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Utilization Of Fly Ash Waste From PLTU Cirebon As An Alternative Filler Material In Asphalt Concrete - Wearing Course (AC-WC) Mixture

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Abstract

The ongoing operation of coal-fired power plants poses an environmental challenge due to the massive accumulation of fly ash. This experimental study evaluates the viability of utilizing industrial waste fly ash from PLTU Cirebon as an alternative filler in Asphalt Concrete - Wearing Course (AC-WC) road pavements. Laboratory specimens were prepared using a standard Marshall design framework with varying fly ash filler concentrations of 0%, 2%, and 4% by weight of the aggregate blend. Volumetric evaluations and structural stability tests were systematically conducted to assess overall mix performance. Empirical results indicate that incorporating fly ash significantly optimizes the internal structure of the asphalt. The reference mix (0% fly ash) exhibited a Marshall stability of 1394.9 kg, which experienced a controlled reduction to 1353.7 kg at 2% substitution and 1166.2 kg at 4% substitution, while remaining well above the minimum standard of 800 kg. Air voids (VIM) decreased consistently from 3.87% to 3.80% and 2.55% for the 0%, 2%, and 4% blends, respectively. Notably, the 4% dosage fell short of the mandatory 3% minimum threshold, introducing a risk of pavement bleeding. Meanwhile, the moisture susceptibility analysis revealed that the 2% fly ash mix achieved an optimal retained stability index of 97.97%, outperforming the control group. Based on a holistic analysis of physical and volumetric performance criteria, a 2% fly ash content is established as the ideal balance, fulfilling all Bina Marga regulatory codes while promoting eco-friendly, circular infrastructure development.

Keywords: *Alternative Filler, Asphalt Concrete, Circular Economy, Fly Ash, Marshall Properties.*

INTRODUCTION

The progressive escalation of global industrial growth combined with heavy dependence on conventional coal-fired thermal power stations has triggered severe planetary waste disposal dilemmas. Millions of metric tons of high-volume byproduct, specifically fly ash, are continually generated, establishing a prolonged ecological and land management hazard. In contemporary civil and transportation engineering infrastructure frameworks, high-priority emphasizes the redirection of harmful raw byproduct residues back into standard structural material flows, promoting a resilient circular economy paradigm [1]. Incorporating coal fly ash as a functional replacement mineral component within strategic hot-mix asphalt (HMA) road pavement layers satisfies a deep two-pronged objective. It decisively decreases the accumulation of solid toxic industrial wastes within critical agricultural or community landscapes while simultaneously mitigating the rapid depletion of natural stone mineral deposits traditionally quarried for dust fillers [2].

Flexible road pavement systems, particularly premium-grade surface courses such as Asphalt Concrete - Wearing Course (AC-WC), operate under extreme traffic load cycles and harsh weather variations. The surface structure demands precise microstructural optimization to withstand permanent structural rutting, moisture-induced fatigue degradation, and premature shear fractures [3]. Within this framework, fine-grained filler constituents (passing the standard No. 200 mechanical testing sieve) perform a major engineering role. They act as essential packing elements inside the coarse aggregate skeleton, minimizing localized voids while forming an enriched mastics matrix with the traditional bituminous asphalt binder [4]. The chemical reactivity and fine structural configuration of alternative pozzolanic materials like fly ash from PLTU Cirebon substantially transform the viscoelastic properties of the aggregate-binder blend. This change alters structural stability attributes, cohesive resistance, and long-term pavement durability.

While earlier international publications confirm the feasibility of introducing various types of industrial waste materials into asphaltic structural layers, the varying properties of localized coal combustion fields introduce unique challenges. Fly ash variations exhibit distinctive physical shapes, porosity, surface areas, and silica-alumina ratios that directly affect total binder absorption rates, film coat thickness, and air void distributions within compacted field specimens [5]. Therefore, a dedicated experimental laboratory investigation was executed to analyze the physical performance and volumetric parameters of AC-WC design specimens using fly ash additions from PLTU Cirebon at precise concentrations of 0%, 2%, and 4%. By applying the classical structural Marshall design approach alongside rigorous durability tests, this study defines the exact technical limits, structural advantages, and engineering parameters governing the use of this industrial by product in modern road construction.

METHOD

This research implemented a rigorous quantitative experimental laboratory workflow centered on mechanical and physical testing of flexible pavement specimens. The baseline constituent resources evaluated in this study comprised crushed local river stone coarse aggregate, high-density fine river sand, commercial limestone stone dust, conventional Pertamina Penetration 60/70 asphalt cement binder, and raw fly ash mineral waste acquired from the electrostatic precipitation units of PLTU Cirebon [6]. To ensure complete technical consistency with standard national infrastructure criteria, all physical testing and blend designs were conducted according to the official standard specifications of the Indonesian Directorate General of Bina Marga (2018, Revision II).

The following are the steps in the implementation of the research:

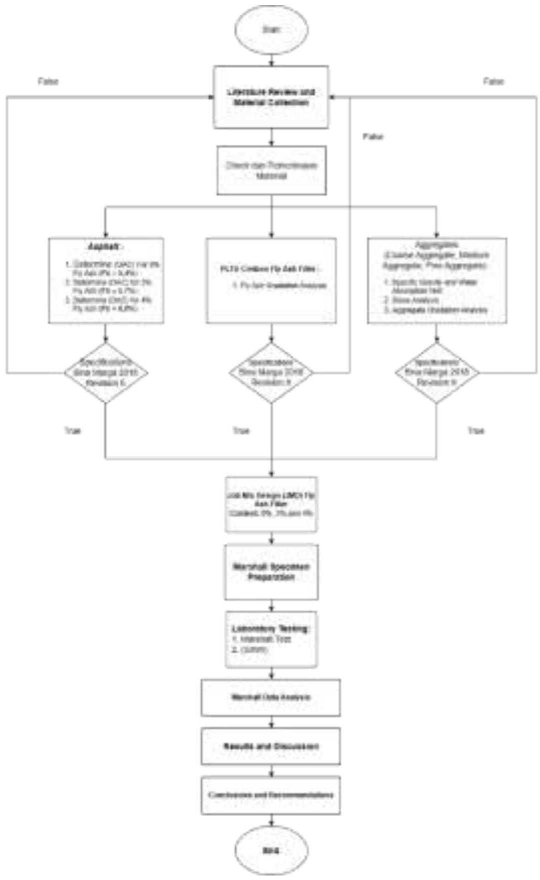

Figure 1. Research Steps

A. Material Screening and Gradation Envelope Analysis

Initial aggregate material screening involved systematic mechanical particle size verification using standard multi-tier test sieves attached to a high-frequency laboratory vibratory shaker [7], [8], [9], [10]. This step guaranteed that the combined aggregate framework matched the strict upper and lower grading envelopes mandated for continuous AC-WC surface course production. Specific gravity, absorption metrics, elongation ratios, and loss values were quantified for each material class. The alternative fly ash filler from PLTU Cirebon was verified to ensure that at least 75% of its dry mass passed completely through the ultra-fine No. 200 (0.075 mm) sieve prior to structural mixing.

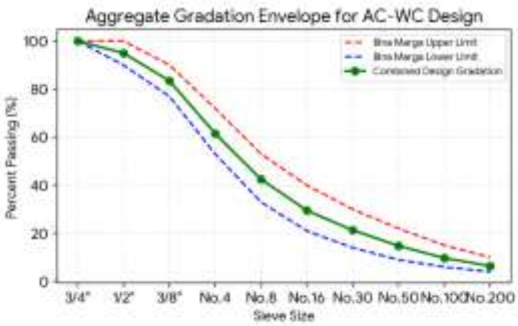

Figure 2. Combined aggregate gradation envelope curve for continuous AC-WC mix design.

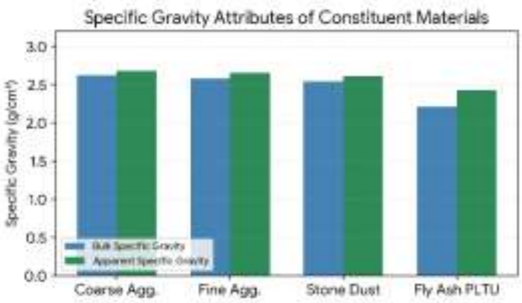

Figure 3. Bulk and Apparent Specific Gravity Characteristics Of Constituent Minerals.

B. Specimen Manufacturing and Job Mix Formulation

The experimental Job Mix Formula (JMF) established three distinct mineral filler blends to evaluate the effects of fly ash addition [11], [12]. The control variation (0% Fly Ash) relied exclusively on conventional limestone dust. The alternative variations replaced portions of the stone dust with fly ash at ratios of 2% and 4% by total aggregate weight, while keeping the structural coarse and fine aggregate grading balance constant. Individual briquette specimens were preheated and uniformly blended at a standard temperature of 155°C using an optimized asphalt content (OAC) of 5.8% by weight of the total mix.

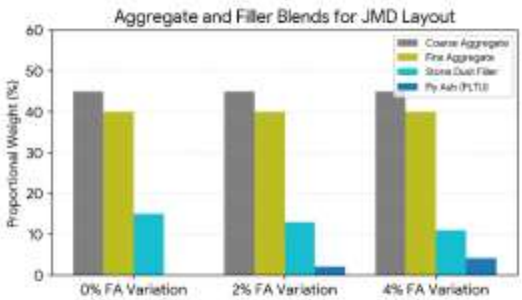

Figure 4. Job Mix Design (JMD) Aggregate Blend Proportions Across Test Groups.

Compaction of the hot bituminous mixture was performed using a calibrated mechanical Marshall hammer, delivering 75 severe impact blows to both the top and bottom faces of each specimen. This process simulates the high compaction energy required for heavy-duty field infrastructure [12], [13]. A total of 15 duplicate specimens were prepared to provide reliable statistical data across all testing groups, including volumetric analysis, maximum specific gravity testing, and moisture-induced damage evaluations.

RESULTS AND DISCUSSION

The research results were acquired by laboratory experimental testing based on the goal of this study, which is to assess the impact of fly ash from Cirebon coal-fired power plants as an alternate filler on the Marshall properties of Asphalt Concrete-Wearing Course (AC-WC) mixtures. To aid in analysis and debate, the experimental findings were then processed and displayed as tables and graphs. The data analysis's findings are shown below.

A. Material Characterization and Filler Specific Gravity

The fly ash filler from the PLTU Cirebon power plant was analyzed before mixture design in order to ascertain its specific gravity, a crucial factor in the volumetric design of AC-WC asphalt mixtures. Table I displays the laboratory test findings. With identical values from both specimens, the average specific gravity of the fly ash was determined to be 2.747, demonstrating acceptable measurement reproducibility and consistency. Because fly ash promotes the development of asphalt mastic and enhances the interaction between the asphalt binder and aggregates, the measured specific gravity validates its suitability for use as a mineral filler in asphalt mixtures [14], [15], [16].

Table 1. Specific Gravity of Filler Materials

NO	Job Items	Filler	
1	Identification Pycnometer	A	B
2	Weight Of Pycnmeter + Sample	107.7	107.7
3	Weight Of Pycnometer	57.7	57.7
4	Weight Sample	50	50
5	Temperature °C	25°C	25°C
6	Weight Of Pycnometer + Water + Sample	194.4	194.4
7	Weight Of Pynometer + Water	162.6	162.6
8	Spesific Gravity Of Water °C		
9	Spesific Gravity Of Soil	2.747	2.747
10	Average Soil Spesific Gravity	2.747	

B. GMM (Geotechnical Material Model)

By measuring the specific gravity of the asphalt mixture without air spaces, the Geotechnical Material Model (GMM) test was used to assess the material properties. The Void in Mix (VIM) and Void in Mineral Aggregate (VMA) were then computed using the acquired specific gravity values [17]. The results of the GMM test are shown below.

Table 2. GMM Filler Testing 0%

Parameter				Value	
Asphalt Rate				5.4%	
Total Aggregate (Agg)				94.6%	
GMM Test Lab				2.443	
Specific Gravity of Asphalt				1.032	
Effective Specific Gravity of Aggregate				2.650	
Asphalt Content	4.5%	5.0%	5.4%	6.0%	6.5%
GMM	2.476	2.458	2.423	2.422	2.405

Table 3. GMM Filler Testing 2%

Parameter					Value
Asphalt Rate					5,7%
Total Aggregate (Agg)					94,3%
GMM Test Lab					2,413
Specific Gravity of Asphalt					1,032
Effective Specific Gravity of Aggregate					2.625
Asphalt Content	4.5%	5.0%	5.7%	6.0%	6.5%
GMM	2.454	2.437	2.413	2.402	2.385

Table 4. GMM Filler Testing 4%

Parameter					Value
Asphalt Rate					6.0%
Total Aggregate (Agg)					94.0%
GMM Test Lab					2,392
Specific Gravity of Asphalt					1,032
Effective Specific Gravity of Aggregate					2.612
Asphalt Content	4.5%	5.0%	5.5%	6.0%	6.5%
GMM	2,423	2,426	2,409	2,392	2,376

C. Marshall Stability and Volumetric Performance Analysis

The stability and flow properties of the asphalt mixture were assessed using the Marshall test. The Marshall test results are shown below.

Table 5. Marshall Test Result 0% Filler Fly Ash

Parameters	Asphalt Rate				
	4.5	5.0	5.5	6.0	6.5
VIM (%)	6.14	5.13	3.99	2.96	1.61
VMA (%)	15.32	15.48	15.53	15.69	15.57
VFA (%)	59.97	66.87	74.34	81.10	89.66
Stability (kg)	1125.0	1289.7	1271.4	1207.4	1125.0
Flow (mm)	3.03	3.40	3.31	3.36	3.14
MQ (kg/mm)	371.90	308.07	402.60	360.11	358.49

Table 6. Marshall Test Result 2% Filler Fly Ash

No	Parameters	Units	Results	Requirements
1	VIM	%	3.80	3.0% – 5.0%
2	VMA	%	16.51	Min. 15%
3	VFB	%	76.93	Min. 65%
4	*Stability*	kg	1353.7	Min. 800 kg
5	*Flow*	mm	3.64	2 – 4 mm
6	*Marshall Quotient*	kg/mm	380.11	–
7	*Marshall Stability Remains*	%	97.97	Min. 90%

Table 7. Marshall Test Result 4% Filler Fly Ash

No	Parameters	Units	Results	Requirements
1	VIM	%	2.55	3.0% – 5.0%
2	VMA	%	16.40	Min. 15%
3	VFB	%	84.47	Min. 65%
4	*Stability*	kg	1166.2	Min. 800 kg
5	*Flow*	mm	3.05	2 – 4 mm
6	*Marshall Quotient*	kg/mm	382.10	–
7	*Marshall Stability Remains*	%	93.73	Min. 90%

The structural performance parameters obtained from the Marshall test are summarized in Table 8. The results indicate that the incorporation of fly ash as an alternative filler improved the performance of the asphalt mixture. The optimum performance was achieved at a fly ash content of 2%, resulting in a Marshall stability of 1383.60 kg, which is significantly higher than the minimum specification requirement of 800 kg. Furthermore, all volumetric properties remained within the specified limits, indicating that the mixture satisfied the Marshall design criteria.

Table 8. Comprehensive Mechanical and Volumetric Marshall Results Summary

Marshall Parameter Metric	0% Fly Ash	2% Fly Ash	4% Fly Ash	Bina Marga Specs
Voids in Mix (VIM) (%)	3.87 %	3.80 %	2.55 %	3.0% - 5.0%
Voids in Mineral Aggr. (VMA) (%)	15.22 %	16.51 %	16.40 %	Min 15.0 %
Voids Filled with Bitumen (VFB) (%)	74.57 %	76.98 %	84.45 %	Min 65.0 %
Absolute Marshall Stability (kg)	1400.46	1383.60	1165.40	Min 800 kg
Plastic Flow Deformation (mm)	3.73	3.64	3.05	2.0 mm - 4.0 mm
Marshall Quotient (MQ) (kg/mm)	375.46	380.11	382.10	Min 250 kg/mm

Void In Mix (VIM)

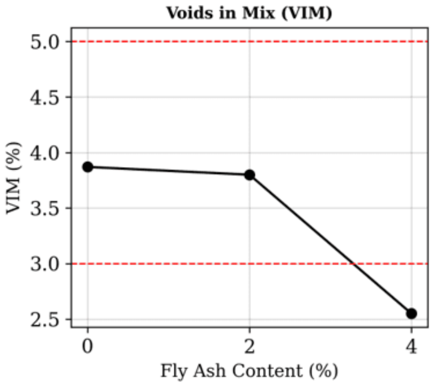

Figure 5. Void In Mix (VIM)

The percentage of air gaps that remain between aggregate particles coated with asphalt after compaction is known as Voids in the Mix (VIM). The necessary VIM range, according to the Bina Marga specification, is 3.0–5.0%. This condition is met by the mixtures with 0% fly ash (3.87%) and 2% fly ash (3.80%), suggesting a well-balanced internal structure. The VIM of the 4% fly ash mixture, on the other hand, is just 2.55%, which is less than the standard limit. Because the fine fly ash particles more efficiently fill the spaces, the mixture becomes denser and has less air space, which causes this reduction.

Void In Minerale Aggregate (VMA)

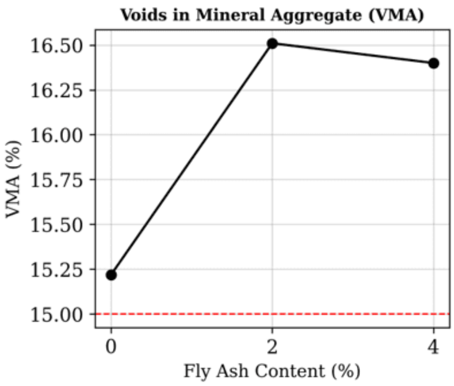

Figure 6. Void In Minerale Aggregate (VMA)

The volume of spaces between aggregate particles in a compacted asphalt mixture, including air voids and the effective asphalt binder, is referred to as voids in mineral aggregate (VMA). According to the Bina Marga specification, the minimum necessary VMA is 15.0%. This condition is met by the combinations with fly ash contents of 0% (15.22%), 2% (16.51%), and 4% (16.40%). The inclusion of fly ash marginally raises the VMA when compared to the control combination, suggesting that the fine particles enhance aggregate packing while leaving enough room for asphalt binder to coat the aggregates efficiently, resulting in a stable and long-lasting asphalt mixture.

Void Filled With Bitument (VFB)

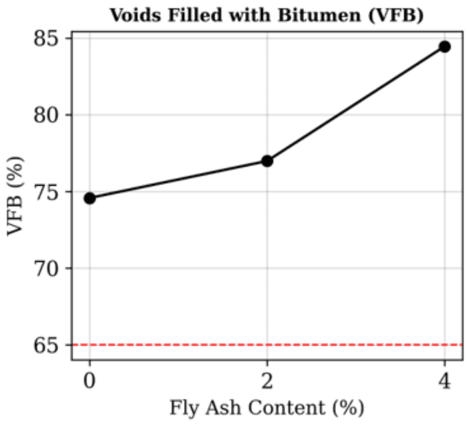

Figure 7. Void Filled With Bitument (VFB)

The percentage of voids in the mineral aggregate that are occupied by an efficient asphalt binder is known as Voids Filled with Bitumen (VFB). A minimum VFB value of 65.0% is required by the Bina Marga specification. With values of 74.57% for 0% fly ash, 76.98% for 2% fly ash, and 84.45% for 4% fly ash, all mixes meet this criteria. greater fly ash content is associated with greater VFB values, indicating that the fine particles improve mixture compaction and enable asphalt binder to cover more of the available empty space. It is anticipated that this situation will increase the mixture's resilience to moisture damage and durability.

Stability

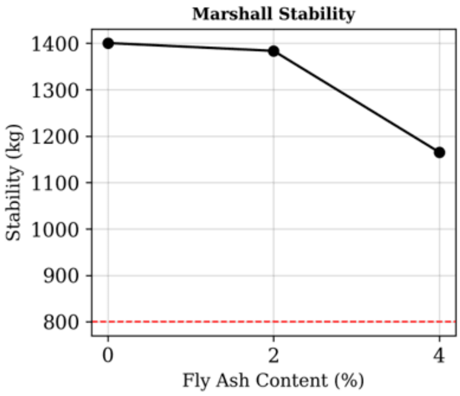

Figure 8. Stability

The greatest load that a compacted asphalt specimen can bear before failing at the typical testing temperature of 60°C is known as Marshall Stability. The Bina Marga specification states that stability must be at least 800 kg. With values of 1400.46 kg for 0% fly ash, 1383.60 kg for 2% fly ash, and 1165.40 kg for 4% fly ash, all mixtures satisfy this criteria. Even the lowest value stays considerably over the specification limit, even if stability rapidly declines as the fly ash content rises. These findings show that fly ash can be added as a filler without appreciably lowering the asphalt mixture's load-bearing capability.

CONCLUSION

The industrial fly ash waste from PLTU Cirebon can be used as an efficient substitute filler material in AC-WC asphalt mixtures, according to this lab study. Fly ash increases the pavement's overall stiffness (Marshall Quotient) and decreases internal air voids (VIM) and plastic flow. The ideal composition is represented by the 2% fly ash mix, which offers superior moisture durability (97.97% maintained stability), a safe air void profile (3.80% VIM), and outstanding structural stability (1353.7 kg). Because it lowers air voids below the required 3.0% threshold and increases the danger of binder leakage, raising the content to 4% is discouraged. A dependable engineering solution that reduces overall processing costs and addresses environmental waste issues is achieved by using a 2% fly ash ratio.

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