Direct Research Journal of Engineering and Information Technology

Vol. 13(1), Pp. 16-23, January 2025,

https://journals.directresearchpublisher.org/index.php/drjeit

Review Article
ISSN: 2354-4155

Marshal Properties Assessment of Hot Mix Asphal Containing Katsina Steel Rolling Furnace Dust as an Additive

Umar Masari Ahmad[1], Kayode David Adeosun[2], and Audu Usman[3]

[1]Department of Civil Engineering Technology, Federal Polytechnic Kaura Namoda, Zamfara State, Nigeria.
[2]Department of Civil Engineering Technology, Federal Polytechnic Kaura Namoda, Zamfara State, Nigeria.
[3]Department of Civil Engineering Technology, Federal Polytechnic Kaura Namoda, Zamfara State, Nigeria.
Corresponding author email: umarmasari79@gmail.com

ABSTRACT

Significant investments have been directed towards road infrastructure development, resulting in a vast network spanning approximately 194,000 kilometers. Responsibility for this network is divided among different government levels, with the Federal Government overseeing 17%, State Governments 16%, and local Governments 67% (Federal Ministry of Works Nigeria, 2013). In the steel industry, by-products like mill scale and oily sludge are generated during the cooling and rolling processes, with an estimated global production of nearly 5 million tons. Research incorporating Steel Dust Residue (SRFD) as an additive in asphalt mixes revealed promising results (Barth, 1990), Optimal bitumen content was identified at 5.4%, meeting the specified requirements outlined in the General Specification of Nigeria Roads and Bridges, 2016. This modified asphalt showcased improved stability (6.61kN versus 5.4kN in control asphalt) and exhibited desirable flow properties (3.9mm). XRF analysis identified the elemental composition of the steel dust used in the research, primarily comprising ferric oxide (Fe2O3 = 31%) and zinc oxide (ZnO = 28%). Experimental findings indicated that Marshall Stability, unit weight, voids filled with bitumen (VFB), and stiffness initially increased and then decreased with higher SRFD content in asphalt mixtures. Notably, a 4% SRFD content by volume of binder met the specified Marshall properties for asphalt mixtures.

***Keywords**: Industrial waste, Steel Rolling Furnace Dust, Marshal Properties, Regression analysis models*

Article information
Received 2 January 2025;
Accepted 23 January 2025;
Published 30 January 2025
DOI: https://doi.org/10.26765/DRJEIT234708167

Citation: Ahmad, U. M., Adeosun, K. D., and Usman, A. (2025). Marshal Properties Assessment of Hot Mix Asphal Containing Katsina Steel Rolling Furnace Dust as an Additive. Direct Research Journal of Engineering and Information Technology Vol. 13(1), Pp. 16-23.

INTRODUCTION

The need to provide asphaltic pavements of greater or improved properties has thus arisen (Erika & Stefano, (2016). A pavement can only be as strong as its constituent materials (Airey & Taylor, 1999). The design of asphalt paving mix, as with the design of other engineering materials is largely a matter of selecting and proportioning constituent materials to obtain the desired properties in the finished pavement structure (Al-Saffar, 2013). Many researchers have carried out a series of investigations extensively by the use of several materials and industrial wastes as modifiers, additives in both concrete (Ogundalu et al., 2013) and hot mix asphalt productions (Masson, 2008), such as waste plastic, waste lignin, waste high-density polyethylene (Bulatović et al., 2014), softwood bark charcoal, nano clay waste express bag, graphene oxide (*Danladi, 2013),* eggshell powder and electric arc funaná dust (EAFD) among others within and across the world (Yuming et al., 2019). It is thus becoming more attractive to reuse and recycle industrial wastes rather than disposing them off in landfills and on dumpsites Steel Rolling Furnace Dust (SRFD) is a steel making by-product from the rolling mill in the steel hot rolling process. Its chemical composition varies according to the type of steel produced and the process used. Depending on the process and nature of product, the weight of mill scale can vary between 20 – 50 Kg per ton of hot rolled product (Dana et al., 2017). The European steel industry alone produces around 500,000 tons annually, with over 30% of this remaining unutilized (Dana et al., 2017).

These metals are therefore found in the resulting dust both as free oxides and in the form of composite structures with iron oxides which may proof good compressive strength, low water absorption and increased apparent density in hot mix asphalt. The technology has been increasing in importance over the past 20 years at the expense of traditional open hearth and basic oxygen converter technology, reaching an estimated 33.4% world share in 1999 (Ebenezer, A. O, et al. 2015). This dust is considered as waste, and it is estimated that the world-wide total production of mill scale or dust could be as high as several million tones, (Cristiana *et al., 2010*).

MATERIALS AND METHODS

Materials

The materials used in this research study are bitumen (60/70 cut back), granite aggregate (coarse), Ordinary Portland cement (OPC), and Steel rolling furnace dust (SRFD). The bitumen and aggregates were obtained from Mother Cat Nigeria Limited situated at No. 15, Mother Cat Road, Off Nnamdi Azikiwe Express Way, Kaduna. The Portland cement was obtained from a cement depot in Zaria and the Steel mill scale dust from Katsina steel rolling mill, Katsina State.

Methods

The laboratory procedures that were conducted in carrying out this research work are:

BITUMEN

Technological Tests

Penetration test (ASTM D5 / D5M-20, 2020), Ductility test (ASTM D113-17, 2017), Softening point test (ASTM D36 / D36M-14, 2020). Flash and fire point (ASTM D92-18, 2018), Solubility test (ASTM D2042-15, 2015).

Physical Test

Specific gravity (ASTM D70/D70M-21, 2021)

AGGREGATES

Physical Test

Elongation index (ASTM D4791-19, 2019), Flakiness index (BS EN 933-3, 2012, Specific gravity (ASTM C127-15, 2015; ASTM C128-15, 2015), Sieve Analysis (ASTM C136 /C136M-19, 2019)

Mechanical Tests

Aggregate crushing value test (BS 812-110, 199), Aggregate impact value test (BS 812-112, 1990).
Los Angeles abrasion test (ASTM C131/C131M-20, 2020).

Marshal Method for Control HMA

Proportioning of Aggregates

The proportioning of aggregates was done in accordance to the Federal Ministry of Works General Specification for Road and Bridges of the Federal Republic of Nigeria, 2016.

Preparation of Pure HMA (Control)

The methods used in obtaining the pure hot mix asphalt are as follows: The pure HMA (control) was prepared in accordance to ASTM Standard (ASTM D6926-20, 2020).

Laboratory Tests on the Control HMA

The laboratory tests carried out on the control HMA were.

Physical test

Bulk Specific Gravity Test (AASHTO T 166, 2016). The void analysis involves (void in the compacted mineral aggregates VMA, voids filled with bitumen VFB.

Mechanical test

Marshal Stability and Flow Tests

The stability is defined as the maximum load resistance in kN that the specimen will achieve at 60^{O}C under specified conditions (Overseas Road Note 31(2019). The flow is the total movement of the specimen in units of 0.01mm during the stability test as the load is increased from zero to the maximum. These were carried out in accordance to ASTM Standard (ASTM D6927-15, 2015).

RESULTS

Test Results on Bitumen

The results obtained for the properties of the bitumen used

Table 1: Test Conducted on the Bitumen.

Test Conducted	Unit	Result	Light Traffic	Medium Traffic	Heavy Traffic
Penetration	0.1mm	67.1	40/50	60/70	80/100
Softening point	ºC	51.9	52-60	48-56	42-50
Ductility @ 25ºC	cm	112.2	100 (Min)	100 min	100 min
Specific gravity	NIL	1.02	1.01-1.06	1.01-1.06	1.01-1.06
Flash-point	ºC	256	250 (Min)	232 min	250 min
Fire-point	ºC	280	NIL	NIL	NIL
Solubility in C_2S	%	99.4	99.5 min	99 min	99.5 min

Table 2: Physical Properties of Aggregates

Properties	Test values	Standard Spec.		Remarks
		Min.	Max.	
Specific Gravity (Coarse)	2.64	2.6	2.9	Satisfactory
Specific Gravity (fine)	2.56			Satisfactory
Specific gravity (granitedust)	2.65			Satisfactory
Specific gravity (SRFD)Flakiness Index	2.22	-	35	Satisfactory
Elongation Index	22.80	-	25	Satisfactory

*Federal Ministry of Works and Housing (FMPWH) specification wearing course mix.

Table 3 Mechanical Properties of Aggregates.

Properties	Test values	Remarks (Max).	
Los Angeles abrasion	29	35	Satisfactory
Aggregate Crushing value (%)	23.64	30	Satisfactory
Aggregate Impact value (%)	10.56	35	Satisfactory

*Federal Ministry of Works and Housing (FMPWH) specification wearing course mix.

are as shown in (Table 1), it can be observed that the entire test conducted falls within the specification for medium weight traffic as 60/70 penetration grade bitumen per the specification of the Federal Ministry of Power, Works, and Housing (FMPW&H, 2016). As such, the bitumen can be used for medium-weight traffic flexible pavement design (*Merv,* 2015). As such, the identified properties of the bitumen sample indicate that the bitumen is suitable for use as a binder in an asphalt mixture of the proposed research work (Nayeem & Mittal, 2016).

Physical Properties Test on Aggregate

The results of physical properties on the aggregates, such as the elongation index, flakiness index, specific gravity, and water absorption tests, are as presented in (Table 2). Flakiness and Elongation index of 31.50 and 22.80, specific gravity and water absorption were all within the allowable limits specified (Naganathan & Musazay, (2014), and this test result shows that the aggregates are of suitable geometry and would not be liable to degradation with the asphalt mixture per BS 812-112, 1990; FMPW&H, 2016.

Mechanical Properties Test on Aggregate

The aggregate impact value is 10.56%, which indicates that the aggregates have good toughness and also offer suitable resistance to sudden impact loads (Rahman ,2013), and it's also within acceptable limits specified per BS 812-112, 1990; FMPW&H, 2016. The aggregate crushing value was 23.64% which indicate a good strength property, as aggregates with ACV greater than 30 are normally regarded as being too weak and brittle for use in pavements. The results are summarized in (Table 3).

Elemental and Oxide Composition of Steel Rolling Furnace dust (SRFD)

The Steel rolling furnace dust was characterized at the laboratories of the chemical engineering in A.B.U Zaria using XRF. The results of analysis are summarized in (Table 4) where itshows that the major components are ferric oxide (Fe_2O_3 = 31%) and zinc oxide ZnO = 28% (S. Saberifara et al., 2014). All samples of SRFD used in this research were passing No. 200 sieve (Gaballah, M, et al, 2013).

Marshal Test for Control HMA

To determine the optimum asphalt content by weight of total mix, Marshall Mix design procedure (ASTM D1559) was followed as a part of this study (Asphalt Institute, 2008). Three specimens at each asphalt content (4.0, 4.5, 5.0, 5.5, and 6.0%) were tested for stability, flow, air voids, unit weight, and voids in mineral aggregate (*Raquel et al.,*

Table 4: SRFD characterization (weight %)

Compound	Percentage
Fe_2O_3	31
ZnO	28
Al_2O_3	1.28
Cu_2O	0.8
SiO_2	4.1
Loss on ignition at 1000 °C	11.63
$CaSO_4$	3.43
$CaCl_2$	1.92
CaO	1.4
NaCl	5.79
K_2O	2.7
MgO	4.66
Others	1.5

Table 5 Marshall Test parameters for Control JMA

Bitumen content (%)	Corrected stability (kN)	Average flow (mm)	Bulk Density (g/cm^3)	Pa (%)	VMA (%)	VFB (%)
4.0	5.41	3.64	2.24	3.00	10.40	71.15
4.5	5.77	3.74	2.26	6.94	18.93	66.66
5.0	5.95	4.05	2.27	6.41	19.23	65.67
5.5	6.4	3.99	2.26	5.78	16.84	65.67
6.0	4.11	4.53	2.25	5.06	20.23	75.00

Table 6: Optimal Values (parameters) of the Modified HMA

Asphalt parameters	0%	2%	4%	8%	10%	Specifications
Stability	5.520kN	5.91kN	6.6kN	6.2kN	5.3kN	>3.5 kN
Flow	2.41mm	3.5mm	3.98mm	4.2mm	4.3mm	2 – 4 mm
Unit-weight	2.25/m^3	2.27kN/m^3	2.28kN/m^3	2.26kN/m^3	2.24kN/m^3	NIL
Pa	4.51%	3.85%	3.45%	5.31%	6.10%	3 – 8%
VMA	15%	13.60%	11.80%	12.21%	16.10%	NIL
VFB	66%	67%	67.50%	68%	68%	65 – 72%

2019). From (Table 5); it was observed that stability rises from 5.5% bitumen content, and then it begins to drop, the flow values rise from 2.7mm to 4.4mm as the bitumen content increases which is per the range of 2mm-6mm specify per FMPW&H, 2016 for wearing course. The bulk density increases and decreases with the maximum bulk density achieved at 5.5% bitumen content. The voids in the mineral aggregate (VMA) with bitumen content rises as the bitumen content increases (Taisir et al., 2013). It is also observed that there is a reduction in percent air void and VFB is inversely related to air voids and thus as air voids decrease, the VFB increases (Alexandra & Henry, 2018)

Marshal test method for SRFD modified HMA

The optimum bitumen content of the control HMA is used for the modified SRFD HMA that yielded the maximum stability, maximum bulk unit weight, and the average of the limits of the percent air voids (Chen, W.F et al, 2003) in the modifies mix at various modifier contents (Csanyi, 1962), as illustrated in (Table 6).From (Table 6), it can be clearly observed that the properties of the SRFD modified HMA at 2%, 4%, 8% and 10% modifier contents, met with the prescribed specifications, but 8% and 10% modifier contents failed with respect to the Marshall Flow properties. ((Peyman & Ehsan, 2016).

Effect of Steel rolling furnace dust (SRFD) on Marshall Properties

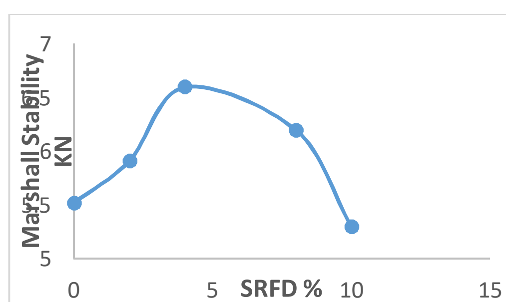

Figure 1: Relationship between percent SRFD and Marshall Stability

Based on the data given in Figure 8, the following equation was developed:

Y_1= -0.0464x2 + 0.4588x + 5.4098 (R^2 = 0.9201) (1)

Where

Y_1 = Marshall Stability of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

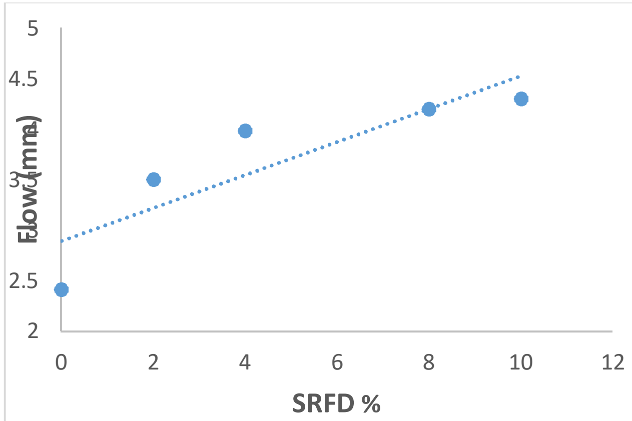

Figure 2: Relationship between percent SRFD and Marshall Flow

Based on the data given in Figure 9, the following equation was developed:

$Y_2 = 0.1635x + 2.8933$ $(R^2 = 0.7694)$ (2)

Where

Y_2 = Flow of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

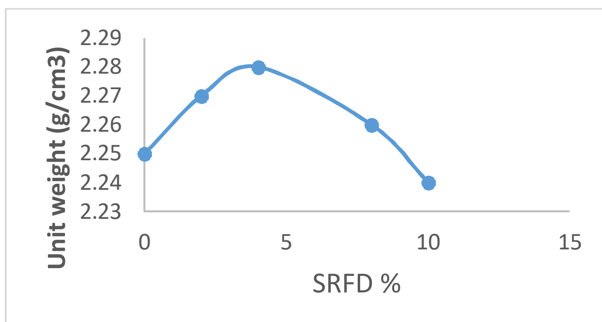

Figure **3:** Relationship between percent SRFD and Unit weight

Based on the data given in Figure 10, the following equation was developed:

$Y_3 = -0.0014x2 + 0.0124x + 2.2506$ $(R^2 = 0.9877)$ (3)

Where

Y_3 = Unit weight of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

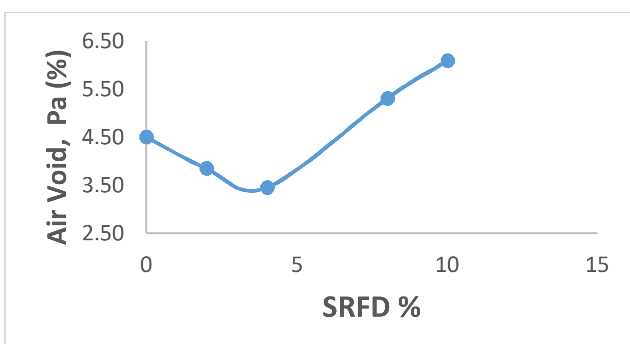

Figure **4:** Relationship between percent SRFD and Air void

Based on the data given in Figure 11, the following equation was developed:

$Y_4 = 0.0615x2 - 0.4298x + 4.4441$ $(R^2 = 0.947)$ (4)

Where

Y_4 = Air Void of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

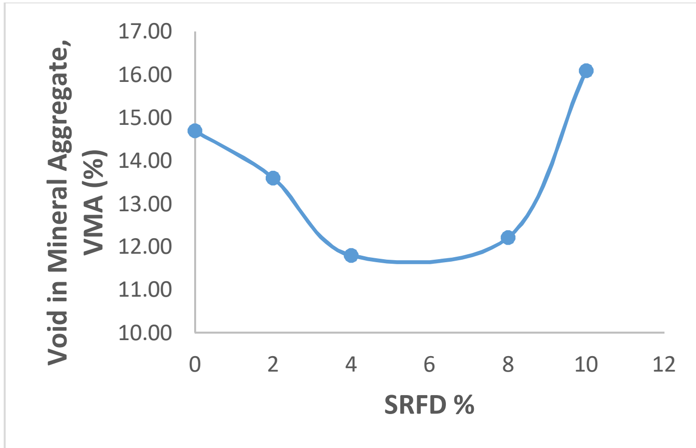

Figure **5:** Relationship between percent SRFD and VMA

Based on the data given in Figure 12, the following equation was developed:

Y_5= 0.1509x2 - 1.4681x + 15.178 *(R^2 = 0.8537)* *(5)*

Where

Y_5 = VMA of asphalt concrete mixtures

x = % of SRFD by volume of binder.

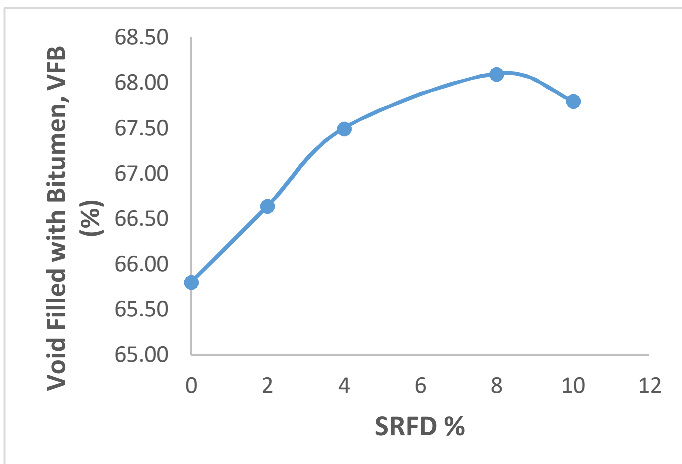

Figure **6:** Relationship between percent SRFD and VFB

Based on the data given in Figure 13, the following equation was developed:

Y_6= y = -0.0372x2 + 0.5829x + 65.738 (R^2 = 0.9926) *(6)*

Where

Y_6= VFB of asphalt concrete mixtures

x = % of SRFD by volume of binder

Table 7: Prediction Model Equations of the Modified HMA Parameters.

Asphalt parameters	Model Equation	R^2
Stability	$Y_1 = -0.0464x^2 + 0.4588x + 5.4098$	$R^2 = 0.9201$
Flow	$Y_2 = 0.1635x + 2.8933$	$R^2 = 0.7694$
Unit-weight	$Y_3 = -0.0014x^2 + 0.0124x + 2.2506$	$R^2 = 0.9877$
Pa	$Y_4 = 0.0615x^2 - 0.4298x + 4.4441$	$R^2 = 0.947$
VMA	$Y_5 = 0.1509x^2 - 1.4681x + 15.178$	$R^2 = 0.8537$
VFB	Y_6= -0.0372x2 + 0.5829x + 65.738	$R^2 = 0.9926$

Conclusion

The findings of the experimental study indicate that the bitumen utilized in this research meets the specifications outlined by the Federal Ministry of Power, Works & Housing (2016) and is suitable for use in asphalt surface construction (Jones, N., 2001). The optimum bitumen content was identified as 5.4%, with other properties such as stability, flow, voids in mineral aggregate (VMA), voids filled with bitumen (VFB), and air voids (Pa) all conforming to the standards specified in the General Specification of Nigeria Roads and Bridges (2016). The chemical composition of steel dust, intended as an additive by weight of the binder, was analyzed using XRF, revealing ferric oxide (Fe_2O_3) at 31% and zinc oxide (ZnO) at 28% as the primary components. Tests on modified asphalt containing steel dust at varying percentages (2%, 4%, 8%, and 10% by volume of binder) demonstrated that Marshall Stability, unit weight, VFB, and stiffness initially increase (Dwight, 2014), before it decreasing as the additive percentage rises. Conversely, Marshall Flow increases steadily, while VMA and air voids decrease initially and then increase with higher additive percentages (Read & Whiteoak, 2003.) Notably, a 4% electric arc furnace dust (EAFD) content by volume of binder was found to satisfy the Marshall Property criteria for asphalt mixtures (Siti et al. 2018).

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