

Performance Evaluation of Hot Mix Asphalt Modified with Fly Ash and Waste Foundry Sand in Road Development

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Abstract. This research evaluates the performance of hot mix asphalt modified with fly ash and waste foundry sand for road development. Preliminary tests were conducted to determine material properties. Hot mix asphalt samples with varying percentages of granite, sand, stone dust, and bitumen (5%, 5.5%, 6%, 6.5%, and 7%) were produced using ASTM D6927 Marshall mix design. The optimum bitumen content (OBC) was found from the mix to be 5.7%. Using the same mix design, bituminous mixtures were created with waste foundry sand as a partial replacement for fine aggregate (10% - 50% at 10% intervals), along with granite, stone dust, and 5.7% bitumen (OBC). The mix with 40% replacement performed optimally. A new mixture, incorporating granite, sand, fly ash (10% - 60% replacement for filler material, at 10% intervals), and 5.7% bitumen (OBC), was produced. The optimal replacement percentage was 50%. A combination mix of the materials, based on derived optimums, achieved a stability value of 26.09 kN, meeting the Asphalt Institute's criteria. Microstructural analysis indicated a densely packed agglomeration of particles, implying good strength properties. This research demonstrates the viability of waste foundry sand and fly ash as alternative materials, enhancing the strength and flexibility of hot mix asphalt. Reusing these waste materials in road construction is a positive step towards sustainability.

Introduction

Urbanization has led to a surge in vehicular traffic, resulting in the rapid deterioration of flexible road pavements. Recycling and reusing some raw materials or waste finished products from other industries has become imperative and significant for the sake of sustainability. Fly ash (FA) which is generated during the combustion of coal, is a thermal power plant industrial by-product which is recognized as an environmental pollutant. Indiscriminate disposal of fly ash generated from thermal power plants and burning of coal is becoming a serious environmental problem as hazardous chemicals are dispersed into the atmosphere through the action of wind. These harmful chemicals are also leached into groundwater over time thereby contaminating it. Fly ash, which accounts for around 500 million tonnes or 75–80 percent of the total amount of coal ash produced each year, makes up the majority of the estimated 600 million tonnes of coal ash produced annually worldwide [1].

There has been a lot of research done on fly ash around the world due to the environmental issues it poses. Hot-mix asphalt benefits from the use of fly ash in terms of mixing, placing and compaction, stability, resistance to water damage, and flexibility [2]. A research on the influence of coal fly ash on the mechanical properties of hot mix asphalt by [3], used four fly ash contents (0, 2%, 4%, and 6%) as filler material by weight of fine aggregate and found out that the stability values of fly ash modified asphalt mixes were higher than that of the conventional mix. It was also discovered that the integration of fly ash also improved the resistance of the mix to moisture damage. The performance of asphalt concrete mix modified with fly ash as partial replacement of limestone dust mineral filler at 0%, 1%, 2%, and 3% was evaluated by [4]. The modified mix was found to have improved resistance to fatigue and permanent deformation, and also showed lower moisture susceptibility and high resilient modulus. In a research by [5], on the influence of fly ash as mineral filler in bituminous mix design,

stone dust was partially replaced by fly ash in 25%, 50%, 75%, and 100% by weight of total filler. It was observed that 25% fly ash by total weight of filler was optimum which met the mix design criteria for medium traffic condition and a mix of optimum fly ash content and optimum bitumen content is suitable for flood prone areas where roads are submerged in water for up to 10 days.

Waste foundry sand (WFS) is derived from casting industries that use sands, binders and additives to form moulds and cores. Sands are used because they are widely accessible, affordable, extremely refractory, and easily bound by clays or other inorganic and organic elements. These are only a few of their many advantages. Castings are created using a mold, and their interior shapes are created using a core [6]. Foundry sand is a by-product of the production of both ferrous and nonferrous metal castings. Waste foundry sand can have properties desirable for use in the technology of substituting fine aggregates in applications such as; structural fills or embankments, road base or sub-base, and hot mix asphalt [7].

In a research on recycling foundry sand within sub-base layer in road construction conducted by [8], which looked into the chemical analysis of foundry sand, the formulation of a sub-grade material and its leaching behavior, were assessed by experimental site monitoring. Results showed that the foundry sand, treated by 5.5% of hydraulic binder (cement), provided acceptable mechanical performances and does not show environmental impacts. The investigation demonstrated that the foundry sand can be used in sub-base layers as road materials. An evaluation on the influence of using WFS as replacement for mineral fine aggregates on the hot mix asphalt properties was done by [9]. HMA samples, made of WFS at 5% replacement and conventional mineral aggregate were compared in terms of their Marshall stability, flow, bulk specific gravity, void in mineral aggregate and voids filled with bitumen in the total mixture. Results showed that the replacement of mineral fine aggregate with WFS has a significant potential use in bituminous mixtures.

Bituminous mix consists primarily of an intimate mixture of aggregates, mineral filler and bitumen. It is important that bituminous mix should be in right proportion and to have a mixture with the desired characteristics and high performance. These performance metrics take into account the ability to resist distresses like low-temperature cracking, fatigue cracking, and permanent deformation of hot mix asphalt (HMA). The commonly used aggregates in HMA are granite and fine aggregate.

Amidst the dual challenges of improving the strength and durability of asphalt concrete road pavements for the benefit of road users and reducing construction costs, the evaluation of HMA modified with fly ash and waste foundry sand emerges as a compelling avenue of research, offering both economic and environmental benefits.

Materials and Methods

The materials used in this research work are fly ash, waste foundry sand, bitumen, granite, sand, and stone dust. The granite, sand, stone dust, bitumen and fly ash were sourced from a commercial supplier at Ota, Ogun state. The waste foundry sand was sourced from mechanical engineering foundry laboratory, Covenant university, Canaan land, Ota, Ogun state. The granite was used as coarse aggregate, the sand as fine aggregate and the stone dust as filler material. The waste foundry sand was used to partially replace the fine aggregate, while the fly ash was used to partially replace the filler material. The coarse aggregate is graded with average size of 9 mm. The fine aggregates passed through 1.25 mm sieve, while the filler materials passed through 75 μ m sieve.

Marshall stability tests were carried out the hot mix asphalt samples produced according to Marshall mix design specified by ASTM D6926, with 75 blows of the hammer given to both sides of each sample to simulate heavy traffic. A conventional mix of granite, sand, stone dust, and bitumen at 5%, 5.5%, 6%, 6.5%, and 7% was first produced using the Marshall mix design according to ASTM D6927. Three (3) samples each per bitumen content were produced and subjected to void analysis, stability, and flow tests so as to derive the optimum bitumen content (OBC), which was determined from the average of three bitumen contents which produce; the maximum stability, maximum unit weight, and exactly 4% air void. Thereafter, bituminous mix of waste foundry sand (in partial replacement of fine aggregate at 10%, 20%, 30%, 40%, and 50%), granite, stone dust and bitumen

was produced, three samples each per percentage replacement, using the same mix design as above and the optimum bitumen content determined in order to ensure consistency in the research work. Another mix of granite, sand, fly ash (in partial replacement of filler material at 10%, 20%, 30%, 40%, 50%, and 60%), and bitumen was produced, three samples each per percentage replacement, using the same mix design and OBC for the previous mix. A combination mix, on the basis of the optimums previously derived, of waste foundry sand (WFS), sand, granite, stone dust, fly ash, and bitumen was then produced using the same method. A total of 51 cylindrical hot mix asphalt samples were produced and tested during the course of the research. The Marshall stability and flow values of the bituminous mixes were evaluated using the Marshall Stability Test according to ASTM D6927.

Results and Discussion

The preliminary tests, Marshall stability tests, and the microstructural test carried out on the various materials, various bituminous mixes, and the combination mix respectively are discussed below.

Preliminary Tests. The penetration test carried out on the bitumen showed that it's 60/70 penetration grade bitumen. The softening point of the bitumen falls within the Nigerian general specification (Roads and Bridges) limit. Table 1 shows the tests result and code limits.

Table 1. Test Results on Bitumen

Test	Test Result	Code Limit
Penetration at 25°C, 0.1 mm	63.3	60 – 70
Softening Point [°C]	49.5	48 – 56
Specific gravity at 25°C	1.05	1.01 – 1.06

The aggregate crushing value of 20.86%, and the aggregate impact value of 9.08% of the coarse aggregates meet the general specification requirement. Table 2 shows the test results on the coarse and fine aggregates. The results fall within the applicable code recommendations which indicate that the aggregates possess strength, toughness, density, and resistance to abrasion, and are able to withstand the challenges of both functionality and durability as needed for asphalt mixtures throughout its intended lifespan.

Table 2. Test Results on Aggregates

Test	Test Result	Code Limit
Aggregate Crushing Value [%]	20.86	Max. 23
Aggregate Impact Value [%]	9.08	Max. 23
Specific Gravity of Coarse Aggregate	2.72	2.54 – 2.75
Specific Gravity of Fine Aggregate	2.54	2.54 – 2.75

Tests were carried out on the fly ash used in this research so as to ascertain its suitability. The specific gravity of fly ash was determined to be 1.74. The fineness of the fly ash was found to be 12.6% which is less than the required specification according to ASTM C786.

X-ray Fluorescence (XRF) test was conducted on the fly ash to determine its chemical properties. From the results, the fly ash is classified as Class F fly ash. Result showing the elemental composition and corresponding concentration of the fly ash is presented in Table 3.

Table 3. X-ray Fluorescence (XRF) Test Result for Fly Ash

Chemical	Concentration [%]
SiO ₂	84.916
Fe ₂ O ₃	0.790
CaO	1.746
Al ₂ O ₃	0.957
P ₂ O ₅	4.857
SO ₃	1.912

The following tests were carried out on the waste foundry sand used in this research so as to determine its physical and chemical properties.

The specific gravity of the waste foundry sand was obtained to be 2.27. The XRF test result indicates the elemental composition of the waste foundry sand. Result showing the elements with the most concentration is presented in Table 4.

Table 4. X-ray Fluorescence (XRF) Test Result for WFS

Chemical	Concentration [%]
SiO ₂	55.006
Fe ₂ O ₃	6.723
CaO	8.199
Al ₂ O ₃	10.880
BaO	4.808
SO ₃	8.951

Marshall Stability Tests. The Marshall stability tests were done according to ASTM D6927 on four different mixes with a total of 51 cylindrical samples of hot mix asphalt produced. The first mix is the conventional mix with varying proportions of bitumen at 5%, 5.5%, 6%, 6.5%, and 7%. The main objective of this mix is the determination of optimum bitumen content. The bitumen contents that produced; the maximum stability, the maximum unit weight, and exactly 4% air voids, were determined from plots shown in Fig. 1, Fig. 2, and Fig. 3 respectively and then averaged, gave an OBC of 5.7%.

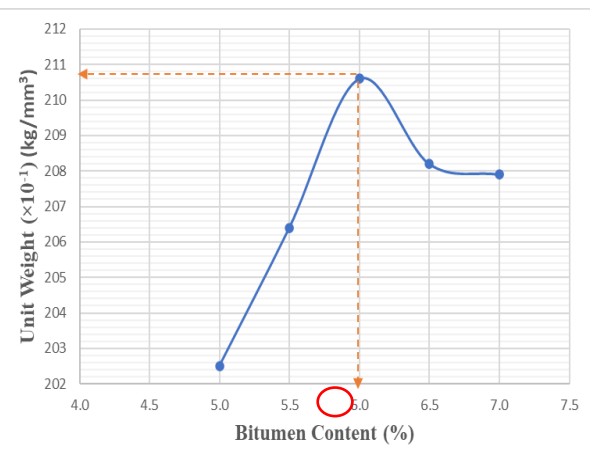
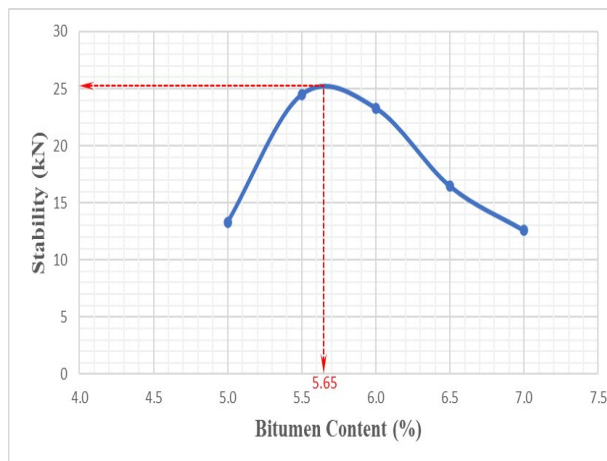


Fig. 1. Stability [kN] vs bitumen content [%] **Fig. 2.** Unit weight ($\times 10^{-1}$) [kg/mm³] vs bitumen content [%]

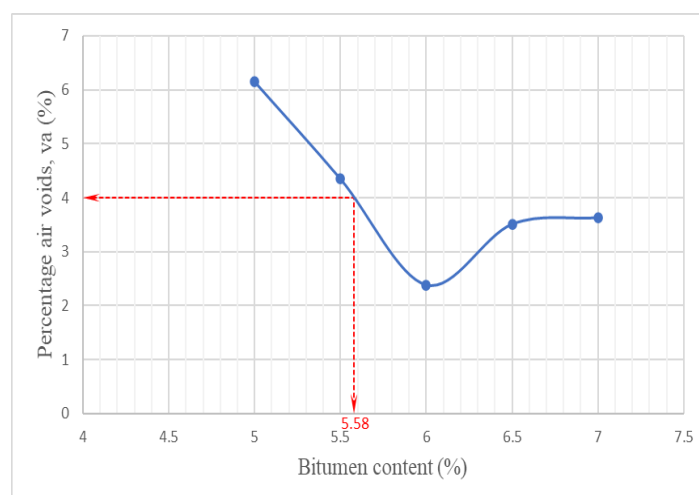


Fig. 3. Percentage air voids [%] vs bitumen content [%]

The second mix was the partial replacement of sand with WFS at 10%, 20%, 30%, 40%, and 50%. Three (3) hot mix asphalt samples each were made per percentage replacement and subjected to Marshall stability test. The average stability and flow were derived from the test and presented in Table 5. The optimum performing replacement was at 40%, in which produced a stability value that met the Asphalt Institute's specifications. The Marshall mix design criteria as required by the Asphalt Institute [10] is shown in Table 6.

The third mix was the partial replacement of the mineral filler (stone dust) with fly ash at 10%, 20%, 30%, 40%, 50%, and 60%. Three (3) hot mix asphalt samples each were made per percentage replacement and subjected to Marshall stability test. The average stability and flow were derived from the test and presented in Table 7. The optimum performing replacement was 50%, and it produced a stability value which met required specifications.

The fourth mix was the combination (optimized) mix which brings the previous mixes together at optimums, 100% granite, 40% WFS, 60% sand, 50% fly ash, 50% stone dust, and 5.7% bitumen. Three (3) samples of hot mix asphalt were produced and the average stability, flow and bulk specific gravity were determined. The average stability and flow of 26.09 kN and 16 mm respectively, meets the Asphalt Institute criteria for medium traffic roads.

Table 5. Marshall stability test result for WFS mix

WFS Content [%]	Stability [kN]	Flow [mm]
10	18.49	12
20	19.35	12
30	21.56	13
40	24.03	15
50	16.92	16

Table 6. Marshall mix design criteria

Marshall Method Criteria	Light Traffic		Medium Traffic		Heavy Traffic	
	Surface and Base		Surface and Base		Surface and Base	
	Min.	Max.	Min.	Max.	Min.	Max.
Compaction (number of blows on each end of sample)	35		50		75	
Stability, [N]	3336	-	5338	-	8006	-
Flow, 0.25 mm	8	18	8	16	8	14
Percent Air Voids	3	5	3	5	3	5

Table 7. Marshall stability test result for fly ash mix

Fly Ash Content [%]	Stability [kN]	Flow [mm]
10	8.29	12.5
20	9.18	14.0
30	9.44	15.5
40	13.28	16.5
50	27.52	17.0
60	23.22	19.0

The Marshall Quotient (MQ), which represents the ratio of stability to flow, serves as an assessment of a HMA's capacity to withstand permanent deformation or rutting. Elevated MQ values are indicative of increased stiffness and enhanced resistance to cracking [11]. The Marshall quotient for the combination HMA was determined, using Eq. 1, to be 1.60 kN/mm, which suggests that the HMA mixture possesses a good balance between stability and flow, indicative of its potential performance under load and deformation conditions.

$$\text{Marshall Quotient} = \frac{\text{Marshall Stability}}{\text{Flow}} \text{ kN/mm} \quad (1)$$

Microstructural Test. Scanning electron microscopy (SEM) test was carried out on samples obtained from the optimized mix so as to determine its microstructural characteristics. Fig. 4 shows the monographs from the SEM test at 500, 1000, and 1500 magnifications respectively.

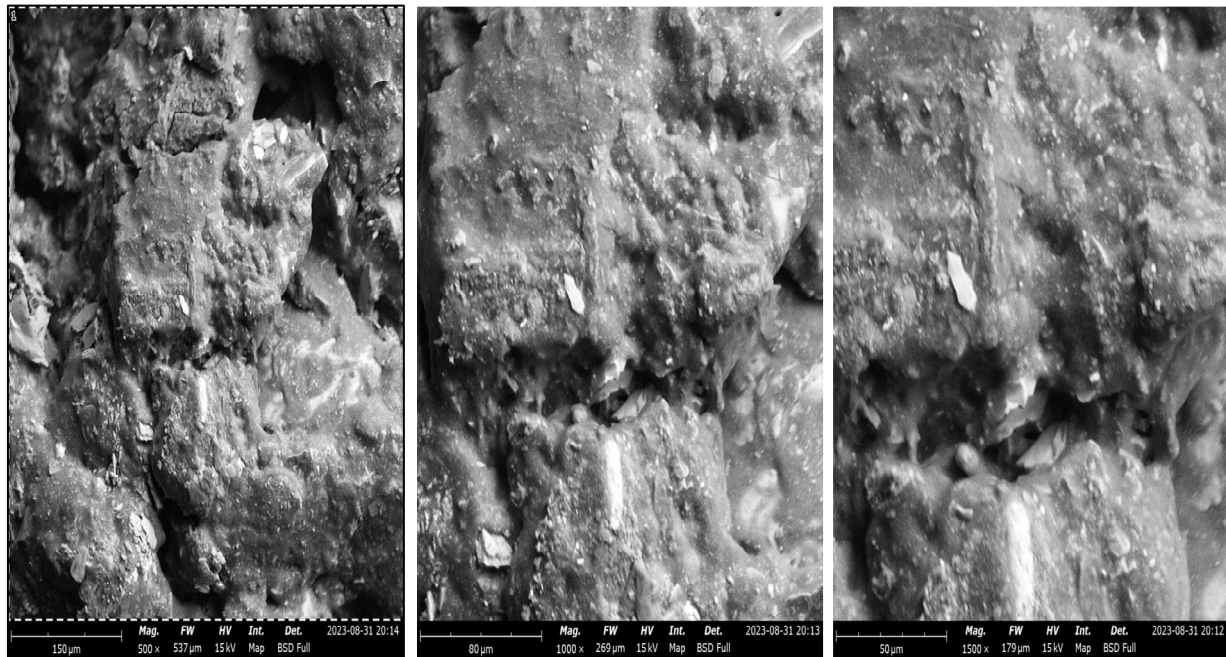


Fig. 4. SEM Test Monograph

The SEM analysis shows a close agglomeration of the materials of the mix, with little pore spaces observed which can be attributed as air voids. Air voids help to prevent bleeding of the asphalt binder from the hot mix asphalt when under loading conditions which is necessary for a good on-field performance.

Conclusion

The following conclusion were drawn from the research; the optimized mix, comprising appropriate proportions of aggregates, bitumen, stone dust, fly ash, and waste foundry sand, demonstrates promising potential for meeting the required specifications and performing well under anticipated traffic and loading conditions. The optimized mix meets the Asphalt Institute's criteria for medium traffic roads. This research proves the viability of waste foundry sand and fly ash as partial replacement materials, enhancing the strength and flexibility of hot mix asphalt. These findings contribute to advancements in sustainable road construction practices and provide a foundation for further research and application in the field.

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