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Mathematical Analysis of Boiler Slag in Hot Mixed Asphalt for Road Construction Materials

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Abstract: This paper explores the viability of utilizing boiler slag as a partial replacement for natural aggregate in asphalt mixtures. The primary objectives include assessing the physical properties of both natural aggregate and boiler slag as well as the Marshall stability and flow characteristics of asphalt mixtures composing of a 70:30 ratio of natural aggregate to boiler slag. The relationship between stability and flow test outcomes were examined. It was concluded that the tests conducted complied to JKR Standards and boiler slag can serve as an effective alternative to natural aggregate in asphalt mixtures, presenting a sustainable solution for road construction that minimizes quarrying activities and mitigates environmental impacts, in line with the sustainable development goal and resilient infrastructure.

Keywords: boiler slag, artificial aggregates, physical properties, volumetric properties, hot mix asphalt (HMA), ACW14.

1. Introduction

Pavement construction holds the largest market share for natural aggregates, making it the primary application for these materials. In Malaysia, around 180,000 km, or 75.6% of all roads, are paved with asphalt, highlighting its importance to the country's infrastructure (KKR Malaysia, Dec 2017). To support the construction of new roads and the maintenance of existing ones, aggregates often need to be transported over considerable distances, sometimes exceeding hundreds of kilometres (Mallick et al., 2013). For instance, over 15,000 tonnes of aggregates are required for every kilometre of bituminous mix surface, highlighting the significant demand driven by rapid urbanization. The extraction of natural aggregates for hot mix asphalt production has substantial environmental implications, threatening conservation and preservation efforts (Bastidas-Martínez et al., 2022).

This study is conducted to dig out the potential of power plant by-product named as boiler slag that is obtained from Tanjung Bin Power Plant. Although the usage has been known for other countries, however in Malaysia the usage remains unexposed. While researchers have dedicated significant effort to recycling coal combustion byproducts from power plants, especially substituting fly ash and bottom ash for traditional aggregates in hot mix asphalt; there has been limited exploration of boiler slag. The unique properties and composition of these materials make them suitable for applications such as highway construction, soil stabilization, and pollution control (Prasad & Kumar, 2015). This material holds promise as a partial replacement for natural aggregate in hot mix asphalt. Previous studies on the addition of coal combustion by-products such as bottom ash to replace natural aggregates in construction materials show that the development of strength characteristics was similar to conventional materials and proves that these by-products are economical alternatives (Rahman et al., 2023). Although significant investigations have been made on fly ash and bottom ash in various construction applications, there remains limited research on boiler slag, particularly in hot mix asphalt applications for road construction.

The study was carried out in the laboratory, in order to test the engineering properties to encourage its application in pavements. Los Angeles (L.A.) Abrasion, Flakiness Index and Aggregate Impact Value (AIV), specific gravity, and water absorption tests were done to investigate the physical properties of both natural aggregates and boiler slag.

The subsequent aim involved utilizing the Marshall mix design to ascertain the volumetric properties of both mix and control samples. This design aims to enhance the stability and durability of asphalt pavements by employing a carefully balanced 70:30 ratio of natural aggregate to boiler slag, along with mineral filler and asphalt binder. The final objective focused on establishing meaningful connections between flow and stability test results for natural aggregate and boiler slag, with implications for refining engineering practices and promoting the development of resilient and sustainable infrastructure.

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2. Materials and Methods

Laboratory experiments are conducted to meet the research objectives. All methods are specified in accordance with those specified by Jabatan Kerja Raya (JKR) Standard Specification for Road Works (JKR/SPJ/2008), American Society for Testing and Materials (ASTM), American Association of State Highway and Transportation Officials (AASHTO) and British adoption of a European standard (BS EN).

The first phase of this research involves assessing the physical and engineering (strength) properties of natural aggregates as well as boiler slag. Marshall Method is then used to design ACW14 asphalt mixtures with asphalt bitumen of penetration (PEN) 60/70 in the second phase. The asphalt mixes are designed at a ratio of 50:50, 30:70 and 20:80 of boiler slag to natural aggregates.

The last phase focused on conducting the laboratory performance tests to compare the asphalt concrete mixtures with and without boiler slag. The findings shall be based on JKR/SPJ/2008-S4 guidelines for road works, ensuring a thorough and accurate analysis of the boiler slag and similar practices in the local construction industry. Table I below tabulates the mix design matrix for the asphalt concrete mixtures in this study.

Table 1: Mix Design Matrix for Asphalt Concrete Mixtures

No.	Factor	Details
1	Gradation	ACW14
2	Mix Design Method	Marshall mix design method
3	Aggregate Source	Granite aggregate sourced from rock quarry operated by Semenyih Quarry Sdn. Bhd.
		Boiler Slag (BS) sourced from TNB Meru Klang
4	Binder Type	Penetration Grade (PEN) 60-70
5	Asphalt Concrete Mix Design Matrix	Aggregate ratio proportions of Boiler Slag:Natural Aggregate 50:50; 30:70; 20:80
		Conventional asphalt concrete mix (100% Natural Aggregate)
6	Performance Test	Characterization: Resilient Modulus Dynamic Creep Test

The testing was specifically focused on the suitability of materials for hot mix asphalt (HMA); therefore, the findings may not be applicable to all pavement types, although they provide valuable insights for asphalt applications.

3. Test Results and Discussion

This section presents the data and analysis derived from tests performed on natural aggregate and boiler slag, utilizing various physical testing methods such as sieve analysis, L.A. abrasion test, flakiness test, aggregate impact value test, specific gravity, and water absorption to determine the physical properties. The investigation utilized fifteen samples with asphalt contents of 4.0%, 4.5%, 5.0%, and 6.0%.

Marshall Stability and Flow tests were then conducted for the ACW14 wearing course to determine the volumetric properties of both the mix sample and the control sample, which facilitated the identification of the optimum bitumen content within the range of 4.0% to 6.0%. The results from the mixed sample are compared to the control sample to evaluate their correlation.

A. Physical Properties of Natural Aggregate and Boiler Slag

The L.A. abrasion test, flakiness test, aggregate impact value test, and assessments of specific gravity and water absorption were used to evaluate the physical properties of both boiler slag and natural aggregate.

1) Los Angeles (L.A.) Abrasion Test

The test utilized a sample weight of 5000g, with an average particle size ranging from 14 mm to 10 mm. Three (3) distinct sample values were carefully collected to calculate the average Los Angeles Abrasion Values for both natural aggregate and boiler slag. The results indicated that the average Los Angeles abrasion values were 28.40% for boiler slag and 28.56% for natural aggregate.

Table 2: comparison of laav of natural aggregate with previous research

Properties	This Research	Previous Researcher (Li et al., 2022)
Los Angeles Abrasion Value, LAAV (%)	28.56	21.6

Table 3: comparison of laav of boiler slag with previous research

Properties	This Research	Previous Researcher (Federal Highway Administration Research and Technology, 2016)
Los Angeles Abrasion Value, LAAV (%)	28.40	24-48

Both average values remained comfortably below the 30% threshold specified in the JKR Standards for MS 30, confirming that both natural aggregate and boiler slag complied with JKR regulations for road work.

2) Flakiness Test

The flakiness test assesses the shape characteristics of three

(3) samples of aggregate particles used in hot mix asphalt (HMA). The results of the flakiness test indicated that the flakiness index for natural aggregate was 13.35% and 23.34% for boiler slag.

Table 4: Comparison of flakiness index with previous research

	Natural Aggregate		Boiler Slag	
Properties	This Research	Previous Researcher (Strzalkowski et al., 2021)	This Research	Previous Reseacher (Thakur, Saklecha, 2019)
Flakiness Index (%)	13.35	18.62	23.34	4.48

Previous studies reported a flakiness index of 4.48%, which is significantly lower than the 23.34% observed in this study. This discrepancy underscores the necessity for more in-depth investigations into the characteristics of boiler slag and emphasizes how different aggregate sources and processing methods can affect the flakiness index.

According to JKR Guideline, the flakiness index when tested in accordance with MS 30 shall be not more than 25%. The presence of excessive flakiness may lead to higher tendency of pavement distress.

3) Aggregate Impact Value Test

The Aggregate Impact Value (AIV) test is a standardized method used to evaluate the resilience and strength of aggregates, providing insights into their ability to withstand shock or sudden impact loads.

The AIV recorded in this study was 14.6% with a 0.6% variation from previous researcher that may be due to differences in aggregate sources. Similarly, previous researcher found an AIV value of 8.25% for boiler slag, compared to this research findings of 10%. Despite these differences, the AIV for boiler slag in this study is consistent with the range typically observed for natural aggregates and aligns with findings from earlier studies.

Table 5: Comparison of Aiv Value with Previous Research

	Natural Aggregate		Boiler Slag	
Properties	This Research	Previous Researcher (Al-Waked et al., 2022)	This Research	Previous Reseacher (Divyanshu et.al, , 2023)
Aggregate Impact Value (%)	14.60	14	10	8.25

Importantly, both values meet the JKR standard, which stipulates that aggregate crushing values for flexible pavement should remain below 25%.

4) Specific gravity and water absorption of natural aggregate and boiler slag

Table 6: Comparison of specific gravity and water absorption with previous research

	Natural Aggregate		Boiler Slag	
Properties	This Research	Previous Researcher (Al-Waked et al., 2022)	This Research	Previous Reseacher (Federal Highway Administration Research and Technology, 2016)
Specific Gravity	2.470	2.480	2.640	2.3-2.9
Water Absorption (%)	0.650	1.500	0.524	0.3-1.1

The results from this study conducted on three (3) different samples showing average reading of specific gravity for natural aggregates at 2.47 is closely aligned with previous researchers' findings, demonstrating the consistency and reliability of the material. Similarly, the average specific gravity of boiler slag measured at 2.640 falls within the established range by Federal Highway Administration Research and Technology. Similarly, the water absorption rate of 0.524 aligns with findings from earlier research.

This variation highlights the importance of recognizing the natural variability of different materials, particularly with respect to boiler slag. Both values meet JKR Standards which stated water absorption when tested in accordance with MS 30 shall be not more than 2%.

B. Marshall Stability and Flow Test Using a 70:30 Ratio of Natural Aggregate to Boiler Slag

This section discusses the Marshall mix design, which involved the preparation of 15 samples, including a control sample, with asphalt contents of 4.0%, 4.5%, 5.0%, and 6.0%.

1) Aggregate Gradation

Aggregate gradation significantly influences the performance of Hot Mix Asphalt (HMA), making it a crucial factor in the mix design. The JKR/SPJ/2008-S4 standard delineates the upper and lower limits for the percentage of aggregate passing through various sieve sizes ensuring uniformity and quality in the mixture. The total weight of the aggregate used in this study was 1146.5 kg, consisting of 42.4% coarse aggregate, 57.6% fine aggregate, and 2% filler. The weights of the boiler slag used as artificial aggregate consist of 15.17 g for 14 mm particles and 20.23 g for 10 mm particles.

Table 7: The Aggregate Gradation for Control Sample

Specification	JKR/SPJ/2008-S4						
Mix Designation	ACW14						
BS Sieve Size (mm)	Lower Limit	Upper Limit	Avg. % Passing	% Retained	Total % Retained	Weight (g)	Accumulated Weight (g)
20	100	100	100	0	42.4 Coarse	0	0
14 (boiler slag)	90	100	91	9		15.17	15.17
14						85.99	101.16
10(boiler slag)	78	86	79	12		20.23	121.39
10						114.65	236.04
5	50	62	57.6	21.4		240.536	476.576
3.35	40	54	53.5	4.1	57.6 Fine	46.084	522.66
1.18	18	34	33	20.5		230.42	753.08
0.425	12	24	19	14		157.36	910.44
0.15	6	14	11.5	7.5		84.3	994.74
0.075	4	8	7	4.5		50.58	1045.32
pan	-	-	0	7		78.68	1124

Table 8: The Aggregate Gradation for Mix Sample

Specification	JKR/SPJ/2008-S4						
Mix Designation	ACW14						
BS Sieve Size (mm)	Lower Limit	Upper Limit	Avg. % Passing	% Retained	Total % Retained	Weight (g)	Accumulated Weight (g)
20	100	100	100	0	42.4 Coarse	0	0
14	90	100	91	9		101.16	101.16
10	78	86	79	12		134.88	236.04
5	50	62	57.6	21.4		240.536	476.576
3.35	40	54	53.5	4.1	57.6 Fine	46.084	522.66
1.18	18	34	33	20.5		230.42	753.08
0.425	12	24	19	14		157.36	910.44
0.15	6	14	11.5	7.5		84.3	994.74
0.075	4	8	7	4.5		50.58	1045.32
pan	-	-	0	7		78.68	1124

2) Aggregate Combined Specific Gravity

This specific gravity value is crucial as it is utilized in the Marshall test results to ascertain the optimum bitumen content. By accurately blending these materials and calculating the combined specific gravity, the asphalt mix can achieve an ideal balance of components. This precise testing is essential for producing high-quality Hot Mix Asphalt that meets both structural and functional requirements. The combined aggregate specific gravity for the control sample was measured at 2.600 and 2.599 for the mix sample.

Table 9: Combine specific gravity for boiler slag

Sieve Size (mm)	Weight (g)	Total Weight (g)	Percentage (%)	Specific Gravity
14	85.99	85.99	8.23	2.603
14 (Boiler Slag)	15.17	15.17	1.45	2.617
10	114.65	114.65	10.97	2.59
10 (Boiler Slag)	20.23	20.23	1.94	2.56
5	240.54	809.28	77.42	2.60
3.35	46.08			
1.18	230.42			
0.425	157.36			
0.15	84.30			
0.075	50.58			
Total		1045.32		
Combined Aggregate Specific Gravity, G_{sb}		$= \frac{(8.23 + 1.45 + 10.97 + 1.94 + 77.42)}{\left(\frac{8.23}{2.603} + \frac{1.45}{2.617} + \frac{10.97}{2.59} + \frac{1.94}{2.56} + \frac{77.42}{2.60}\right)}$ $= 2.599$		

Table 10: Combined specific gravity of aggregates for the control sample

Sieve Size (mm)	Weight (g)	Total Weight (g)	Percentage (%)	Specific Gravity
14	101.6	101.6	9.70	2.603
10	134.88	134.88	12.87	2.59
5	240.54	809.28	77.24	2.60
3.35	46.08			
1.18	230.42			
0.425	157.36			
0.15	84.30			
0.075	50.58			
Total		1045.76		
Combined Aggregate Specific Gravity, G_{sb}		$= \frac{9.7 + 12.87 + 77.24}{\frac{9.70}{2.603} + \frac{12.87}{2.59} + \frac{77.24}{2.60}}$ $= 2.600$		

3) Optimum Bitumen Content

The determination of the optimum bitumen content in the mixture was based on varying bitumen contents of 4.0%, 4.5%, 5.0%, and 6.0%. Each content level consisted of four (4) specimens, including one control sample. Calculations for the theoretical maximum specific gravity (G_{mm}) and bulk specific gravity (G_{mb}) were performed. Average values for air voids (VTM), stiffness, bulk specific gravity, flow, stability, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB) were then obtained.

By identifying the highest peaks for density and stability on the graphs, along with a flow value of 3 mm, 4% air voids, and 75% VFB, the optimum bitumen content was established. The volumetric properties of the specimens containing 70% natural aggregate and 30% boiler slag, alongside the control samples, are presented in Table XI.

4) Samples with 70% natural aggregate and 30% boiler slag

Table 11: Volumetric properties for mix sample.

Sieve Size (mm)	Weight (g)	Total Weight (g)	Percentage (%)	Specific Gravity
14	101.6	101.6	9.70	2.603
10	134.88	134.88	12.87	2.59
5	240.54	809.28	77.24	2.60
3.35	46.08			
1.18	230.42			
0.425	157.36			
0.15	84.30			

0.075	50.58			
Total		1045.76		
Combined Aggregate Specific Gravity, G_{sb}		$= \frac{9.7 + 12.87 + 77.24}{\frac{9.70}{2.603} + \frac{12.87}{2.59} + \frac{77.24}{2.60}} = 2.600$		

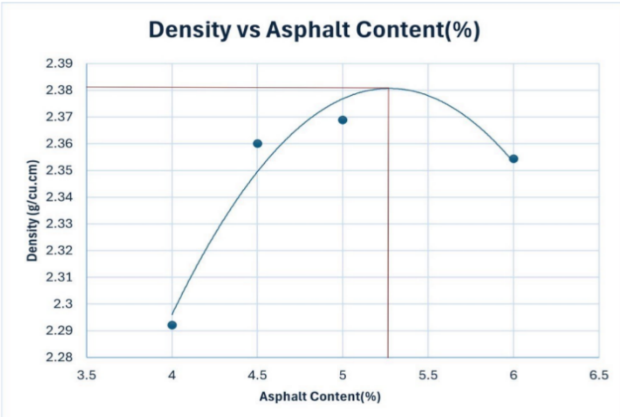

Fig. 1: Density versus asphalt content graph for mix sample

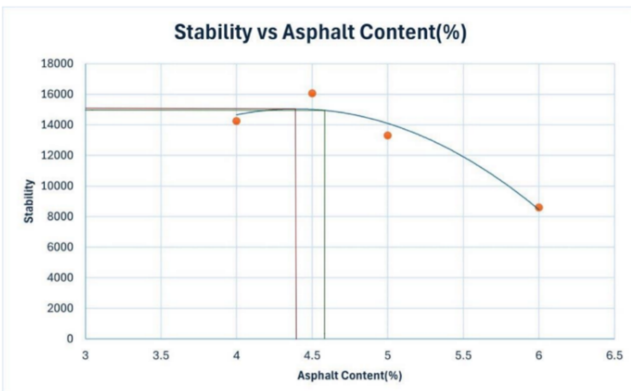

Fig. 2: Stability versus asphalt content graph for mix sample Stability versus asphalt content graph for mix sample

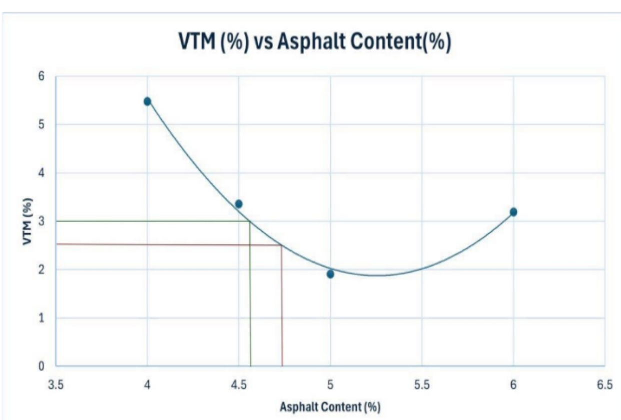

Fig. 3: VTM versus asphalt content graph for mix sample

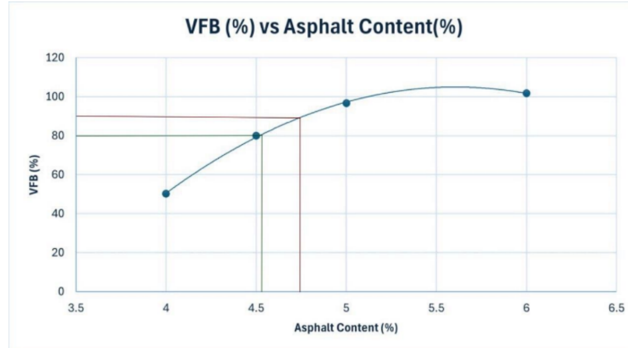

Fig. 4: VFB versus asphalt content graph for mix sample

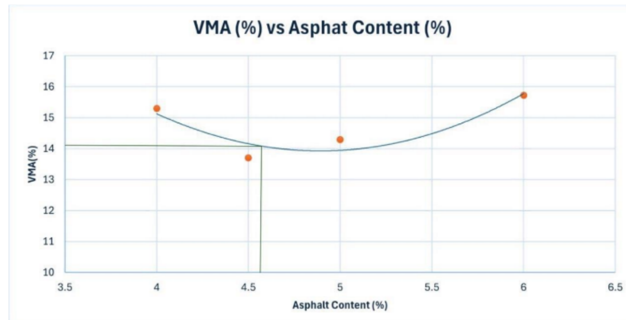

Fig. 5: VMA versus asphalt content graph for mix sample

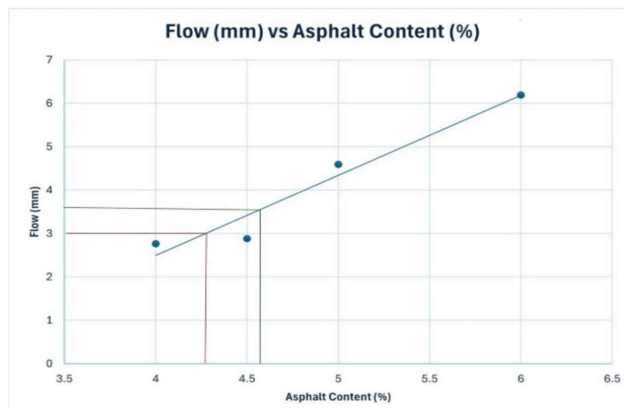

Fig. 6: Flow versus asphalt content graph for mix sample

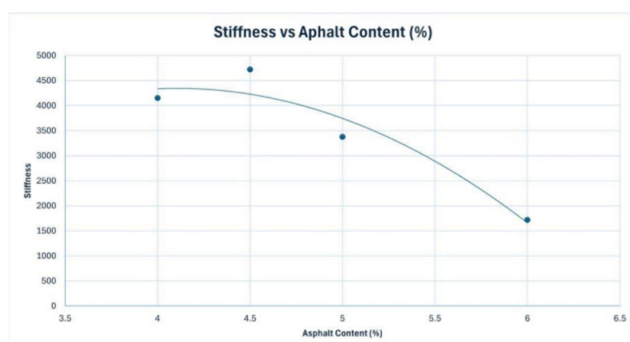

Fig. 7: Stiffness versus asphalt content graph for mix sample

Table 12: Calculation of optimum bitumen content for mix sample

Mixture Properties		Asphalt Content
Density	a	5.25
Stability	b	4.40
VTM	c	4.25
VFB	d	4.75
Flow	e	4.24
Optimum Bitumen Content (OBC)		$=\frac{a+b+c+d+e}{5}$ $=\frac{5.25+4.40+4.25+4.75+4.25}{5}$ $\mathrm{OBC}=4.60$

Table 13: Comparison with jkr specifications

Mixture Properties	Results	JKR Specifications	Remarks
VTM (%)	3	3 - 5	OK
VMA (%)	14.1	None	-
VFB (%)	80	70 - 80	OK
Stability (N)	15,000	>8,000	OK
Flow (mm)	3.6	2 – 4	OK

5) Control Sample

Table 14: Volumetric properties for control sample

Asphalt Content	4.0	4.5	5.0	6.0
Average (G_{mb})	2.272	2.308	2.363	2.353
TMM (G_{mm})	2.293	2.357	2.424	2.476
Air Voids (VTM) (%)	4.543	3.069	3.527	3.774
VMA (%)	17.34	15.60	14.51	15.78
VFB (%)	50.30	60.10	94.84	101.36
Average Stability (N)	10587.00	17777.90	12013.98	11960.00
Average Flow (mm)	2.546	2.721	3.264	4.678
Stiffness, S (N/mm)	3547.30	6533.59	4012.69	2556.65

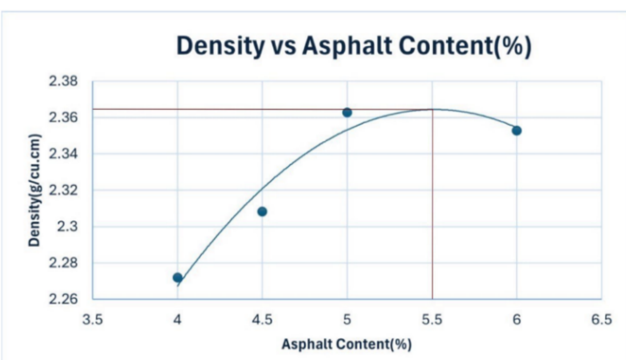

Fig. 8: Density against asphalt content for control sample

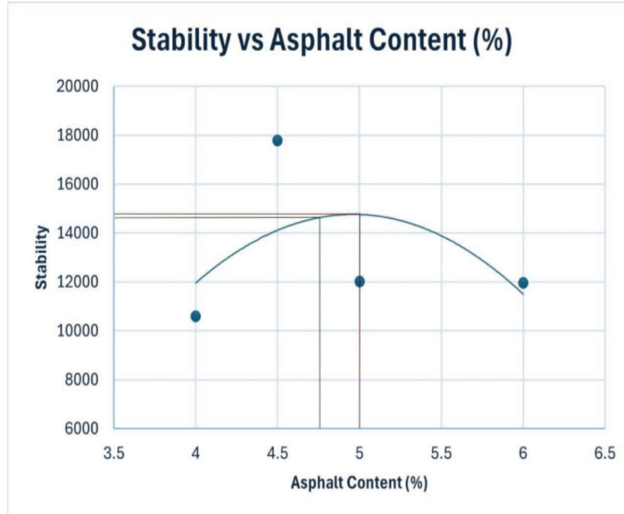

Fig. 9: Stability against asphalt content for control sample

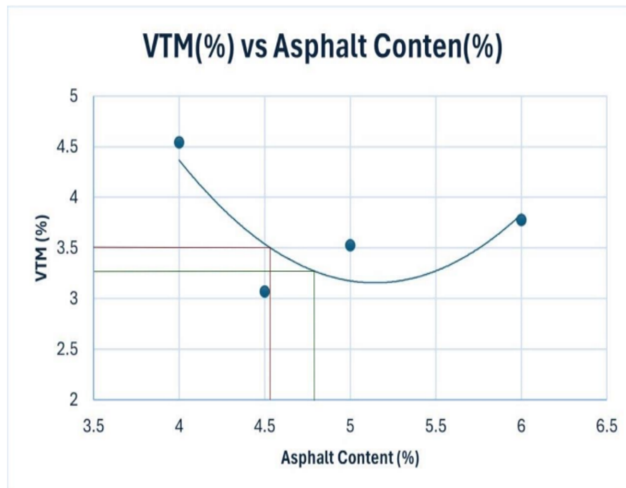

Fig. 10: VTM against asphalt content for control sample

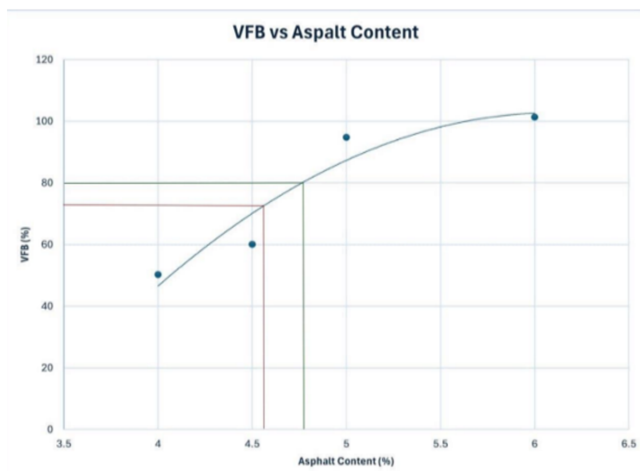

Fig. 11: VFB against asphalt content for control sample

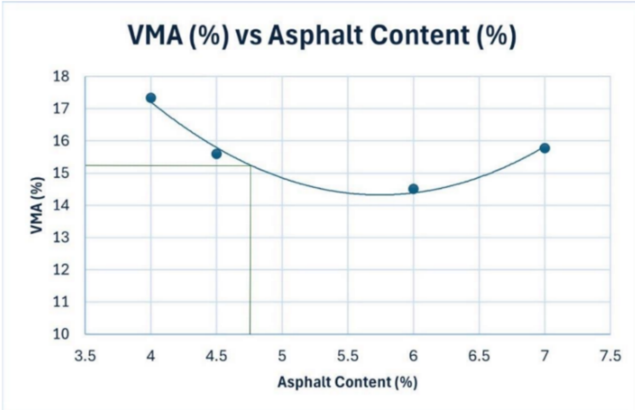

Fig. 12: VMA against asphalt content for control sample

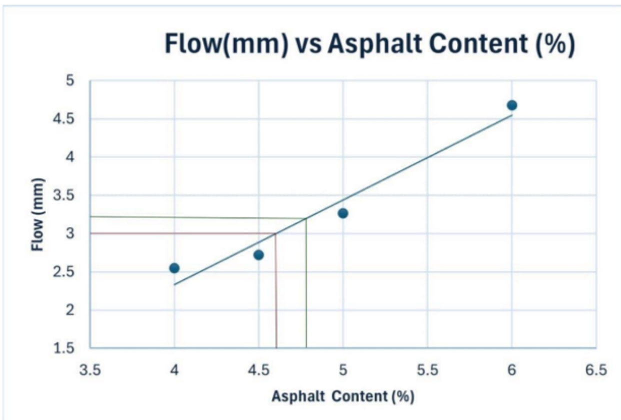

Fig. 13: Flow against asphalt content for control sample

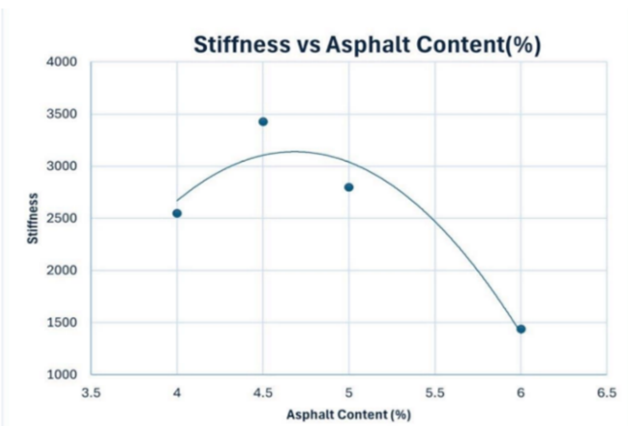

Fig. 14: Stiffness against asphalt content for control sample

Table 15: Calculation of optimum bitumen content for control sample

Mixture Properties		Asphalt Content
Density	*A*	5.50
Stability	*B*	5.00
VTM	*C*	4.55
VFB	*D*	4.60
Flow	*E*	4.60
Optimum Bitumen Content (OBC)		$= \frac{a+b+c+d+e}{5}$ $= \frac{5.50 + 5.00 + 4.55 + 4.60 + 4.60}{5}$ $\mathrm{OBC} = 4.80$

Table 16: Comparison with jkr specifications for control sample

Mixture Properties	Results	JKR Specifications	Remarks
VTM (%)	3.35	3 - 5	OK
VMA (%)	15.2	None	-
VFB (%)	80	70 - 80	OK
Stability (N)	14,400	>8,000	OK
Flow (mm)	3.35	2 – 4	OK

C. Correlation Between the Stability and Flow Test Results of Boiler Slag and Natural Aggregate

This analysis was conducted to determine the performance of the blended materials in meeting the required standards and their potential impact on pavement durability and functionality by examining the mix and control sample to assess how well the optimum bitumen content and volumetric properties align with JKR specifications for asphaltic concrete.

Table 17: Comparison of mixed and control samples with jkr specifications

Mixture Properties	70% Natural Aggregate + 30% Boiler Slag	Control Sample	JKR Specifications	Remarks	Percentage Difference
Optimum Bitumen Content (OBC)	4.6	4.8	For ACW, design bitumen is 4.0 – 6.0	PASSED	-
VTM (%)	3	3.35	3 - 5	PASSED	10.45
VMA (%)	14.1	15.2	None		7.24
VFB (%)	80	80	70 - 80	PASSED	0
Stability (N)	15,000	14,400	>8,000	PASSED	4.00
Flow (mm)	3.6	3.35	2 – 4	PASSED	6.94

The volumetric properties of Marshall stability and flow for the mix sample, 70% natural aggregate and 30% boiler slag, were compared to those of the control sample, as shown in Table XVI. The mix sample achieved an optimal bitumen content of 4.6%, while the control sample required 4.8%. Both values fell within the JKR standard range of 4.0% to 6.0% for ACW14, indicating that the mix sample needed 0.2% less bitumen compared to the control sample.

4. Conclusion

The findings demonstrate the potential of boiler slag as a feasible substitute in asphalt mixtures. All volumetric and physical properties met JKR specifications for asphaltic concrete road work, indicating that boiler slag can effectively replace natural aggregate at a 70:30 ratio, as demonstrated by comparable values in both mix and control samples. This conclusion aligns with previous studies suggesting that the use of artificial aggregate in hot mix asphalt should not exceed 50%.

Beyond its role as an aggregate, boiler slag can also serve as a backfill material and a residual base in various construction contexts. Its well-defined shear strength supports its viability as a promising construction material. The use of boiler slag can significantly minimize the environmental footprint of construction activities, contributing to a more sustainable industry.

References

[1] Abdulhameed, U. A., & Baharudin, K. S. (2012). Potential use of Malaysian thermal power plants coal bottom ash in construction. *International Journal of Sustainable Construction Engineering & Technology*, *3*(2), 25--37.

[2] Abdullah, M. H., Abuelgasim, R., Rashid, A. S. A., & Mohdyunus, N. Z. (2018). Engineering properties of Tanjung Bin bottom ash. *MATEC Web of Conferences*, *250*, Article 01006. https://doi.org/10.1051/matecconf/201825001006

[3] American Association of State Highway and Transportation Officials. (1993). *Guide for design of pavement structures*. AASHTO.

[4] American Coal Ash Association. (2016). *User guidelines for waste and byproduct materials in pavement construction*. ACAA.

[5] Bamigboye, G. O., Bassey, D. E., Olukanni, D. O., Ngene, B. U., Adeyemi, I., Odetoyan, A. O., Kareem, M. A., Enabulele, D. O., & Nworgu, A. T. (2021). Waste materials in highway applications: An overview on generation and utilization implications on sustainability. *Journal of Cleaner Production*, *283*, Article 124581. https://doi.org/10.1016/j.jclepro.2020.124581

[6] Budhu, M. (2011). *Soil mechanics and foundations* (3rd ed.). John Wiley & Sons.

[7] Chudley, R., & Greeno, R. (2007). *Building construction handbook* (6th ed.). Butterworth-Heinemann.

[8] Craig, H. B., & Sabrina, B. (2011). *User guidelines for coal bottom ash and boiler slag in green infrastructure construction*. Recycled Materials Resource Center, University of Wisconsin-Madison.

[9] Das, B. M., Sobhan, K., & Das, B. M. (2014). *Principles of geotechnical engineering* (8th ed.). Cengage Learning.

[10] Dirgeliene, N., Skuodis, S., & Grigusevičius, A. (2017). Experimental and numerical analysis of direct shear test. *Procedia Engineering*, *172*, 218--225. https://doi.org/10.1016/j.proeng.2017.02.026

[11] Friend, M., Bloom, P., Halbach, T., Grosenheider, K., & Johnson, M. (2004). *Screening tool for using waste materials in paving projects (STUWMPP)* (Report No. MN/RC-2005-03). Office of Research Services, Minnesota Department of Transportation.

[12] Gungor, A. G., Orhan, F., & Kasak, S. (2012, June 13--15). *The determination of wearing coarse mixtures using advance asphalt tests*. 5th Eurasphalt & Eurobitume Congress, Istanbul, Turkey.

[13] Holmes, R. (1995). *Introduction to civil engineering construction* (3rd ed.). The College of Estate Management.

[14] Huang, W. H. (1990). *The use of bottom ash in highway embankment and pavement construction* [Doctoral dissertation, Purdue University].

[15] Ke, T. C., & Lovell, C. W. (1992). Corrosivity of Indiana bottom ash. *Transportation Research Record*, *1345*, 34--42.

[16] Langer, W. H. (1988). *Natural aggregates of the conterminous United States* (U.S. Geological Survey Bulletin 1594). U.S. Geological Survey.

[17] Langer, W. H. (2001). Environmental impacts of mining natural aggregate. In *Proceedings of the 35th forum on the geology of industrial minerals* (pp. 127--138). Utah Department of Natural Resources.

[18] Lovell, C. W., Ke, T. C., Huang, W. H., & Lovell, J. E. (1991, January). *Bottom ash as highway material*. 70th Annual Meeting of the Transportation Research Board, Washington, DC, United States.

[19] Luttig, G. W. (1994). Rational management of the geo-environment: A view in favour of geobased planning. In *Report on the 2nd International Aggregate Symposium* (pp. 1--34). Erlangen.

[20] Majizadeh, K., Bokowski, G., & El-Mitiny, R. (1979). Material characteristics of power plant bottom ash and their performance in bituminous mixtures: A laboratory investigation. In *Proceedings of the fifth international ash utilization symposium*. Department of Energy.

[21] Mandal, S., Singh, J. P., & General, A. (2016). *Stabilization of soil using ground granulated blast furnace slag and fly ash*.

[22] Moulton, L. K. (1973). Bottom ash and boiler slag. In *Proceedings of the third international ash utilisation symposium*. U.S. Bureau of Mines.

[23] Moulton, L. K., Seals, R. K., & Anderson, D. A. (1973). Utilisation of ash from coal burning power plants in highway construction. *Transportation Research Record*, *430*, 26--39.

[24] National Energy Technology Laboratory. (2006).

Clean coal technology: Coal utilization by-products. Department of Energy, Office of Fossil Energy.

[25] Norbaya Sidek, Hafez, M. A., Abdul Samad Abd Rahman, & Puteri Elya Ruzilan. (2021). Physical properties and shear strength of boiler slag. *Acta Mechanica Malaysia*, *4*(1), 1--4.

[26] Nurharniza Abdul Rahman, Mohamed Izham Hamzah, & Lee, H. P. (2023). Effectiveness of bottom ash as fine aggregate replacement in engineered cementitious composites. *Journal of Engineering Science and Technology*, *18*(6). https://doi.org/[insert DOI]

[27] Prasad, R., & Kumar, D. (2015). Laboratory investigation of compaction characteristics of flyash-granular soil. *International Journal of Engineering Research and Technology*, *4*(11), 9868--9874.

[28] Rashidi, N. A., & Yusup, S. (2016). Overview on the potential of coal-based bottom ash as low-cost adsorbents. *ACS Sustainable Chemistry and Engineering*, *4*(4), 1870--1884. https://doi.org/10.1021/acssuschemeng.5b01170

[29] Root, R. E., & William, E. G. (1976). West Virginia turns waste material into useful aggregate. *Asphalt*, *29*(2).

[30] Roy, S., & Bhalla, S. K. (2017). Role of geotechnical properties of soil on civil engineering structures. *Resources and Environment*, *7*(4), 103--109. https://doi.org/10.5923/j.re.20170704.03

[31] Skuodis, P., Danuta, B. H., & Walery, J. (2016). *The possibility of using boiler slag as coarse aggregate in high strength concrete*. University of Technology Lublin.

[32] U.S. Environmental Protection Agency & Federal Highway Administration. (2005). *Using coal ash in highway construction: A guide to benefits and impacts* (Report No. EPA-530-K-002). EPA.Whitlow, R. (2004). *Basic soil mechanics* (4th ed.). Pearson/Prentice Hall.