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The Effect of Using Steel Fibers on the Performance of Asphalt Mixtures

Mohamed Fahmy[1], Saad A. Elhamrawy[2] and Ahmed E. Abu El-Maaty[2]

[1] *Ph.D. Candidate, Department of Civil Engineering, Menoufia University, Egypt.*
[2.] *Department of Civil Engineering, Menoufia University, Egypt.*
(Corresponding author: Mohamed.abousaba8@gmail.com)

ABSTRACT

According to the problems that face the Egyptian highway system, a significant portion of the roads face long-term wear, creep, and rutting of the asphalt layers. These distresses may be occurred due to the shortage in the mechanistic properties of either of the binder and/or the asphalt mixtures as well as the increasing of traffic loads. In order to avoid earlier damage and failure, this study compares steel fiber-modified hot mix asphalt mixtures with standard mix to examine how well they function. An experimental programme was designed and put into place to achieve this goal. Six HMA combinations were tested, including control mixtures, with steel fiber contents of 0.25%, 0.5%, 0.75%, 1%, 1.25%, and 1.5 % by weight to the aggregate of HMA. In this study, the steel fibers were chosen as additive in hot asphalt mixtures for its good tensile strength, durability, ductility, stiffness and flexural properties. In addition, the interface between steel fiber and asphalt concrete has a high bonding strength. Performance of the different hot asphalt mixes was evaluated using the Marshall and ITS tests. The scope of the study included studying the performance of both unmodified and modified mixtures by steel fibers. The results of the investigations indicated that the addition of 1% steel fiber by aggregate weight improved the Marshall stability, flow, Marshall quotient, volumetric properties and the indirect tensile strength. The results also indicated that the addition of steel fiber did not improve the moisture susceptibility for all conditioning periods compared with control mixtures.

Keywords: *Steel Fiber (SF); Hot Mix Asphalt (HMA); Marshall Stability; Marshall Quotient; indirect tensile strength (ITS)*

1. Introduction

Significant attention has been paid to asphalt modification and strengthening as workable ways to improve the performance of flexible pavement. This technology's introduction into the transportation sector was primarily motivated by the traditional road materials' subpar performance when subjected to sudden surges in traffic and pattern changes, a necessity that still continues. Since then, numerous forms of modifiers for asphalt mix have been taken into consideration, with fibers being one of them [1]. Numerous fibers and fiber materials, including steel fiber, polyester fiber, asbestos fiber, glass fiber, polypropylene fiber, carbon fiber, cellulose fiber, etc., have been introduced and are still being introduced to the market as novel uses [2]. To enhance the performance of pavements, fibers have been used into asphalt mixtures. Previous studies have documented the reinforcing properties of fiber in asphalt mixes and pavements. In particular for open-graded friction courses (OGFC) and stone-mastic-asphalt (SMA) combinations during material transportation and paving, fiber can stabilize asphalts to reduce asphalt leaks [2], [3], and [4].Fiber decreases pavement and asphalt mixture reflective cracking [5, 6].The main purposes of fiber reinforcement in bituminous mixes are to increase the bituminous mix's strain energy absorption in order to prevent the formation and spread of cracks that could compromise the structural integrity of the road pavement and to add additional tensile strength to the composite that results. The notion was based on the basic premise that reinforcement might be utilized to give the necessary resistance to tensile stresses if HMA is strong in compression and weak in tension. Steel fiber also functions as steel in asphalt concrete, enhancing its anti-rutting properties and extending the lifespan of the asphalt pavement [7], [8]. Although there are many other types of fibers, including glass, synthetic, steel, natural, organic, and inorganic fibers. Steel fibers are the most common in the building sector. The wire was split or cut into the necessary lengths. The primary fibers had rounded, incredibly smooth forms.

Modern steel fibers are currently produced from drawn steel wire, cut sheet steel, or the melt-extraction process, which produces fibers with a crescent-shaped section and are now utilized commercially [9]. After being disconnected and cleaned, raw materials like thin scrap and old steel wire rope are chopped into a type of long fiber called steel fiber. Steel fibers are divided into two categories, regular carbon steel fiber and stainless-steel fiber, depending on the material quality; normal carbon steel fiber makes up the majority. Steel fiber is categorized into five different shapes, including long straight, corrugated, hook-shaped, head-shaped, and twisted styles. Steel fiber is categorized into cutting style, shearing style, milling style, and melt extraction based on the configuration of the section. The main characteristics that set it apart from other fibers are their resilience, resistance to rutting and cracking, and their positive tensile effects [9]. Finally, the main objective of this study is resolving the early damage of asphalt pavement by adding steel fibers to modify and improve the characteristics of asphalt mixtures.

1.2 Literature review

Recently, some studies on the usage of steel fiber in hot asphalt mixtures were carried out. By adding electrically conductive steel and wool fibers to the asphalt mix and activating self-healing by induction heating, Garzia et al. (2009) [10] and Liu et al. (2010) [24] started the development of a self-healing asphalt pavement mix. Liu et al. (2010) [11] produced conductive porous asphalt concrete samples and performed indirect tension testing in order to assess the reinforcing effects. Three different kinds of steel fibers were the subject of a study by Liu et al. (2011) [12]. Steel fibers with a small diameter and a longer length performed better than steel fibers with a large diameter and a shorter length because the fiber-to-fiber contact was better in the first case, which resulted in increased conductivity. The impact of fibers in asphalt concrete mixtures was studied by Serin et al. (2012) [13]. Because fiber additions have a favorable effect on stability, the study came to the conclusion that steel fibers can be utilized in the binder layer of flexible pavements. According to the results, 0.75 % fiber should be used in weights to have the best results. In order to make a porous asphalt mixture electrically conductive and suited for induction heating, steel fibers were added, according to Liu et al. (2013) [14].They came to the conclusion that induction heating enhanced the porous asphalt concrete's capacity to heal based on the strength recovery, stiffness recovery, and fatigue life extension of porous asphalt. A study on the impact of steel fibers on the performance of hot mix asphalt with a 5 % asphalt content at various temperatures and levels of compaction was carried out by Al-Ridha et al. (2014) [15]. According to the test results, it is advised to utilize steel fibers in the binder course and other layers beneath the surface layer in quantities less than or equal to 0.2 percent. Steel fibers were utilized by Guo (2014) [9] to enhance the mechanical characteristics of asphalt concrete. Tests such the freeze-thaw splitting test, low temperature bending test, and rutting test were performed. Additionally, experiments were done comparing the water stability of steel fiber asphalt concrete with regular asphalt concrete as well as the stability of mixtures in high temperature and low temperature. The results showed that adding steel fibers into asphalt concrete might greatly enhance the functionality of the road surface. The cracking resistance of an asphalt concrete reinforced with steel fibers at low temperatures was researched by Park et al. (2015) [16].Regarding aspect ratio (length/diameter), section type, and texture, a great number of steel fiber variables were taken into account. At -20°C, the resulting asphalt mixtures were tested for indirect tensile strength, and the result showed that the fiber addition enhanced the asphalt concrete's indirect tensile strength and toughness. The assessed qualities benefited from the length of the fibers. When the fiber length or diameter was less than 6 mm or 0.01 mm, no reinforcing effects were seen. The toughness of the mixture was not significantly increased by the use of hook-ended or twisted fibers. However, twisted steel fibers with a diameter of 0.3 mm and a length of 30 mm showed the highest results with a toughness improvement of 895%. Steel fiber behavior in asphalt mixtures must be assessed at high temperatures because it was temperature-dependent. The effect of steel wool fiber diameter and length on dense asphalt concrete was studied by Garca et al. (2015) [17]. Following the mixing and compaction operations, a decrease in the fiber length was observed because the fibers had been subjected to shear, tensile stress, and impacts during the mixing phase. Large-diameter fibers showed a less dramatic shortening of their length. Using long fibers (7 mm) as opposed to short ones (2.5 mm) increased the chances of clustering. In mixtures with long fibers, the average cluster percentage was 0.41 %, compared to 0.35 % in mixtures with short fibers. The voids in the mixture were effected with the percentage of clusters. A greater number of voids is implied by a higher percentage of clusters. As a result, asphalt mixes with long fibers showed increased porosity, which affected the resistance to particle loss. In general, particle loss might be impacted by the fact that fibers are not evenly distributed. The addition of steel fibers with a 0.5–1.5 volume percent content, 0.1–0.4 mm diameter, and 6–30 mm length considerably increased the low temperature cracking resistance of asphalt concrete, as shown by Park et al. (2015) [16]. Steel fibers were used in varied amounts (2 %t, 2.5 %, 3 %, 4 %, and 5 %) with 11 mm and 18 mm lengths, as illustrated by Aniruddh and Parveen Berwal (2016) [18]. The results indicated that bituminous concrete's durability significantly improved with 3.5 % steel fiber content with 11mm length. An improvement in the low-temperature and fatigue performance of asphalt mixture was reported. Through single steel fiber pullout tests, Park et al. (2017) [19] studied the interaction between steel fiber and the asphalt mixture and discovered that steel fiber may improve the indirect tensile strength and toughness of asphalt concrete. The steel wool fiber, sometimes referred to as steel fiber with a finer diameter, was shown by He et al. (2017) [20] to be helpful for enhancing the particle loss resistance and flexural strength of dense asphalt concrete. The aggregate grade and bitumen content in the mixture should be controlled to prevent high air voids created by the fiber clusters since steel wool fibers, in contrast to steel fiber, tend to cluster. Sevil Kofteci, (2018) [21] conducted an experimental study using low-cost iron wire that was 6 to 10 mm and 1 mm in diameter in five various contents (1 %, 3 %, 5 %, 7 %, and 9 %) by weight of aggregate. The results showed that adding inexpensive iron fibers to asphalt mixtures in amounts ranging from 1% to 3% increased performance. Steel grit and steel wool improved the indirect tensile strength and moisture susceptibility of porous asphalt mixtures, according to Gonzalez et al. (2018) [22].The mixture stiffened and had more resistant to fatigue cracking at the same time. Very long steel fibers and high contents, according to Tabakovi'c et al. (2019) [23], may cause cluster formation. Furthermore, poor mixing may also lead to clusters. Kureshi et al. (2019) [24] mixed steel fibers to asphalt concrete in different percentages (0.1 %, 0.3 %, and 0.5 % by total volume of mixture). With an increase in pavement performance, surface thickness could be reduced by up to 25% or 30%, resulting in a reduction in overall pavement maintenance expenses. Long-ridged steel fiber was found to produce the best results, however dense bituminous mixtures perform better with an addition of 0.3 % fiber content. Mohammed et al. (2020) [25] demonstrated that the addition of steel fibers increased the stiffness of asphalt mixtures and improved low temperature cracking resistance. Improved fatigue life and a larger rise in indirect tensile strength were obtained by adding 2 % steel fibers to the asphalt mixture. Du, Yinfei, et al. (2021) [26] suggested using steel fiber with a curved hook content of 1.0 %. The results indicated that the deformation resistance decreased when steel fibers were added.

2. MATERIALS AND TESTING

2-1 Experimental Programme

The design experimental program is shown in Figure (1). It consists of three phases. The first phase is defining and selecting materials, while the second phase is HMA mixtures preparation. The third phase is laboratory tests.

2.2 Steel Fiber (SF)

Steel fiber obtained from Chemicals for Modern Building Company (CMB) was used. It was obtained with its attachments (Data Sheet). The Characteristics of the used SF are shown in Table (1). Figure (2) shows SF shape.

Table (1) Characteristics of the Used Steel Fiber

Descriptions	Length (mm)	Thickness (mm)	Density (kg/m³)	Tensile Strength (N/mm²)	Designation Code
Corrugated	50	0.25	7850	Minimum 700	ASTM A820

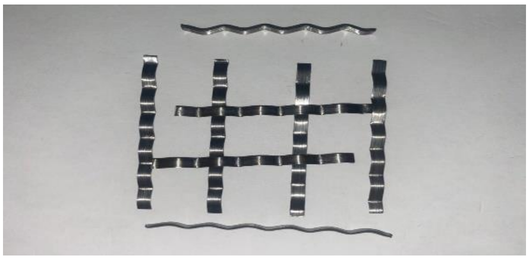

Figure (2): Steel Fiber Shape

2-3 Asphalt Binder

In this study, the asphalt cement was obtained from Suez City. Egypt uses asphalt cement with a grade of 60/70 and a specific gravity of 1.02 for the construction of roadways. Asphalt consistency property tests are conducted, and the results are listed in Table (2).

Table (2) characteristic of Bitumen

Test Name	Result	Egyptian specification [107]	Designation Code
Penetration, mm 0.1	65	70/60	AASHTO T (49)
Softening point, 0C	51	55/45	AASHTO T (53)
Flash point, 0C	270+	250+	AASHTO T (48)
Specific gravity	1.033	-------	ASTM D 70

2-4 Aggregates

Dolomite crushed stones were used as coarse and fine aggregates in this investigation. Table (3) displays the physical characteristics of the aggregates that were used. The aggregate gradation utilized in asphalt mixtures is shown in Table (4). According to the Egyptian roads code, the gradation blending meets the requirements of the HMA type (3D).

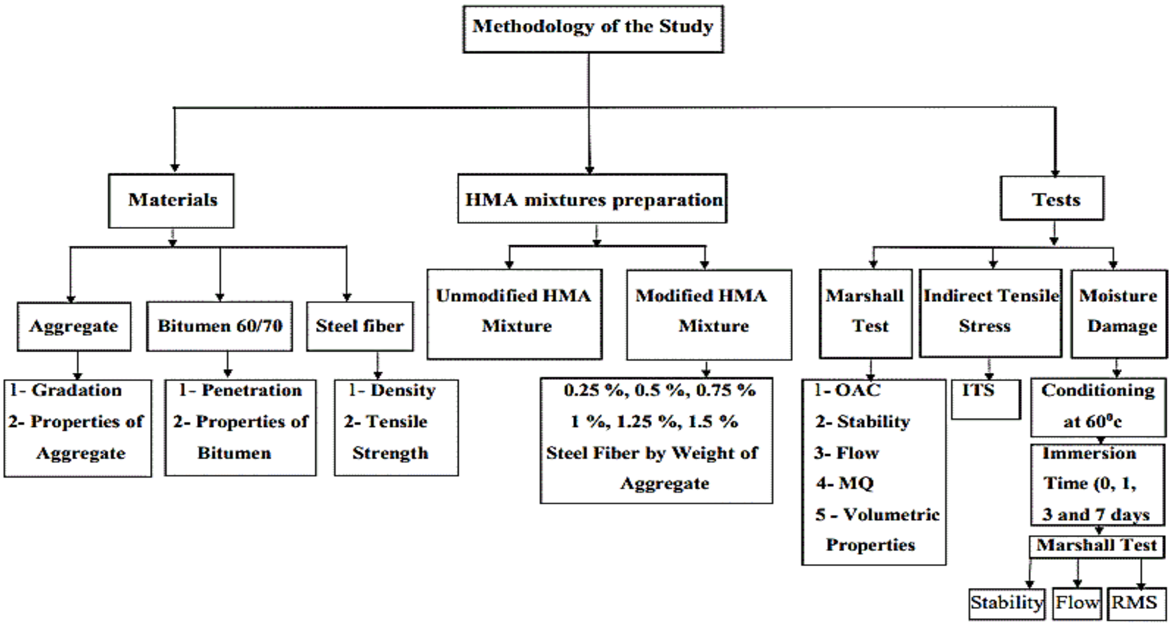

Figure (1): Experimental Programme

Table (3) Aggregates Properties

Test Name	Coarse Aggregate Size (1)	Coarse Aggregate Size (2)	Fine Aggregate	Egyptian Limits [107]
Abrasion After 100 cycle%	5	5	------	≤ %8
Abrasion After 50 cycle%	27	26	------	≤ %35
Volume specific gravity	2.697	2.715	2.69	-------
Apparent specific gravity	2.805	2.798	2.78	-------
(%) Water absorption	2.3	1.9	1.8	≤ %5
Soundness of aggregate	1.	0.2	------	≤ %1
(%) Normal index	3	3	------	≤ %8
(%) Flakiness index	5	4	------	≤ %15

Table (4) Aggregate gradation

sieve size mm	Aggregate (Grade 1)		Aggregate (Grade2)		crushed sand		Natural sand		Design gradient	Egyptian Limitations [107]
	Passing	%35	Passing	%30	Passing	%30	Passing	%5		
25	100	35	100	30	100	30	100	5	100	100
19	100	35	93	27.9	100	30	100	5	97.9	100/75
12.5	100	35	33	9.9	100	30	100	5	79.9	----
9.5	87	30.5	3	0.9	100	30	100	5	66.4	70/45
4.75	7	2.5	0	0	98	29.4	100	5	36.9	50/30
2.38	2.1	0.7	0	0	91	27.3	98	4.9	32.9	35/20
1.19	1.5	0.5	----	----	65	19.5	86	4.3	24.3	----
595.	1.2	0.5	----	----	44	13.2	63	3.2	16.9	20/5
0.297	1	0.4	----	----	24	7.2	29	1.5	9.1	12/3
0.149	0.8	0.3	----	----	14	4.2	8.6	0.4	4.9	8/2
0.075	0.7	0.2	----	----	9.4	7.8	4.4	0.2	3.2	4/0

2-5 Marshall Tests

In this study, the Marshall design method according to Egyptian code [28] and AASHTO T 245 standard [29] is utilized to determine the properties of asphalt mixes. The required asphalt cement (60/70) is estimated and the aggregates (coarse and fine) are prepared. The Marshall test method is used to evaluate the optimal asphalt content (OAC), which achieves the highest stability, highest density, and 5.5 % AV. Control mix are prepared by blending the selected aggregates with 4%, 4.5%, 5%, 5.5%, 6% percentages of asphalt cement by weight of total mix. The determined value for the optimum asphalt content was (4.7%).By using modified asphalt with the specified (OAC) and adding various amounts of SF (0.25, 0.5, 0.75,1, 1.25, and 1.5 %) by weight of aggregate, similar sets of modified test specimens are produced. Marshall tests on modified mix specimens are used to determine the characteristics of modified hot mix asphalt. Figure (3) shows HMA that modified with steel fibers during preparation.

Figure (3): Modified HMA Preparation

2-6 Indirect Tensile Strength (ITS) Test

The ITS test involves compressively loading a cylindrical specimen parallel to and along the vertical diametrical plane, according to AASHTO (T322-03) [30].A rather consistent tensile tension perpendicular to the direction of the applied load emerges under this loading condition. Due of its tensile strength, the specimen ruptures or splits along the vertical diameter before failing. ITS values (St) are computed utilizing the following equation: St = 2P/ (HD), (kg/cm2), where P is the applied force in kg, H is the specimen's height in cm, and D is its diameter in cm.

3. RESULTS AND DISCUSSIONS

3-1 Effect of Adding SF on Marshall Stability

Figure (4) shows the Marshall stability for hot asphalt mixtures reinforced with different contents of steel fibers (SF) at optimum asphalt content. It can be illustrated that the Marshall stability increases by increasing SF percentages up to 1% and then it decreases. The non-homogeneous distribution of steel fibers in the asphalt mixtures, particularly at larger SF contents, may be the cause of these decreases. At high fiber contents, mixture stability reduced because fibers caused clustering in the mixture, which may result in lost interaction between aggregate particles. The maximum stability occurs at 1% SF, the stability increases from 1042 to 1950 kg which represents about 87.52%.

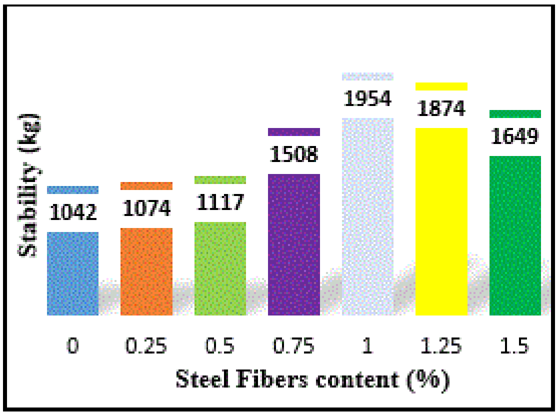

Figure (4) Effect of Steel Fibers on the Marshall Stability

3-2 Effect of Adding SF on Marshall Flow

Figures (5) provides the Marshall flow for HMA mixtures at different steel fibers (SF) percentages at the OAC. It can be showed that the addition of steel fibers decreases the Marshall flow compared to control mixture due to clustering except at 1% steel fiber content where the Marshall flow was as the same as unmodified mixture. Moreover, it can be observed that the flow values matching with the required Egyptian specification range (2-4) mm.

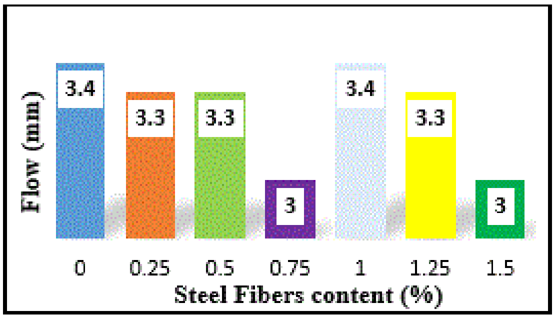

Figure (5) Effect of Steel Fibers on the Marshall Flow

3-3 Effect of Adding SF on Marshall quotient

Marshall quotient (stiffness) is calculated by dividing the Marshall stability by the flow value in kg/mm. Figure (6) shows the HMA mixtures stiffness for all studied steel fibers percentages at OAC. It can be said that the Marshall quotient rises as the SF percentage rises up to 1% before significantly declining after that. Additionally, it is noted that for all values of SF, the stiffness values for the modified mixes are higher than those of the unmodified mix. The Marshall quotient value achieved the highest increase at 1% steel fiber content by about (87.52%).

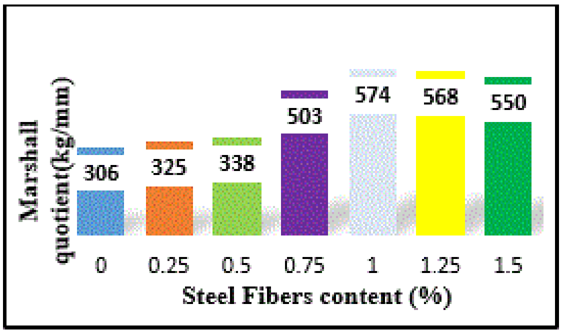

Figure (6) Effect of Steel Fibers on the Marshall Quotient

3-4 Effect of Adding SF on Theoretical Specific Gravity (Gmm)

Figure (7) illustrates the effect of steel fibers addition on the theoretical specific gravity (Gmm) for each mixture. It is observed that all modified mixes provide lower (Gmm) compared with the control mix except MIX-1-SF, which has the same value.

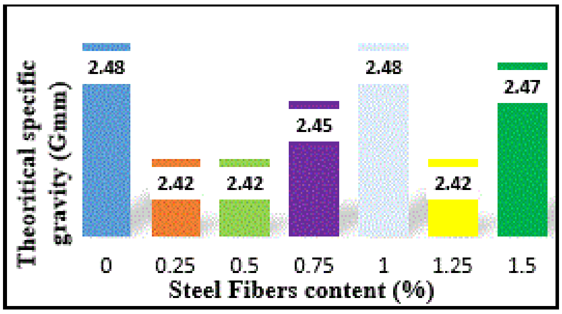

Figure (7) Effect of Steel Fibers on the Theoretical Specific Gravity

3-5 Effect of Adding SF on Bulk Specific Gravity (Gmb)

Figure (8) illustrates the effect of steel fibers on bulk specific gravity (Gmb) for each mixtures. It can observed that the all modified mixes provide lower (Gmb) compared with control mix.

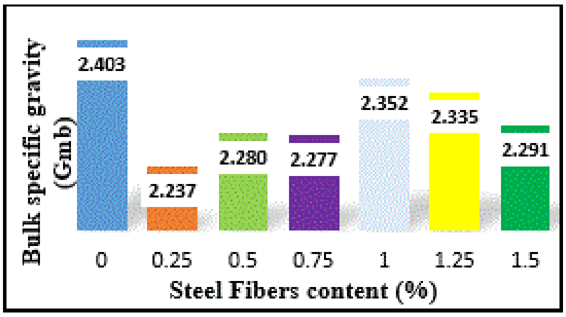

Figure (8) Effect of Steel Fibers on the Bulk Specific Gravity

3-6 Effect of Adding SF on AV %

Figure (9) illustrates the effect of steel fibers on the percentage air voids (AV %) for each mixtures. It can indicated that all modified mixes provide higher air voids compared with the control mix. According to Egyptian specifications [28], the air void ratio for the binder course should be between 3% and 8 %. All air void ratios for all samples are within acceptable limits. Compressing the mixes gets harder when fiber content rises due to the increase in air void values.

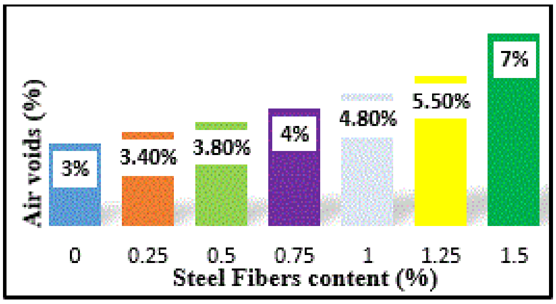

Figure (9) Effect of Steel Fibers on the Percentage of Air Voids

3-7 Effect of Adding SF on VMA %

Figure (10) shows the effect of steel fibers on the percentage of voids in mineral aggregate (VMA %) for each the mixtures. It can observed that all modified mixes provide higher voids in mineral aggregate with compared to the control mix. In order to obtain enough durable and stable mixtures, VMA% value should be not less than 13% for binder course according to Egyptian specification [28].

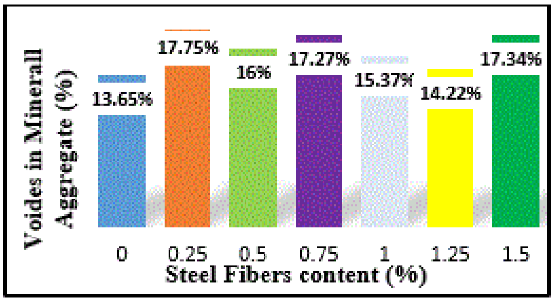

Figure (10) Effect of Steel Fibers on the Percentage of Voids in Mineral Aggregate

3-8 Effect of Adding SF on VFB %

The impact of steel fibers on the percentage of voids filled with bitumen (VFB %) for each mixture is shown in Figure (11).It can be demonstrated that when the fiber content of the mixture increases, the number of voids filled with bitumen decreases because the bitumen content of the mixture becomes insufficient to cover the increased voids. For the binder course, voids filled with bitumen should vary from 70% to 80%, as stated in the Egyptian standard [28].

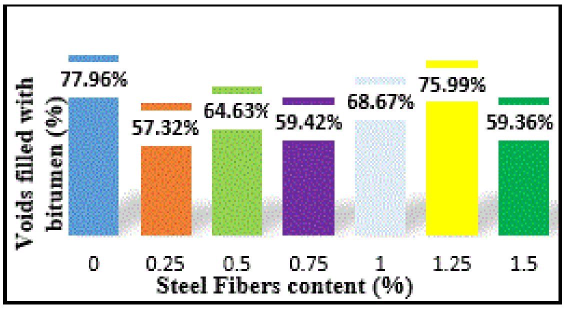

Figure (11) Effect of Steel Fibers on the Percentage of Voids Filled with Bitumen

3-9 Effect of Adding SF on ITS Value

The results of the ITS test for control and modified specimens are shown in Figure (12).The addition of SF makes the modified mix denser and more load resistant. The modified specimen's cementation action raises the ITS value. It is discovered that adding 1% SF to the asphalt mix causes the value of ITS to rise from 7.19 kg/cm2 to 11.09 kg/cm2, or a 54.2 % improvement.

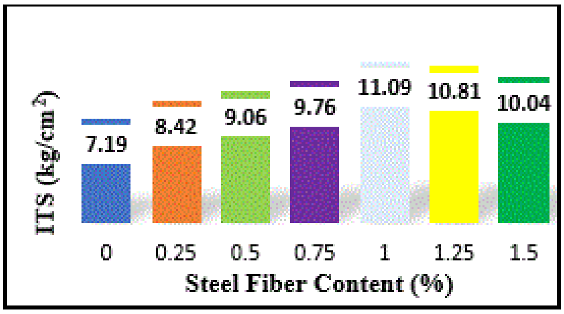

Figure (12) Indirect Tensile Strength values for the Each Additive Content

3.10. Moisture Damage Results According to Marshall Test

To study the effect of moisture conditioning on Marshall stability, flow and retained Marshall stability, the hot asphalt mixtures were soaked in hot water for 1,3,7 days at 600c. According to the previous results, the ratio of 1% steel fiber was chosen to investigate the resistance of modified HMA mixtures to moisture damage. The Marshall stabilities and flows for unmodified (control) mixture as well as modified mixture by 1% steel fiber, after being soaked in hot water for 0,1,3,7 days at 60°C are given in Table (5).

For Marshall stability , the modified mixtures by 1% steel fiber content provide obvious effect on increasing the stability values as shown in Figure (13) compared with un modified mixtures at all conditioning periods (1,3,7) days. Table (5) shows the effect of conditioning on Marshall stability, flow and retained Marshall stability.

Table (5) Effect of Conditioning on Marshall Stability, Flow and Retained Marshall Stability

Mixture Type	Condition period (days)	Stability (kg)	Decreasing In Stability Compared With Unmodified (%) Mixtures	Flow (mm)	Increasing In flow Compared With Unmodified Mixtures (%)	Retained Marshall stability (% RMS)
Unmodified Mixture	Unconditioned Mixture	1065	0	3.9	0	100
	1	830	22	4.2	7.7	77.93
	3	730	31.4	4.6	17.9	68.54
	7	694	34.8	5	28.2	65.16
Modified Mixture With 1% SF	Unconditioned Mixture	1879	0	3	0	100
	1	1371	27	3.9	30	72.96
	3	1179	37.2	4.4	46.6	62.74
	7	1132	39.7	4.8	60	60.24

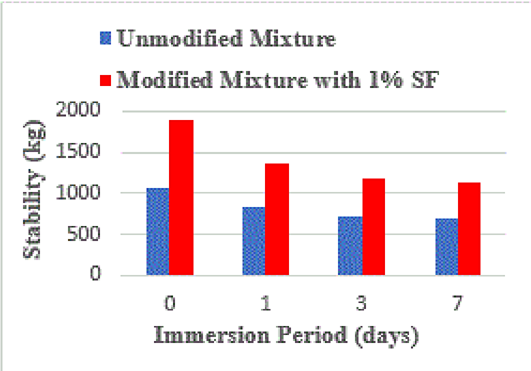

Figure (13) Effect of Conditioning on Marshall Stability

Table (5) shows the decreasing ratios in stability values compared with unconditioned mixtures for both modified and unmodified mixtures at all condition periods (1,3,7) days. With increasing the condition period, the modified mixtures provide lower performance where the decreasing ratios in stability values for modified mixtures are slightly higher than them for unmodified mixtures by about 5% at the same condition period. Thus, it can be concluded that the modification using 1% steel fiber decreases the resistance of HMA to moisture damage according to the decreasing ratio in stability values.

For Marshall flow, the modified mixtures by 1% steel fiber content decrease the flow values at all condition periods compared with unmodified mixtures as shown in Figure (14). Table (5) illustrates the increasing ratio in flow values compared with unmodified mixtures for both modified and unmodified mixtures at all condition periods. With increasing the condition period, the modified mixtures provide lower performance where the increasing ratios in flow values for modified mixtures are obviously higher than them for unmodified mixtures. Thus, it can be concluded that the modification using 1% SF decreases the resistance of HMA to moisture damage according to the increasing ratios in flow values.

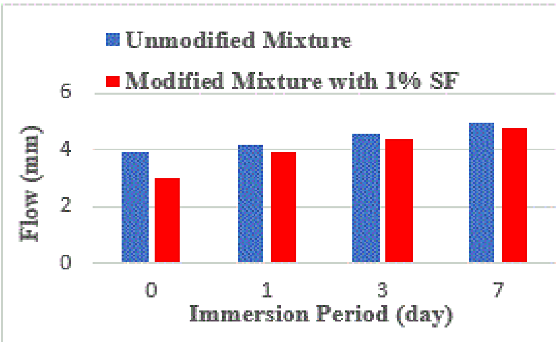

Figure (14) Effect of Conditioning on Marshall Flow

The index of retained Marshall stability (RMS) can be used to measure the resistance of HMA mixtures to moisture damage. As shown in Table (4-11) and Figure (15), it can be obtained that the RMS values slightly decrease with increasing condition period for both modified and unmodified mixtures. The average of RMS reduction values for 1, 3 and 7 days were 77.93%, 68.54% and 65.16% respectively for unmodified mixture and 72.96%, 62.74% and 60.24% respectively for modified mixture with 1% steel fiber. Thus, it can be obtained that the modification using 1% SF decreases the resistance of HMA mixtures to moisture damage according to the decreasing in retained Marshall stability values by about 5% compared with unmodified mixtures at the same condition period.

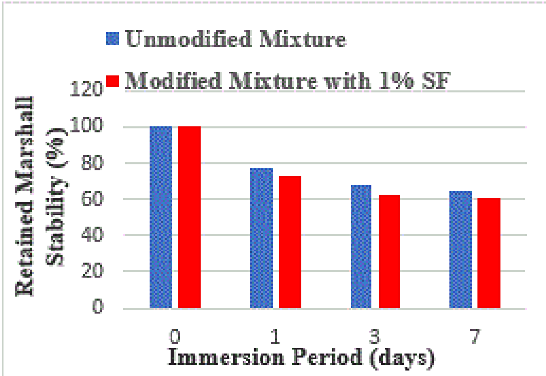

Figure (15) Effect of conditioning on Retained Marshall Stability

3.11. Cost Analysis of Manufacturing the Investigated Mixes

Using asphalt concrete mixtures modified by 1% steel fibers increases the production cost by about 38.28% while there is an increase in the Marshall quotient (MQ) values and stiffness of the modified mixtures, thus this increase in cost can be accepted due to increasing the life of pavement, where the maintenance cost will be decreased during future life of pavement. It recommended to use other types of steel fiber that are less expensive such as factory feathers and iron tie wire.

4. Conclusions

Based on the results obtained from this study, the following conclusions can be drawn:

1. The addition of steel fibers increased Marshall stability by about 87.52% at 1% steel fiber content which considered the best performance stability among modified mixtures with steel fibers.
2. The addition of steel fibers decreased the Marshall flow compared to control mixture by reason of clustering except at 1% steel fiber content which provided flow value as same as control mixture. This flow value that reached to (3.4mm) was matched with the required specifications ranges

and indicated the high flexibility of HMA pavement to deform without cracking.

3. The addition of steel fibers increased Marshall quotient by about 87.58% at 1% steel fiber content. This means that the mixtures gained additional stiffness with the addition of steel fibers. Thus, it provided better strength against permanent deformation.
4. The addition of steel fibers using 1% steel fibers achieved acceptable volumetric properties according to specification ranges.
5. The maximum value was obtained at 1% steel fiber content by raising ratio by about 54.2 % in comparison to control mixtures, indicating that the inclusion of steel fibers had a significant impact on improving the indirect tensile strength.
6. Modified mixture using 1% steel fiber decreases the resistance of HMA to moisture damage according to the decreasing in retained Marshall stability values by about 5% compared with unmodified mixtures at the same condition period.
7. Using asphalt concrete mixtures modified by 1% steel fibers increased the production cost by about 38.28% while there was an increase in the Marshall quotient (MQ) values and stiffness of the modified mixtures, thus this increase in cost can be accepted due to increasing the life of pavement, where the maintenance cost will be decreased during future life of pavement.

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