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Research Article

Evaluation of the effect of para-aramid and micro-polyolefin fibers on permanent displacement in stone mastic asphalt

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ABSTRACT

This study examines the role of fibers formed from para-aramid and micropolyethylene in enhancing the performance of stone mastic asphalt (SMA) mixtures against permanent deformation. The use of SMA mixtures has the potential to mitigate permanent deformation and plasticity. Marshall tests, static creep tests, fatigue tests, and wheel track tests were conducted on samples prepared using the modified Marshall design method to achieve the research objectives. According to the test results, Samples containing 1.5% of the fiber mixture's total weight exhibited greater strength than other samples. Additionally, these samples demonstrated the most minor displacement against rutting among all prepared samples. Based on these findings, incorporating fibers containing Para-aramid and Micro-polyolefin in SMA mixtures can enhance the performance of this type of mixture against permanent deformations.

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1. INTRODUCTION

A multitude of factors influences road longevity. Variances in soil composition, traffic volume, vehicle types, and precipitation levels along different road sections can lead to diverse drawbacks and deficiencies. Failure to inspect, evaluate, and maintain roads promptly can lead to rapid deterioration. This results in significant financial losses and leads to dissatisfaction among road users. Hence, utilizing new asphalt technologies becomes imperative to extend the lifespan of roads and minimize road maintenance expenses. In the 1970s, researchers developed Stone Mastic Asphalt (SMA) mixtures to mitigate road pavement issues. This type of mixture offers significant advantages, including high stability, resistance to permanent deformation, and resilience against rutting [1]. SMA is a gap-graded asphalt mixture characterized by a substantial coarse aggregate, maximizing interlocking between aggregates to establish an efficient load distribution network. The stone skeleton is filled with a bitumen mastic mixture containing filler, to which fibers are added. This addition ensures sufficient stability of the bitumen and prevents drainage of the binder during transport and placement. Typically, SMA consists of a high proportion of coarse aggregates and a minimal amount of fine aggregates, resulting in a particle grading commonly known as gap-graded [2]. Fibers serve multiple purposes in SMA mixtures, including reinforcement, enhancing tensile strength, extending fatigue life, and preventing bitumen drainage. Mineral and cellulosic fibers are the most frequently utilized types within SMA mixtures [3]. Polypropylene fibers, for example, are known to have a beneficial effect on enhancing the resistance of SMAs against rutting [4]. Adding Proplast (Proplast is a highly porous material composed of a Teflon fluorocarbon.) as an additive to SMA mixtures improves their resistance to permanent deformations and reduces settlement caused by rutting [5].

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Table 1. Aggregate characteristics

Characteristic	Code	Unit	Results	Requirement
Coarse specific gravity	ASTM C-127-15 [18]	gr / cm^3	2.751	
Fine specific gravity	ASTM C-128-15 [19]	gr / cm^3	2.747	
Filler specific gravity	ASTM C-128-15 [19]	gr / cm^3	2.750	
Los Angeles	ASTM C-131 [20]	%	16	30 max.
Water absorption	ASTM C-127-15 [18]	%	0.85	2 max.
Flat and elongated	ASTM D-4791 [21]	%	12	5 max.
Crushed content (two faces)	ASTM D-5821 [22]	%	96	90 min.

Laboratory research indicates that using carbon fibers improves the resistance of SMAs to permanent deformations and enhances the load-bearing capacity of the surface layer [6]. The addition of glass fiber improves the properties of SMA mixtures by reducing instability, increasing flow value, and decreasing voids in the mix [7]. Furthermore, adding fiber enhances fatigue properties by increasing resistance to cracking and permanent deformation in bituminous mixtures [6]. Based on conducted studies, using 0.4% basalt fibers in SMA (Stone Mastic Asphalt) mixtures improves their resistance to permanent deformations up to 40 °C. Thus, it significantly prevents the formation of rutting in the wheel path [8]. The use of ethylene-vinyl acetate in SMA mixtures leads to an increase in dynamic modulus and resistance against the rutting phenomenon [9]. The results of uniaxial dynamic creep tests at temperatures of 25, 40, and 60 °C on SMA samples containing FRP (Fiber Reinforced Polymer) fibers plus Viatop (a pelletized blend of natural cellulose fibers and bitumen) indicate that the mentioned additive combination leads to an increase in the load-bearing capacity of the surface layer. These additives play an instrumental role in enhancing the resistance of these mixtures against rutting [10]. Natural fibers can indeed significantly enhance the rut resistance of SMAs. Adding natural fibers to pavement can increase structural resistance against pavement distress [11]. Studies have shown that the combination of basaltic and cellulose fibers has increased the resistance of SMA mixtures against the phenomenon of rutting. Recent research has shown that combining crumb rubber fibers and glass fibers improves the dynamic modulus of Stone Mastic Asphalt (SMA) mixtures [12]. Laboratory research has demonstrated that incorporating a mixture of polypropylene and aramid fibers into hot-mix asphalt enhances its mechanical properties [13]. Research indicates polyolefin-aramid composite fibers resist fatigue cracking within the blend [14]. Several studies have examined the impact of polyolefin-aramid fibers and hydrated lime on porous asphalt mixtures' functional and mechanical performance [15]. The test results indicate that mixtures modified with aramid fibers improve fatigue performance compared to the virgin mixture [16]. Research suggests that despite higher initial costs associated with SMA mixtures containing fibers, repair and maintenance costs are reduced considering the improved performance characteristics of these mixtures. Ultimately, this results in a lower life cycle cost [17]. The use of fibers to enhance the characteristics of asphalt mixtures continues by researchers in various parts of the world. This research aims to investigate the possibility of using fibers that, in addition to being cost-effective, can be easily added to SMA mixtures during the mixing stages, creating a homogeneous mixture.

2. MATERIALS AND METHODS

2.1. Aggregates

Basalt aggregates sourced from Uskumruköy in the western part of İstanbul, Türkiye, were used in this study. Samples underwent qualitative mechanical tests, and the outcomes are detailed in Table 1.

The grading curve depicted in Figure 1 illustrates the aggregate gradation used in the mixture [16].

As depicted in Figure 1, the curves represented by black lines delineate the upper and lower limits of the gradation stipulated in the code. In contrast, the red lines and dark dots illustrate the gradation curves of the aggregates used.

2.2. Binder

In this study, the binder used is 50/70, produced by Tupras Company. The physical characteristics of the used binder are outlined in Table 2.

2.3. Additive

Fibers, including Para-aramid and Micro-polyolefin, are formed from long molecular chains of poly-phenylene terephthalamide, and the inter-chain bonds significantly strengthen the material. These fibers derive some of their high strength from hydrogen bonds between neighboring carbonyl groups of polymer chain molecules. These interactions significantly impact the structure of stiff and sturdy molecules that typically create sheet-like structures. SIRJAN NANO Company, IRAN, provided the fibers used in this study. Some physical properties of the fibers, including Para-aramid and Micro-polyolefin, utilized in this research are presented in Table 3. A fiber image is provided in Figure 2.

2.4. Mix Design

In this research, the Marshall modification method [23]. It was employed to determine the optimal bitumen percentage for the mixture. The volume of air-filled spaces in compacted samples emerges as the paramount design parameter for SMA mixtures [24].

Marshall samples were prepared by gradually adding bitumen at a rate of 0.5%, ranging from 4.5% to 7% by weight

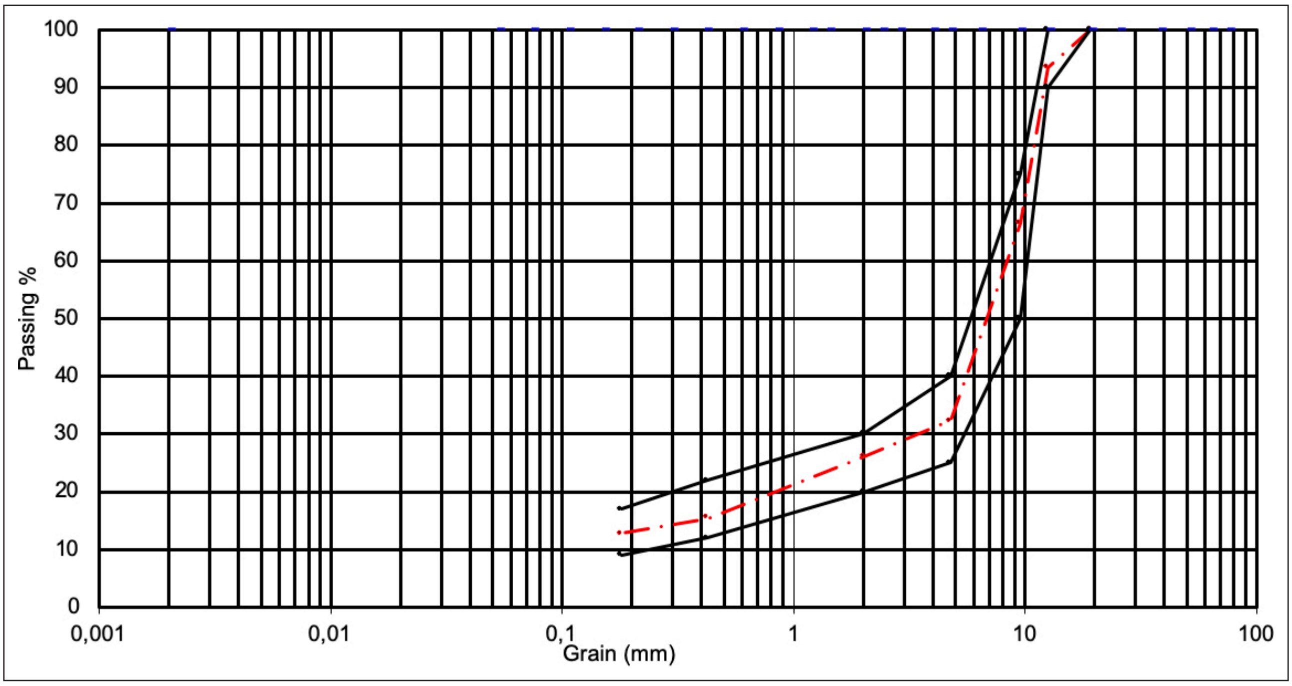

Figure 1. Granulometric curve.

Table 2. The physical properties of 50/70 binder

Test	Code	Unit	Results
Ductility	ASTM D-113	cm	**100+**
Softening point (ring and ball)	ASTM D-36	˚C	49
Penetration at 25 °C	ASTM D-5	mm / 10	60
Flash point	ASTM D-92	˚C	280
Specific gravity	ASTM D-70	gr / cm^3	1.01
Solubility in trichloroethylene	ASTM D-2042	%	**99**

Table 3. Properties of fiber

Properties	Values
Fiber length (mm)	6–19
Black density (g/cm^3)	2.6
Tensile stress (Mpa)	750–900
Flash point (°C)	500

Figure 2. Fiber Image www.sirjannano.com.

of the mixture. Afterward, the samples were compacted by applying 50 blows to both surfaces. Following determining the optimal bitumen content through preliminary tests, fibers were added to the aggregates at percentages of 0.5, 1, 1.5, and 2 of the total weight. In line with the research objectives, 130 Marshall and six samples of slab shape were prepared. In Figure 3, the image of the prepared samples is shown.

2.5. Marshall Quotient

The Marshall quotient is a parameter to estimate the stiffness of the asphalt mixture against permanent deformation (Fig. 4). By increasing the value of it, it can be said that the resistance of the asphalt mixture against permanent deformation has been improved [25].

2.6. Static Creep

The static creep test is crucial to assessing asphalt mixtures' durability under static loads (Fig. 5). In this evaluation, a uniaxial load is applied to the specimen, removed, and the resulting permanent deformation is measured. The creep modulus derived from this test enables the prediction of asphalt mixtures' susceptibility to thermal cracking and rutting. In our investigation, we adhered to the ASTM D6927 standard procedure for conducting the static creep test. Here, specimens were subjected to a 150 kPa compressive load at 25 °C for 3600 seconds, with deformation values

Figure 3. Sample prepare.

Figure 4. Marshall quotient test.

Figure 5. Static creep test.

recorded after this duration. The static creep values for the specimens were determined using Equation (1) [26].

$$Ecq\ (t) = \frac{\sigma}{\varepsilon c(t)} \qquad (1)$$

$E_{cq\,(t)}$: Creep Modulus in Time t (MPa), σ: Stress (MPa), $\varepsilon_{c\,(t)}$: Strain in Time t

2.7. Wheel Track Test

The wheel track test used prepared samples measuring 500 mm in length, 180 mm in width, and 50 mm in height. Approximately twelve hours before initiating the test, the samples were exposed to a temperature of 60 °C. The LCPC device was set up so that each wheel applied a force of 500 N to the samples. A laboratory-tired compactor provided the compaction for the samples. Typically, the tire was rolled over each sample for 30,000 cycles, exerting a load of 500 N to a pneumatic tire inflated to 600 kPa. This study conducted the LCPC test for each prepared mixture at various cycle intervals, specifically at 1000, 3000, 5000, 10,000, 30,000, and 50,000 cycles [27] (Fig. 6).

2.8. Fatigue Test

Asphalt samples endure repeated loading during the indirect tensile fatigue test until failure is reached (Fig. 7). Various stress sources are applied to the samples throughout this process. The fatigue life (N_f) is subsequently calcu-

Figure 6. LCPC test.

lated based on the stress level that triggers failure, which can be derived from the following equation [28].

$$N_f = K_1 \left(\frac{1}{\sigma}\right)^{K_2} \quad (2)$$

where: N_f: Fatigue life, K_1, K_2: Material properties dependent coefficients, σ: Stress

3. RESULTS

3.1. SMA Design Results

The mixing process steps were performed using the modified Marshall method, and the optimal bitumen amount was calculated. These calculations are detailed in Table 4.

As expected, the optimal bitumen percentage increased with the increase in fiber percentage.

3.2. The Marshall Quotient Results

As depicted in Figure 8, samples containing 1.5% fibers, Para-aramid, and Micro polyolefin have notably enhanced the Marshall Quotient. Consequently, it can be inferred that these fibers strengthen the stiffness of the mixture, thereby potentially contributing to the improvement of its resistance against deformations. The results show that samples containing 1.5% fibers Marshall Quotient increased by 26% compared to non-additive samples.

3.3. The Results of Static Creep

Marshall samples were prepared and subjected to a uniaxial static creep test. The results, showing the permanent deformations caused by static loading, are presented in Figure 9.

Figure 7. Indirect tensile fatigue test.

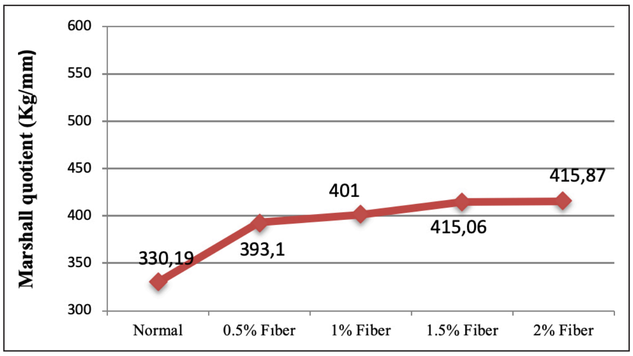

Figure 8. The results of the Marshall quotient.

As illustrated in Figure 9, upon applying load to the sample, there was an initial increase in instantaneous deformation, followed by a period where the rate of deformation increase slowed down. The findings indicated that the rise in instantaneous deformations in fiber sam-

Table 4. Results of Marshall's design

Mix type	Non. add.	0.5% fiber	1% fiber	1.5% fiber	2% fiber
Optimal bitumen (%)	6.59	6.67	6.74	6.79	6.81
Marshall stability (Kg)	1050	1195	1240	1295	1310
Flow (mm)	3.18	3.04	3.09	3.12	3.15
Air voids (%)	4	3,76	3,38	3.18	3.09
Voids in the mineral aggregate (%)	14.52	14,37	14.1	13.96	13.9
Voids filled with asphalt (%)	72.44	73.86	75.99	77.22	77.72

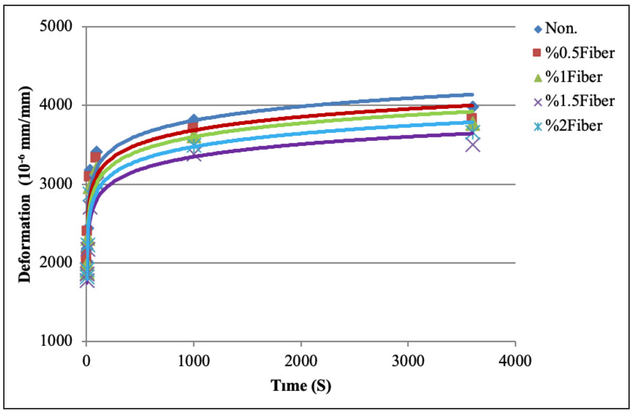

Figure 9. Static creep test results.

ples was lower than those without additives. In samples with additives compared to those without, the amount of these changes at the end of 3600 seconds showed a reduction of approximately 4%, 5.5%, 12%, and 8%, respectively. Adding fibers to the mixture has enhanced the bonding between bituminous aggregates, resulting in the modified mixture exhibiting more excellent resistance under creep loads. Therefore, it can be concluded that adding fibers containing Para-aramid and Micro-polyolefin enhances the resistance of SMAs against the phenomenon of rutting caused by static loads from heavy vehicles.

3.4. The Results of the Wheel Track Test

The results of the wheel track rutting test conducted using the LCPC method are presented in Figure 10.

The rutting on the asphalt surface resulting from 30,000 wheel passes should not exceed 6%, according to the LCPC method. Based on the graphs, it is evident that samples containing fibers with Para-aramid and Micro-polyolefin exhibited superior resistance to rutting. Based on the curves from the Rutting test using the LCPC method, only the samples containing 1.5% fibers could meet the conditions specified in the LCPC test standard. According to the comparative curves, incorporating 1.5% of these fibers in SMAs reduces the percentage of rutting in 30,000 load cycles by 26% compared to samples without additives. Additionally, the analysis of the results revealed that the percentage of rutting increased in samples with a rate exceeding 1.5%. The fibers have enhanced the mixture's resistance to permanent deformation by increasing its hardness. This test's results further validate the Marshall index test findings. Increasing the amount of fibers in the mixture reduces the friction between aggregates and mastic.

3.5 The result of Fatigue Test

The results of the indirect tensile fatigue test are depicted in Figure 11. The test was conducted at a temperature of 25 degrees Celsius using a prepared sample, with loading repeated until a deformation of 4 mm was observed in the samples. As the weight percentage of fiber increased, the number of loading cycles until complete deformation also increased. Furthermore, increasing the weight percentage

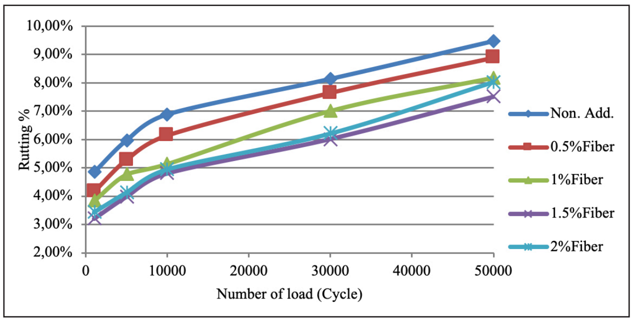

Figure 10. The results of the LCPC test.

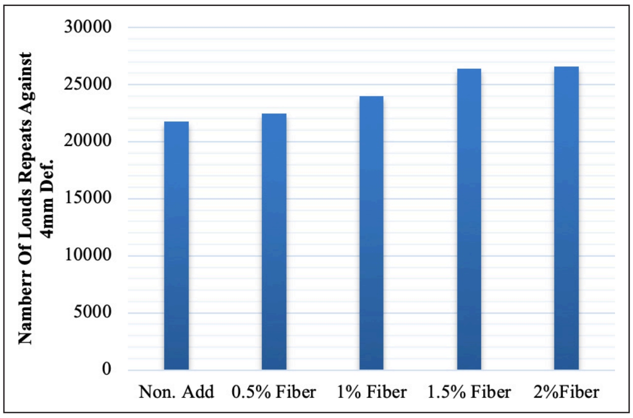

Figure 11. Fatigue test results.

of fibers, particularly those containing Para-aramid and Micro-polyolefin, led to more loading cycles until complete deformation ensued.

Experimental results indicated that including fibers containing Para-aramid and Micro-polyolefin improved the stiffness of the SMA mixture. Analysis of the resulting graph reveals that augmenting the number of fibers containing para-aramid and micro-polyolefin in SMA mixtures increased the load repetition cycle by 22% in the samples. Fibers reinforce the asphalt mix, resulting in improved durability. As a result of stresses acting in various directions, samples with additives experience lower stress concentration and fatigue failure compared to those without additives. Fatigue cracks are a significant contributor to pavement failure. A 30% increase in such failures can impair the performance of asphalt surfaces, necessitating repair operations. Employing protective methods becomes unavoidable [29]. Hence, enhancing fatigue resistance can substantially mitigate maintenance costs. Based on the fatigue test results, it is evident that incorporating para-aramid and micro-polyolefin fibers into Stone Mastic Asphalt (SMA) can effectively lower the maintenance costs associated with these pavement types.

4. CONCLUSONS

This study aimed to evaluate the effects of Para-aramid and Micro-polyolefin fibers on Stone Mastic Asphalts' fatigue and rutting properties. Below are the results of the investigation.

Incorporating fibers containing Para-aramid and Micro-polyolefin as additives to the SMA mixture enhanced the Marshall index parameter of this mixture type. This improvement suggests potential reinforcement against permanent deformations, contingent upon other necessary conditions being met.

The research results demonstrate that adding a combination of Para-aramid and Micro-polyolefin fibers to SMA mixtures enhances their resistance to deformation caused by heavy static loads.

Results from the rutting test revealed that samples without additives exhibited the highest rate of rutting, while those containing 1.5% fibers showed the lowest. Notably, the samples containing 1.5 fiber met the 6% rutting limit specified in the standard for hot asphalt mixtures, as determined by the rutting test conducted via the LCPC method.

Incorporating Para-aramid and Micro-polyolefin fibers into SMA mixtures enhances their fatigue resistance against repeated loading. Consequently, these fibers can reduce repair and retrofitting costs attributed to fatigue-related deterioration.

Those containing 1.5% Para-aramid and Micro-polyolefin fibers exhibited the most favorable outcomes among the prepared samples. However, increasing the fiber percentage disrupts the uniform texture of SMA mixtures, thereby diminishing the fibers' effectiveness in enhancing the mixture's resistance to permanent deformations.

Based on the results obtained from the conducted physical and functional tests, it can be concluded that incorporating fatty fibers containing Para-aramid and Micro-polyolefin into SMA mixtures can effectively contribute to reducing maintenance costs associated with these mixtures.

The research results indicated that this mixture exhibits significantly enhanced resistance to permanent deformations and demonstrates good resilience to rutting in hot climate areas with heavy traffic.

ETHICS

There are no ethical issues with the publication of this manuscript.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

USE OF AI FOR WRITING ASSISTANCE

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PEER-REVIEW

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