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Assessment Resistance Potential to Moisture Damage and Rutting for HMA Mixtures Reinforced by Steel Fibers

Ahmed Abbas Saleem [a*], Mohammed Qadir Ismael [b]

[a] *M.Sc. Student, Department of Civil Engineering, Baghdad University, Baghdad, 10071, Iraq.*

[b] *Assistant Professor, Department of Civil Engineering, Baghdad University, Baghdad, 10071, Iraq.*

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Abstract

Rutting is mainly referring to pavement permanent deformation, it is a major problem for flexible pavement and it is a complicated process and highly observed along with many segments of asphalt pavement in Iraq. The occurrence of this defect is related to several variables such as elevated temperatures and high wheel loads. Studying effective methods to reduce rutting distress is of great significance for providing a safe and along-life road. The asphalt mixture used to be modified by adding different types of additives. The addition of additives typically excesses stiffness, improves temperature susceptibility, and reduces moisture sensitivity. For this work, steel fibres have been used for modifying asphalt mixture as they incorporated in the specimens by three percentages designated as 0.5, 1.0 and 1.5 % by the weight of asphalt mixture. The evaluation process based on conducting Marshall Test, Compressive strength test, and the wheel tracking test. The optimum asphalt content was determined for asphalt mixture. The results of the Marshall quotient and the index of retained strength of modified mixtures were increased by 44.0 and 17.38% respectively with adding 1.0% of steel fibres compared with the conventional mixture. The rut depth and dynamic stability were determined by using a wheel tracking test at two various testing temperatures of 45 and 55°C and two applied stresses of 70 and 80 psi. Results show that adding 1% of steel fibres to asphalt mixtures is very effective in increase the rutting resistance and reduce moisture damage.

Keywords: Rutting Resistance; Moisture Damage; Dynamic Stability; Steel Fibers; Wheel Tracking Test.

1. Introduction

Rutting was a major problem for flexible paving. It is a longitudinal depression in the wheel paths of the roadways, Rutting is the most common is pavement permanent deformations due to repetitive loads of traffic that accumulation of small permanent strains of pavement materials after passing each axle load after a certain time. The design of the asphalt pavement is aimed to calculate the thickness of the pavement layers required to carry repeated loads safely under environmental conditions without significant deformation depend on the properties of the materials used in asphalt pavement layers [1]. The most important properties of the materials used in flexible pavement construction are a cost-effective influence to project specifications. Many factors should be considered to quality control procedures such as long economic life, environmental sustainability, low construction and repair time, low maintenance costs, use of waste materials [1, 2].

The asphalt pavement may be modified by adding various types of additives. The addition of additives normally improves the stiffness and increase temperature susceptibility. The increase of stiffness leads to improve the rutting

* Corresponding author: a.fadhil1101@coeng.uobaghdad.edu.iq

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resistance of the asphalt pavement in the high-temperature weather and allows the use of comparatively flexible asphalt [3]. Despite many uses of fibers, which use in asphalt pavement construction as an asphalt mixture additive is a new field of study [4].

Fibers have provided high modulus, durability, resistance, and deformation resistance for asphalt pavement, and hence with more tensile resistance [5]. Also, fibers have been used as reinforcement of polymer mixtures to be used in other manufactures [6, 7]. These fibers provide the composites with strength and stiffness, therefore, allowing the mixture to better transfer the loads between fibers. Also, the addition of fibers in asphalt mix improves the mixture properties and contributes to sustainability by reducing road maintenance and extending its service life. Using fibers improves the mechanical performance of asphalt mixture, and fibers reinforce hot mix asphalt through a tridimensional network and improving the adhesion in the mix [8].

Mohammed et al. (2020) showed that adding steel fibers increased asphalt mixtures stiffness and presented an improvement in low temperature cracking resistance. Modifying asphalt mixture by 2% of steel fibers leads to improve fatigue life and a higher increase in indirect tensile strength [9]. Kureshi et al. (2019) modified asphalt concrete properties by using steel fibers, the surface thickness can be decreased by up to 25 or 30% with the improve in pavement performance, so, reducing total pavement maintenance costs. That observed the long-ridged steel fiber better results in the parameter chosen and an addition of 0.3% of fibers content improves the performance of dense Bituminous mixtures [10].

Çetin (2014) showed that using Low Carbon Structure Fibers (LCSF) to reinforce asphalt hot mixtures showed acceptable performance in both wearing and binder course [11]. Guo (2014) evaluated the dynamic stability of the asphalt concrete modified by steel fibers at various temperatures, the test uses 1, 2, 3 and 4 % of steel fibers mixing, concludes that adding 2 % of steel fibers to asphalt concrete will significantly improve asphalt pavement performance [12].

Aniruddh and Berwal (2016) studied the efficiency of asphalt concrete Mixtures modified with steel fibers in different quantities (2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5 and 6%) with a length of 18 mm and 11 mm were tested during the conduct of the Marshall stability test for control and modified mixtures, The results presented that a higher improvement in the stability of asphalt mixture was at the optimum percent of added steel fibers for asphalt mixture at 3.5% of 11 mm length steel fiber. so, this fibers content was suggested for the improvement of the bituminous mix parameters [13].

Köfteci (2018) used different amounts of Iron Wire fibers (1%, 3%, 5%, 7%, and 9%) to reach the optimum fibers amount, the results of the investigations show that adding low-cost iron fibers by 3% improve the efficiency of asphalt mixtures [14]. Al-Kaissi et al. (2017) noticed that adding steel fibers to asphalt mixture improved the rutting resistance and modified the asphalt mixture with 0.2 % of steel fibers increased the dynamic stability about 6.4 % compared with the conventional mixture [15].

This research aims to evaluate the efficiency of using steel fibers for enhancement of asphalt mixtures prepared with locally available materials to resist rut occurrence of wearing course in flexible pavement depending on two temperatures and two stresses compared with conventional asphalt mixture and determined the moisture damage by finding the index of retained strength.

2. Materials and Methods

The locally available materials were selected to reach this work and that is economically beneficial. Asphalt cement AC (40-50), aggregate (coarse, fine), and filler were used. The steel fibers were used in this work as an additive, four asphalt concrete mixtures have been prepared in this work for wearing course layer (the conventional mixture and the asphalt mixtures modified by 0.5, 1 and 1.5 % of steel fibers).

The research methods were involved three stages, the first stage included Marshall test to find Optimum Asphalt Content and Marshall quotient, the second stage covered the evaluation of the compressive strength to calculate Index of Retained Strength (IRS), and the third stage included wheel tracking test to calculate the rutting depth and dynamic stability for asphalt mixtures.

2.1. Asphalt

AC (40-50) is the most commonly used in pavement construction in Iraq. It brought from Al-Daurh refinery. The results of asphalt binder tests according to the SCRB (2003) [16]. Table 1 shows asphalt cement physical properties.

Table 1. Asphalt cement physical properties

Test	Units	Results	SCRB 2003 Specification Limits	ASTM Specification No.
Penetration, (25 ºC, 100 g, 5 sec)	1/10 mm	47	40 – 50	D-5
Ductility, (25 ºC, 5 cm/min)	cm	135	≥ 100	D-113
Kinematic Viscosity at 135 ºC	cSt	405	–	D-2170
Softening point (Ring & Ball)	ºC	50	–	D-36
Flash Point (Cleveland Open Cup)	ºC	270	232 min.	D-92
Specific gravity at 25 ºC	–	1.04	–	D-70
After Thin-Film Oven Test (ASTM D 1754)				
Retained Penetration of Residue, (25 ºC, 100 gm, 5 sec)	%	60	55 (Min)	D 5
Ductility, (25 ºC, 5 cm/min)	cm	82	> 25	D-113

2.2. Aggregates

Coarse crushed aggregate was used and obtained from Al-Nibaie quarry. Coarse aggregate sizes range for wearing course is between 12.5 mm and No.4 sieve (4.75 mm). Fine aggregate was bought from a local source (particle size between No.4 and No. 200). Laboratory evaluation described the basic properties of the aggregate. The results are presented in Table 2 according to the specification limit (SCRB, 2003) [16].

Table 2. Coarse and fine aggregate physical properties

Property	ASTM Specification No.	Result	SCRB Specification Limits
Coarse aggregate			
Bulk Specific Gravity	C-127	2.579	---
Apparent Specific Gravity	C-127	2.601	---
Percent of Water Absorption	C-127	0.54	---
Percent of Wear (loss angels' abrasion)	C-131	15.79	30 Max
Fine aggregate			
Bulk Specific Gravity	C-128	2.61	---
Apparent Specific Gravity	C-128	2.632	---
Percent of Water Absorption	C-128	0.952	---

2.3. Mineral Filler

Limestone dust was used for preparing asphalt concrete mixture in this work. The filler which passes through sieve opening (0.075 mm). Filler was bought from the lime factory, Karbala, Iraq. The mineral filler physical properties are shown in Table 3.

Table 3. Mineral filler physical properties

Property	Result
Passing No.200, (%)	95
Specific gravity	2.71

2.4. Additives (Steel Fibers)

The steel fibers used were straight steel fibers bought from the Jingjiang Hongtu steel fiber factory, china. Each steel fiber is about 0.56 mm in diameter and about 30.1 mm length. Table 4 shows the physical properties, and Figure 1 shows the straight steel fibers used in this work.

Table 4. Steel fibers physical properties

Description	Straight
Length, (mm)	30.1
Diameter, (mm)	0.56
Density, (Kg/m^3)	720.6
Tensile Strength Fu, (MPa)	1185
Aspect Ratio	54
Price, ($/Ton)	1000

Figure 1. Straight steel fibers

2.5. Selection of Aggregate and Filler Gradation

Aggregate and filler gradation were selected according to the specification of the (SCRB, 2003) [16], with a nominal maximum size 12.5 (mm), the gradation was selected (wearing course type IIIA). Selected aggregate gradation is showed in Table 5 and Figure 2.

Table 5. Selected gradation (12.5 mm nominal maximum size, wearing course type IIIA) (SCRB, 2003)

English Sieve	Sieve opening, (mm)	Passing by Weight, (%)	
		Selected gradation, (%)	Specification range, (%)
3/4"	19	100	100
1/2"	12.5	95	90-100
3/8"	9.5	83	76-90
No. 4	4.75	59	44-74
No. 8	2.36	43	28-58
No. 50	0.3	13	5-21
No. 200	0.075	7	4-10

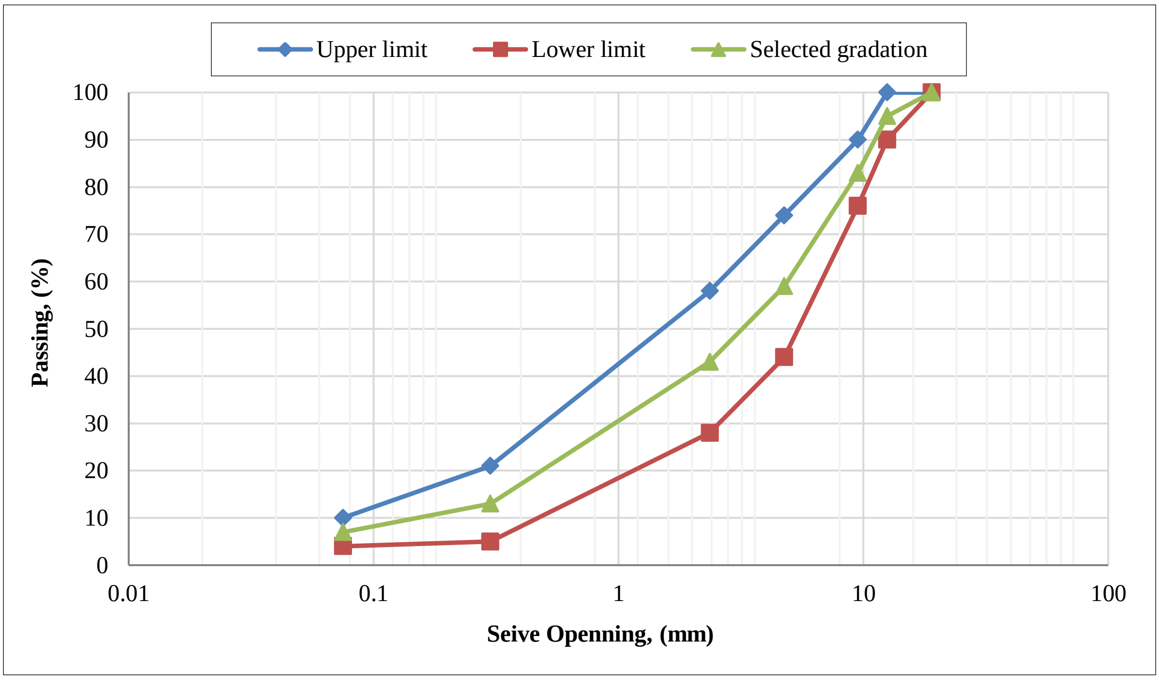

Figure 2. Selected gradation and specification limits for wearing course (12.5 mm nominal maximum size) [16]

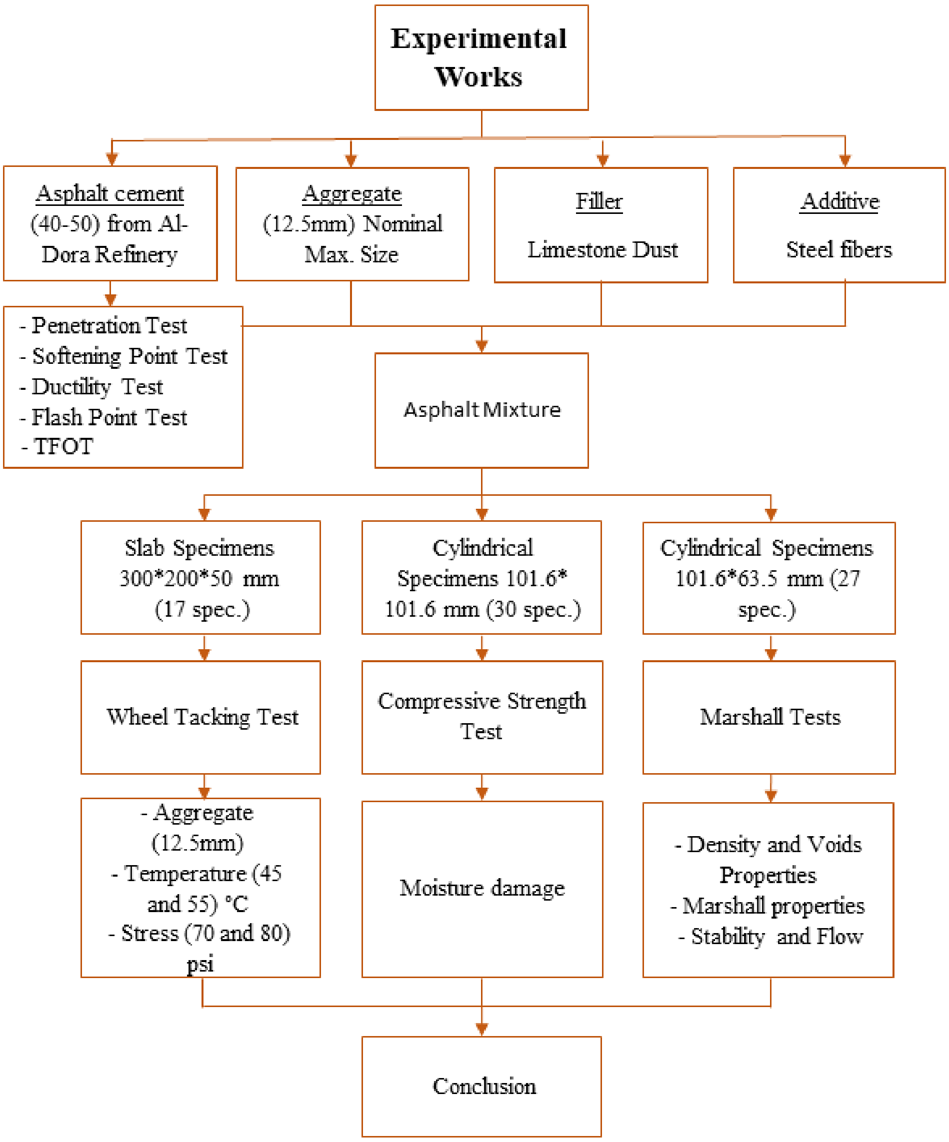

Figure 3. The work program flow chart

2.6. Marshall Test

Calculated the bulk specific gravity and density according to the procedure (ASTM D2726-08) [17], Theoretical (maximum) specific gravity was conducted to the procedure (ASTM D2041-03) [17], and the percent of air voids according to the procedure (ASTM D3203-05) [17] for each specimen. Stability and flow values were calculated for all specimens according to the procedure (ASTM D6927-04) [17] and then calculate the Marshall quotient for all mixtures. The percent of air voids have been determined from equation 1 below:

$$Air\ Voids, (\%) = \left(1 - \frac{Bulk\ SG}{Max.\ theoretical\ SG}\right) \times 100 \tag{1}$$

2.7. Preparation of Conventional and Modified Mixture

The aggregate was sieved for every single size, then blended with filler to reach the desirable gradation for wearing course type IIIA according to the (SCRB, 2003) [16]. Heated the combined aggregate to temperature 155 °C at the same time asphalt was being heated to temperature 163 °C as the upper limit for (40-50) penetration grade. Then, asphalt binder was added with knowing quantity to the heated combined aggregate to reach the required quantity, finally, they mixed about (2 min) until the combined aggregate was coated with asphalt binder.

The preparation of modified mixture with steel fibers differs from a virgin mixture through the amount of additive steel fibers that are added by the total weight of mix as percentage 0.5, 1 and 1.5 % steel fibers that added to the asphalt mixture at temperature 155 °C and mixed about two minutes until the combined aggregate and steel fibers were coated with asphalt cement, Figure 4 presents a group of Marshall specimens.

Figure 4. Group of Marshall Specimens

2.8. Compressive Strength Test

The compressive strength test followed (ASTM D1074-17) [17] procedure. The compressive strength is the capacity of pavement materials to resist axially directed compressive forces. The compressive strength is one of the very important factors determining its suitability for use under the given load and environmental conditions as a highway paving material. The cylindrical specimens were (4.0 in.) in diameter and (4.0 in.) in height, were compacted using a compressive tool and the compaction process will stop when the specified height of the specimen was achieved to reach the target density and Figure 5 illustrated a group of specimens.

Figure 5. Group of compressive strength specimens

2.9. Index of Retained Strength Test

The test is conducted according to (ASTM D1075-11) [17]. This test covers the effect of water on compacted asphaltic mixtures, which is indicating for moisture susceptibility of mixtures. For this reason, prepared six specimens for each four mixtures and divided into two groups each group contains three specimens. Where group one was placed at a controlled 25 °C air bath for 4 hours and after that subjected to compressive strength. Group two placed at controlled 60 °C for 24 hours in a water bath and then placed at controlled 25 °C for 2 hours in another water bath and, then subjected to compressive strength as shown in Figure 6.

Figure 6. Test of compressive strength

2.10. Wheel Tracking Test

A wheel tracking device used to predict rut depths and dynamic stability of the field for specific projects based on the rut depth of the laboratory wheel track. Simulation tests evaluating HMA quality have been used by rolling a small loaded wheel machine repeatedly through a prepared HMA sample, this test measures the rut depth and DS at a stress level of 70 psi and 80 psi applied to rectangular slabs of dimensions (300×200×50) mm at a different test temperature (45 ˚C and 55 ˚C) for 5000 cycles, as shown in Figure 7.

Figure 7. Wheel tracking machine at university of Baghdad [18]

2.11. Preparation Specimens Using Roller Compactor

The asphalt concrete mixture was heated to (150 ˚C) then papers were placed inside the mould after covering the internal surfaces of the mould with a layer of oil. At the same time mould of roller compactor was heated for casting the mixture in, the spatula was used for levelling the mixture and then put the mould in the device for compacting. There are two options for compacting the slab specimen either compacting to a target density or target height, but in this work, the target density (2.3 gm/cm^3) was achieved. The slabs specimens were compacted and left cooling in the mould for (24) hours and then they extraction from moulds and cutting slabs for a wheel tracking test. Figure 8 presents roller-compacted used in this study and Figure 9 presents a group of wheel tracking slabs.

Figure 8. Dyna-Compact roller compaction machine at NCCLR [19]

Figure 9. Group of wheel tracking slabs

3. Results and Discussion

3.1. Marshall Test

A group of Marshall tests (stability, density, and Air voids) was analyzed to find the OAC for asphalt concrete mixtures AC (40-50) and five different asphalt contents for each mixture range from 4 to 6 per cent (by weight of total mix) with an increase of 0.5 %. Three specimens were prepared and tested for each mixture by using aggregate (19 mm maximum size gradation). The OAC was (4.93 %) for conventional and modified mixtures. The Marshall properties for OAC were of the tests meet the Iraqi requirement specification of (SCRB, 2003) [16].

The results showed that the Marshall quotient was increased by 9.62, 44.0 and 19.815% compared with conventional mixture when using modified asphalt mixtures with 0.5%, 1%, and 1.5% steel fibers respectively with aggregate gradation of (SCRB, 2003) [16], It was concluded that all the properties of the bituminous Concrete have been improved with the addition of the steel fibers, This is probably due to the well-distributed steel fibers in different directions of the bituminous matrix, which are highly resistant to shear displacement and strongly prevent any movement of aggregate particles as presented in Figure 10.

The maximum Marshall Quotient value was obtained at 1% fibers content. Then Marshall Quotient values decreased. The reason is due to the fibers may not distribute homogeneously in the mixture. Generally, applied loads are taken by the aggregate mass by means of contact points in Marshall samples. Because fibers created clustering in the mixture, as a result, the aggregate particles cannot be fully interlocked and contact between aggregate particles may be lost.

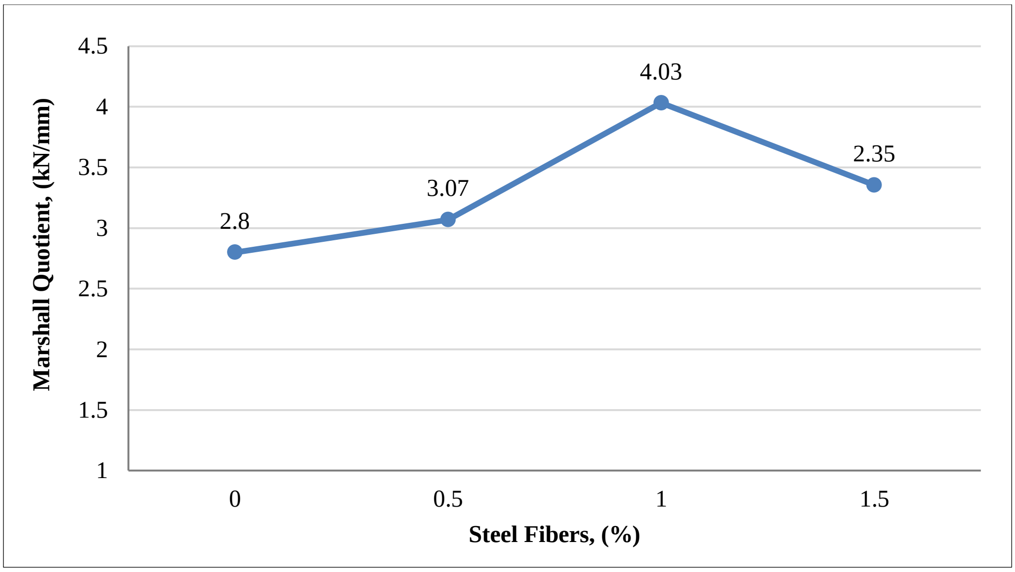

Figure 10. Effect steel fibers on Marshall Quotient

3.2. Compressive Strength Test

Evaluate moisture damage susceptibility by using Index of Retaining Strength (IRS) according to ASTM D-1074 and D-1075 [17]. The SCRB (2003) [16] pointed to the acceptable value of the IRS is (70%) or above which calculated as the ratio of compressive strength for conditioned specimens to the unconditioned specimens. the dry compressive strength increased by 22.46, 46.39 and 37.17% with addition of 0.5, 1 and 1.5% steel fibers. The modified asphalt mixtures with steel fibers were having the highest effect in wet condition, where the wet compressive strength improved by 28.04, 71.96 and 52.03% for the same content of steel fibers, the compressive strength test results divulge that modified asphalt with Steel Fibers less sensitivity to moisture damage than conventional mixture. The results of the IRS at the OAC for modified mixtures with 0.5, 1 and 1.5% of steel fibers higher than the conventional mixture by 4.55, 17.38 and 10.76% respectively, and this lead to reduce the moisture sensitivity of asphalt pavement, and the moisture resistance improve with the improve of IRS, Figure 11 stated the Index of Retained Strength test results.

All modified mixtures show higher compressive strength than the control mixture. This may be due to the improvement in the stiffness of the asphalt mixture. The presence of additive may strengthen the bonding between the aggregates provided by the binder and thereby enhancing the aggregate to aggregate contact. This will result in increasing the resistance to crushing for asphalt pavement.

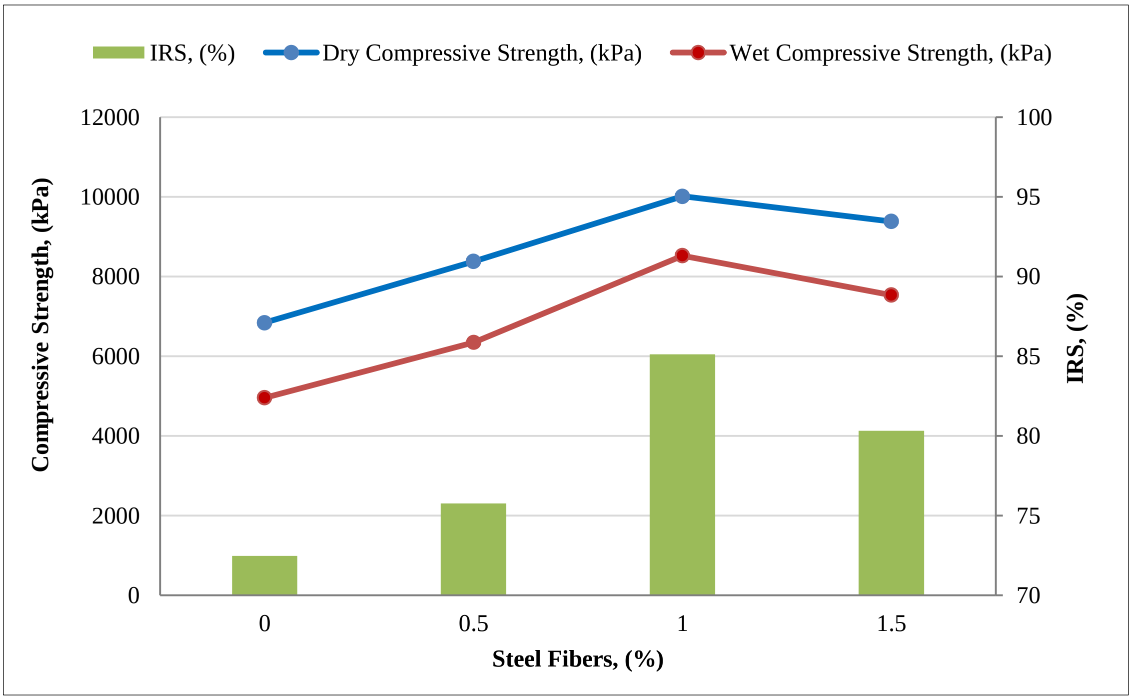

Figure 11. Effect steel fibers on Index of Retaining Strength

3.3. Wheel Tracking Test

The dynamic stability (DS) of the tested asphalt mixtures has been calculated according to Equation 2 [20]:

$$DS = \frac{N_2 - N_1}{d_2 - d_1} \times C_1 \times C_2 \quad (2)$$

Where: DS is dynamic stability (cycle/mm), N_1 is 3750 cycle, N_2 is 5000 cycle, d_1 is rut depth corresponding to N_1 (mm), d_2 is rut depth corresponding to N_2 (mm), C_1 and C_2 are coefficients equal one in this study.

Figures 12 to 15 show that modified asphalt mixtures with steel fibers have higher dynamic stability compared with the conventional mixture, Figure 12 shows a reduction in rut depth was 31.15, 65.57 and 49.18% with the addition of 0.5, 1 and 1.5% steel fibers, respectively, at temperature 45 ˚C and stress 70 psi, into the conventional mixture, and Figure 13 present the reduction in rut depth was 17.14, 70.48 and 44.76% with the addition of 0.5, 1 and 1.5% steel fibers, respectively, at temperature 55 ˚C and stress 70 psi, into the conventional mixture, and Figure 14 shows the reduction in rut depth was 16.44, 60.27 and 34.25% with the addition of 0.5, 1 and 1.5% steel fibers, respectively, at temperature 45 ˚C and stress 80 psi, into the conventional mixture and Figure 15 present the reduction in rut depth was 19.53, 51.56 and 38.28% with the addition of 0.5, 1 and 1.5% steel fibers, respectively, at temperature 55 ˚C and stress 80 psi, into the conventional mixture. This is probably due to the well-distributed steel fibers in different directions of the bituminous matrix, which are highly resistant to shear displacement and strongly prevent any movement of aggregate particles, therefore, the rutting resistance of the mixture increasing.

The dynamic stability values decreased and the rutting depth increased at the high content of steel fibers in asphalt mixture. The reason is due to the fibers may not distribute homogeneously in the mixture and created clustering in the mixture, as a result, the aggregate particles cannot be fully interlocked and contact between aggregate particles may be lost.

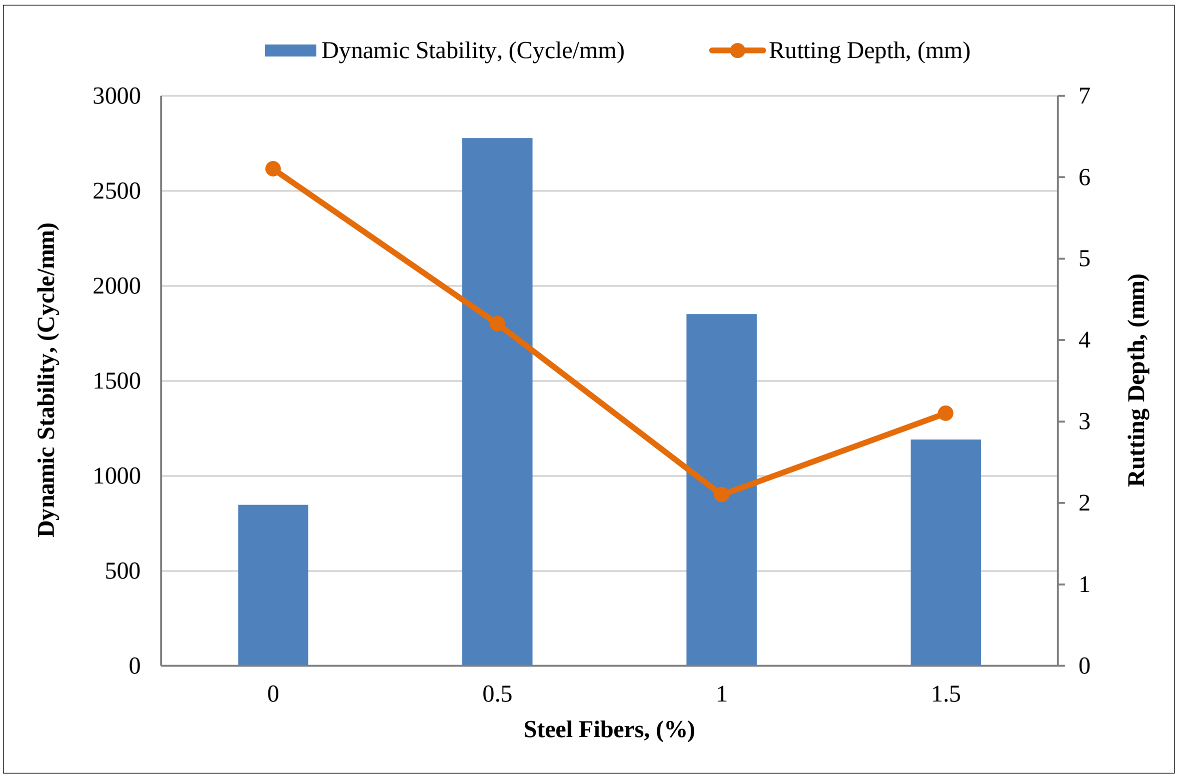

Figure 12. Present the effect of steel fibers on dynamic stability and rutting depth for (5000 cycle, 45 °C, 70 psi)

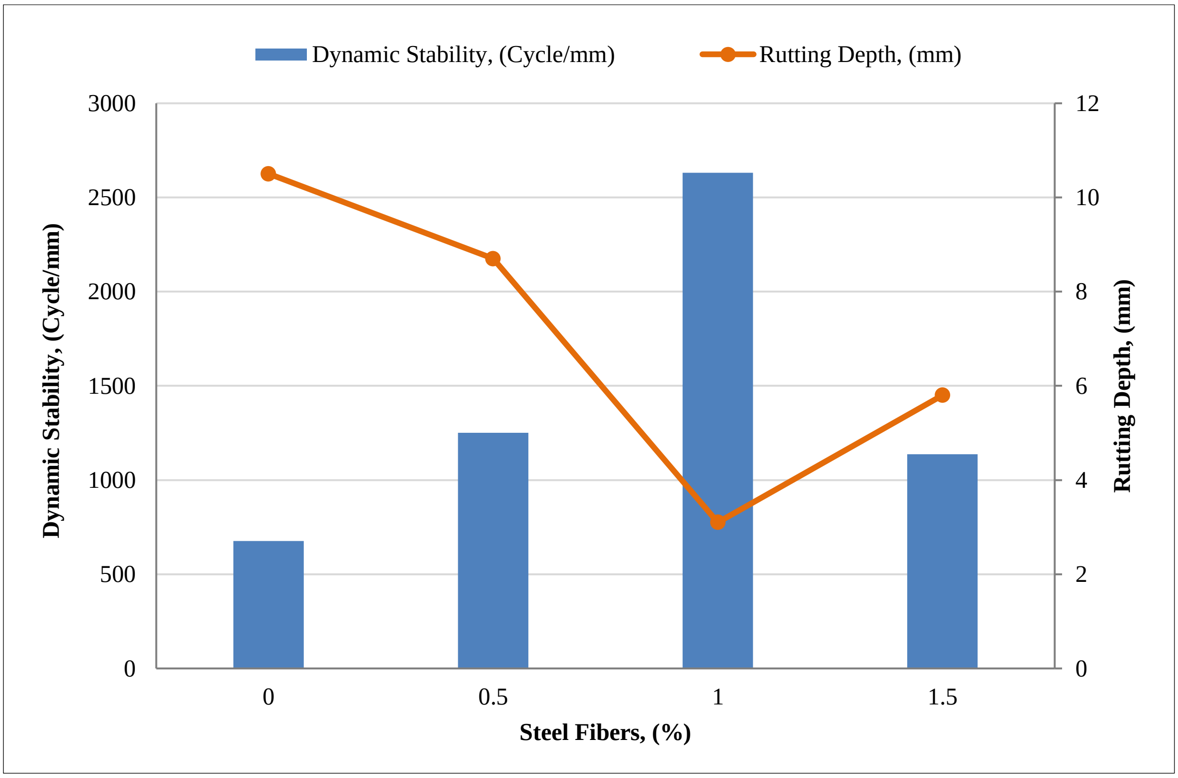

Figure 13. Present the effect of steel fibers on dynamic stability and rutting depth for (5000 cycle, 55 °C, 70 psi)

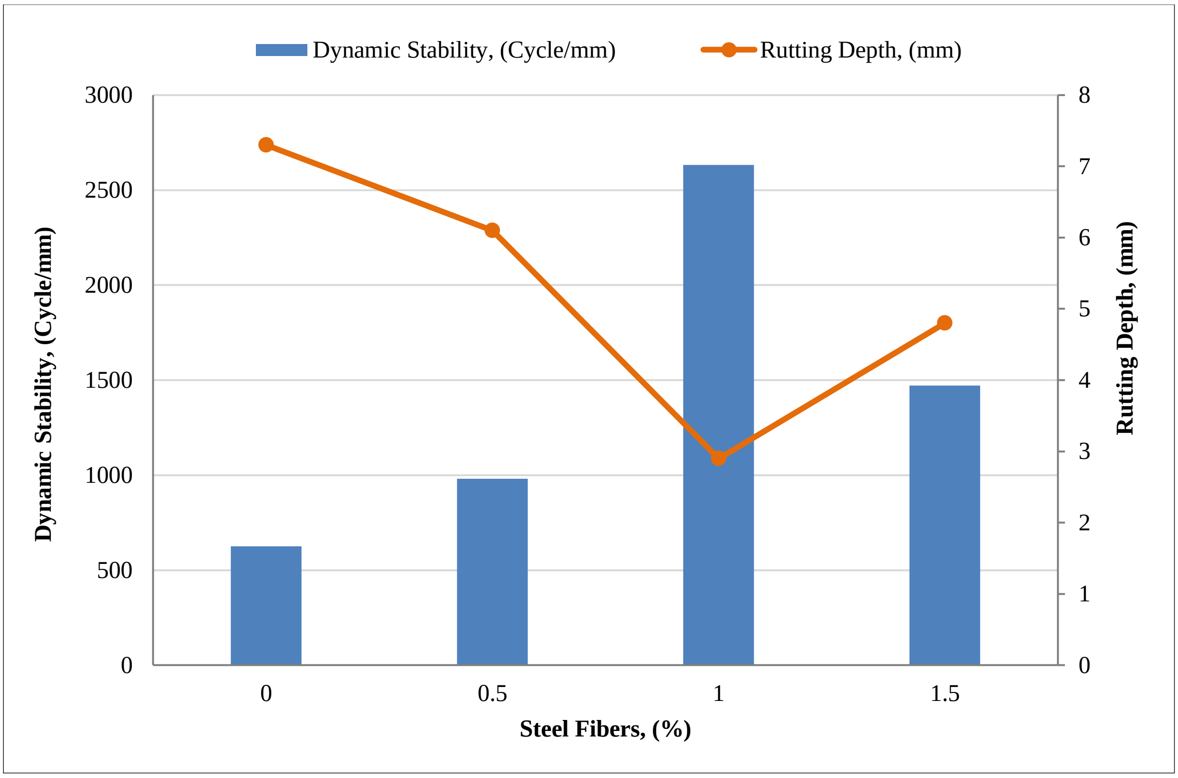

Figure 14. Present the effect of steel fibers on dynamic stability and rutting depth for (5000 cycle, 45 °C, 80 psi)

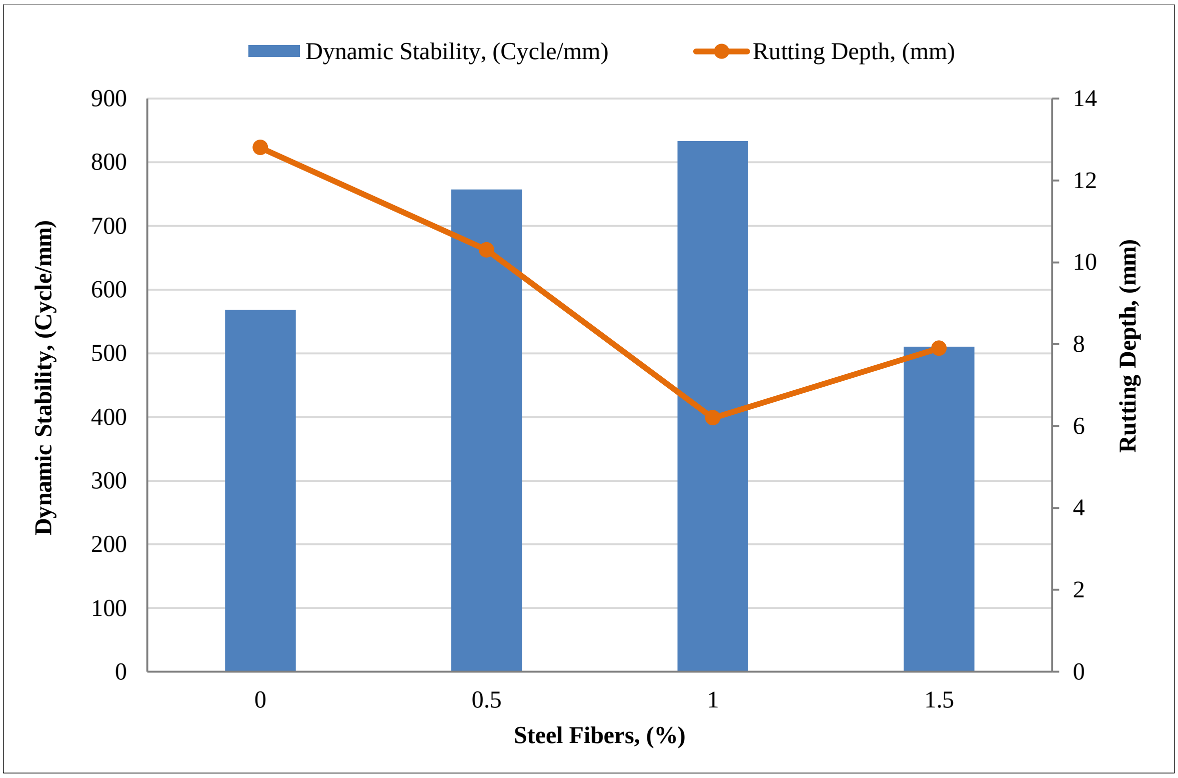

Figure 15. Present the effect of steel fibers on dynamic stability and rutting depth for (5000 cycle, 55 °C, 80 psi)

4. Conclusions

- Based on Marshall design method (stability and density voids analysis), the O.A.C was determined to be 4.93 % for conventional and modified asphalt mixtures using AC (40-50) Furthermore, the magnitude of the Marshall quotient was increased by 9.62, 44.0 and 19.82% for mixtures modified by steel fibers with 0.5, 1.0 and 1.5 % of respectively.

- The modified asphalt mixtures with 0.5, 1 and 1.5 % of steel fibers have an index of retained strength higher than conventional mixture by 4.55, 17.38 and 10.76% respectively. This referred to much more moisture damage resistance.
- The results of the wheel tracking test for modified asphalt mixtures with steel fibers showed higher values of dynamic stability compared with the conventional mixture.
- Reinforced asphalt mixtures with 0.5, 1.0 and 1.5 % of steel fibers have a rut depth lower than the conventional mixture by 31.15, 65.57 and 49.18 % respectively for 5000 cycles at 45 ˚C and 70 psi applied stress while this reduction values became 17.14, 70.48 and 44.76% as the temperature elevated to 55 ˚C. When the stress level increased to 80 psi, the same trend was observed.
- The overall results marked the magnitude of optimal steel fibers to be 1.0 %. Even though some additional cost will be witnessed, yet the gainful benefit from reducing the maintenance cost highly justify the worthily of using such fibers.

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7. Conflicts of Interest

The authors declare no conflict of interest.

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