

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

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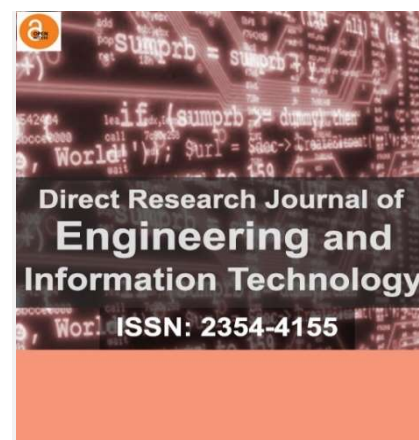
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ABSTRACT

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. The European steel industry alone produces around 500,000 tons annually, with over 30% of this remaining unutilized (Dana et al., 2017). Research incorporating Steel Dust Residue (SRFD) as an additive in asphalt mixes revealed promising results. 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 ($Fe_2O_3 = 31\%$) and zinc oxide ($ZnO = 28\%$). Experimental findings indicated that Marshal 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 Marshal properties for asphalt mixtures.

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



Article information

Received 9 August 2025;

Accepted 12 September 2025;

Published 10 October 2025

DOI: <https://doi.org/10.26765/DRJEIT290858747>

Citation: Masar U.A., Murana A. A. (2025) Marshal Properties Assessment of Hot Mix Asphalt Containing Katsina Steel Rolling Furnace Dust as an Additive. Direct Research Journal of Engineering and Information Technology, 13(3), 64-68. This article is published under the terms of the Creative Commons Attribution License 4.0

INTRODUCTION

The need to provide asphaltic pavements of greater or improved properties has thus arisen. A pavement can only be as strong as its constituent materials. 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 and hot mix asphalt productions such as waste plastic, waste lignin, waste high-density polyethylene, softwood bark charcoal, nano clay waste express bag, graphene oxide, 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.

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	°C	51.9	52-60	48-56	42-50
Ductility @ 25°C	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	°C	256	250 (Min)	232 min	250 min
Fire-point	°C	280	NIL	NIL	NIL
Solubility in C ₂ S	%	99.4	99.5 min	99 min	99.5 min

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).

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. 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 METHOD

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.

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			
	31.50	-	35	Satisfactory
Elongation Index	22.80	-	25	Satisfactory
Aggregate Crushing value (%)	21.52	-	30	Satisfactory
Aggregate Impact value (%)	10.50	-	35	Satisfactory

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

Table 3 Mechanical Properties of Aggregates

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

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°C under specified conditions. 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 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. 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.

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, 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, 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)

Table 4: SRFD characterization (weight %)

Compound	Percentage
Fe ₂ O ₃	31
ZnO	28
Al ₂ O ₃	1.28
Cu ₂ O	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 ₂ O	2.7
MgO	4.66
Others	1.5

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 it shows that the major components are ferric oxide (Fe₂O₃ = 31%) and zinc oxide (ZnO = 28%). All

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%

samples of SRFD used in this research were passing No. 200 sieve.

Marshal Test for Control HMA

To determine the optimum asphalt content by weight of total mix, Marshal 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.

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. 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.

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 in the modifies mix at various modifier contents as illustrated in Table 4

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 Marshal Flow properties.

Effect of Steel Rolling Furnace Dust (SRFD) on Marshal Properties

The variation of Marshal Stability with SRFD content, as

shown in Figure 1, follows a quadratic relationship expressed by:
 $Y_1 = -0.0464x^2 + 0.4588x + 5.4098$ ($R^2 = 0.9201$).
 The trend indicates that stability initially increases with SRFD addition up to an optimum level before declining. This implies that a moderate proportion of SRFD improves the stiffness and load-bearing capacity of the asphalt mix by acting as a fine filler that enhances particle interlock. However, excessive SRFD content introduces too many fines, which interfere with proper binder–aggregate bonding, resulting in reduced stability.

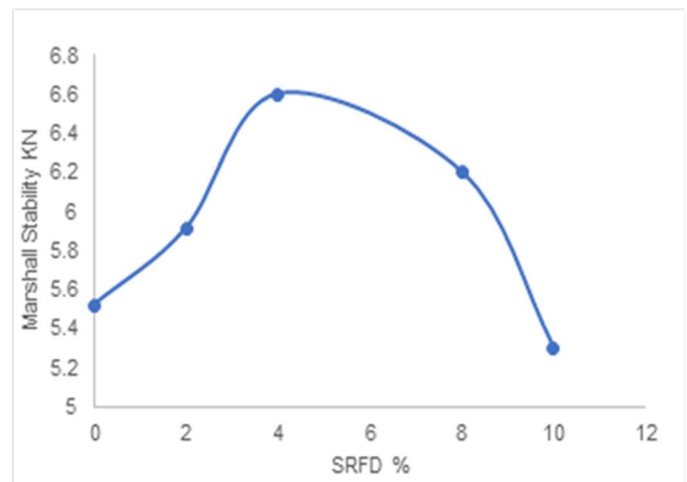


Figure 1: Relationship between percent SRFD and Marshall Stability
 Based on the data given in Figure 8, the following equation was developed:

$$Y_1 = -0.0464x^2 + 0.4588x + 5.4098 \quad (R^2 = 0.9201) \quad (1)$$

Where

Y_1 = Marshall stability of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

As observed in Figure 2, Marshal Flow increases linearly with SRFD content according to
 $Y_2 = 0.1635x + 2.8933$ ($R^2 = 0.7694$).
 This increase suggests that the asphalt mixture becomes more flexible and deformable as SRFD content rises. While a slight increase in flow can enhance flexibility,

excessive flow indicates plastic deformation, which may compromise the pavement's resistance to rutting and deformation under traffic loads.

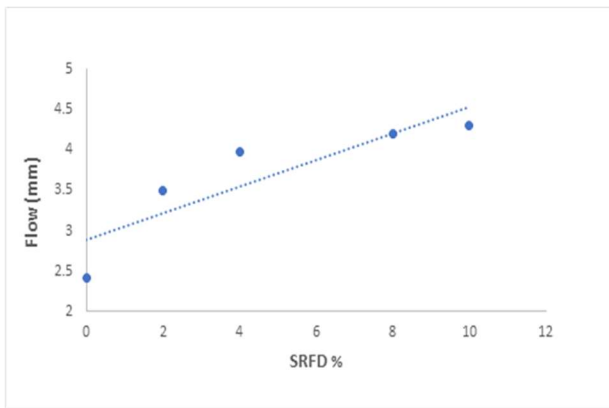


Figure 2: Relationship between percent SRFD and Marshall Flow Based on the data given in Figure 9, the following equation was developed:

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

Where

Y_2 = Flow of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

The relationship between SRFD and unit weight, presented in Figure 3, follows $Y_3 = -0.0014x^2 + 0.0124x + 2.2506$ ($R^2 = 0.9877$). Unit weight increases slightly with SRFD content up to a certain level, beyond which it decreases. The initial rise results from SRFD's filler effect, which helps fill voids between aggregates and densifies the mix. At higher contents, however, excess dust leads to poor compaction and entrapped air, thereby reducing the overall density.

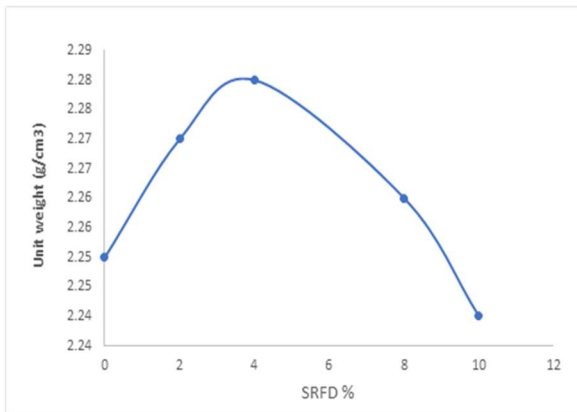


Figure 3: Relationship between percent SRFD and Unit weight Based on the data given in Figure 10, the following equation was developed:

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

Where

Y_3 = Unit weight of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

In Figure 4, the relationship between SRFD and air voids is shown as:

$Y_4 = 0.0615x^2 - 0.4298x + 4.4441$ ($R^2 = 0.947$). Air voids decrease with increasing SRFD up to an optimum level, then increase again. This pattern indicates that moderate SRFD enhances compaction by filling voids, resulting in a denser structure. Excessive SRFD, however, coats aggregate surfaces excessively and traps air, leading to higher air void values.

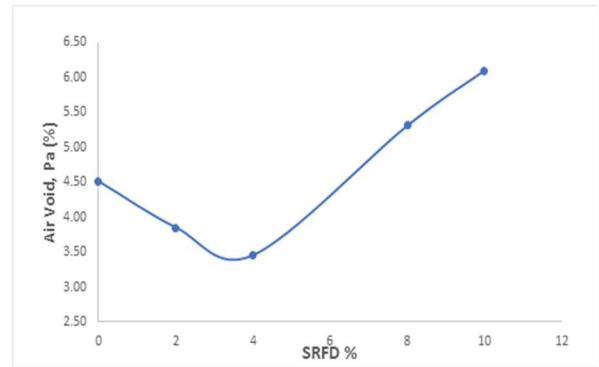


Figure 4: Relationship between percent SRFD and Air void Based on the data given in Figure 11, the following equation was developed:

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

Where

Y_4 = Air Void of asphalt concrete mixtures.

x = % of SRFD by volume of binder.

The effect of SRFD on Voids in Mineral Aggregate (VMA) is presented in Figure 5, described by $Y_5 = 0.1509x^2 - 1.4681x + 15.178$ ($R^2 = 0.8537$). VMA decreases at first, showing improved aggregate packing, but begins to rise at higher SRFD contents due to disruption of the aggregate skeleton structure. This behavior shows that an optimal SRFD level improves the internal structure of the mix, while excessive amounts have an adverse effect.

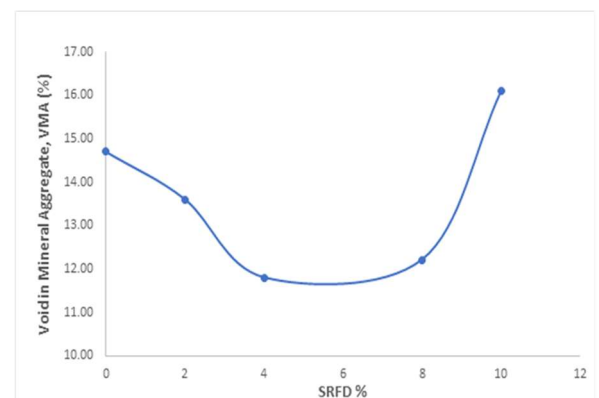


Figure 5: Relationship between percent SRFD and VMA Based on the data given in Figure 12, the following equation was developed:

$$Y_5 = 0.1509x^2 - 1.4681x + 15.178 \quad (R^2 = 0.8537) \quad (5)$$

Where

Y_5 = VMA of asphalt concrete mixtures

x = % of SRFD by volume of binder.

Similarly, Figure 6 illustrates the relationship between

SRFD and Voids Filled with Bitumen (VFB), given by $Y_6 = -0.0372x^2 + 0.5829x + 65.738$ ($R^2 = 0.9926$). VFB increases with SRFD addition up to an optimum point, indicating improved bitumen filling capacity and better coating of aggregates due to the fine filler effect. Beyond the optimum level, however, VFB decreases slightly, suggesting bitumen-rich zones that weaken the mixture's structural integrity (Table7).

CONCLUSION

The result of the experimental study shows that:

1. The properties of bitumen used in this research were satisfactory within limits as specifications by the Federal Ministry of Power, Works & Housing (FMPW&H, 2016) and can be used in the construction of Asphalt surfaces.
2. The optimum bitumen content was determined to be 5.4%. Other properties such as stability, flow, VMA, VFB, and Pa are all within the specification (General Specification of Nigeria Roads and Bridges, 2016).
3. The elemental and oxide chemical compositions of the steel dust to be used as an additive by weight of the binder used for this research were determined using XRF analysis, the major components are ferric oxide ($Fe_2O_3 = 31\%$) and zinc oxide ($ZnO = 28\%$).
- 6 The tests on modified asphalt with SRFD at 2%, 4%, 8% and 10% by volume of binder additive contents, indicates that Marshal stability, unit weight, voids filled with bitumen (VFB) and stiffness increase then decrease with the increasing % SRFD in the asphalt concrete mixtures.
- 7 Marshal Flow increases with the increasing % SRFD in the asphalt concrete mixtures, while VMA and air voids decrease then increase with the increasing % SRFD in the asphalt concrete mixtures.
- 8 A 4% EAFD content by volume of binder is found to meet the criteria of Marshal properties of asphalt mixtures.

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