increased due to its porous nature, slightly affecting the slump. To maintain workability, the utilization of superplasticizers is essential within the target range despite increasing IRA content.

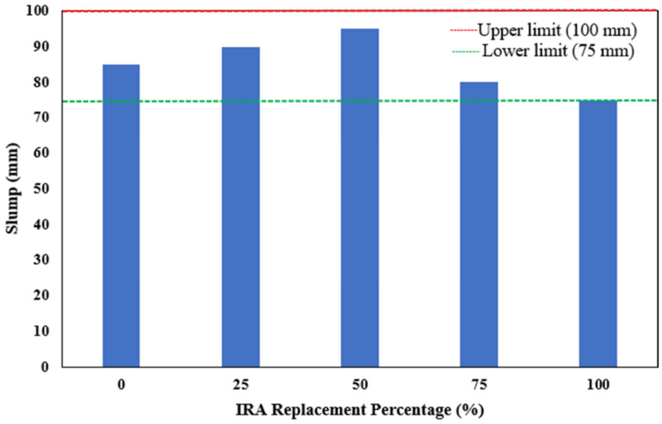

Fig. 1. Slump test results for all concrete mixtures.

C. Compressive Strength

The compressive strength test estimates the mechanical performance of the different mixtures of green concrete, providing significant information about its ability to withstand axial loads without failure [16]. By analyzing these variations in test values, the study can detect the optimal mix proportions for enhancing this property while utilizing sustainable materials. Figure 2 and Tables III and VI present the findings of the compressive strength tests carried out for all specimens.

All variations demonstrate a significant increase in compressive strength during the early curing period (from 3 to 7 days) with 0% IRA showing a 30.76% rise and 100% IRA reaching a 44.44%. This behavior is caused by the hydration of cement (in PCC) and the early geopolymerization reactions in mixes with IRA. Higher IRA content slows down the early strength increase due to the decreased calcium silicate hydrate (C-S-H) production. From 7 to 28 days, the compressive strength increases with slower rate, exhibiting its highest percentage at 100% IRA (28%). At 28 days, the control mix (0% IRA) reaches the highest compressive strength (31 MPa), while 100% IRA exhibits a value of 25 MPa. This decline is caused by the lower binding effectiveness of aluminosilicate gel in comparison with C-S-H gel. The addition of IRA introduces fine particles that improve packing density at moderate levels (25%-50%), while excessive replacement leads to weaker bonds between particles due to lacking calcium ions, necessary for strong C-S-H gel formation. Thus, the highest compressive strength values are exhibited in the mix with 0% IRA at 28 days (31 MPa), closely followed by the 25% IRA mix (30 MPa). These values reach the design strength value of 30 MPa, making them suitable for structural applications, with the 25% IRA combination being the optimal mixture balancing both strength and sustainability.

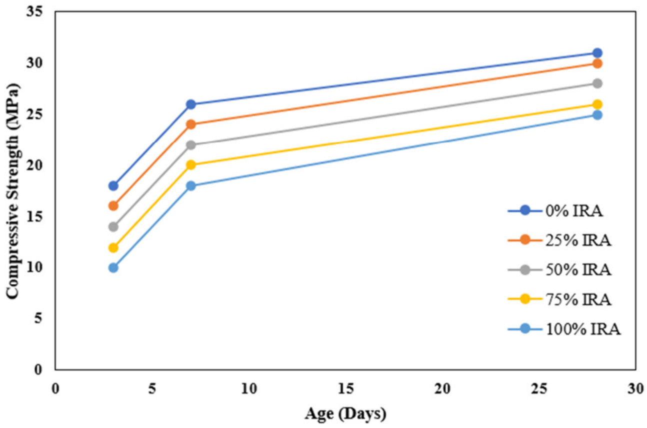

Fig. 2. Compressive strength test result.

TABLE III. COMPRESSIVE STRENGTH

Age (days)	Compressive Strength				
	0% IRA (MPa)	25% IRA (MPa)	50% IRA (MPa)	75% IRA (MPa)	100% IRA (MPa)
3	18	16	14	12	10
7	26	24	22	20	18
28	31	30	28	26	25

TABLE IV. INCREASE PERCENTAGE COMPARISON BY AGE IN COMPRESSIVE STRENGTH

Age (days)	Percentages				
	0% IRA (%)	25% IRA (%)	50% IRA (%)	75% IRA (%)	100% IRA (%)
3 → 7	30.76	33.33	36.37	40.00	44.44
7 → 28	16.13	20.00	21.43	23.10	28.00

D. Life Cycle Assessment (LCA)

LCA is a modeling tool for quantifying the environmental effects of a product or even a process [17]. For example, LCA results can assess if one product is environmentally preferable to another. In this study, LCA is utilized in order to evaluate the impact of incorporating IRA into cement as an alternative sustainable material. The quantification is developed at the input materials (PCC, IRA), the energy consumption, the transportation distances, and the emission factors related to each substitution scenario.

- IRA: The ash obtained from the incineration of waste materials. The composition can range depending on the waste type, containing heavy metals and other pollutants.
- PCC: The primary component for cement production, emitting plenty quantities of CO_2 due to calcination process [18].

Each scenario is reviewed based on the following parameters:

1) Global Warming Potential (GWP)

Impact: The replacement of PCC with IRA material reduces the emitted CO_2 coming from cement production.

Trend: GWP decreases with the addition of IRA. This means that a full IRA replacement would lead to maximum CO_2 reduction.

2) Acidification Potential (AP)

Acidification is caused by cement production due to sulphur emissions derived from limestone and fuel that used in calcination [19].

Impact: IRA also contains sulphur compounds, so it is important to control its quantity to avoid further acidity.

Trend: AP can be decreased with the addition of IRA, if sulphur content is kept low.

3) Eutrophication Potential (EP)

Eutrophication happens when extra nitrogen and phosphorus insert water systems, causing harmful algal blooms [20].

Impact: Substituting IRA with PCC may present more nutrients into the system.

Trend: Eutrophication can be mitigated if IRA contains lower phosphorus and nitrogen content.

4) Resource Depletion

Impact: Cement is produced particularly by raw materials. The addition of IRA lowers resource depletion.

Trend: As IRA quantity increases, a greater reduction occurs in resource depletion.

5) Toxicity

Impact: Heavy metals such as cadmium, mercury, and lead can be found in IRA causing toxicity. So, its replacement with PCC in cement production increases the possibility for pollution if it is not well-managed.

Trend: The toxicity risk increases with higher IRA change.

V. CONCLUSION

This study examines the potential of replacing Portland Composite Concrete (PCC) with Incineration Residue Ash (IRA) in concrete production. Mechanical Performance testing and a Life Cycle Assessment (LCA) were developed in extreme mining road conditions. The conclusions are summarized as follows:

- The LCA suggested that the addition of IRA as an alternative sustainable material in concrete production, can mitigates CO_2 emissions and maintains the natural resources promoting waste recycling.
- The development of green concrete requires the optimization of the mix to ensure that it meets the specific needs of mining roads, which are subject to heavy loads, wear, and environmental stress.
- The mixture with 25% of IRA achieves the same compressive strength with traditional concrete (30 MPa).

To evaluate long-term performance and durability in extreme environments like mining roads, further research is necessary. Additionally, supportive policies and regulations such as acceptable setting standards for IRA composition and environmental safety, are important aspects that must be considered.

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