Empirical Study of Steel Slag Powder on Modification of Asphalt Concrete

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Abstract: The huge number of industrial wastes has increased rapidly in Iraq. Discarding these wastes become a very serious problem. As a result, an enormous part of the land is being set for the disposal of these advantageous wastes. Steel slag is a by-product material in the industrial area and can be used as an additive in the asphalt mixture modification. Improving slag utilization is an important way to resolve these problems. This study evaluates the use of steel slag as additional replacement material in the production of hot mix asphalt (HMA) for road construction. There are two methods used to add steel slag to bituminous mixes: the wet and dry method. The main purpose is to find the ideal steel slag ratio for the mix using the dry process. Optimum Binder Content (OBC) was found for the mix using the Marshall Mix design. A sequence of samples was prepared with different percentages of steel slag comparing with conventional samples which were 0, 10, 20 and 30% by the total weight of bitumen. For each sample aggregate, asphalt and Marshall mix design tests were conducted and investigated. The results gained from mix design for optimum binder and steel slag ratio, based on average maximum stability, density, and air void for 4%, were found to be 4.8% and 29.5% respectively. Comparing with conventional samples, the empirical analysis of the results indicated that with increasing doses of steel slag, stability and density will increase while keeping air void in the range. Adequate stability needed for ensuring resistance to deformation under dynamic or repeated loads, in another meaning, more stability leads to more strength of asphalt concrete and rutting resistance. Also, durability for the mixture should have sufficient air voids not to hasten aging process.

Keywords: Steel Slag, Hot Mix Asphalt (HMA), Optimum Binder Content (OBC), Marshall Mix Design, Dry Process

1. Introduction

The main goal for many developed countries in the world is sustainable growth. Rapid development demands a great need of heavy industries which produce the required material. There are great requirement and demand for constructing countless heavy industries and factories for manufacturing different needs of the developed population (Nguyen, Lu, & Le 2018). In recent years, Kurdistan Region has become a place for huge industries. It has been seen with the country's motivation on renovation and reconstruction, the construction area is developing year by year. Because of the existence huge amount of blast furnace slag, the implementation of steel slag was not charming, the

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history of steel slag reported after the mid-19th century (Zumrawi & Khalill, 2017). The idea of modifying asphalt by adding modification binders is not recent subject, while the additional material with asphalt is something new.

There have been numerous efforts to modify asphalt concrete to get superiority and excellent quality of performance and getting better asphalt mixtures. Recent researchers and scientists discovered plenty of waste or residue materials to be recycled and reused for different purposes in engineering. Among them steel slag is a byproduct acquired from steel industry. Steel slag is procreated as a deposit or residue throughout the manufacture of steel (Hainin et al. 2015). Numerous scholars have attempted to consume steel slag in asphalt concrete. The earlier investigations were mostly applied on hot mix asphalt (HMA), by adding various dosages or percentages of steel slag aggregate (SSA), which are extremely angular, roughly cubical fragments with flat or elongated shapes. (E Zumrawi and A Khalill 2017). Also, Zumrawi and Khalill reported that the previous studies mostly were based on utilization of steel slag in HMA as substitution of coarse aggregate. This study relates with the powdered waste steel slag as partly replacement of bitumen in HMA. Powdered steel slag provides the particle interconnection, well compaction and higher stability or strength which is essential for long life serviceability pavements. The crucial features that the bituminous mixtures should include are stability, durability, flexibility, and skid resistance, as well as to have an economical blend from several mixes. For this purpose a suitable mix should be prepared from (aggregate, asphalt and modification binders) and also an appropriate design technique should be followed (Asi, Qasrawi, and Shalabi 2007). Generally there are three main bituminous mix design techniques, they are Marshall, Hveem and Superpave techniques (Method n.d.). The typical laboratory design procedure used in this study was Marshall mix design procedures, which is the widely used method in Kurdistan.

2. Empirical Study

2.1 Aggregate Tests

Aggregates (organic and inorganic) are stiff and passive materials such as sand, gravel, crushed stone, etc. Aggregates with different sizes are selected and graded appropriately. Aggregates occupy 90 to 95 percent of the total weight of the mixture. Some of the laboratory tests were made for aggregate since it is important to know the property of aggregate like, size and grading, particle shape, toughness, absorption, and cleanliness.

Sieve analysis experiment is implemented to determine the proportion of different grain sizes included within an aggregate, through a different standard sieve using either manually or mechanically (Asmaa Mamhusseini, ICEEAS 2016). The particle size distribution curve, also recognized as a gradation curve, can be performed to any type of construction granular material. In this study, the aggregate distribution applied for the surface course of flexible pavement, based on job mix limits.

Table 1: Sieve analysis test for surface course

Sieves Size (mm)	Coarse aggr.		Fine aggr.		Filler	Combined Gradation Passing %	Job Mix Limits		Surface Course Specification	
	Medium aggregate	Fine aggregate	Crushed Sand	0						
19.5	100.0	100.0	100.0	0.0	100.0	100	100	100	100.0	100.0
12.5	27.6	100.0	100.0	0.0	100.0	93	87	99	90.0	100.0
9.5	1.3	76.0	100.0	0.0	100.0	82	76	88	76.0	90.0
4.8	0.3	6.6	93.5	0.0	100.0	52	46	58	44.0	74.0
2.4	0.3	1.0	66.8	0.0	100.0	37	33	41	28.0	58.0
0.3	0.3	1.0	19.4	0.0	100.0	13	9	17	5.0	27.0
0.075	0.3	1.0	7.5	0.0	95.5	7.0	5.0	9.0	4.0	10.0

Specific gravity for coarse, fine and filler aggregates was followed later as shown in Table 2. The specific gravity is the ratio of the weight of a given volume of aggregate to the weight of an equal volume of water. The purpose of this test is to measure the strength or quality of the aggregates. Based on ASTM C 128-97 and AASHTO T-84, the absorption values are performed to compute the variation in the mass of an aggregate due to water absorbed in the pore spaces within the constituent particles, compared to the dry condition. In addition to sieve analysis and specific gravity tests, additional tests were done for the aggregates, which include L.A. abrasion, flakiness, etc. as it's given in Table 3.

Table 2: Specific gravity tests for coarse, fine and filler

	sp.gr. (gr/cm^3)	absorption (%)	apparent sp.gr (gr/cm^3)
Coarse aggregate 1	2.654	0.8	2.714
Coarse aggregate 2	2.602	0.6	2.644
Fine aggregate	2.649	0.9	2.711
Filler	2.721	-	2.724
Limits	-	< 2	-
Standards	ASTM C-127,128		

Table 3: Other properties of aggregate

Los Angeles abrasion value %, AASHTO T 96, ASTM 131	19.0	≤ 30
Flakiness in coarse aggregate, ASTM D 4791	8.0	≤ 10 According to Iraqi Spe.
Percentage of fractured particles in coarse aggregate, ASTM D 5821	93.0	90 min

2.2 Bitumen Tests

The neat bitumen used in this study was with penetration grade of PG 40-60, the basic properties of neat bitumen are listed in Table 4, with a softening temperature of 160 ˚C. It's shown that the specific gravity of bitumen is 1.03, with penetration grade of 46 ˚C., the penetration test is used to specify the grade or consistency of the bitumen, as well as it is a good indication for using under various climatic conditions. The PG 40-60 grade bitumen describes the penetration grade of bitumen which is between 40 & 60.

Table 4 shows that the ductility and softening point test results are 150 cm and 52 ˚C respectively. Ductility is essential for bitumen since the temperature changes in asphalt mixtures and the repeated deformations that take place in flexible pavements due to the traffic loads. It is important that the binders form ductile thin films around the aggregates (The Chemical Educator, 1997). Flash and fire point test is a protection test from fire and an indication for critical temperature before working with asphalt above and at a level of a point where precautions are needed to reduce or remove the fire threats during its applications in the laboratory.

Table 4: Basic properties of neat bitumen PG 40-60

Name of the test	test value	limits	Standards
Bitumen specific gravity	1.03	0.92-1.06	ASHTTO T228
Penetration, (25 ˚C, 100 g, 5 s)	46	40-60	ASTM D5-05a
Ductility, (25 ˚C/min, cm)	150	>100	ASTM D113-99
Softening Point (Ring & Ball), (˚C)	52	51-62	ASTM D36-06
Flash point (˚C)	281	>232	ASTM D92-05a
Fire point (˚C)	287	-	ASTM D92-05a

2.3 Marshall Mix Design Test

For determining and evaluating the bituminous mixes, the common technique used in this study, which is the Marshall mix design method. (Mamhusseini, 2018) in the mix there are some criteria to be considered. An adequate binder content is needed for a long-lasting pavement by providing a waterproof on the aggregate particles and binding them together under appropriate compaction. In addition, an ideal stability in the term of strength is provided for the mix to resist deformation under repeated loads. Adequate void is necessary in the compacted mix for the further compaction under repeated loads. While high voids are harmful in the mix because it causes quick hardening of bitumen and decreases service life achieving a brittle pavement. Dry and wet processes are two methods in Marshall design based on mixing procedure. Dry process is used, by mixing steel slag with aggregate prior to bitumen. The followings are the steps for sample preparation of the mix.

1. Aggregate selection.
2. Determination of specific gravities of the aggregate (course, fine and filler) and bitumen.
3. Preparation of the trial specimens with (4%, 4.5%, 5%, 5.5 and 6%) asphalt contents.
4. Determination of the specific gravity of each compacted specimen.
5. Perform stability and flow tests on the specimens and calculate the percentage of voids, and percent voids filled with Bitumen in each specimen.

6. Selection of the Optimum Binder Content (OBC) from the data obtained.
7. Evaluation of the design with the design requirements

2.4 Void and Specific Gravity Calculations in The Mix

Bulk density of the mix is the ratio of mass of the mix in air in a mix volume.

$$Bulk\ Density = \frac{mass\ of\ the\ mix\ in\ air}{volume\ of\ the\ mix}$$

Theoretical Specific Gravity of the Mix (Gmm): Is the specific gravity with ignoring the air void.

W1,2,3= Weight of aggregate, Wb = Weight of bitumen, G1,2,3= Specific gravity of aggregate, Gb= Specific gravity of bitumen

$$Gmm = \frac{W_1 + W_2 + W_3 + W_b}{\frac{W_1}{G_1} + \frac{W_2}{G_2} + \frac{W_3}{G_3} + \frac{W_b}{G_b}}$$

Bulk Specific Gravity of Mix (Gmb): Is the actual specific gravity with considering the air void in the mix.

$$G_{mb} = \frac{W_m}{W_M - W_W}$$

Air Voids (Va, %): Is the total air void percent in the mix.

$$Va = \frac{(G_{mm} - G_{mb}) * 100}{G_{mm}}$$

Percent Volume of Bitumen (Vb, %): Is the total bitumen percent in the mix.

$$V_b = \frac{\frac{W_b}{G_b}}{\frac{W_1 + W_2 + W_3 + W_b}{G_{mb}}}$$

Percent of Voids in Mineral Aggregate (VMA, %): are the voids between the aggregate particles of the compacted mix. In other words, sum of bitumen and aggregate voids in the mix.

$$VMA = V_a + V_b$$

Percentage of Voids Filled with Asphalt (VFA, %): is the portion of voids in the aggregate which is filled with non-absorbed bitumen in the compacted mix.

$$VFA = \frac{V_b * 100}{VMA}$$

The Marshall design is appropriate procedure for estimating the optimum binder content. The data shown in table 6. below is obtained by compacting the samples with an approximate compaction temperature of 150 °C. Then these samples were balanced to get weight in air, water and saturated surface dry SSD determined for each sample. This study was performed for medium traffic having 50 blows per each side.

3. Mix Design Results

The design of asphalt mixes with the addition of steel slag needs standard laboratory procedures. As well as the requirements of ASTM D5106 (Annual Book of ASTM Standards, 1994) and ASTM D4792 (Annual Book of ASTM Standards, 1996) outline recommended properties of steel slag aggregate for use in the hot mix asphalt. Some of the mix properties that are of interest when steel slag is used in asphalt concrete mixes include stability, stripping resistance, and rutting resistance (Chesner, Warren H., Robert J. Collins, Michael H. MacKay, and John Emery, 2002). Optimum Binder Content (OBC) should be determined for the Marshall mix design. Table 5: shows the detail of the work with five different percentages arranged for each percentage, 3 samples were prepared and tested.

Table 5: Details for determining OBC value

Sample NO.	Bitumen		Compaction Temperature	Wight of sample in air(gm)	Wight of sample in water(gm)	S.S.D Wight of sample (gm)	Volume of sample (cm^3)	Specific Gravity of sample (gm/(cm^3)	Water Absorption
	P_b%	gm							
1	4	48.0	150 C°	1087.4	620.0	1090.2	470.2	2.313	0.3
2			150 C°	1069.3	610.0	1073.0	463.0	2.310	0.3
3			150 C°	1083.8	616.0	1086.0	470.0	2.306	0.2
Average								2.309	0.3
1	4.5	54.0	150 C°	1092.0	628.0	1095.6	467.6	2.335	0.3
2			150 C°	1079.8	618.0	1080.6	462.6	2.334	0.1
3			150 C°	1086.0	621.0	1090.3	469.3	2.314	0.4
Average								2.328	0.2
1	5.0	60.0	150 C°	1106.2	634.3	1107.4	473.1	2.338	0.1
2			150 C°	1090.0	625.0	1092.0	467.0	2.334	0.2
3			150 C°	1093.0	624.4	1094.0	469.6	2.328	0.1
Average								2.333	0.1
1	5.5	66.0	150 C°	1090.0	619.6	1092.0	472.4	2.307	0.2
2			150 C°	1102.2	624.5	1103.3	478.8	2.302	0.1
3			150 C°	1100.8	624.3	1101.7	477.4	2.306	0.1
Average								2.305	0.1
1	6	72.0	150 C°	1116.8	628.4	1117.7	489.3	2.282	0.1
2			150 C°	1125.2	632.4	1127.0	494.6	2.275	0.2
3			150 C°	1116.7	628.3	1117.1	488.8	2.285	0.0
Average								2.281	0.1

Table 6: Stability, V_a %, VMA %, VFA % and Flow for different BC

Sample NO.	Bitumen		Max.Theo. Specific Gravity(gm/(cm3)	Va %	VMA %	VFA %	Flow (mm)	Stability (Kg)
	P_b%	gm						
1	4	48.0	2.516	8.2	15.7	48	2.5	1204
2							2.4	1309
3							2.5	1309
Average							2.5	1274
1	4.5	54.0	2.470	5.7	15.5	63	2.3	1440
2							2.2	1440
3							2.3	1414
Average							2.3	1431
1	5.0	60.0	2.415	3.4	15.7	78	2.9	1379
2							2.8	1414
3							3.0	1440
Average							2.9	1411
1	5.5	66.0	2.383	3.3	17.2	81	2.9	1304
2							3.0	1254
3							2.9	1254
Average							2.9	1271
1	6	72.0	2.340	2.5	18.5	86	3.4	1007
2							3.3	1103
3							3.4	1155
Average							3.4	1055

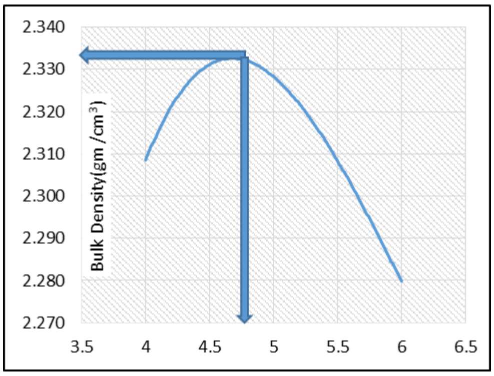

Figure 1: Maximum value of bulk density

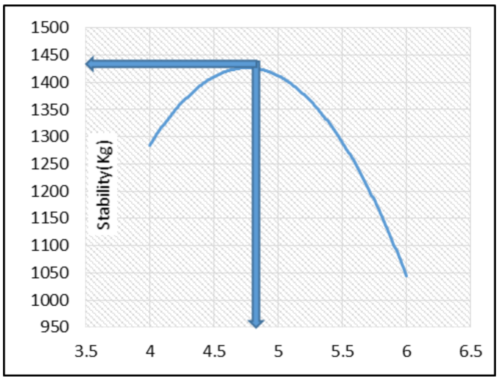

Figure 2: Maximum value of stability

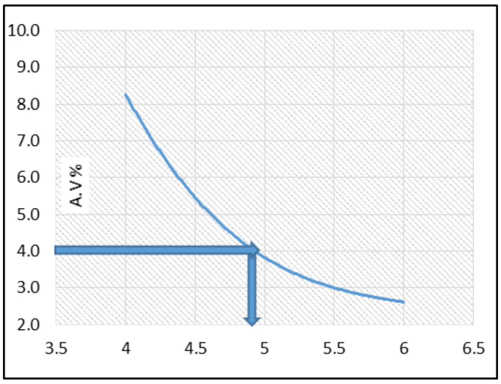

Figure 3: Value of bitumen content at 4% air voids

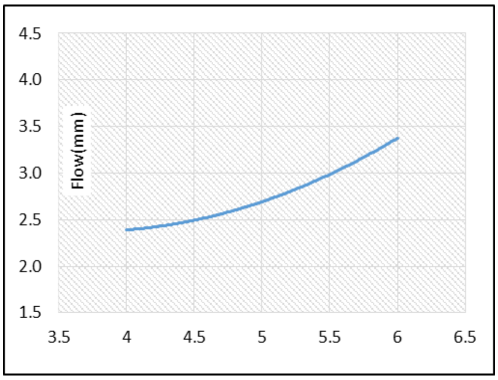

Figure 4: Flow curve with different bitumen content

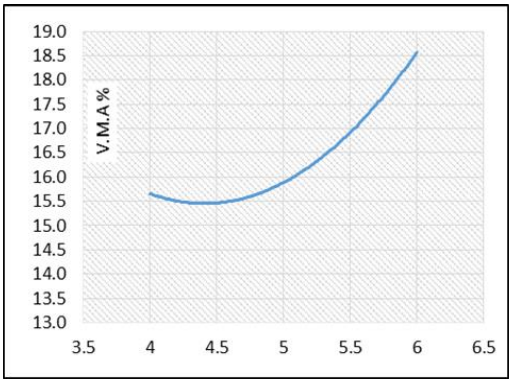

Figure 5: VMA% curve with different bitumen content

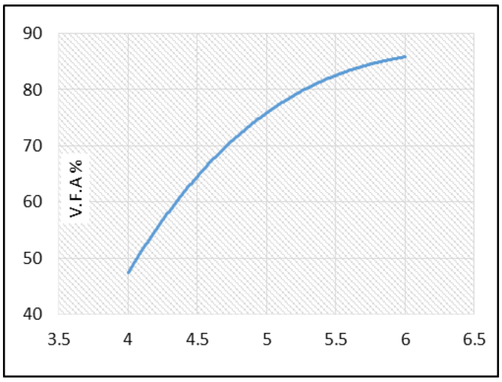

Figure 6: VFA% curve with different bitumen content

The above figures illustrate the variations of various characteristics of the design mix after the addition of steel slag. The above results are determined after conducting Marshall Stability test on the samples made. Figure 1. depicts the variation of bulk density with the different percentages of bitumen content. It represents that the maximum value of bulk density (2.332 gm/cm3) is found at 4.7% of bitumen content in the mix. Figure 2. shows the maximum stability of the samples which was found to be maximum at 4.8% of the bitumen content. Figure 3. illustrates the air voids present in the samples that was found to be 4% as the maximum value at 4.8% of the bitumen content. The air voids are the skeletons formed by coarse aggregates, including the asphalt binder, fine aggregates. The air void plays a role in determining the aggregate interlocking to some extent, and it also can reflect the aggregate compaction. Figure 4 shows that as the content of the bitumen increases in the samples so does their flow. The maximum flow (mm) was found out to be around 3.4 mm at a percentage of 6% of bitumen in the samples. Figure 5. & 6. depict the variation of VMA and VFA with the change in the bitumen content respectively. With the increase in the percentage of the bitumen in the samples, the properties VMA and VFA also change. Though the VMA increase gradually, while the other first increases with increase in the percentage of bitumen with a slight dip in the curve and again an increase towards 6% of the bitumen. VMA represents the space that is available to accommodate the asphalt and the volume of air voids necessary in the mixture while as VFA is the volume of space between the aggregate particles of the compacted paving mixture filled with asphalt binder.

Determining the optimum binder content for the mix design by taking average value of the following three bitumen contents found form the graphs of (bulk density, stability and 4% of Va):

- Maximum value of bulk density (2.332 gm/cm3) = 4.7% of bitumen
- Maximum value of stability (1430 kg) = 4.8 % of bitumen
- Binder content at 4% air void = 4.9% of bitumen

$$Average = \frac{4.7 + 4.8 + 4.9}{3} = 4.8\ \%\ or\ 57.6\ gm\ of\ bitumen$$

Then from the above figures and tables 4.8 % content of bitumen and all the six curves are checked and the values for getting new density, stability, flow, etc. are checked, that whether (bulk specific gravity, stability, Va %, flow, VMA and VFA) are within Marshall Mix design specifications.

Table 7: ASHTTO and ASTM limitations for Marshall Mix design

	standard	limittation	value at 4.8% bitumen
Bulk Density (gm/cm^3)	AASHTO T166	~	2.332
Stability (kg/cm^3)	ASTM D1559 & AASHTO T245	815 Kg/cm^3 Min.	1430.0
Air Voids Va%	AASHTO T209,T283	3→5	4.0
Flow (mm)	ASTM D1559 &AASHTO T245	2→4	2.6
Void in Mineral aggregate VMA%	------------	13 Min.	15.6
Void Fill With Asphalt VFA%	-----------	60→80	72.0

Table 8: Maximum nominal aggregate size with min. requirement of VMA%

Sample No.	Steel Slag		Bulk Density (gm/cm^3)	Avarage	Flow (mm)	Avarage	Stability (Kg)	Avarage	Stability (Kn)
	Ps%	gm							
1	0	0.0	2.334	2.334	2.7	2.6	1381	1430	14.0
2			2.335		2.5		1479		
1	10	5.8	2.334	2.332	2.6	2.5	1345	1359	13.3
2			2.331		2.4		1373		
1	20	11.5	2.336	2.335	2.5	2.55	1446	1476	14.5
2			2.334		2.6		1507		
1	30	17.3	2.338	2.339	2.6	2.5	1595	1573	15.4
2			2.341		2.4		1552		

As its shows above, the values are within standards OBC was determined to be 4.8%.

4. Optimum Binder Content Result for Steel Slag

For finding optimum content of steel slag, two samples were prepared with different steel slag percentages. Then as discussed earlier the same procedure but with the modification of adding steel slag of different percentages (0%, 10%, 20% and 30%) with aggregates and using same percentage of OBC (4.8%) for each content, all the calculations are summarized in following tables.

Table 9: Different content of steel slag with Bulk density, Stability, Flow, VMA% and VMA%

Nominal Maximum Aggregate Size	Min. Requirment of VMA %		
	Va %		
	3.0	4.0	5.0
2.36 mm	19.0	20.0	21.0
4.75 mm	16.0	17.0	18.0
9.50 mm	14.0	15.0	16.0
12.5 mm	13.0	14.0	15.0
19.0 mm	12.0	13.0	14.0
25.0 mm	11.0	12.0	13.0
37.5 mm	10.0	11.0	12.0
50.0 mm	9.5	10.5	11.5
63.0 mm	9.0	10.0	11.0

Table 10: Bulk density, Flow and Stability for different percentages of steel slag

Content %	Content (gm)	Bulk Density (gm/cm^3)	Stability (Kn)	Va %	Flow (mm)	VMA %	VFA %
0%	0	2.334	14.0	4.4	2.6	15.54	72.0
10%	5.8	2.332	13.3	4.38	2.5	15.48	71.3
20%	11.5	2.335	14.5	4.23	2.55	15.37	72.7
30%	17.3	2.339	15.4	3.97	2.5	15.31	73.5

The following figures are formed to specify the optimum steel slag for the mix.

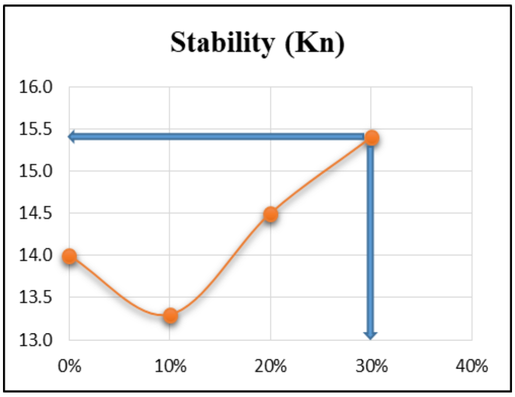

Figure 7: Maximum value of bulk density

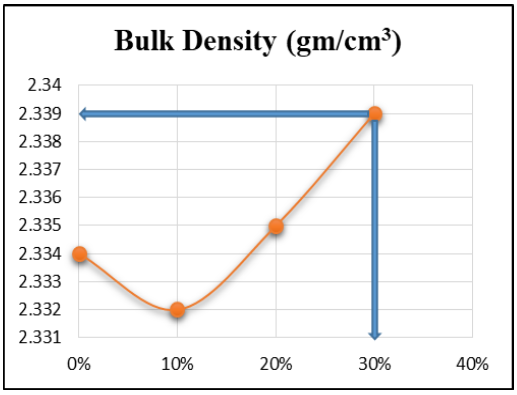

Figure 8: Maximum value of stability

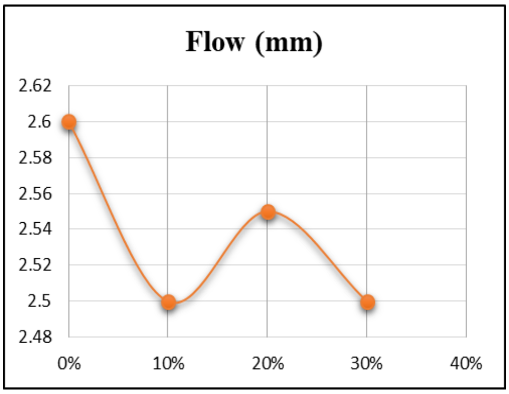

Figure 9: Value of steel slag content at 4% air voids

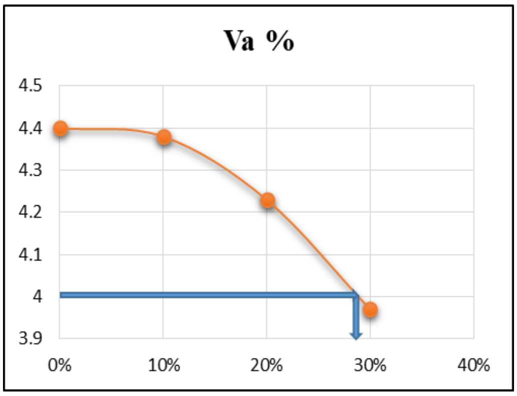

Figure 10: Flow with different steel slag content

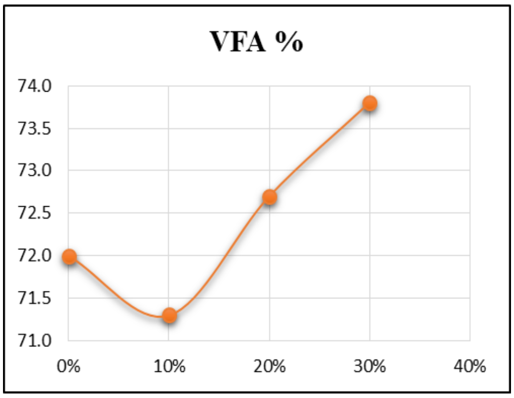

Figure 11. VMA% with different steel slag content

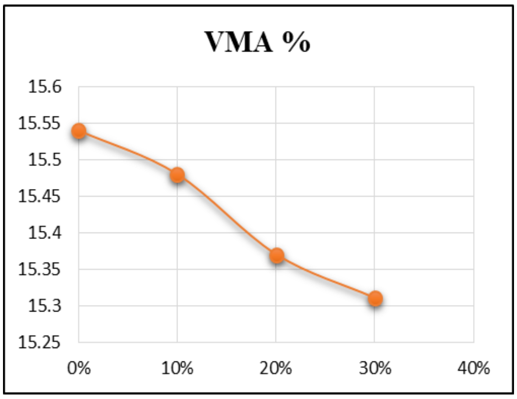

Figure 12: VFA% with different steel slag content

The optimum steel slag content is determined for the mix by taking the average value of the following three steel slag contents originated from the graphs of (bulk density, stability and 4% of Va). The average of optimum steel slag percent in the mix is 29.5%.

Table 11: Mix properties at 29.5 % of steel slag content

	value at 29.5% of steel slag
Bulk Density (gm/cm^3)	2.3388
Stability (Kn)	15.45
Va %	3.98
Flow (mm)	2.503
VMA %	15.32
VFA %	73.75

Checking all values of (bulk specific gravity, stability, Va, flow, VMA and VFA) from the tables above indicates that all the values are within Marshall Mix design specifications.

5. Conclusion

This study is carried out to find (OBC) and investigate the effect of using steel slag added with asphalt concrete mixes. To increase the density, and stability of surface layer with keeping Va% within standard limitations. In addition, this research is used to determine the optimal steel slag ratio. Based on the test results that have been conducted in this research for Marshall samples, before adding steel slag, (4%, 4.5%, 5%, 5.5% and 6%) of bitumen in the total mix of 1200g has been used, for which the Optimum Binder Content was found to be 4.8% or 57.6 gm of bitumen where it was more sufficient for this mixture. Also based on the tests that have been conducted in this research, after adding steel slag by (0%, 10%, 20% and 30%) of bitumen content, it was found that 29.5% or 17gm of steel slag is the optimal steel slag ratio. Analysis and evaluation of the laboratory test data combined with the literature search by increasing the amount of steel slag to the mix, the stability increased, this indicates that adding steel slag to the mixes results in high stability value comparing to conventional mixes with typical flow properties. These high stability and average flow results in a mix, resists rutting when it became cooler. Rutting resistance is a good property for areas subjected to heavy axle load. Due to the hardness and stiffness of the steel slag, it gives good durability to the mix as well as good resistance to weathering.

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