

## Strength Properties Model of Modified Hot Mix Asphalt

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### ABSTRACT

Researchers have extensively investigated the use of various materials and industrial wastes as modifiers and additives in concrete and hot mix asphalt production. Reusing and recycling industrial wastes has become more appealing, steering away from their disposal in landfills and dumpsites. This particular study aimed to enhance asphaltic concrete properties by incorporating Katsina Steel Rolling Furnace Dust (SRFD), a waste product estimated at 15-20 kg per ton of steel produced, as an additive. The SRFD was introduced into the asphalt mix at different concentrations (0%, 2%, 4%, 8%, and 10%) relative to the volume of binder. The study found the optimal bitumen content to be 5.4%, meeting the General Specification of Nigeria Roads and Bridges, 2016. Key properties such as stability, flow, VMA (voids in mineral aggregate), VFB (voids filled with bitumen), and Pa (air voids) fell within specified ranges. Notably, the modified asphalt with SRFD exhibited improved stability (6.61kN compared to 5.4kN in the control asphalt) and a flow of 3.9mm. This change suggested increased bulk density, potentially reinforcing road pavement against damage from traffic loads. Statistical analysis using one-way ANOVA indicated that SRFD did not significantly impact stability, flow, and percentage of air voids (*P*-values were 0.517292, 0.06201, and 0.22976, respectively, with *F*-calculated values lower than *F*-critical values). However, for unit weight, VMA, and VFB, SRFD did have a significant role in the variance of the measured properties. Regression analysis is used to develop a relationship that could be applied in similar circumstance. The models exhibited good prediction capacity with coefficient of determination (*R*<sup>2</sup> values) within the range of 76% to 99%.

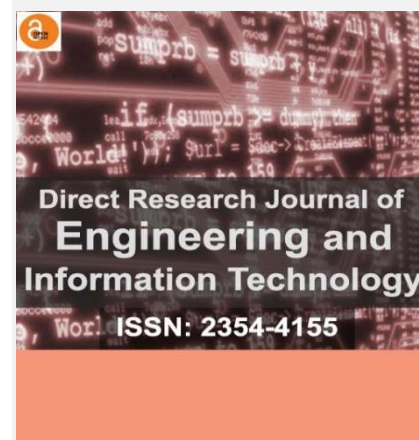
**Keywords:** Steel Rolling Furnace Dust, Marshal Properties, Analysis of Variance,

### INTRODUCTION

Huge sums of resources have been sunk into road development (Airey & Taylor, 1999). The road network is currently estimated at about 194,000 kilometers, with the Federal Government being responsible for about 17 percent, State Governments 16 percent and local Governments 67 percent (Federal Ministry of Works Nigeria (2013). In Nigeria it can be noted that most of the roads in the country are in various states of disrepair and many of them have become hazardous and sources of

economic drain in terms of high road users cost, loss of lives and property and loss of highway investment. (Danladi, 2013). Major Nigerian highways are known to fail shortly after construction and well before their design life, the fast-growing rate of population and the increase in axle loads, heavy traffic, severe climate conditions, and construction failures has led to the enhancement of bitumen properties (Bulatović *et al.*, 2014). The need to provide asphaltic pavements of greater or improved

### Regression analysis models



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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). 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 provide 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).

In the whole world, 13.5 million tons of steel rolling furnace waste are generated annually, mill scale is suitable for direct recycling to ferroalloys, in cement plants and in the petrochemicals and construction industry (Gaballah *et al.*, 2013), having the produced amounts of SRFD byproduct could be a potential risk for our surrounding environment, This situation was a driving force for this research to investigate an appropriate solution by assessing the marshal properties of hot mix asphalt concrete containing steel rolling furnace dust as an additive. Steel rolling furnace dust is also from these materials. It cannot be incinerated and it cannot be composted. The left option is burying it in the landfills, but landfilling of steel scale is harmful to land and eventually to environment

## 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°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).

### **Analysis of Variance (ANOVA)**

ANOVA analysis was carried out to evaluate Katsina Steel Rolling Furnace Dust (SRFD) as an additive in hot mix asphalt to see how significantly the presence of the SRFD affected each of the Marshal properties. ANOVA was carried out using the excel computer software.

### **Regression Analysis**

Regression analysis was used to examine the relationship between the SRFD and the marshal properties of the hot mix asphalt. Mathematical models showing these relationships were made using regression analysis where the percentage variation of the SRFD content were the independent variables and the respective marshal properties were the dependent variables.

#### **Linear regression**

A linear regression is a straight-line function. Having the form as shown in Equation below containing an independent variable (x) and two parameters (A, B).

$$Y = Ax + B \dots\dots\dots 3.1$$

The coefficients in the Equation 3.1 would be derived using equations below:

$$B = \frac{\sum_{i=1}^n (xi - \bar{x})(Yi - \bar{Y})}{\sum_{i=1}^n (xi - \bar{x})^2} \dots\dots\dots 3.2$$

$$A = \bar{Y} - B\bar{X} \dots\dots\dots 3.3$$

The coefficient of determination can be calculated from Equation below:

$$r^2 = \frac{\sum_{i=1}^n (xi - \bar{x})(yi - \bar{y})}{\sum_{i=1}^n (xi - \bar{x})^2 \sum_{i=1}^n (yi - \bar{y})^2} \dots\dots\dots 3.4$$

#### **Polynomial regression**

A polynomial regression generally has the form as shown in Equation below. A polynomial regression contains more than one independent variable and the parameters are determined by the corresponding number of variables.

$$Y = A_m X^m + \dots + A_1 X + A_0 \dots\dots\dots 3.5$$

The polynomial regression model achieved in this work were cubic and quadratic.

#### **A cubic function**

By regression analysis is modelled by Equation below. Where, the coefficients A, B, C and D help to give a better description of the function.

$$Y = AX^3 + BX^2 + CX + D \dots\dots\dots 3.6$$

#### **Scan Electron Microscopy (SEM)**

Verios 5 XHR Scan Electron Microscopy Machine for imaging and ImageJ Software version j153-win-java8 for analysis and measurement.

## **RESULTS AND DISCUSSION**

### **Analysis of Variance (ANOVA)**

An analysis of variance on the SRFD modified hot mix asphalt was calculated at a significance level of 0.05 to analyze the data of the marshal stability, flow, bulk density, % Air voids, Voids in Mineral Aggregates and Voids filled with Bitumen. Judging by the P-values obtained at a significant level of 0.05, if the values obtained are greater than 0.05, it means that there is no statistically significant difference between means due to a factor (Table 1). Table 1 shows results for ANOVA. From the table, the P-values obtained for stability, flow and % Air voids are 0.517292, 0.062005 and 0.229759 respectively which are all greater than 0.05 and thus implies that the SRFD additive has no significant effect on these three properties statistically. The values for bulk density, voids in mineral aggregates and voids filled with bitumen in table 1 are all less than 0.05 and implies that the SRFD contents result in significant change in the properties.

### **Regression Analysis**

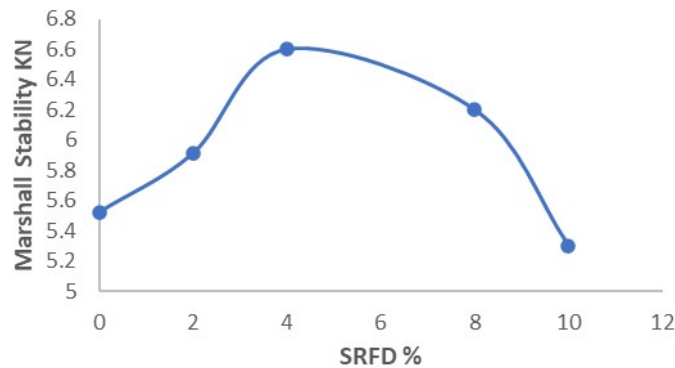
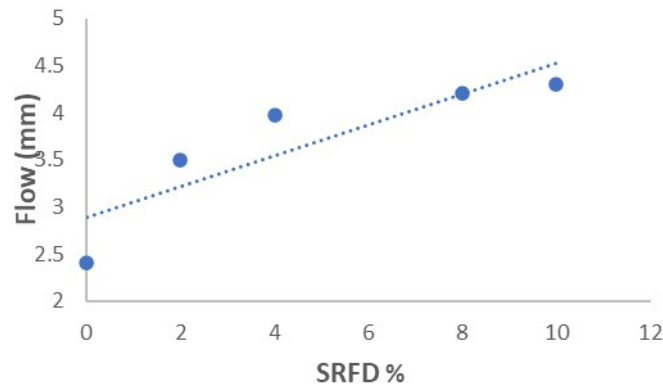
Regression analysis for the SRFD in Hot mix Asphalt was carried out for the various marshal properties and each model was gotten depending on the nature of the function; being either linear or polynomial.

#### **Marshall Stability**

Figure 1 shows the effect of SRFD on Marshall stability of asphalt concrete mixtures for each SRFD additive concentration, it indicates that there is a strong correlation of ( $R^2 = 0.9201$ ) between SRFD and Marshall Stability, the stability increases, at 4% SRFD at optimum stability of 6.6 kN was obtained, which lies within specification of not less than 3.5kN (NGSRB, 2016), then decreases with the increasing of percentages SRFD in the asphalt mix.

**Table 1:** ANOVA analysis for SRFD in HMA.

%SRFD	Stability	Flow	Bulk Density	% Air Voids	VMA	VFB
2	3.65	3.38	2.278	4.58	17.79	74.26
4	3.9	3.2	2.287	4.31	17.57	75.47
8	7.02	2.75	2.276	3.98	17.85	77.7
10	5.02	2.43	2.277	3.94	17.91	78
P value	0.51729	0.06201	0.03018	0.22976	3.48E-05	7.21E-11
F Calc.	0.4588	4.70053	6.91621	1.69036	68.1487	1978.18
F Critical	5.31766	5.31766	5.31766	5.31766	5.31766	5.31766
Remarks	No Significant effect	No Significant effect	Have Significant effect	No Significant effect	Have Significant effect	Have Significant effect

**Figure 1:** Relationship between percent SRFD and Marshall Stability.**Figure 2:** Relationship between percent SRFD and Marshall Flow

From the plot of Marshal Stability against SRFD content in Figure 2, it is observed that the plot is best described by a square function having a power raised to two ( $x^2$ ). From the solutions of Equations 1 gives the coefficients of the regression model:

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

Where

$Y_1$  = Marshall stability (Dependent Variable).

$x$  = % of SRFD (Independent variable)

The coefficient of determination  $R^2 = 0.9201$  was gotten by substituting the dependent and independent variables into Equations 3.1 - 3.6. It explains that 92.01% of the variation in the SRFD is related to stability property with respect to

the model i.e. the values of X can predict the consistency values of Y to a degree of 92.01%.

### Marshal Flow

The Figure 2 shows the effect of SRFD on Marshall flow of asphalt concrete mixtures for each SRFD concentration. It shows a good correlation with ( $R^2 = 0.7694$ ) and that the Marshall flow increases with the increasing of SRFD waste concentration in the asphalt mix. This is due to that the cohesion of the binder decreases and hence, the mixture trends to flow more as evaluated by Taisir et al. (2013). The flow of 3.98mm was obtained at SRFD content of 4%, the lies within the Nigerian General Specification for road and Bridge, 2016 (2mm – 4mm). The stiffening increases the resistance of the mix to rutting and fatigue cracking.

From the plot of Marshal Flow against SRFD content, it was observed that the plot is best described by a linear function having the form as in Equation 2:

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

Where

$Y_2$  = Flow (Dependent Variable).

$x$  = % of SRFD. (Independent variable)

The regression coefficients were gotten from solution of Equation 2, the coefficient of determination  $R^2 = 0.7694$  was gotten by substituting the dependent and independent variables into Equation 2. It explains that 76.94% of the variation in the SRFD is related to flow property

### Bulk Density

Figure 3 shows the effect of SRFD on the unit weight of asphalt concrete mixtures for each SRFD concentration, it indicates that there is a strong correlation with ( $R^2 = 0.9877$ ) between SRFD and Unit Weight, the unit weight increases to an optimum unit weight of  $2.28\text{g/cm}^3$  at SRFD of 4%, then decreases with the increasing percentages of SRFD in the asphalt mix. Voids in the mix will be filled with SRFD and hence, lower unit weight will result. From the plot of bulk density against SRFD content in (Figure 3) it was observed that the plot is best described by a square function having a power raised to two ( $x^2$ ). From the solutions of Equations 3 gives the coefficients of the regression model:

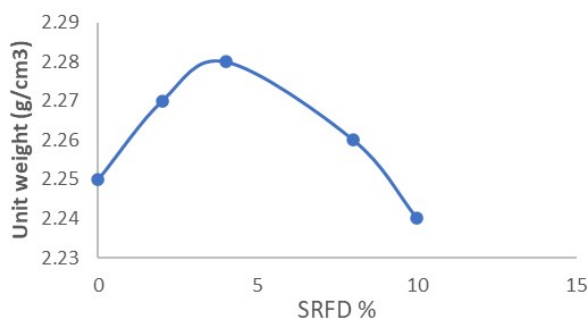


Figure 3: Relationship between percent SRFD and Unit weight

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

Where

$Y_3$  = Unit weight (Dependent Variable).

$x$  = % of SRFD (Independent variable)

The coefficient of determination  $R^2 = 0.9877$  was gotten by substituting the dependent and independent variables into Equations 3. It explains that 98.77% of the variation in the SRFD is related to stability property with respect to the model i.e. the values of X can predict the consistency values of Y to a degree of 98.77% with respect to the

regression model.

### % Air Voids

Figure 4 shows the effect of SRFD on voids in mineral aggregate of asphalt concrete mixtures for each SRFD percentages. There is a strong correlation between SRFD and Air Voids with ( $R^2 = 0.947$ ). It also indicates that voids in mineral aggregate decreases to a minimum value of 3.25% Air void at 3.5% SRFD, then increases with the increasing of SRFD concentration in the asphalt mix. Excessive air voids in the mixture would result in cracking due to inadequate bitumen binders to coat on the aggregates, while too low air void may induce more plastic flow (rutting) and bitumen bleeding. The general trend for the % air void is a decreasing air void with decrease in SRFD content from 4% as seen in figure 4. The function best describes the % air void property having the form as seen in Equation 4:

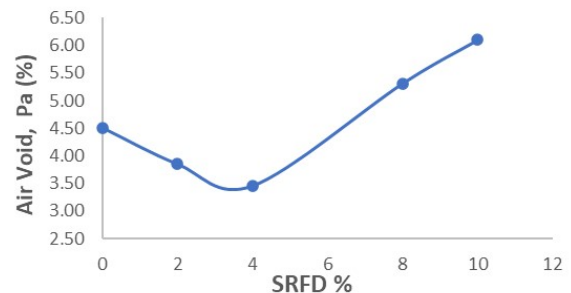


Figure 4: Relationship between percent SRFD and Air void

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

Where

$Y_4$  = Air Void (Dependent Variable)..

$x$  = % of SRFD (Independent variable)

The regression coefficients were gotten from solution of Equation 4 resulting to a value of 0.847 which interprets that 94.7% of the variation in the PSRFD is related to the % air void property with respect to the model.

### Void in Mineral Aggregates (VMA)

Figure 5 shows the effect of SRFD on voids in mineral aggregate of asphalt concrete mixtures for each SRFD concentration. It shows a good correlation with ( $R^2 = 0.8537$ ). The voids in mineral aggregate decreases to an optimum minimum value of 11.5% at 4.5% SRFD, then increases with the increasing of SRFD concentration in the asphalt mix. This could be attributed to the absorption of bitumen in the mix with increase in SRFD as observed by Erika &, Stefano (2016). A polynomial function describes the graph of the VMA-SRFD relationship in figure 5. The quadratic function in the form of Equation 5:

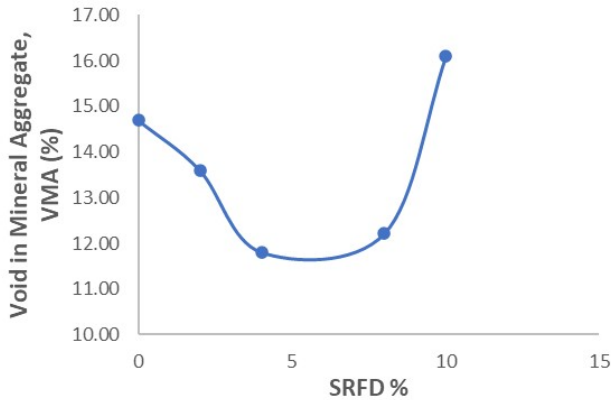


Figure 5: Relationship between percent SRFD and VMA

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

Where

$Y_5 =$  VMA (Dependent Variable).

$x =$  % of SRFD (Independent variable)

Substituting the variables from Equation 5 will give the result for the coefficient of determination  $R^2$  which equates 0.8537. It is 85.37% close to the variations. The value of X can predict the consistency values of Y in the model up to 85.37%.

### Void filled with Bitumen (VFB)

Figure 6 presents the effect of SRFD on VFB of asphalt concrete mixtures for each SRFD percent concentration by volume of binder. There is a strong correlation between SRFD additive and Voids Filled with Binder (VFB ( $R^2 = 0.972$ .) It also shows that the optimum VFB of 68.2% was obtained and is within range specified in the code from 65 to 72%, the decrease of VFB SRFD could be attributed to increase porosity with the increasing of SRFD concentration in the asphalt mix (Table 2). As observed by Taisir et al. (2013). The % air voids, the voids filled with bitumen is also shown by the function form shown in Equation 6 with ( $R^2 = 0.9926$ ):

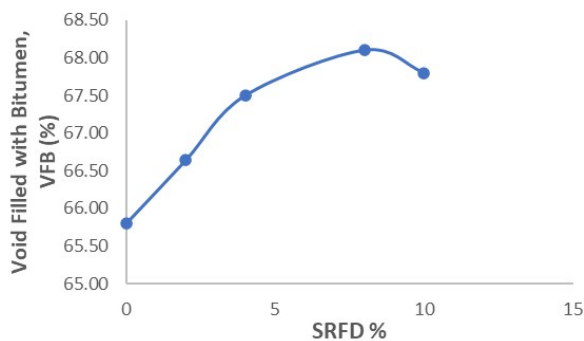


Figure 6: Relationship between percent SRFD and VFB

$$Y_6 = -0.0372x^2 + 0.5829x + 65.738 \quad (6)$$

Table 2: Regression 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	$Y_6 = -0.0372x^2 + 0.5829x + 65.738$	$R^2 = 0.9926$

Where

$Y_6 =$  VFB (Dependent Variable).

$x =$  % of SRFD (Independent variable)

The regression coefficients were gotten from solution of Equation 6 resulting to a value of 0.9926 which interprets that 99.26% of the variation in the SRFD is related to the VMA property with respect to the model.

### Scanning Electron Microscopy (SEM)

A scanning electron microscopy was used to observe the morphology and microstructure of the different mixes. Plates I, and II show the microstructure of three different blends. From Plate I it can be seen that the aggregates are coated completely by the bitumen binder giving the asphaltic concrete a densely compacted structure. Plate II; in comparison with the control mix, it can be observed that as SRFD was added to the mix there is an increase in voids and there is less adhesion in the mix. The loss in adhesion could be attributed to the hydrophilic properties of SRFD as well as its lack of absorption of bitumen.

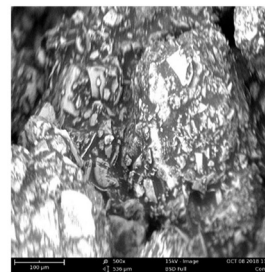


Plate I. Electron microscopy for control HMA's mix

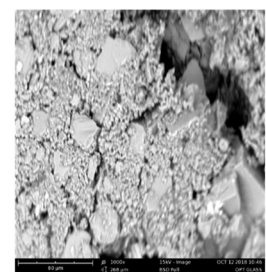


Plate II. Electron microscopy for SRFD mix

### Conclusion

This study comprehensively evaluated the role of Silica-Rich Fly Dust (SRFD) in enhancing the performance of Hot Mix Asphalt (HMA). Statistical analysis using one-way ANOVA revealed that SRFD does not significantly influence Marshall Stability parameters such as stability, flow, and air voids, as indicated by p-values greater than 0.05 and F-calculated values below the critical threshold. However, SRFD showed a statistically significant effect on unit weight, voids in mineral aggregate (VMA), and voids filled with bitumen (VFB), suggesting its potential to improve volumetric properties of HMA. Regression modeling demonstrated strong predictive capabilities, with coefficients of determination ranging from 76% to 99%,

confirming the reliability and robustness of the developed equations. Furthermore, Scanning Electron Microscopy (SEM) analysis provided microstructural evidence of SRFD's stabilizing effect, particularly in reducing moisture penetration and mitigating the stripping phenomenon. These findings underscore the potential of SRFD as a sustainable additive in asphalt mix design, offering both mechanical and durability enhancements. The predictive models derived from this study can serve as valuable tools for future mix optimization and performance forecasting.

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