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Enhancement of mechanical properties of the surface pavement layer asphalt mixture using iron filings waste as partially fine aggregate replacement

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Abstract

The surface layer of road pavement is in direct contact with high traffic loads and weather conditions. Therefore, it bears burdens of the impact of traffic loads and weathering. The addition of iron filing wastes improves the properties of the surface layers and works to eliminate their negative effects on the environment. Adding proportions of fine iron filing waste FIFW as a partial substitute for fine aggregate (sand) in the asphalt mixture will improve Marshall stability, Marshall flow, volumetric properties, Marshall stiffness, and pavement water-sensitivity. The findings from this study indicate that adding 30% of FIFW retained on sieve No.50 and No.200 has shown an increase of 29% in the value of Marshall stability, a decrease of 13% in the value of Marshall flow, an increase of 55% in Marshall stiffness and increasing 20% in the index of retained strength when immersed in water. Also, there is a 3% decrease in the percentage of voids filled with asphalts (VFB) and an increase in the actual unit weight of the asphalt mixture. Improving the properties of the surface layer mixture means an increase in stability, durability, and sufficient flexibility.

Key words: Marshall, fine iron filing waste, Marshall stability, Marshall flow

1. Introduction

The main advantages of using low-cost iron filings waste are to improve the properties of the asphalt mixture and the recycling of this waste to reduce its environmental impact. Waste iron filings are mainly iron (Fe) metals so they will not be affected by the mixing temperature of asphalt (about 160 Cº) [1]. Also, the self-healing property will be significantly improved due to the thermal and electrical conductivity of the iron filings waste [2, 5].

Zhu, Cai [6] concluded that the fatigue deformations of iron powder-improved asphalt are less than those of ordinary asphalt. Adding 8% to 12% of iron powder increases the fatigue life by 100% to 150% respectively for asphalt samples at 5Cº compared to the normal samples at similar conditions. Afaf [7] found that when adding percentages of iron slag (0, 10, and 20%) to the total weight of the asphalt mixture, there was an increase in Marshall stability, and a slight increase in indirect tensile stress was also observed when the percentage of iron slag was increased. Eisa [8], [9] used glass fibers and iron fillings of percentages (15, 20, 25, 35, 50, and 75%) by weight of mineral filler in an asphalt mixture as a surface layer and examined its significant improvements on the volumetric properties (VTM%, VFB%, and VMA%). Oluwasola, Hainin [10] and Alimohammadi, Schaefer [11] found out that the use of steel slag and/or copper mine tailings would improve Marshall stability, Marshall flow, and all volumetric properties. The addition was made as a percentage of the total weight of the asphalt mixture and the results were evaluated using an f-test for all design criteria.

Köfteci [12] studied the effect of adding low-cost iron wire fibers to the asphalt mixture using the ratios (1, 3, 5, 7, 9)% of the total weight of the asphalt mix. The results showed that adding 1% to 3% of iron wire fibers would increase the quality of asphalt mixtures with respect to mechanical and physical properties. It also showed that when the percentage of fibers increased by more than 3%, the percentage of air voids increased and the bonds between the bitumen and aggregate weakened. Xu, Wu [13] examined the use of steel slag and steel fibers to replace part of the aggregate in asphalt mixtures. The proportions were 2%, 4%, and 6% by volume of the total mixture, and it was found that the use of steel fibers for the asphalt mixture reduced the effects of moisture and deformations due to high temperatures, but it is not resistant to the effect of water [14]. The self-healing action improved significantly with steel slag but decreased in steel fibers [15].

Yan and Hao [16] studied samples of asphalt mixture with different percentages of steel slag. They also applied indirect tensile, uniaxial compression tests to study crack resistance at low temperatures. Those stress tests were performed on the modified asphalt samples. They found that the addition of furnace slag increases the cohesive strength of the mixture components and thus developing the shear strength in the modified samples compared to the original samples. Arabani and Mirabdolazimi [17] used waste iron filings in the asphalt mixture as percentages of (2.5, 5, 7.5, 10)% to replace the fine aggregate. To follow the self-healing of micro-cracks in cold-modified asphalt concrete [18, 19], the prepared samples were cooled using iron filings to -20Cº and smashed using a fracture tester.

In this way, the samples were placed in the microwave for 90, 120, and 140 seconds. Then, temperatures were recorded and samples were broken using a fracture tester. The results were compared with those of the control mixture. It was concluded that increasing the proportion of iron filings, which are thermally conductive metals, has led to an increase in the temperature of the samples at the specified time. An increase in the fracture resistance value was also observed when the iron filings content was increased. Shafik Jendia, Ramlawi [20] stated that adding steel wool (SW) to asphalt concrete improved Marshall stability, Marshall creep, and the volumetric properties. The (SW) was added as percentages (3.5 and 7) % by weight of the total asphalt mixture to twenty samples. The conductivity of (SW) steel wool has also been studied due to its effect on the self-healing property of asphalt. It was observed that 5% of steel wool has improved the conductivity of the asphalt concrete.

In this work, fine iron filings retained on sieve No. 50 (0.3 mm) and No. 200 (0.075 mm) are used to replace part of the fine aggregate (sand) from the fresh asphalt mixture included in the job mix formula for surface layer mix.

2. Materials and methods

To obtain a good performance of highway pavements, the gradation of aggregates conforming to the standard specifications and the optimum percentage of asphalt must be determined.

2.1 Methodology

Marshall method was adopted to design the hot asphalt mixture, and thus determining stability, flow, and volumetric properties. The main steps of this work methodology were performed as follows by preparing the asphalt mixture materials, such as coarse aggregate, fine aggregate, mineral filler, and bitumen. The aggregates gradations were designed to meet the specifications of surface layer asphalt mixture. Then, Marshall design method is used to select optimum bitumen content and determining the characteristics of the mixture without FIFW (For fresh or control mix). The iron powder was obtained from workshops scraps then sieved to meet the requirements of the asphalt mixture. The addition of fine iron fillings retained on sieve No.50 (0.3 mm) and sieve No.200 (0.075 mm) with 10%, 20%, 30%, 40%, and 50% as a partial replacement of the fine aggregate as reported by job mix formula. Finally, Marshall design method was used to determine new characteristics of each % FIFW.

2.2. Materials

The bitumen was obtained from an Iraqi refinery plant with the properties shown in Table 1 below:

Table 1: Properties of the used bitumen.

Property	Standard (ASTM 2013)	Result	Specification limits
Pent. Grade	ASTM D5-06	46	40/50
Ductility	ASTM D113-99	124	>100
Softening point	ASTM D36-95	56 C^o	35—70 C^o
Flash point, C^o	ASTM D93-05	255	>232
Loss on penetration value (%)	ASTM D5-06	64	>55
Ductility after aging (cm)	ASTM D113-99	78	>25

The mineral filler used is an ordinary Portland cement (OPC) with the following properties presented in Table 2.

Table 2: Properties of the mineral filler.

Sieve size (mm)	% passing
0.6	100
0.3 (No.50)	100
0.075 (No.200)	80
Unit weight	3.0

The gradations of the actual used materials (coarse aggregate, medium aggregate, fine aggregate, coarse sand, river sand, and filler) were performed by the trial and error method [21] to meet limits of specification. These specification limits and aggregate properties are shown in Table 3.

Table 3: Materials gradation of aggregates for surface layer type (III).

Sieve size (mm)	Sieve size in.	% Passing medium coarse aggregate	% Passing fine aggregate	% Passing Coarse sand	% Passing River sand	% Passing mineral filler	Job mix %	ASTM Specifications limits
19	3/4	100	100	100	100	100	100	100
12.5	1/2	77	100	100	100	100	95	90---100
9.5	3/8	24	100	99	99	100	84	76---90
4.75	No.4	5	28	87	87	100	54	44---74
2.36	No.8	0	11	60	77	100	36	28---58
0.3	No.50	0	0	17	54	100	15	5---21
0.075	No.200	0	0	4	1	80	6	4---10
% of mixing		20%	30%	40%	5%	5%	100%	
Abrasion of aggregate		18%	18%					Max. 30%
Unit weight of Coarse Aggregate	2.65							C127-88
Unit weight of Fine Aggregate	2.67							C128-01

The Iron filings are wasted materials obtained from local workshop residues (shown in Fig. 1). Table 4. shows the properties of the fine iron fillings used in the study. It should be noted that the specific gravity of FIFW varies according to the percent of carbons on iron metal.

Fig. 1: Sample of the iron fillings waste used in the study.

Table 4: Properties of fine iron filings waste FIFW.

Sieve size mm	% passing
4.75 (No.4)	100
2.36 (No.8)	99
0.3 (No.50)	49
0.075 (No.200)	10
Unit weight	3.9 --- 7.2

Marshall design method for hot mix asphalt is adopted for selecting optimum asphalt content and aggregate gradation to justify the maximum actual unit weight, maximum Marshall stability, and Marshall flow within the specification limits. The volumetric properties (VTM, VMA, VFB) within specifications limits [21, 22], were also evaluated according to Marshall mix design method. The asphalt mixture prepared for this study followed the job mix formula specifications [23, 24] as listed in Table 5.

Table 5: Job mix formula for asphalt surface layer (type III).

Sieve size (mm)	% Job mix	Job mix limits	Specifications (ASTM)
19	100	100	100
12.5	95	90---100	90---100
9.5	84	78---90	76---90
4.75	54	48---60	44---74
2.36	36	32---40	28---58
0.3	15	11---19	5---21
0.075	6	4---8	4---10
%AC	5	4.7---5.3	4---6

Fifteen Marshall samples were prepared following the job mix formula procedure shown in Table 5. According to the limits of %AC presented in the specifications of surface layer type (III), three samples have been compacted on a special Marshall mold (4-inch diameter, 4.5-inch height) with 4%, 4.5%, 5%, 5.5%, 6% of bitumen, respectively. Each Marshall sample weighed 1200 gm after mixing aggregates with bitumen as listed in the job mix formula. The mixing temperature is 160C^{o} and the materials were compacted with 75 blows on each end of the mold by using Marshall hammer 10 Ib dropping from 18 inch height [21, 22].

Marshall sample unit weight is calculated by using water balance at 25C^{o} as in Eq. 1.

$$\text{Act. Gm} = W_{air} / (W_{S.D} - W_{W}) \tag{1}$$

Where:

Act. Gm: is the actual unit weight of asphalt mix.

W_{air}: is the weight of sample in air, gm.

$W_{S.D}$: is the weight of sample saturated with water and surface dried in air, gm.

W_{W}: is the weight of sample in water, gm.

Maximum theoretical specific gravity for the new asphalt mixture is determined according to AASHTO T 209 Eq. 2 . Vacuum pressure is used to remove air voids from loose mixture at 25 C^{o} [25].

$$\text{Max.Gm} = A/(A+D-E) \tag{2}$$

Where,

Max.Gm: is the maximum theoretical specific gravity.

A: is the weight of the oven-dried sample in air, gm.

D: is the weight of over plate and flask filled with water at 25 C^{o}, gm.

E: is the weight of flask, cover plate, sample, and water at 25 C^{o}, gm.

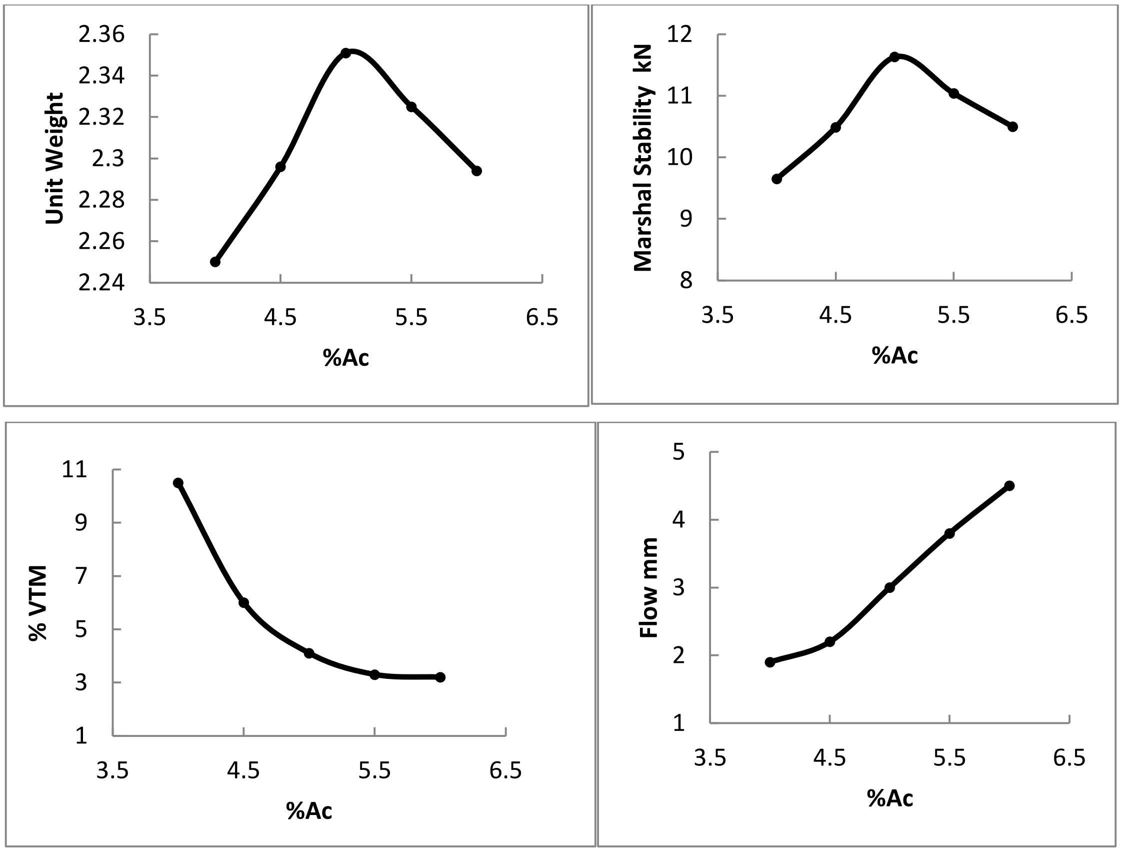
Volumetric analysis for Marshal samples with %AC to calculate %VTM , %VMA , %VFB ,% absorbed asphalt, and % effective asphalt. Marshall apparatus is used to determine Marshall stability and Marshall flow. Correction is made for Marshall stability if the sample height was not equal to 63.5 mm. Marshall stiffness is calculated as the ratio of stability to flow at 60Cº [21, 22]. The results of these calculations for the original and test mixtures are presented in Tables 6 &Table 7 and the graphs of the results are shown in Fig. 2.

Table 6: Marshal results for asphalt surface layer type (III).

AC%	Ave. Actual unit weight	Ave. corrected Stability (kN)	Flow (mm)	%V.T.M	%V.F.B	%V.M.A	MS
4	2.250	9.65	1.9	10.5	66	16	5
4.5	2.296	10.49	2.2	6	73	15.4	4.76
5	2.351	11.63	3	4.1	77.0	14.5	3.87
5.5	2.325	11.04	3.8	3.3	80	15.3	2.9
6	2.294	10.5	4.5	3.2	83.5	16.7	2.33

Table 7: Characteristics of control surface asphalt mixture.

AC%	Unit weight	Stability(kN))	Flow(mm)	%VFB	%VTM	%VMA	MS (kN/mm))
5%	2.351	11.63	3	77	4.1	14.5	3.87
Specification	-	>9	2---4	70---85	3---5	12---16	-



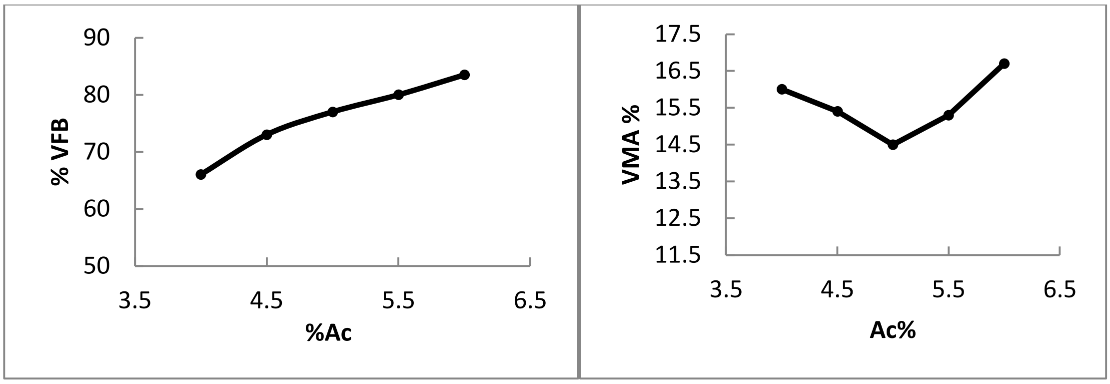


Fig. 2: Graphs of Marshall test properties results.

After the addition of fine iron filings waste FIFW, Fifteen Marshall samples were made to perform new tests. Fine iron filings retained on sieve No.50 (0.3mm) and sieve NO.200 (0.075 mm) were added to each Marshall sample as a percent of the total mix. Three Marshall samples are prepared for each suggested proportion of fine iron powder waste (FIFW) 10%, 20%, 30%, 40%, and 50%, respectively. Table 8. shows the replacement of FIFW weights of each size of Marshall specimens.

Table 8: Replacement of FIFW weights of each size of Marshall specimens.

Sieve size (mm)	% passing	% Retained	10% of FIFW weight in gm	20% of FIFW weight in gm	30% of FIFW weight in gm	40% of FIFW weight in gm	50% of FIFW weight in gm
19	100	0	0	0	0	0	0
12.5	95	5	57	57	57	57	57
9.5	84	11	125.4	125.4	125.4	125.4	125.4
4.75	54	30	342	342	342	342	342
2.36	36	18	205.2	205.2	205.2	205.2	205.2
0.3	15	21	(215.4+24)	(191.4+48)	(167.4+72)	(143.4+96)	(119.4+120)
0.075	6	9	(92.3+10.3)	(82.1+20.5)	(71.9+30.7)	(61.6+41)	(51.3+51.3)
Cement		6	68.4	68.4	68.4	68.4	68.4
AC%	5	5	60	60	60	60	60
∑			1200	1200	1200	1200	1200

Marshall properties for each proportion (10%, 20%, 30%, 40%, 50%) are computed by the same procedures followed in samples without FIFW presented above. Index of retained strength was also computed using Eq. 3 to determine asphalt mix water sensitivity. Twelve samples of 4-inch diameter and 4-inch height are compacted (two sample for each percent of FIFW 0%,10%,20%,30%,40%,50%) .

$$\text{Index of retained strength} = P_{wet} / P_{dry} * 100\% \quad (3)$$

Where,

P_{wet} : is the load computed at failure by compressive strength machine for sample submerged for 24hrs in water, kN.

P_{dry}: is the load computed at failure by compressive strength machine for dry sample, kN.

New Marshall results for surface layer type (III) for each FIFW are shown in Table.9.

Table 9: New Marshall results for surface layer type (III) after FIFW addition.

FIFW %	Actual Density gm/cm^3	Ave. corrected Stability (kN)	Flow (mm)	%V.T.M	Max. Gm	%V.F.B	%V.M.A	M.S	Index of retained strength%
0	2.351	11.63	3	4.1	2.451	77.0	14.5	3.87	80
10	2.360	12.1	2.9	3.8	2.458	74.8	15	4.31	83

20	2.369	13.7	2.7	3.9	2.465	74.7	15.3	4.73	86
30	2.375	15.0	2.6	4.2	2.476	74.6	15.8	6.00	90
40	2.386	16.1	2.3	4.6	2.490	73.3	16	7.68	92
50	2.392	17.5	1.9	5.5	2.507	72	16.4	9.74	95

3. Results and discussions

3.1 Effect of FIFW on unit weight

There is a noted increase in the density or unit weight of pavement surface layer type when adding fine iron filings because they fill the air voids as well as due to the high unit weight of fine iron filings. Unit weight should stay within a reasonable value and does not reduce the asphalt mix flexibility. From the results obtained after the addition of fine iron powder, the unit weight of asphalt mix is 2.375 at 30% of fine iron filings waste which could be an acceptable value. Fig.3 shows the effect of fine iron filings on unit weight.

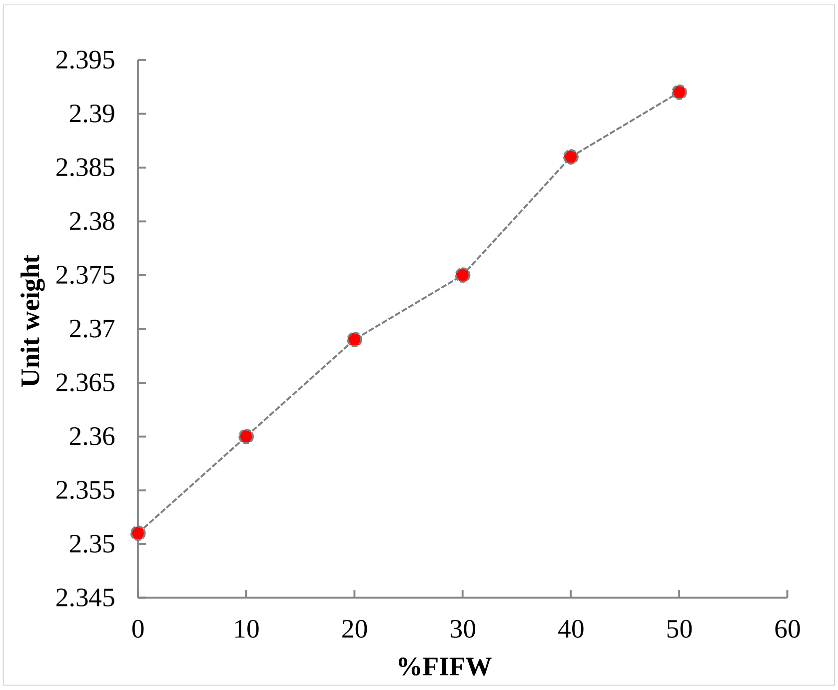


Fig.3: Effect of FIFW on unit weight

Increasing the %FIFW by more than 30% would produce a high-density asphalt mixture with higher unit weight. This can result in reducing the air voids necessary for asphalt mix flexibility during mixing and compaction, which can decrease the asphalt resistance to traffic loads.

3.2 Effect of FIFW on air voids (VTM%)

Fig.4 presents the results of air voids after the addition of fine iron filings. It can be seen that there is no significant change in the air voids until 30% of FIFW. This could result from the replacement of the same particle size with the fine aggregate so the air voids stay at 4.2%, which keeps them near the mid specification value. However, when adding higher percentages of FIFW content, the air voids will increase.

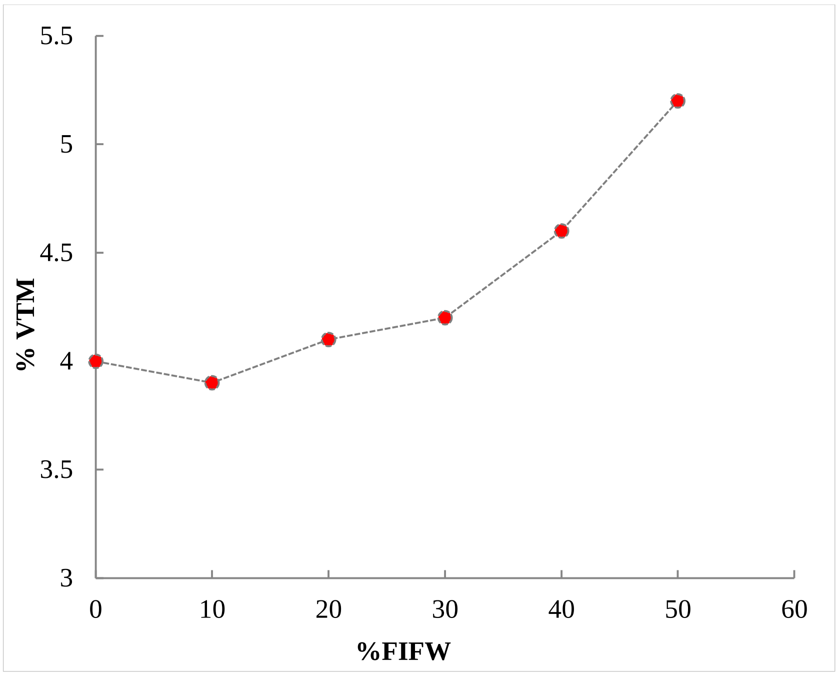


Fig.4: Effect of FIFW on air voids (VTM%)

Rounded-extended shape and roughly surface texture cause increasing on VTM% when increasing FIFW%.

3.3 Effect of FIFW on Marshall stability

Fig.5 shows that Marshall stability increases as the content of FIFW increases. It can be noticed that at the proportion of 30% FIFW, there is about a 29% increase in Marshall stability compared to that of the control mixture. Due to the good bond between iron filings and bitumen, an excessive percentage of FIFW content will affect the flexibility of new asphalt mixtures.

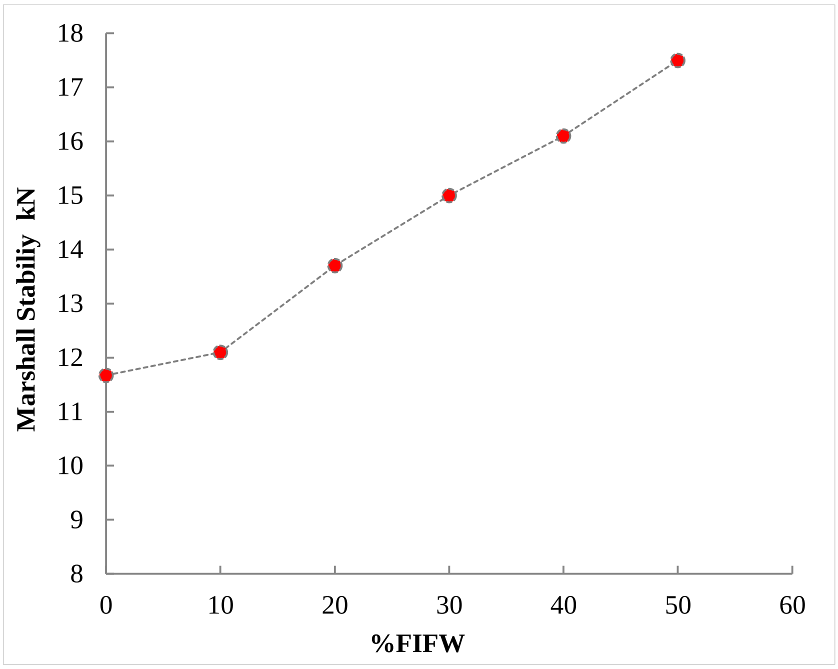


Fig.5: Effect of FIFW on Marshall stability.

One of the main reasons for increasing the Marshall stability is the cohesion between bitumen and FIFW particles. This allows the bitumen to intervene between these particles increasing the contact point, which also requires more bitumen to fill the voids. This enhanced bond between bitumen and the FIFW would increase the tensile strength of the asphalt, thus preventing rutting.

3.4 Effect of FIFW on Marshall flow

The value of Marshall flow decreases with increasing FIFW content due to the increase of fine particles in the asphalt mixture. Results presented in Fig.6 show that at 30% of FIFW content, Marshall flow value decreases about 13% compared to control asphalt mixture. An excessive reduction of Marshall flow might affect pavement flexibility under traffic loads.

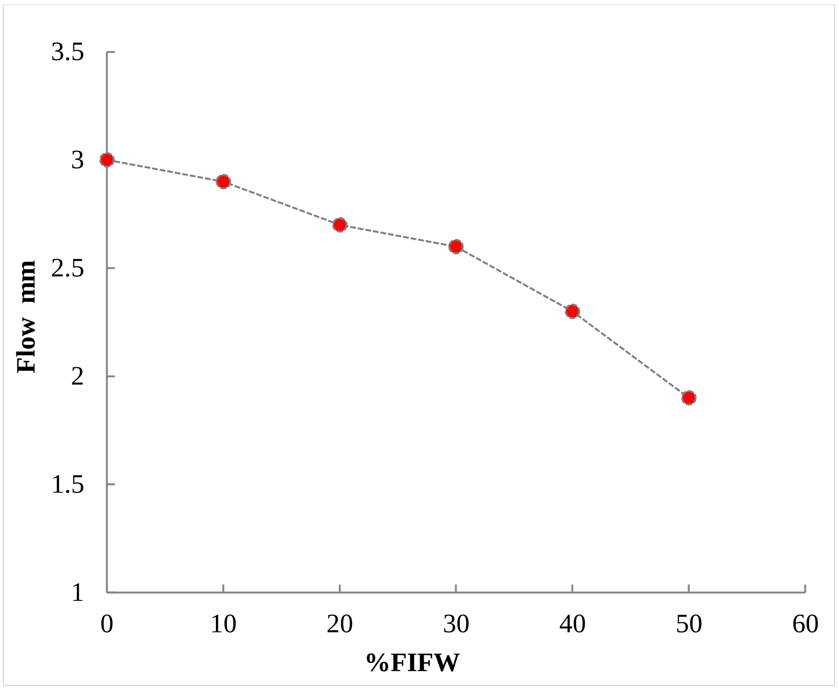


Fig.6: Effect of FIFW on Marshall flow

Marshall specimens with FIFW show higher resistance to flow than specimens without FIFW. This could result from the enhanced bond between FIFW and bitumen which can eventually increase the bond strength between bitumen and aggregate.

3.5 Effect of FIFW on Marshall stiffness(MS)

Marshall stiffness increases with the increase of FIFW content because of the high Marshall stability and lower Marshall flow. Asphalt mixture should present a reasonable Marshall stiffness to be flexible during mixing and compaction. The results show that a 30% of FIFW content could lead to a 55% increase in Marshall stiffness. Fig.7 shows the effect of FIFW on Marshall stiffness (MS).

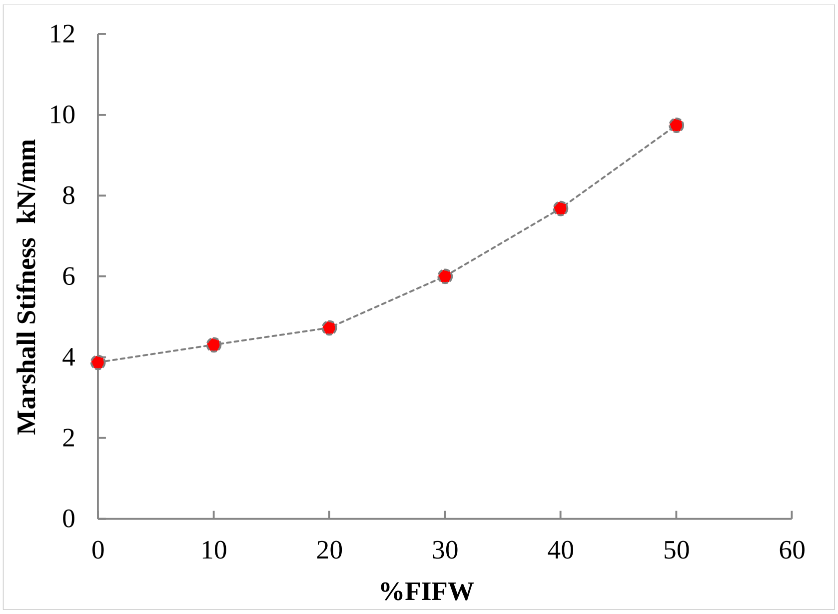


Fig.7: Effect of FIFW on Marshall stiffness (MS)

Marshall stiffness must be within a value that allows the mix to be flexible and easily compactable to reach the design density. This value of Marshall stiffness seems to be achieved when adding 30% of FIFW.

3.6 Effect of FIFW on VFB%

The percentage of voids filled with binder (bitumen) VFB% in the fresh asphalt mixture was 77%, after adding 30% FIFW content, it was noted that this value decreased by 3%. This could explain the insignificant effect of FIFW on %VFB compared to its effect on the other properties mentioned in the previous sections. Fig.8 shows the effect of FIFW on VFB%.

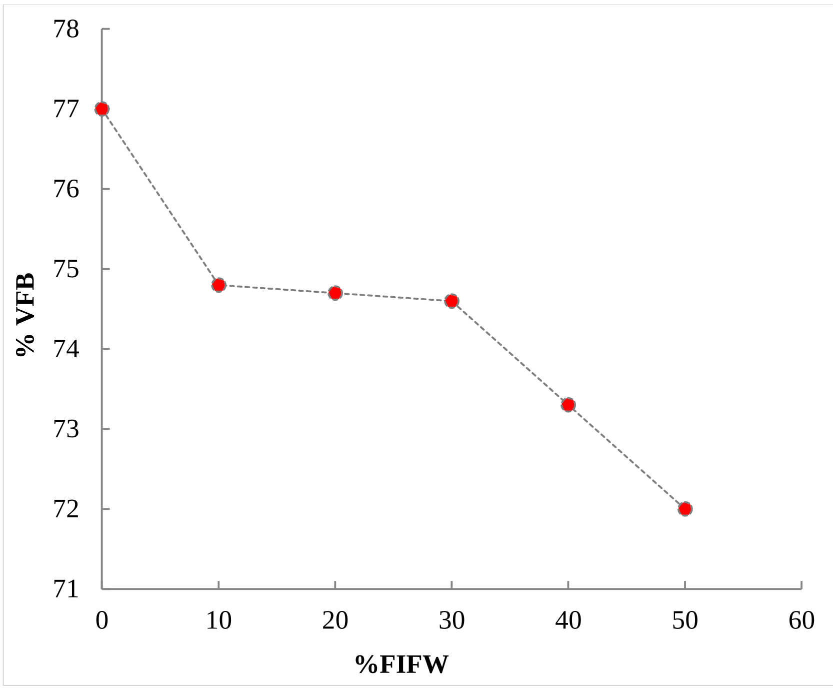


Fig.8: Effect of FIFW on VFB%

It can be seen that the effect of higher percentages of FIFW (more than 30%) is influencing the %VFB due to the roughness of the surface of the particles. With constant bitumen content, the %VFB is decreasing with increasing %FIFW. It is noticed that the %VFB almost remains 75% with %FIFW at 10% to 30%. This also confirms the suitable content of %FIFW that should not exceed 30%.

3.7 Effect of FIFW on the index of retained strength (water sensitivity)

The index of retained strength of compacted asphalt mixture increased by 12.5% compared to that of the control mix when adding 30% of FIFW content. Fig. 9 shows that any addition of FIFW higher than 30% by weight of the total mix will increase the index of retained strength but with the possibility of a negative effect on other properties.

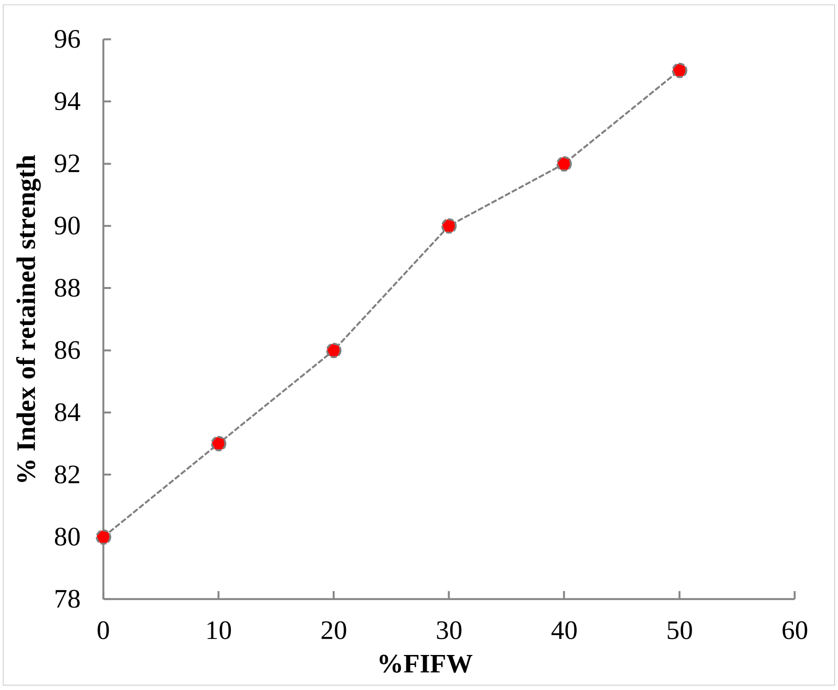


Fig. 9: Effect of FIFW on the index of retained strength

Immersing Marshall specimens in water after 24 hrs., it was noticed that specimens with FIFW presented less susceptibility to the water and still maintaining the strength to fracture. This increase in strength continues, although increasing the %FIFW would lead to a reaction between air and the iron particles performing patches of rust on the asphalt surface.

4. Conclusions

From the presented results and discussions of this research, the following conclusions can be drawn:

- The addition of fine iron filing wastes can improve the stability of the surface asphalt mixture and increase its resistance to traffic loads because of the strong bonds between bitumen and the particles of fine iron filings.
- Adding 30% of FIFW could lead to a decrease in Marshall flow. This increased Marshall stiffness without affecting pavement flexibility.
- Voids filled with bitumen (VFB) and voids in mineral aggregate (VMA) remained within the specification limits after adding FIFW to the asphalt mixture.
- Using iron filings retained on sieve No.50 (0.3 mm) and No.200 (0.075 mm) will not affect the optimum air voids (VTM), which is related to the percentage of minerals filler in the mix. In this way, the sizes of iron filings have no obvious effect on the roughness of the pavement surface layer. This could mean that this type of hard additives (fine iron filings waste) is not affected by the high temperature of mixing in asphalt plants.
- The addition of fine iron filings waste increased the durability of the pavement surface layer because of the increase of the index of retained strength, which means reducing the water action.
- The optimum use of iron filings waste is 30% of fine-size FIFW. This results from the low percentage of iron powder and abnormality shapes of large sizes in iron filings waste. Using 30% of FIFW (8.5% of total mix) can recycle a large amount of iron filings waste, which could have a positive effect on the environment.
- This type of modified surface layer of road pavement could be used in parking areas and approaches to intersections and checkpoint stations.

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